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TITLE OF THESIS..... Large Area Scanning Electron Microscopy

UNIVERSITY..... Carleton University

DEGREE FOR WHICH THESIS WAS PRESENTED..... Ph.D.

YEAR THIS DEGREE GRANTED..... 1974

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DATED..... May 9..... 1974

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LARGE AREA SCANNING ELECTRON MICROSCOPY

By

Bryan Douglas Forster, M.Eng.

A thesis submitted to the Faculty of
Graduate Studies in partial fulfilment
of the requirements for the degree of
Doctor of Philosophy

Carleton University
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May, 1974

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ABSTRACT

One of the difficulties associated with presently available scanning electron microscopes arises out of the use of the instrument to examine and photograph large specimen areas at high magnifications. The source of the difficulty is that only a small specimen area can be examined at any one time at high magnification so that many micrographs must be obtained to fully characterize the surface of a large specimen.

This difficulty becomes acute in the field of solid state device analysis and failure interpretation where many sample devices must be examined in detail over their entire surface areas to be certain that important detail is not overlooked. This necessitates that a very large number of micrographs be taken which is both time consuming and tedious. In addition, the probability of missing important detail while mechanically traversing the specimen is high.

One solution to this problem is to obtain a single *high resolution*, low magnification micrograph of the entire device surface which can later be expanded photographically to the desired end magnification. This solution, however, requires that two major changes be made in the standard scanning electron microscope. The microscope must be equipped with a high resolution display and recording system and the electron optics must be improved to reduce the deflection aberrations so that the microscope column resolution will be compatible with the high resolution display.

Suitable high resolution CRT display and recording systems are available commercially. The utilization of these on a standard scanning electron microscope is discussed in detail in the thesis. Also discussed are the photographic considerations which are involved in obtaining high quality micrographs from such a display system.

An analysis of the aberrations which can affect the focusing of an electron beam on axis in the scanning electron microscope is made in the thesis. Its purpose is to show that there is a distinct advantage to be gained by using postlens deflection for large area scanning electron microscopy and that, even with the longer working distance which postlens deflection entails, the axial resolution achievable in the microscope is satisfactory.

The aberrations introduced into the electron beam when it is deflected simultaneously in two orthogonal directions by magnetic fields are examined in detail in the thesis. The results of this study are intended to provide guidance for the design of deflection coils with smaller aberration coefficients and to provide the basis for a computer program which generates aberrated spot patterns as a function of deflection (electron beam spot profile "maps") for any given choice of aberration coefficient magnitudes and phase angles.

Experimental electron beam spot profile maps for five different deflection coils are presented together with matching computer-generated maps for three of these coils. The magnitudes and phase angles of the deflection aberration coefficients involved in these three matching maps are tabulated.

On the basis of this experimental work, one of the five experimental deflection coils is selected as suitable for large area scanning electron microscopy. This coil is shown to be capable of deflecting an electron beam over the necessary specimen area while maintaining the electron beam spot size at, essentially, its axial value. High resolution, low magnification micrographs are presented to demonstrate this.

Other potential applications of a deflection coil capable of deflecting an electron beam over a relatively large area while maintaining the electron beam resolution at its axial value are presented briefly as part of a discussion on suggested future work by means of which the large area scanning electron microscopy system could be improved.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Dr. J.A. Goldak, faculty advisor, for his continued support and encouragement throughout the duration of the project and for many stimulating discussions.

The author also wishes to express his appreciation to Dr. D.A. Shaw, formerly of the Communications Research Centre, Department of Communications and presently with SEMCO Instruments Co. Ltd., who, as external advisor, contributed through many stimulating discussions, advice, and encouragement to the success of the project.

Special appreciation is expressed to Dr. A.R. Molozzi of the Communications Research Centre for making available all the facilities of CRC and to Dr. C.D. Cox, who is presently with SEMCO Instruments Co. Ltd. and in whose former Reliability Analysis Group at CRC the project was carried out; without their cooperation, this project would not have been possible.

Special appreciation is also expressed to S.P. Newberry of Microbit Corp., Lexington, Mass. who agreed to serve as the external examiner.

Many members of the staff of the Communications Research Centre assisted in the completion of this project and it would be impossible to name them all. A few, however, deserve special mention: Dr. D.V. Sulway and W.W. Leus for helpful discussions; D.H. Gow for drafting; R.B. Bilodeau for the machine shop work including many revisions; J.E. Sawtell and G.G. Bower for the electronics assembly; K.C. Gustafson, J.A. Bingham, and J.P.M. Leduc for assistance with the final mechanical and vacuum pumping assemblies; W.A. Hartman for writing the computer program and for assistance in applying it; R.P. Beaulieu for assistance with the large area scanning microscopy; and I. Flentje and J.Y. Laflamme for assistance with the polymethyl methacrylate. Dr. Sulway and Messrs. Leus, Bingham, Leduc, and Beaulieu are presently with SEMCO Instruments Co. Ltd.

The first two years of the research work for this project were supported by a Post Industrial Experience Research (PIER) fellowship

awarded to the author by the National Research Council of Canada. The remaining year was supported in part by a personal services contract with the Communications Research Centre and in part by a Department of Communications University Research Contract awarded to Carleton University. Receipt of this support is gratefully acknowledged.

The author also wishes to thank Mrs. Ruth Thomas who typed the thesis in its final form from a difficult and sometimes confusing manuscript.

Finally, the author wishes to express his appreciation to his wife, Bernice, who mounted all the photographs and who, together with the author's family, was a constant and understanding support during the entire project.

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CHAPTER 1

INTRODUCTION

It is well known that the deflection of a focused electron beam, whether by electrostatic or magnetic means, causes the size of the focused spot to increase with increasing deflection angle, often at a greater than linear rate [1,2]. The cause of this spot growth is the introduction of aberrations into the electron beam by the deflection system, these aberrations being functions of the deflection angle and the deflecting field.

This phenomenon limits the performance of such devices as cathode ray tubes and has been the subject of investigations aimed at improving the characteristics of these tubes, particularly with respect to colour television applications [3,4,5].

More recently, interest has developed in the use of scanned electron beams for micromachining [6], pattern generation for integrated circuit photolithographic masks [7], direct pattern exposure on integrated circuits [8], and mass data storage [9]. All these applications share two characteristics. To be successful, they must be able to scan the electron beam over a relatively large area and they must maintain their focused spot size over this area. To achieve these characteristics requires that the deflection aberrations be controlled in some way.

The control of these aberrations for the case of a magnetically deflected electron beam is the subject of this thesis. For this work, the scanning electron microscope has been chosen as a vehicle for displaying these aberrations and their control. There is a difference in the standard scanning electron microscope as it is normally used, however, in that the presence therein of deflection aberrations and the resulting increase in focused spot size with deflection do not seriously affect the performance of this instrument.

The reason for this is related to the way in which the scanning electron microscope produces a magnified image of a specimen. This magnification is achieved by scanning an area on the specimen and then displaying the signal derived from this area on a cathode ray tube. The magnification is simply the size of the raster on the cathode ray

tube screen divided by the size of the scanned area on the specimen. To increase the magnification, the size of the scanned area on the specimen is reduced while the size of the cathode ray tube raster remains fixed.

Inasmuch as the cathode ray tube can resolve only a specified number of scan lines, there is no point in scanning more lines than this on the specimen and it is therefore seen that the probe size for the microscope electron beam can be allowed to increase as the magnification decreases. Accordingly, at low magnifications where the scanned area on the specimen is large, the increase in the electron beam focused spot size caused by the deflection aberrations does not seriously reduce the performance of the instrument, as it is normally used, below its higher magnification performance.

There is, however, a potential application of the scanning electron microscope in which the presence of deflection aberrations would affect the performance of the instrument. This application arises out of the difficulty associated with using presently available scanning electron microscopes to examine and photograph large specimen areas at high magnifications. The source of the difficulty is that, at high magnifications, only a small specimen area can be examined at one time; to examine and photograph the high magnification details of a large specimen area requires many micrographs.

This problem becomes acute in the field of solid state device analysis and failure interpretation. Here, nearly every sample device should be examined in detail over its entire area if important items are not to be overlooked. But to obtain many micrographs of a large number of devices in this way is very time consuming and tedious. In addition, the necessity of mechanically traversing the specimen while carrying out a high magnification inspection can easily result in important detail being missed.

One solution to this problem is to obtain a single high resolution, low magnification micrograph of an entire device in the scanning electron microscope and then to photographically enlarge this micrograph to the desired end magnification. To carry out this solution with presently available scanning electron microscopes, however, requires two major changes. The first is that the microscope must be equipped with a much

higher resolution display and recording system. The second is that the electron optics in the microscope must be improved to affect a considerable reduction in the deflection aberrations present in order to provide microscope column resolution compatible with that of the display/recording system required.

It is with this reduction and control of the magnetic deflection aberrations present in the scanning electron microscope so as to permit realization of the foregoing solution that this thesis is specifically concerned.

In the next chapter the utilization of a high resolution cathode ray tube display and recording system on a conventional scanning electron microscope is explored. The following chapter is concerned with scanning theory in high resolution cathode ray tubes and with obtaining high resolution photographs from the screen of such a tube. The balance of the thesis examines the reduction of electron optical aberrations to provide the necessary resolution in the microscope.

CHAPTER 2

LARGE AREA SCANNING MICROSCOPY

INTRODUCTION

The cathode ray tubes (CRT's) presently used to provide the display in a scanning electron microscope (SEM) have resolutions of, typically, 800 lines on a 10 cm. square screen. They therefore display images containing $(800)^2$ picture elements with each picture element occupying an area $10 \div 800 = 0.0125$ cm or $125 \mu\text{m}$ square. Although the SEM, with suitable corrections, could provide many more picture elements than this, the CRT's in common use could not display such higher information densities.

The resolution of the human eye is about $200 \mu\text{m}$ so that a photograph taken from one of the above CRT's could be enlarged by

$$\frac{200}{125} = X1.6$$

Any further enlargement would provide no further real information and would serve only to increase the apparent graininess of the photograph. It is instructive to examine this in terms of solid state device inspection.

Most of the integrated circuits currently in use are manufactured on chips 0.050 to 0.200 inch square. If it were desired to form a permanent record of a 0.100 inch square chip on a single micrograph using the present image display system, a magnification of X40 or less would have to be used. With the maximum permissible photographic enlargement of X1.6, the final photograph would have a magnification of no more than X64. Little useful information about an integrated circuit is revealed at such a low magnification; experience has shown that only at a magnification of about X350 does sufficiently detailed structure become visible to permit an assessment of device quality to be carried out. Using the present system of SEM recording, however, eighty micrographs would be required to completely cover a 0.100 inch square circuit at X350 magnification. Particularly when large numbers of devices are being examined, such a method is indeed out of the question.

As device size decreases, the maximum possible magnification increases so that, for small, discrete transistors, complete documentation at a

sufficiently high magnification is possible on one micrograph.

The foregoing is summarized in Figure 2-1. Curve A gives the maximum magnification possible, as a function of device size, for display of the complete device on the CRT of a standard SEM display; Curve B gives the same information incorporating the maximum permissible photographic enlargement of X1.6. (Curves C and D of Figure 2-1 are discussed later.)

THE HIGH RESOLUTION DISPLAY SYSTEM

There are currently at least two manufacturers marketing CRT display systems capable of resolving 5000 lines on a 3 inch square raster and with the associated magnetics and electronics necessary to provide linearity, repeatability, etc. commensurate with this resolution. The size of a picture element on such a CRT is 15 μ m square, making possible a maximum photographic enlargement of

$$\frac{200}{15} = X13.3$$

compared with X1.6 in the presently used system.

This is shown on curves C and D of Figure 2-1. Curve C gives the maximum possible magnification, as a function of device size, for display of a complete device within the 3 inch square raster of the high resolution CRT; for a given device size, curve C shows a smaller permissible magnification than curve A since the high resolution CRT raster is smaller than that of the presently used CRT. Curve D gives the same information as curve C but with the maximum permissible photographic enlargement of X13.3 included. Curve D shows that a 0.100 inch square device could, with such a high resolution display system, be fully documented in one micrograph at a magnification of X400.

In the case of smaller devices, correspondingly larger magnifications could be used. The maximum achievable magnification is limited, however, by the recording time required to maintain a given signal-to-noise ratio in the video signal from the SEM. (This is not immediately obvious; it is due to the fact that, to maintain 5000 scan lines on a small specimen, a small electron beam spot size must be used which, in turn, necessitates use of a low beam current. To maintain signal-to-noise ratio with a low

FIGURE 2-1
MAXIMUM MAGNIFICATION VS. DEVICE SIZE

beam current, a long recording time must be used.) At very small device sizes, this recording time becomes excessively long so that a limit must be set on the smallest device size which would be magnified the maximum possible amount. This limit could be set, for example, such that the frame recording time never exceeds 1500 seconds; this corresponds to a maximum overall system enlargement of X5000 for a 0.2 mm square device.

A photograph from such a high resolution system, enlarged the full X13.3 times, would be 40 inches square. It is anticipated that, normally, only a portion of the negative would be enlarged and printed and that the permanent record of the device would be the film negative. Alternately, the film negative could be projected with a X13.3 enlargement or scanned in a X13.3 magnification transmitted light microscope for examination.

SEM RESOLUTION

To exploit fully the capabilities of such a display system, the SEM must provide data to the same degree of resolution. Presently available SEM's, however, cannot do this without modification. At low magnifications, the electron beam in a SEM is deflected through relatively large angles (typically about 15°); with such large angle deflections, the deflection aberrations degrade the spot size of the electron beam on the specimen and consequently degrade the resolution attainable. Normally, this loss of resolution is unimportant since it occurs only at low magnifications and, with a standard display system, is not detectable. With a high resolution display system, however, these aberrations become important in that they limit the performance capabilities of the overall system. The resolution required in the SEM can be calculated as follows.

With a constant photographic enlargement of X13.3, the total system magnification is X13.3M, where M is the SEM magnification. Since the size of one picture element in the final image should be just equal to the resolution of the human eye, 200 μm , the size of a picture element on the specimen is given by

$$\frac{200}{13.3M} \mu\text{m}$$

The SEM magnification, M is given by

$$M = \frac{\text{scan size on CRT display}}{\text{scan size on specimen}}$$

which, assuming a 3 inch square scan on the CRT display, becomes

$$M = \frac{3 \times 2.54}{\text{scan size on specimen, cm.}}$$

The size of a picture element on the specimen then becomes

$$\frac{200}{13.3} \times \frac{\text{scan size on specimen, cm}}{3 \times 2.54} \text{ } \mu\text{m.}$$

Simplified, this gives

$$\text{required SEM resolution, } \lambda = 2000 \times \text{scan size on specimen in mm}$$

where picture element size has been equated to SEM resolution.

This is shown in curve A of Figure 2-2 for the device size range of interest. Also shown in curve B of Figure 2-2 is the resolution obtainable in a standard, unmodified Cambridge Stereoscan SEM as determined by Chang and Stewart [10]. Together, these two curves show that the Stereoscan will only provide the required resolution over the limited device size range of 0.40 to 1.15 mm and that resolution degrades rapidly for device sizes greater than 1.15 mm. (It should be noted here that device size is given by the length of the side of a square chip; the critical distance for electron optics, on the other hand, is one half the length of the diagonal of the square chip.)

Curves C, D, and E of Figure 2-2 show the resolution which can be obtained by applying both focus and astigmatism aberration corrections to the SEM electron optics. These curves were obtained from a Stereoscan SEM at working distances of 1, 5, and 10 cm, respectively by Chang and Wallman [11]. Curve D shows that, at a working distance of 5 cm and with appropriate aberration corrections, sufficient resolution can be obtained over the device size range of 0.40 to 3.8 mm, which is more than adequate for the majority of solid state device analyses.

FIGURE 2-2

DEVICE SIZE VS. SEM RESOLUTION

Curves B, C, D, and E of Figure 2-2 come together at a device size of about 0.40 mm square indicating that, for small device sizes, the microscope will provide the same resolution whether dynamically corrected or not. In addition, these curves, if extrapolated to the left, indicate an axial resolution of about $700\text{\AA}$, suggesting that they were obtained on a microscope adjusted to deliver a relatively high probe current. For small device sizes, i.e. those less than about 0.40 mm square, the microscope would be adjusted to provide a lower probe current and axial probe size so that for these devices another family of curves would apply. This reduced axial probe size, together with the reduced scan required with smaller devices which would in turn reduce the deflection-induced aberrations, permits sufficient resolution to be obtained on small devices without dynamic corrections.

Figure 2-2 discloses that, with suitable electron optics corrections, the SEM can be used in conjunction with a high resolution CRT display system for solid state device analysis in the manner outlined previously. It also shows that, over a limited range of device sizes, the SEM is compatible, without correction, with such a display system and device analysis procedure.

MICROGRAPH RECORDING TIME

Of equal importance with the resolution required of such a system is the recording time necessary to produce a satisfactory micrograph of a device. This time is dictated by two requirements: the first that the video signal from the SEM have a sufficiently high signal-to-noise ratio to permit recording of the required number of transmissivity steps on the film; the second that the recording time be consistent with the required exposure time for the film.

In Figure 2-3, the maximum permissible beam current which can be used for a given device size, at 5000 scan lines per frame, is plotted against device size; this curve also was obtained from Chang and Wallman's work [11] and applies to a tungsten thermionic emitter. Any increase in beam current above the value indicated in Figure 2-3 would degrade the resolution below the minimum acceptable value shown in Figure 2-2. With Figure 2-3, the recording time for a micrograph can be determined.

FIGURE 2-3
DEVICE SIZE VS. MAXIMUM BEAM CURRENT

The high resolution display will contain 5000 scan lines and $(5000)^2$ or 25×10^6 picture elements. If the time to record one micrograph is T seconds, then the time to record one picture element, t will be

$$t = \frac{T}{25 \times 10^6} \text{ sec.}$$

If the electron beam current incident on the specimen in the SEM is I_b , then the number of electrons incident per picture element, n will be

$$n = \frac{T}{25 \times 10^6} \times \frac{I_b}{e},$$

where e is the electronic charge. Since this is a random process, the uncertainty in this value is

$$\sqrt{n} = \frac{1}{5 \times 10^3} \sqrt{\frac{I_b T}{e}}$$

This is the signal-to-noise ratio at the point of impact of the incident beam on the specimen. The signal-to-noise ratio at the output of the SEM will be less than this due to the secondary electron emission process and the collection efficiency.

The above expression for signal-to-noise ratio can be equated to the signal-to-noise ratio required and can be used, with the data of Figure 2-3, to produce a curve of frame exposure time vs. device size. What is required, then, is the necessary signal-to-noise ratio.

Rose [12] states that the signal-to-noise ratio is related to the threshold contrast, C_T through a parameter he calls the threshold signal-to-noise ratio, k and that for visual observation $k = 5$

$$\begin{aligned} S/N &= k \cdot \frac{1}{C_T} \\ &= 5 \cdot \frac{1}{C_T} \end{aligned}$$

Rose also states that the threshold contrast is expressible in terms of the maximum luminance, L and the change of luminance per step, ΔL from the CRT:

$$C_T = \frac{\Delta L}{L}$$

Suppose it is desired, for example, to operate over a range of CRT luminance of 100 to 1 and that it is desired to detect 13 steps (14 levels) within this range. In this instance, it is evident that

$$L = 100,$$

$$\Delta L = \frac{100}{13} = 7.7,$$

$$C_T = \frac{7.7}{100} = \frac{1}{13},$$

and

$$S/N = 5 \times 13 = 65.$$

It is also evident that 7.7% incremental steps in the video signal could be detected with such a system.

For the present, it will be assumed that this signal-to-noise ratio of 65 is the required value for the SEM output signal. Later, in Chapter 3, it will be shown that it is an acceptable value through a consideration of the recording film which will be used.

Oatley, Nixon, and Pease [13] point out that the signal-to-noise ratio at the point of incidence of the electron beam with the specimen must be greater than the above value to allow for the extra noise introduced by the secondary electron emission process and by the collection efficiency; they quote a factor of two for this degradation, in agreement with Everhart [14]. Thus, a signal-to-noise ratio of 130 is required at the point of impact of the primary beam with the specimen. This can be equated with the previously obtained signal-to-noise expression, to yield

$$130 = \frac{1}{5000} \sqrt{\frac{I_b T}{e}}$$

This expression, together with the data of Figure 2-3, has been solved to produce Figure 2-4, a curve of frame exposure time vs. device size for 5000 line frames. This curve specifies the micrograph recording time on the basis of adequate signal-to-noise ratio in the film image. It is based on the use of a tungsten thermionic emitter; by changing to a lanthanum hexaboride emitter, for which the brightness is greater by a factor of ten, these recording times can be reduced by a factor of ten [11].

The frame exposure time required on the basis of film exposure is explored in the next chapter.

FIGURE 2-4
DEVICE SIZE VS. FRAME RECORDING TIME

CHAPTER 3

THE HIGH RESOLUTION CATHODE RAY TUBE DISPLAY AND RECORDING SYSTEM

INTRODUCTION

In the application of a high resolution cathode ray tube display system to a wide-field-of-view scanning electron microscope, one important parameter is the necessary dwell time for the CRT electron beam on a specific picture element of the image for correct film exposure. This parameter is of considerable importance as it can limit the minimum useable frame exposure time. The procedure for determining this time is presented in this chapter.

Also presented is a general discussion of photographic film and printing paper followed by a development of the specifications which the film and paper must meet to properly record the CRT image.

Finally, this chapter presents a discussion of the factors which contribute to nonuniform CRT luminance, and hence to errors in the final photographic print, as well as a discussion of the CRT modulation transfer factor and the CRT spot size. In particular, the CRT scanning geometry which must be used is developed.

THE LIGHT OUTPUT OF CATHODE RAY TUBES

In the operation of a CRT, an electron beam containing a known amount of current is accelerated by the anode potential to the face plate of the CRT. This face plate comprises a layer of phosphor deposited on the inside of the face plate glass and may or may not include a layer of aluminum deposited over this phosphor. The many factors entering into the construction of a CRT face plate, such as type, thickness, and surface finish of the phosphor and thickness and surface finish of the face plate glass, all affect the efficiency with which electron beam power is converted to light output. To attempt to calculate this efficiency for a specific CRT, many assumptions and approximations would have to be made. It is considered more realistic to accept a manufacturer's measured figure of efficiency, wherein for a known beam power the light output from the CRT face is measured directly, and to use this figure for subsequent calculations of film illumination.

The total light output from a source is generally specified in lumens which, by definition, incorporate the spectral response of the human visual system. Since, in the recording of CRT images on photographic film, the human visual system need not enter into the discussion (at least not until the final photographs are to be viewed), there is no advantage to be gained by employing photometric units. The calculations to follow will, therefore, employ radiometric units. This does not present any difficulty since it is becoming increasingly common to specify photographic film in terms of radiometric exposure, particularly for films intended for CRT recording.

The Litton Industries' high resolution cathode ray tube being considered for this application has an accelerating potential of 25 kV and a beam current of up to 1 μ A. The efficiency of conversion of beam power to light for this CRT, which has a P11 phosphor, is 1.5%, as measured by Litton Industries [15]. Thus, a maximum of 375 μ W of light can issue from the front of the CRT, integrated over the spectral band 400 to 700 nm. (This is measured on a 2 inch square raster and could be 25 to 50% high for a point or line, according to Litton Industries.)

The luminance of self-luminous and diffusely reflecting surfaces is often independent of the angle of inclination from the surface normal to the direction of observation, θ ; i.e., the luminance of the surface is the same in all directions. This requires that the luminous intensity of any element of the surface be proportional to cosine θ . Surfaces behaving in this fashion are called uniformly diffusing surfaces and are said to obey Lambert's cosine law of emission. Reflecting surfaces which obey the cosine law of emission for all directions of incident light are called uniformly diffuse reflectors and, if such surfaces reflect all the incident light, they are called perfectly diffusing surfaces. It is customary to consider CRT faces as perfectly diffusing surfaces [16]. (Reference may be made to Appendix 1 for clarification of this argument.)

CRT faces thus radiate their light flux in accordance with Lambert's cosine law of emission. In the specific case at hand, this light flux has a maximum value of 375 μ W, integrated over the spectral band 400 to 700 nm. To determine film illumination, it is necessary to find the portion of this flux which is collected by the objective lens of the recording camera.

FILM ILLUMINATION

The portion of the CRT flux which is effective in exposing the film is given by

$$E' = \frac{kF}{dS} \sin^2 \theta'_{\max} \quad (A1-21)$$

in which E' is the film illumination in watts per meter squared, k is the transmissivity of the camera lens, F is the flux emitted from the CRT in watts, dS is the area of one picture element on the CRT face in centimeters squared, and $\theta'_{\max}$ is the half-angle subtended at the film image point by the camera exit pupil. (Equation (A1-21) is derived in Appendix 1).

Inasmuch as the angle involved is small, the term $\sin^2 \theta'_{\max}$ can be expressed accurately enough by

$$\sin^2 \theta'_{\max} = \left(\frac{D/2}{f} \right)^2 \quad (3-1)$$

in which D is the diameter of the exit pupil of the camera lens in millimeters and f is the focal length of the camera lens, also in millimeters. Equation (3-1) applied provided the object distance for the lens is infinite; in practice, this condition is met if the object distance is some 300 to 400 times the focal length of the lens. In those instances where the object distance is short or *finite* a correction must be applied to the indicated f /number of aperture setting of the camera lens. This correction is discussed in detail below.

The f /number of the camera lens can also be expressed in terms of D , and f and is given by

$$f/\text{number} = \frac{f}{D} \quad (3-2)$$

Accordingly, $\sin^2 \theta'_{\max}$ can be written as

$$\sin^2 \theta'_{\max} = \frac{1}{4(f/\text{number})^2} \quad (3-3)$$

and the film illumination can be presented in the form

$$E' = \frac{kF}{dS} \cdot \frac{1}{4(f/\text{number})^2} \quad (3.4)$$

Now the camera lens transmissivity is a measure of the light lost due to internal absorption and reflection. In the case of lenses intended for critical illuminance applications, it is convenient to recalibrate the lens aperture markings in terms of so-called "T stops" which take this loss into consideration (see Kingslake [17]). The relationship between the two numbering systems is

$$T/\text{number} = \frac{f/\text{number}}{k^2} ; \quad (3-5)$$

the film illumination therefore simplifies to

$$E' \approx \frac{F}{dS} \cdot \frac{1}{4(T/\text{number})^2} \quad (3-6)$$

In instances where the camera lens must work between finite object and image distances, the effective T/number is less than the indicated T/number and this so-called bellows extension correction must be included in equation (3-6). The correction is given by [17]

$$\text{effective } T/\text{number} = \text{indicated } T/\text{number} \cdot \frac{v}{f} \quad (3-7)$$

where v is the image distance. But the ratio v/f is expressible in terms of the camera magnification, m through the basic lens equation

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v} \quad (3-8)$$

in which u is the object distance and the other parameters have been previously defined.

Multiplying equation (3-8) through by v gives

$$\frac{v}{f} = \frac{v}{u} + 1 \quad (3-9)$$

The ratio v/u is defined as the camera magnification, m so that the ratio v/f becomes

$$\frac{v}{f} = m + 1 \quad (3-10)$$

Accordingly, equation (3.7) can be rewritten as

$$\text{effective T/number} = \text{indicated T/number} \cdot (m + 1) \quad (3-11)$$

and the film illumination can be expressed as

$$E' = \frac{F}{4dS} \cdot \frac{1}{(\text{indicated T/number})^2} \cdot \frac{1}{(m + 1)^2} \quad (3-12)$$

Equation (3-12) is correct for the illumination of an on-axis image point. For the illumination of off-axis image points, the reduction in illumination as a function of the angle, ϕ between the principal ray and the axis must be taken into account [19].

Consider Figure 3-1. dS_1 is an element of a uniformly diffusing surface whose luminance in all directions is L . dS_2 is an elemental area illuminated by dS_1 . The luminous intensity of dS_1 in the direction of dS_2 is $LdS_1 \cos \phi$; this is the flux per unit solid angle emitted in the direction ϕ . Now dS_2 subtends the solid angle $dS_2 \cos \phi / r^2$ at dS_1 so that the total flux received by dS_2 from dS_1 is

$$dF = LdS_1 \cos \phi \cdot \frac{dS_2 \cos \phi}{r^2}$$

The illumination of dS_2 is, then,

$$dE = \frac{dF}{dS_2} = \frac{LdS_1 \cos \phi \cos \phi}{r^2}$$

FIGURE 3-1
ILLUMINATION OF AN OFF-AXIS IMAGE POINT

The distance r is given by

$$r = \frac{u}{\cos \phi} + \frac{v}{\cos \phi}$$

$$= \frac{u + v}{\cos \phi}$$

Substituting,

$$dE = \frac{LdS_1}{(u + v)^2} \cos^4 \phi \quad (3-13)$$

The distribution of illumination across the film plane is, then, proportional to $\cos^4 \phi$; the term $\frac{LdS_1}{(u+v)^2}$ is the axial value of the illumination.

Inserting this term into equation (3-12) gives the final expression for film illumination:

$$E' = \frac{F}{4dS} \cdot \frac{1}{(\text{indicated } T/\text{number})^2} \cdot \frac{1}{(m+1)^2} \cdot \cos^4 \phi \quad (3-14)$$

in which F is the flux emitted from the CRT in watts, dS is the area of one picture element on the CRT face in centimeters squared, indicated T/number is the aperture setting on the lens shutter and applies in those instances where the lens aperture markings have been recalibrated to take into consideration transmission losses in the lens, m is the camera magnification given most directly by film image size divided by CRT raster size, and ϕ is the angle between the camera axis and a line from the centre of the lens to the corner of the film image (for the extreme case of film illumination reduction); E' , the film illumination, is then given in units of ergs per centimeter squared - second.

This film illumination, when incident on the film for a length of time known as the exposure time, gives the film exposure. In the next section the exposure time is considered and this is followed by a discussion of film exposure.

EXPOSURE TIME

At this point consideration can be given to the exposure time per picture element in the CRT and the decay time of the CRT P11 phosphor, during which time light is still being emitted that will contribute to film exposure.

Integration of a typical characteristic curve [20] for the decay of a P11 phosphor shows that, during this decay interval, an equivalent film exposure time per picture element of 32×10^{-6} seconds applies. To this must be added the film exposure time which will apply when the CRT electron beam is bombarding the picture element in question. Taking this latter time as $t \times 10^{-6}$ seconds, the total film exposure time becomes $(32 + t) \times 10^{-6}$ seconds for both the active fluorescence and decay mode phosphorescence together.

It should be noted that the above integration was performed on a typical published curve. In the operation of a specific CRT, it may be necessary to make some adjustment in the above exposure time figure to take account of different manufacturers' phosphors and different CRT accelerating potentials, electron beam currents, etc.

FILM EXPOSURE

As pointed out in a previous section, film exposure is the product of film illumination and exposure time. Accordingly, equation (3-14) for film illumination can be combined with the exposure time found in the previous section and the result solved, after substitution for the parameters involved. The expression to be solved is

$$\text{film exposure} = \frac{F}{4dS} \cdot \frac{1}{(\text{indicated } T/\text{number})^2} \cdot \frac{1}{(m+1)^2} \cdot (32+t) \times 10^{-6} \quad (3-15)$$

where the term $\cos^4 \phi$ in equation (3-14) has been omitted; account of its effect will be taken separately.

In a later section, which discusses the recording film, it will be seen that, in order to arrive at a standard film speed, a film exposure of 1 erg/cm² is required. With this in mind, the following choices are made for the parameters of equation (3-15).

F, the flux emitted from the CRT in watts, was found earlier to have a maximum value of 375 μ W. To ensure that the CRT meets its spot size specification, which will be discussed fully in a later section, it is desirable not to run the CRT at this maximum output [21]. Accordingly, an output flux of less than 375 μ W or 3750 erg/sec should be chosen.

dS is the area of one picture element on the CRT face in centimeters squared. Since the CRT raster is 3 inches square and comprises 5000 scan lines with 5000 picture elements per line, the area occupied by each picture element is

$$\frac{3 \times 2.54}{5000} = 0.001524 \text{ cm square}$$

The actual spot, however, is round so that its area is

$$dS = \frac{\pi}{4} \cdot (0.001524)^2 = 1.825 \times 10^{-6} \text{ cm}^2$$

m is the camera magnification and is given by the ratio of the film image size to the CRT raster size. In the case of 4 x 5 sheet film, the film image is 3.75 inches square so that the camera magnification is

$$m = \frac{3.75}{3} = 1.25$$

In the case of 120 roll film, the film image is 55 mm or 2.16 inches square so that the camera magnification is

$$m = \frac{2.16}{3} = 0.72$$

The camera lens which is to be used is a Rodenstock Apo Ronar 150 mm, T/9 lens mounted in a Synchro Compur shutter. The shutter has full and half T stops from T/9 through T/45.

t is the active picture element exposure time, i.e. the time during which the CRT electron beam is actively bombarding the picture element in question. It must be chosen in conjunction with the frame exposure time found in Chapter 2 from signal-to-noise ratio considerations. Accepting for now that 0.4 mm square is the smallest device size which would be examined, the required frame exposure time is seen to be, from

Figure 2-4, 340 seconds. This time decreases, as can also be seen from Figure 2-4, with increasing device size to 2.8 seconds for a device 2.5 mm square which is about the largest device that would be examined in a single exposure. These two frame exposure times correspond to the following picture element exposure times on the basis of 25×10^6 picture elements per frame:

$$t_{\max} = \frac{340}{25 \times 10^6} = 13.6 \text{ } \mu\text{sec}$$

$$t_{\min} = \frac{2.8}{25 \times 10^6} = 0.112 \text{ } \mu\text{sec}$$

Choosing $t_{\max} = 13.6 \text{ } \mu\text{sec}$ together with $m = 0.72$, $F = 96 \text{ } \mu\text{W} = 960 \text{ erg/sec}$, $dS = 1.825 \times 10^{-6} \text{ cm}^2$, and $T/\text{number} = 45$, the film exposure is found to be, from equation (3-15), 1 erg/cm^2 .

Choosing, on the other hand, $t_{\min} = 0.112 \text{ } \mu\text{sec}$ together with $m = 1.25$, $F = 234 \text{ } \mu\text{W} = 2340 \text{ erg/sec}$, $dS = 1.825 \times 10^{-6} \text{ cm}^2$, and $T/\text{number} = 45$, the film exposure is again found to be, from equation (3.15), 1 erg/cm^2 .

Thus, the desired film exposure of 1 erg/cm^2 can be obtained by balancing the flux emitted from the CRT against the variations encountered in the other parameters in equation (3.15).

Before leaving this section, it is necessary to examine the extent to which the film exposure at the corners of the image will differ from that at the camera axis; this distribution is proportional to $\cos^4 \phi$ where ϕ is the angle between the camera axis and a line from the centre of the camera lens to the corner of the image.

To determine the angle ϕ , the image distance v from the camera lens to the film plane is required. From equation (3-10), v is seen to be

$$v = f(m + 1) \quad (3-16)$$

L

For the case where $m = 1.25$ (4 x 5 sheet film), v is

$$v = 150 (1.25 + 1)$$

$$= 337.5 \text{ mm}$$

(The focal length of the lens, f is 150 mm, as noted previously.) The distance, ℓ from the camera axis to the corner of the 3.75 inch square image is given by

$$\ell = \sqrt{2} \times \frac{3.75}{2}$$

$$= 2.65 \text{ inches}$$

$$= 67.3 \text{ mm}$$

Accordingly,

$$\phi = \tan^{-1} \frac{67.3}{337.5}$$

$$= 11.28^\circ$$

and

$$\cos^4 \phi = 0.9250$$

The film exposure for the case of 4 x 5 sheet film will therefore be 7.5% less at the corners of the image than on the camera axis.

For the case of 120 roll film ($m = 0.72$), v is

$$v = 150 (0.72 + 1)$$

$$= 258 \text{ mm}$$

The distance ℓ is, since the image is 55 mm square,

$$\ell = \sqrt{2} \times \frac{55}{2}$$

$$= 38.9 \text{ mm}$$

Accordingly,

$$\phi = \tan^{-1} \frac{38.9}{258}$$

$$= 8.57^\circ$$

and

$$\cos^4 \phi = 0.9560$$

The film exposure for the case of 120 roll film will therefore be 4.6% less at the corners of the image than on the camera axis.

In both cases this departure from uniform film exposure is unacceptable and it must therefore be corrected for. Two methods suggest themselves. In the first method, the microscope scan generator could be redesigned to decrease the scan speed slightly as the CRT spot moved away from the camera axis thereby increasing the exposure time slightly for off-axis picture elements in proportion to $\cos^4 \phi$. In the second, a field of uniform luminance, 3 inches square, could be photographed with the camera under discussion and the resulting negative could then be used in the camera to decrease the film exposure on-axis with respect to that off-axis. Theoretically, this exposure correction plate could be used anywhere between the CRT screen and the film plane but to ensure that any flaws in it were not in focus it would be best located as close to the lens as practicable, after being reduced to the proper size. The exposure correction plate, while correcting the nonuniform distribution of illumination across the film plane, would reduce this illumination by a few percent. A small increase in the CRT output flux would take care of this error.

