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CHARACTERIZATION OF ENHANCED CONDUCTIVITY
DIELECTRICS FOR USE IN SEMICONDUCTOR DEVICES

by

DAVID R. DOUCET, B. Eng.

A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Engineering.

Faculty of Engineering
Department of Electronics
Carleton University

April 1986

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DIELECTRICS FOR USE IN SEMICONDUCTOR
DEVICES"

Submitted by David R. Doucet in partial fulfillment of the
requirements for the degree of Master of Engineering

Prof. N.G. Tarr

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April 1986

ABSTRACT

Various enhanced conductivity dielectrics have been characterized. Such dielectrics are potentially very useful for applications involving electrically alterable read only memory (EAROM) devices. The characterization of these dielectrics involved standard techniques such as ellipsometry, I-V measurements, and C-V measurements, as well as other techniques including SIMS, TEM, constant voltage stressing, and current transient measurements. Two different types of dielectrics are examined: chemical vapor deposited (CVD) SiO_2 , and ion implanted, thermally grown SiO_2 . Ellipsometry and I-V results are presented for the CVD oxides, whereas a complete set of results for all the above techniques is presented for the ion implanted oxides. In addition, preliminary results are presented for a new technique called photo-induced current transient spectroscopy (PICTS).

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Chapter 1:

Introduction

There are two types of dielectrics in use today in silicon MOS devices: dielectrics with good insulating properties (notably silicon dioxide), which are used for most applications (ROMs, RAMs, capacitors, etc...), and dielectrics with enhanced conduction properties, which are used in programmable memory devices (EPROMs, EAROMs). In this thesis, the properties of silicon oxides with enhanced conduction will be investigated. In order to simplify references to these types of dielectrics, they will be referred to as "leaky" oxides. A major commercial application for leaky oxides lies in E²PROM devices. The work presented here is thus oriented towards E²PROM applications for the oxides examined. Another important achievement of this thesis has been the development of a new technique for characterizing traps in oxides called photo-induced current transient spectroscopy or PICTS.

Two distinct types of leaky oxides have been examined in this thesis: chemical vapor deposited (CVD) silicon dioxide exposed to various heat treatment cycles, and thermally grown SiO₂ which has been implanted with either phosphorous or silicon ions. The CVD oxides' dielectric properties are not as good as those of a thermally grown oxide. A heat treatment step is used to improve the CVD oxide dielectric properties. In this manner, some control over the leakage through the oxide is obtained. The properties of the CVD oxides have been examined using standard optical and electrical measurement techniques. For the implanted oxides, the implant species, dose, and energy are used to controllably degrade the dielectric properties of the oxide. For the purposes of this thesis, only the effect of the species is examined. The silicon dioxide films implanted with silicon or phosphorous have also been examined using standard measurement techniques [19,20,23]. Similar oxides have been studied for possible application in

E²PROM devices because of their enhanced conductivity at moderate to high electric fields [11-15,17]. The use of implantation allows oxides to be grown to standard gate oxide thickness and still conduct enough current to allow programming of an E²PROM device (thus avoiding a reliance on tunneling current which is critically dependent upon oxide thickness). Previous work has been limited to nonstoichiometric deposited oxides [24,18,12]. Although some work has been published on implanted SiO₂ [16] the implant was intended to dope the underlying Si substrate and was not optimized to be constrained within the SiO₂ layer. The work in this thesis concentrates primarily on stoichiometric oxides. Some of these oxides are implanted with phosphorous or silicon. These implanted oxides offer characteristics which are very desirable for E²PROM applications.

This thesis is divided in the following manner. Chapter 2 gives a review of the dielectric characterization techniques used in the experiments performed for this thesis. It shows what each technique can be used for and what sort of equipment is required. Chapter 3 describes the processing used for the preparation of the samples used in the experiments. The fourth chapter describes the actual equipment used for each measurement technique. In Chapter 5, the results of the experiments are presented and some explanations for the observations are given. The final chapter consists of discussion and conclusions which may be drawn from the observed results.

Chapter 2:

Dielectric Characterization Techniques

This chapter will introduce various techniques for characterizing semiconductor dielectrics. Emphasis will be placed on Al-SiO₂-Si MOS type devices. The devices used for testing are MOS capacitors. (A comprehensive reference book on the MOS capacitor has been published by Nicollian and Brews [1]).

Many different techniques were used in the characterization of leaky oxides for this thesis. Each of the techniques will be described in order to gain some insight into the results and their meaning. Following is a list of the measurement techniques used:

A. Material characterization techniques:

- ellipsometry
- secondary ion mass spectroscopy (SIMS)
- transmission electron microscopy (TEM).

B. Electrical characterization techniques:

- capacitance vs. voltage (C-V) measurements
- current vs. voltage (I-V) measurements
- constant voltage stressing
- current transient measurements
- photo induced current transient spectroscopy (PICTS)

2.1 Material Characterization Techniques

The physical and material properties of semiconductor dielectrics can be determined using various optical techniques. Some of the physical properties can also be determined with electrical measurement techniques (e.g. thickness of oxide from C-V curve). Optical techniques can provide us with a more direct view of the material properties than do electrical techniques since we may isolate the material to be studied from some or all of the various materials (i.e. electrodes) and/or effects (i.e. noise, leakage) associated with electrical measurements. With this in mind, we may now consider the material characterization techniques used.

2.1.1 Ellipsometry [2]:

Ellipsometry is a measurement technique used to obtain an accurate value of oxide (or dielectric) thickness when the thickness is known approximately (within roughly 2000Å). It consists of shining monochromatic light whose polarization is known at an angle to the surface of the oxide. This light is reflected from both the silicon dioxide and the underlying silicon substrate surface. The portion of the incident light wave which is polarized normal to the plane of incidence is reflected differently from that which is polarized parallel to the plane of incidence. This effect is expressed by the Fresnel formula and will not be detailed here. If a light polarized at 45° to the plane of incidence is reflected from an oxidized silicon wafer, the reflected beam will be elliptically polarized. Ellipticity is measured and related to the film's properties by means of graphed solutions to the ellipsometry equations. In this manner, the thickness of the film and its index of refraction may be determined.

2.1.2 Secondary Ion Mass Spectroscopy (SIMS) (see Ref. [4] p. 32, [5] pp. 214-217):

SIMS is used to obtain a chemical depth profile for a material. It is useful in obtaining profiles for impurities in semiconductor materials. The technique consists of forming a beam of ions with energies from 500 eV to 20 keV and focussing this beam upon the surface of the material to be analyzed in a vacuum chamber. These ions interact in a nearly classical manner with the surface atoms, knocking them into the vacuum with elastic collisions. Some of the ejected particles are ionized and can be detected using a mass spectrometer (which can provide a count of various mass to charge ratios). Since particles are actually sputtered from the material's surface, depth calibration can be inferred after measurement of the resulting crater depth (assuming a constant sputtering rate).

2.1.3 Transmission Electron Microscopy (TEM) (see Ref. [3] pp. 39-43):

Transmission electron microscopy may be used to obtain a picture of a material and its interfaces to other materials (e.g. Si-SiO₂ interface), and it may also be used to obtain a Laue diffraction pattern in order to help determine crystallinity and orientation of a material. As the name implies, an image is formed not from a reflected beam but from a beam transmitted through the material. In order to obtain an image of the interface between two materials, the sample is first bevel etched to give a better view of the interface. The electron beam is then focussed through the sample to form an image on a phosphor screen. A Laue diffraction pattern is obtained using identical apparatus, but the sample is usually a

single type of material and the beam is not focussed but collimated. A mask is usually placed in front of the screen where the beam center would be to prevent burning the screen. The image obtained consists of a pattern of dots from which orientation of a crystal may be determined if the crystal structure is known. (The pattern of dots is determined by the Bragg equation $2d \sin \theta = n\lambda$ (Ref. [3] pp. 29-30)). For example, a cubic crystal oriented in the [111] direction would give a Laue dot pattern with three-fold symmetry. The Laue pattern may also be used to determine the crystallinity of a material - if no dots are present, the material is considered to be amorphous.

2.2 Electrical Characterization Techniques

The electrical properties and some physical properties of semiconductor dielectrics can be determined using various electrical techniques. While material characterization techniques provide us with often valuable information concerning the physical structure of semiconductors and dielectrics, electrical measurements provide us with the more practical electrical characteristics. These characteristics are often used as a starting point for the modelling of a device's behaviour.

2.2.1 Capacitance vs. Voltage (C-V) Measurements:

The capacitance vs. voltage curve is perhaps the oldest and most familiar type of measurement used to characterize MOS structures. It is thus the best understood technique and is used to determine many properties of a MOS

structure, including oxide thickness, substrate doping, bulk oxide trap properties, and Si-SiO₂ interface trap properties.

The instrumentation involved in making C-V measurements need not be very complex. The simplest setup would require a capacitance meter which can be supplied with a DC bias from an external voltage source, a variable DC voltage source, and a voltmeter. The sample is connected to the capacitance meter, the voltage is varied, and readings are taken of the bias voltage and the capacitance (see Figure 2.1). If the sample is not a packaged device, it must be shielded from light to prevent generation of carriers in the silicon.

Figure 2.1: Four terminal pair measurement principle.

2.2.2 Current vs. Voltage (I-V) Measurements:

The current vs. voltage characteristic curve of a MOS capacitor is of little importance for most types of devices. Usually the leakage current at the device's operating voltage is measured, and if this is low enough, the device is considered to be good. However, for a device such as an EAROM (electrically alterable read only memory) the current vs. voltage characteristics for the MOS capacitor must be known over a range of operating voltages (Figure 2.2 shows a typical setup). The leakage current for such a device must be negligible at its regular operating voltage (usually 5 volts), but should be relatively large at its programming voltage. The programming voltage is chosen by consulting the I-V curve for the MOS structure and finding a suitable current level at which programming may be performed relatively quickly and with minimal degradation of the oxide.

