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Performance of Gas Microstrip Detectors Constructed on Plastic Substrates

by

Stephen C. Taylor, B. Appl. Sc.

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

Master of Science

Department of Physics

Ottawa-Carleton Institute for Physics

Ottawa, Ontario

December 21, 1994

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Performance of Gas Microstrip Detectors Constructed on Plastic Substrates

submitted by Stephen C. Taylor, B. Appl. Sc.
in partial fulfillment of the requirements for
the degree of Master of Science

Thesis Supervisor

Chair, Department of Physics

Carleton University
December 21, 1994

Abstract

The development and construction of Gas Microstrip Detectors (GMDs) is reviewed. Several Gas Microstrip Detectors were constructed on plastic substrates. The performance of these detectors in the laboratory and at particle accelerator facilities is examined. Results from these studies are given. The electric field configuration within these detectors is examined and the consequences of these fields on detector performance are discussed. A model of high flux operation is detailed. Some applications of this new detector technology are given.

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Chapter 1

Description of Gas Microstrip Detectors

Gas Microstrip Detectors (GMDs), also known as Microstrip Gas Counters (MS-GCs), are an advanced form of proportional gas counter. In essence, these devices detect radiation by using the principle that charged particle interactions in a gaseous medium normally result in the ionization of a number of the atoms in the gas. Static electric fields are applied to the gas volume to collect and amplify the resulting electrons and ions. This provides an electrical signal from which the passage of a particle can be inferred.

Proportional gas counters are one of the earliest forms of particle detectors. As such, they represent a tried and true technology, having served the physics community with distinction through much of the last century. In that time, the technology has gone through several transitions, to produce new and better detectors that serve a wide variety of applications. Still, the limits of this technology have not yet been reached. With the development of Gas Microstrip Detectors, proportional gas counters have spawned a new generation of advanced particle detectors ready to participate in the high energy, high luminosity physics experiments of the next century.

Figure 1.1: The basic elements of a single wire gas counter.

1.1 Historical Development of Gas Chambers

The first development of a gas counter has been credited to Geiger in 1929 [1]. Hans Geiger was a colleague of Ernest Rutherford at Manchester, and he developed the detector to automate the famous Gold Leaf experiment which had involved observing a phosphorous screen by eye to that point. Geiger counters have changed very little since that time. The apparatus for such a device, identical in structure to a single wire proportional gas counter, is shown schematically in Figure 1.1.

1.1.1 The Single Wire Gas Counter

The cylinder shown in Figure 1.1 contains the gas volume, typically argon, and is held at ground to serve as the cathode. The anode wire runs along the axis of the cylinder and is electrically isolated from the cylinder. A high voltage can be applied to the anode wire to create a radially symmetric electric field in the gas. Because of the small radius of the anode wire, the electric field strength is quite high within a few radii of the wire.

As a charged particle passes through the gas volume, it leaves behind a trail

of electron-ion pairs. The movement of the liberated charges in the electric field induces a signal on the external circuit. Once the electrons have migrated to the high field region around the anode wire, they may achieve sufficient momentum to cause secondary ionization of the gas, and an electrical avalanche results. The effect on the signal induced in the external circuit depends on the anode voltage. Figure 1.2 shows that there are five regions of operation of the gas counter. At low voltage, some of the electrons are able to recombine before they are collected by the anode wire. In the ionization counter region, the electrons do not achieve sufficient momentum for secondary ionization, and so only the charges liberated directly by the particle are collected. In the proportional counter region, an avalanche occurs and the overall signal is increased. In this region, the signal is in proportion to the initial ionization in the gas, but is increased or multiplied by a factor that depends on the anode voltage. This is referred to as the gas gain. In the Geiger counter region, the avalanche is sufficiently strong to cause a breakdown of the gas. This produces a very large signal, but it is independent of the amount of ionization initially deposited. In the last region, the counter continuously discharges from anode to cathode.

1.1.2 The Multiwire Proportional Counter

The Multiwire Proportional Counter (MWPC) was an important extension to gas counter technology made by Charpak and his collaborators at CERN [2] — work for which he was later to receive the Nobel Prize for Physics. The MWPC consists of several anode wires lying in a plane and separated by two cathode planes, as shown in Figure 1.3. Each anode wire acts as an individual proportional gas counter, but the anode wires are much more closely packed than would be possible with an array of individual single wire counters.

The performance of the MWPC is a strong function of the proximity of the anode wires. Besides improving the spatial resolution of the detector, closely

Figure 1.2: The voltage characteristics of a gas counter. The regions of operation are: the recombination (R) region, the ion collection (IC) region, the proportional counter (PC) region, the Geiger counter (GC) region, and the discharge (D) region.

Figure 1.3: Multiwire Proportional Counter cross-section showing typical dimensions.

spaced wires reduce dead time since the greater number of wires share the load. However, because of electrostatic repulsion between the similarly charged anode wires, the wire spacing in a MWPC is limited. Wires begin to bend and stagger themselves outside of the anode plane if too closely packed. This can lead to gain variations and possibly breakage of an anode wire during operation of the chamber. Typically, anode wires are limited to greater than 1 mm pitch for a useful detector size.

Another feature of MWPC is the rather large drift distance that the ions need to travel from their point of creation in the avalanche region around the anode wire to the cathode plane. The long travel time for these ions induces a slow pulse on the external circuit, increasing the resolving time. In addition, the long lived space charge distorts the electric field in the counter, degrading performance at high particle flux. Efforts to move the cathode plane closer to the anodes causes further wire bending and gain variations, while at the same time reducing the interaction volume and detection efficiency.

1.2 The Gas Microstrip Detector

The Gas Microstrip Detector (GMD) was first introduced by Oed [3] in an effort to improve on the MWPC in the areas mentioned above. In a GMD, the anode wires of the MWPC are replaced by metallic strips formed by lithography on an insulating substrate. The cross section of a typical GMD is shown schematically in Figure 1.4. Because the anodes are now fixed on a substrate, there is no bending or breakage of anodes due to electrostatic repulsion, and it is possible to bring the anodes much closer together than in a MWPC. Typical anode pitch in a GMD is on the order of 0.2 mm. Cathode strips, running parallel to the anode strips, are placed between each successive anode. This is achieved by interleaving the anode and cathode strips, as demonstrated in the schematic plan view of a GMD in Figure 1.5. It is conjectured that a large fractions of the ions formed in

Figure 1.4: Gas Microstrip Detector cross-section showing typical dimensions.

the avalanche over the anode strips will drift not to the distant “drift” electrode, but to the much closer cathode strips, thus improving the resolving time for particle passage and the high particle flux performance.

GMD operation begins with the interaction of a charged particle in the gas volume, as shown in Figure 1.4. The interaction leaves behind a number of clusters of electron-ion pairs, resulting in a subsequent avalanche at the anodes as in the single wire counter. Typically, the number of liberated electrons due to the avalanche in a GMD ranges from several hundred to several thousand for each primary electron.

The electrons formed in the avalanche are quickly absorbed by the anodes. This fast collection of charge creates a fast impulse in the external circuit. The newly created ions, on the other hand, have to travel to the drift plane or cathodes, and are collected over a longer period of time, producing a slow pulse on the external circuit. Generally, the total signal induced on the external circuit is not large enough to be useful and requires amplification. For a GMD, with typically 2 to 5 anodes per millimeter, many amplifier channels are required for a large area of detector coverage.

Figure 1.5: Gas Microstrip Detector plan view showing typical dimensions.

Gas gain, drift times, and general performance of the GMD can be affected by modifications to the electric field configuration in the gas volume. Figure 1.6 shows the kind of field configuration one generally finds in these devices. The cathode strips are sufficiently close to the anodes that the observed gas gain is a very strong function of anode to cathode strip potential. The drift electrode, being further away, has less effect on gain. It is desirable to keep the drift potential as low as possible to avoid attracting a large fraction of ions from the avalanche region. The back electrode or backplane is located on the underside of the substrate. This electrode is useful under some conditions to shape the field lines in the gas in order to improve the performance of the detector. Some studies have shown [4] that a backplane segmented in a direction perpendicular to the anode direction can be used to provide a second dimension of position information for the particle passage. This is accomplished by reading the small induced signals appearing on the backplane in the vicinity of the avalanche.

Figure 1.6: Typical electric field configuration in a GMD.

Chapter 2

Design and Manufacture

Since their conception, GMDs have undergone many changes and improvements in an effort to achieve the best performance in terms of resolution, sensitivity, and longevity. This last item, measured in terms of radiation hardness and stability of performance with time, is of particular importance for high energy physics applications where detectors are expected to function with little or no maintenance for many years of operation. In attempting to achieve these goals, a wide range of parameters can be adjusted including geometry, materials used, lithographic techniques, and operating conditions.