RECORDING FILM: GENERAL DISCUSSION

With the film exposure defined, it is now possible to select a film for recording the CRT image. There are five main film parameters which must first be discussed before a specific recording film can be chosen from the great number available; these parameters are exposure range, density range, gamma, speed, and resolving power.

Three of these parameters, the exposure range, density range, and gamma, are related through a curve known variously as the film characteristic

curve, the D-logE curve, the H and D curve, and the Hurter and Driffield curve after its originators. Essentially, this curve describes the way in which a photographic material responds to exposure and development, as is described below [22].

An example of the film characteristic curve is shown in Figure 3-2. To produce such a curve, the photographic material is given a series of carefully controlled exposures, each exposure step differing from the preceding step by a constant factor such as 2 or the square root of 2. After this step exposure, development under standardized conditions produces a grey scale with a series of steps differing in density. The density of each of these steps is then measured with a densitometer and a curve of density vs. logarithm of exposure is drawn. In Figure 3-2 an exposure scale is also shown as well as an opacity scale (antilog density) and a transmissivity scale (reciprocal of opacity). Traditionally, the exposure scale is given in units of meter-candle-seconds, 1 m-c-s being equal to 5 ergs/cm². The slope of any part of the curve indicates how rapidly the density will change with a change in exposure. In view of the general shape of the characteristic curve, it may be discussed in terms of the three distinct regions shown in Figure 3-2.

The toe region: Exposures less than that designated A produce no image density on development. Exposures from A to B (the toe region) do produce measurable densities on development. Since, in this region, the slope of the curve increases with increasing exposure, the relationship between density and log exposure is nonlinear. This portion of the curve is widely used in making negatives.

The straight-line region: In the region of the curve from B to C the gradient is constant and the density increases as a direct function of the logarithm of exposure. In this region, if the exposures for all the image areas are doubled, for example as by doubling the exposure time, the densities of all the areas will be increased equally and there will be no change in the density separations between the various image areas. This region also is widely used in making negatives.

FIGURE 3-2
FILM CHARACTERISTIC CURVE
(FROM EASTMAN KODAK COMPANY [22])

The shoulder region: Above C, the gradient of the curve decreases for further increases in exposure; this is the region of overexposure. Eventually the curve becomes horizontal and exposure differences are no longer recorded as density differences. Negatives recorded in this region show a loss of separation of highlight tones, the characteristic of extreme overexposure. This region should not be used in making negatives.

The slope of the straight-line region of the characteristic curve is designated the *gamma* of the film. A knowledge of the gamma of a film provides two useful pieces of information. In the first place, the film gamma is a measure of the contrast that a particular film will provide in a photographed image, a higher gamma film providing a higher contrast photograph. The gamma of some films is so high, in fact, that they can be considered almost binary in nature. Such films find application in the photocopying of line drawings and would be most unsatisfactory for recording pictorial images. The second useful piece of information provided by the film gamma is based on the fact that it can be plotted against the development time, for specified conditions of agitation and temperature. The resulting time-gamma curve can be used to determine the development time required to produce a desired degree of development for the particular film and developer combination investigated.

The *exposure range* or latitude of a film is the range of luminance values which can be reproduced by the film. It is indicated on the characteristic curve by the log exposure interval between a point fairly low on the toe of the curve and a point on the shoulder.

The *density range* which can be produced on a film is related to the exposure range of the film, as defined above, through the film gamma. It is the density range which determines the exposure required for the printing paper and the "scale index" for the particular paper which must be used. The degree of development is the single most important factor in controlling the density range of a film.

The *speed* of a photographic film is determined from the exposure required to produce a film density of 0.1 above base plus fog. Base density is that density which is measured on unexposed and undeveloped film; base plus fog density is that density which is measured on

unexposed but developed film. Specifically, film speed is defined [23] by USA Standard PH2.5 as 80% of the reciprocal of the exposure, E_S in meter-candle-seconds required to produce a density, D_S of 0.1, above base plus fog density, D_f :

$$\text{USAS film speed} = \frac{0.80}{E_S \text{ at } D_S = 0.1 + D_f}$$

The final main parameter describing photographic films which must be discussed in this general introduction is *resolving power* [24]. Actually, resolving power is only one of three factors of interest which are normally grouped under the heading *definition*; they are sharpness, graininess, and resolving power. *Definition* is the impression of detail which is received by an observer when viewing a photograph. Although often used erroneously as a synonym for sharpness, definition refers to the overall appearance of detail while sharpness is concerned only with the boundaries of well-resolved elements of detail.

If a knife edge is placed in contact with a photographic film and the film is exposed, the density of the developed image does not change abruptly at the former site of the knife edge but encroaches into the shielded area forming a diffuse boundary. The variation in density across this boundary controls the impression of *sharpness*. The spreading of density into the shielded area is due to the diffusion of light within the emulsion and is affected by the distribution of grain sizes in the emulsion and the emulsion thickness.

If a negative is viewed at high magnification, a grainy or granular appearance is evident. This impression of image nonuniformity is called *graininess* and it is caused by the irregular distribution of the silver grains rather than by the size of the grains themselves. Graininess tends to increase with emulsion speed as well as with the density of the negative so that overexposure or overdevelopment of the negative should be avoided. The graininess of both negatives and prints increases with increasing gamma of the material on which they are made. Since, generally, a low gamma negative is printed on a high gamma paper and vice versa, what is gained by holding down the gamma of one is lost by the high gamma of the other. However it is generally true that a low gamma negative and

a high gamma paper is a more favorable combination than the reverse. Graininess in the print is most apparent in the lighter middle tones, especially in large, uniform areas. It can be concealed somewhat by defocusing slightly in enlarging or by using rough surface paper but only at a sacrifice in sharpness.

Resolving power refers to the ability of an emulsion to record fine detail distinguishably. It is measured by photographing a parallel-line test chart and examining the resulting developed image in a microscope. The maximum number of line pairs per millimeter that are just recognizable as separate lines and spaces is termed the limiting resolving power of the film. The resolving power of a film depends on the contrast of the test chart but is only slightly affected by the degree of development of the film. Resolving power falls off rapidly at high and low exposure values, reaching a maximum at some intermediate exposure. It is at this intermediate exposure that the limiting resolving power capability of a film is quoted. This loss of resolving power with over- and under-exposure is one reason for ensuring that negatives are exposed correctly. The resolving power of a camera/film combination is also affected by the resolving power of the lens. To realize the maximum resolving power which a film is capable of, the lens resolving power should be at least three times that of the film.

From the foregoing, it is apparent that graininess, resolving power, and sharpness together affect film definition. It is possible, however, under certain conditions for one of these factors to be more important than the others in controlling the definition of a photograph.

If a negative made on coarse grained film is enlarged, graininess usually becomes objectionable before the loss of resolving power or sharpness; thus, in this instance, graininess becomes the limiting factor in definition.

Resolving power is not a definite indication of a film's ability to produce sharp pictures and it can in some instances be misleading. Under normal viewing conditions and at normal reading distances the eye can resolve about 2.5 line pairs per millimeter. If the film resolving power is too low to reproduce detail about twice this fine in the print, the definition will be limited by the resolving power. On the other hand,

if the resolving power is adequate for the purpose at hand and if graininess is not noticeable, the sharpness of the image is the important factor affecting definition.

Before leaving this general discussion of recording film, consideration should be given to the printing paper on which the final image will be produced [25]. There are six properties of photographic paper which are of interest to the photographer. These are (1) the printing grade of the paper, (2) the speed of the emulsion, (3) the tint of the paper, (4) the texture of the paper surface, (5) the gloss of the paper surface, and (6) the colour of the photographic image. The first two properties may be considered photographic properties while the others deal mainly with physical characteristics. For the purposes of this thesis, only the first property, the printing grade of the paper, need be dealt with; the other properties are of more interest to the darkroom technician.

The response of a photographic paper to exposure by light can be represented by a characteristic curve which is obtained by plotting the reflection density of the developed image against the logarithm of the exposure. (The reflection density is the logarithm of the reciprocal of the reflectance of the image.) Such a curve is similar to the D-logE curve of negative material and is called a sensitometric curve. The slope of this curve is called the gradient of the paper.

For the case of Kodak papers, there are six different grades available. The maximum and minimum reflection densities for all six grades tend to be the same, if the surface is the same, but the rate at which the reflection density increases with exposure is least for grade zero and greatest for grade 5 paper. Papers with semimatte and matte surfaces have the same minimum reflection densities as glossy paper but the maximum reflection densities are lower, that for matte paper being the lowest of the three.

The exposure scale of a paper is a measure of the range of illumination required to produce a print with a full range of tones from white to black. It is normally expressed in logarithmic units to facilitate comparison with the density scale on the negative through which the illumination range is obtained. The log exposure scale usually

is rounded off to the nearest figure after the decimal point and is termed the scale index of the paper. Thus a log exposure scale of 1.48, derived from a sensitometric curve, would be rounded off to a scale index of 1.5.

The grade numbers 0,1,2,3,4, and 5 are used as an approximate indication of the type of negative which can be successfully printed on each grade of paper. A negative with a long density scale usually prints best on grade 0 paper since the latter has a long scale index. On the other hand, a negative with a short density scale usually prints best on grade 5 paper since grade 5 paper has a short scale index. For most papers, a fairly definite relation exists between grade number and scale index.

Due to variations in the subject matter of original scenes, no exact relation can be given between the density scale of a negative and the scale index of the paper which will yield a good print. Experience at the Eastman Kodak Company has shown [25], however, that, in general, the paper scale index should exceed the negative density scale by about 0.2. The reason seems to be that the paper scale index takes into account the complete scale of the paper whereas in practice it is better not to use the extreme shoulder portion of the paper curve. Table 3-1 shows the recommended relation between the density scale of the negative and the scale index or grade number of the paper. Also shown is the gradient of each grade number of paper; - this is based on a reflection density range of 0.05 to 1.75 which is applicable for glossy paper.

With this general discussion of recording film as background, it is now possible to discuss the selection of a recording film for the CRT image. There are several factors in a cathode ray tube display system which may cause the luminance of what is supposed to be a uniformly luminous area on the CRT face to depart from uniform luminance. These factors are video signal noise, CRT display system electronics noise, nonuniformities in the CRT phosphor, and the scanning geometry employed in the CRT. Whether or not the nonuniformity of luminance due to these factors will be recorded on the final photographic print to a degree which will be apparent will depend, of course, on the magnitude of the nonuniformity but, more important in the present discussion, it will also depend on the gamma

TABLE 3-1
RELATION BETWEEN NEGATIVE DENSITY SCALE AND SCALE INDEX
OR GRADE NUMBER OF PRINTING PAPER

PAPER GRADE NUMBER	SCALE INDEX	RECOMMENDED DENSITY SCALE OF NEGATIVE	GRADIENT OF PAPER
0	1.7	1.40 or higher	1.00
1	1.5	1.2 to 1.4	1.13
2	1.3	1.0 to 1.2	1.31
3	1.1	0.8 to 1.0	1.54
4	0.9	0.6 to 0.8	1.69
5	0.7	0.6 or lower	2.43

of the film negative and on the gradient of the printing paper. This is because it is the film gamma and the paper gradient which translate exposure variations into density differences.

Mees [26] has pointed out that the smallest perceptible density increment on a print is 0.02. Before a film or a printing paper can be chosen, the magnitude of the nonuniformity of luminance due to the above factors must first be determined and the recording film and printing paper must then be chosen to have characteristics such that this nonuniformity does not cause a density increment on the print of greater than 0.02.

THE CATHODE RAY TUBE DISPLAY SYSTEM

It was mentioned in the previous section that (1) video signal noise, (2) CRT display system electronics noise, (3) nonuniformities in the CRT phosphor, and (4) the scanning geometry employed in the CRT all contribute to nonuniformity of the CRT luminance and that the combined effect of these four factors must be determined before the recording film and printing paper can be chosen. Each of these factors is dealt with in this section.

The contribution to CRT luminance nonuniformity attributable to the video signal noise is a direct consequence of the signal-to-noise ratio in the SEM output signal. This ratio was chosen to be 65 in Chapter 2 which implies a noise content of

$$\frac{1}{65} \times 100 = 1.54\%$$

Taking this as random noise, it can be written as $\pm 0.77\%$ about the mean value of the video signal and therefore about the mean luminance.

From conversations with the manufacturer of the high resolution CRT display system, Constantine Engineering Laboratories Co., Upland, California, it is known that CRT luminance nonuniformity from both the display system electronics noise and the CRT phosphor nonuniformities can be held within 0.6% if the system is equipped with a phosphor noise correction system or within 2% if it is not. Largely for economical reasons, the phosphor noise correction system was not purchased so that a noise figure of 2% from these two sources together applies. Again taking this as random noise, the figure can be rewritten as a $\pm 1\%$ fluctuation about the mean luminance.

The contribution to CRT luminance nonuniformity attributable to the CRT scanning geometry is not so easily arrived at. This is examined in the next section.

CRT SCANNING GEOMETRY AND RESOLUTION

In a CRT, the resolving power is dependent upon the resolution limit of the detecting surface, the electronics, and the geometry of the scanning process. It is known that the manufacturer of the high resolution display system which will be used can provide a sufficiently fine grained phosphor and high resolution electronics to fulfil the requirements of the present application. It is necessary here to determine the proper scanning geometry which should be employed.

In a scanned display, the resolution along the scanned lines is limited by the bandwidth or rise time of the video amplifier while the resolution across the scanned lines is limited by the width of the scan line or the diameter of the scanning spot. The spot in a CRT does not, however, have a specific diameter inasmuch as it has a Gaussian profile. Resolution across the scanned lines is thus a function of the centre-to-centre spacing of the lines. This spacing cannot be decreased without limit, however, since closer packing of the scan lines reduces the modulation transfer factor of the display system. Some criterion for selecting the proper centre-to-centre spacing of the scan lines is therefore required. In the present application, this criterion is flat field response.

In the application of a CRT display system to a scanning electron microscope, areas of the specimen which give rise to a constant video signal are required to be displayed with a constant luminance on the CRT face, within some small deviation. The magnitude of this deviation, the departure from true flat field response, is, in a system where the display is to be photographed, that fluctuation which will produce a just-barely-perceptible variation in the density of the final print. Accordingly, it is also dependent upon the film gamma and the paper gradient.

To determine the contribution of the scanning geometry to the CRT luminance nonuniformity, luminance calculations for a scanned raster must be carried out. This has been done assuming a Gaussian profile for the CRT spot; the main calculations are reproduced below.

Figure 3-3 shows the Gaussian profiles of five overlapping scan lines; the peak luminance of each line is normalized to unity to simplify the calculations. At $x = 0$, the peak luminance is

$$L_0 = 1 + 2\exp\left[-\frac{1}{2}\left(\frac{c}{\sigma}\right)^2\right] + 2\exp\left[-\frac{1}{2}\left(\frac{2c}{\sigma}\right)^2\right] + \dots$$

in which σ is the standard deviation of the Gaussian at which point the luminance has fallen to 60.6% of its peak value; the first term is the luminance contribution from the scan line centred on $x = 0$, the second term is the combined contributions from the two nearest neighboring scan lines, and the third term is the combined contributions from the two next nearest neighbors. At $x = \pm c/2$, the peak luminance is

$$L_{c/2} = 2\exp\left[-\frac{1}{2}\left(\frac{c}{2\sigma}\right)^2\right] + 2\exp\left[-\frac{1}{2}\left(\frac{3c}{2\sigma}\right)^2\right] + \dots$$

in which the first term is the combined contributions from the two nearest scan lines and the second term is the combined contributions from the two next nearest scan lines.

For flat field response, the luminance at $x = 0$ must equal the luminance at $x = \pm c/2$. Substituting $B = c^2/8\sigma^2$, the requirement for flat field response can be written as

$$1 + 2\exp(-4B) + 2\exp(-16B) + \dots = 2\exp(-B) + 2\exp(-9B) + \dots$$

in which the left hand side is the luminance at $x = 0$ and the right hand side is the luminance at $x = \pm c/2$.

This equation has been solved for selected values of B ; the results are summarized in Table 3-2. From this table, the mean of the two values for L_0 and $L_{c/2}$ would give the mean luminance of a scanned area. The difference column gives the peak-to-peak fluctuation in luminance of a scanned area. If the choice of scanning geometry were such that $B = 0.5$, calculations based on the data of Table 3-2 show that the scanning geometry would contribute $\pm 1.43\%$ to the total deviation from flat field response.

Before leaving this section to collect the contributions to non-uniformity of CRT luminance and decide on an appropriate recording film

FIGURE 3-3
LUMINANCE OF SCAN LINES HAVING GAUSSIAN PROFILES

TABLE 3-2
PEAK LUMINANCE AND DEVIATION FROM FLAT FIELD RESPONSE IN CRT
AS FUNCTION OF LINE SCAN SPACING

$B = c^2/8\sigma^2$	L_0	$L_{c/2}$	DIFFERENCE
0.25	$1 + 0.7358 + 0.0366$ = 1.7724	$1.5576 + 0.2108$ = 1.7684	0.0040
0.30	$1 + 0.6024 + 0.0164$ = 1.6188	$1.4816 + 0.1344$ = 1.6160	0.0028
0.33	$1 + 0.5342 + 0.0102$ = 1.5444	$1.4378 + 0.1026$ = 1.5400	0.0040
0.35	$1 + 0.4932 + 0.0074$ = 1.5006	$1.4094 + 0.0856$ = 1.4950	0.0056
0.38	$1 + 0.4374 + 0.0046$ = 1.4420	$1.3678 + 0.0654$ = 1.4332	0.0088
0.40	$1 + 0.4038 + 0.0032$ = 1.4070	$1.3406 + 0.0546$ = 1.3952	0.0118
0.50	$1 + 0.2706 + 0.0006$ = 1.2712	$1.2130 + 0.0222$ = 1.2352	0.0360
0.60	$1 + 0.1814$ = 1.1814	$1.0976 + 0.0090$ = 1.1066	0.0748
0.70	$1 + 0.1216$ = 1.1216	$0.9932 + 0.0036$ = 0.9968	0.1248

and printing paper, it is advisable to first examine the effect of scanning geometry on the modulation transfer factor of the CRT display system.

CRT MODULATION TRANSFER FACTOR

The question to be answered in this section is whether or not the display system will have an acceptable modulation transfer factor for a given choice of scanning geometry.

Choosing again a scanning geometry such that $B = 0.5$,

$$B = 0.5 = \frac{c^2}{8\sigma^2},$$

gives

$$c = 2\sigma$$

Thus, the distance from the centre of a scan line to the crossover point with its nearest neighbor scan line is σ , where σ is the standard deviation of the Gaussian profile. At $x = \sigma$, the luminance of a scan line is

$$L = \exp\left[-\frac{1}{2}\left(\frac{x}{\sigma}\right)^2\right] = \exp(-\frac{1}{2}) = 0.606$$

The lines are therefore scanned so that they cross at 60.6% of their peak luminances. One picture element in the CRT raster is therefore 2σ wide. This is the so-called shrinking raster criterion of specifying CRT resolution.

Now with the scan lines crossing at $x = \sigma$, the modulation which will be presented on the CRT face for every second scan line blanked off, i.e., for a 100% modulation input, is required. This will be the modulation transfer factor of the display system at maximum resolution.

Modulation is defined as [27]

$$M = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}}$$

With every second scan line blanked off, $L_{\max}$ is essentially the peak luminance of a single scan line, 1.00 for the case being discussed;

$L_{\min}$ is essentially the combined contributions from the two nearest neighbor scan lines only, at the position of the blanked off line - 0.27 for the case being discussed. The modulation for this case then is

$$\begin{aligned} M &= \frac{1.00 + 0.27}{1.00 + 0.27} \\ &= 0.575 \end{aligned}$$

The modulation transfer factor at maximum resolution for this case then is

$$\begin{aligned} \text{MTF} &= \frac{M_{\text{out}}}{M_{\text{in}}} \\ &= \frac{0.575}{1.00} \\ &= 0.575 \end{aligned}$$

which is acceptable.

CRT SPOT SIZE

It is possible now to determine the required CRT spot size. In the system being considered, 5000 lines must be scanned in a 3 inch square raster in accordance with the scanning geometry outlined previously. This dictates a specific value for σ , the standard deviation of the Gaussian spot profile, which must be found.

It was previously shown that one picture element is to be 2σ wide. But a 3 inch square raster with 5000 scan lines defines a picture element width, w of

$$\begin{aligned} w &= \frac{3}{5000} \\ &= 0.0006 \text{ inch.} \end{aligned}$$

Since

$$w = 2\sigma,$$

it follows that

$$\begin{aligned} \sigma &= \frac{0.0006}{2} \\ &= 0.0003 \text{ inch.} \end{aligned}$$

CRT spot sizes, however, are normally measured at 50% of their peak luminances at which point their diameters are 2.35σ . Accordingly, the required spot diameter, ϕ in the present case is

$$\begin{aligned}\phi &= 2.35 \sigma \\ &= 2.35 \times 0.0003 \\ &= 0.0007 \text{ inch.}\end{aligned}$$

The Litton Industries' cathode ray tube used in the high resolution display system meets this specification exactly at all points on its scanned area.

RECORDING FILM: SPECIFICATION

From the foregoing, it is known that the total nonuniformity in CRT luminance is equivalent to $\pm 3.2\%$, this figure being made up of ± 0.77 from the video signal noise, $\pm 1\%$ from both the display system electronics noise and the CRT phosphor irregularities together, and $\pm 1.43\%$ from the scanning geometry. It is also known from the foregoing that the smallest perceptible reflection density change on a final print is 0.02. In this section, it is necessary to combine these facts into a statement of recording film specifications. (It is unlikely that the above contributions would add directly. Since they are uncorrelated, a quadratic, rather than a linear, combination would be more likely. This would give a total nonuniformity of $\pm 1.9\%$. The linear combination is used here, however, since it is the most conservative combination possible.)

Picking an exposure range, ΔE for the film of 100:1 to correspond with the CRT luminance range chosen in Chapter 2 and a film gamma, γ of 0.7 gives a film density range, ΔD of

$$\begin{aligned}\Delta D &= \gamma \Delta \log E \\ &= 0.7 \times 2 \\ &= 1.4\end{aligned}$$

As can be seen by referring to Table 3-1, this density range is recommended for use with a Grade 1 printing paper for which the scale index is 1.5 and the gradient is 1.13.

An examination of photographic film data sheets indicates that the values chosen above for film exposure range and gamma are readily attainable with commonly available films and developers. Grade 1 paper also is readily available in a variety of sizes, textures, glosses, etc.

As has been pointed out previously, the total nonuniformity in CRT LUMINANCE, δE is translated into a nonuniformity in reflection density of the final print, δD_p through the film gamma and the paper gradient, G :

$$\delta D_p = \gamma G \delta \log E$$

With $\delta E = \pm 3.2\%$, which corresponds to a change $\delta \log E = \pm 0.014$, $\gamma = 0.7$, and $G = 1.13$, this gives

$$\begin{aligned} \delta D_p &= \pm 0.7 \times 1.13 \times 0.014 \\ &= \pm 0.011 \end{aligned}$$

which corresponds almost exactly with the smallest reflection density change which can be detected, 0.02. Thus, the above choices for film and printing paper parameters are acceptable.

Before leaving this section, the required speed and resolving power of the film must be determined. It was stated previously that film speed is defined as 80% of the exposure, E_S in meter-candle-seconds required to produce a film density, D_S of 0.1 above base plus fog density, D_f :

$$\text{USAS film speed} = \frac{0.8}{E_S \text{ at } D_S = 0.1 + D_f}$$

The value for film exposure of 1 erg/cm² which was found earlier should be identified as the maximum film exposure since the CRT output flux cannot be increased much above the value to which this film exposure corresponds without contributing to excessive spot growth. Accordingly, the minimum exposure will be 0.01 erg/cm² since ΔE has been chosen as 100:1. This minimum exposure is specified as that which will produce a film density of 0.1 above base plus fog. The film speed therefore must be

$$\begin{aligned} \text{USAS film speed} &= \frac{0.8}{0.01 \times 1/5} \\ &= 400 \end{aligned}$$

in which the film exposure has been converted to meter-candle-seconds (1 m-c-s = 5 erg/cm²). There are several films available with this speed.

The maximum spatial frequency which the film can be called upon to resolve in the present application can be calculated from the size of the film image and the number of CRT scan lines in that image. It is

$$k = \frac{5000}{55}$$

$$= 91 \text{ lines per millimeter}$$

for 120 roll film (55 mm square image).

Now the specifications of photographic film resolving power are normally stated as "limiting resolving power", i.e. they are specified at a very low modulation transfer factor of about 0.005 and at a very high test object contrast (TOC) of 1000 : 1 [28]. In addition, they are specified in terms of optical lines per millimeter whereas the spatial frequency calculated above as 91 lines per millimeter refers to TV lines. An optical line consists of the line itself together with a space of the same width and moreover is measured further down on the Gaussian spot profile where the spot diameter is 2.83σ [29]. One optical line, then, equals $2\sqrt{2}$ TV lines; the $\sqrt{2}$ factor is frequently referred to as the Kell factor.

What is required for this application can therefore be identified as a photographic film with a resolving power of at least $91/2\sqrt{2}$ optical lines per millimeter (lpm), at a fairly high MTF of, say, 0.5 to 0.6 and at a low TOC of, say, 4:1 or 10:1. In the usually photographic film terms, this implies a film with a limiting resolving power of about 95 lpm.

Of the many commercially available films, one which will meet the requirements set forth above is Kodak Tri-X panchromatic film. Its gamma can be controlled to 0.7 with straightforward development procedures and it meets the other requirements exactly except for its limiting resolving power which is quoted at 75 to 90 lpm. This disadvantage is considered to be offset by the film's other specifications, by its ready availability, and by the fact that, being well known, it should not present any difficulties in the darkroom.

CONCLUSIONS

This concludes the examination of the high resolution CRT display and recording system. It has been shown that the system can be arranged to provide a maximum film exposure of 1 erg/cm^2 and that, with a film exposure range of 100:1, this corresponds to a film with a USAS film speed of 400. It has also been shown that a film with a gamma of 0.7 and a density range of 0.1 to 1.4 is compatible with a variation in CRT luminance from all sources of $\pm 3.2\%$ and that this is consistent with the performance that can be expected from the system. Finally it has been shown that the system MTF at maximum resolution will be 57.5%, that the system spot size must be 0.0007 inch at 50% of its peak amplitude, and that the film's limiting resolving power must be 95 lpm. Kodak Tri-X panchromatic film was found to meet the film specifications satisfactorily.

The high resolution CRT system is thus capable of performing as is required for the large area scanning microscopy concept. It is now necessary to examine the feasibility of providing the required resolution in the microscope.

CHAPTER 4

ABERRATIONS IN ELECTRON OPTICS

The quality of the image produced by a scanning electron microscope is dependent upon the degree to which aberrations are introduced into it by the various microscope components. In general, the aberrations which can arise may be grouped into four broad categories depending upon their origin. Three of these categories are more applicable to the focusing of an electron probe; the fourth is concerned with the deflection of this probe to produce a raster. In view of the importance of this last category to the present work, it is discussed fully in the next chapter. The first three categories are examined briefly below.

ELECTRONIC ABERRATIONS

Aberrations which are caused by properties of the electron beam itself are termed electronic aberrations. Included in this category are chromatic aberration, relativistic error, space charge error, and diffraction error.

Chromatic aberration

Chromatic aberration arises from variations in the velocity of the electrons in the electron optical column. Electrons thermionically emitted from a cathode have a distribution in velocity in accordance with the Maxwell-Boltzmann law. This distribution is 1.2 volts in extent at the points within which eighty percent of the total current is emitted. This, as Pease has pointed out [30], corresponds with the usual definition of beam diameter and results in a fractional spread in beam voltage, $\Delta V/V$ of 60 ppm for a 20 keV beam of electrons.

The other common source of electron velocity fluctuations is variations in accelerating potential and lens excitation; these fluctuations are minimized by using very stable voltage and current supplies. The fractional spread in beam voltage, $\Delta V/V$ from the beam voltage (accelerating potential) power supply can be held to 10 ppm for voltages up to 50 kV. The fractional spread in lens excitation current, $\Delta I/I$ from the best constant current lens power supplies is 50 ppm but, because the focal length of a lens is proportional to the square of the magnetic field, a figure of 100 ppm must be used in calculating the magnitude of the resulting chromatic aberration.

The cause of image aberrations in the presence of these electron velocity fluctuations is that an increase in velocity leads to a decrease in wavelength for which the refracting power of a given lens is less. Accordingly, the magnification is reduced and, with magnetic lenses, the amount of rotation is also reduced. A point focus at the image plane is therefore impossible.

Instead, a disc of confusion results, the diameter of which is given by [31]

$$d_C = C_C \left(\frac{\Delta V}{V} \right)_{\text{equiv}} \alpha \quad (4-1)$$

in which C_C is the chromatic aberration coefficient determined by the form of the focusing field and typically having a value of about 1 cm; $(\Delta V/V)_{\text{equiv}}$ is the rms combined value of the instabilities due to the Maxwell-Boltzmann distribution, the high voltage supply, and the lens current supply and has the value 117 ppm using the figures quoted above; α is the half-angle of convergence of the electron beam which would typically be about 10 mrad. Using these figures, the chromatic disc of confusion has a diameter of 117 Å, a significant size in many applications.

Relativistic error

Relativistic aberration is a particular type of chromatic aberration caused by variations in electron mass with velocity. At higher beam energies relativistic effects result in an apparent increase in the focal length of a lens; this is not normally significant in the scanning electron microscope.

Space charge error

The space charge error owes its origin to the fact that the electrons in a highly concentrated beam will repel each other and cause the beam to spread. For the beam intensities normally encountered in scanning microscopy this effect is not serious but recent work by Broers [32] using lanthanum hexaboride high brightness electron guns has shown that the effect does occur. The result is a widening of the Maxwellian distribution of emitted energies leading to an increase in the size of the chromatic disc of confusion, the so-called Boersch effect.

This effect seems to occur at beam crossover points where the electron density is highest.

Diffraction error

As soon as electron rays are focused into beams with semiangles of convergence comparable to the wavelength of the electrons in the rays, the wave nature of the electrons must be taken into account. The work of de Broglie has shown that a wave is associated with every particle and that both the frequency and the wavelength which characterize this wave depend upon the energy of the particle.

As electrons have a wave nature, it is to be expected that, if a point source is imaged by an electron optical system of small aperture, the image will be a diffraction pattern and not a point; further, if the aperture is circular, the pattern will be the familiar Airy disc. This will obviously limit the minimum probe size obtainable as well as affect the ability of the system to resolve two closely spaced object points.

The Rayleigh criterion for the limit of resolution of two points is that the maximum of the Airy disc of one coincide with the first minimum of the other. Thus, two points spaced closer together than the radius of the Airy disc cannot be resolved. The diameter to the first minimum of the Airy disc is given by

$$d_f = 1.22 \frac{\lambda}{\alpha} \quad (4-2)$$

in which λ is the wavelength of the electron and α is the half-angle of convergence of the electron beam, typically 10 mrad in the scanning microscope. The wavelength of the electron is given by

$$\lambda = \frac{12.25}{\sqrt{V_{\text{volts}}}} \text{ \AA} \quad (4-3)$$

where V_{volts} is the potential through which the electrons have been accelerated. This equation has not been corrected for relativistic effects but it is normally sufficiently accurate for acceleration potentials of up to 50 kV.

Applied to a 20 keV beam of electrons passing through an aperture whose half-angle of convergence is 10 mrad, this theory shows that the diffraction limited probe size is $10.6 \text{ \AA}$ while the limit of resolution is $5.3 \text{ \AA}$. Applied to a 500 eV beam of electrons, such as would be used in low energy and mirror microscopy, the theory predicts a diffraction limited probe size of $67 \text{ \AA}$ and a limit of resolution of $33.5 \text{ \AA}$ for the same beam half-angle of convergence.

It is evident that the diffraction effect can be appreciable at low beam acceleration potentials.

MECHANICAL ABERRATIONS

Imperfections in machining or alignment will reduce the symmetry of the electron optical system and will introduce aberrations which are termed mechanical aberrations. In actual fact these are additional geometrical aberrations but they are separated out to draw attention to their origin.

Dust or dirt on apertures and inhomogeneities in the magnetic material of pole pieces also will introduce asymmetries as will stray magnetic or electric fields; aberrations resulting from these sources are included under mechanical aberrations.

In many instances it is the mechanical aberrations which limit the resolution attainable in an electron optical system, representing as they do the limit of perfection to which the system can be built.

GEOMETRICAL ABERRATIONS

Aberrations attributable to the lens field are termed geometrical aberrations. These include the equivalent of the five Seidel aberrations of glass optics, distortion, curvature of field, astigmatism, coma, and spherical aberration together with, in the case of magnetic lenses, anisotropic distortion, astigmatism, and coma. In the discussion of these aberrations which follows, the characteristic function method is used. This is the treatment used by Glaser [34] and Sturrock [36] as well as Hawkes [33], upon whose analysis the following is based.

Fermat's principle, the characteristic function and perturbation theory

Fermat's principle states that the optical path followed by a ray of light between two arbitrary points is an extremum. Hence, if $n(x,y,z)$ is the refractive index at any point,

$$\delta \int_A^B n dS = 0 \quad (4-4)$$

Glaser [34] has shown that this same principle is applicable to electron optics provided the refractive index is identified with the scalar electrostatic potential, $\phi(x,y,z)$ and the vector magnetic potential, $\bar{A}(x,y,z)$. Consider

$$\delta \int_A^B k p dS = 0 \quad (4-5)$$

This is the mathematical statement of the principle of least action; it states that, for a particle moving between two arbitrary points, the action integral for that path is a minimum where the action is given by the product of the particle momentum, p and the distance travelled. Since the principle holds equally well if the momentum is multiplied by a constant, such a constant, k has been included for generality. The principle of least action is the mechanical equivalent of Fermat's principle in optics and the two principles define an equivalence between the index of refraction in optics and the momentum in mechanics.

Now the generalized momentum, p can be obtained from the Lagrangian, L for a system by

$$p = \frac{\partial L}{\partial v}, \quad (4-6)$$

where v is the particle velocity.

The Lagrangian for a single particle in an electromagnetic field is given by (see, for example, Goldstein [35])

$$L = -m_0 c^2 (1 - v^2/c^2)^{1/2} - q\phi + q\bar{A} \cdot \bar{v} \quad (4-7)$$

from which

$$\begin{aligned}
 p &= \frac{m_0 v}{(1 - v^2/c^2)^{1/2}} + q\bar{A} \\
 &= \frac{m_0 v}{(1 - v^2/c^2)^{1/2}} + q\bar{A} \cdot \bar{S}
 \end{aligned}
 \tag{4-8}$$

in which m_0 , q , and v are the rest mass, charge, and velocity of the particle, respectively, c is the velocity of light in free space, ϕ is the scalar electrostatic potential, $\bar{A}$ is the vector magnetic potential, and $\bar{S}$ is the unit vector tangent to the path of the particle.

The first term on the right hand side of equation (4-8) can be related to the scalar electrostatic potential, ϕ by (see appendix 2)

$$\frac{m_0 v}{(1 - v^2/c^2)^{1/2}} = \sqrt{2em_0\phi(1 + \epsilon\phi)}
 \tag{4-9}$$

in which e is the electronic charge and ϵ is given by

$$\epsilon = \frac{e}{2m_0 c^2}
 \tag{4-10}$$

Substituting equation (4-9) into equation (4-8) and converting the particle charge q to e so that the equation refers specifically to electrons yields

$$\begin{aligned}
 p &= \sqrt{2em_0\phi(1 + \epsilon\phi)} - e\bar{A} \cdot \bar{S} \\
 &= \sqrt{2em_0} \left[\sqrt{\phi(1 + \epsilon\phi)} - \sqrt{\frac{e}{2m_0}} \bar{A} \cdot \bar{S} \right]
 \end{aligned}
 \tag{4-11}$$

Setting

$$k = \frac{1}{\sqrt{2em_0}}$$

equation (4-11) can be written

$$k_p = \sqrt{\phi(1 + \epsilon\phi)} - \sqrt{\frac{e}{2m_0}} A \cdot \vec{S} \quad (4-12)$$

k_p is identified as the index of refraction in electron optics.