The curve is typically plotted using a log (current) scale since the current varies over several orders of magnitude between zero bias and the breakdown voltage. Shown in Table 2.1 are some documented conduction mechanisms along with their voltage and temperature dependence. Also shown are graphs (Figure 2.3) which indicate their relative dependences on voltage.

Figure 2.2: I-V apparatus.

CONDUCTION PROCESS	VOLTAGE AND TEMPERATURE DEPENDENCE
Schottky Emission	$\sim T^2 \exp (a \sqrt{V/T} - q\phi_B/kT)$
Frenkel-Poole Emission	$\sim V \exp (2a \sqrt{V/T} - q\phi_B/kT)$
Tunnel or Field Emission	$\sim V^2 \exp (-b/V)$
Space-Charge-Limited	$\sim V^2$
Ohmic	$\sim V \exp (-c/T)$
Ionic Conduction	$\sim \frac{V}{T} \exp (-d/T)$

Table 2.1: Basic conduction processes in insulators.

($a \equiv \sqrt{q/4\pi \epsilon_1 t_{ox}/k}$; $b, c, d \rightarrow$ constants

independent of V, T)

Figure 2.3: Graphs for various oxide conduction mechanisms.

2.2.3 Constant Voltage Stressing:

Constant voltage stressing consists of measuring current vs. time for a constant applied voltage across a MOS capacitor. If the current drops as time passes, it can be that the oxide is being charged with electrons. This implies that the oxide contains deep electron traps. Depending on the magnitude of the current drop, a measure of quality of the oxide may be determined: the larger the drop, the worse the oxide.

2.2.4 Current Transient Measurements:

A current transient measurement is essentially the same as a constant voltage stress measurement. The difference between the two is that a constant voltage stress measurement typically involves much longer times. When trapping effects are present, the decay in current appears to drop exponentially with a relatively long (longer than any circuit time constants) time constant which is related to the trapping depth, concentration, and proximity to the injecting electrode.

2.2.5 Photo-Induced Current Transient Spectroscopy (PICTS):

Photo-induced current transient spectroscopy (PICTS) is a measurement technique which involves shining monochromatic light on the sample being tested and monitoring the current which results from this (Figure 2.4). There are at least two ways in which to perform the measurement. One involves varying the wavelength of the monochromator from long (low energy) to short (high energy) wavelengths at a constant rate and monitoring the current flowing

Figure 2.4: PICTS apparatus.

through the sample [8]. Another technique can be used which pulses light of a given wavelength onto the sample while monitoring the current transient through the sample. Again the wavelength is varied from long to short. Only one reference [8] was found which made use of a constantly varying wavelength for obtaining information about traps in dielectrics. No previous work has been found which uses this optical technique for the silicon MOS system, and no other work has been found which uses the pulsed light technique described above. This pulsed light technique makes use of the same principles as DLTS uses for obtaining trap information for silicon and has been named photo-induced current transient spectroscopy (PICTS).

The basic idea is to first fill the traps in the dielectric, and then to cause detrapping at a known energy while monitoring the amount of charge being detrapped. In this manner, the energy level and relative concentration of traps in the oxide may be determined.

There are two basic methods of filling traps in a dielectric in the MOS system. The first and most used in practice is avalanche injection of carriers into the oxide from the silicon substrate. This is easy to accomplish if a MOS transistor is used as the sample device since it is quite simple to have the field near the drain-substrate junction exceed the avalanche breakdown field and cause injection of carriers into the oxide. However, if a simple MOS capacitor is the test device, then the voltage at which the avalanche breakdown field in the silicon is reached becomes heavily dependent on the substrate doping. If the substrate doping is too low, the voltage required for avalanche breakdown in the silicon may exceed the voltage at which the dielectric itself breaks down. This sort of

situation makes avalanche injection impossible. There is another technique which may be used to fill traps in the oxide which is known as photogeneration. A short wavelength light source is shone on the sample in order to cause carriers to jump from the valence band to the conduction band (or into trap levels). The energy of the photons involved should be at least as great as the band gap energy difference (9 eV for SiO_2). For silicon dioxide, this requires light having a wavelength of roughly 130 nm or less.

Once the traps have been filled, PICTS may be used to obtain trapping information. The current transients obtained may be analyzed in a manner similar to that used for DLTS. A spectrum of the traps may be obtained with wavelength as the horizontal axis. In order to obtain current transients which may be deemed to be caused by detrapping of oxide traps, the sample should be biased at the flatband voltage so that carriers which may be generated in the silicon substrate do not drift to the substrate electrode and thus contribute to the measured current.

Chapter 3:

Sample Preparation

In this chapter, various techniques for preparing leaky oxides for use in semiconductor devices will be discussed. The actual preparation of samples used for this thesis will then be described along with some process simulator results.

Controllably leaky oxides, as mentioned previously can be very useful in semiconductor devices such as EAROMs. An EAROM requires that a charge sheet or floating gate within a dielectric be capable of being charged and discharged. A charge sheet structure may be obtained by using two dielectrics stacked one upon another (Figure 3.1a). The interface between two such dielectrics will have some interface charge associated with it, and this interface may be charged through one or both of the dielectric layers. This, of course, requires a dielectric which will allow current to pass. A floating gate structure involves a gate material sandwiched between two dielectric layers (Figure 3.1b). Again, current must pass through one or both layers in order to program the device. In either case, a dielectric with controllable conductivity is required. Therefore, rather than producing a complete EAROM structure, it was decided to examine dielectric conductivity by itself using a simple MOS capacitor structure (Figure 3.1c).

Figure 3.1: a/ charge sheet EAROM, b/. floating gate EAROM, c/ MOS capacitor.

Leaky oxides can be produced in a few different ways. The oxide may be deposited using a chemical vapor deposition (CVD) system. This produces an oxide whose structure is more loosely bound than an oxide which is thermally grown and hence contains more impurities and loose bonds. Such nonuniformities in the oxide make it much easier for charge carriers to travel through the oxide. Another method for producing leaky oxides consists of growing a good (non-leaky) thermal oxide and then introducing some impurity in a known manner. Such impurities may be introduced into the oxide by diffusion or implantation. This sort of technique allows the impurity to be placed where it is required in a known manner, whereas a deposited oxide would have a more or less uniform distribution of impurities which could not be easily controlled. A third method of producing a leaky oxide could be used which consists of growing part of the oxide thermally, and then using a CVD oxide on top of the thermally grown one. This method would also allow some control over impurity distribution, but might cause problems because of the possibility of an interface charge sheet between the thermal and CVD oxides. This study is confined to the examination of leaky oxides as produced by CVD and by implanting thermally grown SiO_2 with silicon or phosphorous.

3.1 CVD Oxides

The chemical vapor deposited oxides were prepared on n-type $\langle 100 \rangle$ silicon substrates with resistivity in the range 3-7 Ωcm . Some of these wafers were oxidized at 1000°C in a dry ambient to a thickness of 75 nm and subsequently annealed at 1000°C for 20 minutes. The remainder of the wafers had 75 nm of oxide deposited on their surface. Of the wafers with deposited oxide, some

were annealed at 800°C for 60 minutes in a nitrogen ambient, some were annealed at 1000°C for 60 minutes in a nitrogen ambient, and the remainder were not annealed. Aluminum electrodes were then patterned to form 1 mm dot capacitors on all test wafers. Four different sample types were thus produced: unannealed deposited oxide, 800°C annealed deposited oxide, 1000°C annealed deposited oxide, and thermally grown silicon dioxide control samples.

3.2 Implanted Oxides

The implanted oxides were prepared and tested separately from the CVD oxides. P-type $\langle 100 \rangle$ silicon substrates with resistivity in the range 3-7 Ω cm were oxidized at 1000°C in a dry ambient to a thickness of 100 nm. The samples were then implanted with either ^{28}Si or ^{31}P or left unimplanted (for comparison). The implant dose was $2 \times 10^{16} \text{ cm}^{-2}$ and the implant energy was 20 keV for both Si and P. The simulation results for the phosphorous implant are shown in Figure 3.2. The process simulator SUPREM 3 was used. Since the mass and atomic radius of silicon are very close to those of phosphorous, we can assume that the silicon distribution in SiO_2 after implantation is very similar to that of phosphorous. A 60 minute anneal at 1000°C in N_2 ambient followed to remove the damage caused during implantation. Some samples were then chemically etched to remove 20 nm of the oxide. This depth corresponds to the peak of the as-implanted profile. Aluminum electrodes were patterned to form 1-mm dot capacitors on most of the wafers. Some of the wafers had an electrode patterned with a 5 μm aluminum line which formed a snaking pattern (these snaking electrodes were for use in PICTS experiments to allow light to shine into the oxide).

Figure 3.2: Simulated profiles of the phosphorous implant into SiO₂.

Dose = $2 \times 10^{16}/\text{cm}^2$ at 20 keV.

In all, six different types of samples were examined: thermal SiO_2 , Si-implanted SiO_2 , P-implanted SiO_2 , and etched versions of the above three types.

Chapter 4:

Experimental Setup

Many of the measurements which were made on the test capacitors were sensitive to noise and leakage. Because of this, a description of the experimental setup and details of some of the measurement techniques used will be presented in this chapter. Since the ellipsometry, SIMS, and TEM measurements were not performed by this author, the instrumentation used for them will only be described briefly and the following discussion will concentrate on the electrical characterization techniques.