2.1 Choice of Substrate

Originally, GMDs were manufactured on very insulating substrate materials, such as ordinary glass, to minimize heating and noise due to currents in the substrate. It was quickly realized [3, 5, 6] that these devices exhibited instabilities and gain modifications over time, especially during high rate operation. These changes were attributed [3] to the charging of the insulating substrate between the electrodes. If some of the ions formed in an avalanche around the anode drift onto the surface of the substrate, it is possible for a region of positive charge to build

Substrate	Nominal bulk Resistivity (Ω -cm)	Reference
Hoya SL (soda-lime) glass	10^{15}	[5]
Murano glass ^a	10^{12}	[5]
Pestov (iron-silicate) glass ^b	10^{12}	[7]
Borosilicate glass (low alkali)	10^8	[8]
Tedlar ^c vinyl fluoride film	10^{14}	[9]
Kapton ^c polyimide film	10^{17}	[9]
Silicon dioxide	10^{17}	[10]
Alumina	10^{16}	[6, 11]
Quartz	10^{19}	[8]

^aMurano, Stazione Sperimentale del Vetro, Venezia, Italy.

^bScientific Research Institute of Electrovacuum Glass, Moscow, Russia.

^cTedlar and Kapton are trade names of DuPont de Nemours Co.

Table 2.1: Substrate materials investigated for use with GMDs

up there due to their reduced mobility in the insulator. This has the effect of changing the electric field configuration, and therefore the gas gain, in the GMD.

The backplane electrode was introduced to partially reduce this problem. Presumably, adjustment of the backplane voltage can have the effect of repelling ions away from the substrate surface, thus avoiding charging effects. A more permanent solution is to reduce the resistivity of the substrate to allow any charge buildup to be neutralized quickly by surface currents. Care must be taken however: large substrate currents could lead to problems with heat dissipation and shot noise. Quite a large amount of effort has been devoted in the past few years to testing GMDs built on various possible substrates. Researchers look for gain instabilities over time, for instantaneous gain loss at high particle flux, and for localized permanent gain loss due to exposure to a large integrated flux. Table 2.1 provides a list of some of the bulk substrates examined in the past.

Each of the substrates listed in Table 2.1 has its own unique and desirable

properties. In particular, glass and silicon substrates are particularly easy to perform lithography on, and so produce high quality prints with few defects. Plastic substrates, while being difficult to process, are more flexible and robust than thin glass. Plastic GMDs could presumably take many shapes, including a cylindrical geometry with small radius. The fact that plastics can be made very thin, and that they are low Z materials, makes them especially attractive for use in high energy physics experiments where multiple scattering needs to be kept to a minimum.

The desire to tune the substrate properties to a precise level has lead researchers to explore various techniques of treating existing substrates to modify their electrical characteristics. Some groups [12, 13] have concentrated on the deposition of a thin conductive layer after lithography. Others [14, 9] have subjected substrates to ion bombardment to increase the conductivity at the surface.

A useful measure in the study of substrate conduction is the *surface resistivity* of the substrate. Surface resistivity for a bulk conductor is defined as the resistivity of the conductor divided by its thickness. Even if a substrate exhibits non-uniform currents over its thickness, such as for a substrate with treated inter-electrode surface, surface resistivity can be used as a measure of the currents expected between anode and cathode. The units of surface resistivity are Ω , but values are often quoted in $\Omega/\square$ to distinguish from units of resistance. The symbol $\square$ originates from the ability to measure the length/width ratio between two conductors by counting the number of *squares* between them. For instance, if two parallel electrodes evaporated onto a surface conducting material are each 1.0 cm long and are separated by 2.0 cm, then it is possible to construct 2 equal sized squares between the conductors. If a resistance of 80Ω is measured between the conductors then the surface resistivity is $80 \div 2 = 40 \Omega/\square$. A desirable range of surface resistivities as a compromise between charging effects and shot noise is 10^{12} to $10^{14} \Omega/\square$.

2.1.1 Ion Implantation of Plastic Substrates

As mentioned above, ion bombardment (or implantation) of substrate surfaces has been suggested as a means of lowering the surface resistivity of insulating substrates. In order to study the effect of this technique on plastics — in particular, polyimide film — an experiment was conducted [15]. The results of this study are reproduced here.

A poly [N,N' -(p,p' -oxydiphenylene) pyromellitimide] film $[(C_{22}H_{10}O_5N_2)_n]$ manufactured by DuPont under the trade name *Kapton* was chosen for study because of its lightness, strength, and resistance to the high temperatures incurred during implantation. Polyimides are particularly useful for high energy physics applications as they are a low Z material which can be made very thin and exhibit high radiation resistance. The nominal surface resistivity of untreated Kapton is $10^{19} \Omega/\square$, which is considered too high for use in GMDs. Previous studies on the properties of ion-implanted Kapton have been conducted [16, 17], and are useful for comparison purposes.

Kapton film of $125 \mu\text{m}$ thickness was cut into 28 samples of 3 inch diameter. Each sample was mounted on a 3 inch aluminum disc with epoxy and individually labeled. Two discs — labeled A and B — were treated at each ion dose and energy setting used. Table 2.2 lists the ion dose and energy used for each sample. These parameters were chosen so that the effect of dose, energy and ion species could be studied independently.

After implantation, performed by Orenda (Hawker-Siddeley Canada), the samples which had received a heavier ion dose were observed to have noticeably darkened in colour. Whereas untreated Kapton is a translucent light brown, samples 4 and 11 were a grey colour with an almost metallic sheen and more opaque. Additionally, the Kapton film in sample 4 had pulled off the aluminum backing in several places, possibly as a result of over-heating of the sample during implantation.

Sample	Ion Type	Dose (cm^{-2})	Energy (keV)
1A, 1B	copper	10^{13}	300
2A, 2B	"	10^{14}	300
3A, 3B	"	10^{15}	300
4A, 4B	"	10^{16}	300
5A, 5B	"	10^{14}	50
6A, 6B	"	10^{14}	100
7A, 7B	"	10^{14}	400
8A, 8B	carbon	10^{13}	100
9A, 9B	"	10^{14}	100
10A, 10B	"	10^{15}	100
11A, 11B	"	10^{16}	100
12A, 12B	"	10^{14}	50
13A, 13B	"	10^{14}	200
14A, 14B	"	10^{14}	400

Table 2.2: Implantation parameters for ion-implanted samples.

In order to measure the surface resistivity of the Kapton samples, a Hewlett-Packard 4329A High Resistance Meter was employed in conjunction with a HP 16008A Resistivity Cell. The High Resistance Meter consisted of a high voltage (1000V) DC supply and a sensitive parametric current meter. A switch on the meter provided a *Charge* setting which exposed the sample to the test voltage without connecting the current meter, allowing any high currents due to capacitive effects to dissipate in advance.

The Resistivity Cell consisted of a circular anode 5 cm in diameter surrounded by an annular cathode 7 cm in diameter and 1 cm wide. The circular geometry eliminated fringe electrical field effects and allowed for a very accurate calculation of the effective width/length.

After applying the test voltage (from 10 to 1000 VDC) to each sample using the *Charge* setting for a few minutes, the current meter was connected and the resistance reading allowed to settle to an equilibrium value. Capacitive and

charging effects as well as the slow action of the current meter caused gradual changes in meter reading for the first few minutes. An equilibrium was usually established after a period of 10–20 minutes. If the resistance of the sample proved too low, or if noise due to corona effects was detected, the test voltage was reduced (after a period of rest) and the process repeated. If a sample needed to be remeasured for any reason, a period of at least 10 minutes was allowed between measurements to allow any charge buildup to diffuse through the sample. Once a final resistance for the sample in the cell was obtained, the result was multiplied by the *geometry factor* — the number of *squares* in the cell — to obtain the surface resistivity of the sample.

The samples were measured initially in the open atmosphere. Results using different voltage settings indicated roughly Ohmic behavior for all the samples. Measurements in the open atmosphere proved to be repeatable to within a factor of 5. With the belief that moisture in the atmosphere might be affecting the readings, half the samples were placed in a dry nitrogen atmosphere and were left for the period of a week. The entire measuring apparatus was placed in the “dry box” and could be operated from the outside with rubber sleeves. Comparison of the two sets of samples after a week indicated that the resistivities in the dry atmosphere had not changed significantly, but that results were more repeatable in the dry box — to within a factor of 2.

All the samples were placed in the dry box, and the samples were measured every couple of weeks to see if there was a temporal dependence to the surface resistivity of ion-implanted Kapton.

An attempt was made at mapping the concentration of implanted ions in the Kapton samples as a function of depth into the sample. This was accomplished by means of an Auger electron microscope, which could measure concentrations of certain ion species near the surface of a sample, coupled with a rastered ion beam which slowly burned away layer after layer of Kapton. However, the concentration of ions at any depth proved too low for the rated sensitivity of the Auger electron

Figure 2.1: Surface resistivities of ion-implanted Kapton samples.

detector, and this analysis proved impossible.

Figure 2.1 shows the effect of increased ion dose on surface resistivity of Kapton. Clearly, a heavy dose has the effect of reducing the surface resistivity quite dramatically. The surface resistivities of the samples measured spread over the entire range of the measuring apparatus used — from 10^8 to 10^{18} $\Omega/\square$. The lowest surface resistivity measured, with a dose of 10^{16} ions/cm², was a full 10 orders of magnitude below that of untreated Kapton. As Figure 2.1 demonstrates, it is certainly possible to tune the surface resistivity of Kapton film with this technique. It appears that the copper and carbon doped samples were effected roughly equally by the ion implantation, leading one to believe that the reduction in surface resistivity has more to do with the radiation damage caused by the ions rather than the presence of a new species of ion residing in the sample.