It is convenient at this point to introduce a cartesian coordinate system x, y, z and to transform the variational equation (4-5) into the form

$$\delta \int_A^B F dz = 0 \quad (4-13)$$

Equation (4-12) can be rewritten as

$$k_p = \sqrt{U} - \eta A_x \frac{dx}{dS} - \eta A_y \frac{dy}{dS} - \eta A_z \frac{dz}{dS} \quad (4-14)$$

in which the substitutions

$$U = \phi(1 + \epsilon\phi)$$

and

$$\eta = \sqrt{\frac{e}{2m_0}}$$

have been made. Noting that

$$k_p dS = dS \sqrt{U} - \eta A_x dx - \eta A_y dy - \eta A_z dz$$

and that

$$\begin{aligned}
 dS &= (dx^2 + dy^2 + dz^2)^{1/2} \\
 &= dz \left(\frac{dx^2}{dz^2} + \frac{dy^2}{dz^2} + 1 \right)^{1/2} \\
 &= dz(x'^2 + y'^2 + 1)^{1/2}
 \end{aligned}$$

one obtains

$$\begin{aligned}
 kpdS &= \left[\sqrt{U(1 + x'^2 + y'^2)} - \eta A_x \frac{dx}{dz} - \eta A_y \frac{dy}{dz} - \eta A_z \right] dz \\
 &= \left[\sqrt{U(1 + x'^2 + y'^2)} - \eta A_x x' - \eta A_y y' - \eta A_z \right] dz \quad (4-15) \\
 &= F dz
 \end{aligned}$$

where

$$F = \sqrt{U(1 + x'^2 + y'^2)} - \eta A_x x' - \eta A_y y' - \eta A_z \quad (4-16)$$

and where a prime denotes differentiation with respect to z . It is seen that the electron optical index of refraction, F is a function of the electron itself, the field in which it is moving, and the direction it is moving.

If the functions $\phi(x,y,z)$, $A_x(x,y,z)$, $A_y(x,y,z)$, and $A_z(x,y,z)$ are expanded as power series in x and y and if these expansions are substituted back into equation (4-16), it is found that F is composed of a series of terms which can be grouped according to their dependence on x and y and their derivatives:

$$F = F^{(0)} + F^{(2)} + F^{(4)} + \dots F^{(2n)} + \dots$$

where $F^{(2n)}$ represents all the terms of degree $2n$. The details of the expansions and the substitutions are given in Hawkes' paper [33].

The notation

$$p = \frac{\partial F}{\partial x'} \quad q = \frac{\partial F}{\partial y'} \quad (4-17)$$

is now introduced. Suppose that the arbitrary optical path joining points $(x_\alpha, y_\alpha, z_\alpha)$ and $(x_\beta, y_\beta, z_\beta)$ is denoted by S :

$$S = \int_{z_\alpha}^{z_\beta} F dz$$

The optical path S^* along a neighboring curve joining two points in the same planes $z = z_\alpha$ and $z = z_\beta$ is then given by

$$S^* = S + \delta S$$

where

$$\delta S \approx \int_{z_\alpha}^{z_\beta} \left(\delta x \frac{\partial F}{\partial x} + \delta y \frac{\partial F}{\partial y} + \delta x' \frac{\partial F}{\partial x'} + \delta y' \frac{\partial F}{\partial y'} \right) dz$$

This can be integrated to yield

$$\begin{aligned} \delta S &= (p_\beta \delta x_\beta + q_\beta \delta y_\beta) - (p_\alpha \delta x_\alpha + q_\alpha \delta y_\alpha) \\ &\quad - \int_{z_\alpha}^{z_\beta} \left[\delta x \left(\frac{dp}{dz} - \frac{\partial F}{\partial x} \right) + \delta y \left(\frac{dq}{dz} - \frac{\partial F}{\partial y} \right) \right] dz \end{aligned}$$

If the path of integration is a ray and if the end points are not changed, δS must vanish. Accordingly

$$\frac{dp}{dz} = \frac{\partial F}{\partial x} \qquad \frac{dq}{dz} = \frac{\partial F}{\partial y} \qquad (4-18)$$

These are the Euler equations corresponding to the variational equation (4-13).

The value of S when the path of integration is a ray is denoted $V_{\alpha\beta}$ so that

$$V_{\alpha\beta} = \int_{z_{\alpha}}^{z_{\beta}} F dz \quad (4-19)$$

and

$$\delta V_{\alpha\beta} = p_{\beta} \delta x_{\beta} + q_{\beta} \delta y_{\beta} - p_{\alpha} \delta x_{\alpha} - q_{\alpha} \delta y_{\alpha} \quad (4-20)$$

$V_{\alpha\beta}$ is Hamilton's point characteristic function; it is a function of the x and y coordinates of the end points. The suffix $\alpha\beta$ denotes that z_{α} and z_{β} are the integration limits.

If, now, $F(x,y,z)$ is replaced by a slightly different function, $F(x,y,z) + F^I(x,y,z)$,

$$V_{\alpha\beta}^I = \int_{z_{\alpha}}^{z_{\beta}} F^I(x,y,z) dz \quad (4-21)$$

and

$$\begin{aligned} \delta V_{\alpha\beta}^I &= (p_{\beta}^I \delta x_{\beta} + q_{\beta}^I \delta y_{\beta} - x_{\beta}^I \delta p_{\beta} - y_{\beta}^I \delta q_{\beta}) \\ &\quad - (p_{\alpha}^I \delta x_{\alpha} + q_{\alpha}^I \delta y_{\alpha} - x_{\alpha}^I \delta p_{\alpha} - y_{\alpha}^I \delta q_{\alpha}) \end{aligned} \quad (4-22)$$

(The detailed reasoning leading to equation (4-22) is set out in Sturrock's paper [16].) Provided there is no stigmatic focusing present, the end points can be held fixed; accordingly,

$$x_{\alpha}^I = y_{\alpha}^I = x_{\beta}^I = y_{\beta}^I = 0 \quad \text{and}$$

$$\delta V_{\alpha\beta}^I = p_{\beta}^I \delta x_{\beta} + q_{\beta}^I \delta y_{\beta} - p_{\alpha}^I \delta x_{\alpha} - q_{\alpha}^I \delta y_{\alpha} \quad (4-23)$$

From this relationship one can obtain

$$p_{\alpha}^I = - \frac{\partial V_{\alpha\beta}^I}{\partial x_{\alpha}} \quad q_{\alpha}^I = - \frac{\partial V_{\alpha\beta}^I}{\partial y_{\alpha}} \quad (4-24a)$$

$$p_{\beta}^I = + \frac{\partial V_{\alpha\beta}^I}{\partial x_{\beta}} \quad q_{\beta}^I = + \frac{\partial V_{\alpha\beta}^I}{\partial y_{\beta}}$$

These are the perturbed counterparts of the differential equations obtainable from equation (4-20):

$$p_{\alpha} = - \frac{\partial V_{\alpha\beta}}{\partial x_{\alpha}} \quad q_{\alpha} = - \frac{\partial V_{\alpha\beta}}{\partial y_{\alpha}} \quad (4-24b)$$

$$p_{\beta} = + \frac{\partial V_{\alpha\beta}}{\partial x_{\beta}} \quad q_{\beta} = + \frac{\partial V_{\alpha\beta}}{\partial y_{\beta}}$$

$V_{\alpha\beta}^I$ is the point perturbation characteristic function since its arguments are point coordinates. Also derivable is an angle perturbation characteristic function ($p_{\alpha}^I = q_{\alpha}^I = p_{\beta}^I = q_{\beta}^I = 0$) and a mixed perturbation characteristic function ($p_{\alpha}^I = q_{\alpha}^I = x_{\beta}^I = y_{\beta}^I = 0$ or $x_{\alpha}^I = y_{\alpha}^I = p_{\beta}^I = q_{\beta}^I = 0$).

To obtain the Gaussian properties of an electron optical system, all but the lowest order terms in x and y in the index of refraction expression F are rejected; these are the terms $F^{(2)}$. Then, by using $F^{(2)}$ for F in equation (4-18), the Gaussian equations of motion are obtained.

To obtain the third order approximation, a small perturbation is introduced: for $F + F^I$ one writes $F^{(2)} + F^{(4)}$ and obtains a small improvement on the relatively crude Gaussian approximation.

Equations (4-24a) do not provide the information which is normally required; in most cases one wishes to know where an electron ray will intersect a given image plane if it emerges from a particular object point and if it is restricted by an aperture in some aperture plane. To obtain this information one proceeds as follows.

Let $z = z_o$ define the object plane, $z = z_a$ the aperture plane, and $z = z_c$ an arbitrary current plane which may be the Gaussian image plane. In equation (4-22) substitute z_o for z_α and z_c for z_β and take the differential, first with respect to x_a to obtain

$$\frac{\partial V_{oc}^I}{\partial x_a} = p_c^I \frac{\partial x_c}{\partial x_a} + q_c^I \frac{\partial y_c}{\partial x_a} - x_c^I \frac{\partial p_c}{\partial x_a} - y_c^I \frac{\partial q_c}{\partial x_a}, \quad (4-25a)$$

then with respect to y_a to obtain

$$\frac{\partial V_{oc}^I}{\partial y_a} = p_c^I \frac{\partial x_c}{\partial y_a} + q_c^I \frac{\partial y_c}{\partial y_a} - x_c^I \frac{\partial p_c}{\partial y_a} - y_c^I \frac{\partial q_c}{\partial y_a}. \quad (4-25b)$$

Now substitute in equation (4-22) z_a for z_α and z_c for z_β and take the differential, first with respect to x_o to obtain

$$\frac{\partial V_{ac}^I}{\partial x_o} = p_c^I \frac{\partial x_c}{\partial x_o} + q_c^I \frac{\partial y_c}{\partial x_o} - x_c^I \frac{\partial p_c}{\partial x_o} - y_c^I \frac{\partial q_c}{\partial x_o}, \quad (4-25c)$$

then with respect to y_o to obtain

$$\frac{\partial V_{ac}^I}{\partial y_o} = p_c^I \frac{\partial x_c}{\partial y_o} + q_c^I \frac{\partial y_c}{\partial y_o} - x_c^I \frac{\partial p_c}{\partial y_o} - y_c^I \frac{\partial q_c}{\partial y_o}. \quad (4-25d)$$

These four simultaneous equations (4-25) can be solved for p_c^I , q_c^I , x_c^I , and y_c^I to give the effect of F^I on the positions and slopes of rays intersecting the current plane.

To simplify the discussion somewhat, only the third order aberrations will be considered; in this case, $V^{(4)}$ is written in place of V^I and $F^{(4)}$ in place of F^I . $V^{(4)}$ is obtained by integrating $F^{(4)}$ with respect to z . In place of x, y and their derivatives in $F^{(4)}$, the expressions obtained from the Gaussian approximation are substituted; i.e., the solutions of the Gaussian equations of motion. The form of the solutions is dependent upon the form of $F^{(2)}$ which in turn depends upon whether the system is round or orthogonal.

Restricting the discussion to round systems, $F^{(2)}$ is given by

$$F^{(2)} = \frac{1}{2}C(x'^2 + y'^2) + \frac{1}{2}\bar{C}(x^2 + y^2) \quad (4-26)$$

in which C and $\bar{C}$ are functions of z involving the scalar electrostatic and vector magnetic potentials. (A detailed derivation of equation (4-26) is given in Hawkes' paper [33].)

Partial integration of equation (4-26) with respect to x, y, x' and y' yields the following relationships:

$$\frac{\partial F^{(2)}}{\partial x} = \bar{C}x = \frac{dp}{dz} \quad \text{by equation (4-18)} \quad (4-27a)$$

$$\frac{\partial F^{(2)}}{\partial y} = \bar{C}y = \frac{dq}{dz} \quad \text{by equation (4-18)} \quad (4-27b)$$

$$\frac{\partial F^{(2)}}{\partial x'} = Cx' = p \quad \text{by equation (4-17)} \quad (4-27c)$$

$$\frac{\partial F^{(2)}}{\partial y'} = Cy' = q \quad \text{by equation (4-17)} \quad (4-27d)$$

from which the equations of motion can be obtained:

$$\frac{d}{dz}(Cx') = \bar{C}x' \quad \frac{d}{dz}(Cy') = \bar{C}y' \quad (4-28)$$

The general solution of each of the equations (4-28) consists of a linear combination of two linearly independent solutions for which the functions $g(z)$ and $h(z)$ are chosen; $g(z)$ and $h(z)$ must satisfy the boundary conditions

$$g(z_0) = h(z_a) = 1 \quad g(z_a) = h(z_0) = 0 \quad (4-29)$$

The general solutions then are

$$\begin{aligned} x(z) &= x_0 g(z) + x_a h(z) \\ y(z) &= y_0 g(z) + y_a h(z) \end{aligned} \quad (4-30)$$

From equations (4-25), (4-27) and (4-30), together with some tedious algebra, the final solutions for the effect of $F^{(4)}$ on the positions and slopes of rays intersecting the current plane can be found:

$$x_c^{(4)} = \frac{h_c(\partial V_{ac}^{(4)}/\partial x_0) - g_c(\partial V_{oc}^{(4)}/\partial x_a)}{C(g_c h_c' - g_c' h_c)} \quad (4-31a)$$

$$y_c^{(4)} = \frac{h_c(\partial V_{ac}^{(4)}/\partial y_0) - g_c(\partial V_{oc}^{(4)}/\partial y_a)}{C(g_c h_c' - g_c' h_c)} \quad (4-31b)$$

$$p_c^{(4)} = \frac{h_c'(\partial V_{ac}^{(4)}/\partial x_0) - g_c'(\partial V_{oc}^{(4)}/\partial x_a)}{g_c h_c' - g_c' h_c} \quad (4-31c)$$

$$q_c^{(4)} = \frac{h_c' (\partial V_{ac}^{(4)} / \partial y_o) - g_c' (\partial V_{oc}^{(4)} / \partial y_a)}{g_c h_c' - g_c' h_c} \quad (4-31d)$$

On some occasions it is advantageous to work with complex coordinates instead of cartesian coordinates. Writing $U = x + iy$, $S = p + iq$, $\bar{U} = x - iy$, $\bar{S} = p - iq$, and $k = C(g_c h_c' - g_c' h_c)$, equations (4-31) can be rewritten

$$kU_c^{(4)} = 2h_c \frac{\partial V_{ac}^{(4)}}{\partial \bar{U}_o} - 2g_c \frac{\partial V_{oc}^{(4)}}{\partial \bar{U}_a} \quad (4-32a)$$

$$kS_c^{(4)} = 2Ch_c' \frac{\partial V_{ac}^{(4)}}{\partial \bar{U}_o} - 2Cg_c' \frac{\partial V_{oc}^{(4)}}{\partial \bar{U}_a} \quad (4-32b)$$

Symmetry

The characteristic function of an electron optical system is a measure of the optical path length between two points on a ray. Because the characteristic function contains all the information about the optics of its respective system, it must faithfully reflect any symmetry conditions present in the system itself. This proves to be a powerful key to obtaining data on the aberrations affecting the imagery produced in an electron optical system, given the symmetry conditions present in the system.

Using complex coordinates, $U = x + iy$, $\bar{U} = x - iy$, the point of intersection of a ray with an arbitrary current plane, U_c can be expressed as a function of its points of intersection with the object and aperture planes, U_o and U_a :

$$U_c = U_c(U_o, \bar{U}_o, U_a, \bar{U}_a)$$

Expansion of U_c as a power series gives

$$U_c = \sum_{\alpha+\beta+\gamma+\delta=1}^{\alpha+\beta+\gamma+\delta=n} (\alpha\beta\gamma\delta) U_o^\alpha \bar{U}_o^\beta U_a^\gamma \bar{U}_a^\delta \quad (4-33)$$

in which the $(\alpha\beta\gamma\delta)$ are real or complex functions of z .

Interpretation of equation (4-33) will be restricted to round systems and to terms of up to the third order only; i.e., terms for which $\alpha+\beta+\gamma+\delta=3$. In round systems, if the ray intersecting the object and aperture planes at U_o and U_a intersects the current plane at U_c , then the ray which intersects the object and aperture planes at $U_o e^{i\theta}$ and $U_a e^{i\theta}$ must intersect the current plane at $U_c e^{i\theta}$. Accordingly,

$$U_c e^{i\theta} = \sum_{\alpha+\beta+\gamma+\delta=1}^{\alpha+\beta+\gamma+\delta=3} (\alpha\beta\gamma\delta) U_o^\alpha \bar{U}_o^\beta U_a^\gamma \bar{U}_a^\delta \exp i(\alpha-\beta+\gamma-\delta)\theta$$

This can only be true for all θ if $\alpha-\beta+\gamma-\delta=1$. Equation (4-33) can therefore be expanded subject to the conditions

$$\begin{aligned} \alpha - \beta + \gamma - \delta &= 1 \\ 1 &\leq \alpha + \beta + \gamma + \delta \leq 3 \end{aligned}$$

The result is

$$\begin{aligned} U_c &= (1000)U_o + (0010)U_a \\ &+ (2100)U_o^2 \bar{U}_o + (2001)U_o^2 \bar{U}_a + (1011)U_o U_a \bar{U}_a \\ &+ (0021)U_a^2 \bar{U}_a + (1110)U_o \bar{U}_o U_a + (0120)\bar{U}_o U_a^2. \end{aligned} \quad (4-34)$$

Only two first order terms are present, (1000) which is the system magnification and (0010) which defines first order defocusing or curvature of the image field. In addition, there are six third order terms, (2100) which measures the distortion, (2001) which measures astigmatism, (1110) which measures field curvature, (0021) which measures spherical or aperture aberration, and (1011) and (0120) which will be seen later to be related and which together define coma. These five third order aberrations of round systems are the five Seidel aberrations of glass optics.

To ascertain whether there are any relationships amongst these aberration coefficients, the form of the perturbation characteristic function, $V_{\alpha\beta}^{(4)}$ must be examined.

The perturbation characteristic function, $V_{\alpha\beta}^{(4)}$ must be

- (a) a function of U_o , $\bar{U}_o$, U_a , and $\bar{U}_a$
- (b) of the fourth order
- (c) invariant under rotation for round systems.

Accordingly, it can be expressed by

$$\begin{aligned}
 V_{\alpha\beta}^{(4)} = & a_{11} U_o^2 \bar{U}_o^2 + a_{12} U_o^2 \bar{U}_o \bar{U}_a + a_{13} U_o^2 \bar{U}_a^2 \\
 & + a_{21} U_o U_a \bar{U}_o^2 + a_{22} U_o U_a \bar{U}_o \bar{U}_a + a_{23} U_o U_a \bar{U}_a^2 \\
 & + a_{31} U_a^2 \bar{U}_o^2 + a_{32} U_a^2 \bar{U}_o \bar{U}_a + a_{33} U_a^2 \bar{U}_a^2
 \end{aligned}$$

in which the 3×3 square matrix $A = a_{jk}$ is the coefficient matrix. This can be expressed more compactly by

$$V_{\alpha\beta}^{(4)} = \begin{pmatrix} U_o^2 \\ U_o U_a \\ U_a^2 \end{pmatrix}^T \begin{pmatrix} & \\ & A \\ & \end{pmatrix} \begin{pmatrix} \bar{U}_o^2 \\ U_o U_a \\ \bar{U}_a^2 \end{pmatrix} \quad (4-35a)$$

In order to satisfy the condition of invariance under rotation for $V_{\alpha\beta}^{(4)}$, the coefficient matrix, (A) must be Hermitian. Therefore (A) must be symmetric and the terms in its main diagonal must be real.

Matrix (A) may be written out in full as

$$(A) = \begin{pmatrix} 2200 & 2101 & 2002 \\ 1210 & 1111 & 1012 \\ 0220 & 0121 & 0022 \end{pmatrix} \quad (4-35b)$$

which, since (A) is Hermitian may be rewritten as

$$(A) = \begin{pmatrix} 2200(r) & 2101 & 2002 \\ \overline{2101} & 1111(r) & 1012 \\ \overline{2002} & \overline{1012} & 0022(r) \end{pmatrix} \quad (4-35c)$$

in which (r) signifies a real term and a bar signifies a complex conjugate.

From equations (4-32a) and (4-35a) one can obtain

$$kU_c^{(4)} = 2 \begin{pmatrix} U_o^2 \\ U_o U_a \\ U_a^2 \end{pmatrix} \begin{pmatrix} B \end{pmatrix} \left[h_c \begin{pmatrix} 2\overline{U}_o \\ \overline{U}_a \end{pmatrix} - g_c \begin{pmatrix} \overline{U}_o \\ 2\overline{U}_a \end{pmatrix} \right] \quad (4-36)$$

in which (B) is the coefficient matrix for $U_c^{(4)}$, the perturbed ray coordinates in the current plane.

In the Gaussian image plane $h_c = 0$ (since $h_o = 0$ and the rays from the object are focused on the Gaussian image plane) so that

$$kU_c^{(4)} = -2 \begin{pmatrix} U_o^2 \\ U_o U_a \\ U_a^2 \end{pmatrix} \begin{pmatrix} B \end{pmatrix} g_c \begin{pmatrix} \overline{U}_o \\ 2\overline{U}_a \end{pmatrix} \quad (4-37a)$$

in which the matrix (B) is given by

$$(B) = \begin{pmatrix} 2100 & 1110 & 0120 \\ 2001 & 1011 & 0021 \end{pmatrix} \quad (4-37b)$$

The relationship between the terms of matrices (A) and (B) is obtained as follows. Insert matrix (A) of equation (4-35b) into equation (4-35a) and expand to obtain the full equation for $V_{\alpha\beta}^{(4)}$. Differentiate this equation with respect to $\bar{U}_a$ and multiply the result by $-2g_c$. The result is then compared with equation (4-34) giving

$$\begin{aligned} k(2100) &= -2g_c[2101] \\ k(2001) &= -4g_c[2002] \\ k(1110) &= -2g_c[1111] \\ k(1011) &= -4g_c[1012] \\ k(0120) &= -2g_c[0120] \\ k(0021) &= -4g_c[0022] \end{aligned} \quad (4-38)$$

in which the coefficients of the (A) matrix have been enclosed in square brackets to differentiate them from the coefficients of the (B) matrix, the third order aberration coefficients.

From equation (4-35c), coefficients [1111] and [0022] are real. Therefore, with reference to equations (4-38), aberration coefficients (1110), field curvature, and (0021), spherical aberration, are real. Also from equations (4-38) it is seen that the two coma coefficients, (1011) and (0120) are related by

$$(1011) = 2(0120)$$

It should be mentioned at this point that for round electrostatic lenses the perturbation characteristic function must also be invariant under a change from right-handed to left-handed axes. Therefore the (A) matrix must be real Hermitian and all the coefficients of the (B) matrix will be real.

With round magnetic lenses there are four complex terms which give rise to the three anisotropic aberrations present with magnetic lenses in addition to the five Seidel aberrations: anisotropic distortion, astigmatism, and coma.

It is instructive at this point to examine briefly the consequences of a departure from circular symmetry. In the event of this occurring, the condition $\alpha + \beta + \gamma + \delta = 1$ in equation (4-33) no longer applies and more terms result in the expression for U_c . In the extreme case a total of four first order terms, ten second order terms, and twenty third order terms are present. For reference, these are listed in Table 4-1 together with the type of aberration each produces and the symmetry which each possesses. It should be noted that the eight terms found earlier (equation (4-34)) as applying to round systems are the only terms displaying rotational symmetry. It is also instructive to note that the distortion terms are forms of degree zero in the aperture coordinates while the astigmatism and defocusing terms are of degree one, the coma terms are of degree two, and the spherical aberration terms are of degree three.

With what has been developed thus far, it is possible to carry out an extensive examination of the geometry of the aberrated image which results from each of the aberration terms in turn. This will not be done, except for spherical aberration. With the electron optical column arrangement which will be used for the present work, the other geometrical aberrations, while not being identically zero, will be negligibly small. This will be discussed more fully later but first, spherical aberration will be examined.

Spherical aberration

The spherical aberration term is, from equation (4-34),

$$U_c^{(4)} = (0021)U_a^2\bar{U}_a$$

and, from equations (4-35c) and (4-38), this term is real. Writing $U = re^{i\theta}$ and $(\alpha\beta\gamma\delta) = |\alpha\beta\gamma\delta|\exp i\langle\alpha\beta\gamma\delta\rangle$, $U_c^{(4)}$ can be rewritten as

$$U_c^{(4)} = r_a^3 |0021| e^{i\theta_a} \quad (4-39)$$

TABLE 4-1
GEOMETRICAL ABERRATIONS AND THEIR SYMMETRY

TERM	TYPE	SYMMETRY	TERM	TYPE	SYMMETRY
1000	magnification	rotational	0003	spherical	4 fold
0100	distortion	2 fold	2100	distortion	rotational
0010	defocusing	rotational	2010	defocusing	2 fold
0001	astigmatism	2 fold	2001	astigmatism	rotational
2000	distortion	mirror	1200	distortion	2 fold
0200	distortion	3 fold	0210	defocusing	2 fold
0020	coma	mirror	0201	astigmatism	4 fold
0002	coma	3 fold	1020	coma	2 fold
1100	distortion	mirror	0120	coma	rotational
1010	defocusing	mirror	0021	spherical	rotational
1001	astigmatism	mirror	1002	coma	2 fold
0110	defocusing	mirror	0102	coma	4 fold
0101	astigmatism	3 fold	0012	spherical	2 fold
0011	coma	mirror	1110	defocusing	rotational
3000	distortion	2 fold	1101	astigmatism	2 fold
0300	distortion	4 fold	1011	coma	rotational
0030	spherical	2 fold	0111	coma	2 fold

in which r_a signifies the radial coordinate of the ray in the aperture plane; the maximum value of r_a is R_a , the aperture radius. $U_c^{(4)}$ therefore represents a circle of radius $R_a^3 |0021|$ centred on the Gaussian image point.

The spherical aberration coefficient, $|0021|$ is known to be positive; with this fact, equation (4-39) shows that marginal rays, for which $r_a = R_a$, intersect the optic axis in front of the Gaussian image plane. Axial rays, on the other hand, intersect the optic axis at the Gaussian image plane since for them $r_a \rightarrow 0$.

The geometry is set out in Figure 4-1. From this figure

$$\frac{R_a}{R_a^3 |0021|} = \frac{b}{\delta z_a}$$

and

$$b + \delta z_a = \frac{R_a}{h_c}$$

Accordingly,

$$\begin{aligned} \frac{1}{R_a^2 |0021|} &= \frac{1}{h_c \delta z_a} - \frac{1}{R_a} \\ &\approx \frac{1}{h_c \delta z_a} \end{aligned}$$

from which

$$\delta z_a = \frac{|0021| R_a^2}{h_c} \quad (4-40)$$

δz_a is known as the longitudinal spherical aberration.

FIGURE 4-1

FORMATION OF THE SPHERICAL ABERRATION DISC.
 A IS THE APERTURE PLANE, M THE MARGINAL
 IMAGE PLANE, AND G THE GAUSSIAN IMAGE PLANE.

If all the rays from axial to marginal are considered, further geometrical arguments show that, at a distance $\frac{3}{4}\delta z_a$ in front of the Gaussian image plane, the rays are constricted to a minimum diameter, the circle of least confusion. The radius of this circle is $\frac{1}{4}|0021|R_a^3$ and the plane at which it occurs is called the plane of best focus.

The optics of the scanning electron microscope

The electron optical arrangement normally used in the final stage of a scanning electron microscope is shown in Figure 4-2. This arrangement is a compromise aimed at keeping the working distance short, so as to ensure that the final lens is operating in a demagnifying condition, while at the same time permitting reasonably large areas to be scanned. The arrangement introduces a considerable number of aberrations into the probe at low magnifications where the scan angles are large but, because of the unique method of imaging employed, these are not troublesome.

There are two main sources of these aberrations at low magnifications. The first source stems from the fact that, at low magnifications, the image radius, r_i is large and this, in turn, means that the virtual object radius, r_o' is larger than this by the amount of the final lens magnification; the lens aberrations under these conditions become very large. The second source is due to the rays entering the second deflection coil at an appreciable angle to its axis; as will be seen in the next chapter, this increases the number of deflection aberration terms from eight to eighteen.

The present work requires relatively high resolution at low magnifications. In view of the above, an alternative compromise will be adopted: deflection after the final lens demagnification. This will increase the working distance and therefore the spherical aberration coefficient but will reduce the other lens geometrical aberrations to negligible proportions since r_o , the radius of the virtual source in the electron gun demagnified by the two condenser lenses, is so small. In addition, only eight deflection aberration terms will have to be dealt with.

The adoption of this compromise makes possible positive identification of the source of aberrations detected in the probe: the lens will be the

FIGURE 4-2

ELECTRON OPTICAL ARRANGEMENT OF FINAL STAGE OF
 DEMAGNIFICATION IN THE SCANNING ELECTRON MICROSCOPE.
 r_i IS IMAGE RADIUS, r'_0 IS VIRTUAL OBJECT RADIUS,
 AND r_0 IS RADIUS OF DEMAGNIFIED VIRTUAL SOURCE.

source of any spherical aberration present, since deflection coils do not contribute this aberration; all other aberrations present will be caused by the deflection coils.

The deflection aberrations, on the control of which this work depends, will be examined in the next chapter.

CHAPTER 5

DEFLECTION ABERRATIONS

INTRODUCTION

The errors in the points of intersection of the individual rays of an electron beam with the Gaussian image plane which result when that beam is deflected simultaneously in two directions by orthogonal magnetic fields are discussed in this chapter. It will be seen that reduction of these errors to an acceptable level is mandatory for success of the large area scanning microscopy concept. The analysis of the origin of these errors is based on the procedure outlined by Haantjes and Lubbin [3].

THE EQUATION OF THE ELECTRON PATH

In Chapter 4 it was shown that the variational equation can be written in the form

$$\delta \int_A^B F dz = 0 \quad (4-13)$$

where

$$F = \sqrt{U(1 + x'^2 + y'^2)} - \eta A_x x' - \eta A_y y' - \eta A_z \quad (4-16)$$

and where A_x , A_y , and A_z are the components of the magnetic vector potential, $\eta = (e/2m_0)^{1/2}$, $U = \phi(1 + \epsilon\phi)$, $\epsilon = e/2m_0 c^2$, e and m_0 are the charge and rest mass of the electron, respectively, c is the velocity of light in free space, and the primes denote differentiation with respect to z .

It was also shown in Chapter 4 that the Euler equations corresponding to the variational equation (4-13) are, by combining equations (4-17) and (4-18),

$$\frac{\partial F}{\partial x} - \frac{d}{dz} \left(\frac{\partial F}{\partial x'} \right) = 0$$

(5-1)

$$\frac{\partial F}{\partial y} - \frac{d}{dz} \left(\frac{\partial F}{\partial y'} \right) = 0$$

If the expression for F, equation (4-16), is substituted into equations (5-1), the equations of motion of the electron result:

$$\frac{1}{2\sqrt{U}} \sqrt{1+x'^2+y'^2} \frac{\partial U}{\partial x} - \eta x' \frac{\partial A_x}{\partial x} - \eta y' \frac{\partial A_y}{\partial x} - \eta \frac{\partial A_z}{\partial x} =$$

$$\frac{d}{dz} \left[\frac{\sqrt{U} x'}{\sqrt{1+x'^2+y'^2}} - \eta A_x \right] \quad (5-2a)$$

$$\frac{1}{2\sqrt{U}} \sqrt{1+x'^2+y'^2} \frac{\partial U}{\partial y} - \eta x' \frac{\partial A_x}{\partial y} - \eta y' \frac{\partial A_y}{\partial y} - \eta \frac{\partial A_z}{\partial y} =$$

$$\frac{d}{dz} \left[\frac{\sqrt{U} y'}{\sqrt{1+x'^2+y'^2}} - \eta A_y \right] \quad (5-2b)$$

By applying the relation $\text{curl } \vec{A} = \vec{H}$, equations (5-2) can be rewritten in a form involving the magnetic field instead of the magnetic vector potential:

$$\frac{1}{2\sqrt{U}} \sqrt{1+x'^2+y'^2} \frac{\partial U}{\partial x} - \eta y' H_z + \eta H_y = \frac{d}{dz} \left[\frac{\sqrt{U} x'}{\sqrt{1+x'^2+y'^2}} \right] \quad (5-2c)$$

$$\frac{1}{2\sqrt{U}} \sqrt{1+x'^2+y'^2} \frac{\partial U}{\partial y} + \eta x' H_z - \eta H_x = \frac{d}{dz} \left[\frac{\sqrt{U} y'}{\sqrt{1+x'^2+y'^2}} \right] \quad (5-2d)$$

Solution of equations (5-2a) and (5-2b) or of equations (5-2c) and (5-2d) will give the path of the electron.

MAGNETIC DEFLECTION FIELD

The deflection of a beam of electrons with a magnetic field is accomplished in the scanning electron microscope by passing a current through two identical coils which are connected in series and located on opposite sides of the electron optical axis. The connection between the coils is such that their magnetic fields are in the same direction. Such a pair of coils is shown schematically in Figure 5-1; the axes of a cartesian coordinate system are superimposed on the figure.

The z axis coincides with the electron optical axis of the microscope column and the electrons are considered to be travelling in the positive z direction. It is usual for such coils to display a degree of symmetry of both shape and position. In the present work, mirror symmetry of shape and position in both the x-z and the y-z planes is assumed. Since this is normally the case in microscope construction, it is not restrictive. No symmetry with respect to the x-y plane is assumed in this work.

An examination of the magnetic field produced by a pair of coils subject to these symmetry conditions reveals that it displays the following symmetries when the main field component is in the x direction:

$$\begin{aligned} H_x(x,y,z) &= H_x(-x,y,z) = H_x(x,-y,z) \\ H_y(x,y,z) &= -H_y(-x,y,z) = -H_y(x,-y,z) \\ H_z(x,y,z) &= -H_z(-x,y,z) = H_z(x,-y,z) \end{aligned} \quad (5-3)$$

Since it is the field close to the z axis and within the boundaries of the deflection coils that is of interest and since no current flows in this volume, curl $\vec{H}$ for this volume is zero and the magnetic field may be described in terms of a magnetic scalar potential, Φ_m by $\vec{H} = \text{grad} \Phi_m$. (The magnetic field associated with the electron beam is very small and is neglected.) The magnetic scalar potential in the vicinity of the z axis is written as a power series in x and y giving

FIGURE 5-1
COORDINATE SYSTEM ORIENTATION WITH RESPECT
TO DEFLECTION COILS

$$\begin{aligned}
\phi_m = & \phi_0 + a_{10}x + a_{01}y + a_{20}x^2 + a_{11}xy + a_{02}y^2 + a_{30}x^3 \\
& + a_{21}x^2y + a_{12}xy^2 + a_{03}y^3 + a_{40}x^4 + a_{31}x^3y + a_{22}x^2y^2 \\
& + a_{13}xy^3 + a_{04}y^4 + a_{50}x^5 + a_{41}x^4y + a_{32}x^3y^2 + a_{23}x^2y^3 \\
& + a_{14}xy^4 + a_{05}y^5 + a_{60}x^6 + a_{51}x^5y + a_{42}x^4y^2 + a_{33}x^3y^3 \\
& + a_{24}x^2y^4 + a_{15}xy^5 + a_{06}y^6 + \dots
\end{aligned} \tag{5-4}$$

in which ϕ_0 and the coefficients a_{mn} are functions of z only.