4.1 Material Characterization Equipment

Ellipsometric measurements were made using a Rudolph automatic ellipsometer. The light source used was a helium-neon laser with a wavelength of 632.8 nm. The light was shone onto the sample at an angle of incidence of 70°. The measurements were performed by I. Few at Northern Telecom Electronics in Ottawa and were cross-checked with further measurements made at the National Research Council labs on a different ellipsometer. The two sets of measurements showed excellent agreement.

The SIMS measurements were obtained using the Cameca IMS 3-f ion microscope of the Surface Science group at the University of Western Ontario [9]. Oxygen or cesium was used as the bombarding species and positive secondary ions were monitored.

The TEM examination was made by Bob Mallard of Bell Northern Research using a Philips EM 300 transmission electron microscope at Energy, Mines, and Resources [10]. The samples were prepared from the center of each wafer by chemical jet polishing in 4:1 HNO₃:HF₄ from the substrate side until perforation. The resolution of the TEM is roughly 10 nm.

4.2 Electrical Characterization Laboratory

The electrical characterization laboratory of the Advanced Device Research group (Dept. P986 of Northern Telecom Electronics' Semiconductor Components Group) contained all the equipment required for making the electrical characterization measurements presented in this thesis. Almost all the equipment was housed within a stainless steel shielded room in order to eliminate the effects of external electromagnetic interference (EMI).

Almost all of the measurement equipment could be computer controlled through the Hewlett-Packard Interface Bus (HPIB), which is equivalent to the IEEE-488 bus. The computer used to control the various instruments was a Hewlett-Packard 9845B. In the earlier stages of experimentation, the HP9845B was housed within the shielded room with the measurement equipment, but when a fiber optic link for the HPIB was finally acquired, the HP9845B could be moved out of the shielded room, thus eliminating a source of EMI. Since the devices to be tested were all on silicon wafers, probing stations were used to connect the devices to the measurement instruments.

Two types of probe stations were available in the laboratory, 1/ automatic probe stations which could be computer controlled to step across a wafer in order to test many devices during a single test run, and 2/ manual probe stations which were placed in a shielded black box to eliminate EMI as well as to prevent light from reaching the test sample and causing generation of carriers in the silicon. An automatic probe station was used to obtain statistical information regarding parameters such as oxide breakdown field, whereas a shielded station was used to obtain more accurate measurements.

When a shielded station was used for making a sensitive measurement, all unused equipment in the shielded room was powered down to further reduce sources of EMI. This discussion has described the general procedures followed and some of the equipment used in making electrical measurements in general. A description of equipment and techniques used for each type of electrical measurement will be presented in the following text.

4.2.1 C-V Measurements

The capacitance versus voltage measurements for the sample wafers were all conducted using the shielded box in the shielded room. High frequency C-V curves were obtained using a Hewlett-Packard 4275 multi-frequency LCR meter at a frequency of 1 MHz. Quasi-static C-V curves were obtained using a Hewlett-Packard 4140 pA meter/voltage source. The software used on the HP 9845B to program these instruments and generate graphics plots is shown in Appendix A. The high temperature C-V measurements were performed by A. Kalnitsky. (Calculations made for oxide thickness, etc., are described in Appendix C).

4.2.2 I-V Measurements

The current versus voltage measurements were all conducted using a Hewlett-Packard 4140 pA meter/voltage source. Some of the measurements were made to determine breakdown statistics for the oxides and made use of an Electroglass automatic prober. Both these pieces of equipment were programmed using the HP 9845B and the software is included in Appendix A. Many of the I-V measurements were obtained using the shielded probe station

in the shielded room. Using the HP 4140 and the shielded probe station, the cable leakage and noise was kept below 0.1 pA.

4.2.3 Constant Voltage Stressing

The constant voltage stress measurements were made using the HP 4140 in combination with the shielded probe station in the shielded room. The software to program the HP 4140 using the HP 9845B is provided in Appendix A. As for the I-V measurements, noise was kept below 0.1 pA.

4.2.4 Current Transient Measurements

The current transient measurements were made using the same setup as the constant voltage stress measurements.

4.2.5 Photo-Induced Current Transient Spectroscopy (PICTS)

Special equipment was required for making PICTS measurements. A Keithley 617 electrometer was used for collecting the raw current measurements. A Bausch and Lomb monochromator was used with a tungsten light source for the detrapping portion of the measurement. An automatic shutter in combination with a few metal surface mirrors was used to redirect and control when the light from the monochromator would shine on the sample. The monochromator was installed just outside the black box for the probe station. The HP 4140 was used to trigger the automatic shutter. Software to control the setup and process the raw data is given in Appendix A. Provision was made in the software to average many transients due to the extremely small currents

involved (changes in current of 1 fA or less could be observed if averaged).

Since the substrate doping of the samples used was so low, avalanche injection could not be used to inject carriers into the oxide in order to fill traps. Because of this, a light source of relatively short wavelength was required to fill traps. A fluorescent "black light" was obtained for this purpose and was installed within the black box. It was turned on, before any measurements were to be made on the sample, to cause carriers to jump into defect states. The black light was used only at the beginning of the complete set of measurements for a given sample and not before each measurement. A set of measurements was made beginning with the longest wavelength on the monochromator, averaging a set of current transients for that wavelength, shortening the wavelength on the monochromator, averaging another set of curves, and so on, until the shortest wavelength was reached.

Chapter 5:

Results

The results of measurements made on the various oxides are presented in this chapter. Measurements made with the CVD deposited oxides will be examined separately from the remainder of the oxides. Not all the measurement techniques presented earlier were used for the CVD oxides for reasons which will be made apparent. The CVD oxide measurement results will be presented first, followed by the implanted oxide results. Preliminary optical DLTS measurements will be presented.

5.1 CVD Oxide Measurement Results

5.1.1 Ellipsometry:

Ellipsometry thickness measurements were made on all the CVD oxides including a thermally grown SiO_2 sample. The results are given in Table 5.1. The target thickness for all these samples was 75 nm. There is an obvious discrepancy between the thickness of the thermally grown SiO_2 as compared to the CVD oxides. This is due to the fact that the CVD and implanted oxides were produced at different times. Note the steady decrease in thickness of the CVD oxides as the heat treatment temperature increases. This is due to the fact that the deposited silicon dioxide is originally a loosely bound structure, which, when heated, becomes more tightly bound (a process known as densification).

5.1.2 I-V Results:

Current vs. voltage curves were obtained for all three of the CVD oxide types as well as the thermally grown silicon dioxide. In addition to this,

	20 min. 1000°C	no heat treatment	60 min. 800°C	60 min. 1000°C
thermal SiO ₂	73.9 nm	-	-	-
CVD oxide	-	68.6 nm	67.7 nm	66.2 nm

Table 5.1: CVD ellipsometry thickness measurement results.

some statistics were obtained regarding the current flow through the test capacitors in the form of histograms indicating in which voltage range the capacitor allowed a current density of $100 \mu\text{A}/\text{cm}^2$ to pass through it. For each histogram, 256 samples were tested from a single wafer.

The histogram for thermally grown SiO_2 is shown in Figure 5.1. Note that a very small number of the samples are conductive at voltages below 35 V and that the clear majority of the samples fall into the 35-40 V bin. This is indicative of a good insulating oxide which is very reproducible. A typical I-V curve for the thermal SiO_2 is shown in Figure 5.2.

The histogram for the untreated CVD oxide is shown in Figure 5.3. Every sample tested conducted heavily at low voltage. Looking at Figure 5.4 indicates that the untreated oxides are essentially short circuits and are thus useless for MOS transistor applications.

The histogram for the CVD oxide treated at 800°C for 60 minutes is given in Figure 5.5. There is a high incidence of "short circuit" oxides, (see Figure 5.6) but some of the tested samples only conduct at higher voltages. Unfortunately, many of these reach breakdown and are thereafter short circuits (also the yield on such samples is very low). Thus, these samples would also be useless for MOS transistor applications.

The data for the CVD oxide treated at 1000°C for 60 minutes is given in Figures 5.7. Note that there is a large drop in the number of short circuit oxides. Despite this, the short circuit oxides still constitute a major portion of the sampling. A current vs. voltage curve is shown in Figure 5.8

Figure 5.1: Histogram for 75 nm thermal SiO₂ (current $\geq 100 \mu\text{A}/\text{cm}^2$).

Figure 5.2: Typical I-V curve for thermal SiO₂.

Figure 5.3: Histogram for 75 nm untreated CVD oxide (current $\geq 100 \mu\text{A}/\text{cm}^2$).

Figure 5.4: I-V curves for untreated CVD oxide.

Figure 5.5: Histogram for 75 nm 800°C treated CVD oxide (current $\geq 100 \mu\text{A}/\text{cm}^2$).

Figure 5.6: I-V curve for 800°C treated CVD oxide.

Figure 5.7: Histogram for 75 nm 1000°C treated CVD oxide (current $\geq 100 \mu\text{A}/\text{cm}^2$).

Figure 5.8: I-V curve for 1000°C treated CVD oxide.

which exhibits some of the characteristics of the CVD oxides which break down at higher voltages: the curve is not very smooth, and sudden inexplicable and unpredictable changes in conduction are evident. This sort of characteristic is unpredictable and unreliable, something which cannot be tolerated in MOS transistor applications (especially in memory devices such as EAROMs).

From this information, it was deemed that CVD oxides were not really appropriate to use in semiconductor devices such as EAROMs where high reliability and yield are as important as controlled conductivity. Further testing was thus given up on the CVD oxides in order that research could proceed with the implanted oxides.