Unfortunately, a number of the samples whose doping levels were in the 10^{14} cm⁻² range proved too high in resistance to be measured with the Resistance Cell. As this was the implantation level chosen for the variation in ion energy, the effect of ion energy on surface resistivity could not be studied with

Figure 2.2: Aging of ion-implanted Kapton samples.

the existing apparatus.

A number of the samples did consistently give measurable readings, however, and these were used to study the longevity of the modifications to surface resistivity caused by ion implantation. Figure 2.2 shows the aging of the samples over a period of 90 days from the day of implantation. During the period in which measurements were taken, no increase, or "decay", of the surface resistivity was observable, although random fluctuations of within a factor of 2 were noticed. It may be that some rapid decay in surface resistivity occurred in the first few days following the implantation, but if so the decay had reached an equilibrium point before measurements had begun. No further decay in surface resistivity was projected for the lifetime of the samples.

The results given above show that ion implantation is indeed a powerful method of tuning the surface resistivity of plastic films. Variation over at least 10 orders of magnitude is possible. Resulting surface resistivities seem to be fairly independent of ion species used and quite independent of time.

The mechanism by which this reduction in surface resistivity occurs through

ion implantation remains a subject of some debate. However, there is no doubt that this technique has a number of important applications, including use in GMDs. In the future, methods of handling and irradiating larger samples will need to be investigated.

2.2 Printing and Lithography

Because of the small feature size of GMD electrodes (anodes strips are typically 10–20 μm wide), special techniques must be employed to ensure accuracy and uniformity of the metal strips during production. Photolithography, a technique for printing small metal features, has been developed to an art by the microelectronics industry, and is ideal for printing GMDs. These techniques boast accuracies down to the 1 μm level.

At the heart of any photolithographic process is the use of a photosensitive organic material called *photoresist*. The substrate surface is coated with a layer of photoresist, and this layer is selectively exposed to light through a *photomask* carrying the pattern to be transferred. The photoresist is then developed to transfer the light intensity pattern onto the organic film. This film then serves as a mask for subsequent etching or processing. Photoresists can be either negative or positive. Exposure to light renders negative photoresist insoluble to the developer, whereas positive photoresist becomes soluble under light.

A second important step in the photolithographic preparation of GMD prints is the deposition of the metal used to form the electrode strips. Several different metals have been used in the past to form these strips, including chromium, aluminum and gold. In some cases, especially for deposition on plastic substrates, a multi-layered metallization is used, including a thin *adhesion layer* constructed of a metal which has proven to adhere well to the substrate surface. A thicker, more conductive layer can then be applied on top of the adhesion layer.

Metal deposition is normally accomplished through one of two techniques:

vacuum evaporation or sputtering. With both techniques, the substrate is placed in a vacuum chamber some distance from the source of the metal atoms. With vacuum evaporation, the metal source is heated to give a substantial vapor pressure. The mean free path in the chamber must be greater than the source to substrate distance. Heating can be accomplished by placing the metal source in a tungsten *boat* and passing large currents through this boat. This method can introduce contaminants from the boat into the deposited layer, however. More advanced evaporation systems use radio frequency (RF) induction or a high-energy (~ 10 keV) electron beam to heat the metal source.

Sputtering techniques involve the introduction of an inert gas (typically argon) into the vacuum chamber. The metal source, or *target*, is run at a high RF voltage which acts to ionize the gas. These ions achieve sufficient energy to bombard the target and release the surface metal atoms. If the substrate is located sufficiently close to the resulting plasma, some metal ions will redeposit on the surface, forming a metal layer.

Two different photolithographic methods of forming a GMD pattern on a substrate have been explored, each having some advantages over the other. They are outlined below.

2.2.1 Wet Chemical Etching

In a wet chemical etching process, the substrate is first coated uniformly with metal. Photoresist is then applied and developed such that the metal to be removed is exposed as shown in Figure 2.3. The exposed metal is then subjected to a strong aqueous acid solution to remove it. The key to successful chemical etching is the *selectivity* of the acid — the solution should attack the metal more quickly than it does the hardened photoresist, and should not etch the substrate material.

Figure 2.3 also shows the results of *undercutting* of the metal layer, which often

Figure 2.3: The wet chemical etching process.

accompanies wet etched prints. This distortion of edge features can have profound implications to the electric field configuration in the GMD near the electrodes. If the electrodes (especially the anode) are made too narrow by undercutting, the photomask may be *biased* as shown.

2.2.2 Lift-Off

The lift-off technique requires a thick negative photoresist to be applied to the substrate first. The photoresist is exposed so that gaps appear where the metal lines are to be, as shown in Figure 2.4. Metal is then deposited and the photoresist dissolved in acetone, leaving the metal in the gap and removing the metal that coated the photoresist. To improve the edge quality of the resulting metal strips, an overhang can be created in the photoresist layer, as shown.

2.2.3 Print Artifacts and Defects

Though photolithographic techniques claim the ability to produce structures with resolutions better than 1 micron, even the most careful process can leave behind defects which can cause the resulting device to fail. In the microelectronics industry, the term *defect density* is used to describe the mean number of lethal defects per unit area on a silicon wafer. In a typical multilayer fabrication process, a value of 4 defects/cm² is not uncommon [18, p.156]. Fortunately for this industry, the size of each device (chip) is small, so that a number of devices escape without any defects. GMD prints, on the other hand, are made to be of a much larger size. Single devices can be 100 cm² or greater. Although there are many fewer steps involved in the fabrication of a GMD than a silicon integrated circuit, one can still expect a fair number of defects to appear on such a large print.

In addition, whereas photolithography on silicon is a tried and true technology, applying these techniques to some of the diverse substrates used in GMDs presents unique and challenging problems. Photolithography on plastics, in particular, has

Figure 2.4: The lift-off process.

Figure 2.5: Optical microscope picture of a break defect.

required much iteration to reduce the defect density.

GMD print defects normally involve the absence of desired metal or the introduction of spurious metal on the substrate surface. If sufficient metal is absent, a *break* can result (Figure 2.5), rendering part of the print unbiased and blind to incident radiation. A large amount of spurious metal can lead to a *short* (Figure 2.6) which leaves one or more anodes useless. Intermediate sized defects are *islands*, *spurs*, *blobs* and *bites* (Figure 2.7) which don't disable any part of the print, but the resulting oddly shaped electrodes will distort the desired electric field configuration of the GMD and create unpredictable and non-uniform results. In addition, the high fields located in the vicinity of a sharp point created by such a defect can cause the counting gas to electrically break down at low bias. The resulting noise may be too large for acceptable GMD operation, and so an artificial limit to the gas gain is imposed on the device.

Figure 2.6: Optical microscope picture of a short defect.

Figure 2.7: Intermediate print defects.

2.3 GMD Infrastructure

The substrate and lithographic print are but a small part of what makes up a complete Gas Microstrip Detector. A volume of counting gas must be provided above the substrate surface. Connections must be made from the print to the high voltage supplies and external readouts. A print holder and box have been designed to satisfy these needs.

Figure 2.8 shows a G10 fiberglass or printed circuit (PC) board used to hold the GMD print. Metallized lines are printed on this board to carry the high voltage and signal lines to and from the print. Current limiting resistors and RF blocking low-pass filters are mounted directly on the board. A large square area of metal is printed below where the print is located and is used to provide the backplane potential. In this way, the back surface of the substrate does not have to be metallized — saving an extra process step. Connections from the PC board to the print are made through the use of heat seal strip connectors¹. These connectors are strips of tape with embedded metal traces spaced every 2 mm running across the tape. Connections are made by matching pads on the print with the corresponding pads on the PC board and sealing the Elform tape over the gap using a heated press. Signal (anode) lines are run from the print along the left side of the PC board to a pin connector on top of the board. Preliminary electronics are connected at this point. Of the 24 signal channels that are extracted from each print, the inner 16 are derived from individual anode strips whereas the outside 8 are *groups* of ganged anodes.

To house the print and provide a gas volume, a box as shown in Figure 2.9 is used. Shown in the Figure are the high voltage BNC connectors on the right, the gas inlet/outlets on the sides of the box, and the box housing the preamplifying electronics mounted on the signal pin connector at the top left. In the middle of

¹Manufactured by Nipon Graphitic, Japan and distributed by Elform Co., Reno, Nevada.

Figure 2.8: Printed circuit board used to hold the print.

Figure 2.9: Box used to house the GMD with preamplifiers attached.

the box is a Mylar² plastic window which provides a seal to the gas volume while providing minimal attenuation to radiation. A wire mesh is placed just below this window to serve as the drift electrode.

²Trademark of DuPont.

Chapter 3

Laboratory Performance

Empirical laboratory studies of GMDs are useful in determining the viability of a particular GMD design or manufacturing technique. In addition, these tests can produce insights into the general characteristics of GMDs, including performance limitations. Three different laboratory techniques have been used to study GMDs manufactured on plastic substrates: low rate studies using radioactive sources, higher rate studies using an X-ray generator, and studies with minimum ionizing particles (MIPs) at particle accelerator facilities.

3.1 Low Rate Performance

A convenient initial test of a GMD is to measure its response to low rate radiation from a radioactive source. If the chamber is operating in the proportional mode, a measure of the gas gain and energy resolution can also be obtained by looking for the characteristic energy lines of the source in the spectrum measured with the detector. Figure 3.1 schematically shows the apparatus that was used to make these measurements.