The expression for H_x is derived from equation (5-4):

$$\begin{aligned}
H_x = \partial\phi_m/\partial x = & a_{10} + 2a_{20}x + a_{11}y + 3a_{30}x^2 + 2a_{21}xy \\
& + a_{12}y^2 + 4a_{40}x^3 + 3a_{31}x^2y + 2a_{22}xy^2 + a_{13}y^3 \\
& + 5a_{50}x^4 + 4a_{41}x^3y + 3a_{32}x^2y^2 + 2a_{23}xy^3 \\
& + a_{14}y^4 + 6a_{60}x^5 + 5a_{51}x^4y + 4a_{42}x^3y^2 \\
& + 3a_{33}x^2y^3 + 2a_{24}xy^4 + a_{15}y^5 + \dots
\end{aligned} \tag{5-5}$$

But equation (5-3) states that all H_x terms must be even in x and in y . Equation (5-5) therefore reduces to

$$H_x = a_{10} + 3a_{30}x^2 + a_{12}y^2 + 5a_{50}x^4 + 3a_{32}x^2y^2 + a_{14}y^4 + \dots \tag{5-6}$$

with

$$\begin{aligned}
a_{20} = a_{11} = a_{21} = a_{40} = a_{31} = a_{22} = a_{13} = a_{41} = a_{23} = a_{60} \\
= a_{51} = a_{42} = a_{33} = a_{24} = a_{15} = 0
\end{aligned} \tag{5-7}$$

Combining equations (5-7) and (5-4), the expression for H_y can be derived in similar fashion:

$$H_y = \partial \phi_m / \partial y = a_{01} + 2a_{02}'y + 2a_{12}'xy + 3a_{03}'y^2 + 4a_{04}'y^3 + 2a_{32}'x^3y + 4a_{14}'xy^3 + 5a_{05}'y^4 + 6a_{06}'y^5 + \dots \quad (5-8)$$

But equation (5-3) dictates that H_y contain only terms odd in x and in y . Accordingly,

$$H_y = 2a_{12}'xy + 2a_{32}'x^3y + 4a_{14}'xy^3 + \dots \quad (5-9)$$

and

$$a_{01} = a_{02} = a_{03} = a_{04} = a_{05} = a_{06} = 0 \quad (5-10)$$

Finally, the combination of equations (5-10), (5-7), and (5-4) permits the derivation of the expression for H_z :

$$H_z = \partial \phi_m / \partial z = \phi_0' + a_{10}'x + a_{30}'x^3 + a_{12}'xy^2 + a_{50}'x^5 + a_{32}'x^3y^2 + a_{14}'xy^4 + \dots \quad (5-11)$$

Equation (5-3), however, allows only terms in H_z which are odd in x and even in y . It follows that

$$\phi_0' = 0 \quad (5-12)$$

or ϕ_0 is a constant and

$$H_z = a_{10}'x + a_{30}'x^3 + a_{12}'xy^2 + a_{50}'x^5 + a_{32}'x^3y^2 + a_{14}'xy^4 + \dots \quad (5-13)$$

Relationships amongst the a_{mn} coefficients in equations (5-6), (5-9), and (5-13) for H_x , H_y , and H_z may now be determined by substituting for H_x , H_y , and H_z in the expression $\text{div } \vec{H} = 0$:

$$\begin{aligned}
 &6a_{30}x + 20a_{50}x^3 + 6a_{32}xy^2 + \dots \\
 &+ 2a_{12}x + 2a_{32}x^3 + 12a_{14}xy^2 + \dots \\
 &+ a_{10}''x + a_{30}''x^3 + a_{12}''xy^2 + \dots = 0
 \end{aligned}
 \tag{5-14}$$

This is an identity in x and y so that

$$\begin{aligned}
 6a_{30} + 2a_{12} + a_{10}'' &= 0 \\
 20a_{50} + 2a_{32} + a_{30}'' &= 0 \\
 6a_{32} + 12a_{14} + a_{12}'' &= 0
 \end{aligned}
 \tag{5-15}$$

from which

$$\begin{aligned}
 a_{30} &= -\frac{a_{12}}{3} - \frac{a_{10}''}{6} \\
 a_{32} &= -2a_{14} - \frac{a_{12}''}{6} \\
 a_{50} &= -\frac{a_{32}}{10} - \frac{a_{30}''}{20} \\
 &= \frac{a_{14}}{5} + \frac{a_{12}''}{60} + \frac{a_{12}''}{60} + \frac{a_{10}''''}{120} \\
 &= \frac{a_{14}}{5} + \frac{a_{12}''}{30} + \frac{a_{10}''''}{120}
 \end{aligned}
 \tag{5-16}$$

The notation

$$a_{10} = H_{\text{O}} \quad a_{12} = H_2 \quad a_{14} = H_4 \tag{5-17}$$

is introduced, permitting the potential Φ to be rewritten as

$$\begin{aligned}
L^{\phi} = & L^{\phi}_0 + L^H_0 x - \left(\frac{L^H_2}{3} + \frac{L^{H''}_0}{6} \right) x^3 + L^H_2 xy^2 \\
& + \left(\frac{L^H_4}{5} + \frac{L^{H''}_2}{30} + \frac{L^{H''''}_0}{120} \right) x^5 - \left(2L^H_4 + \frac{L^{H''}_2}{6} \right) x^3 y^2 \\
& + L^H_4 xy^4 + \dots
\end{aligned} \tag{5-18}$$

in which the prefix L has been added to signify that is the potential whose main component is in the line or x-direction which is being considered.

From equation (5-18), the components of the line-directed magnetic field can be determined:

$$\begin{aligned}
L^H_x = & L^H_0 - \left(L^H_2 + \frac{L^{H''}_0}{2} \right) x^2 + L^H_2 y^2 + \left(L^H_4 + \frac{L^{H''}_2}{6} + \frac{L^{H''''}_0}{24} \right) x^4 \\
& - \left(6L^H_4 + \frac{L^{H''}_2}{2} \right) x^2 y^2 + L^H_4 y^4 + \dots
\end{aligned} \tag{5-19}$$

$$L^H_y = 2L^H_2 xy - \left(4L^H_4 + \frac{L^{H''}_2}{3} \right) x^3 y + 4L^H_4 xy^3 + \dots \tag{5-20}$$

$$L^H_z = L^{H'}_0 x - \left(\frac{L^{H_2'}}{3} + \frac{L^{H'''}_0}{6} \right) x^3 + L^{H_2'} xy^2 + \dots \tag{5-21}$$

The quantities L^H_0 , L^H_2 , and L^H_4 are completely independent of one another and are functions of z.

In a completely analogous way, it is possible to derive the expressions for the frame or y-directed potential and deflecting field. The expressions for these are obtainable from equations (5-18) through (5-21) by interchanging x and y:

$$\begin{aligned}
 F^{\phi} = & F^{\phi}_0 + F^H_0 y - \left(\frac{F^H_2}{3} + \frac{F^{H''}_0}{6} \right) y^3 + F^H_2 x^2 y \\
 & + \left(\frac{F^H_4}{5} + \frac{F^H_2''}{30} + \frac{F^{H''''}_0}{120} \right) y^5 - \left(2F^H_4 + \frac{F^H_2''}{6} \right) x^2 y^3 \\
 & + F^H_4 x^4 y + \dots
 \end{aligned} \tag{5-22}$$

$$F^H_x = 2F^H_2 xy - \left(4F^H_4 + \frac{F^H_2''}{3} \right) xy^3 + 4F^H_4 x^3 y + \dots \tag{5-23}$$

$$\begin{aligned}
 F^H_y = & F^H_0 - \left(F^H_2 + \frac{F^{H''}_0}{2} \right) y^2 + F^H_2 x^2 + \left(F^H_4 + \frac{F^H_2''}{6} + \frac{F^{H''''}_0}{24} \right) y^4 \\
 & - \left(6F^H_4 + \frac{F^H_2''}{2} \right) x^2 y^2 + F^H_4 x^4 + \dots
 \end{aligned} \tag{5-24}$$

$$F^H_z = F^{H_0'} y - \left(\frac{F^{H_2'}}{3} + \frac{F^{H_0''''}}{6} \right) y^3 + F^{H_2'} x^2 y + \dots \tag{5-25}$$

Finally, expressions for the total field in each of the coordinate directions can be determined:

$$\begin{aligned}
 H_x = & L^H_x + F^H_x \\
 = & L^H_0 - \left(L^H_2 + \frac{L^{H''}_0}{2} \right) x^2 + 2F^H_2 xy + L^H_2 y^2 \\
 & + \left(L^H_4 + \frac{L^H_2''}{6} + \frac{L^{H''''}_0}{24} \right) x^4 + 4F^H_4 x^3 y - \left(6L^H_4 + \frac{L^H_2''}{2} \right) x^2 y^2 \\
 & - \left(4F^H_4 + \frac{F^H_2''}{3} \right) xy^3 + L^H_4 y^4 + \dots
 \end{aligned} \tag{5-26}$$

$$H_y = L_y + F_y$$

$$\begin{aligned}
 &= F_{H_0} + F_{H_2}x^2 + 2L_{H_2}xy - (F_{H_2} + \frac{F_{H_0}''}{2})y^2 \\
 &+ F_{H_4}x^4 - (4L_{H_4} + \frac{L_{H_2}''}{3})x^3y - (6F_{H_4} + \frac{F_{H_2}''}{2})x^2y^2 \\
 &+ 4L_{H_4}xy^3 + (F_{H_4} + \frac{F_{H_2}''}{6} + \frac{F_{H_0}''''}{24})y^4 + \dots
 \end{aligned} \tag{5-27}$$

$$H_z = L_z + F_z$$

$$\begin{aligned}
 &= L_{H_0}'x + F_{H_0}'y - (\frac{L_{H_2}'}{3} + \frac{L_{H_0}'''}{6})x^3 + F_{H_2}'x^2y \\
 &+ L_{H_2}'xy^2 - (\frac{F_{H_2}'}{3} + \frac{F_{H_0}'''}{6})y^3 + \dots
 \end{aligned} \tag{5-28}$$

ELECTRON BEAM DEFLECTION

The equations governing the deflection of an electron by a purely magnetic field may now be determined. The path of the electron is given by a solution of equations (5-2c) and (5-2d) and for this purpose the expressions for H_x , H_y , and H_z given by equations (5-26) to (5-28) are substituted into equations (5-2c) and (5-2d). The resulting equations are then solved by successive approximations.

In these approximations, only terms of up to the second order in x, y, x' , and y' are considered. In addition, the electron beam accelerating potential, U is constant so that terms involving derivatives of U drop out. Under these conditions, the substitutions into equations (5-2c) and (5-2d) yield

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$$\frac{d}{dz} \left[\frac{\sqrt{U} x'}{\sqrt{1+x'^2+y'^2}} \right] = -\eta x y' L H_o' - \eta y' y_F H_o' + \eta_F H_o$$

$$+ \eta x^2 F H_2 + 2\eta x y_L H_2 - \eta y^2 F H_2 - \frac{1}{2} \eta y^2 F H_o'' \quad (5-29a)$$

$$\frac{d}{dz} \left[\frac{\sqrt{U} y'}{\sqrt{1+x'^2+y'^2}} \right] = \eta x' x_L H_o' + \eta x' y_F H_o' - \eta_L H_o + \eta x^2 L H_2$$

$$+ \frac{1}{2} \eta x^2 L H_o'' - 2\eta x y_F H_2 - \eta y^2 L H_2 \quad (5-29b)$$

First approximation solution

In this approximation, only terms of degree zero in x, y, x' , and y' are admitted from the right hand side of equations (5-29) and the expression $\sqrt{1+x'^2+y'^2}$ is replaced by unity. The equations of the electron path then become

$$\frac{d}{dz} (\sqrt{U} x') = \eta_F H_o \quad (5-30a)$$

$$\frac{d}{dz} (\sqrt{U} y') = -\eta_L H_o \quad (5-30b)$$

which reduce to

$$x'' = k_F H_o \quad (5-31a)$$

$$y'' = -k_L H_o \quad (5-31b)$$

in which

$$k = \frac{\eta}{\sqrt{U}} \quad (5-32)$$

has been substituted.

A first integration of equation (5-31a) gives

$$x' = k \int_{z_0}^z F H_0(\zeta) d\zeta + \text{cst.}$$

The electron is taken as entering the deflection field at the point x_0, y_0, z_0 with a slope x'_0, y'_0 . Accordingly, at $H_0 = 0$, $x' = x'_0$ and the constant of integration is x'_0 . Therefore

$$x' = x'_0 + k \int_{z_0}^z F H_0(\zeta) d\zeta. \quad (5-33a)$$

$$= x'_0 + X' \quad (5-33b)$$

Similarly, a first integration of equation (5-31b) gives

$$y' = -k \int_{z_0}^z L H_0(\zeta) d\zeta + \text{cst.}$$

with the constant of integration being found as before to be y'_0 . Thus

$$y' = y'_0 - k \int_{z_0}^z L H_0(\zeta) d\zeta \quad (5-34a)$$

$$= y'_0 + Y' \quad (5-34b)$$

A second integration of equation (5-31a) gives

$$x = x_0 + k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} F H_0 dz + \text{cst.}$$

At $H_0 = 0$, $x = x_0 + x'_0(z - z_0)$ so that the constant of integration is $x'_0(z - z_0)$ and

$$x_g = x_o + x_o'(z-z_o) + k \int_{z_o}^z d\zeta \int_{z_o}^{\zeta} F H_o dz \quad (5-35a)$$

$$= x_o + x_o'(z-z_o) + X \quad (5-35b)$$

In a similar fashion, a second integration of equation (5-31b) yields

$$y = y_o - k \int_{z_o}^z d\zeta \int_{z_o}^{\zeta} L H_o dz + \text{cst.}$$

and the constant of integration is found to be $y_o'(z-z_o)$. Accordingly,

$$y_g = y_o + y_o'(z-z_o) - k \int_{z_o}^z d\zeta \int_{z_o}^{\zeta} L H_o dz \quad (5-36a)$$

$$= y_o + y_o'(z-z_o) + Y \quad (5-36b)$$

The subscripts g in equations (5-35) and (5-36) have been attached to indicate that these solutions are equivalent to the Gaussian solutions.

Second approximation solution

In this solution, terms of up to the second order in x, y, x' , and y' are admitted and the following approximations are made:

$$\frac{x'}{\sqrt{1+x'^2+y'^2}} \approx x' - \frac{1}{2}x'^3 - \frac{1}{2}x'y'^2 \quad (5-37a)$$

$$\frac{y'}{\sqrt{1+x'^2+y'^2}} \approx y' - \frac{1}{2}y'x'^2 - \frac{1}{2}y'^3 \quad (5-37b)$$

Equations (5-29a) and (5-29b) then become

$$\begin{aligned} \frac{d}{dz}(x' - \frac{1}{2}x'^3 - \frac{1}{2}x'y'^2) = & -k(LH_0'xy' + FH_0'yy' - FH_0 \\ & - FH_2x^2 - 2LH_2xy + (FH_2 + FH_0'')y^2) \end{aligned} \quad (5-38a)$$

$$\begin{aligned} \frac{d}{dz}(y' - \frac{1}{2}x'^2y' - \frac{1}{2}y'^3) = & -k(-LH_0'xx' - FH_0'x'y + LH_0 \\ & - (LH_2 + \frac{LH_0''}{2})x^2 + 2FH_2xy + LH_2y^2) \end{aligned} \quad (5-38b)$$

A first integration of equations (5-38) yields

$$\begin{aligned} (x' - x_0') - (\frac{1}{2}x'^3 - \frac{1}{2}x_0'^3) - (\frac{1}{2}x'y'^2 - \frac{1}{2}x_0'y_0'^2) = \\ -k \int_{z_0}^z LH_0'xy'd\zeta - k \int_{z_0}^z FH_0'yy'd\zeta + k \int_{z_0}^z FH_0 d\zeta \\ + k \int_{z_0}^z FH_2x^2d\zeta + 2k \int_{z_0}^z LH_2xyd\zeta - k \int_{z_0}^z FH_2y^2d\zeta \\ - \frac{1}{2}k \int_{z_0}^z FH_0''y^2d\zeta \end{aligned} \quad (5-39a)$$

and

$$\begin{aligned} (y' - y_0') - (\frac{1}{2}x'^2y' - \frac{1}{2}x_0'^2y_0') - (\frac{1}{2}y'^3 - \frac{1}{2}y_0'^3) = \\ + k \int_{z_0}^z LH_0'xx'd\zeta + k \int_{z_0}^z FH_0'x'yd\zeta - k \int_{z_0}^z LH_0 d\zeta \\ + k \int_{z_0}^z LH_2x^2d\zeta + \frac{1}{2}k \int_{z_0}^z LH_0''x^2d\zeta - 2k \int_{z_0}^z FH_2xyd\zeta \\ - k \int_{z_0}^z LH_2y^2d\zeta \end{aligned} \quad (5-39b)$$

The constants of integration are zero since, at $H = 0$,

$$x' - \frac{1}{2}x'^3 - \frac{1}{2}x'y'^2 = x_0' - \frac{1}{2}x_0'^3 - \frac{1}{2}x_0'y_0'^2 \text{ and } y' - \frac{1}{2}x'^2y' - \frac{1}{2}y'^3 = y_0' - \frac{1}{2}x_0'^2y_0' - \frac{1}{2}y_0'^3.$$

Rearranging equations (5-39) and attaching the subscript g to indicate the coordinates corresponding to the Gaussian ray gives

$$\begin{aligned}
 x' = & x_0' + \frac{1}{2}(x_g'^3 - x_0'^3) + \frac{1}{2}(x_g'y_g'^2 - x_0'y_0'^2) \\
 & - k \int_{z_0}^z L_{H_0}' x_g y_g' d\zeta - k \int_{z_0}^z F_{H_0}' y_g y_g' d\zeta + k \int_{z_0}^z F_{H_0}' d\zeta \\
 & + k \int_{z_0}^z F_{H_2}' x_g^2 d\zeta + 2k \int_{z_0}^z L_{H_2}' x_g y_g' d\zeta - k \int_{z_0}^z F_{H_2}' y_g^2 d\zeta \\
 & - \frac{1}{2} k \int_{z_0}^z F_{H_0}'' y_g^2 d\zeta
 \end{aligned} \tag{5-40a}$$

and

$$\begin{aligned}
 y' = & y_0' + \frac{1}{2}(x_g'^2 y_g' - x_0'^2 y_0') + \frac{1}{2}(y_g'^3 - y_0'^3) + k \int_{z_0}^z L_{H_0}' x_g x_g' d\zeta \\
 & + k \int_{z_0}^z F_{H_0}' x_g' y_g d\zeta - k \int_{z_0}^z L_{H_0}' d\zeta + k \int_{z_0}^z L_{H_2}' x_g^2 d\zeta \\
 & + \frac{1}{2} k \int_{z_0}^z L_{H_0}'' x_g^2 d\zeta - 2k \int_{z_0}^z F_{H_2}' x_g y_g d\zeta - k \int_{z_0}^z L_{H_2}' y_g^2 d\zeta
 \end{aligned} \tag{5-40b}$$

A second integration of equations (5-38) gives

$$\begin{aligned}
 x = & x_0 + x_0'(z - z_0) + \frac{1}{2} \int_{z_0}^z (x_g'^3 - x_0'^3) d\zeta + \frac{1}{2} \int_{z_0}^z (x_g'y_g'^2 - x_0'y_0'^2) d\zeta \\
 & - k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} L_{H_0}' x_g y_g' dz - k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} F_{H_0}' y_g y_g' dz + k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} F_{H_0}' dz \\
 & + k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} F_{H_2}' x_g^2 dz + 2k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} L_{H_2}' x_g y_g' dz - k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} F_{H_2}' y_g^2 dz \\
 & - \frac{1}{2} k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} F_{H_0}'' y_g^2 dz
 \end{aligned} \tag{5-41a}$$

and

$$\begin{aligned}
y = & y_0 + y_0'(z - z_0) + \frac{1}{2} \int_{z_0}^z (x_g'^2 y_g' - x_0'^2 y_0') d\zeta + \frac{1}{2} \int_{z_0}^z (y_g'^3 - y_0'^3) d\zeta \\
& + k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} L^{H_0} x_g x_g' dz + k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} F^{H_0} x_g' y_g dz - k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} L^{H_0} dz \\
& + k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} L^{H_2} x_g^2 dz + \frac{1}{2} k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} L^{H_0} x_g^2 dz - 2k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} F^{H_2} x_g y_g dz \\
& - k \int_{z_0}^z d\zeta \int_{z_0}^{\zeta} L^{H_2} y_g^2 dz
\end{aligned} \tag{5-41b}$$

The constants of integration are zero since, at $H = 0$,

$$\begin{aligned}
x = & x_0 + x_0'(z - z_0) + \frac{1}{2} \int_{z_0}^z (x_g'^3 - x_0'^3) d\zeta + \frac{1}{2} \int_{z_0}^z (x_g' y_g'^2 - x_0' y_0'^2) d\zeta \\
\text{and } y = & y_0 + y_0'(z - z_0) + \frac{1}{2} \int_{z_0}^z (x_g'^2 y_g' - x_0'^2 y_0') d\zeta + \frac{1}{2} \int_{z_0}^z (y_g'^3 - y_0'^3) d\zeta.
\end{aligned}$$

In equations (5-35b) and (5-36b),

$$x_g = x_0 + x_0'(z - z_0) + X \tag{5-35b}$$

$$y_g = y_0 + y_0'(z - z_0) + Y \tag{5-36b}$$

let

$$x_s = x_0 + x_0'(z_s - z_0) \tag{5-42a}$$

$$x_s' = x_0' \tag{5-42b}$$

$$y_s = y_0 + y_0'(z_s - z_0) \tag{5-42c}$$

$$y_s' = y_0' \tag{5-42d}$$

Substituting relations (5-42) into (5-35b) and (5-36b) gives

$$\begin{aligned} x_g &= x_s - x_s'(z_s - z_0) + x_s'(z - z_0) + X \\ &= x_s + x_s'(z - z_s) + X \end{aligned} \quad (5-43a)$$

and

$$\begin{aligned} y_g &= y_s - y_s'(z_s - z_0) + y_s'(z - z_0) + Y \\ &= y_s + y_s'(z - z_s) + Y \end{aligned} \quad (5-43b)$$

This gives the coordinates of the Gaussian solution in terms of the coordinates x_s and y_s and the directions x_s' and y_s' which the electron beam would have at the specimen plane $z=z_s$ if no deflecting field were present.

It is desired to know to what extent the second approximation solutions, as represented by equations (5-41a) and (5-41b), differ from the Gaussian solutions, represented by (5-43a) and (5-43b). Accordingly, the Gaussian solutions are substituted for x_g and y_g in equations (5-41a) and (5-41b), the Gaussian solutions are then subtracted from the results of the substitutions, and these final equations are rearranged according to the dependence of their terms upon x_s , y_s , x_s' , y_s' , X , and Y . The results, the deviation of the second approximation solution from the Gaussian or first approximation solution, are the expressions for the deflection aberrations. The results are:

$$\begin{aligned} \Delta x &= \left[\frac{1}{2} \int_{z_0}^{z_s} X'^3 dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F_{H_2} X^2 dz \right] + \left[-X + \frac{1}{2} \int_{z_0}^{z_s} X' Y'^2 dz \right. \\ &\quad - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L_{H_0}' X Y' dz - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F_{H_0}' Y Y' dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F_{H_0} dz \\ &\quad \left. + 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L_{H_2} X Y dz - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F_{H_2} Y^2 dz - \frac{1}{2} k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F_{H_0}'' Y^2 dz \right] \end{aligned}$$

$$+ x_s' \left[\frac{3}{2} \int_{z_0}^{z_s} X'^2 dz + \frac{1}{2} \int_{z_0}^{z_s} Y'^2 dz - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L^{H_0'}(z - z_s) Y' dz \right. \\ \left. + 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_2}(z - z_s) X dz + 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L^{H_2}(z - z_s) Y dz \right]$$

$$+ y_s' \left[\int_{z_0}^{z_s} X' Y' dz - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L^{H_0'} X dz - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_0'} Y dz \right. \\ \left. - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_0'}(z - z_s) Y' dz - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_2}(z - z_s) Y dz \right. \\ \left. - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_0''}(z - z_s) Y dz + 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L^{H_2}(z - z_s) X dz \right]$$

$$+ x_s'^2 \left[\frac{3}{2} \int_{z_0}^{z_s} X'^2 dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_2}(z - z_s)^2 dz \right]$$

$$+ y_s'^2 \left[\frac{1}{2} \int_{z_0}^{z_s} X' dz - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_0'}(z - z_s) dz - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_2}(z - z_s)^2 dz \right.$$

$$\left. - \frac{1}{2} k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_0''}(z - z_s)^2 dz \right] + x_s' y_s' \left[\int_{z_0}^{z_s} Y' dz \right.$$

$$\left. - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L^{H_0'}(z - z_s) dz + 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L^{H_2}(z - z_s)^2 dz \right]$$

$$\begin{aligned}
& + x_s \left[-k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L^{H_0} Y' dz + 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_2} X dz + 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L^{H_2} Y dz \right] \\
& + y_s \left[-k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_0} Y' dz + 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L^{H_2} X dz - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_2} Y dz \right. \\
& \left. - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_0} Y'' dz \right] + x_s^2 \left[k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_2} dz \right] \\
& + y_s^2 \left[-k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_2} dz - \frac{1}{2} k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_0} dz \right] \\
& + x_s y_s \left[2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L^{H_2} dz \right] + x_s x_s' \left[2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_2} (z - z_s) dz \right] \\
& + y_s x_s' \left[2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L^{H_2} (z - z_s) dz \right] + y_s y_s' \left[-k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_0} dz \right. \\
& \left. - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_2} (z - z_s) dz - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F^{H_0} (z - z_s) dz \right] \\
& + x_s y_s' \left[-k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L^{H_0} dz + 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L^{H_2} (z - z_s) dz \right]
\end{aligned}$$

(5-44a)

and

$$\begin{aligned}
\Delta y = & \left[\frac{1}{2} \int_{z_0}^{z_s} Y'^3 dz - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L H_2 Y^2 dz \right] + \left[-Y + \frac{1}{2} \int_{z_0}^{z_s} X'^2 Y' dz \right. \\
& + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L H_0' X X' dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F H_0' X' Y dz - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L H_0 dz \\
& + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L H_2 X^2 dz + \frac{1}{2} k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L H_0'' dz - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F H_2 X Y dz \left. \right] \\
& + y_s' \left[\frac{1}{2} \int_{z_0}^{z_s} X'^2 dz + \frac{3}{2} \int_{z_0}^{z_s} Y'^2 dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F H_0' (z - z_s) X' dz \right. \\
& - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F H_2 (z - z_s) X dz - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L H_2 (z - z_s) Y dz \left. \right] \\
& + x_s' \left[\int_{z_0}^{z_s} X' Y' dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L H_0' X dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L H_0' (z - z_s) X' dz \right. \\
& + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F H_0' Y dz + 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L H_2 (z - z_s) X dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L H_0'' (z - z_s) X dz \\
& - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F H_2 (z - z_s) Y dz \left. \right] + y_s'^2 \left[\frac{3}{2} \int_{z_0}^{z_s} Y' dz - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L H_2 (z - z_s)^2 dz \right] \\
& + x_s'^2 \left[\frac{1}{2} \int_{z_0}^{z_s} Y' dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L H_0' (z - z_s) dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L H_2 (z - z_s)^2 dz \right. \\
& + \frac{1}{2} k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L H_0'' (z - z_s)^2 dz \left. \right] + x_s' y_s' \left[\int_{z_0}^{z_s} X' dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F H_0' (z - z_s) dz \right.
\end{aligned}$$

$$\begin{aligned}
& -2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F_{H_2} (z-z_s)^2 dz \Big] + y_s \Big[k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F_{H_0}' X' dz - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F_{H_2} X dz \\
& - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L_{H_2} Y dz \Big] + x_s \Big[k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L_{H_0}' X' dz + 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L_{H_2} X dz \\
& + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L_{H_0}'' X dz - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F_{H_2} Y dz \Big] + y_s^2 \Big[-k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L_{H_2} dz \Big] \\
& + x_s^2 \Big[k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L_{H_2} dz + \frac{1}{2} k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L_{H_0}'' dz \Big] + x_s y_s \Big[-2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F_{H_2} dz \Big] \\
& + y_s y_s' \Big[-2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L_{H_2} (z-z_s) dz \Big] + x_s y_s' \Big[-2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F_{H_2} (z-z_s) dz \Big] \\
& + x_s x_s' \Big[k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L_{H_0}' dz + 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L_{H_2} (z-z_s) dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} L_{H_0}'' (z-z_s) dz \Big] \\
& + x_s' y_s \Big[k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F_{H_0}' dz - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} F_{H_2} (z-z_s) dz \Big] \tag{5-44b}
\end{aligned}$$

If these expressions are worked out in detail, the final deflection aberration equations are found to be:

$$\begin{aligned}
\Delta x = & A1X_s + (A2 + B3)X_s Y_s^2 + (A4X_s^2 + B5Y_s^2)X_s' \\
& + (A6 + B6)X_s Y_s y_s' + A7X_s x_s'^2 + A8X_s y_s'^2 \\
& + 2B8Y_s x_s' y_s' + (A9X_s^2 + B10Y_s^2)x_s + (B11 + A12)X_s Y_s y_s \\
& + A13X_s x_s^2 + A14X_s y_s^2 + B15Y_s x_s y_s' + A16X_s x_s x_s' \\
& + B17Y_s y_s x_s' + A18X_s y_s y_s' + B18Y_s x_s y_s' \tag{5-45a}
\end{aligned}$$

and

$$\begin{aligned}
 \Delta y = & B1Y_s^3 + (B2 + A3)X_s^2Y_s + (B4Y_s^2 + A5X_s^2)y_s' \\
 & + (A6 + B6)X_sY_sx_s' + B7Y_sy_s'^2 + B8Y_sx_s'^2 \\
 & + 2A8X_sx_s'y_s' + (B9Y_s^2 + A10X_s^2)y_s + (A11 + B12)X_sY_sx_s \\
 & + B13Y_sy_s'^2 + B14Y_sx_s'^2 + A15X_sx_sy_s + B16Y_sy_sy_s' \\
 & + A17X_sx_sy_s' + B18Y_sx_sx_s' + A18X_sx_s'y_s
 \end{aligned} \tag{5-45b}$$

The coefficients A_m and B_m are given in complete form in Appendix 3.

X_s and Y_s are the X and Y of equations (5-35) and (5-36) evaluated at the specimen plane, $z = z_s$ and are the Gaussian deflections at this plane. x_s and y_s are the electron beam coordinates at $z = z_s$ with zero deflection while x_s' and y_s' are the slopes of the undeflected beam at $z = z_s$.

DISCUSSION OF RESULTS

In the scanning electron microscope, the point at which an undeflected electron beam strikes the specimen is $x_s = y_s = 0$ or at the specimen centre. Equations (5-45) can therefore be simplified for the present application:

$$\begin{aligned}
 \Delta x = & A1X_s^3 + (A2 + B3)X_sY_s^2 + (A4X_s^2 + B5Y_s^2)x_s' \\
 & + (A6 + B6)X_sY_sy_s' + A7X_sx_s'^2 + A8X_sy_s'^2 \\
 & + 2B8Y_sx_s'y_s'
 \end{aligned} \tag{5-46a}$$

$$\begin{aligned}
 \Delta y = & B1Y_s^3 + (B2 + A3)X_s^2Y_s + (B4Y_s^2 + A5X_s^2)y_s' \\
 & + (A6 + B6)X_sY_sx_s' + B7Y_sy_s'^2 + B8Y_sx_s'^2 \\
 & + 2A8X_sx_s'y_s'
 \end{aligned} \tag{5-46b}$$

The errors described by equations (5-46) are classified according to their dependence on the angle between the electron optical axis and electron ray, x_s' and y_s' . Distortion is independent of this angle while

astigmatism and field curvature are linearly dependent on it and coma is quadratically dependent on it. Spherical aberration would display a cubic dependence on this angle; an examination of equations (5-46) shows that deflection systems do not introduce spherical aberration.

Raster distortion

The distortion terms are

$$\begin{aligned}\Delta x &= A_1 X_s^3 + (A_2 + B_3) X_s Y_s^2 \\ \Delta y &= B_1 Y_s^3 + (B_2 + A_3) X_s^2 Y_s\end{aligned}\tag{5-47}$$

Coefficients A_1 and B_1 cause nonlinear deflections. These can be corrected for by using nonlinear deflection amplifiers or by using nonlinear signals to drive the deflection amplifiers. Coefficients $(A_2 + B_3)$ and $(B_2 + A_3)$ cause barrel distortion if they are negative or pincushion distortion if they are positive. To avoid these distortions it is necessary that $(A_2 + B_3) = (B_2 + A_3) = 0$.

Astigmatism and field curvature

The astigmatism and field curvature terms are

$$\begin{aligned}\Delta x &= (A_4 X_s^2 + B_5 Y_s^2) x_s' + (A_6 + B_6) X_s Y_s y_s' \\ \Delta y &= (B_4 Y_s^2 + A_5 X_s^2) y_s' + (A_6 + B_6) X_s Y_s x_s'\end{aligned}\tag{5-48}$$

The terms containing A_4 , A_5 , B_4 , and B_5 cause isotropic astigmatism. In the presence of this aberration, electron rays on the periphery of the beam strike the specimen plane in an ellipse rather than at a point as in the undeflected case. Such an astigmatic beam forms two orthogonal line foci before it strikes the specimen plane; the planes at which these line foci occur are the sagittal and meridional image planes. At one point between the sagittal and meridional planes, the beam cross-section is a circle; the plane at which this occurs is the average image plane. If the sagittal and meridional image planes coincide with the average image plane, the beam cross-section at this plane is a point and the image is

said to be anastigmatic. This plane, however, will not coincide with the plane $z = z_s$ if the error curvature of the image plane still remaining.

The terms containing A_6 and B_6 are anisotropic astigmatism. This aberration enlarges the spot to a circle which has its greatest diameter on the raster diagonals. On the x and y axes these terms are zero.

Taken together, these terms enlarge the spot to an ellipse, the size and orientation of which varies with its position on the raster. In general, its size is greatest at the raster edges.

Coma

The coma terms are

$$\begin{aligned}\Delta x &= A_7 X_s x_s'^2 + A_8 X_s y_s'^2 + 2B_8 Y_s x_s' y_s' \\ \Delta y &= B_7 Y_s y_s'^2 + B_8 Y_s x_s'^2 + 2A_8 X_s x_s' y_s'\end{aligned}\quad (5-49)$$

In general, the effect of coma is to enlarge the spot to an elliptical, cardioid, 3-leaved rose, or comet shape depending upon the magnitude of the parameters involved. The centre of the shape is normally displaced from the Gaussian deflection point.

CONVERSION TO COMPLEX COORDINATES

It is convenient to reexpress the deflection aberrations described by equations (5-46) in complex coordinates, as is done by Amboss and Wolf [37]. But it should first be noted that the terms in equations (5-46) which describe the distortion affect only the faithfulness with which the image on the display system represents the specimen; they do not affect the resolution. They do not, therefore, fit into the present context of high scanning electron microscope resolution over large areas and they are therefore not included in the present discussion.

This is not meant to imply that distortion is unimportant; obviously, in applications such as electron beam exposure of photoresist for the purpose of making masks for the semiconductor industry, it is of paramount importance. But in the present application, on the other hand, distortion serves mainly as an annoyance; its presence does not affect the precision of the results.