The conduction mechanism in these oxides is defect related. This mechanism is heavily dependent on carriers hopping between defects (Frenkel-Poole mechanism), and thus, on defect concentration and distribution. For oxides which are not impregnated with defects throughout the thickness of the oxide, another mechanism, known as Fowler-Nordheim tunnelling becomes more important. This mechanism is less dependent on the band structure of the oxide but is heavily field dependent (see Table 2.1), as it is due to tunnelling which occurs at high fields where the oxide valence band is bent to the point that the resulting thin triangular barrier may be tunnelled through.

5.2 Implanted Oxide Measurement Results

5.2.1 Material Properties:

The optical properties of the implanted oxides were evaluated by ellipsometry and the results are displayed in Table 5.2. It was found that after implantation and annealing, the samples were approximately 4% thicker than the control samples. After the 20-nm etch the P-rich samples and the unimplanted samples have almost identical indices of refraction; this indicates that the phosphorous had piled up at the air-SiO₂ interface during the annealing and that most of it was removed by the etch. SIMS analysis also supports this conclusion. The index of refraction of the Si-rich SiO₂ is significantly different than that of the unimplanted SiO₂ both before and after etch, indicating that this oxide is non-stoichiometric in either case. It also has nearly the same value indicating that the silicon must be relatively uniformly distributed within the oxide after the anneal.

The SIMS results are shown in Figures 5.9 and 5.10 for the P-rich and Si-rich SiO₂ respectively. The analysis was done using a cesium beam and positive secondaries. Both samples had received a 20 nm etch. The phosphorus profile decreases sharply away from the air-SiO₂ interface in accordance with the ellipsometry results. There is no evidence of a phosphorous pile-up at the Si-SiO₂ interface. The Si-rich results are displayed in Figure 5.10. The implanted species is ²⁸Si. It is monitored as Si₂⁺ (m/q = 56) and Si⁺⁺ (m/q = 14). Also monitored is ³⁰Si⁺ which is a natural isotope of silicon and is therefore part

ELLIPSO-METRIC DATA

	before etch	after etch	before etch	after etch
n_{SiO_2}	1.468	1.473	1.459	1.463
t_{ox} (nm)	103.8	83.4	154.9	134.9
$n_{\text{Si-rich}}$	1.500	1.495	1.486	1.470
t_{ox} (nm)	108.3	87.9	165.4	145.4
$n_{\text{P-rich}}$	1.481	1.476	1.466	1.462
t_{ox} (nm)	108.4	83.6	164.1	138.4

Table 5.2 Index of refraction and oxide thickness as determined by ellipsometry ($\lambda = 632.8 \text{ nm}$, $\psi = 70^\circ$).

Depth profile

Figure 5.9: SIMS profile of the phosphorous-rich SiO_2 after annealing and 20 nm etch. The various curves are labelled by atomic mass ($^{30}\text{Si}^+$, $^{28}\text{Si}^{++}$ ($m/q = 14$), and $^{31}\text{P}^+$).

Figure 5.10: SIMS profiles of the Si-rich SiO_2 after annealing. The curves are labelled by atomic mass ($^{30}\text{Si}^+$, $^{28}\text{Si}_2^+$ ($m/q = 56$), $^{28}\text{Si}^{++}$ ($m/q = 14$)).

of the thermal SiO_2 . There is a broad "hump" on the mass 14 profile which appears to correspond to a dip in mass 30. It was expected that the mass 30 profile would stay constant throughout the oxide as it is in Figure 5.10 but this is obviously not the case.

TEM studies have not revealed the presence of crystalline clusters within these oxides, to the limit of our resolution (~ 10 nm). The electron diffraction pattern of Si-implanted oxide is displayed in Figure 5.11. It is characteristic of an amorphous sample. The earlier reports of non-stoichiometric SiO_2 fabricated by the chemical vapor deposition have indicated the presence of Si crystals in the oxide. These were thought to be responsible for the enhanced conduction by a tunnelling mechanism. Since the implanted oxides do not contain these crystals, the enhanced conduction of the implanted oxides can be explained by a Poole-Frenkel mechanism, due to the presence of traps within the dielectric.

5.2.2 I-V Results:

Histograms were obtained for the unetched implanted oxide samples. One histogram was obtained for each of: the thermal unimplanted SiO_2 (Figure 5.12), the P-implanted SiO_2 (Figure 5.13), and the Si-implanted SiO_2 (Figure 5.14). The conditions for obtaining these histograms are the same as for the CVD oxides (i.e. a given sample registers on the histogram when the current through it is larger than or equal to $100 \mu\text{A}/\text{cm}^2$).

The histogram for the thermal silicon dioxide, shown in Figure 5.12, shows a distribution similar to that shown by the thermally grown oxide used in the

Figure 5.11: Electron diffraction pattern of the Si-rich SiO_2 sample.

Figure 5.12: Histogram for 100 nm thermal SiO₂ (current $\geq 100 \mu\text{A}/\text{cm}^2$).

Figure 5.13: Histogram for 100 nm P-implanted SiO₂ (current $\geq 100 \mu\text{A}/\text{cm}^2$).

Figure 5.14: Histogram for 100 nm Si-implanted SiO₂ (current $\geq 100 \mu\text{A}/\text{cm}^2$).

CVD oxide tests. It indicates a reliable, high yield oxide. It should be noted, however, that the fact that there is obviously some standard deviation in the distribution, suggests some statistical randomness, which further implies that a good portion of the oxides actually break down (become short circuits) once they reach the $100 \mu\text{A}/\text{cm}^2$ current level. This means that the thermally grown silicon dioxide is actually not very reliable at that current level.

The histogram for the P-implanted sample is shown in Figure 5.13. The distribution appears to be almost purely random, indicating very low reliability for these oxides. Despite this, the characteristic I-V curve for these samples appears to be free from noise (cf. CVD oxides), and is definitely characteristic of the oxide (i.e. the curve is very repeatable but does not always show high voltage breakdown). For this reason, further testing of the P-implanted samples was carried out.

Figure 5.14 shows the histogram for the Si-implanted silicon dioxide. It indicates that the Si-implanted oxide has extremely repeatable characteristics and is, therefore, very reliable for the current level tested. This tells us that the Si-implanted oxide can be produced with very high yields and can be considered highly reliable at relatively large current levels.

The characteristic I-V curves of these samples are now examined. The accumulation current-voltage characteristics of three unetched samples are shown in Figure 5.15. The voltage was stepped by 0.2 V with a delay time of 1 second. The current was measured only after the delay had elapsed. The

Figure 5.15: Current-voltage characteristics of the 3 different types of oxides used in this study, $T_{\text{ox}} = 100$ nm before implantation, Area = 1 mm^2 .

worst case 90% response time for the meter is 0.6 s. The different samples exhibit very different current-voltage characteristics. The standard oxide behaves in a predictable manner: at low voltages a small leakage current flows (due to leakage in the measurement setup), but as the voltage is raised, Fowler-Nordheim tunnelling takes place. All standard oxide capacitors tested with retrace I-V followed the same curve whether the voltage was increased or decreased. The Si-implanted oxide capacitors had a characteristic I-V trace which increased monotonically with voltage and had two characteristic "bumps": one centered between 35 and 40 V and a second, larger one extending from 47 V to near the breakdown voltage. It is suspected that each bump represents a separate current conduction mechanism at work. These mechanisms are as yet unexplained but are thought to be due to trapping centers caused by dangling Si bonds in the Si_xO_y structure near the oxide-aluminum interface. Figure 5.16 shows that the I-V characteristic has some hysteresis in it. The current, when stepping the voltage down (always in accumulation), drops below the original curve and actually becomes negative with respect to the applied voltage. When a second retrace curve is obtained immediately after the first is completed (Fig. 5.17), the current is initially negative with respect to voltage, but quickly becomes positive again, indicating some charging effect. This charging effect may be explained if we consider the possibility of electron traps in the Si-rich portion of the implanted oxide. Initially, these are empty and therefore cannot be filled until electrons are injected into the oxide. When a negative voltage is applied to the Al electrode and stepped up, the electric field becomes large enough to inject these electrons into the oxide traps (near the electrode). If these traps are shallow, the electrons are emitted relatively quickly. Due to the high concentration of

Figure 5.16: Retrace I-V characteristic of the Si-rich SiO₂ without etching.

Figure 5.17: Retrace I-V characteristic of the Si-rich SiO_2 without etching.

traps, most of the electrons will remain in or near the Si-rich portion of the oxide until the electric field becomes smaller. When this occurs, some electrons may reach the Al electrode and, if the number of trapped electrons is large, actually cause a reversal of the current. Note that the first characteristic bump has disappeared on the second retrace. This shows that there is a likelihood of trapping occurring at the higher fields since the first characteristic bump only appears on the initial ramping up of voltage. This trapping effect would be relatively inactive at room temperature (since the bump does not reappear in the second retrace) and would therefore be expected to have an activation energy greater than 0.5 eV.

The nature of the second bump on the I-V curve has not been examined in any depth but may be due to a combination of Poole-Frenkel and Fowler-Nordheim tunnelling effects (the Si-rich portion of the SiO_2 acting somewhat like a conductor, thus making the oxide appear to be thinner than the original grown oxide). This second bump may also be due to direct tunnelling in and out of very deep traps or charge centers.