Figure 3.2 shows a pulse height spectrum obtained in the laboratory using an Fe-55 source, which is a 5.9 keV X-ray source. The GMD used consisted of gold

Figure 3.1: Laboratory apparatus for radioactive source testing.

metallization on an ion-implanted Upilex¹ plastic substrate. The anode pitch was 400 μm and the gas was 90% argon, 10% isobutane. The spectrum shown was produced by “ganging” all the anodes together on the print, and using a long amplifier integration time. In this way, a single channel collected all the charge created in the chamber from each X-ray. The position of the large peak corresponds to the pulse height achieved when the 5.9 keV X-ray is completely absorbed in the gas volume. The second, smaller *argon escape peak* appears as a consequence of the mechanism of X-ray interaction with the gas. In the case of Fe-55, X-rays interact via the photoelectric effect, producing a photoelectron with average energy 2.9 keV, and an ion in an excited state. The photoelectron ionizes the gas atoms and is absorbed in the gas volume. The excited ion then relaxes and produces either an Auger electron or a secondary X-ray. The energy of this second X-ray is just below the absorption edge of the argon atoms. It therefore has a very low cross-section for absorption, and thus escapes the gas volume. In this case, only a total of 3.0 keV is absorbed in the gas, and a count appears in the escape peak of the pulse height spectrum. The relative number of

¹Upilex is a polyimide film produced by UBE, Japan.

Figure 3.2: Pulse height spectrum using an Fe-55 source.

counts in the main and escape peaks is a measure of the branching ratio for the two relaxation mechanisms of the excited argon ion. Also shown in the Figure is the edge of the noise spectrum at about 1 keV. A discriminator is used to remove much of the noise in order to keep the dead time of the multichannel analyzer (MCA) low.

Since ionization is a statistical processes, the peaks in Figure 3.2 are Gaussian in shape with a finite width. Electronics noise also contributes to the peak width. The standard deviation of either peak is a measure of the energy resolution of the detector. In order to determine the gas gain from the spectrum, the MCA must be calibrated. This is accomplished by injecting a known quantity of charge (by pulsing a known voltage through a small capacitor) into the front of the electronics as shown in Figure 3.1. The amount of charge collected by the amplifier associated with the center of the main Fe-55 peak Q_p is related to the injected (pulser) charge Q_c by,

$$Q_p = \frac{N_p}{N_c} Q_c \quad (3.1)$$

where N_p and N_c are the main peak and pulser channel numbers, respectively. A charge sensitive pre-amplifier (Ortec 142PC) with a fast rise time and slow fall time was used to ensure minimum attenuation of the GMD pulse [19]. A calculation of the expected total ionization from the incident X-ray Q_x can be conducted using the Bethe-Bloch equations [20, p.46] for a particular gas mix. The gas gain, G , can then be found,

$$G = \frac{Q_p}{Q_x} = \frac{N_p Q_c}{N_c Q_x} \quad (3.2)$$

For Fe-55 and Ar-Isobutane 90/10, $Q_x \approx 223$ electrons.

Gas gain is sensitive to a number of design and operating parameters, making it an important metric for changes. The gas gain is most sensitive to the anode to cathode strip potential. Because of the proximity of these adjacent strips, small changes in this potential strongly affect the local electric field strength and the gas gain. Figure 3.3 shows the gas gain for a typical GMD as a function of cathode voltage (V_c). In this case the anode voltage is held at ground ($V_a = 0$ V) to simplify read-out. The other parameters given in the Figure are drift plane voltage (V_d), backplane voltage (V_b), anode pitch, print and substrate materials, and gas mix used.

A second use of gas gain is to monitor stability of detector performance over time. In the absence of parameter changes, a uniform gas gain over time is desirable, especially in applications where a fixed pulse height threshold is used to reject noise. Figure 3.4 demonstrates this stability for an aluminum on Tedlar GMD. There is some change in gain immediately after voltage is applied due to charge-up of the substrate as explained in section 4.2, but the detector eventually settles into a uniform mode of operation, at least at low flux. Note that this detector, built on fairly resistive Tedlar, approaches this equilibrium rather slowly. More conductive prints, such as those constructed on ion-implanted Upilex, exhibit much faster gain stabilization.

Figure 3.3: Gas Gain dependence on Cathode Voltage.

Figure 3.4: Changes in gas gain from time of voltage turn on.

Gas gain can also be used to measure the uniformity of the lithography. When monitoring signals from individual anodes, changes in gain from anode strip to strip are indicative of print defects, or of difficulties in achieving the same geometry in different parts of the print. Scanning the print with a collimated Fe-55 source is useful for picking out problem areas, such as thinned anodes, breaks, spurs, bites, and so on.

It is interesting to examine the dependence of gas gain on backplane voltage, V_b . Figure 3.5 shows the change in gas gain with V_b for three different prints. The response to changes in backplane potential seems to vary with the surface resistivity of the print. The print with the highest resistivity can be described as bulk conducting since its surface resistivity is that of untreated bulk substrate (Upilex). It experiences a pronounced increase in gas gain with backplane voltage. The other two prints are surface conducting — their surface resistivity is lower than the bulk substrate, due to surface treatment (in this case ion-implantation). There is no observable backplane dependence of gas gain for these prints. Certain prints have been ion-implanted, and yet continue to have a rather high surface resistivity (the 10^{15} to $10^{16} \Omega/\square$ range). These prints exhibit a *transient backplane effect*. That is, the gas gain changes momentarily when the backplane potential is adjusted, but returns in time to its original value. Figure 3.6 shows the response of such a print to a change in backplane potential from $V_b = 600 \text{ V}$ to $V_b = 0 \text{ V}$ at time $t = 0$. The print used in this Figure is quite resistive ($5 \times 10^{15} \Omega/\square$), so the effect appears to last for some time. More conductive prints experience transient effects that last for a much shorter period of time. GMD prints can be classified into three categories: those with a backplane dependence, those with no backplane dependence, and those with a transient backplane dependence. The nature of these three behaviors will be investigated in section 4.2.1.

Figure 3.5: Effect of backplane voltage for prints of three different resistivities.

Figure 3.6: The transient backplane effect for $V_b = 600 \rightarrow 0$ V.

3.2 High Rate Performance Using X-rays

A large set of potential GMD applications involve operations in environments with high rates of incident radiation. Like the parent technology (MWPCs), GMDs are subject to electric field modification and degradation in performance at high rates. It is therefore desirable to characterize these limitations through empirical study. Theoretical work in this area is equally interesting, as will be discussed in section 4.3.

To study GMD performance at high flux, a copper target X-ray generator was used. This device was capable of producing X-rays of up to 30 keV in energy using up to 2.0 mA of electron current. The X-rays could be passed through a collimator before illuminating the active gas volume. Using this device, interaction fluxes between 25 and 10^7 X-rays $\text{mm}^{-2} \text{s}^{-1}$ were possible on a spot size as small as 4 mm^2 .

Ideally, the output of the source in X-rays/second is proportional to the electron, or filament current used. To verify this, a gold on ion-implanted Upilex GMD was used to count X-ray signals above a fixed threshold for a wide range of filament currents. In order to extend the results to very high rates, where the GMD may be susceptible to gain loss, or the electronics to pile-up, the detector needed to be shielded somewhat by placing an absorber in the beam or moving the detector far away from the source. The results are shown in Figure 3.7 for several different tube voltages. The rise in count rate for the higher tube voltages is a result of the increase in width of the X-ray continuum. In each case, the degree of linearity is acceptable.

The simplest method to measure gas gain, as described in the last section, is to locate the peak of an energy spectrum on a calibrated MCA scale. The copper X-ray spectrum exhibits a K_α/K_β twin peak at about 8.0 keV [21] as well as an escape peak on top of an energy continuum. These peaks in the spectrum are useful at low rates. However, at high rates this spectrum begins to lose its shape

Figure 3.7: X-ray generator output linearity for several voltages.

because of pile-up in the electronics, and the peaks become indistinguishable from the background continuum. Conveniently, avalanche currents become large enough to measure by conventional means at these large rates. This provides a second means of measuring gas gain. If the total incident photon rate through the gas volume is N and each photon produces on average n primary electron-ion pairs, and G is the mean secondary pair production per primary electron (gas gain), then nNG electrons per second drift towards the anodes and nNG ions move towards the drift and cathode electrodes. The total effective current produced between electrodes is

$$I_t = nNGe \quad (3.3)$$

where e is the electronic charge. If all anodes are ganged and tied through a current meter to V_a , a current $I_a = I_t$ can be measured. Similarly, the currents from the drift electrode, I_d , and all cathode strips, I_c , can be summed to form $I_d + I_c = I_t$. Working backwards from equation (3.3) a value for the gas gain, G ,

can be evaluated. Of course, the incident rate N must first be determined; this is normally accomplished by extrapolating measured count rates at low flux. The output linearity of the X-ray source with filament current (Figure 3.7) makes this possible. In addition, the X-ray source is not monoenergetic as is, essentially, an Fe-55 source, so the average number of primary electron-ion pairs per X-ray, n , must be calculated by examining the shape of the X-ray spectrum. A spectrum is gathered at low rate and weighted mean employed to determine the average X-ray energy, from which n can be derived. The shape of the spectrum is assumed not to change at higher filament currents.