Equations (5-46) are therefore rewritten without the distortion terms:

$$\begin{aligned}\Delta x_i = & (A4X_s^2 + B5Y_s^2 + B5Y_s^2)x_s' + (A6 + B6)X_s Y_s y_s' \\ & + A7X_s x_s'^2 + A8X_s y_s'^2 + 2B8Y_s x_s' y_s'\end{aligned}\quad (5-50a)$$

$$\begin{aligned}\Delta y_i = & (B4Y_s^2 + A5X_s^2)y_s' + (A6 + B6)X_s Y_s x_s' \\ & + B7Y_s y_s'^2 + B8Y_s x_s'^2 + 2A8X_s x_s' y_s'\end{aligned}\quad (5-50b)$$

Now the parameters x_s' and y_s' , being the components of the angle between the undeflected electron ray and the electron optical axis, can be equally well represented by x_a and y_a , the coordinates of the electron ray at the aperture plane. In addition, equations (5-50) can be combined by noting that, in complex coordinates, $\Delta U_i = \Delta x_i + i\Delta y_i$. With these two changes, equations (5-50) become

$$\begin{aligned}\Delta U_i = & A4X_s^2 x_a + B5Y_s^2 x_a + A6X_s Y_s y_a \\ & + B6X_s Y_s y_a + A7X_s x_a^2 + A8X_s y_a^2 \\ & + 2B8Y_s x_a y_a + iB4Y_s^2 y_a + iA5X_s^2 y_a \\ & + iA6X_s Y_s x_a + iB6X_s Y_s x_a + iB7Y_s y_a^2 \\ & + iB8Y_s x_a^2 + 2iA8X_s x_a y_a\end{aligned}\quad (5-51)$$

The following conversions to complex coordinates are now made:

$$\begin{aligned}X_s + iY_s &= U_s & x_a + iy_a &= U_a \\ X_s - iY_s &= \bar{U}_s & x_a - iy_a &= \bar{U}_a \\ X_s &= \frac{U_s + \bar{U}_s}{2} & x_a &= \frac{U_a + \bar{U}_a}{2} \\ Y_s &= \frac{U_s - \bar{U}_s}{2} & y_a &= \frac{U_a - \bar{U}_a}{2}\end{aligned}$$

Substitution of these relations into equation (5-51) yields, after considerable algebraic reduction,

$$\begin{aligned}
\Delta U_i = & 1/8 U_s^2 U_a (A4 + A5 - B4 - B5) \\
& + 1/4 U_s \bar{U}_s U_a (A4 + A5 + B4 + B5) \\
& + 1/8 \bar{U}_s^2 U_a (A4 + A5 - B4 - B5) \\
& + 1/8 U_s^2 \bar{U}_a (A4 - A5 + B4 - B5 + 2A6 + 2B6) \\
& + 1/4 U_s \bar{U}_s \bar{U}_a (A4 - A5 - B4 + B5) \\
& + 1/8 \bar{U}_s^2 \bar{U}_a (A4 - A5 + B4 - B5 - 2A6 - 2B6) \\
& + 1/8 U_s U_a^2 (A7 + A8 - B7 - B8) \\
& + 1/4 U_s U_a \bar{U}_a (A7 + A8 + B7 + B8) \\
& + 1/8 U_s \bar{U}_a^2 (A7 - 3A8 - B7 + 3B8) \\
& + 1/8 \bar{U}_s U_a^2 (A7 + A8 + B7 + B8) \\
& + 1/4 \bar{U}_s U_a \bar{U}_a (A7 + A8 - B7 - B8) \\
& + 1/8 \bar{U}_s \bar{U}_a^2 (A7 - 3A8 + B7 - 3B8)
\end{aligned} \tag{5-52}$$

which can be rewritten, using the simplified notation of Chapter 4, as

$$\begin{aligned}
\Delta U_i = & (2010) U_s^2 U_a + (1110) U_s \bar{U}_s U_a + (0210) \bar{U}_s^2 U_a \\
& + (2001) U_s^2 \bar{U}_a + (1101) U_s \bar{U}_s \bar{U}_a + (0201) \bar{U}_s^2 \bar{U}_a \\
& + (1020) U_s U_a^2 + (1011) U_s U_a \bar{U}_a + (1002) U_s \bar{U}_a^2 \\
& + (0120) \bar{U}_s U_a^2 + (0111) \bar{U}_s U_a \bar{U}_a + (0102) \bar{U}_s \bar{U}_a^2
\end{aligned} \tag{5-53}$$

A comparison of equations (5-52) and (5-53) discloses that

$$\begin{aligned}
(2010) &= (0210) \\
(1011) &= 2(0120) \\
(0111) &= 2(1020)
\end{aligned} \tag{5-54}$$

which allows equation (5-53) to be rewritten as

$$\begin{aligned}
\Delta U_1 = & (0210)(U_s^2 U_a + \bar{U}_s^2 U_a) + (1110)(U_s \bar{U}_s U_a) \\
& + (2001)(U_s^2 \bar{U}_a) + (1101)(U_s \bar{U}_s \bar{U}_a) + (0201)(\bar{U}_s^2 \bar{U}_a) \\
& + (1020)(U_s U_a^2 + 2\bar{U}_s U_a \bar{U}_a) + (0120)(2U_s U_a \bar{U}_a + \bar{U}_s U_a^2) \\
& + (1002)(U_s \bar{U}_a^2) + (0102)(\bar{U}_s \bar{U}_a^2)
\end{aligned} \tag{5-55}$$

Reference to equation (A3-8) of Appendix 3 shows that

$$\bar{A}B = 1 - A7$$

$$B8 = 1 - B7$$

An examination of each of the coefficients of equations (5-52) and (5-53) which contain A7, A8, B7, and B8 discloses the following points:

$$\begin{aligned}
(1020) &= 1/8(A7 + A8 - B7 - B8) \\
&= 1/8(A7 + 1 - A7 - B7 - 1 + B7) \\
&= 0
\end{aligned} \tag{5-56a}$$

$$\begin{aligned}
(1011) &= 1/4(A7 + A8 + B7 + B8) \\
&= 1/4(A7 + 1 - A7 + B7 + 1 - B7) \\
&= 1/2
\end{aligned} \tag{5-56b}$$

$$\begin{aligned}
(1002) &= 1/8(A7 - 3A8 - B7 + 3B8) \\
&= 1/8(A7 - 3 + 3A7 - B7 + 3 - 3B7) \\
&= 1/2(A7 - B7)
\end{aligned} \tag{5-56c}$$

$$\begin{aligned}
(0120) &= 1/8(A7 + A8 + B7 + B8) \\
&= 1/8(A7 + 1 - A7 + B7 + 1 - B7) \\
&= 1/4
\end{aligned} \tag{5-56d}$$

$$\begin{aligned}
(0111) &= 1/4(A7 + A8 - B7 - B8) \\
&= 1/4(A7 + 1 - A7 - B7 - 1 + B7) \\
&= 0
\end{aligned} \tag{5-56e}$$

$$\begin{aligned}
(0102) &= 1/8(A7 - 3A8 + B7 - 3B8) \\
&= 1/8(A7 - 3 + 3A7 + B7 - 3 + 3B7) \\
&= 1/2(A7 + B7) - 3/4
\end{aligned} \tag{5-56f}$$

Substitution of relations (5-56a,b,d, and e) into equation (5-55) gives

$$\begin{aligned} \Delta U_i = & (0210)(U_s^2 U_a + \bar{U}_s^2 \bar{U}_a) + (1110)(U_s \bar{U}_s U_a) \\ & + (2001)(U_s^2 \bar{U}_a) + (1101)(U_s \bar{U}_s \bar{U}_a) + (0201)(\bar{U}_s^2 \bar{U}_a) \\ & + (1002)(U_s \bar{U}_a^2) + (0102)(\bar{U}_s \bar{U}_a^2) + 1/4(2U_s U_a \bar{U}_a + \bar{U}_s U_a^2) \end{aligned} \quad (5-57)$$

Therefore, of the twelve deflection aberration coefficients in equation (5-53), there are seven which are unknown, three which are known (of which two are fixed), and two which are identically zero. This is summarized in Table 5-1. Also shown in Table 5-1 is the type of aberration each term produces and the symmetry each possesses.

Finally, it should be noted that there is a certain amount of inter-relationship amongst the seven unknown coefficients as can be seen from a comparison of equations (5-52) and (5-53):

$$\begin{aligned} 4(1110) &= (A4 + A5) + (B4 + B5) \\ 8(0210) &= (A4 + A5) - (B4 + B5) \\ 8(2001) &= (A4 - A5) + (B4 - B5) + 2(A6 + B6) \\ 4(1101) &= (A4 - A5) - (B4 - B5) \\ 8(0201) &= (A4 - A5) + (B4 - B5) - 2(A6 + B6) \\ 2(1002) &= (A7 - B7) \\ 2(0102) &= (A7 + B7) - 3/2 \end{aligned} \quad (5-58)$$

Equation (5-57) expresses the deflection aberrations in the form most suited to the analysis of the deflection coils which will be described in Chapter 7.

TABLE 5-1
DEFLECTION ABERRATIONS AND THEIR SYMMETRY

TERM	TYPE	SYMMETRY	VALUE
(2010)	ASTIGMATISM AND CURVATURE OF THE IMAGE FIELD	2 fold	= (0210)
(1110)		rotational	unknown
(0210)		2 fold	unknown
(2001)		rotational	unknown
(1101)		2 fold	unknown
(0201)		4 fold	unknown
(1020)	COMA	2 fold	0
(1011)		rotational	1/2
(1002)		2 fold	unknown
(0120)		rotational	1/4
(0111)		2 fold	0
(0102)		4 fold	unknown

CHAPTER 6

DESCRIPTION OF THE EXPERIMENTAL METHOD AND EQUIPMENT

INTRODUCTION

There are two experimental aims for this thesis. The first is to demonstrate the design of a deflection coil which, when used to deflect the electron beam in a standard scanning electron microscope, will permit examination of specimens of up to 3 mm square with the resolutions given by curve A of Figure 2-2. The second aim is to demonstrate the recording of scanning electron micrographs of specimens approximately 3 mm square with resolutions such that the final system magnifications given by curve D of Figure 2-1 are realized. In this chapter, the equipment and the procedure which were used are discussed.

OUTLINE OF EXPERIMENTAL METHOD

To demonstrate that a particular deflection coil is able to scan an electron beam over a specimen while maintaining the resolution set forth in curve A of Figure 2-2, a means of displaying the size and shape of the deflected electron beam spot (the electron beam spot profile) is required. The technique chosen was that described by Amboss and Wolf [37] which is outlined below.

Essentially, the technique consists of statically deflecting an axially-focused and blanked-off electron beam to a given Gaussian deflection point on the specimen plane and then unblanking the beam for a period of time sufficient to expose an electron sensitive film located at that specimen plane. Repeated over an array of spots, this technique provides a map of the electron beam spot profile over the specimen surface.

While this technique provides a knowledge of the variation in spot profile as the electron beam is deflected over the specimen plane, it does not provide a knowledge of the deflection aberrations present in the deflection coil which cause this variation. The spot profile map therefore gives no guidance as to what changes in the deflection coil design should be affected to minimize this variation.

To obtain this information, a computer program was developed, based on the results of Chapter 5. With this program, a map of the electron beam spot profile over the specimen surface can be synthesized for any chosen set of aberration coefficient values. It is thus possible to generate a map which duplicates that obtained experimentally, thereby defining the coefficient values applicable to the experimental deflection coil under test. A brief overview of the computer program developed is given in Appendix 4. This computer matching method is not unlike that employed by Amboss and Wolf [37] in their work.

With a knowledge of the aberration coefficients applicable to the coil being tested as guidance, a second deflection coil can be designed and evaluated in the same way as the first. Some help as to the effect of certain changes in the size and shape of a deflection coil on its aberration coefficients is obtainable from Kaashoek's work [5]. By this iterative process, a deflection coil capable of deflecting an electron beam over a given specimen area without variation in its spot profile can be found.

This coil can then be installed in a scanning electron microscope and used to produce scanning electron micrographs. Provided that the deflection coil tests indicate that the coil is capable of deflecting the electron beam while maintaining the resolutions set forth in curve A of Figure 2-2, the micrographs thus produced will have resolutions such that the final system magnifications given by curve D of Figure 2-1 are realized. This, of course, assumes that the microscope is equipped with a high resolution CRT display and recording system meeting the specifications of Chapter 3 and that it is capable of providing the required resolution on axis.

THE DEFLECTION COIL TEST EQUIPMENT

The deflection coil test equipment used to produce the maps of the electron beam spot profiles over the specimen surface was essentially a single lens scanning electron microscope with some additional features not necessarily common to standard instruments. A single lens system was chosen largely to ensure that the exposed axial spot, together with any other exposed spots not greatly enlarged by deflection aberrations, could be readily examined on the electron sensitive film with an optical

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This coil can then be installed in a scanning electron microscope and used to produce scanning electron micrographs. Provided that the deflection coil tests indicate that the coil is capable of deflecting the electron beam while maintaining the resolutions set forth in curve A of Figure 2-2, the micrographs thus produced will have resolutions such that the final system magnifications given by curve D of Figure 2-1 are realized. This, of course, assumes that the microscope is equipped with a high resolution CRT display and recording system meeting the specifications of Chapter 3 and that it is capable of providing the required resolution on axis.

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microscope and could therefore be easily recorded photographically.

The reasons for providing special equipment on which to produce the spot profile maps, rather than producing them directly on the microscope for which the deflection coil was intended, are threefold. The primary reason was that the microscope which was to be used was required for other work during the period of time when the deflection coils were to be evaluated. In addition, the microscope had not been provided with a beam blanking capability; accordingly, it had no beam blanking coil and no beam defining aperture above this coil. Finally, the microscope had no provision for monitoring the current in the deflection coils. While deflection current monitoring and a beam blanking coil could have been provided easily, such was not the case with the beam defining aperture. The construction of the electron gun on the microscope is such that there is insufficient space for the mounting of both a beam blanking coil and a centring mechanism for an aperture below the anode. The decision was therefore made to design and build a separate piece of equipment on which to evaluate the deflection coils.

Figure 6-1 is an outline drawing of the electron optical column for this equipment which shows the location of the electron gun, the spacer tube, the lens, the postlens deflection coil, the two aperture planes, the specimen plane, and the deflection coil shield. These items are all discussed in this chapter. As can be determined from the dimensions in this figure, the Gaussian demagnification of the gun crossover (taken as midway between the Wehnelt cylinder and the anode in the gun) onto the specimen plane in this column is $1/8$. If the size of the gun crossover is taken as being 25 to 50 μm in diameter, in agreement with Haine and Einstein [43], then the image spot would be expected to be between 3 and 6 μm approximately in diameter from a Gaussian optics point of view wherein aberrations are neglected. This image spot size will be utilized later in a discussion concerning lens aberrations in the deflection coil test equipment under *Computer Matching*.

The lens for this special equipment was designed to have the same electron optical properties as the final lens in the microscope which was to be used. There is no compelling reason for doing this for the

FIGURE 6-1

OUTLINE DRAWING OF ELECTRON OPTICAL COLUMN
 FOR DEFLECTION COIL TEST EQUIPMENT

present work. There are future plans, however, (see FUTURE WORK in Chapter 9) for developing deflection coils capable of deflecting an electron beam with an axial resolution of down to $300 \text{ \AA}$ in the scanning microscope over specimen areas as large as 12.5 mm square . In this case, spherical aberration will have to be considered although it is not of concern at present. Since spherical aberration⁷ is a function of the final lens, it was considered advisable, to accommodate the future work, to make the lens in the deflection coil test equipment as much like the final lens in the microscope as possible.

The stage which supported the film on which the electron beam spot profile maps were recorded was similar to the stage normally used with a scanning microscope except that no specimen tilt or rotation motions were provided. Special precautions were taken to ensure that the specimen plane was exactly normal to the main electron optical axis of the equipment. In addition, the stage was provided with special focusing marks with which the beam could be initially focused without exposing the specimen film.

The electron gun was an autobiasd triode gun similar to that used in the microscope but scaled up to be operable at potentials of up to 50 kV. (The present work does not require such a high potential but there are future plans to investigate higher voltage scanning electron microscopy). The anode-to-Wehnelt or -grid spacing in this gun was 0.5 inch. The anode was centrally located with respect to the electron optical axis during the original construction of the gun. The filament mount was adjustable so that the filament could be centred with respect to the Wehnelt by eye or with the aid of a jeweller's loupe. The Wehnelt/filament assembly was moveable and could be centred with respect to the anode by means of centring screws from outside the column while the gun was operating. In this way, the gun crossover could be adjusted onto the electron optical axis. The Wehnelt screwed onto the outside of the filament mount so that it could be adjusted axially with respect to the filament to control the filament-to-Wehnelt spacing; this spacing was set by eye with a jeweller's loupe. The filaments used were 0.005 inch tungsten hairpin filaments.

In order to have the lens working in a demagnifying fashion, it was necessary to have the gun crossover located well above the lens. Accordingly,

a spacer was fitted between the bottom of the gun and the top of the final aperture housing. This spacer was fitted with a 0.250 inch I.D. aluminum tube centrally located on the electron optical axis. The tube was vacuum sealed into the spacer so that only the tube itself was evacuated.

The final aperture was mounted on an aperture centring mechanism in the final aperture housing just above the lens. Its purpose was to define the electron beam convergence angle onto the specimen and to serve as a beam blanking aperture.

In order to provide for the beam blanking feature, a second aperture, in addition to the main aperture above the lens, was provided in the gun below the anode. Its purpose is to define the size of the beam so that a known field can be assured of deflecting the electron beam completely away from the main aperture. The beam blanking field is provided by a ferrite cored toroidal coil located in the gun housing just below the second aperture.

The static deflection feature was provided by a HOLD function on both axes of the scan generator. Its purpose is to defeat the normal ramp outputs of the scan generator, which provide the raster scanning in a scanning microscope, and instead permit the electron beam to be located at a fixed position relative to the electron optical axis. The resulting dc currents through the deflection coils are measured and displayed on a digital panel meter as the voltage drops across two sensing resistors. Thus, to deflect the electron beam to a given Gaussian deflection point, the required deflection coil currents are calculated and then set directly while the electron beam is in the blanked-off state.

The specimens which provided the maps of the electron beam spot profiles were films of Dupont Elvacite 2041 polymethyl methacrylate acrylic resin spun onto silicon slices. Details concerning the preparation, exposure, and development of these films are given in the section headed DETAILED EXPERIMENTAL PROCEDURE later in this chapter.

In order to ensure that vibration did not affect the results, considerable effort was made to provide, as much as possible, a vibration-free system. The entire electron optical column and specimen chamber are mounted at the centre of a heavy (100 pounds) triangular steel plate and

below this plate are suspended the high vacuum valve, the diffusion pump, and some 100 pounds of lead bricks to lower the centre of gravity and add mass. This triangular plate is mounted above the main table of the equipment on three Firestone 1X84D-1 Airmounts specially provided by Firestone Industrial Rubber Products Company, Noblesville, Indiana with thin (0.1 inch thick) rubber walls. Each Airmount is provided with its own separate air reservoir of 650 cubic inches volume; the volume of the Airmounts themselves is approximately 90 cubic inches each.

The main equipment table is estimated to weigh 300 pounds and it is supported on the floor by four 2.80/2.50 x 4.00 pneumatic tires. At an estimated load of 160 pounds per Airmount and with 20 psi pressure in each Airmount/reservoir combination, a computer analysis by Firestone indicated that the system would have a natural resonant frequency of approximately 35 cycles per minute.

Due to a lack of sufficiently sensitive vibration measuring equipment, no quantitative data was obtainable on the degree of isolation provided by the anti-vibration system. Use of the measuring equipment which was available, however, indicated that it provided isolation of at least one order of magnitude more than the isolation systems employed in either the Cambridge Scientific Instruments Company Stereoscan or the Communications Research Centre Minicolumn scanning electron microscopes to the usual vibrations found in a laboratory building.

Figure 6-2 is a photograph of the deflection coil test equipment. It shows the vibration isolation system, vacuum pumping, and electron optics on the right and the associated electronics on the left.

THE BEAM BLANKING FEATURE

The beam blanking feature on the deflection coil test equipment was provided because, as discussed above, it is necessary in this work to deflect a blanked-off electron beam to a given location on the specimen plane and to unblank that beam only long enough to expose a spot in the specimen film. It is instructive, therefore, to examine the electron beam turn-on and turn-off times of which the beam blanking circuit is capable in order to determine what effect these times may have on the test results.

FIGURE 6-2
THE DEFLECTION COIL TEST EQUIPMENT

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When the beam blanking circuit is activated, a dc current of 14 mA is supplied to the beam blanking coil; the electron beam is therefore normally in a blanked-off state. To unblank the electron beam, a rectangular pulse, whose width equals the desired unblank period, is applied to the output transistor of the beam blanking circuit, biasing it off and thereby interrupting the blanking coil current to unblank the beam. An examination of this interruption in the blanking coil current, using a Tektronix P6042 current probe with a Tektronix RM15 oscilloscope, showed that the current fell to zero in about 1.5 μ sec followed by a 3 μ sec period of slight ringing. The current rose again in less than 0.2 μ sec to within 85% of its steady state value and settled to this steady state value in a further 3 μ sec. A suppression diode was placed across the coil to prevent excessive ringing in order to achieve the above performance. In view of the exposure times which were to be used (600 to 3600 μ sec), the above rise and fall times were judged to be negligible.

It was considered advisable to take this investigation one step further and determine the response of the electron beam to such an interruption in the blanking coil current. Accordingly, an unscanned electron beam was focused at a point on a specimen from which a strong secondary electron signal could be derived and this signal was displayed on an oscilloscope; the pulse which was used to bias the output transistor of the beam blanking circuit off was used to trigger the oscilloscope. A pulse of electron beam current was thus displayed on the oscilloscope which showed that the electron beam was being pulsed from the fully-off state through fully-on and back to fully-off. (The fully-off state was determined by noting the signal level on the oscilloscope when the electron gun supply was turned off; the fully-on state was determined by turning off the beam blanking circuit.)

By this method, the electron-beam current pulse was found to have very long rise and fall times of approximately 350 μ sec each. The integrated area under this pulse was judged, however, to be essentially equal to the area it would have had with zero rise and fall times; no error in film exposure would therefore result from the use of this pulse (provided the pulse width always exceeds, say, 400 μ sec). This long switching time of the beam blanking coil is felt to be due to the

mounting of the coil which utilized a thick-walled (2.4 mm thick) aluminum tube coaxial with the main axis of the coil. The beam blanking coil was clamped to this tube. The electron beam passed through the centre of the tube and was deflected by flux from the coil passing through the tube orthogonally to the electron beam axis. (Essentially, the coil consists of two windings on a ferrite toroidal core, the windings being so polarized that their fluxes oppose each other in the ferrite. To complete their paths, the fluxes must flow in an aiding fashion across the central hole of the toroid.) The long switching time is felt to be the result of the time taken for the flux to penetrate the aluminum tube and build up the required value inside the tube. Due to the eddy currents which would be set up in the tube material, this time could be of the order of 300 to 400 μ sec.

THE SCANNING ELECTRON MICROSCOPE AND THE HIGH RESOLUTION CRT DISPLAY AND RECORDING SYSTEM

The scanning electron microscope which was used for the present work, the Minicolumn scanning electron microscope, is a standard instrument which was designed and developed at the Communications Research Centre of the Department of Communications in Ottawa. For the work described herein, it was coupled to a high resolution CRT display and recording system and was fitted with a special adapter to permit mounting of the postlens deflection coil which was selected on the basis of tests carried out on the deflection coil test equipment.

The display system was custom built to meet the specifications set out in Chapter 3 by Constantine Engineering Laboratories, Company (CELCO) of Mahwah, N.J. and Upland, Calif. The cathode ray tube used in the display system was manufactured by Litton Industries, San Carlos, Calif., again to the specifications of Chapter 3. The recording system is based on a Linhof Kardan Colour 45 S camera equipped with a Rodenstock Apo Ronar 150 mm f/9 lens.

The scan electronics in the Minicolumn microscope was unfortunately not able to provide the 5000 line frame required to fully utilize the display system due to instabilities and noise inherent in its basic design. Attempts to improve its performance indicated that the solution to the problem would involve a major redesign for which time was not available. An interim solution was therefore adopted to provide a 3000 line frame from the work covered in this thesis.

This 3000 line frame was not entirely noise-free, however, so that the CRT spot, which ideally occupies a picture element area 0.0006 inch in diameter, was effectively increased in size by the noise to occupy an area 0.0010 inch in diameter. This is essentially the same as the technique called spot wobble which is used in CRT display systems when the basic CRT spot is smaller than desired. All the specifications of the earlier chapters are met with this modification present except that the overall maximum photographic enlargement must be reduced by $\frac{3}{5}$ from X13.7 to X8.

EXPERIMENTAL DEFLECTION COIL DESIGN

A review of Chapter 5 shows that magnetic deflection aberrations are mainly dependent upon the field parameters H_0 and H_2 . It is to be expected that these field parameters would be influenced in turn by the size and shape of the deflection coil. This expectation is supported by Kaashoek's work [5]. Accordingly, it should be possible to exercise a certain amount of control over magnetic deflection aberrations by controlling the geometry of the deflection coil.

If it is desired to maintain simple coil geometries, then the geometrical parameters available to the designer are relatively few in number: coil radius, coil length-to-diameter ratio, and coil circumference angle, together with the possibility of varying these parameters along the length of the coil. Figure 6-3 defines these parameters. In this thesis, the distribution of the coil turns as a function of the coil circumference angle, as in a sine distribution, is not included in simple coil geometries.

Both Kaashoek [5] and Haantjes and Lubben [4] have shown that the coil circumference angle, θ is a very useful design parameter. It should be used, however, more in a qualitative than in a quantitative manner, particularly when the coil is short with respect to its diameter, i.e. when the coil length is approximately equal to or less than its diameter, or when large deflection angles are being used. In these cases the field from the circular portions of a saddle coil becomes important and, in the experience of Haantjes and Lubben, these circular portions affect the deflection aberrations to a greater extent than theoretical considerations would predict. This, they postulate, may be due to the beam passing close

FIGURE 6-3
SCHEMATIC OF DEFLECTION COIL COMPRISING
TWO COIL SECTIONS, EACH OF RADIUS r ,
LENGTH L , AND CIRCUMFERENCE ANGLE θ .

to the end of the coil when large deflection angles are used; at the end of the coil, the field distribution may not be the same as it is near the axis.

Both Kaashoek and Haantjes and Lubben have shown that, with a coil circumference angle, θ of 120° per coil section, the field parameter H_2 is approximately zero. With θ less than 120° , H_2 is predominantly negative while a positive H_2 results if θ is more than 120° . Kaashoek points out that, while H_2 is strongly dependent upon θ , H_0 is unaffected by its value, within the range of 115° to 130° . This is, according to Kaashoek, the useful range of θ .

Kaashoek has also shown that, if θ is fixed at some value of, say, 120° , a decrease in either the diameter or the axial length of the coil will cause an increase in both the maximum and minimum values of H_2 while the effective field length will decrease and the deflection point will shift away from the image plane towards the gun.

Both Kaashoek and Haantjes and Lubben also point out that it is a common misconception that a homogeneous deflection field will avoid deflection errors. Such a field, Haantjes and Lubben show, gives isotropic astigmatism and pincushion distortion although it does eliminate anisotropic astigmatism and coma.

Kaashoek points out that a uniform field is achieved if the winding distribution gives a current density at any point around the circumference of the coil which is a cosine function of the angle between some symmetry plane, which is used as a reference plane, and the plane through the point in question and the coil axis. Any deviation from a cosine function will give a non-uniform field.

With the above work for background and guidance, a series of five experimental deflection coils were constructed for evaluation. Details of the construction of these five coils are presented in the following paragraphs. Also presented are the construction details for the prelens double deflection coils originally provided for the Minicolumn scanning electron microscope; these coils were evaluated as a comparison for the postlens deflection coils.

It will be noted in the construction details that the number of turns per coil section is not constant. This variation in the number of turns compensates for the changes in the size of the coils and provides a constant field magnitude at the coil centres for a given deflection current.

Experimental deflection coil #1 was designed in the same style as one of the coils of the double deflection system used in the Minicolumn microscope, i.e. as two pairs of rectangular Helmholtz coil sections arranged as shown in Figure 6-4. The purpose of this was to determine whether or not the style of deflection coil used in the Minicolumn, when used as a postlens deflection coil and at a longer working distance, was capable of providing the necessary resolution over the relatively large deflection area needed for the purpose at hand.

The x or line deflection coil sections each had an outside length of 22.5 mm, an inside length of 17.5 mm, an outside width of 22.5 mm, and an inside width of 17.5 mm. They were spaced 10.0 mm apart centre-to-centre and had a winding width of 2.5 mm. With the working distance used of 54 mm, the coil "throw" was 42.7 mm from the mid point of the coil sections to the specimen plane. The coil sections were wound with 7 turns each of #23 AWG wire.

The y or frame deflection coil sections each had an outside length of 17.5 mm, an inside length of 11.5 mm, an outside width of 22.5 mm, and an inside width of 17.5 mm. They were spaced 10.0 mm apart centre-to-centre and had a winding width of 2.5 mm. The coil throw was 42.7 mm as it was in the case of the line deflection coil sections. The coil sections were wound with 9 turns each of #23 AWG wire.

In experimental deflection coil #2, shown in Figure 6-5, the individual coil sections were shaped similarly to those of coil #1 except that the ends of the sections lay along the circumference of a circle which lay in a plane perpendicular to the z or optic axis. These sections were thus shaped more like the familiar saddle coils used on cathode ray tubes. In addition, the lengths and radii of the line coil sections and the frame coil sections were adjusted so that both required the same number of turns.

FIGURE 6-4
BASIC CONFIGURATION OF EXPERIMENTAL DEFLECTION COIL #1

FIGURE 6-5
BASIC CONFIGURATION OF EXPERIMENTAL DEFLECTION COIL #2

The x or line deflection coil sections each had an outside length of 22.5 mm, an inside length of 17.5 mm, an outside radius of 10.75 mm, an inside radius of 8.25 mm, and a circumference angle of 120° centre-to-centre. The coil throw was 42.7 mm, as with coil #1, and the coil sections were wound with 7 turns each of #23 AWG wire.

The y or frame deflection coil sections each had an outside length of 13.2 mm, an inside length of 8.2 mm, an outside radius of 6.25 mm, an inside radius of 3.75 mm, and a circumference angle of 120° centre-to-centre. The coil throw was again 42.7 mm and the coil sections were wound with 7 turns each of #23 AWG wire.

Experimental deflection coils ##3, 4, and 5, shown in Figure 6-6, were all wound like coil #2 except that the lengths of the frame deflection coil sections were increased to equal the lengths of the line deflection coil sections. In coils ##3, 4, and 5, the effect of varying the circumference angle was explored.

The x or line coil sections of deflection coils ##3, 4, and 5 all had an outside length of 22.5 mm, an inside length of 17.5 mm, an outside radius of 18.5 mm, and an inside radius of 13.5 mm. The coil throw was again 42.7 mm. The circumference angle was 120° for coil #3, 110° for coil #4, and 130° for coil #5. The coil sections were wound with 14 turns each of #23 AWG wire for coil #3, 15 turns each of #23 AWG wire for coil #4, and 13 turns each of #23 AWG wire for coil #5.

The y or frame coil sections of deflection coils ##3, 4, and 5 all had an outside length of 22.5 mm, an inside length of 17.5 mm, an outside radius of 7.5 mm, and an inside radius of 5.0 mm. The coil throw was again 42.7 mm. The circumference angle was 120° for coil #3, 110° for coil #4, and 130° for coil #5. The coil sections were wound with 5 turns each of #23 AWG wire for coil #3, 5 turns each of #23 AWG wire for coil #4, and $4\frac{1}{2}$ turns each of #23 AWG wire for coil #5.

The Minicolumn prelens double deflection coils were constructed like experimental deflection coil #1, two such coils being used to provide the double deflection. Figure 4-2 is a ray diagram for such a deflection system. In this construction, the numbers of turns in the upper and lower coils, the axial spacing between the coils, and the location of the coils along

Following development, the silicon slice carrying the electron beam spot profile map was examined in an optical microscope and each spot was photographed at X800 magnification. The individual photographs were then assembled in the proper order to produce the finished map.

After ~~computer~~ computer matching of this map to determine the aberration coefficients present in the deflection coil, a second coil would be designed, constructed, and tested in the same manner as the first. In the present work, however, five coils were designed and constructed as a group and were then evaluated following the procedure given in this section. The intention was to determine as quickly as possible the degree to which physical changes in a deflection coil used for a scanning microscope would affect its deflection aberrations. As will be seen in the following two chapters, however, one of these coils proved to be sufficiently free from deflection aberrations to be suitable for the microscopy work of this thesis.

Determination of Electron Beam Cross-Section

It became apparent during preparation of the electron beam spot profile maps that the electron beam cross-section would enter into discussions of spot growth vs. deflection. Accordingly, the change in the electron beam spot profile as the exposure time was increased was recorded in PMMA both for an axial and for an off-axis (2 mm deflection simultaneously in the x and y directions) spot. The results were photographed in the optical microscope at X800 magnification.

These spots were recorded in essentially the same way as the spots for the spot profile maps except that the electron beam was held stationary between exposures while the specimen was moved with the mechanical stage motions to position a fresh, unexposed section of the PMMA film under the blanked-off beam. The width of the unblanking pulse was changed between exposures.

Computer Matching

Having obtained the experimental spot profile maps, the next step was to match these with computer-generated maps and thereby identify the

the electron optical axis with respect to the final lens plane are all interrelated.

The x or line deflection coil sections of both the upper and lower coils each had an outside length of 17.6 mm, an inside length of 13.8 mm, an outside width of 14.2 mm, and an inside width of 10.4 mm. They were spaced 12.3 mm apart centre-to-centre and had a winding width of 1.9 mm. The sections of the upper coil were wound with 4 turns each of #29 AWG wire while those of the lower coil were wound with 30 turns each of #29 AWG wire.

The y or frame deflection coil sections of both the upper and lower coils each had an outside length of 13.8 mm, an inside length of 10.0 mm, an outside width of 14.2 mm, and an inside width of 10.4 mm. They were spaced 12.3 mm apart centre-to-centre and had a winding width of 1.9 mm. The sections of the upper coil were wound with 5 turns each of #29 AWG wire while those of the lower coil were wound with 37 turns each of #29 AWG wire.

These coils were located inside the bore of the final lens. The upper coil was separated from the lower coil by an axial distance of 69.8 mm centre-to-centre. The centre of the lower coil was located 10.8 mm above the centre of the gap in the lens magnetic circuit.

DETAILED EXPERIMENTAL PROCEDURE

Deflection Coil Tests

The deflection coil to be tested was mounted in the deflection coil test equipment, as shown in Figure 6-7, so that it was accurately centred with respect to the electron optical axis and so that its line and frame sections would deflect the electron beam in the desired line and frame directions on the specimen; i.e., the coil was not positioned at any arbitrary angle of rotation about the electron optical axis. This was accomplished through a centring ring fitted around the coil which located the coil centrally inside a coil clamp; the coil clamp was itself mounted centrally on the lens. A hole in this centring ring which mated with a locating pin on the coil clamp positioned the coil with respect to rotation about the optic axis. The coil clamp was designed to hold the deflection

FIGURE 6-7

DETAIL OF POSTLENS DEFLECTION COIL MOUNTING SHOWING LENS SHELL (1), LENS POLE PIECE (2), VACUUM SEALING PLATE (3), LENS POLE PLATE (4), DEFLECTION COIL CLAMP (5), LOCATING PIN (6), CLAMPING RING (7), CENTRING RING (8), DEFLECTION COIL FORMER (9), AND SHIELDING PLATE AND TUBE (10).

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coil firmly against the lens pole plate to control its axial position.

The base of the deflection coil was protected from backscattered electrons by a flat, electrically grounded copper plate with a small hole coincident with the electron optical axis to permit passage of the electron beam. Surrounding this hole and attached to the copper plate was a stainless steel tube which extended from the copper plate through the bore of the deflection coil to the lens pole plate. Together, this tube and plate assembly shielded the insulating portions of the deflection coil and its leads from the direct beam and from backscattered primary electrons.

The connections to the deflection coil from the scan amplifier were made in such a way that a positive line deflection current deflected the electron beam in the positive line direction on the specimen while a positive frame deflection current deflected the beam in the positive frame direction on the specimen. This was necessary because it is particularly important that the coil sections giving rise to a specific deflection be clearly identified. In addition, this specific deflection must be clearly identified on the specimen if computer matching of the spot profile maps is to be successfully carried out.

The specimen on which the spot profile map was to be produced was prepared by spinning a film of Dupont Elvacite 2041 polymethyl methacrylate acrylic resin (PMMA), some 3000 Å thick, onto a silicon slice. Silicon was chosen as the support medium for the films since it was flat, smooth, and readily available. A spin coating speed of 5000 rpm was used and the spinning time was 60 seconds. A 7% solution in methyl ethyl ketone (MEK) (7 grams PMMA plus 93 cc MEK) was used, dissolution being accomplished by stirring at 50°C. The solution was filtered prior to use. The spun film was prebaked at 170°C for 15 minutes to improve adhesion and reduce stresses in the film prior to exposure. Due apparently to rapid evaporation of the MEK from the silicon slice during spinning, the surface temperature of the slice is evidently depressed since some difficulty was experienced with moisture from the air condensing onto the slice surface. The result was a foggy, as opposed to the normally clear, film with entirely different exposure characteristics. To avoid this difficulty, the air surrounding the spin coater was warmed with a hot air blower.

For mounting the specimen in the test equipment, the stage was provided with a block containing a circular depression into which the slice was placed; this block was constructed to hold the slice perpendicular to the electron optical axis. To ensure that the slice was properly grounded, it was secured to the stage block with three or four drops of silver cement around its periphery. A scratch mark, which was oriented with respect to the deflection coil, was made in the PMMA at the edge of the slice to key the spot profile map to the deflection coil.

For both column alignment and focusing, the test set was used in the secondary electron mode of operation for a scanning electron microscope. For focusing the beam, a transmission microscope specimen grid was cemented to the stage block at a point which was the same axial distance from the lens pole plate as the top surface of the silicon slice and which was sufficiently far from the silicon slice laterally to avoid premature exposure of the PMMA during focusing operations. The electron beam was then focused on this specimen grid by varying the lens current and the correct setting of the lens current was locked in.

The specimen grid used for beam focusing was also used for column alignment. Column alignment with only one lens and two apertures was carried out by aligning the upper aperture at the base of the gun first with the lower aperture withdrawn from the vicinity of the optic axis by its centring mechanism. Once the upper aperture was aligned, the lower aperture above the lens was aligned. Alignment in the reverse order was not possible since, without the upper aperture in position, the beam was so large in the plane of the lower aperture that portions of it bypassed the aperture entirely, making determination of alignment difficult. The condition for alignment was the usual condition for a scanning microscope, that a small artifact in the image, located on the optic axis, did not shift when the lens current was varied through focus. The upper aperture used was 100 μm in diameter while the lower aperture was 500 μm in diameter. The lower aperture was purposely made large to ensure that the dependency of the deflection aberrations upon the aperture radius would be detected. The upper aperture was chosen to constrict the electron beam somewhat less than the lower aperture so that the lower aperture would do the actual beam defining.

Following column alignment and focusing, the electron beam was blanked off and the PMMA-coated slice moved via the stage x and y controls so that the electron optical axis coincided approximately with the slice centre. This position was known, as was that of the specimen grid, by the settings of the micrometer drums on the stage x and y controls.

Both axes of the scan generator were then placed in the HOLD mode and the beam positioned with respect to the optic axis at the first location of interest for the spot profile map. This was done by adjusting the static deflection currents through the line and frame sections of the deflection coil with controls provided on the scan generator while monitoring the digital panel meter displaying these currents.