In Figure 5.18, two I-V plots are shown for the P-implanted SiO_2 . The curves were taken in sequence on a single capacitor. There are two "bumps" which appear on the characteristic curve, the first occurring at about 20 to 25 V and the second at about 45 to 50 V. The cause of the first bump in Figure 5.18 has not been determined at present. The second "bump" shifted in voltage on the second retrace curve. This can be explained in a similar manner to the Si-implanted sample by assuming that electron trapping occurs as the field is increased past this bump. Again, this implies a trap energy level greater than 0.5 eV.

Figure 5.18: Retrace I-V characteristic of the P-rich SiO₂ without etching.

5.2.3 C-V Results:

Capacitance voltage curves were obtained for the three types of samples (Fig. 5.19). As can be seen, the Si-implanted samples behave almost exactly like standard oxide samples except that $C_{\max}/C_{\min}$ is smaller. The P-implanted samples, on the other hand, act almost like constant capacitances. This behaviour has been observed in the past [18] and may be due to the polarizability of phosphorous doped oxides.

5.2.4 Constant Voltage Stress Results:

Voltage stress tests were performed on the different capacitor samples. The standard oxide showed no variation in current over an 8-hour period with 50 V stress applied. The magnitude of the current through the Si-implanted samples dropped by a factor of about 2.5 when stressed at 50 V for 8 hrs. The P-implanted sample showed one order of magnitude drop at 50 V for 8 hrs. Any significant change in current is undesirable. This indicates that Si-implanted SiO_2 exhibits better long-term characteristics than P-implanted SiO_2 .

5.2.5 Photo-Induced Current Transient Spectroscopy (PICTS) Results:

PICTS was used to examine characteristics of the thermal SiO_2 and the Si-implanted SiO_2 samples. Each current transient curve used in the analysis program (Appendix D) was obtained by averaging 20 measured transients. A sample averaged transient is shown in Figure 5.20. For each sample examined, 21 of these averaged transient curves were gathered over

Figure 5.19: C-V characteristics of the 3 types of oxides.

Figure 5.20: Typical averaged transient response curve for PICTS experiment.

the wavelength range of 700 nm to 200 nm (one curve at each 25 nm mark). It was found that the curves for wavelengths below 400 nm were very unreliable, and the analysis results obtained for them was unpredictable. This can be explained by examining the monochromator calibration curve in Appendix E which indicates that there is little or no output from the monochromator below 400 nm. For this reason, the results for wavelengths below 400 nm are not present in the figures.

The data for the samples are presented in the form of a spectrum with transient response (current) plotted against the wavelength of light. The transient response was obtained by simply taking the difference in current between the peak of the transient ($t \approx 2.0$ sec) and at steady state ($t \approx 10.0$ sec). The emission rate at each wavelength was calculated by performing a least squares fit of an exponential curve to the measured transient curve and obtaining the time constant from this fit. The emission rate was plotted against wavelength and also against energy for each sample.

5.2.5.1. Thermal SiO₂:

Two sets of data were gathered for thermal SiO₂: one set of data was taken after 30 minutes of exposure to the black light and a second set of data was gathered after 24 hours of exposure to the black light. The raw data was normalized using the monochromator calibration curve (Appendix E) before being analyzed. Plots of the normalized current response are shown in Figures 5.21 and 5.22 for the short (30 min) and long (24 hour) exposures, respectively. It is obvious from these two figures that there is

Figure 5.21: PICTS response for thermally grown SiO₂ (30 min. UV exposure).

Figure 5.22: PICTS response for thermally grown SiO₂ (24 hr. UV exposure).

an overall increase in response in the curve for the sample with the longer exposure time. It is also evident that there is a substantially larger increase in response over the range 450 nm-550 nm than elsewhere on the curve. This can also be noticed by careful scrutiny of the emission rate plots versus wavelength (Figures 5.23 and 5.24) as well as versus energy (Figures 5.25 and 5.26). However, by analyzing the difference in response between long and short exposure times (Figure 5.27), the wavelengths and energy range over which the difference is observed becomes obvious. The plot has three peaks in it: one at roughly 1.8 eV (700 nm), another at 2.0 eV (600 nm) and a third, wider peak from 2.2-2.4 eV (550-500 nm). The peak at 1.8 eV could easily be due to traps (or states) at lower energy levels than 1.8 eV. This is because 1.8 eV is the lowest energy at which data was gathered. The 2.0 eV peak could be due to a nonbridging oxygen center (Ref. 21). The wide peak which falls off at 2.4 eV could be caused by the well documented (Ref. 22) '2.4 eV trap' which is thought to be due to sodium contamination. High temperature C-V measurements on the thermal SiO₂ sample did not indicate any measurable shift in threshold. This suggests that PICTS is a much more sensitive detection technique for Na⁺ than other techniques currently in use.

5.2.5.2 Si-Implanted SiO₂:

As for the thermal SiO₂, two sets of data were gathered for the Si implanted oxide. One set was gathered after a short exposure (30 min) and the second was gathered after a long (12 hour) exposure to the black light. The normalized data is presented in Figures 5.28 and 5.29. There is an obvious increase in response at about 600 nm when the exposure time is

Figure 5.23: Emission rate vs. wavelength for thermal SiO_2 (30 min. UV exposure).

Figure 5.24: Emission rate vs. wavelength for thermal SiO_2 (24 hr. UV exposure).

Figure 5.25: Emission rate vs. energy for thermal SiO_2 (30 min. UV exposure).

Figure 5.26: Emission rate vs. energy for thermal SiO₂ (24 hr. UV exposure).

Figure 5.27: PICTS response difference between long and short UV exposure (thermal SiO₂).

Figure 5.28: PICTS response for Si-implanted SiO₂ (30 min. UV exposure).

Figure 5.29: PICTS response for Si-implanted SiO₂ (12 hr. UV exposure).

increased. The emission rate plots are shown in Figures 5.30-5.33 for the normalized data. Again, the difference in response was analyzed (as for the thermal SiO_2). The plot of the difference in response is shown in Figure 5.34. Several peaks are evident in the plot, however, most of these register less than 1.0 femto-amp. Such data points are not considered to be very reliable since some drift (usually 0.5 fA but sometimes as high as 1.0 fA) has been observed in the transient response even after averaging has taken place. This means that there is only one truly significant peak in the response at 600 nm. This translates to an energy level of roughly 2.1 eV.

Figure 5.30: Emission rate vs. wavelength for Si-implanted SiO_2 (30 min. UV exposure).

Figure 5.31: Emission rate vs. wavelength for Si-implanted SiO_2 (12 hr. UV exposure).

Figure 5.32: Emission rate vs. energy for Si-implanted SiO_2 (30 min. UV exposure).

Figure 5.33: Emission rate vs. energy for Si-implanted SiO_2 (12 hr. UV exposure).

Figure 5.34: PICTS response difference between long and short UV exposure (Si-implanted SiO₂).

Chapter 6:

Discussion and Conclusions

The main objective of this study was to examine the characteristics (esp. conductivity) of various "leaky" oxides which could be used in semiconductor devices. The reason for doing this was to determine the suitability of such oxides for use in devices for which a dielectric with controlled conductivity characteristics is desired. Currently, electrically alterable read only memory (EAROM or E²PROM) devices fall into this category. The oxides examined in this thesis include chemical vapor deposited (CVD) silicon dioxide with various annealing steps, and thermally grown silicon dioxide implanted with either silicon or phosphorous ions.

It was found that both the CVD and implanted oxides displayed enhanced conductivity characteristics with respect to thermally grown SiO₂ control samples. The CVD oxide samples showed unpredictable conduction characteristics with catastrophic breakdown, and were thus deemed unsuitable for use in E²PROM devices. The implanted oxides exhibited much more repeatable characteristics for conduction, but after performing C-V testing, it was found that the phosphorous implanted samples could not have the silicon surface inverted. For this reason, the phosphorous implanted SiO₂ was also deemed unsuitable for use in E²PROM devices. The silicon implanted SiO₂, on the other hand, was found to have very desirable characteristics for both I-V and C-V tests. The mechanism responsible for conduction in the Si-implanted SiO₂ is thought to be a combination of Poole-Frenkel and Fowler-Nordheim tunnelling. Explanations for the behaviour of the various samples has been presented with the results.

An important finding which occurred during the course of this thesis has been the discovery of PICTS as a technique for extracting information about oxide

defects or traps from a metal-oxide-semiconductor structure. Some work has been done previously using metal-oxide-metal structures [Ref. 8], but no published material could be found which applied this sort of technique to MOS devices or which measured current transients due to pulsed light. The results obtained with PICTS for the samples described in the previous text are promising: a documented trap (at 2.4 eV) [22] has been uncovered in thermal SiO₂ along with a few other traps (described in the text). The measurement setup currently in use could be improved considerably, however, by obtaining a higher quality, automatic drive monochromator and a good short wavelength ultraviolet source. PICTS is thus considered to be a useful technique, but the measurement setup in use at this time could use some improvements.

In conclusion, several different samples of leaky dielectrics have been examined for possible use in semiconductor devices such as EAROMs. It was found that thermally grown SiO₂ implanted with phosphorous would not be useful in such an application. The discovery was made that CVD oxides could have potential use, but their unreliable characteristics makes them an impractical choice for use in such devices. The thermally grown SiO₂ implanted with silicon exhibited characteristics which would prove most useful in an EAROM device. There is some question, however, as to how such an oxide could be made thinner in order to keep up with the miniaturization of devices in general. The samples tested were 100 nm thick and used an implantation energy of 10 keV, which is about as low an implantation energy as can be practically obtained at this time. Oxides of 50 nm or 25 nm (or possibly thinner) would be desirable if not necessary for EAROM devices at the current level of technology. This would require implantation energies

of 5 keV or lower, which are difficult to obtain at this time. Thus, there is some promise that leaky dielectrics can be used in EAROMs, but further research is required before they become a practical alternative to tunnelling dielectrics.