As mentioned previously, the *pulse* method is used at low flux, and the *current* method at high flux. There is some discrepancy between these two methods in the area of overlap (around $10^4 \text{ mm}^{-2} \text{ s}^{-1}$). The size of the signal seen by the MCA in the pulse method is dependent on the ratio of the ion collection time to the integration time of the amplifier. Since this ratio remains constant throughout the experiment, the results are comparable on relative terms, but a fixed factor remains between this relative gain and the absolute gain. The current method on the other hand has an effectively infinite integration time. At high rates (around 10^6 counts/sec), where the shaping time of the amplifiers is necessarily small to prevent pile-up, the measured gas gain by the pulse method is expected to be lower than the absolute gain as measured by the current method. Data from these two ranges can be combined by scaling the pulse method data to match the current method data in the overlap region.

Figure 3.8 shows a graph of measured gas gain as a function of incident particle flux (per unit area, per second). The gas gain begins to decrease at a flux of 10^6 X-rays $\text{mm}^{-2} \text{ s}^{-1}$ for this low resistivity ($5 \times 10^{14} \Omega/\square$) ion-implanted Upilex print. This behavior is evidence of field modification within the GMD because of gas to substrate currents (as will be discussed in section 4.3) or space charge effects, and is expected for all GMD prints. However, the flux at which this decrease begins to appear seems to depend on the nature of the print. In particular, those with

Figure 3.8: Measured gas gain as a function of incident particle flux for a low resistivity ion-implanted Upilex print.

high surface resistivity ($> 10^{16} \Omega/\square$) substrates degrade in performance earlier than ion-implanted or otherwise treated prints ($< 10^{15} \Omega/\square$). The degradation is severe enough that these prints are unusable as detectors in environments where moderate to high incident particle fluxes are expected. Prints with quite low resistivities (around $10^{13} \Omega/\square$) have been tested without loss in performance at fluxes up to $10^6 \text{ mm}^{-2} \text{s}^{-1}$ [13].

Another interesting flux dependent phenomenon seems to appear only in prints with mid-range (10^{15} to $10^{16} \Omega/\square$) surface resistivities. Figure 3.9 shows the curve for four such prints. In this case a noticeable increase in gas gain is observed as flux increased in the low flux range. The gain reaches a maximum around $5 \times 10^4 \text{ mm}^{-2} \text{s}^{-1}$ followed by the usual drop-off. The reasons for this behavior will be explored in section 4.3.

Figure 3.9: Demonstration of increase in gas gain with rate for mid-range resistivity prints.

3.3 Microstrip Detectors in the Test Beam Environment

Because of the nature of X-ray interactions, it is impossible to measure certain important characteristics of particle detectors with these species. It is desirable for some measurements to make use of particles which can deposit a small portion of their energy in the detector and yet pass through the detector virtually undisturbed. These minimum ionizing particles, or MIPs, are charged leptons or hadrons with a fairly high momentum. Generally one needs to make use of a particle accelerator to produce such particles in sufficient quantities to be useful. GMDs have been tested at two particle accelerator facilities to exploit this capability. The apparatus used at both facilities was similar, and so the setup for only one of the tests (the TRIUMF test) is described in detail.

3.3.1 The SPS Ring at CERN

In July of 1993, the Carleton/CRPP² group joined groups from Manchester University, Liverpool University, Rutherford Appleton Laboratories, and the University of Montreal in setting up a GMD test bed at CERN in Geneva, Switzerland. The GMDs were located on the H6 secondary beam, part of the Super Proton Synchrotron (SPS) North Area. A 450 GeV/c primary proton beam was extracted from SPS ring in a 2.6 second *spill* every 14.4 seconds. Several 10^{12} protons per spill were directed on the T4 primary target. The H6 beam was one of three secondary beams derived from this target. Hadrons, electrons or muons with momenta between 10 and 205 GeV/c were available from the H6 beam, with intensities ranging up to a few 10^6 particles/spill [22].

The H6 beam at CERN offered an excellent test bed for tracking particles between GMDs because of the high energy and therefore low multiple scattering of the beam particles. In addition, particle fluxes approaching 2×10^5 particles $\text{mm}^{-2} \text{s}^{-1}$ afforded the opportunity to study changes in performance at high operating rates.

The GMDs used at this site were low resistivity ($10^{13} \Omega/\square$) gold on ion-implanted Upilex prints produced by the lift-off technique. Although the surface resistivity was optimum for use at high rates, the quality of lithography was poor so that each print contained many dead channels.

3.3.2 The TRIUMF Cyclotron

A beam test was conducted in January of 1994 at the TRIUMF facility in Vancouver, B.C. by groups from Carleton/CRPP, University of Montreal, Purdue University and TRIUMF. The GMDs were located in the M13 area, as shown in Figure 3.10. A 500 MeV primary proton beam was extracted from the cyclotron in 5 ns bursts every 43 ns. The beam struck the T1 target, from which

²The Centre for Research in Particle Physics, Ottawa, Canada.

Figure 3.10: Plan view of the TRIUMF site showing location of GMDs.

the M13 secondary beam was extracted. This beam consisted of electrons, pions and muons with momenta of 130 MeV/c. Particle fluxes on the order of 10^3 particles $\text{mm}^{-2} \text{s}^{-1}$ were provided [23].

The TRIUMF beam was much lower in energy than the CERN beam, making tracking studies difficult due to multiple scattering. Some care had to be taken to achieve useful tracking data. Particle flux was also lower at the TRIUMF site, so high rate studies were not possible.

Mid-range resistivity ($10^{15} \Omega/\square$) gold on ion-implanted Upilex prints were used at this test. They were manufactured using a wet etch technique and quality of lithography was excellent, so that nearly all signal channels were usable.

Figure 3.11: GMD test bed apparatus at TRIUMF.

3.3.3 Test Bed and Apparatus

At both sites, a test bed was set up to fix the GMDs in the beam line. Figure 3.11 depicts the apparatus used at TRIUMF. Several of the chamber boxes as described in Section 2.3 are shown arranged to align the centres of the detector windows with the beam axis; the entire apparatus had to be surveyed into position prior to use. One of the chambers was mounted on a rotation stage, with the ability to pivot 30 degrees about its vertical axis. In addition, one chamber could be mounted on its side to allow for a vertical profile of the beam. Gas lines were brought in from below the chambers. Signal and high voltage cables were brought from above the setup by way of the large aluminum frame shown.

The smaller boxes mounted above each of the chambers housed the pream-

plifier electronics. These were QPA02 preamplifier chips designed at Fermilab for use with silicon microstrip detectors. These fast differential amplifiers had an impulse response with a 10-90% rise time of 7 ns followed by a return to base line after another 25 ns. A gain of 9 mV/fC and noise equivalent of 2000 electrons was typical. Each chip provided 4 signal channels, and was mounted onto a multilayer circuit board which allowed a total of 24 signal channels for each chamber. A protection diode circuit was placed at the input of each preamplifier channel to allow for the possibility of large currents arising from electrical breakdown between the anode and cathode strips. These amplifiers produce differential signals, which means that each signal is carried by two lines in such a way that any noise picked up in phase by both lines, called *common mode noise*, is cancelled at the destination when the two signals are recombined.

It is important to note that, due to the fast shaping time of the QPA02 preamplifiers, for slow gases such as argon-isobutane only a fraction of the ionization charge is seen and this must be considered when analyzing the performance of the GMDs.

Two different gas mixtures were used at the TRIUMF test beam: argon-isobutane (90/10) and CF₄-isobutane (80/20). For both mixtures a flow of 100 cm³/min at atmospheric pressure was used. The Ar-isobutane mixture was subsequently vented, whereas the CF₄-isobutane mixture was recirculated with a loss of 7%. During recirculation, the mixture was filtered with a R3-11 activated copper (BASF) filter and with a 3 Angstrom molecular sieve. Gas purities of greater than 99.5% were used, and oxygen and H₂O levels were monitored to be less than 15 and 20 ppm, respectively. At the CERN test, an argon-isobutane (84/16) gas mix was used.

3.3.4 Data Acquisition System

In addition to the GMD chambers themselves, several plastic scintillator paddles coupled to photomultiplier tubes were placed in the beam line. Two 5×5 mm scintillators and one 6×6 cm scintillator served as triggers to start the data acquisition (DAQ) system. A schematic of the system used at TRIUMF is shown in Figure 3.12. The three scintillators were used in coincidence as shown to provide a stop pulse to the DL 305 Flash ADC (FADC) modules. These modules had 96 input channels, allowing for full instrumentation of four GMDs (at 24 channels each), and a 6 bit non-linear dynamic range. The function of the FADC was to continuously digitize the voltage levels from each of the input signals with a sampling time of 10 ns, and store these samples in a 256 sample circular list buffer. The FADCs were operated in common stop mode, and when this stop signal was received, the FADC buffers contained a snapshot of the 96 input signals, covering a time interval of 2.56 microseconds. It then dumped this data to a host computer, which selectively stored a portion of the data on Exabyte digital magnetic tape for off-line analysis. The readout was limited to about 70 events per second by the tape writing process.