The first spot on the spot profile map was then exposed by sending an unblanking pulse of the correct exposure time width to the beam blanking unit. In general, the exposure time was 1200 μ sec, based on an electron dose of between 10^{-3} and 10^{-4} Coulombs per cm^2 for proper exposure of the PMMA (see Hatzakis [38] and Haller, Hatzakis, and Srinivasan [39]). The electron beam current at the specimen had been previously measured at 0.55×10^{-6} ampere by collecting the beam in a Faraday cup connected through an electrometer to ground. The accelerating potential was 22.5 kV, chosen in conjunction with the deflection coil designs as that potential for which one ampere of deflection coil current gave a Gaussian deflection of one millimeter at the specimen plane. Repeated over all the spots of interest, this procedure gave the electron beam spot profile map for the deflection coil being tested.

The exposed PMMA-coated silicon slice was then removed from the test set and developed in a mixture of 3 parts isopropanol to 1 part methyl isobutyl ketone for 60 to 90 seconds. Development was followed by an isopropanol rinse for 60 seconds after which the slice was dried with a hot air blower.

Other details on the use of PMMA as an electron sensitive resist may be found in the papers by Hatzakis [38], by Haller, Hatzakis, and Srinivasan [39], and by Harris [40].

Following development, the silicon slice carrying the electron beam spot profile map was examined in an optical microscope and each spot was photographed at X800 magnification. The individual photographs were then assembled in the proper order to produce the finished map. .

After ~~computer~~ computer matching of this map to determine the aberration coefficients present in the deflection coil, a second coil would be designed, constructed, and tested in the same manner as the first. In the present work, however, five coils were designed and constructed as a group and were then evaluated following the procedure given in this section. The intention was to determine as quickly as possible the degree to which physical changes in a deflection coil used for a scanning microscope would affect its deflection aberrations. As will be seen in the following two chapters, however, one of these coils proved to be sufficiently free from deflection aberrations to be suitable for the microscopy work of this thesis.

Determination of Electron Beam Cross-Section

It became apparent during preparation of the electron beam spot profile maps that the electron beam cross-section would enter into discussions of spot growth vs. deflection. Accordingly, the change in the electron beam spot profile as the exposure time was increased was recorded in PMMA both for an axial and for an off-axis (2 mm deflection simultaneously in the x and y directions) spot. The results were photographed in the optical microscope at X800 magnification.

These spots were recorded in essentially the same way as the spots for the spot profile maps except that the electron beam was held stationary between exposures while the specimen was moved with the mechanical stage motions to position a fresh, unexposed section of the PMMA film under the blanked-off beam. The width of the unblanking pulse was changed between exposures.

Computer Matching

Having obtained the experimental spot profile maps, the next step was to match these with computer-generated maps and thereby identify the

aberration coefficients present in each of the deflection coils. To do this, the lens and deflection aberration coefficients which might be present had to be identified from all those listed in Tables 4-1 and 5-1.

As discussed previously under THE DEFLECTION COIL TEST EQUIPMENT, the lens for the test equipment was designed to have the same electron optical properties as the final lens in the Minicoll scanning electron microscope. Since this microscope is capable of resolving detail as fine as approximately $250 \text{ \AA}$, the final lens in the microscope could only be aberrating an axial electron beam to a small extent. It was therefore concluded that, when a similar lens was used in the test equipment to focus a considerably larger electron beam (see Figure 6-1 and the related discussion), all the lens aberrations in Table 4-1 would be negligible and could therefore be ignored except one. This one aberration, (1000) magnification, would have to be retained to account for the finite size of the image spot.

As will be seen in Chapter 7, it was found when the computer matching was undertaken that some asymmetry had been inadvertently built into the test equipment lens and that some terms from Table 4-1 other than (1000) were required to obtain a computer-generated spot which matched the axial spot obtained experimentally. These nonrotationally symmetric terms are:

(0001)	astigmatism
(0020)	coma
(0002)	coma
(0011)	coma

To these was added (0010) defocusing to account for the finite size of the image spot. (The choice of (1000) magnification vs. (0010) defocusing is immaterial here. In this work, no attempt was made to separate magnification from axial defocusing; either or both together will provide a finite sized axial spot.)

To these must be added the ten non-zero deflection aberration coefficients from Table 5-1:

(2010) = (0210)	}	astigmatism and curvature of the image field
(1110)		
(0210) = (2010)		
(2001)		
(1101)		
(0201)	}	coma
(1011) = $\frac{1}{2}$		
(1002)		
(0120) = $\frac{1}{4}$		
(0102)		

This gave a total of 15 aberration terms which had to be considered when computer matching of an experimentally-obtained spot profile map was attempted; the five lens aberration terms were used to affect a match with the axial spot and the ten deflection aberration terms were used to alter the axial spot shape as required to obtain a match with the off-axis spots.

Large Area Scanning Electron Microscopy Tests

Using the deflection coil selected from the deflection coil tests and the computer matching, the coil was mounted in the scanning electron microscope, taking the same precautions with respect to centring, axial positioning, rotation, lead connections, and shielding as were taken in mounting the coil in the deflection coil test set.

Prior to using this deflection coil to scan the electron beam over a relatively large specimen scan area and showing that the deflection coil was maintaining the axial resolution throughout this area, it was necessary to set the microscope's axial resolution at the required value. Referring back to Chapter 2, in which picture element size was equated to microscope resolution, and noting that only 3000 scan lines per frame are now being used, the required axial resolution is seen to be

$$\text{SEM resolution, } \mu\text{m} = \frac{\text{specimen scan size, mm}}{3}$$

Accordingly, once the size of the specimen scan area has been decided upon, the required axial resolution can be calculated.

The importance of this setting can be seen from the following discussion. The scanning system in the microscope will scan 3000 lines in the specimen area selected. Should the probe size of the electron beam in the microscope be too large, excessive overlap of these scan lines will occur, along with a lack of resolution. Should the probe size, on the other hand, be too small, gaps will be present between the scan lines on the specimen; portions of the specimen will therefore not be scanned at all while in those areas that are scanned, greater resolution than necessary will be obtained. In addition, erroneous signal levels can result from scanning with too small an electron probe in areas in which the output signal varies rapidly with position on the specimen.

The axial resolution was controlled by adjusting the currents in the two condenser lenses in the microscope, thereby adjusting the overall column demagnification of the gun-crossover size. To determine whether the correct adjustments had been made, a high magnification micrograph was produced of a specimen with detail somewhat finer than the required axial resolution. The magnification had to be sufficiently high that the area of the micrograph was essentially "on axis" and to expand detail of the size of the required axial resolution sufficiently to be seen by eye in the micrograph. If detail equal in size to the required axial resolution was visible in the micrograph and detail appreciably smaller was not, it was concluded that the two condenser lenses were correctly set; if not, the lenses were reset and the micrograph retaken until the correct axial resolution was achieved.

To show that the selected deflection coil maintained this axial resolution throughout the large specimen scan area, this high magnification micrograph could have been repeated at each corner of the large scan area by shifting the small, high magnification raster over the specimen to the appropriate four locations by means of a dc shift signal superimposed on the high magnification raster. This, however, would have required a very stable dc power supply. For example, if the length and width of the high

magnification micrograph were each $1/20$ of the length and width of the large specimen scan area, then the required dc power supply stability would have to be in the order of

$$\pm \frac{\sim \frac{1}{4} \text{ line}}{20 \times 3000 \text{ lines}}$$

or about ± 4 ppm. Such a power supply was not available and an alternate means was therefore required of showing that the selected deflection coil did not reduce the resolution of the electron beam as it was deflected over the large specimen scan area. As part of a program of future work, however, it is planned to obtain a power supply with the above stability and explore the possibility of electronically shifting a high magnification raster over a large specimen area as an alternative to mechanically moving the specimen. Such a technique would permit elimination of one of the more costly and vibration-sensitive components of the scanning electron microscope, the mechanical stage.

An alternate means of showing that the selected deflection coil maintains axial resolution throughout the large specimen scan area is to produce a single micrograph of the entire scan area and examine its resolution of fine specimen detail under an optical microscope. This was the method which was adopted for this thesis. A 54 mm working distance was used for this work to provide room for the postlens deflection coil between the final lens of the microscope and the specimen. (The working distance of the final lens in a scanning electron microscope is normally taken as the distance from the midpoint of the gap in the magnetic circuit to the image or specimen plane; it is therefore essentially equal to the image distance of a light optics lens.) The gun accelerating potential used was 20 kV and the specimen current was approximately 10^{-9} ampere. The frame exposure time was 100 seconds which, with 3000 scan lines per frame, gave a line scan time of 33 msec. The final aperture used to define the electron beam in the microscope was 100 μm in diameter; this choice is examined in detail below.

For comparison, the same specimen was also examined using the original prelens double deflection system provided for the Minicolumn microscope and a comparative micrograph was made at each of two different working distances, 10 mm and 21 mm. These are typical of the working distance normally used on this microscope. The gun accelerating potential, specimen current, and frame and line scan times were all the same as were used in the postlens deflection case. In addition, the final beam defining aperture used was also the same.

In doing the microscopy work involving the prelens double deflection system, it was desired to have the microscope operating in as close to a normal or typical fashion as possible. For this reason, the final beam defining aperture was made 100 μm in diameter and the working distance was set at 10 mm in the one instance and 21 mm in the other. The only intentional departure from typical operation was that the specimen was maintained perpendicular to the beam to avoid defocusing errors caused by the beam being deflected so far from the optical axis. This departure had the disadvantage, particularly at the 10 mm working distance, that the secondary electron signal collection efficiency was not entirely uniform over the full surface area of the specimen. Normally, the specimen is tilted away from perpendicularity with the incident electron beam towards the secondary electron collector to enhance signal collection.

The microscopy work involving the postlens single deflection system was also done with a 100 μm diameter final beam defining aperture. This may appear to be a poor choice: in the first place it represents a five-fold reduction in size from the aperture used in the deflection aberrations test set and in the second place it leads, with the increased working distance of 54 mm, to a reduction in the electron beam angle of convergence onto the specimen.

A change in aperture size, however, between determination of the deflection aberrations present in a particular deflection coil and the use of that coil in a scanning electron microscope is not of major consequence. As will be seen in Chapter 7, the effect of the aperture size on the deflection aberrations is only of the second order compared with the effect of the Gaussian deflection at the image plane. That this should be so may

be appreciated by examining Equation 5-53 in Chapter 5 and noting that $U_s = r_s \exp(i\theta_s)$ ranges in magnitude up to approximately 4 mm for the size of specimen scan area planned while $U_a = r_a \exp(i\theta_a)$ ranges in magnitude from 50 μm to 250 μm as the aperture varies from 100 μm to 500 μm in diameter.

The justification for not retaining a constant beam convergence angle is perhaps less obvious. An examination of the theory of Chapter 5 shows that, although Equation 5-53 is written in terms of the aperture radius, the important fundamental parameter is the angle the undeflected ray makes with the electron optical axis; this is the beam convergence angle in the case of postlens deflection. The theory of Chapter 5 assumes that the beam is focused onto the specimen plane before it reaches the deflection coil and that the beam is not subject to any further focusing after it passes through that deflection coil. In the case of prelens deflection, where the beam is focused onto the specimen *after* it is deflected, the important parameter is not the beam convergence angle onto the specimen but is instead the angle the beam *entering* the deflection coil makes with the optic axis. To make this angle equal to the beam convergence angle in the case of postlens deflection would have required a very large aperture for the prelens case which would have produced a very large beam convergence angle. This would have upset the conditions of normal operation which it was desired to retain in the microscope with prelens deflection.

The prelens case is further complicated in that it is a double deflection system. The angle which the deflected beam entering the second deflection coil makes with the optic axis is large in the case of a large specimen scan area and could not possibly be made equal to the angle of convergence in the postlens case. The prelens case is also complicated by the fact that the undeflected ray emerging from the second deflection coil does not strike the specimen at the optic axis unless there is also no deflection from the first deflection coil. Accordingly, Equation 5-53 would not apply to the second coil and Equations 5-45 would have to be used to describe the aberrations from it.

In view of the above arguments, it is not possible to employ the same beam angles in both the prelens and the postlens deflection cases.

The comparison between the two must therefore be made in a general, as opposed to a rigorous, sense.

CONCLUSIONS

In this chapter, the equipment and techniques which were used to demonstrate that a particular deflection coil could deflect an electron beam over a large specimen area while maintaining the resolution set forth in Curve A of Figure 2-2 were discussed. Also discussed were the equipment and techniques which were used to demonstrate the recording of scanning electron micrographs of large area specimens with resolutions yielding the overall magnifications of Curve D in Figure 2-1. Some theoretical background for certain of the choices and decisions involved in the equipment and techniques is also included in this chapter.

In the next chapter, the results of the deflection coil tests and the choice of the deflection coil for the large area scanning microscopy are presented and discussed. The following chapter presents and discusses the results of the large area scanning microscopy of suitable specimens.

CHAPTER 7

THE RESULTS OF THE DEFLECTION COIL TESTS

INTRODUCTION

In this chapter, the experimentally obtained electron beam spot profile maps for the five experimental deflection coils, whose constructions were presented in the previous chapter, are discussed. This is followed by spot profile maps which were synthesized by computer, using the results of Chapter 5, to match the experimental maps. Only three of the five experimentally studied deflection coils were matched by computer since the desired information was obtained with these three and the amount of computer time required to obtain a matching map for each coil was considerably longer than had been originally anticipated. The magnitudes and phase angles of the aberration coefficients used in each of the computer syntheses are listed.

Also presented in this chapter are data to show that the electron beam cross-section of both an undeflected and a deflected electron beam is Gaussian. The effect of this on the experimental and synthesized spot profile maps is discussed.

THE ELECTRON BEAM CROSS-SECTION

Figure 7-1 presents the growth in the size of an axial electron beam spot recorded in PMMA as the exposure time is increased. It thus presents the change in the size of the electron beam spot profile at increasingly smaller percentages of the peak height of the electron beam cross-section.

The individual photographs which make up Figure 7-1 are typical of the spot profile photographs which are presented throughout this chapter. The area enclosed by the dark outline in each photograph is an area where the PMMA has been removed through exposure by the electron beam and development, thus leaving the surface of the silicon slice which supports the PMMA film visible; outside this dark outline is the surface of the PMMA film. The edges of the exposed area have an appreciable slope which photographed dark in the light microscope, thus accounting for the broad, dark outline. The lack of sharpness in this outline is due to vibration in the light microscope which proved impossible to eliminate completely.

FIGURE 7-1
VARIATION IN THE SIZE OF AN AXIAL ELECTRON BEAM SPOT
RECORDED IN PMMA AS A FUNCTION OF EXPOSURE TIME

The lines radiating out from some of the spot profiles are cracks in the PMMA film, the result of stress in the film which was not completely annealed out in the pre-exposure heat treatment.

The specks on the PMMA film, more noticeable in some of the other figures of this chapter, are a combination of flaws in the PMMA film, dust on the PMMA film, and dust on the optics of the light microscope.

The dark, centrally located spots within the spot profiles, which begin to be detected with the 2000 μ sec exposure and grow increasingly more noticeable with increasing exposure, are due to overexposure of the PMMA at that point. Overexposure cross-links the polymer, rendering it completely insoluble in the developer as well as in the usual film stripping agent, acetone. The overexposed point thus corresponds to the point of maximum current density in the spot profile.

Using Figure 7-1, the radii of the spot profiles were measured and these were plotted against the reciprocal of their exposure times to yield the cross-section of the axial electron beam. Both the radius in the x direction (horizontally in the photograph) and the radius in the y direction (vertically in the photograph) were considered and both resulting cross-sections were obtained.

Figure 7-2 shows the electron beam cross-section in the x direction while Figure 7-3 shows the cross-section applicable to the y direction. Also shown in these two figures are true Gaussian curves which were fitted to the experimental points on a best fit basis. As can be seen, the axial electron beam cross-section in both the x and the y directions is within a few percent of being a true Gaussian.

A similar study was carried out on a spot which had been deflected 2 mm off-axis in both the x and y directions simultaneously to determine whether it, too, was Gaussian. An early version of experimental deflection coil #4 was used to provide the deflection. Figure 7-4 presents the growth in the size of this off-axis electron beam spot, again recorded in PMMA, as a function of the exposure time while Figures 7-5 and 7-6 present the electron beam cross-sections in the x and y directions, respectively. True Gaussian curves are again superimposed on a best fit basis on the experimental points of Figures 7-5 and 7-6. It can be seen that the off-axis electron beam cross-section in both the x and y directions is also within a few percent of being a true Gaussian.

FIGURE 7-4

VARIATION IN THE SIZE OF AN OFF-AXIS ELECTRON BEAM SPOT
 RECORDED IN PMMA AS A FUNCTION OF EXPOSURE TIME.
 DEFLECTION IS 2mm OFF-AXIS IN X AND Y DIRECTIONS,
 SIMULTANEOUSLY.

An examination of the axial and off-axis electron beam cross-sections indicates that the peak height of the off-axis beam is reduced while its standard deviation is increased, compared with the axial electron beam cross-section. This is to be expected because, while deflection aberrations tend in general to broaden the beam, the total current contained in the beam must remain constant, thereby necessitating a decrease in the peak height and an increase in the standard deviation of the electron beam cross-section.

This fact complicates the interpretation of the electron beam spot profile map somewhat. This map is recorded in a film of fixed sensitivity, the parameter film sensitivity being expressible in units of ampere-seconds/cm² or coulombs/cm². To expose the film, the product of the electron beam current density and the exposure time must equal the film sensitivity. But, because the electron beam has a Gaussian cross-section, its current density is greatest at its centre (in the unaberrated case) and decreases with increasing radius. Therefore, with increasingly longer exposure times, spots of increasingly greater radii will be exposed. This is indicated schematically in Figure 7-7. For a given exposure time, the radius of the exposed spot in the film corresponds to the radius of the electron beam cross-section at the appropriate current density, this current density being an unknown percentage of the peak current density.

Consider, now, a second electron beam with a different peak current density and a different cross-section but with the same total current as the first which exposes a film with the same sensitivity as before and for the same exposure time as before. The radius of this second exposed spot will be related through the film sensitivity to the radius of the second electron beam cross-section at the current density appropriate for this second exposure; this radius will again be unknown and will occur at a current density which will again be an unknown percentage of the peak current density of this second electron beam. (For the purpose of the argument being developed here, this second electron beam can be thought of as a separate electron beam or as the first beam deflected through such an angle that its cross-section and its peak current density have been altered by deflection aberrations.) Now, because the two beams are related through their total currents being the same, it is possible to express the peak current density, the standard deviation, and the exposed spot radius

FIGURE 7-7
RELATIONSHIP BETWEEN EXPOSED SPOT RADIUS
AND EXPOSURE TIME

FIGURE 7-8
RELATIONSHIP BETWEEN EXPOSED SPOT RADII FROM AN ELECTRON BEAM WITH VARYING
PEAK CURRENT DENSITY AND CROSS-SECTION BUT WITH FIXED TOTAL CURRENT. NOTE
THAT EXPOSED SPOT RADII DO NOT INDICATE TRUE CHANGE OF SPOT SIZE.
(σ INDICATES STANDARD DEVIATION)

(for a fixed film sensitivity and exposure time) corresponding to the second beam in terms of the same parameters for the first beam.

If this is done, it is found that the exposed spot radii of all the spots in an electron beam spot profile map occur at the same current density, and therefore at the same percentage of the peak current density, of, say, the axial spot. On the other hand, each occurs at its own unique percentage of its own peak current density, assuming all the spots to have different peak current densities and standard deviations. This is shown in Figure 7-8. The electron beam spot profile map therefore does not indicate directly the true increase in the spot size of an electron beam with deflection since this true increase can only be obtained by comparing the spot diameters at some fixed percentage of their own peak current densities.

To obtain this true increase, it would be necessary to obtain two spot profile maps at two different exposure times and, with the two radii which these maps would yield for any given spot, calculate the standard deviation (or any other radius at a known percentage of the peak height) for the spot in question. (Such a calculation would, of course, only be valid if the electron beam cross-section had a known, mathematically-describable shape; in the present case, the shape of the cross-section is known to be Gaussian.) This approach, if repeated over a complete spot profile map, would give the variation in, say, the standard deviation of the electron beam cross-section with deflection.

While acceptable from a theoretical point of view, this approach does not represent a usable solution. This is because it is not possible to measure the electron beam spot profile radii with sufficient precision for any calculations of the standard deviation to be meaningful. For this reason, a compromise approach was adopted which will be discussed later in this chapter in the section headed THE COMPUTER-GENERATED ELECTRON BEAM SPOT PROFILE MAPS.

THE EXPERIMENTAL ELECTRON BEAM SPOT PROFILE MAPS

The electron beam spot profile map which resulted when experimental deflection coil #1 was used to deflect the electron beam in the deflection coil test equipment is shown in Figure 7-9. This figure shows the spot profile of the electron beam on axis and at 1 mm and 2 mm deflections off axis in the positive and negative line (x) and frame (y) directions. It thus gives a map of the spot profile over a 4 mm square field on the specimen plane. The map was recorded at the plane of best axial focus.

Some of the spots in the map are seen to have a dark, centrally-located core which, as discussed earlier in this chapter under THE ELECTRON BEAM CROSS-SECTION, is due to overexposure of the PMMA at this point. As stated earlier, this overexposed point corresponds to the point of maximum current density in the spot profile. It does not necessarily correspond, however, to the Gaussian deflection point which, in spot profiles of this type, is difficult to locate accurately. Wang [41] has published computer-generated density plots applicable to a magnetically deflected electron beam which demonstrate this.

In four of the spots in Figure 7-7, dark areas are present which appear to be due to overexposure of the PMMA. A reexamination of the original specimen showed them to be due, however, to contamination of the PMMA surface. The spots are located at $x = -1$ mm, $y = +1$ mm; $x = -2$ mm, $y = +1$ mm; $x = +1$ mm, $y = 0$; and $x = -1$ mm, $y = -2$ mm.

The axial spot in Figure 7-9 shows a protrusion in its upper right quadrant. By looking ahead to the spot profile maps for the other deflection coils, it is seen that this feature remains, although the axial spots are not identical, in spite of the fact that the column was realigned before each map was obtained. This feature is, therefore, felt to be attributable to a lack of symmetry in the lens field which would be unaffected by column realignment. The relatively minor differences between the axial spots are attributed to differences in the column alignment applicable to each map.

It is probable that an axial octopole stigmator would have improved the quality of the axial spot. The deflection coil test equipment was not provided with a stigmator, however, since it was not intended to operate at high axial resolution.

FIGURE 7-9
ELECTRON BEAM SPOT PROFILE MAP FOR EXPERIMENTAL
DEFLECTION COIL #1 RECORDED AT THE PLANE OF BEST AXIAL FOCUS.

A few of the spots in Figure 7-9 show a double dark outline. This is due to the vibration in the light microscope used to make the photographs. This vibration, which was also mentioned in the discussion under THE ELECTRON BEAM CROSS-SECTION, proved at times to be quite troublesome.

Not all the spots in Figure 7-9 have overexposed central regions. This is because the more heavily aberrated spots have spread and their peak current densities have been correspondingly reduced to below the critical level for overexposure. That these more heavily aberrated spots do not appear remarkably larger was discussed under THE ELECTRON BEAM CROSS-SECTION and is due to the fact that their spot profiles correspond to a higher percentage of their peak current densities than do the spot profiles for the less aberrated spots.

The electron beam spot profile maps which describe the results of using each of experimental deflection coils #2, 3, 4, and 5 in turn to deflect the electron beam in the deflection coil test equipment are shown in Figures 7-10 through 7-13, respectively. Like Figure 7-9, these figures show the electron beam spot profile on axis and at 1 mm and 2 mm deflections off axis in the positive and negative line (x) and frame (y) directions. They therefore give the maps of the spot profile over 4 mm square fields on the specimen plane. The maps were all recorded at the plane of best axial focus.

The features present in Figures 7-10 to 7-13, inclusive are essentially the same as those which have already been discussed in connection with Figures 7-9 and 7-1 with two exceptions.

In Figure 7-12, four of the spot profiles show dark areas which appear to be due to overexposure of the PMMA but which, in fact, are contamination, as a reexamination of the original specimen showed. The spots in question are located at $x = 0, y = 0$; $x = -1 \text{ mm}, y = 0$; $x = -2 \text{ mm}, y = 0$; and $x = +2 \text{ mm}, y = +1 \text{ mm}$. It is interesting to note that the undeflected, axial spot in Figure 7-12 contains no overexposed area while several of the deflected spots do. This is the inverse of expected behaviour in that the axial spot would ordinarily be the most likely spot to contain an overexposed area. It is felt that the answer to this anomaly lies in the complexity of current density distribution within an aberrated spot where, in this case, the aberrations may be due to the lens, the deflection system, or both. To determine the true current density distribution in an aberrated

FIGURE 7-10
ELECTRON BEAM SPOT PROFILE MAP FOR EXPERIMENTAL
DEFLECTION COIL #2 RECORDED AT THE PLANE OF BEST AXIAL FOCUS.

FIGURE 7-11
ELECTRON BEAM SPOT PROFILE MAP FOR EXPERIMENTAL
DEFLECTION COIL #3 RECORDED AT THE PLANE OF BEST AXIAL FOCUS.

FIGURE 7-12
ELECTRON BEAM SPOT PROFILE MAP FOR EXPERIMENTAL
DEFLECTION COIL #4 RECORDED AT THE PLANE OF BEST AXIAL FOCUS.

FIGURE 7-13
ELECTRON BEAM SPOT PROFILE MAP FOR EXPERIMENTAL
DEFLECTION COIL #5 RECORDED AT THE PLANE OF BEST AXIAL FOCUS.

electron beam involves a detailed study since, for example, the presence of coma results in a double exposure in portions of the spot; such a study was not carried out for this thesis. From Wang's work [42], however, it is known that two spots can have almost identical profiles and yet have completely different current density distributions, one being essentially uniform, the other having a high current density at one point. Such a phenomenon, it is felt, could explain the presence and absence of over-exposed areas in the spots of Figure 7-12.

In Figure 7-11, the spot located at $x = -2$ mm, $y = -2$ mm is badly misshapen. When this fault was first detected, it was felt to be caused by a flaw in the PMMA and the map was rerun. Essentially the same results were obtained with this second map. When computer matching of this map was attempted, it was found that no combination of deflection aberrations would successfully match this spot without also affecting its neighboring spots. The fault therefore was accepted as an anomalous result, attributable in some way to the production of the experimental spot profile map.

The spot in question is located at the corner of a 4 mm by 4 mm scan area on the specimen plane. By experimentation, it was determined that the electron beam in the deflection coil test equipment could be scanned over at least a 5 mm by 5 mm area on the specimen, using the same conditions as were used to produce the spot profile maps, without any interference of the beam by the shielding tube and plate protecting the deflection coil. The fault evidently was not caused by an obstruction of the electron beam. It was therefore concluded that the fault had probably been caused by the charging up of a fleck of dust, in, or at the end of, the shielding tube within the bore of the deflection coil which interfered with the beam at this deflection point only. The spot profile map could have been rerun after cleaning this tube but it was not considered worthwhile, particularly as experimental time was running short.

THE COMPUTER-GENERATED ELECTRON BEAM SPOT PROFILE MAPS

The computer-generated electron beam spot profile map which matches that obtained experimentally with deflection coil #5 is presented in Figure 7-14. This figure shows the spot profile of the electron beam

FIGURE 7-14
COMPUTER-GENERATED ELECTRON BEAM SPOT PROFILE
MAP FOR EXPERIMENTAL DEFLECTION COIL #5.

on axis and at 1 mm and 2 mm deflections off axis in the positive and negative line (x) and frame (y) directions. Like the corresponding experimentally-obtained spot profile map, this figure is a map of the spot profile over a 4 mm square field on the specimen plane. Each spot profile in this map is contained within a 25 μ m square, as were the experimental spot profiles; the centre point of each square is marked.

In obtaining Figure 7-14, it was found that the line deflection coil sections of deflection coil #5 were not contributing any significant aberrations while the frame deflection coil sections contributed different deflection aberrations depending upon whether the deflection was in the positive or the negative frame direction. Due to these differences together with a limitation in the computer program whereby it was able to work with only one set of aberration coefficients at a time, the entire spot profile map could not be generated for Figure 7-14.

The difference in behaviour between the line and frame coil sections of deflection coil #5 is attributed in part to the effect of the coil circumference angle on the deflection aberrations being dependent upon the coil radius; this was pointed out in Chapter 6 under EXPERIMENTAL DEFLECTION COIL DESIGN and is due to Kaashoek [5]. It is also attributed to winding nonuniformities which are more difficult to eliminate in the smaller radius coil. In deflection coil #5, the frame deflection coil sections have a radius of less than half that of the line deflection coil sections. These winding nonuniformities are also felt to be the cause of the difference in behaviour of the frame deflection coil sections with positive and negative deflections.

The computer generates spot profiles at a fixed percentage of their peak current densities, say at the standard deviation, whereas each spot in an experimentally derived map is, or can be, recorded at a different percentage of its peak current density (see THE ELECTRON BEAM CROSS-SECTION earlier in this chapter). For this reason, it is not possible for all the spots in a computer-generated map to match the corresponding spots in an experimental map. For example, if a match is secured for the axial spot, the computer-generated spot for an extreme deflection will, in general, be larger than the corresponding experimentally obtained spot. Conversely, if a match is secured for a spot at an extreme deflection, the computer-generated spot for the axial position will, in general, be

smaller than the corresponding experimentally obtained spot. This makes it difficult to determine whether or not the correct aberration coefficients have been chosen for the computer matching.

To avoid this difficulty as much as possible, a compromise approach was adopted. This approach consisted of obtaining as accurate a match as possible for the axial spot, using the full 500 μm diameter size of the final aperture in the computer program, and of obtaining as accurate a match as possible for the deflected spots by using, if necessary, a somewhat smaller aperture size in the computer program. In other words, the size of the computer-generated deflected spot was scaled down by reducing the aperture size so as to match the size of the experimental spot and thus make comparison easier.

In experimenting with this scaling technique, it became clear that the size of aperture used in the computer program had only a second order effect on the deflection aberrations but had a major effect on the lens aberrations used to match the axial spot. Accordingly, a reduction in the size of the aperture used in the computer program served mainly to shrink the spot being generated while leaving its shape relatively unaltered. Since the percentage of the peak current density of the electron beam at which the spot profile occurs is unknown, it is the spot's shape (i.e. profile) and not its size which is of primary interest. (This relative independence of deflection aberrations on the aperture radius was previously discussed from a more theoretical point of view under *Large Area Scanning Electron Microscopy Tests* in Chapter 6).

The above scaling technique is not unlike the matching method used by Amboss and Wolf [37]. Although they do not discuss it in their paper, an examination of their experimental and computer-generated maps indicates that they chose to ignore the lens aberrations and consider only the deflection aberrations. In securing a match at a corner of their map, they automatically obtained a point for their computer-generated axial spot, compared with a finite-sized spot in their experimental map. Depending upon the precision they may have required in their work, this may have been a justifiable approach since their deflection aberrations far outweighed their lens aberrations. In the present case, however, the lens aberrations form a significant part of the spot profiles and

cannot be ignored. The scaling technique was therefore adopted to permit matching of the deflected spots while still admitting the lens aberrations but on a somewhat reduced scale. A further discussion of the work of Amboss and Wolf will be presented in the DISCUSSION AND CONCLUSIONS section of this chapter.

It should be stressed that the computer-generated maps contained in this thesis are not put forward as *exact* matches but rather as sufficiently close matches for the purpose at hand; i.e., they contain all the *significant* aberrations but not necessarily all those which may be present in very small amounts. Therefore, the magnitudes and phase angles quoted for the aberration coefficients are not held to be precise; it is felt, however, that they are within approximately ten percent of their correct values. The computer-generated spot profiles did not vary significantly when the coefficients were altered by ten percent of their stated values.

The moduli and arguments of the lens and aberration coefficients used to generate Figure 7-14 are given in Table 7-1. The aperture radii used for each of the deflection directions are also given in the table.

The computer-generated electron beam spot profile map matching that obtained experimentally for deflection coil #4 is given in Figure 7-15. As was the case with coil #5, the frame deflection coil sections were found to contain asymmetries which caused them to contribute different deflection aberrations depending upon whether the electron beam was deflected in the positive or the negative frame direction. The line deflection coil sections also were found to be slightly asymmetric so that, although they contributed no significant deflection aberrations for deflection in the positive line direction, they introduced a small amount of aberration for deflection in the negative line direction.

As was found with deflection coil #5, the differences in behaviour between the line and frame coil sections of deflection coil #4 are partially attributed to the dependence on the coil radius of the effect of the coil circumference angle on deflection aberrations and partially attributed to winding nonuniformities. Due to these differences and to the limitation in the computer program referred to in the discussion concerning deflection

TABLE 7-1
ABERRATIONS PRESENT IN COMPUTER-GENERATED
ELECTRON BEAM SPOT PROFILE MAP FOR
EXPERIMENTAL DEFLECTION COIL #5

[illegible]

FIGURE 7-15
COMPUTER-GENERATED ELECTRON BEAM SPOT PROFILE
MAP FOR EXPERIMENTAL DEFLECTION COIL #4.

coil #5, the entire spot profile map was not generated for Figure 7-15. As was done in Figure 7-14, scaling was employed in producing Figure 7-15 in order to provide accurate matching.

Table 7-2 presents the moduli and arguments of the lens and aberration coefficients used to generate Figure 7-15. Also given in Table 7-2 are the aperture radii used in scaling Figure 7-15 in each of the deflection directions.

The computer-generated electron beam spot profile map matching that obtained experimentally with deflection coil #3 is given in Figure 7-16. In this instance, only a small amount of astigmatism and curvature of the image field was detectable and no asymmetry in performance between the line coil sections, between the frame coil sections, or between the line and frame coils was apparent.

The improved performance of deflection coil #3 is attributed to a correct choice of the coil circumference angle together with the elimination of winding nonuniformities, at least to a level consistent with the performance demonstrated in Figure 7-16. Due to the symmetry displayed by deflection coil #3, the limitation in the computer program does not apply and the entire spot profile map was therefore generated for Figure 7-16. In addition, scaling was not required in producing Figure 7-16 due to the very small deflection aberration content in the deflected spots; i.e., the deflected spots differ only slightly from the axial spot.

The moduli and arguments of the lens and aberration coefficients used to generate Figure 7-16 are presented in Table 7-3. The aperture radius used in generating Figure 7-16, 250 μm , is included in the table as a reminder that scaling was not employed in generating this figure.

DISCUSSION AND CONCLUSIONS

From the analysis of deflection coils contained in this chapter, it is clear that winding nonuniformities will introduce asymmetrical behaviour into deflection coils and may also introduce deflection aberrations. This is particularly true of smaller coils, due partly to their being more difficult to wind uniformly and partly to the fact that a given error in

TABLE 7-2
ABERRATIONS PRESENT IN COMPUTER-GENERATED
ELECTRON BEAM SPOT PROFILE MAP FOR
EXPERIMENTAL DEFLECTION COIL #4

[illegible]

FIGURE 7-16
COMPUTER-GENERATED ELECTRON BEAM SPOT PROFILE
MAP FOR EXPERIMENTAL DEFLECTION COIL #3.

the location of a portion of a winding will have a greater effect on a small coil than on a larger one. From these results it is clearly evident that small postlens deflection coils, such as would be needed in a scanning electron microscope which was required to work at a relatively short working distance (say 10 to 20 mm), would have to be very critically wound to eliminate all possible winding nonuniformities.

With larger deflection coils, this dependence upon freedom from winding nonuniformities for acceptable performance is far less demanding. The line (x) deflection coil sections of deflection coils #3, 4, and 5 all proved acceptable when evaluated although their designs were not identical. This is believed to be due to the comparative ease with which they could be wound uniformly due to their larger size. The relative independence of the behaviour of these larger line deflection coil sections from changes in the coil circumference angle is believed to be due to the fact that these coils are not required, in the present application, to deflect the electron beam through a very large angle. With the coil throw being used of 42.7 mm, the deflection angle to the edges of a 4 mm square specimen scan area is only 2.7°. It is believed that the effect of the coil circumference angle, together with the effects of other coil geometrical factors, would become more pronounced as the working distance was reduced and the deflection angle therefore increased.