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Appendix A:

List of Symbols

2 of/de 2

MicroD

List of Symbols

Symbol	Description	Unit
A	area	cm ²
C	capacitance	F
E	energy	eV
E _c	bottom of conduction band	eV
E _F	Fermi energy level	eV
E _G	energy bandgap	eV
E _i	intrinsic energy level	eV
E _v	top of valence band	eV
h	Planck constant	J-s
h _v	photon energy	eV
I	current	A
k	Boltzmann constant	J/K
kT	thermal energy	eV
n	refractive index	
N	doping concentration	cm ⁻³
q	magnitude of electronic charge	C
Q	charge	C
t _{ox}	oxide thickness	nm
T	temperature	K
V	voltage	V
W	thickness	cm
ε ₀	permittivity in vacuum	F/cm

List of Symbols

<u>Symbol</u>	<u>Description</u>	<u>Unit</u>
ϵ_{Si}	relative permittivity of silicon	
ϵ_{ox}	relative permittivity of oxide	
θ	angle	
λ	wavelength	nm
ν	frequency of light	Hz
ϕ_B	barrier height	V
ϕ_m	metal work function	V

Appendix B:

Physical Constants

Physical Constants

Quantity	Symbol	Value
Boltzmann constant	k	$1.38066 \times 10^{-23} \text{ J/K}$
Elementary charge	q	$1.60218 \times 10^{-19} \text{ C}$
Electron volt	eV	$1 \text{ eV} = 1.60218 \times 10^{-19} \text{ J}$
Permittivity in vacuum	ϵ_0	$8.85418 \times 10^{-14} \text{ F/cm}$
Relative permittivity of silicon	ϵ_{Si}	11.7
Relative permittivity of SiO_2	ϵ_{ox}	3.9
Planck constant	h	$6.62617 \times 10^{-34} \text{ J-s}$
Reduced Planck constant	$\hbar$	$1.05458 \times 10^{-34} \text{ J-s}$
Thermal voltage at 300K	kT/q	0.0259 V
Refractive index of SiO_2	n_{SiO_2}	1.46

Appendix C:

Measurement Software

Software property of Northern Telecom Ltd. and is therefore withheld from publication.

The following text derives some of the equations used in making calculations from C-V results.

There are two basic types of C-V measurements: low frequency or quasi-static C-V, and high frequency C-V. The basic difference between the two measurements is that at low frequencies and when biased heavily into depletion, minority carriers have time to respond and can form an inversion layer at the silicon surface, whereas at high frequencies this cannot happen and the surface instead remains depleted.

The oxide thickness is determined from the maximum value of capacitance on either a high or low frequency C-V curve.

$$t_{ox} = \frac{A \epsilon_{SiO_2} \epsilon_0}{C_{max}}$$

where

C_{max} = maximum value of capacitance

A = area of the electrode.

The doping concentration near the silicon surface can be determined using the results from a high frequency C-V curve.

When the silicon surface is accumulated, the measured capacitance is equal to the oxide capacitance. On the C-V curve, this will be the maximum capacitance,

$$C_{\max} = C_{\text{ox}} = \frac{A \epsilon_{\text{ox}} \epsilon_0}{t_{\text{ox}}}$$

as mentioned previously. When the silicon surface is heavily depleted, such that the depletion width is at its maximum value ($W_{\max}$), then the measured capacitance is at its minimum since the oxide and silicon capacitances act as if connected in series.

$$C_{\min} = \frac{1}{\frac{1}{C_{\text{ox}}} + \frac{1}{C_{\text{Si}_{\min}}}} = \frac{C_{\text{ox}} C_{\text{Si}_{\min}}}{C_{\text{ox}} + C_{\text{Si}_{\min}}}$$

$$C_{\text{Si}_{\min}} = \frac{A \epsilon_{\text{Si}} \epsilon_0}{W_{\max}}$$

$C_{\min}$ and C_{ox} can be measured. We can then solve for $C_{\text{Si}_{\min}}$ and $W_{\max}$.

$$C_{\text{Si}_{\min}} = \frac{1}{\frac{1}{C_{\min}} - \frac{1}{C_{\text{ox}}}} = \frac{C_{\min} C_{\text{ox}}}{C_{\text{ox}} - C_{\min}}$$

$$W_{\max} = \frac{A \epsilon_{\text{Si}} \epsilon_0}{C_{\text{Si}_{\min}}} = t_{\text{ox}} \frac{\epsilon_{\text{Si}}}{\epsilon_{\text{ox}}} \left(\frac{C_{\text{ox}}}{C_{\min}} - 1 \right)$$

We know that the maximum depletion width is reached at the onset of strong inversion, which occurs when the silicon band bending is twice the Fermi voltage (ϕ_F) (see ref. [6] p. 268).

$$\phi_{inv} = 2|\phi_F| = 2 \frac{kT}{q} \ln \left(\frac{N_o}{n_i} \right)$$

we know that the silicon surface potential is given by (ref. [7] p. 372),

$$\phi_s = \frac{q N_o W^2}{2 \epsilon_{Si} \epsilon_o}$$

Rearranging for the onset of strong inversion, we obtain:

$$N_o = \frac{2 \epsilon_{Si} \epsilon_o}{W_{max}^2 q} \phi_{inv}$$

or

$$N_o = 4 \left(\frac{kT}{q} \right) \frac{\epsilon_{Si} \epsilon_o}{W_{max}^2 q} \ln \left(\frac{N_o}{n_i} \right)$$

This equation can be solved for N_o iteratively

$$N_o^+ = 4 \left(\frac{kT}{q} \right) \frac{\epsilon_{Si} \epsilon_o}{W_{max}^2 q} \ln \left(\frac{N_o^-}{n_i} \right)$$

and the dopant concentration is thus obtained.

C-V techniques are not quite as useful in determining bulk oxide trap or charge properties, but can still yield some useful information when used in conjunction with bias-temperature stressing. The combination of these techniques can help to distinguish between oxide fixed charge, oxide trapped charge, and mobile ionic charge.

Figure A.1: Distinguishing Between Various Bulk Oxide Charge Types

The Symbols (i) denotes the initial C-V curve; (f+), after positive bias-temperature aging, and (f-), after negative bias-temperature aging. (a) Oxide fixed charge; (b) oxide trapped charge; (c) mobile ionic charge.

C-V measurements can also yield information on Si-SiO₂ surface state properties.

The oxide fixed charge can be calculated easily if we can assume negligible charge within the oxide. In this case, the flatband voltage is simply

$$V_{FB} = \phi_{ms} - \frac{Q_f}{C_{ox}}$$

and the oxide fixed charge

$$\frac{Q_f}{A} = \frac{C_{ox}}{A} (\phi_{ms} - V_{FB})$$

The oxide fixed charge is then easily obtained

$$\frac{Q_f}{qA} = \frac{C_{ox}}{qA} (\phi_{ms} - V_{FB})$$

The flatband voltage is obtained by first calculating the flatband capacitance (see ref. [7] pp. 366-372)

$$C_{FB} = \frac{\epsilon_{ox} \epsilon_o A}{t_{ox} + (\epsilon_{ox}/\epsilon_{Si}) \sqrt{kT \epsilon_{Si} \epsilon_o / N_o} q^2}$$

and then finding the gate voltage corresponding to C_{FB} on the measured C-V curve.

The work function difference, ϕ_{ms} , from aluminum to silicon is

for p-type Si
$$\phi_{ms} = -0.6 \text{ V} - \phi_F = -0.6 \text{ V} - \frac{kT}{q} \ln \left(\frac{N_o}{n_1} \right)$$

for n-type Si
$$\phi_{ms} = -0.6 \text{ V} + \frac{kT}{q} \ln \left(\frac{N_o}{n_1} \right)$$

Figure A.2: Al-SiO₂-Si band diagram.

Thus, from the above equations, the surface state density can be determined using the measured C-V results.

Appendix D:

Photo-Induced Current Transient Spectroscopy Analysis Software


```

100 !$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
110 !
120 !
130 ! ..... TITLE PAGE .....
140 !
150 PRINTER IS 1
160 OUTPUT 2;"K";
170 BEEP
180 GINIT
190 GRAPHICS ON
200 LORG 5
210 CSIZE 5,.6
220 MOVE 66,95
230 LABEL "WELCOME"
240 MOVE 66,85
250 LABEL "TO THE"
260 CSIZE 17,.7
270 MOVE 66,60
280 LABEL "ODLTS"
290 MOVE 66,50
300 LABEL "ANALYSIS"
310 CSIZE 5.5,.6
320 MOVE 66,47
340 CSIZE 3.7,.6
350 MOVE 66,30
360 LABEL "NORTHERN TELECOM : DEPT P986 : FALL 1985"
370 INPUT "HIT ""CONT"" TO PROCEED... ",Dummy$—
380 GRAPHICS OFF
390 ALPHA ON
400 BEEP
410 !.....
420 !
430 PRINT " *****
      "
440 PRINT " ** ANALYSIS **
      "
450 PRINT " *****
      "
460 PRINT " "
470 PRINT " "
500 PRINT " "
510 PRINT " THIS ROUTINE WILL PROMPT FOR: "
520 PRINT "
530 PRINT " 1. FILENAME of the STORED DATA "
540 PRINT " 2. TYPE of ANALYSIS DESIRED
550 PRINT "
560 PRINT "
570 !
580 !
590 !