Figure 3.13 shows the data gathered during an event for a few of the signal channels. Each of the small plots show a voltage versus time graph digitized by the FADC module, covering a time of 400 ns. In this event, one anode in each of three chambers received a *hit* as demonstrated by the large voltage peak. One might surmise that the three peaks in this event represent the passage of a particle through the three chambers, leaving a *track* of ionization as it went.

3.4 Analysis of Test Beam Studies

The CERN and TRIUMF beam tests have produced a wealth of data. These data have been analyzed in order to extract some information about the char-

Figure 3.12: TRIUMF beam test data acquisition system.

Figure 3.13: Event snapshot during a TRIUMF test beam run.

acteristics of GMDs in general and of GMDs constructed on plastic substrates in particular. A variety of such characteristics can be measured, including efficiency of particle detection, resolution in position and time, and the effect of angled particle tracks [14, 24].

3.4.1 Detector Efficiency

When a fixed signal threshold is used to cut out noise, the passage of a particle must produce a signal (charge or voltage) above this threshold in order to be detected. Detection efficiency is defined to be the fraction of particle tracks that are detected in this manner. Various mechanisms prevent a particular track from producing sufficient signal amplitude including statistics of ionization in the gas, possibility of recombination of the primary electrons, statistics of gas amplification and integration time of the first stage electronics.

Measurement of detection efficiency first requires positive identification of particle passage through the detector independent of information derived from the detector itself. Fortunately, it is possible to use the other GMDs in the setup to make this determination. Consider the alignment of three GMDs in a particle

beam as shown schematically in Figure 3.14, and suppose the measurement of interest is the efficiency of the middle detector (chamber 2). Shown in the Figure is a particle track which passes through both small scintillator paddles and the three GMDs. It is desired to identify this track and determine whether it was *seen* by chamber 2. As mentioned previously, a coincidence of the two scintillators is required for data capture — providing a minimum requirement. The *position* of particle passage through the outside detectors (chambers 1 and 3) can be determined by numbering consecutive anodes and conducting a centroid finding procedure weighted by pulse height. To allow for the cleanest data set possible, events with multiple *clusters* of hits in chambers 1 and 3 were rejected (a cluster is a group of consecutive anodes whose pulse heights cross a fixed threshold). The centroid of a cluster of n hits running from anode numbers a_0 to a_n is given by

$$c = \sum_{i=0}^n a_i p_i / \sum_{i=0}^n p_i \quad (3.4)$$

where p_i is the pulse height recorded in anode a_i . This is called the *hit position*. Knowing the relative alignment of chambers 1 and 3, a *road* can be constructed which passes through the hit positions for chambers 1 and 3. It remains only to look along this road to determine the expected hit position in chamber 2, and see if indeed a hit was recorded in that position.

Before proceeding, it is important to note the way in which the three chambers were oriented. In any procedure or measurement where tracking the flight path of a particle is required, the possibility of multiple scattering is an important consideration. Deflection of the particle between chambers 1 and 3 would cause inaccurate construction of the road in the measurement discussed above, and a possible misinterpretation of the activity in chamber 2, leading to an inaccurate result. Multiple scattering was a particular concern at the TRIUMF site because of the low momentum of the beam. To minimize multiple scattering, the chambers were oriented as in Figure 3.14 to reduce as much as possible the detector material

Figure 3.14: Alignment of three GMDs to measure efficiency in the TRIUMF beam.

between the three chambers. Chamber 1 was mounted in "reverse", with its support board facing the beam, and Chamber 2 had a hole cut in its support board. As can be seen in the Figure, this eliminated all support boards between the active areas of the three detectors, which represents the majority of the material exposed to the beam.

The first step in efficiency analysis is to determine the relative alignment of the chambers exposed to the beam. This can be done by looking at correlations in hit positions between the chambers. Figure 3.15 shows the correlation between hit positions in chambers 1 and 2 for a subset of the TRIUMF data. The numbers along each axis represent the anode or position numbers for each chamber. The strong diagonal on this two dimensional histogram is indicative of the presence of particle tracks. In this case, the two chambers appear to be aligned such that anode numbers correspond. Note however that there is a *width* to this diagonal due to scattering and the inherent position resolution of the detector (see section 3.4.2), as well as the angular distribution of the beam.

Once the relative position of chambers 1 and 3 in Figure 3.14 have been established, the data are surveyed for events where a track is suspected. For this step a centroid hit position is calculated for chamber 2, and is compared to the expected position derived by interpolating hits in the outer chambers. Figure 3.16 shows a histogram of the difference between expected and actual hit positions (the *residuals*) for events in chamber 2 for a subset of the TRIUMF data. Only those event where hits in chambers 1 and 3 gave clear evidence of a particle track were used in this histogram. Events with no hit in chamber 2 were not included in this histogram.

Figure 3.16 shows a clear peak in the middle of the histogram. Again, this is clear evidence of tracks passing through the chamber. However, it is also evident that the hit does not always match the expected position due to multiple scattering and the spatial resolution of the detector. In fact, it is just this kind of histogram which is used to measure positional resolution, to be discussed in the

Figure 3.15: Correlation of hits in chambers 1 and 2.

Figure 3.16: Histogram of (actual - expected) position for hits in chamber 2.

next section. It is now possible to attribute a *width* to the road discussed above. That is, an acceptance region is defined, say within 4 standard deviations (4σ) of the residual peak from the expected position as shown, wherein a hit must lie for the event to be considered as an *efficient* event.

Figure 3.17 is a histogram of signal amplitudes, or *pulse heights* for the largest hit in chamber 2 which lies within the acceptance region discussed above. A minimum threshold of 20 mV was required in this analysis, so that all events with pulse heights lower than this threshold are included in the “zero height” bin. It should be clear that the efficiency of the detector at a given signal threshold can be determined from the histogram in Figure 3.17 simply by dividing the integral above the specified threshold by the total number of counts in the histogram. Values of efficiency are calculated and plotted as a function of this threshold in Figure 3.18. Data from the TRIUMF beam test was used to derive this plot. Also shown on the plot is an estimation of the *pedestal* — the nominal FADC output corresponding to an input of 0 VDC — and the r.m.s. noise level produced by the electronics. The pedestal and noise estimation was derived by examining a large number of signal channels with no pulses in them. From this plot it is clear that an efficiency of 90% can be achieved, even for thresholds set well (several standard deviations) above the noise.

As mentioned previously, many factors can affect the efficiency of a GMD. Several of these factors can be explored in a beam test environment. In particular, changes in efficiency with gas gain (cathode voltage) and with particle flux were studied.

A study of efficiency as a function of cathode voltage was conducted at the TRIUMF beam test. In order to minimize multiple scattering at this low momentum beam, the chambers were pressed against each other in a *close-packed* arrangement, and were oriented as shown in Figure 3.14. In addition, the electronics were set to trigger on only the electron part of the beam by using the time of flight.

Figure 3.17: Histogram of pulse heights for events with a track.

Figure 3.18: Plot of efficiency versus pulse height threshold.

Figure 3.19: Plot of efficiency as a function of cathode voltage.

As the cathode voltage in the central chamber was varied from run to run, it was possible to measure efficiency as a function of cathode voltage for these runs. Figure 3.19 shows the results. The three different data sets correspond to different pulse height cuts for the centre detector, as indicated. It is evident that as the gas gain increases, not only does the fraction of particles detected increase, but the average pulse height increases so that the results for the three (relatively low) pulse height cuts become similar. For a typical operating voltage and pulse height cut, this graph shows that these detectors were running with an efficiency of about 90%.

Efficiency as a function of particle flux was studied at the CERN beam test. As particle flux increases, gas gain may decrease as a result of substrate currents and space charge effects, so efficiency would see a corresponding decrease. A relative insensitivity of efficiency to high flux would be an indication of the detector's ability to operate without degradation at these rates. Though the CERN beam was excellent for tracking, with very little multiple scattering, the efficiency was more difficult to determine compared to the TRIUMF test because of the large

Run #	Vcath (V)	Vdrift (V)	Intensity (mm ⁻² s ⁻¹)	Efficiency
638	530	1000	5×10^4	0.36
639	530	1000	2×10^5	0.33
640	530	1000	2×10^5	0.32
641	530	1500	2×10^5	0.39
642	550	1500	2×10^5	0.54
643	550	1500	2×10^4	0.54
644	550	1500	1×10^3	0.59

Standard error in efficiency estimates ~ 0.03 .

Table 3.1: Efficiency results from the CERN beam test.

number of dead anodes in each chamber at the CERN test. In this case, efficiencies were possibly underestimated since particles passing through regions over dead anodes might be missed and the event erroneously counted as inefficient.

Table 3.1 shows the results from the CERN beam test. Operating conditions are given for each run, including cathode and drift voltage and an estimate of the particle flux. Efficiencies were calculated using a threshold of 15 mV above pedestal. Additional cuts had to be applied to the data to achieve these numbers because of the large flux of particles — there was a significant chance that a second particle could pass through the detectors within the FADC time window and contaminate the results. For this reason, cuts on the relative timing between hits in the chambers were made that were not present in the TRIUMF analysis. Since the timing resolution for the gas used (Ar-isobutane) is rather poor, these cuts may also have caused efficiency to be underestimated. For this reason and the reasons discussed above, the efficiency values from the two beam tests may not be directly comparable.