With smaller deflection coils, the effect of the coil circumference angle would be expected to become pronounced as the deflection angle is increased. This is, in fact, supported by an examination of the results for the frame (y) deflection coil sections of deflection coils #3, 4, and 5 where some of the differences in performance are attributable to changes in the coil circumference angle. This can best be appreciated by a study of Tables 7-1, 7-2, and 7-3. In Table 7-1 for deflection coil #5, the most likely deflection aberrations attributable to the coil design, as opposed to its (nonuniform) construction, are (2001) and (0201). This conclusion is drawn because they are the only two aberrations present which are common to both the positive and negative frame or y deflection directions; that they are not equal is attributed to winding nonuniformities. In Table 7-2 for deflection coil #4, the most

TABLE 7-3

[illegible]

likely deflection aberrations attributable to the coil design are (1110) and (1101); again their inequalities are attributed to winding non-uniformities. Thus, a change in coil circumference angle from 130° for coil #5 to 110° for coil #4 has changed the design-induced aberrations from astigmatism which is dependent upon the angle of the Gaussian deflection squared to astigmatism which is independent of the Gaussian deflection angle. Midway between these two coil circumference angles is 120° which is applicable to coil #3. In Table 7-3, which applies to coil #3, it is seen that only a residual amount of (1110) and (1101) remains. A coil circumference angle of 120° , it is concluded, is nearly optimum. The remaining differences in performance of the frame deflection coil sections of deflection coils #3, 4, and 5 are attributed to winding nonuniformities which, as mentioned above, would be expected to be more pronounced in small coils.

Experimental deflection coil #1 proved in its evaluation to be only slightly inferior to coil #3 which was the best of the five coils tested; this can be seen by comparing Figures 7-9 and 7-11. This is felt to be due mostly to its construction which, because it was made up of rectangular Helmholtz coil sections, could be wound very uniformly. Part of the reason for its performance must also be credited to the angle subtended at the coil centre by the ends of the coil sections which was 127° for both the line and frame coil sections; i.e., this angle was close to the near-optimum coil circumference angle of 120° .

Experimental deflection coil #2 was also shown to be not too inferior to coil #3, as can be seen by comparing Figures 7-10 and 7-11. This is again attributed to the coil circumference angle being at the near-optimum angle of 120° together with a construction which had few winding non-uniformities. Some evidence of nonuniformity in the frame (y) deflection coil sections can be seen by examining Figure 7-10, however.

From the data presented in this chapter, it is evident that experimental deflection coil #3 is the best deflection coil tested, as evidenced by its freedom from both winding nonuniformities and deflection aberrations. The results also show that freedom from winding nonuniformities is of paramount

importance in high quality deflection coils. As part of a program of future work, it is intended that these winding nonuniformities be controlled by improved coil construction techniques so that more detailed investigations of the aberration coefficients can be carried out. It is anticipated that such a study will yield even better coils than deflection coil #3.

The presence of winding nonuniformities in the coils tested for the present work has caused asymmetries and possibly additional deflection aberrations to be introduced into these coils, thereby complicating the computer matching as well as the interpretation of the results. Nevertheless, computer matching has been shown to be a valid technique which should prove its full value in the future development of deflection coils superior to deflection coil #3. Plans for such a future development have been mentioned previously in Chapter 6 under THE DEFLECTION COIL TEST EQUIPMENT and in Chapter 7 under *Large Area Scanning Electron Microscopy Tests* and will be discussed in detail in Chapter 9.

The technique used in this thesis to display the size and shape of a deflected electron beam spot was that of Amboss and Wolf [37]. These authors were not attempting to develop deflection coils, however, but rather were attempting to evaluate the aberration content of the deflected electron beam spot from a standard scanning electron microscope, the Cambridge Instruments Co. scanning electron microscope. Their purpose was to assess the capability of the equipment available to them from the point of view of using it for integrated circuit mask making and pattern generation. Although their experimental technique was similar to the technique adopted for the present work, the computer matching methods used were different. The differences lie mainly in the assumptions which were made.

Their program, like that of the present work, was based on the simplified results of Haantjes and Lubben [3], the final equations for which are (5-46a and b). These equations, however, have been simplified on the basis that the electron beam coordinates at the specimen plane with no deflection present are zero. Now the equipment used by Amboss and Wolf employed prelens double deflection. For such a deflection system, the simplification involved in equations (5-46a and b) is valid

only for the upper coil; in the case of the lower coil, the simplification is not valid due to the previous deflection of the beam by the upper coil. For the lower coil, the unsimplified equations (5-45a and b) must be used.

It can be argued that the authors' intention was to assess the upper and lower coils together as a system on the basis that, since the coils would not be used separately, they should not be assessed separately. However, the Gaussian deflection in Equations (5-46a and b) is determined by the position of the deflected beam at the specimen plane. This is not the deflection applicable to either the upper or lower coil, which can be seen by a study of Figure 4-2.

Finally, it is not clear whether or not Amboss and Wolf have included the necessary terms to account for the lens aberrations. In their work, they used a working distance of 10 mm and examined the effect of deflection on an electron beam deflected over a 2 mm square area on the specimen plane. At the edges of this area, the electron beam makes an angle of 5.7° with the optic axis which would normally be large enough for the lens to introduce aberrations into the beam. It would appear from their computer matching that Amboss and Wolf did not include lens aberrations but that this exclusion may have been justified on the basis of the very large deflection aberration content of their spots.

On the basis of the foregoing experimental results, it is concluded that experimental deflection coil #3 is sufficiently good to demonstrate large area scanning electron microscopy of specimens approximately 3 mm square with the resolutions and magnifications set forth previously. The next chapter is concerned with this aspect of the work.

CHAPTER 8

THE RESULTS OF THE LARGE AREA SCANNING ELECTRON MICROSCOPY TESTS

INTRODUCTION

In the previous chapter, experimental deflection coil #3 was identified as being sufficiently good to demonstrate large area scanning electron microscopy of specimens approximately 3 mm square. In this chapter, the results of this series of tests, using deflection coil #3, the Minicolumn scanning electron microscope, and the CELCO high resolution CRT display system, are presented.

Also presented in this chapter, for comparison, are the results of examining the same specimen with the original prelens double deflection coils provided for the Minicolumn microscope.

The results in this chapter are based primarily on the examination of a test specimen formed from an etched copper mesh. Also presented, in a somewhat briefer fashion, are the results of examining an array of small geometry transistors.

It should perhaps be pointed out here that the relatively poor axial resolution displayed in the spot-profile maps of Chapter 7 will not affect the results of this chapter. Axial resolution is a consequence of the electron optical column and not the deflection coil. It will therefore not be transferred from the deflection coil test equipment to the scanning electron microscope.

RESULTS

As discussed in Chapter 6 under *Large Area Scanning Electron Microscopy Tests*, it is necessary to set the axial resolution of the microscope to the correct value for the size of specimen area it is proposed to examine before producing a large area micrograph. Since it was proposed to examine a specimen area 3.35 mm square and since a frame of 3000 scan lines was being used, the required axial resolution in the microscope was $(3.35 \div 3000)$ mm or 1.12 μ m.

Figure 8-1 is a high magnification micrograph of an etched copper mesh which was selected as the specimen for this portion of the work. As nearly as can be determined from optical measurements, the mesh in this specimen had $29.3 \mu\text{m}$ wires located $180.7 \mu\text{m}$ apart centre-to-centre. Caution should be exercised in scaling the photographs of this chapter, however; uneven shrinkage of the prints makes erroneous results likely. The original micrograph for Figure 8-1 was produced at a magnification of X550 and this micrograph was enlarged photographically by a factor of two to produce the figure. If the required axial resolution, $1.12 \mu\text{m}$, is increased by the overall magnification of Figure 8-1, 1100 times, a figure of 1.23 mm is obtained. A correct setting of the axial resolution of the microscope would be indicated if the finest specimen detail being resolved measured 1.23 mm in Figure 8-1. An examination of Figure 8-1 shows that this is essentially the case; the finest detail present is of this order. Accordingly, it was concluded that the microscope axial resolution was correctly set for examination of a specimen area 3.35 mm square. (The bands running across Figure 8-1 were caused by a faulty connection to the filament in the electron gun on the microscope which caused a fluctuation in the emission current; they should be ignored.)

The correct axial resolution having been obtained, a large area micrograph of the etched copper mesh was produced, using experimental deflection coil #3. The scan area on the specimen was 3.35 mm square and the microscope magnification was X22. The resulting micrograph was photographically enlarged by a factor of two to produce Figure 8-2. As discussed in Chapter 6 under THE SCANNING ELECTRON MICROSCOPE AND THE HIGH RESOLUTION CRT DISPLAY AND RECORDING SYSTEM, the permissible enlargement of these micrographs is X8 so that a further enlargement of Figure 8-2 by a factor of four may be made.

An examination of Figure 8-2, using a low power optical microscope to provide this enlargement, shows that essentially the same detail is being resolved at all locations in the figure. There is no noticeable decrease in resolution at the edges with respect to the centre of the figure, the centre corresponding to the axial area of the specimen. It is therefore concluded that Figure 8-2 demonstrates the feasibility of large area

FIGURE 8-1.

MICROGRAPH OF COPPER MESH PRODUCED WITH POSTLENS
SINGLE DEFLECTION COIL (#3) AT A WORKING DISTANCE
OF 54mm. MICROSCOPE MAGNIFICATION X550, PHOTO-
GRAPHIC ENLARGEMENT X2

FIGURE 8-2
MICROGRAPH OF COPPER MESH PRODUCED WITH POSTLENS
SINGLE DEFLECTION COIL (#3) AT A WORKING DISTANCE
OF 54mm. MICROSCOPE MAGNIFICATION X22, PHOTO-
GRAPHIC ENLARGEMENT X2

scanning electron microscopy as set forth in this thesis, within the limitation of there being only 3000 scan lines per frame.

For comparison, two large area micrographs of the same specimen were produced using the original prelens double deflection coils and working distances of 10 mm and 21 mm, as discussed in Chapter 6 under *Large Area Scanning Electron Microscopy Tests*. The micrograph for the 10 mm working distance was produced over a scan area on the specimen of 3.07 mm square and had a magnification of X24. It was photographically enlarged by a factor of two to produce Figure 8-3. Although this figure is poor in that it has been produced with too much contrast, it shows clearly that the microscope resolution is not maintained at its axial value throughout the micrograph with this deflection coil. This was to be expected from the results that were obtained by Amboss and Wolf [37] under similar conditions and from the theoretical results of this thesis; see, for example, the DISCUSSION AND CONCLUSIONS section of Chapter 7.

The micrograph for the 21 mm working distance was produced over a specimen scan area of 2.93 mm and had a magnification of X26. It was photographically enlarged by a factor of two to produce Figure 8-4. An examination of this figure shows that in this case, also, the microscope resolution is not being maintained at its axial value as the electron beam is deflected. Some improvement is evident from a comparison of Figures 8-3 and 8-4 but it is apparent that sufficient improvement on the strength of increasing the working distance alone would require an impractical increase in this dimension. The small improvement that is present is due to the reduction allowed in the deflection angle when essentially the same area is covered on the specimen from a more distant deflection point.

The drop in signal level in the lower right quadrant of Figure 8-4 is due to inefficient signal collection in the Minicolumn microscope when it is used to examine large specimen areas at short working distances. As discussed in Chapter 6 under *Large Area Scanning Electron Microscopy Tests*, the collection system in the Minicolumn microscope was designed to operate with the specimen inclined toward it to enhance the signal collection.

FIGURE 8-3

MICROGRAPH OF COPPER MESH PRODUCED WITH PRELENS
DOUBLE DEFLECTION COILS AT A WORKING DISTANCE OF
10 mm. MICROSCOPE MAGNIFICATION X24, PHOTOGRAPHIC
ENLARGEMENT X2

FIGURE 8-4
MICROGRAPH OF COPPER MESH PRODUCED WITH PRELENS
DOUBLE DEFLECTION COILS AT A WORKING DISTANCE OF
21mm. MICROSCOPE MAGNIFICATION X26, PHOTOGRAPHIC
ENLARGEMENT X2

In the present work, the specimen was maintained perpendicular to the electron optical axis to avoid defocusing errors caused by the beam being deflected so far from the axis. This same problem is present in Figure 8-3 also but it has been masked by the excessive contrast in this figure.

Since this thesis was premised on the analysis of solid state devices, it was felt that a large area micrograph of a suitable solid state specimen should be included. Accordingly, a section of a silicon slice bearing a number of identical, small geometry transistors on its surface was selected for examination. An array of small transistors was chosen in preference to one large integrated circuit so that the same detail would be available for examination at all points in the micrograph. From optical measurements, the width of the metallization pads in this specimen was 91 μm . As stated in connection with the wire mesh micrographs, caution should be exercised in scaling these photographs in view of the uneven shrinkage of the prints.

Figure 8-5 is a micrograph of this specimen taken at a microscope magnification of X260 and photographically enlarged by a factor of two. Like Figure 8-1, its purpose is to demonstrate the setting of the microscope axial resolution. Since, in this instance, it was desired to examine a specimen area 2.67 mm square, the required axial resolution in the microscope was $(2.67 \div 3000)$ mm or 0.89 μm . Expanded through the overall magnification of Figure 8.5, X520, the required resolution in Figure 8-5 for correct setting of the microscope condenser lenses is therefore 0.46 mm. An examination of the figure shows that the finest detail it is resolving is of this order, indicating correct setting of the microscope axial resolution for examination of a specimen 2.67 mm square. (The dark vertical line in Figure 8-5 is a contamination line on the specimen caused by the microscope being left in the line scan mode for an extended period of time while its column alignment was adjusted.)

Figure 8-6 is a large area micrograph of the transistor array which was obtained with experimental deflection coil #3. The scan area on the specimen was 2.67 mm square, and the microscope magnification was X29; the micrograph was enlarged photographically by a factor of two to produce the figure. As was done with Figure 8-2, this figure was examined with a X4 optical microscope. No noticeable decrease in resolution at the corners

FIGURE 8-5
MICROGRAPH OF TRANSISTOR ARRAY PRODUCED WITH POSTLENS
SINGLE DEFLECTION COIL (#3) AT A WORKING DISTANCE OF
54mm. MICROSCOPE MAGNIFICATION X260, PHOTOGRAPHIC
ENLARGEMENT X2

FIGURE 8-6

MICROGRAPH OF TRANSISTOR ARRAY PRODUCED WITH POSTLENS
SINGLE DEFLECTION COIL (#3) AT A WORKING DISTANCE OF
54mm. MICROSCOPE MAGNIFICATION X29, PHOTOGRAPHIC
ENLARGEMENT X2

of the figure with respect to its centre was detected. It is concluded that Figure 8-6, like Figure 8-2, demonstrates the feasibility of large area scanning electron microscopy, within the limitation of 3000 scan lines per frame.

Figure 8-7 is a large area micrograph of the transistor array obtained with the Minicolumn prelens double deflection coils at a working distance of 21 mm. The scan area on the specimen was 2.98 mm square and the microscope magnification was X26. The micrograph was enlarged photographically by a factor of two to produce the figure. Again, as was seen in connection with Figure 8-4, the microscope resolution is not being maintained at its axial value as the electron beam is deflected.

DISCUSSION AND CONCLUSIONS

From the data presented in this chapter, it is evident that prelens double deflection of the electron beam in a scanning electron microscope is, in general, incompatible with maintaining microscope resolution at its axial value over large specimen areas. This is to be expected in view of the large deflection angles involved in such coils which result in both large deflection aberrations and large lens aberrations being introduced into the beam. Although some improvement was obtained with increased working distance, sufficient improvement on the strength of increasing this dimension alone cannot be expected; this view is supported by Chang, whose work was cited earlier in the thesis [44]. Some form of control of these aberrations must therefore be utilized:

The Minicolumn prelens deflection coils also exhibited considerable asymmetry, as can be seen from Figures 8-3, 8-4, and 8-7. Although experimental deflection coil #1, which was wound like the prelens coils, showed some evidence of asymmetry, notably in the frame or y direction as can be seen from Figure 7-9, the large amount present in the prelens coils was not expected. It is known that these coils had been overheated prior to these tests and it is possible that some distortion of the windings may have occurred which is contributing to this asymmetry.

FIGURE 8-7

MICROGRAPH OF TRANSISTOR ARRAY PRODUCED WITH PRELENS
DOUBLE DEFLECTION COILS AT A WORKING DISTANCE OF 21mm.
MICROSCOPE MAGNIFICATION. X26, PHOTOGRAPHIC ENLARGEMENT
X2

Improvement of the scan system in the microscope to provide 5000 scan lines per frame would not be expected to affect the results of this chapter. The small increase in the required axial resolution is of no consequence since the microscope is capable of axial resolution down to $250 \text{ \AA}$. In addition, the aberration content of experimental deflection coil #3 is so small that a somewhat smaller (60%) probe size would not be noticeably affected by these aberrations. This argument is supported by the fact that the axial resolution in the deflection aberrations test set, in which coil #3 was found to be acceptable for large area scanning electron microscopy, was several times poorer than that of the microscope in which this coil was found to perform acceptably. A further small increase in microscope axial resolution would not be expected to degrade the results.

To be fully satisfactory as an analytical instrument, the large area scanning electron microscope must have a better signal collection system than that presently used in the Minicolumn microscope. A collection system capable of collecting signals from a large specimen area which is perpendicular to the electron optical axis and which is perhaps only 20 mm away from the lower surface of the deflection coil shield must be built before the instrument could be used routinely for large area microscopy.

* * *

On the basis of the results of this chapter, it is concluded that the concept of large area scanning electron microscopy as set forth in this thesis is a viable technique for the documentation of large surface areas without the customary large quantity of micrographs. It was previously shown that the success of this method depends in large part on control of the deflection aberrations in the coil which scans the electron beam in the microscope. In this chapter, it has been demonstrated that this control can be derived from a properly designed and constructed deflection coil. It has therefore been demonstrated that complex electronic circuitry for the correction of defocusing and astigmatism errors due to deflection of the electron beam is not required.

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CHAPTER 9

CONCLUSIONS AND FUTURE WORK

CONCLUSIONS

On the basis of the theoretical and experimental investigations which have been carried out for this thesis, it is concluded that the concept of large area scanning electron microscopy presented at the beginning of the thesis is both realizable in terms of a working instrument and worthwhile in terms of the usefulness of that instrument. The instrument is particularly useful when many large area specimens must be examined and details concerning their structures recorded.

Specifically, it has been shown that, if a high resolution CRT display and recording system and a magnetic deflection coil, designed to have its deflection aberrations minimized, are appended to a standard scanning electron microscope, the concept of large area scanning electron microscopy can be realized. Using a 5000 line resolution display, specimen magnifications of up to $1000 \div \text{specimen size in mm}$, to a limit of 5000 times, are possible in one micrograph with this system, including a maximum permissible photographic enlargement of X13.3. Such a system permits a reduction of from eighty to one in the number of micrographs required to fully document a 2.5 mm square specimen at a magnification of X350, for example.

To maintain a consistent quality in the micrographs obtained from such a system, it was shown that the micrograph recording time must be increased as the specimen size decreases in order that the signal-to-noise ratio in the micrograph remain constant. In addition, the parameters involved in photographing the high resolution CRT display, including the camera, the film, and the display itself, were examined and it was shown that high quality micrographs were achievable using readily available materials and standard techniques.

A commercial high resolution CRT display and recording system, manufactured by Constantine Engineering Laboratories Company of Upland, Calif. and equipped with a Linhof camera and a Rodenstock lens, were found

to satisfy the display and recording aspects of the large area scanning electron microscope.

Realization of the system was also shown to be heavily dependent upon control of the electron beam spot size in the scanning electron microscope. This control was shown to fall logically into two categories: control of the size of the axial or undeflected spot and control of the growth in the size of the axial spot with deflection. It was shown that this latter control could not be achieved by an increase in the working distance of the microscope alone and that either electronic focus and astigmatism corrections or control of the deflection aberrations through the design of the magnetic deflection coil were required; control of the deflection aberrations through the design of the coil was the approach chosen.

The alternate approach, correction of the deflection aberrations present in an electron beam by electronic means, is possible only with some of the aberrations: isotropic distortion, pincushion or barrel distortion, curvature of the image field, and isotropic astigmatism. Anisotropic astigmatism and coma cannot be corrected for electronically and must be controlled through the design of the coil. To correct for distortion, the output voltage of the scan generator, which controls the output current from the scan amplifier to the deflection coils, must be altered as a function of the desired beam position on the specimen. To do this, the magnitude of the distortion present must be known beforehand. Curvature of the image field is corrected for by altering the current to the final focusing lens as a function of the deflection of the electron beam in accordance with previously-obtained knowledge of the magnitude of this curvature. To correct for isotropic astigmatism, a set of coils arranged symmetrically about the optic axis and known as an octopole stigmator is used. These coils can be located within the bore of the final (asymmetrical) lens above the gap in its magnetic circuit. From a knowledge of the magnitude of the isotropic astigmatism introduced by the deflection coil, the stigmator coils can be provided with currents to provide suitable beam-shaping fields as a function of the deflection of the beam.

An extensive analysis of lens aberrations showed the advantage of keeping the electron beam on axis as it passes through the focusing system; it was shown that, in this way, spherical aberration is the only geometrical aberration contributed by the lens. To keep the beam on axis through the focusing system, single postlens deflection had to be adopted in preference to the more usual prelens double deflection.

Chromatic aberration was shown to be negligible for the lens and gun accelerating potential power supply stabilities presently available and for the accelerating potentials normally used in scanning microscopy. Diffraction also was shown to be negligible for the aperture sizes and accelerating potentials normally used.

An extensive analysis of magnetic deflection aberrations was made and it resulted in data which provided background information for the deflection coil designs and in data for the computer matching program. This program provided a means of finding the modulus and the argument of each of the aberration coefficients active in any given deflection coil.

The results of experimental measurements were presented to show that the electron beam cross-section was Gaussian whether the beam was deflected or undeflected.

Design data for five postlens single deflection coils were presented as were experimentally obtained spot profile maps for each of the coils. These maps demonstrated that one of the coils, experimental deflection coil #3, was sufficiently free from deflection aberrations to be acceptable for large area scanning microscopy.

Computer-generated spot profile maps for three of the five experimental deflection coils were presented. These matched their corresponding experimentally obtained maps and defined the moduli and arguments of the deflection aberration coefficients present in each of the three coils.

It was found that winding nonuniformities severely limit the performance of a deflection coil, particularly in the case of smaller coils. It is imperative that these nonuniformities be eliminated from high quality deflection coils.

The importance of the coil circumference angle, together with the effects of other coil geometrical factors, was demonstrated. For the size of deflection coils used in this work, the optimum coil circumference

angle would appear to be close to, and slightly larger than, 120° . This conclusion is based on the results of Chapter 7. In the DISCUSSION AND CONCLUSIONS section of that chapter, it was pointed out that the deflection aberrations most likely attributable to the design of deflection coil #5, as opposed to its (nonuniform) construction, were (2001) and (0201); the coil circumference angle of coil #5 is 130° . On the other hand, the deflection aberrations most probably attributable to the design of deflection coil #4, for which the coil circumference angle is 110° , were given as (1110) and (1101). Midway between these two coil circumference angles is 120° , the angle to which deflection coil #3 was constructed. The aberrations contributed by this coil were small amounts of (1110) and (1101). Accordingly, as the coil circumference angle is reduced from 130° to 110° , the aberrations contributed by the coil design change from (2001) and (0201) to (1110) and (1101). Since, at a coil angle of 120° , a small amount of (1110) and (1101) remains, the changeover point evidently occurs at a coil angle of slightly greater than 120° . The angle at which this changeover point occurs is taken as the optimum coil circumference angle. It was found to be more critical for smaller deflection coils.

Computer matching was shown to be a valid technique for determining the values of the deflection aberration coefficients present in a deflection coil. It is expected that this technique will prove its full value in the future development of higher performance deflection coils.

Scanning electron micrographs were presented which were taken using the standard prelens double deflection coil and the new postlens single deflection coil. These showed the improvement realizable by using a postlens deflection coil which was constructed so as to be essentially free of both asymmetries and deflection aberrations.

The micrographs taken with the prelens deflection coil showed that some improvement in performance is possible by increasing the working distance, but that sufficient improvement by increasing this dimension alone cannot be expected; some form of controlling these aberrations must be utilized.

In conclusion, large area scanning electron microscopy has been shown in this thesis to be a suitable method of examining and recording the details of large specimen areas which avoids the present tedium of having

to obtain large numbers of small area micrographs for each specimen. The method has been shown to depend largely for its success on control of the deflection aberrations originating in the microscope deflection coil, this control being achievable through the design and construction of the deflection coil itself. It has therefore been shown that it is not necessary to employ electronic correction for the deflection aberrations in this application.

FUTURE WORK

In carrying out the experimental work for this project, a number of areas in which further work in the future would be of benefit were identified. These are discussed in this section.

The scan generator

As pointed out in the body of the thesis, the scan generator in the Minicolumn scanning electron microscope cannot scan 5000 lines in one frame. The maximum number of lines presently achievable is 3000. To fully utilize the capability of the CELCO high resolution CRT display system and to exploit large area scanning electron microscopy to the fullest extent possible, the scan generator must be redesigned.

Work has therefore recently been initiated on a new scan generator with a 5000 scan line capability. The technique chosen to provide the line scan is to use a constant current generator to charge a capacitor and to sense the voltage across this capacitor with a high input impedance amplifier. The output voltage of this amplifier is used to drive the line side of the scan amplifier which provides the deflection current for the line deflection coil sections.

The upper and lower charge levels of the capacitor are sensed with a set/reset flip flop. When the charge in the capacitor builds up to the upper level, the flip flop sets and turns on a transistor to discharge the capacitor. When the charge drops to the lower level, the flip flop resets, turns off the discharging transistor, and allows the charge in the capacitor to build up again. The upper and lower levels are set so that the line generator operates over the most linear portion of its characteristic.

To provide the frame scan, a normally-off constant current generator is turned on by a pulse triggered by the setting of the line generator flip flop. This constant current generator also delivers charge to a capacitor and the voltage across this capacitor is sensed by a second high input impedance amplifier. The output voltage of this amplifier drives the frame side of the scan amplifier which provides the deflection current for the frame deflection coil sections.

The frame constant current generator delivers charge to its capacitor only for a period of time equal to the width of its driving pulse. Therefore, by adjusting the width of this pulse, the spacing between the scan lines making up the frame can be adjusted. After 5000 pulses have been counted, the frame generator capacitor is discharged to reset the line scan to the beginning of the frame. An option simply stops the driving pulse generator after 5000 pulses until the system is manually reset. In this way, a single frame for recording purposes is obtained.

The signal collection system

The secondary electron collection system in the Minicolumn scanning electron microscope also should be redesigned to improve its ability to collect signals uniformly from large specimen areas. The use of a large area diode detector fixed to the lower face of the postlens deflection coil for the detection of backscattered primary electrons could provide a solution to this problem.

These detectors comprise a disk of 3000 Ωcm n type silicon onto which a layer, some 300 $\text{\AA}$ thick, of gold is evaporated. On the back surface, a 1 μm layer of aluminum provides an ohmic contact. The device is operated at zero bias as a surface barrier diode, the contact potential between the gold and the silicon forming a depletion region at the silicon surface. A current gain of about 10^3 is possible with these detectors so that, for an incident electron beam current of as low as 10^{-12} amps., no difficulty in detecting and amplifying the detector output current would exist. There is no difficulty experienced in providing a central hole in the silicon disk for the incident electron beam and disks up to 75 mm in diameter can be

manufactured. Such large disks would provide uniform signal collection from an area half this diameter, since backscattered electrons are emitted specularly, or from an area about 25 mm square. A resolution of 400 to 500Å should be achievable with such a detector [50], making possible large area scanning electron microscopy of specimens down to 200 to 250 μm square.

Recent work by Robinson [51] suggests that a backscattered electron detector may be preferable for the examination of integrated circuits when compared with the usual secondary electron detector. Using a backscattered electron detector which subtended a solid angle of 2π radians at the specimen, this author was able to examine an uncoated insulator without charge buildup on the specimen severely degrading the image. Integrated circuits contain, particularly in the case of those packaged in flat packs, a considerable amount of insulating material. If this material becomes charged, the resulting surface voltages will have a far greater effect on the low energy secondary electron trajectories than they will on the higher energy backscattered electron trajectories. This effect will occur even if the insulating areas are not directly irradiated by the incident electron beam, due to the large amount of electron scattering that takes place within the specimen chamber of the microscope.

An alternate solution to the detector problem would be to redesign the standard Everhart-Thornley detector [58] so as to provide it with a rectangular input port of large aspect ratio instead of the present circular input port. By careful design together with experimental evaluation, a detector capable of detecting secondary electron signals from specimen areas several millimeters square and with good discrimination of secondary electrons over backscattered primary electrons should be possible. (A good Everhart-Thornley type detector will accept a signal of which 10 to 20 percent is due to backscattered electrons.)

Another interesting possible solution to the detector problem is the channel multiplier. These consist of glass tubes, some 2 cm. long, on the inside of which is deposited a high resistivity film. The resistance between the ends of the tube is typically 10^8 to 10^9 ohms. The end of the tube at which the electrons enter is maintained at ground potential while

the opposite end is maintained at a positive potential of, typically, 1500 to 3000 volts. The secondary electron coefficient of channel multipliers is greater than unity so that, for every electron which enters the tube and collides with its inner wall, more than one secondary electron is generated. These secondary electrons move down the tube under the influence of the electric field and collide again with the walls of the tube to generate more secondary electrons. Due to the multiple collisions which occur, the overall gain of a channel multiplier is in the order of 10^6 .

At each collision point, ions are also generated and these are accelerated back up the tube by the electric field. In colliding with the tube wall, these ions, too, generate secondary electrons which, if their number becomes large, can cause a space charge problem. To control this problem, the channel multiplier tube is normally wound in a spiral so that the ions are not accelerated through great distances before they undergo a collision.

To detect the output signal from a channel multiplier tube, the lower end of the tube is connected to the input of an amplifier which is floating at the tube accelerating potential in order to obviate the need for capacitor decoupling which would destroy the dc response of the system. So that the entire system will not be at this high accelerating potential, the amplifier output is fed into a photodiode and the light output of this photodiode is optically detected by a photomultiplier; the output of the photomultiplier is fed into a head amplifier in the usual way.

The channel multiplier is a small area detector, much smaller than the standard Everhart-Thornley detector. This makes this type of detector a less than obvious choice for large area scanning microscopy. The solution to this problem lies with the channel plate which, in essence, is a large area channel multiplier. For this detector, a glass plate in the order of 25 mm in diameter and 6 mm thick is used. A very large number of small holes, 5 to 10 μm in diameter, through this plate each serve as a miniature channel multiplier. The accelerating potential is applied between the two faces of the glass plate and the holes are lined with high resistivity material. By following the plate with a scintillator/photomultiplier assembly, a large area detector for electrons could be built.

In the design of any collection system for use on a microscope with postlens deflection, consideration must be given to the possibility of stray magnetic fields from the deflection coils affecting the trajectories of electrons travelling to the collector. This is particularly true for the trajectories of low energy secondary electrons. This phenomenon has been reported by Dinnis [55] although in his application he did not find the effect to be very serious.

The recording film

From the point of view of improving the micrographs themselves, a film with a finer grain structure would provide less film noise and higher film resolution. This would ensure that it is the system resolution and not the film which limits the micrograph quality. Kodak Tri-X film, which was used to produce the micrographs for this thesis, is not generally considered to be a high resolution film. Private conversations with photographers, both professional and amateur, however, suggest that sufficient resolution for the present task, without a sacrifice in film speed or a change in film gamma, may be obtainable with this film with a proper choice of fine grain developer and developing time. Experimentation would be required to verify this. Alternately, either Ilford HP4 or Agfa-Gevaert Agfapan 400 film would probably be suitable substitutes for Kodak Tri-X film, although experimentation would again be required to determine their acceptability.

The electron gun

In Chapter 2 of the thesis, it was mentioned in connection with Figure 2-4 that, by using a lanthanum hexaboride emitter in the electron gun in place of the conventional tungsten thermionic emitter, the recording time for a given device size could be reduced by a factor of ten. The brightness, the current density per unit solid angle contained in the beam, approaches 10^5 amps/cm²-ster for a tungsten thermionic emitter [43] and 10^6 amps/cm² - ster for a lanthanum hexaboride emitter [49].

In the present system, a limit in the frame recording time of 500 seconds, for example, corresponds to a minimum device size of 340 μ m square which may be magnified the maximum permissible amount, as can be seen from Figure 2-4.

The maximum magnification in this instance is 3000 times. With some specimens, these figures may represent a restriction in that they may not allow sufficient magnification. The base window in the transistor shown in Figure 8-5, for example, is only approximately 100 μm square; it cannot be magnified the maximum permissible amount unless a frame recording time of 5500 seconds is used. By using a lanthanum hexaboride emitter, on the other hand, magnification of a 100 μm square specimen area by the maximum permissible amount could be accomplished with a frame recording time of 550 seconds. In this instance, the maximum magnification would be 10,000 times.

Other applications of large area deflection

A drawback of large area microscopy stems from the cost of the display system, approximately \$40,000. Large volume manufacturers of semiconductor devices would possibly be able to offset this cost with the time saved in assessing their device quality. Large area microscopy is not, however, limited to the investigation of semiconductor devices. In the field of biology, for example, it is likely that hospitals and the research sections of university medical schools could benefit from the advantages of large area microscopy in examining larger tissue specimens. Such users, however, would probably not find it as easy to justify the initial capital expense. It is not immediately clear how this cost could be substantially reduced so as to make commercial exploitation feasible. In fact, commercial exploitation of the complete system may not be viable and the large area deflection coils may only be useful in other areas of application.

The ability to deflect an electron beam over a relatively large area without deflection aberrations increasing its size makes systems other than large area scanning electron microscopy possible. Of immediately obvious application are the areas of integrated circuit mask making and integrated circuit pattern generation directly on the surface of a silicon slice.

In mask making, since optical methods would still be used to expose the photoresist on the silicon slice surface, line widths of less than $2\text{ }\mu\text{m}$ cannot be resolved. Therefore, an electron beam resolution of $1/5$ to $1/10$ of this, or 2000 to 4000 Å, is the best that would be required. If this resolution could be maintained over an area of, say, 3 mm square, most of the integrated circuit mask making requirements would be satisfied. The mask plate would have to be mechanically stepped between circuits to permit electron beam exposure of the approximately 140 3 mm square circuits which would be contained in the mask for a 50 mm diameter silicon slice. At the present time, a resolution of $1\text{ }\mu\text{m}$ over a 3 mm square is being maintained. Improvement of this resolution by 2.5 to 5 times would satisfy the resolution requirements of integrated circuit mask making. There is, in fact, no positive indication that the present deflection coil would not satisfy this requirement immediately; an evaluation of its ability to maintain constant resolution over a 3 mm square area with an axial probe resolution of 2000 Å should therefore be the starting point of an investigation into integrated circuit mask making. Also of interest in such an investigation would be the amount of spread or reduction in resolution which would occur in the emulsion of the mask plate. Almost certainly, some loss of resolution would occur at this point.

Of equal importance in mask making with maintaining resolution over a given area is the registration requirement from mask to mask in the set of masks required to produce a complete circuit. To satisfy this requirement, registration marks would have to be recorded on each mask plate in conjunction with the plate mechanical-stepping system with which each circuit area in turn would be brought under the electron beam. (Laser interferometers are normally used for measuring this mechanical-stepping motion.) These registration marks would then be used later for aligning each mask accurately with the pattern on the silicon slice from the previous mask of the set.

From the requirement for maintaining an exposed spot size of 2000 to 4000 Å over a 3 mm square, the requirements for the scan generator for an integrated circuit mask making system can be determined. Calculations show that the scan generator would be required to scan 7500 to 15000 lines

per frame, a somewhat more stringent requirement than that for the present scan generator.

Integrated circuit pattern generation directly on the surface of a silicon slice is attractive to circuit manufacturers since only in this way can they provide circuit geometries with dimensions less than $2\text{ }\mu\text{m}$ for high frequency devices. In this application, the device sizes involved are much smaller than those for the mask making application so that large area scanning is not a factor. The resolution required is also increased in the same order, however, so that the number of lines the system would have to be able to scan over a device surface would be of the same order as in the mask making application.

If, for example, it was desired to expose $1000\text{ }\text{\AA}$ lines on the surface of a $200\text{ }\mu\text{m}$ square device, the system scan generator would be required to be able to scan 10,000 to 20,000 lines per frame, taking again that the electron beam resolution would have to be $1/5$ to $1/10$ of the finest geometry required, as in the mask making application. The actual electron beam probe size required would depend on the amount of spread to be expected in the electron sensitive resist. For polymethyl methacrylate, a factor of somewhere between 2 and 4 would appear, from the literature, to apply. (This resist is capable of resolving $1000\text{ }\text{\AA}$ lines and may possibly be able to do somewhat better; see, for example, Hatzakis' work [38, 39].)

In small devices such as these, only the submicron geometries would normally be produced by direct electron beam exposure, the remainder being provided by photolithographic techniques. Registration marks would therefore be required for correctly registering the electron beam exposure. Chang [52] has discussed the use of such registration marks.