```

```

600  I
610  I
620  REAL Emission,Initialcap,Concentration,U2,Interval,Tempor(1:128)
650  COM /Plot1/ Labely$(30),Labelx$(30),Unitsy$(20),Unitsx$(20),Deltacap(1:150
,1:132)
660  COM /Datafield/,Data2(1:150,1:2)
670  COM /Scale/ Maxy,Maxx,Minx,Miny
680  INTEGER Counter,Done,I,J,I1,JJ,Start,R1(1:128),Im(1:128),Coeff(1:150,1:2,0
:10),Code,Arraysizes,N,M,T1,T2,Endpoint
690  I
700  I
710  I
720  Input_dist: I
730  I
780  I  PROMPT FOR FILENAME OF STORED COEFFICIENTS
790  I
800  Input_file: INPUT "FILENAME of COEFFICIENTS?",File$
810  IF File$="" THEN
820      GOTO Input_file
830  END IF
840  I
860  ASSIGN @File TO File$":INTERNAL,4,1"
900  I
910  ON END @File GOTO Data_in
920  I
930  ENTER @File;X,X,X,Interval,Length
940  ENTER @File;Deltacap(*)
950  I
951  Data_in: I
953  FOR I=1 TO Length
954      FOR J=5 TO 132
955          IF Deltacap(I,J)<>999999 THEN
956              Deltacap(I,J)=Deltacap(I,J)*1.E+15
957              Endpoint=J
959          END IF
960      NEXT J
961  NEXT I
962  I
963      Counter=Length
970  PRINT CHR$(129); " DATA RECIEVED: ";CHR$(128); "      # OF DATA POINTS IS",L
length
980  I
981  Critical=.01  IpAMPS  THIS IS THE LIMIT AT WHICH ANALYSIS IS PERFORMED
982  I              FOR THAT WAVELENGTH
990  I
1410 I
1420 BEEP
1430 I .....
1440 I
1450 I  ##### PROMPT FOR TYPE OF ANALYSIS DESIRED
1460 I
1470 Analysis_type: OUTPUT 2: F";
1480 GRAPHICS OFF
1490 PRINT CHR$(10); "ANALYSIS TYPES:"
1500 PRINT CHR$(10); "      1 = MAXIMUM CURRENT - MINIMUM CURRENT (DELTA CURRENT
)"
1530 PRINT CHR$(10); "      4 = CONVENTIONAL RATE WINDOW TECHNIQUE (C2-C1) SELECT
ING T2 & T1
1550 PRINT CHR$(10); "      6 = EMISSION RATE CALCULATED USING THE EXPONENTIAL CU
RVE FIT

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1570 PRINT CHR$(10); "      8 = EXIT PROGRAM "
1580 INPUT "TYPE of ANALYSIS? # ", Choise1
1590 IF (Choise1=0 OR Choise1>8) THEN
1600     GOTO Analysis_type
1610 END IF
1620 I
1630 OUTPUT 2;"K";
1640 I
1650 FOR I=1 TO Counter
1660     Data2(I,1)=0
1670     Data2(I,2)=0
1680 NEXT I
1690 I
1700 SELECT Choise1
1710 I .....
1720 CASE 1
1730     BEEP
1740     PRINT " "
1750     PRINT "      THIS ANALYSIS PLOTS THE DIFFERENCE IN THE MAXIMUM "
1760     PRINT "      AMPLITUDE OF THE CURRENT TRANSIENT VERSES WAVELENGTH
"
1770 I
1780     FOR I=1 TO Counter
1790         Data2(I,1)=Deltacap(I,1)
1793         Data2(I,2)=Deltacap(I,Endpoint)-Deltacap(I,2+4)
1810     NEXT I
1820 I
1830     CALL Scale_it(Data2(*),Counter)
1840 I
1850     Labely$="CURRENT"
1860     Labelx$="WAVELENGTH "
1870     Unitsy$="(fA)"
1880     Unitsx$="(nm) "
1890 I
1900     PRINTER IS 701
1910     PRINT " "
1920     PRINT "      MAXIMUM CURRENT DIFFERENCE VERSES WAVELENG
TH"
1960     PRINT "      SAMPLE INTERVAL (uS) :",Interval
1970     PRINT " "
1980     PRINT " "
1990     PRINTER IS 1
2000 I
2010     CALL Plot_rout(Counter,Maxy,Maxx,Minx,Miny)
2020     GOTO Analysis_type
2030 I
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2840 PRINT " Built-in constraint for the EMISSION RATE is: T2/T1 FIXED"
2850 PRINT " "
2860 PRINT " T2=N*T1 where "N" is chosen by the USER "
2870 PRINT " The recommended values is about 10 to 20 "
2880 PRINT " "
2890 PRINT " The value of T1 is chosen to be "M"*(Sample interval) "
2900 PRINT " Where the value of "M" is chosen by the USER "
2910 PRINT " "
2920 PRINT " Be sure that the value of T2 is within the DATA WINDOW "
2930 PRINT " If T2 is out of the data window then I(T2)-I(T1)=0 "
2940 PRINT " "
2950 I
2960 N_input: I
2970 N=-1
2980 INPUT "What is the value of N=T2/T1 do you want? ",N
2990 IF N<>INT(N) OR N<=0. THEN
3000 GOTO N_input
3010 END IF
3020 I
3030 I
-3040 Once=0
3050 M_input: I
3060 M=-1
3070 INPUT "What is the value of M = T1/(SAMPLE INTERVAL) ? ",M
3080 IF M<>INT(M) OR M<1 THEN
3090 GOTO M_input
3100 END IF
3110 I
3120 OUTPUT 2;"K";
3130 PRINT " "; " T1=";M*Interval;" T2=";N*M*Interval;" S
EC "
3140 Emission=LOG(N)/(N*M*Interval-M*Interval)
3150 PRINT " "
3160 PRINT " CONVENTIONAL RATE WINDOW TECHNIQUE"
3170 PRINT " THE EMISSION RATE WINDOW IS ";Emission;"SEC^-1"
3180 I
3190 FOR I=1 TO Counter
3200 Data2(I,1)=Deltacap(I,1)
3210 Start=Deltacap(I,3)
3220 T1=M*Start+4
3230 T2=N*M*Start+4
3240 IF T2<=Endpoint THEN
3250 Data2(I,2)=Deltacap(I,T2)-Deltacap(I,T1)
3260 ELSE
3270 Data2(I,2)=0.
3280 END IF
3290 I
3300 NEXT I
3310 I
3320 IF NOT Once THEN
3330 CALL Scale_11(Data2,Counter)
3340 END IF
3350 I
3360 Label1$="SIGNAL"
3370 Units1$="(In)"
3380 Label1$="WAVELENGTH"
3390 Units1$="(nm)"
3400 I
3410 I
3420 I
3430 PRINTER IS 701
3440 PRINT "

```

```

3450      PRINT "                CONVENTIONAL RATE WINDOW TECHNIQUE VERSES W
AVELENGTH"
3460      PRINT "                QUIESCENT BIAS VOLTAGE:" ,Qbvolt
3490      PRINT "                SAMPLE INTERVAL (SEC) : " ,Interval
3500      PRINT "                EMISSION RATE (SEC-1): " ,Emission
3510      PRINT "                N=T2/T1                : " ,N
3520      PRINT "                T1 (SEC)                : " ,M*Interval
3530      PRINT " "
3540      PRINT " "
3550      PRINTER IS 1
3560
3570      CALL Plot_rout(Counter,Maxy,Maxx,Minx,Miny)
3580
3590      Another=0
3600      INPUT "DO YOU WANT ANOTHER EMISSION RATE PLOT ? 1=YES ,0=NO " ,Another
3610      IF Another=1 THEN
3620          Once=1
3630          GOTO M_input
3640      ELSE
3650          GOTO Analysis_type
3660      END IF
3670
3680
5850
5860
5870      CASE 6
5880          EXPONENTIAL: Y=A EXP(-Et)
5890
5900      OUTPUT 2;"K";
5910      PRINT CHR$(130);" EXPONENTIAL CURVE FIT IN PROGRESS ";CHR$(129);" ...
PLEASE WAIT ";CHR$(128)
5920      FOR I=1 TO Length
5930          Data2(I,1)=Deltacap(I,1)
5940          Trail=(Deltacap(I,Endpoint)+Deltacap(I,Endpoint-1)+Deltacap(I,En
dpoint-2)+Deltacap(I,Endpoint-3))/4.0
6010          Ignore=.001!THIS IS TO IGNORE THE POINTS THAT HAVE OCCURED AFTER
6020              ! THE TRANSIENT
6030              ! THIS REDUCES THE EFFECT OF NOISE ON THE CALCULATION
6040              ! FOR THE CURVE FITTING ROUTINE
6050              ! IE. NOISE WILL CAUSE THE EXPONENT "E" TO INCREASE
6060              ! WHILE THE COEFFICIENT "A" WILL JUST BE SMALL
6080          FOR Jj=1 TO Endpoint-4
6090              Tempon(Jj)=-Trail+Deltacap(I,Jj+4)
6100          NEXT Jj
6110          X=0.
6120          Sum_xlny=0.
6130          Sum_x=0.
6140          Sum_lny=0.
6150          Sum_xe2=0.
6160          Ncount=0
6170          Start=2
6174          Points=Endpoint-4
6178
6180          FOR Jj=Start TO Points
6190              IF Tempon(Jj) > Ignore THEN
6200                  Sum_xlny=Sum_xlny+X*LOG(Tempon(Jj))
6210                  Sum_x=Sum_x+X
6220                  Sum_lny=Sum_lny+LOG(Tempon(Jj))
6230                  Sum_xe2=Sum_xe2+X*X
6240                  Ncount=Ncount+1