Obvious trends are evident when examining Table 3.1. As was evident with the TRIUMF data, changes in gas gain as a result of changing the cathode or drift voltages have a significant effect on efficiency. However, efficiency seems

to have remained stable at the highest flux (within experimental error), which is in agreement with the results of high rate X-ray studies on low resistivity ion-implanted prints, as reported previously.

3.4.2 Positional Resolution

Positional or spatial resolution is a quantity describing the distribution of *hit locations* measured by the detector for a large number of similar particle tracks. That is, if all particle tracks pass through the detector at $x = 0$, the positions x_{meas} measured by the detector should be distributed with variance equal to the square of the positional resolution. Obviously, this quantity is highly dependent on the technique used to determine the hit position from the detector data. If only one anode of a GMD bears any indication of collecting charge from a particle passage, then this assignment is trivial. In this case the expected position resolution for a GMD is the anode pitch divided by $\sqrt{12}$. Because of the large GMD pitch ($400\ \mu\text{m}$) and fast electronics used at the TRIUMF beam test, almost all hits involved a single anode, and this result is expected.

A distribution of residuals similar to the one shown in Figure 3.16 was used in studying the position resolution of the GMDs at the beam test. Centroid finding was performed on all three chambers. The residual in this case is the difference between the measured hit position in chamber 2 and the position calculated by averaging the hit positions in chambers 1 and 3 (note that interpolation by use of an average assumes equal spacing between the chambers — a good approximation in this case). The resulting distribution could be fit to a Gaussian, and the variance determined.

The residual distribution had contributions from both inherent detector resolution and multiple scattering. In particular, scattering off the middle chamber could produce erroneous track construction between chambers 1 and 3, with the result that the hit in chamber 2 would seem to be “off-line”. By far the biggest

scattering source in the middle chamber was the drift mesh, which was approximately $100\text{ }\mu\text{m}$ thick steel with a 50% coverage. A rough calculation shows that this mesh would produce a 5.6 mrad r.m.s. scattering angle for 130 MeV electrons, which corresponds to a $300\text{ }\mu\text{m}$ spread over one interchamber distance (5.4 cm) in the “close-packed” arrangement. This being the case, the contribution from the expected positional resolution of $400\text{ }\mu\text{m}/\sqrt{12} = 116\text{ }\mu\text{m}$ would be overwhelmed by the multiple scattering.

Measurements of the residual distribution from the TRIUMF test give a width of $220 \pm 10\text{ }\mu\text{m}$ for the “close-packed” arrangement, and $360 \pm 10\text{ }\mu\text{m}$ for the arrangement where the chambers were placed on their pedestals. These standard deviations are consistent with the large multiple scattering expected from the low momentum TRIUMF beam. Beam momentum was high enough to avoid this problem at the CERN test, but the high number of missing anode channels made positional resolution measurements impossible.

3.4.3 Timing Resolution

Timing resolution is a measure of the variation in differences between the time of passage of a particle and the arrival time of the signal from the detector and electronics. For instance, consider the case where a particle passes through the gas volume of a GMD at time $t = 0$ and the signal from the appropriate electronics channel crosses a fixed threshold at time $t = T$ (a useful prescription for “arrival time” of the pulse). If T were normally distributed with mean T and variance σ_T^2 , then the standard deviation of this distribution, σ_T , would be the timing resolution of the detector. Unfortunately, in practice T has an oddly shaped distribution having to do with the geometry of the GMD, as discussed below. Therefore, a more careful approach to the definition of timing resolution is required. In general, factors which influence timing resolution are the properties of the gas (drift velocity, ionization density), the chamber geometry (drift gap,

anode pitch) and the electronics (shaping time, gain).

Timing resolution is most conveniently measured using a time/digital converter (TDC). An external trigger indicating passage of a particle sends a START signal to the TDC, and a discriminator coupled to the output of the GMD sends a STOP signal. At the two beam tests, a coincidence of plastic scintillator signals was used as the external trigger. The timing resolution of these devices is typically much better than a GMD using a slow gas, so this did not affect the measurement. Instead of a TDC, flash analog/digital converters (FADCs) were used. The scintillator signal was delayed, and then used to stop the FADCs. It was then possible to look back in time (through the FADC memory) to see the arrival of the pulses from the GMDs. Since the FADCs had a digitization time of 10 ns, this was the limit to the measurement of timing resolution using this scheme. While a typical TDC has a much better resolution, sufficiently slow gas mixtures were used during most of the beam test runs that this limitation was not an issue.

Figure 3.20 shows a typical timing distribution for a single anode from a subset of the TRIUMF data. Argon-Isobutane (90/10) was the counting gas used during this run. The distribution has the following characteristic features: a sharp rise on the left, a peak, and a shoulder or tail on the right. The shape of this distribution can be explained by examining Figure 3.21. The two tracks shown in the Figure both create primary electrons clusters within the *cell* of the middle anode. In the constant drift field region which extends through most of the GMD gas volume, the contribution to the timing distribution for each of these events is proportional to the distance between the anode and the primary electrons as shown. We can construct *isochrones*, or lines of equal arrival time, which are equivalently lines of equal distance from the anode, as shown in for the last anode cell in the Figure. (Note that this very simplistic model does not account for electron diffusion, nor the complex shape of the flux lines near the anode, but serves the purpose at hand.) Notice that the relative area between

Figure 3.20: Single anode timing distribution from the TRIUMF data.

each successive isochrone, which in a way represents the relative height of each bin in the timing distribution, quickly reaches a maximum near the anode, and then drops away as the *sides* of the cell begin to crop the arc — this is the peak of the distribution. In the drift region, the area between isochrones is essentially constant over a wide range of times — this is the long tail. The width of the distribution at the base represents the drift time for an electron crossing the full drift gap. Since this distance is known to be 4 mm, the mean drift velocity in the particular gas mix used can be estimated. In this case (Ar-Iso 90/10), a drift velocity of $30 \mu\text{m/ns}$ was determined using the timing distribution data.

Of course, since the signal time is usually measured using the rising edge of the GMD signal, often only a fraction of the charge need be collected. In the case of straight tracks and a low trigger threshold, the timing measurement will be more sensitive to clusters generated near the anode, raising the height of the peak of the distribution relative to the tail. In fact, under these conditions one wouldn't expect to see much of a tail at all. There are two reasons that the tail may be prominent: angled tracks, and amplifier response. Angled tracks, as

Figure 3.21: A simple timing distribution model.

shown in Figure 3.21, may leave primary clusters of ionization up high in the drift region since the track is *clipped* as it passes into the next cell. Since tracks with a given angle would be uniformly distributed in the drift region, this phenomenon produces a flat-topped tail in the timing distribution. The larger the angles are allowed to become, the higher the tail.

The amplification and DAQ system may also contribute to the shape of the timing tail. At both beam tests, very fast pre-amplifiers were used, with shaping times on the order of 20 ns. Additionally, a threshold of ~ 15 mV was used to trigger the timing "stop". As a result, sufficient primary ionization had to arrive at the anode to produce 15 mV of signal within a short period of time (the shaping time) in order to be measured at all. If we assume an average cluster size of 3.5 electrons for Ar-Isobutane (90/10), a gas gain of 1000, and a pre-amplifier gain of 9 mV/fC, a simple calculation tells us that a minimum of 3 clusters are needed to trigger the timing "stop". It is therefore necessary that 3 or more clusters be *grouped* sufficiently close together to arrive all within the amplifier shaping time. If these groups are sufficiently numerous in a single event, then no tail should be generated for straight tracks. If, on the other hand, such a group is so rare that only one ever occurs, if at all, then no particular region in the cell is favoured, and a large flat tail is expected. In between these two extremes, the timing distribution exhibits a sloped tail, as groups further down in the drift region are favoured over those higher up. The typical timing distribution acquired during the TRIUMF beam test exhibited this sloped tail.

A simple Monte-Carlo model was constructed using these ideas. The Monte-Carlo model generated tracks similar to those shown in Figure 3.21, with a uniformly distributed x , a normally distributed θ , and primary clusters of electrons produced according to Poisson statistics. Cluster arrival times were examined for groups arriving within a given amplifier shaping time. The results of this Monte-Carlo model are compared to experiment in Figure 3.22. The shape is clearly predicted by the model. Not surprisingly, the relative height of the tail increases

and becomes flatter with the width of the angle (θ) distribution. As well, the tail height reduces and becomes more sloped as the shaping time is increased. For the Monte-Carlo result shown in Figure 3.22 the following parameters were used: $\sigma_\theta = 1.5^\circ$, $V_{drift} = 30 \mu\text{m/ns}$, $t_{shape} = 20 \text{ ns}$. The experimental data shown in the Figure was derived using a pulse height cut of 20 mV above pedestal, and a timing threshold of 15 mV above pedestal. To simulate this large threshold, 4 clusters arrivals were required within the shaping time, and the arrival time of the third cluster was histogrammed. Also shown are distributions simulated for the case of angled track effects alone ($\sigma_\theta = 1.5^\circ$) and shaping time effects alone ($t_{shape} = 20 \text{ ns}$). Shaping time effects appear to have a greater contribution to the overall shape of the distribution.