In summary, electron beam pattern generation on the surface of a silicon slice offers the only means of obtaining submicron geometries in solid state devices. Its success would depend largely on the ability of the electron beam system to scan in the order of 10,000 to 20,000 lines per frame and to maintain high resolution over areas of approximately $200\text{ }\mu\text{m}$ square.

Another possible application of large area scanning in the field of solid state devices is that of integrated circuit testing. Mechanical probing of a completed integrated circuit to test its performance is difficult and can easily result in damage to the circuit. Such testing could be facilitated by using an electron beam probe to contact the circuit and inject current. Coupled with a voltage sensitive detector [53] and with the scanning electron microscope operating in the conduction mode of operation [54], the ability to scan the electron beam over the entire area of an integrated circuit while maintaining high resolution would provide a powerful means of assessing the performance of these circuits. In general, a system capable of making masks for integrated circuits would be capable, electron optically, of testing these circuits.

Departing from the field of solid state devices, another area in which the ability to scan a high resolution electron beam over a large area is required is electron beam data storage. The advantages of this method of storing information have been discussed fully by Newberry [9] and will not be repeated here. Briefly, however, the essential requirements are the maintenance of small probe size over a large area on the surface of the storage medium and repeatability; i.e., the electron beam must be able to be readdressed to the same point on the storage medium repeatably and accurately.

The problem of repeatability is largely one of hysteresis in any magnetic materials present. The problem is not necessarily eliminated by using air-cored deflection coils; any coupling of the deflection coil field to any magnetic material, such as the lens pole plate, may result in hysteresis effects being detected.

The present deflection coil and scan generator should be capable of providing a small scale electron beam memory without further improvement, ignoring for the moment the possibility of hysteresis effects. At present, a resolution of about $1 \mu\text{m}$ is being maintained over an area approaching 4 mm square. Allowing an area $2 \mu\text{m}$ square for each address point, a total of 2000 information bits could be stored in one scan line in a suitable medium or 4×10^6 bits in an area 4 mm square. With 100 such small areas

or cells, each positioned to turn by a mechanical stage, a storage system with reasonable capacity in a small overall area is possible. The cells could be positioned in a manner similar to that which would be used to position the individual circuit areas in an integrated circuit mask making system.

In a system such as the one just described, one obvious problem is speed. In addition to the actual time taken to read or write an individual information bit, the time taken to position the electron beam at an address point must be considered. While certain of the parameters affecting this deflection time are electronic, e.g. amplifier settling time, one parameter more related to the deflection coil itself is eddy currents. These can be established in any conducting material with which the deflecting field interacts and can seriously increase the total recording time per bit. In attempting to develop an electron beam information storage system based on the present large area scanning microscopy system, an investigation into eddy currents and hysteresis would be a logical starting point.

Somewhat akin to electron beam information storage is electron beam recording for which there is a number of interesting potential applications. One of these is concerned with the recording of data from satellites, such as the Earth Resources Technology Satellite. Although the bit rate from this satellite is high, 15 Mbps in the case of the multispectral point scanner system, the method of transmission is such that this rate is maintained for only a few (9.6) microseconds, followed by a relatively long (40.5 msec) period in which no transmission occurs. By using a small (144 bit) memory and by using a separate electron beam/film system for each spectral band (there are four in the multispectral point scanner system), a recording time of 264 nsec per bit would be available.

This may be very short in terms of deflection time and settling time but in terms of recording it is not too restrictive. Taking the required dose for maximum film exposure as 10^{12} electrons per cm^2 or 1.6×10^{-7} coulombs per cm^2 and allowing, say, 100 nsec for the actual film exposure time per bit, the required electron beam current density is 1.6 amps/ cm^2 .

Assuming a tungsten thermionic emitter with a brightness of 10^5 amps/cm²-ster, the required beam solid angle is 1.6×10^{-5} steradian at the film surface or a beam semiangle of convergence onto the film of about 2.2 mrad, an acceptable value. If a 70 mm film is used, for which the frame is 55 mm wide, the line width on the film must be 16.6 μ m wide (there are 3314 lines in the multispectral point scanner image for each of the four spectral bands). Assuming the spot to be round, its area in this instance must be 216 μ m² which implies an electron beam current of 3.5 μ amps, a high but not unrealistic value.

This is in the same order as the beam size and current which were used in the deflection coil test equipment for the present work. Accordingly, a single lens electron optical column would suffice for such a recording system. Whether it could be realized, however, would evidently depend on the electronics for the scan system. In addition, a deflection coil capable of scanning a 16.6 μ m diameter beam over a field 55 mm square would be required. This may not be too straightforward since the deflection angle required, depending on the working distance, may have to be large. On the other hand, Kaashoek [5] has developed deflection coils for 90° shadow mask tubes in which the deflection angles are large.

Another potential application of electron beam recording is concerned with sideways-looking radar. Sideways-looking radar is a scanning type of radar which is mounted on the side of an aircraft and provides information on the terrain flown over. At the present time, the returning signal is displayed on a cathode ray tube in such a way that the left hand side of the display represents terrain close to the aircraft while the right hand side represents terrain far from the aircraft. The cathode ray tube display is photographed on a continuous length of film which is oriented at right angles to the near/far axis of the tube; the long dimension of the film strip thus corresponds to the direction the aircraft is travelling.

To interpret the film, which contains a series of pulses with positive, negative, and zero doppler shifts, it is illuminated with a laser in a manner somewhat analogous to the viewing of a hologram. The resulting image, at the present time, however, is of limited value, due to the poor

resolution of the cathode ray tube. It is envisaged that considerable improvement could be provided by using electron beam recording of the film in place of the cathode ray tube. If, for example, an electron beam recorder capable of recording $5.5 \mu\text{m}$ lines across the 55 mm wide frame of 70 mm film could be developed, an improvement in resolution of almost 50 times could be realized (the presently-used cathode ray tube has a spot size of 0.010 inch). This would be equivalent to redeveloping the satellite electron beam recorder to cover the same frame size but with three times the resolution; the scan system would be required to provide a 10,000 line frame.

For such an application, continuous, automatic film processing would be required, preferably with a "dry" process. Special considerations for the airborne aspect of the system would also have to be taken.

Before discussing a further potential application of electron beam recording, a possible application of very large area deflection coils, such as would be required for the recording of both satellite and sideways-looking radar information, should be discussed. This application arises from the current need for an inexpensive scanning electron microscope of medium resolution, say $1000 \text{ \AA}$, to compete with the best optical microscopes currently available.

If a scanning electron microscope with a 10 cm square display screen and a maximum magnification of $\times 2000$ is considered, the minimum scan area on the specimen would be $50 \mu\text{m}$ square. If it were desired to examine a 10 mm square specimen under these conditions, either the specimen would have to be moved or the $50 \mu\text{m}$ square scan area would have to be shifted over the surface of the specimen. Considering the latter alternative, the $50 \mu\text{m}$ square scan area would have to be shifted to $(200)^2$ separate locations to fully cover the 10 mm square specimen. If the CRT display had 500 scan lines, then each $50 \mu\text{m}$ scan area on the specimen would also have 500 scan lines and, in scanning a complete 10 mm square specimen, a total of 100,000 scan lines would be used. Therefore, by superimposing dc shift currents on the ac scan currents in the deflection coil, any portion of a 10 mm square specimen could be examined in unit areas as small as $50 \mu\text{m}$ square.

The scan generator requirements in this case are straightforward, 500 lines per frame. The dc shift current, however, would have to be stable to within, say $\pm \frac{1}{2}$ line or ± 5 ppm. Such power supplies are available [56] but are expensive. The deflection coil would have to be able to maintain a resolution of 1000 Å over a 10 mm field, using the above figures.

A microscope with the above capability, besides providing an inexpensive, general purpose instrument of medium resolution, offers some interesting possibilities. Equipped with a cold stage, it could be used to examine biopsy specimens in hospitals without requiring extensive specimen preparation, thus saving valuable surgical time. Equipped with a hot stage, it could be used for metallurgical studies of, say, phase transitions or precipitation formation, where the improved depth of field of the scanning microscope would provide a distinct advantage. Metallurgical studies of fractures could be studied by equipping such a microscope with a tensile stage. Finally, such a microscope could possibly be used *in situ* in an electron beam welder to examine electron beam welds on small parts.

With a microscope such as the one just discussed, a further possible application of electron beam recording becomes potentially feasible. In some instances, specimens such as biological specimens will not withstand extended exposure to the electron beam. At the same time, a lengthy examination may be required. It should be possible in such cases to use a second electron beam column in which to record the signal from the first or examining column. In this way, a delicate specimen of up to 10 mm square would need to be examined directly only for as long as it would take to record details of its surface structure in the second, electron beam recording column. Such a recording would have the advantage that it would not be limited to a total of 5000 lines, as it would be if the high resolution display were being used, and it would have the same resolution as the examining electron beam. In view of the resolution capabilities of recording media, it would be necessary for this recording to be considerably larger than the original specimen, about 50 mm if a total of 100,000 lines were scanned and Kodak High Resolution Plates were used, for which the

resolution exceeds 2000 lines per mm [57]. Experimentation with these plates would be required to determine electron beam sensitivity, recording time, etc.

Such a recording would form an information replica of the specimen surface. It could be subjected to lengthy examination at any time subsequent to the original examination in either a scanning electron microscope or in an optical microscope. Examination with a flying spot scanner and display of the resulting signal on a television monitor might also be possible if sufficient resolution in the flying spot scanner could be achieved.

Charge storage tubes are another means of providing information replicas of specimen surfaces. Their resolution, however, is limited to less than 5000 lines. In most instances, in fact, these tubes have resolutions of only 800 to 1200 lines.

In a number of instances in this discussion of potential future applications, deflection coils with superior characteristics to the one used for the present work have been identified. A continuation of the deflection coil development program used for this thesis would therefore be required. From the results of Chapter 7, it is clear that the elimination of winding nonuniformities must take precedence in any such program. To accomplish this, it is proposed to experiment with thin, insulated copper ribbon in place of wire, since this material can be positioned and held much more accurately. On the assumption that this type of structure will eliminate asymmetrical behaviour, a more accurate determination of the optimum value of the coil circumference angle for a given coil radius and coil length would be the next priority. Following this, a determination of the effect of varying either or both the coil circumference angle and the coil radius as a function of position along the length of the coil could be carried out. Finally, a determination of what improvements are realizable by using semi-distributed windings in place of lumped windings could be made. In all these instances, optimum values, if any exist, would be determined. The use of magnetic materials,

such as ferrite, would also be investigated as a means of increasing the magnitude of the deflecting field for a given value of deflection current. Such a step will most probably be required in those applications calling for deflection over a 50 mm square field. To shape the deflecting field in such a case, the ferrite core pole pieces would have to be ground to the proper shape, a not particularly attractive solution.

To develop such coils would require improvements in the computer matching program. The limitation in this program mentioned in the body of the thesis, whereby different aberration coefficients for the different sections of a deflection coil could not be considered, would have to be overcome. In addition, matching of an experimental spot profile map would be greatly facilitated by arranging the computer program to generate spot profiles which correspond to a fixed exposure level in the experimental map rather than, as at present, corresponding to a fixed percentage of the peak height of each spot. In this way, the scaling employed in the present work would not be required.

In conclusion, it should be mentioned that, for some applications, particularly electron beam information storage, electromagnetic deflection is not fast enough. Serious consideration should therefore be given to studying electrostatic deflection with a view to developing a fast, aberration-free electrostatic deflection system capable of deflecting an electron beam over a large area. Field shaping with such a system would offer advantages over the electromagnetic system in that the deflection plates could be machined accurately to the required shape and there would be essentially no question of nonuniformities.

APPENDIX 1

BASIC PHOTOMETRY

The following is adapted from Longhurst [45].

In those cases where the response of the human visual system can be excluded from the considerations, flux can be simply defined as the total flow of energy from the source per second, within the limits of 400 to 700 nm in wavelength. It is expressed in radiometric units as ergs per second or joules per second (watts).

The intensity of a source in a given direction is defined as the flux emitted into a unit solid angle in that direction from a small spot or element of the source. The source does not necessarily have to radiate equally in all directions. If the portion of the total flux, F which is radiated into the unit solid angle $d\omega$ centred at the angle θ from some reference is dF , then the intensity in the direction θ is

$$I_{\theta} = \frac{dF}{d\omega} \quad (A1-1)$$

It is expressed in radiometric units as watts per steradian.

Illumination is defined as flux incident on a surface per unit area of that surface and is expressed in radiometric units as watts per meter squared. If an element of area dS receives flux dF , the illumination is

$$E = \frac{dF}{dS} \quad (A1-2)$$

In Figure A1-1, the elementary area dS receives light from point source P . The distance from P to dS is r and the normal to dS is inclined at the angle θ to the direction P - dS . The solid angle subtended at P by dS is

$$d\omega = \frac{dS \cos \theta}{r^2} \quad (A1-3)$$

If the intensity of P in the direction of dS is I , then the flux radiated into the solid angle $d\omega$ is

FIGURE A1-1
ILLUMINATION OF A SURFACE ELEMENT

$$\begin{aligned}
 dF &= Idw \\
 &= \frac{IdS \cos \theta}{r^2}
 \end{aligned}
 \tag{A1-4}$$

The illumination at dS is then

$$\begin{aligned}
 E &= \frac{dF}{dS} \\
 &= \frac{I \cos \theta}{r^2}
 \end{aligned}
 \tag{A1-5}$$

This embodies the two fundamental laws of photometry: the inverse square law and the cosine law of illumination.

In general, a surface will reflect some of the light incident upon it and this reflected light will be distributed over a wide range of directions. A reflecting surface of this type therefore resembles a self-luminous surface; each element of such a surface will have a certain intensity in each direction.

At any point on a surface, the intensity per unit projected area in a given direction is the luminance at that point in the direction concerned. In radiometric units, the luminance is expressed as watts per steradian per meter squared. If an elementary area dS of a surface has an intensity I_θ in a direction inclined at an angle θ to the surface normal, the projected area in the direction θ is $dS \cos \theta$ and the luminance is

$$L = \frac{I_\theta}{dS \cos \theta} \tag{A1-6}$$

The behaviour of surfaces obeying Lambert's cosine law of emission can now be clarified. For these surfaces, the intensity in some direction θ from the normal is $I_n \cos \theta$, where I_n is the intensity normal to the surface. The luminance of such a surface is

$$L = \frac{I_n \cos \theta}{dS \cos \theta}$$

$$= \frac{I_n}{dS}$$

(A1-7)

which is a constant independent of direction.

The total flux radiated by a uniformly diffusing, Lambertian surface element dS of luminance L can now be calculated. Referring to Figure A1-2, the intensity of the element dS in the direction θ is $LdS \cos \theta$. The flux radiated from dS between the cones of semi-angles θ and $\theta + d\theta$ is the product of the intensity and the solid angle involved. This is the solid angle subtended at dS by the annular strip of area $2\pi r \sin \theta \cdot r d\theta$ on the hemisphere of radius r inscribed above dS . The solid angle is thus $2\pi \sin \theta d\theta$ and the flux, dF radiated into it is given by

$$dF = 2\pi L dS \sin \theta \cos \theta d\theta \quad (A1-8)$$

The flux radiated into the cone of semi-angle θ is

$$F = \int_0^\theta 2\pi L dS \sin \theta \cos \theta d\theta$$

$$= \pi L dS \sin^2 \theta \quad (A1-9)$$

It is now possible to evaluate the illumination of the image formed by an optical system. Referring to Figure A1-3, EP and EP' are the entrance and exit pupils, respectively, of an optical system which forms an image dS' of a uniformly diffusing surface element dS of luminance L perpendicular to the optical axis. The flux entering the system in the annular zone θ to $\theta + d\theta$ is

$$dF = 2\pi L dS \sin \theta \cos \theta d\theta \quad (A1-10)$$

The flux emerging from the system in the annular zone θ' to $\theta' + d\theta'$ is

$$dF' = k dF, \quad (A1-11)$$

where k is the transmission factor of the instrument.

FIGURE A1-2
TOTAL RADIATION FROM A SURFACE ELEMENT

FIGURE A1-3
LUMINANCE OF AN IMAGE

For good imagery of linear object elements perpendicular to the axis, the sine relation must be satisfied for all zones of the aperture. The sine relation is

$$nh \sin \theta = n' h' \sin \theta', \quad (A1-12)$$

where n and n' are the refractive indices of object and image space, respectively, and h and h' are the object and image heights, respectively. Accordingly,

$$n^2 dS \sin^2 \theta = n'^2 dS' \sin^2 \theta' \quad (A1-13)$$

for conjugate elements dS and dS' . Differentiation of equation (A1-13) gives

$$2n^2 dS \sin \theta \cos \theta d\theta = 2n'^2 dS' \sin \theta' \cos \theta' d\theta' \quad (A1-14)$$

By applying equations (A1-10), (A1-11), and (A1-14), the flux emerging from the optical system between the limits θ' and $\theta' + d\theta'$ can now be written as

$$dF' = k dF = 2\pi k L \left(\frac{n'}{n}\right)^2 dS' \sin \theta' \cos \theta' d\theta' \quad (A1-15)$$

and the total flux leaving the instrument is then given by

$$\begin{aligned} F' &= \int_0^{\theta'_{\max}} dF' \\ &= k\pi L \left(\frac{n'}{n}\right)^2 dS' \sin^2 \theta'_{\max} \end{aligned} \quad (A1-16)$$

in which $\theta'_{\max}$ is defined by the exit pupil of the optical system. The illumination of the image then is

$$\begin{aligned} E' &= \frac{F'}{dS'} \\ &= k\pi L \left(\frac{n'}{n}\right)^2 \sin^2 \theta'_{\max}; \end{aligned} \quad (A1-17)$$

the importance of photographic lenses with large angular apertures is evident.

In the case where the face of a cathode ray tube is to be photographed, it is necessary to express the image illumination in terms of the total flux radiated outwards from the surface of the tube face in accordance with Lambert's cosine law of emission. (It is customary to consider CRT faces as Lambertian radiators.) From equation (A1-9), the total flux radiated outwards from an element of surface dS of a perfect diffuser is found by setting $\theta = 90^\circ$ and is

$$F = \pi L dS \quad (A1-18)$$

where L is the luminance of the surface element.

Rearranging equation (A1-18) gives

$$L = \frac{F}{\pi dS} \quad (A1-19)$$

which can be substituted into equation (A1-17) for image illumination to yield

$$E' = \frac{kF}{dS} \left(\frac{n'}{n}\right)^2 \sin^2 \theta'_{\max} \quad (A1-20)$$

and, since $n = n'$ for most systems of this type, to yield finally

$$E' = \frac{kF}{dS} \sin^2 \theta'_{\max} \quad (A1-21)$$

This equation gives the portion of the CRT flux, F which is effective in illuminating the film in a CRT camera, the exit pupil of which subtends a half-angle $\theta'_{\max}$ at the film plane; dS is the area of a single picture element on the CRT face.

APPENDIX 2

Proof that $\frac{m_0 v}{\sqrt{1 - v^2/c^2}} = \sqrt{2em_0 \phi(1 + \epsilon\phi)}$

This proof is based on Glaser [46].

The Lorentz force equation is

$$\begin{aligned}\bar{F} &= -e\bar{E} + e\bar{B} \times \bar{v} \\ &= m_0 \bar{a} \\ &= \frac{d}{dt} \frac{m_0 \bar{v}}{(1 - v^2/c^2)^{1/2}}\end{aligned}\quad (A2-1)$$

Establish a coordinate system at some point $\bar{x}$ on the trajectory of the electron such that $\bar{t}$ is the tangential vector tangent to the path of the electron, $\bar{n}$ is the main normal vector, and $\bar{b}$ is the binormal vector.

Then

$$\bar{v} = v\bar{t}$$

and

$$\frac{d\bar{v}}{dt} = \frac{d}{dt}(v\bar{t}) = \bar{t} \frac{dv}{dt} + v \frac{d\bar{t}}{dt}$$

Now $d\bar{t}/dt$ can be rewritten as

$$\begin{aligned}\frac{d\bar{t}}{dt} &= \frac{d\bar{t}}{dS} \frac{dS}{dt} \\ &= \frac{d\bar{t}}{dS} v\end{aligned}$$

and $d\bar{t}/dS$ is, from the first Frenet formula of differential geometry (see, for example Kreyszig [47]),

$$\frac{d\bar{t}}{dS} = k\bar{n} = \frac{1}{\rho} \bar{n}$$

in which S is a length along the electron path and in which k is the curvature of the trajectory and ρ is its radius of curvature.

From this

$$\frac{d\bar{v}}{dt} = \bar{t} \frac{dv}{dt} + \frac{v^2 \bar{n}}{\rho} \quad (A2-2)$$

Equation (A2-1) can then be rewritten as

$$-e\bar{E} + e\bar{B} \times \bar{v} = \frac{m_0}{(1-v^2/c^2)^{1/2}} \frac{v^2 \bar{n}}{\rho} + \frac{d}{dt} \frac{m_0 v}{(1-v^2/c^2)^{1/2}} \bar{t} \quad (A2-3)$$

The second term on the right hand side is of the form

$$\frac{d}{dt} \left(\frac{u}{v} \right)$$

so that

$$\frac{d}{dt} \frac{m_0 v}{(1-v^2/c^2)^{1/2}} = \frac{m_0}{(1-v^2/c^2)^{3/2}} \frac{dv}{dt}$$

Equation (A2-3) then becomes

$$-e\bar{E} + e\bar{B} \times \bar{v} = \frac{m_0}{(1-v^2/c^2)^{1/2}} \frac{v^2 \bar{n}}{\rho} + \frac{m_0}{(1-v^2/c^2)^{3/2}} \frac{dv}{dt} \bar{t} \quad (A2-4)$$

Scalar multiplication by $\bar{v}$ gives

$$-e\bar{E} \cdot \bar{v} = \frac{m_0 v}{(1-v^2/c^2)^{3/2}} \frac{dv}{dt} = \frac{d}{dt} \frac{m_0 c^2}{(1-v^2/c^2)^{1/2}} \quad (A2-5)$$

In the case of static fields, integration yields

$$e\phi = \frac{m_0 c^2}{(1 - v^2/c^2)^{1/2}} - m_0 c^2 \quad (\text{A2-6})$$

where the constant of integration, $m_0 c^2$ has been so chosen that $v = 0$ when $\phi = 0$.

Equation (A2-6) can be solved for v ;

$$v = \frac{\sqrt{\frac{2e\phi}{m_0}} \sqrt{1 + \frac{e\phi}{2m_0 c^2}}}{\left(1 + \frac{e\phi}{m_0 c^2}\right)} \quad (\text{A2-7})$$

Substituting

$$\epsilon = \frac{e}{2m_0 c^2} \quad (\text{A2-8})$$

into equation (A2-7) gives

$$v = \frac{\sqrt{\frac{2e\phi}{m_0}} \sqrt{1 + \epsilon\phi}}{(1 + 2\epsilon\phi)} \quad (\text{A2-9})$$

Scalar multiplication of equation (A2-4) by $\bar{n}$ gives

$$\frac{m_0}{(1 - v^2/c^2)^{1/2}} \frac{v^2}{\rho} = -eE_n + B_b v, \quad (\text{A2-10})$$

in which E_n is the component of $\bar{E}$ in the main normal direction, $\bar{n}$ and B_b is the component of $\bar{B}$ in the binormal direction, $\bar{b}$.

Substitute for $(1 - v^2/c^2)^{1/2}$ from equation (A2-6) and for v^2 from equation (A2-9) and solve for ρ , the radius of curvature of the electron trajectory:

$$\frac{1}{\rho} = \frac{1}{2\phi} \frac{1 + 2\epsilon\phi}{1 + \epsilon\phi} \frac{\partial\phi}{\partial n} + \sqrt{\frac{e}{2m_0}} \frac{B_b}{(\phi(1 + \epsilon\phi))^{1/2}} \quad (A2-11)$$

in which $\partial\phi/\partial n$ has been substituted for E_n .

In a purely magnetic field, $\partial\phi/\partial n = 0$ so that

$$\begin{aligned} B_b \rho &= \sqrt{\frac{2m_0}{e} \phi(1 + \epsilon\phi)} \\ &= \frac{1}{e} \sqrt{2em_0 \phi(1 + \epsilon\phi)} \end{aligned} \quad (A2-12)$$

But the radius of curvature of an electron path in a magnetic field is given by

$$B_b \rho = \frac{m_0 v}{e(1 + v^2/c^2)^{1/2}} \quad (A2-13)$$

which is the electron momentum divided by the electronic charge.

Equating equations (A2-12) and (A2-13) yields the desired relationship:

$$\text{momentum} = \frac{m_0 v}{(1 + v^2/c^2)^{1/2}} = \sqrt{2em_0 \phi(1 + \epsilon\phi)} \quad (A2-14)$$

Q.E.D.

APPENDIX 3

The coefficients introduced in equations (5-45) are defined as:

$$A1 = \frac{1}{2} \int_{z_0}^{z_s} \frac{X'^3}{X_s^3} dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H2} X^2}{X_s^3} dz \quad (A3-1)$$

$$A2 = \frac{1}{4} \int_{z_0}^{z_s} \frac{X' Y'^2}{X_s Y_s^2} dz - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H2} Y^2}{X_s Y_s^2} dz - \frac{1}{2} k \int_{z_0}^{z_s} \frac{F_{H0}' Y^2}{X_s Y_s^2} dz \quad (A3-2)$$

$$A3 = k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H0}' X' Y}{X_s^2 Y_s} dz - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H2} X Y}{X_s^2 Y_s} dz + \frac{1}{4} \int_{z_0}^{z_s} \frac{X'^2 Y'}{X_s^2 Y_s} dz \quad (A3-3)$$

$$A4 = \frac{3}{2} \int_{z_0}^{z_s} \frac{X'^2}{X_s^2} dz + 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H2} (z-z_s) X}{X_s^2} dz \quad (A3-4)$$

$$A5 = \frac{1}{2} \int_{z_0}^{z_s} \frac{X'^2}{X_s^2} dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H0}' (z-z_s) X'}{X_s^2} dz - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H2} (z-z_s) X}{X_s^2} dz \quad (A3-5)$$

$$A6 = \frac{1}{2} \int_{z_0}^{z_s} \frac{X' Y'}{X_s Y_s} dz + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H0}' Y}{X_s Y_s} dz - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H2} (z-z_s) Y}{X_s Y_s} dz \quad (A3-6)$$

$$A7 = \frac{3}{2} + k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H2} (z-z_s)^2}{X_s} dz \quad (A3-7)$$

$$A8 = \frac{1}{2} - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H2} (z-z_s)^2}{X_s} dz = 1 - A7 \quad (A3-8)$$

$$A_9 = 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H_2}^X}{X_s^2} dz \quad (A3-9)$$

$$A_{10} = k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H_0}^X}{X_s^2} dz - 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H_2}^X}{X_s^2} dz \quad (A3-10)$$

$$A_{11} = -2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H_2}^Y}{X_s Y_s} dz \quad (A3-11)$$

$$A_{12} = -2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H_2}^Y}{X_s Y_s} dz - k \int_{z_0}^{z_s} \frac{F_{H_0}^Y}{X_s Y_s} dz \quad (A3-12)$$

$$A_{13} = k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H_2}}{X_s} dz \quad (A3-13)$$

$$A_{14} = -k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H_2}}{X_s} dz - \frac{1}{2} k \int_{z_0}^{z_s} \frac{F_{H_0}}{X_s} dz \quad (A3-14)$$

$$A_{15} = -2A_{13} \quad (A3-15)$$

$$A_{16} = 2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H_2}(z-z_s)}{X_s} dz \quad (A3-16)$$

$$A_{17} = -A_{16} \quad (A3-17)$$

$$A_{18} = -2k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H_2}(z-z_s)}{X_s} dz - k \int_{z_0}^{z_s} d\zeta \int_{z_0}^{\zeta} \frac{F_{H_0}^X(z-z_s)}{X_s} dz \quad (A3-18)$$

The corresponding B_m coefficients are obtained from the A_m coefficients by replacing F_{H_0} by $-L_{H_0}$, F_{H_2} by $-L_{H_2}$, and by interchanging X and Y .

APPENDIX 4

COMPUTER PROGRAM FOR SIMULATION OF ELECTRON BEAM SPOT PROFILES

The computer program used in this thesis to simulate the spot profiles of electromagnetically deflected electron beams was developed by the Computer Aided Design Facility at the Communications Research Centre, Department of Communications, Ottawa by W.A. Hartman. This Appendix is a condensation of a paper by Mr. Hartman and two of his colleagues which was presented at the Third Man-Computer Communications Seminar held in Ottawa on May 30 and 31, 1973 [48].

INTRODUCTION

ICPL (Interactive Control Program Language) is a language for writing programs for the interactive computer driven display. It provides a simple tool to express the interaction between an application program and a human operator, by means of a light-pen or other pointing device, and can be extended to other interaction devices such as function keys or an alphanumeric keyboard.

There is no intrinsic difficulty in programming a computer to display a series of messages and pictures on a CRT or in transferring control to specific routines when requested to do so by an operator interaction. However, a practical difficulty in programming an interactive display is that each hardware configuration tends to have its own idiosyncrasies and conventions, and a surprising amount of detailed coding can be required for even a simple task. This tends to discourage the use of interactive graphics and decreases the clarity and maintainability of the programs.

The development of ICPL was an attempt to identify the key concepts that are shared by the members of a broad class of interactive graphics programs and to embody these in a language and programming system that would be simple to use and would yield programs that are clear and easy to maintain. To a large extent the programs are hardware-independent so that the programmer need not become conversant with the fine details of the particular hardware employed.

Figure A4-1 is a block diagram of a typical interactive system. The data base contains the raw material of the interaction and may be edited and displayed in a variety of forms. The block identified as "Control Program" is concerned with the generation of light-button "menus", the identification of light-pen "strikes" and other means of interaction, and with the activation of program segments in accordance with a prearranged scheme. These program segments control the execution of specialized functions such as data extraction, numerical computation and data display. Most of the idiosyncrasies of the display and identification hardware are found in the control program. This program can be very tedious to write and to modify if the logic of the interaction is written in an improper programming language. ICPL has been developed especially for writing control programs with features that are tailored to this task. It is not intended to be a general-purpose language and the remainder of a complete interactive system will be written in other languages (e.g., Fortran and assembly language).

AN ICPL PROGRAM

Consider the following program written in ICPL:

* ANY STATEMENT WITH '*' IN COLUMN 1 IS A COMMENT.

CONTROL PROGRAM MOVE

* THE FOLLOWING THREE STATEMENTS ARE DECLARATIONS

INTEGER V1

SYMBOLS TEXT1

EXTERNAL PROGRAM PICT,MOVUP,MOVDN

* THIS BLOCK IS EXECUTED WHEN THE PROGRAM IS ENTERED

ENTRY

LET V1 = 1

SET OA,12,S1

1 DISPLAY

SEEK

* EACH 'OBJECT' STATEMENT HEADS A BLOCK OF CODE THAT GENERATES

* ONE OBJECT IN THE DISPLAY FILE. THE FIRST OBJECT IS ONLY

* GENERATED FOR A PARTICULAR VALUE OF THE STATE VARIABLE V1,

* AND IS GENERATED BY CALLING THE EXTERNAL ROUTINE 'PICT'.

* NOTE THAT NOTHING HAPPENS WHEN THE LIGHT-PEN SEES IT.

FIGURE A4-1: STRUCTURE OF AN INTERACTIVE SYSTEM

OBJECT IF V1 EQ 2

DO PICT

* THE NEXT OBJECT IS A LIGHT-BUTTON

OBJECT

TEXT 1500,1500/'ON'

* THIS TIME WE GET SOME ACTION (BUT ONLY IF V1 = 1)

ACTION IF V1 EQ 1

LET V1 = 2

GOTO 1

OBJECT

TEXT 1500,1400/'OFF'

ACTION IF V1 EQ 2

LET V1 = 1

GOTO 1

OBJECT

TEXT 1500,1300/'UP'

ACTION IF V1 EQ 2

DO MOVUP

GOTO 1

* 'MOVUP' AND 'MOVDN' ARE EXTERNAL ROUTINES THAT

* PERFORM THE CHORE OF MOVING THE PICTURE

OBJECT

TEXT 1500,1200/'DOWN'

ACTION IF V1 EQ 2

DO MOVON

GOTO 1

END

It can be seen that the language exemplifies the logical structure of the program model, as seen by the user, and provides him with a facility to express his particular requirements without unnecessary detail.

A picture of some sort is generated by the external routine PICT and can be switched on and off by pointing the light-pen at the light-buttons ON and OFF, and moved upwards or downwards on the screen by the light-buttons, UP and DOWN. This process could be represented by a finite-state

machine having two states, $V1 = 1$ and $V1 = 2$, where $V1$ is an integer variable. When $V1$ is 1 the picture is switched off but when $V1$ is 2, it is displayed and the UP and DOWN light-buttons can be activated.

On entry to the program, the code in the ENTRY block is executed. This execution initializes the variable $V1$, sets three parameters of the display system (origin mode, beam intensity, symbol set), displays the light-buttons, and looks for a light-pen strike.

The five OBJECT statements, each with its associated block of code, define the contents of the display file each time a DISPLAY statement is executed. The first OBJECT statement is qualified by the condition that $V1$ should be 2 in order for the routine PICT to be executed. The other OBJECT statements are unqualified so that the four light-buttons are always displayed. The statements in OBJECT blocks, like those in the blocks headed by ACTION or ENTRY statements, are indented to column 4 and may be labelled.

An OBJECT statement may be followed by as many ACTION blocks as desired, each specifying a possible course of action when the display object associated with that OBJECT statement causes a light-pen strike. ACTION statements may be conditional or unconditional and are tested in the order in which they appear in the program. In the example program the actions consist of changing the state variable $V1$ and calling the external routines MOVUP and MOVDN to move the picture. The actions terminate with a branch to the statement labelled 1 in the ENTRY block which rewrites the display file. The following statement, SEEK, causes the system to await a new light-pen strike. If none of the action block conditions are satisfied when a light-pen strike occurs, an automatic SEEK is executed.

(The macroprocessor, STAGE2 used to translate ICPL programs to assembly code necessitates a rigid format so that extra spaces should not be inserted in the statements. Statements that start with a '*' in column 1 are treated as comments and ignored during translation.)

APPLICATION

The description of the application package which was written for the PDP-9 based interactive computer graphics system at the Communications Research Centre to simulate the spot profiles of electromagnetically

deflected electron beams is given below. This description is not intended to give complete information about the detailed organization and operation of this package but is rather an overview of its design and use.

MAGNET - Interactive Design of Magnetic Deflection Electron Optical Systems

In the scanning electron microscope the electron optical system forms an image of the electron source on the image plane; a raster is then formed by scanning this image spot, using a magnetic deflection system, across the image plane in the x and y directions. The designer of such a deflection system must know how the size and shape of the spot will vary as the spot is scanned off the optical axis of the system and as the magnitudes of various system variables are changed. Theoretically, it should be possible to determine, from the physical properties of the deflection system, the magnetic field distribution. This distribution could then be related to the type of optical aberrations that would be produced by such a system. An aberration-free system, one for which the image spot size and shape does not vary as it is scanned, could then be designed. This is, however, not a practical method of design, because of the labor involved and the inaccuracies of the calculations. Nor is it efficient or practical to design by the "cut-and-try" method of making a large number of coils of different sizes, shapes, etc. until the deflection system is sufficiently aberration-free. Therefore, because there was a need for a design aid in this type of work, the interactive graphics program package known as MAGNET was developed using ICPL.

The Fortran analysis routines for this application are based upon the fact that for a system with aberrations the deviation from the ideal aberration-free case can be expressed as a power series in certain system variables; the various terms and their combinations represent the standard aberrations, such as coma and astigmatism, that are present in optical systems. The coefficients of this series are known as the aberration coefficients. Using these routines, it is possible to determine the spot outline at any point in the image area to be scanned, for a chosen set of coefficients. ICPL programs control the entry of data - the magnitudes and phases of up to sixteen aberration coefficients and the deflection co-ordinates of the point being considered - and display the spot outline

for that point in the image plane. The operator can examine one point at a time or the spot outline at as many as 25 points in the scan area can be shown simultaneously. Plots of the displayed spot outlines can be made.

To use MAGNET in designing, a deflection system is constructed with a certain coil configuration. A photographic record is made of the actual spot size and shape at several different points in the image area and then as close a match as possible to this pattern of spots is made by using MAGNET and varying the aberration coefficients. When the patterns match, the coefficients and hence the types of aberrations that are having the most effect are known. Using this knowledge, a different system configuration can be tried and the process repeated until most aberrations are eliminated.

This method is still somewhat "trial-and-error", but there are other factors that make it workable. First, for the type of electron optical systems being considered, there are relationships between the coefficients so that only some of them need be varied independently of the others. Secondly, this interactive method is such that many combinations can be tried in a few minutes; in that time it can be seen which coefficients are having the most effect in working toward the experimental pattern. By concentrating on these coefficients, the match can then be made very quickly.

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