```

```

6250         END IF
6260         X=X+Interval
6270     NEXT J
6280     IF Ncount>3 THEN      I SHOULD HAVE MORE THAN 3 POINTS I
6290         Num=Sum_x*lny-Sum_x*Sum_lny/Ncount
6300         Denom=Sum_xe2-Sum_x*Sum_x/Ncount
6310         IF Denom<>0 THEN
6320             Data2(I,2)=-Num/Denom
6330         ELSE
6340             Data2(I,2)=0.
6350         END IF
6360     ELSE
6370         Data2(I,2)=0
6380     END IF
6390     PRINT I,Ncount
6400 NEXT I
6410
6420     BEEP
6430     OUTPUT 2;"K";
6440
6450     CALL Scale_it(Data2(*),Counter)
6460
6470     Labely$="EMISSION RATE"
6480     Unitsy$="(SEC^-1)"
6490     Labelx$="WAVELENGTH "
6500     Unitsx$="(nm)"
6510
6520     PRINTER IS 701
6530     PRINT "
6540     PRINT "          EMISSION RATE DERIVED FROM EXPONENTIAL CURVE FIT VS. WA
VELENGTH "
6550     PRINT " "
6590     PRINT "          SAMPLE INTERVAL          : ",Interval
6600     PRINT " "
6610
6620     CALL Plot_rout(Counter,Maxy,Maxx,Minx,Miny)
6630
6640     CALL Arrhen(Data2(*),Counter)
6650
6660     GOTO Analysis_type
6670
6680
6690
6970 CASE 8
6980
6990     PRINT "PROGRAM TERMINATED....."
7000     GOTO Finish
7010
7020
7030 CASE ELSE
7040
7050     PRINT "IMPROPER CHOISE OF ANALYSIS"
7060     GOTO Analysis_type
7070
7080 END SELECT
7090
7100 Finish:END
7110
7120
7130
7140

```

```

7150 I *****
7160 SUB Arrhen(Data2(*),INTEGER Counter)
7170     COM /Scale/ Maxy,Maxx,Minx,Miny
7180     COM /Plot1/ Labely$,Labelx$,Unitsy$,Unitsex$,Deltacap(1:150,1:132)
7190 I
7200     OUTPUT 2;"K";
7210 Input_continue:PRINT CHR$(10);"SHOULD THE ANALYSIS CONTINUE WITH THE ENERGY
PLOT ? "
7220     PRINT "? (1=YES,0=NO (DEFAULT))"
7230     INPUT " ( 1=YES , 0=NO ) ",Choise3
7240     IF (Choise3<0 OR Choise3>1) THEN
7250         GOTO Input_continue
7260     END IF
7270 I
7280     IF Choise3=0 THEN
7290         GOTO Leave_arrh
7300     END IF
7310 I
7320     FOR I=1 TO Counter
7330         Data2(I,1)=1240./Deltacap(I,1)  IE=HC/LAMBDA
7390     NEXT I
7400 I
7410     CALL Scale_it(Data2(*),Counter)
7420 I
7430     Labely$="CURRENT"
7440     Unitsy$="(fA)"
7450     Labelx$="ENERGY"
7460     Unitsex$="(eV)"
7470 I
7480     PRINTER IS 701
7490     PRINT " "
7500     PRINT "          ENERGY PLOT: CURRENT VERSES ENERGY"
7510     PRINT " "
7520     PRINTER IS 1
7530 I
7540     CALL Plot_rout(Counter,Maxy,Maxx,Minx,Miny)
7550 I
7560     OUTPUT 2;"K";
7570     Ans=0
7571     GOTO Leave_arrh
7580     INPUT "DO YOU WANT TO CALCULATE ANY ENERGIES & CONCENTRATION? (1=YES
, DEFAULT=NO)",Ans
7590     IF Ans THEN
7600         GRAPHICS OFF
7610 I
7620         PRINT " "
7630         PRINT " THIS ROUTINE WILL CALCULATE THE ACTIVATION ENERGY "
7640         PRINT " OF THE TRAPS FOUND IN THE SPECTRUM"
7650         PRINT " "
7660         PRINT " Since there may be more than one trap in the spectrum, "
7670         PRINT " the user must specify the regime of that trap."
7680         PRINT " This is done by specifying the window in which to look."
7690         PRINT " "
7700         PRINT " "
7710         PRINT " The next statement will prompt the user for the window:
"
7720         PRINT " Use the TEMPERATURE scale to discern the WINDOW "
7730         PRINT " "
7740 Energy:
7750         INPUT "What is the LOWER limit of the TRAP WINDOW (K)?",Lowerlim

```

```

7760      INPUT "What is the HIGHER limit of the TRAP WINDOW (K)?" ,Higher1
7770      1m
7780
7790      X=0.
7800      Sum_xy=0.
7810      Sum_x=0.
7820      Sum_y=0.
7830      Sum_xe2=0.
7840      Ncount=0
7850      FOR I1=1 TO Counter
7860          IF Data2(I1,1)>1000./Higher1m AND Data2(I1,1)<1000./Lower1
1m AND Data2(I1,2)>0 THEN
7870              IF Ncount<1. THEN
7880                  Lowtemp=1000./Data2(I1,1)
7890              END IF
7900              Hightemp=1000./Data2(I1,1)
7910
7920              Sum_xy=Sum_xy+Data2(I1,1)*Data2(I1,2)
7930              Sum_x=Sum_x+Data2(I1,1)
7940              Sum_y=Sum_y+Data2(I1,2)
7950              Sum_xe2=Sum_xe2+Data2(I1,1)*Data2(I1,1)
7960              Ncount=Ncount+1
7970          END IF
7980      NEXT I1
7990      IF Ncount>3 THEN      I SHOULD HAVE MORE THAN 3 POINTS.
8000          Avetemp=(Lowtemp+Hightemp)/2.
8010          Num=Sum_xy-Sum_x*Sum_y/Ncount
8020          Denom=Sum_xe2-Sum_x*Sum_x/Ncount
8030          IF Denom<>0 THEN
8040              Slope=Num/Denom
8050              Energy=(Slope*1000.-2*Avetemp)*(1.381E-23)/1.602E-19
8060              Energy=DROUND(Energy,3)
8070              PRINT " "
8080              PRINT "NUMBER OF POINTS USED TO CALCULATE ENERGY: ";Nc
ount
8090              PRINT " "
8100              PRINT " THE ENERGY OF THIS TRAP IS ";Energy;" eV"
8110              PRINT " "
8120              Ans=0
8130              INPUT " DO YOU WANT THIS PRINTED TO THE PRINTER ? (1=Y
ES, DEFAULT=NO)" ,Ans
8140              IF Ans THEN
8150                  PRINTER IS 701
8160                  PRINT " "
8170                  PRINT Ncount;" POINTS USED BETWEEN"
8180                  PRINT Lower1m;" AND ";Higher1m
8190                  PRINT " THE ENERGY OF THIS TRAP IS ";Energy;" eV"
8200                  PRINTER IS 1
8210              END IF
8220          ELSE
8230              PRINT "CAN'T CALCULATE THE SLOPE FOR SOME REASON"
8240          END IF
8250      ELSE
8260          PRINT "NOT ENOUGH DATA POINTS TO CALCULATE THE SLOPE"
8270      END IF
8280      Ans=0
8290      INPUT " DO YOU WANT TO CALCULATE ANOTHER ENERGY FOR ANOTHER TRAP
? (1=YES or Default=NO)" ,Ans
8300      IF Ans THEN

```


[illegible]

```

9330     FOR I=1 TO Finish
9340         DRAW Data2(I,1),Data2(I,2)
9370     NEXT I
9380     LINE TYPE 3
9390     MOVE Minx,0
9400     DRAW Maxx,0.
9410     PRINTER IS 701
9420     Dump$="YES"
9430     INPUT "DO YOU WANT TO DUMP THE GRAPHICS? N=NO DEFAULT=YES ",Dump$
9440     IF TRIM$(Dump$)<>"N" THEN
9450         DUMP GRAPHICS
9460     END IF
9470     GRAPHICS OFF
9480     PRINTER IS 1
9490 SUBEND
9500 !
9510 !*****
9520 !
9530 SUB Scale_it(Values(*),INTEGER Counter)
9540 !
9550 !   A SUBROUTINE TO SCALE THE PLOT OF DATA2(*)
9560 !
9570     COM /Scale/ Maxy,Maxx,Minx,Miny
9580 !
9590 !   SCALE THE Y-AXIS
9600 !
9610     Miny=Values(1,2)
9620     Maxy=Values(1,2)
9630     FOR I=1 TO Counter
9640         IF (Miny>Values(I,2) AND Values(I,2)<>0) THEN
9650             Miny=Values(I,2)
9660         END IF
9670         IF (Maxy<Values(I,2) AND Values(I,2)<>0) THEN
9680             Maxy=Values(I,2)
9690         END IF
9700     NEXT I
9730 !
9740 !   SCALE THE X-AXIS
9750 !
9760     Maxx=Values(1,1)
9770     Minx=Values(1,1)
9780     FOR I=1 TO Counter
9790         IF (Minx>Values(I,1) AND Values(I,1)<>0) THEN
9800             Minx=Values(I,1)
9810         END IF
9820         IF (Maxx<Values(I,1) AND Values(I,1)<>0) THEN
9830             Maxx=Values(I,1)
9840         END IF
9850     NEXT I
9880 !
9890 SUBEND
9900 !

```

Appendix E:

Monochromator Calibration Curve

END

09-08-88

FIN