One area where the Monte-Carlo deviates from experiment should be pointed out. As the required pulse height threshold is raised, meaning that a larger number of appropriately grouped clusters is needed, the tail of the distribution is expected to rise as the limit of one group per event is reached. This is the behaviour of the Monte-Carlo, but not of the experimental data, where quite the opposite is true — clusters close to the anode are favoured under these conditions. Diffusion provides one plausible explanation for this behaviour. As the primary electrons drift towards the anodes, they diffuse in both the lateral and transverse direction. A computer simulation [25] has predicted that transverse diffusion can be as high as $240 \mu\text{m}$ for argon-isobutane (90/10) and a 4 mm drift distance at 4 kV/cm. Because of this, large groups of clusters formed high up in the drift region may not remain together by the time they reach the anodes, and may not produce a measureable signal after all. In this case, only those clusters near the anode are capable of producing a signal, and are favoured in the timing distribution.

For the purposes of assigning a value for the timing resolution of a detector, the width of the distribution peak can be used. Experience with the Monte-Carlo has indicated that the width of this peak is relatively insensitive to angled

Figure 3.22: Experimental (a) and simulated (b) timing distributions. Also shown are simulated distributions arising from (c) angle effects alone and (d) shaping time effects alone.

Figure 3.23: Timing distribution for single anodes using (a) argon-isobutane (90/10) and (b) CF₄-isobutane (80/20).

track and amplifier effects. For the argon-isobutane (90/10) data acquired at the TRIUMF beam test, a timing resolution of $\sigma_t = 17$ ns can be derived using this prescription.

As mentioned previously, the timing resolution is a strong function of the electron drift velocity in the counting gas mix used. To investigate this, a CF₄-isobutane (80/20) mix was used in one chamber for a number of TRIUMF runs. This gas mix has a predicted electron drift velocity of about $120 \mu\text{m}/\text{ns}$ for the drift field of $4 \text{ kV}/\text{cm}$ [26]. Figure 3.23 compares the resulting timing distributions for the slow argon-isobutane and the fast CF₄-isobutane gas mixes. Both devices were $200 \mu\text{m}$ pitch, and the distributions for individual anodes are shown. Clearly, the timing resolution is much superior for the faster CF₄-isobutane mix. In fact, the width of this distribution is smaller than the resolution of the FADCs (10 ns), meaning that the timing resolution is not directly measurable with this technique.

It should be pointed out that this same narrow distribution could have arisen from recombination of primary electrons in the drift region. In this case, only

those electrons produced near the anode would have survived. The CF_4 -Isobutane mix is notorious for this effect [27]. This possibility could not be ruled out. However, the base width of the timing distribution is consistent with the full drift distance at the predicted velocity.

Chapter 4

Theory of Operation

The Gas Microstrip Detector has undergone a great deal of empirical examination by many groups over the globe, but relatively little effort has been expended in attempting to explain some peculiar behaviours of these devices. A GMD is in principal similar in operation to a wire chamber (MWPC), a well understood device, but sufficient differences exist between the two technologies that this understanding is not directly transferable. The chief source of the discrepancy is the presence of the dielectric substrate — introduced simply as a means of fixing the metal strips to counter the electrostatic forces between them, this medium plays an enormous role in the general operation of the GMD.

For future development and applications of GMDs it is important to understand such phenomena as time and rate dependence of gas gain due to so called *substrate* or *high rate charging*, the effects of backplane voltage, spatial and timing resolution, effects of angled tracks, and others. Calculations and models to describe this behaviour are presented in this chapter.

4.1 Electric Field Calculations

An indispensable tool in examining the fundamental properties of the GMD is the electrostatic modeler. A number of microcomputer-based electrostatic modelling programs have been employed in this manner, using a variety of approximation techniques. In particular a package called ELECTRO¹, which uses a boundary element technique, has been used with great success. The field diagrams presented in this thesis were generated by inserting ELECTRO data into a private flux line drawing routine.

It is of course impractical to model the entire active area of a GMD, with hundreds of electrodes covering a large area. Fortunately symmetry can be employed. Assuming the spacing between electrodes and the width of the electrodes remains constant over their length (not the case for *keystoned* prints) then the electric field does not vary in the direction parallel to the electrodes. Thus, the problem reduces to two dimensions in a cross-section perpendicular to the electrodes. Furthermore, symmetry in this plane suggests that the field configuration around each anode or cathode strip should be the same, at least away from the edges of the print. Figure 4.1 shows the dimensions of a GMD *cell*, covering the distance between two successive cathodes, in which the two-dimensional electrostatic potential can be solved. This technique gives a good representation of the E-field configuration throughout the print, except at any of the edges. In fact, the solution area shown in Figure 4.1 is also redundant, since the two *half-cells* are mirror symmetric.

In order to ensure proper behaviour at the sides of a GMD cell, a *Neumann* condition must be specified at these boundaries; that is,

$$\frac{dV}{d\vec{n}} = 0 \quad (4.1)$$

¹ELECTRO is a product of Integrated Engineering Software, Winnipeg, Man., Canada

Figure 4.1: A GMD cell showing boundary conditions.

where $\vec{n}$ is a vector perpendicular to the boundary. This prevents field lines from crossing from one cell to another. Thus, the entire problem is contained within the cell. The voltages of each of the four electrodes (anode, cathode, drift plane and back plane) are specified using *Dirichlet* boundary conditions.

Because of the presence of several different media in the problem, two solutions are possible: the *dielectric* solution, and the *conductive* solution. These solutions differ in the way they treat the transmission of the electric field at the boundary between media, and correspond to the initial and steady state solutions, respectively. In the dielectric analysis of a GMD, the electrostatic potential ϕ_e obeys the equation

$$\nabla \cdot (\epsilon \nabla \phi_e) = -\rho \quad (4.2)$$

where ϵ is the dielectric constant of the medium and ρ is the local space charge density. The electric field strength is given by

$$\vec{E} = -\nabla \phi_e. \quad (4.3)$$

In the absence of free charges, the boundary conditions at the interface between the substrate and the gas can be shown to be

$$E_s^x = E_g^x \quad (4.4)$$

$$\epsilon_s E_s^y = \epsilon_g E_g^y \quad (4.5)$$

where the axes are shown in Figure 4.1 and the subscripts *s* and *g* denote substrate and gas, respectively. In this solution, the conductivity of the substrate is ignored, so that no substrate currents exist. This would be essentially true at the instant of voltage turn on, so this solution corresponds to the initial, or $t = 0$ electric field configuration.

The conductive solution presents a modified equation for the electrostatic potential:

$$\nabla \cdot (\sigma \nabla \phi_e) = j_s \quad (4.6)$$

where σ is the conductivity of the medium and j_s is the local current source density. By analogy with the dielectric equation, it is easy to see that the conditions for the gas/substrate interface are

$$E_s^x = E_g^x \quad (4.7)$$

$$\sigma_s E_s^y = \sigma_g E_g^y \quad (4.8)$$

In this case, steady state currents are established in the substrate, and the solution corresponds to the $t = \infty$ electric field configuration. Notice that if we assume the conductivity of the gas is essentially zero, so that $\sigma_g = 0$, this last equation implies that

$$E_s^y = 0 \quad (4.9)$$

which means that no field lines cross the substrate-gas interface from below. Note that this does not imply anything about the field strength on the gas side of the

interface. This result comes naturally from the idea of steady state currents. If field lines in the substrate (sourced by one of the three electrodes on its periphery) were to cross into the gas, electrons would drift along these lines and ultimately become trapped at the interface, unable to continue into the non-conductive gas. Ultimately, sufficient charge would build up at this location to repel the field lines, shutting off the current flow. Thus, at steady state a layer of charge exists right at the substrate-gas interface. In addition to repelling field lines from within the substrate, this charge serves to source field lines above the substrate. In general then, $E_y^g \neq 0$ at steady state.

Obviously, some period of time is required to move from the turn-on to the equilibrium solution. The time constant for this transition, τ_c , (sometimes called the dielectric relaxation time) [28, p.68] is given by:

$$\tau_c = \frac{\epsilon}{\sigma} \quad (4.10)$$

where ϵ is the permittivity and σ is the conductivity of the medium. This indicates that ion-implanted prints will be faster at approaching equilibrium than untreated prints.

As will be discussed in the next section, the discrepancy between these two different solutions for the same electrode voltages have some important consequences for detector performance. In general, though, the conductive solution is of more interest since voltage can be applied to the detector for sufficient time to approach steady state (minutes or hours) before readings are taken.

Figures 4.2 and 4.3 show the electric field configuration in a GMD cell centered about an anode for eight different sets of parameters. Each plot represents a print with gold metallization on a 125 μm thick Upilex substrate. The anode and cathode strip widths are 20 μm and 88 μm , respectively, and the total anode to anode distance (pitch) is 400 μm . The drift gap is 4000 μm , but only the first 300 μm above the substrate surface is shown. The anode potential is $V_a = 0$ V, the

cathode strips are at $V_c = -650$ V, and the drift electrode is set to $V_d = -2000$ V. The plots in Figure 4.2 have the backplane voltage set equal to the anode potential ($V_b = V_a$), whereas those in Figure 4.3 have equal backplane and cathode strip potentials ($V_b = V_c$). Plots A, C, E, and G represent unimplanted Upilex, whereas plots B, D, F and H have a $2\text{ }\mu\text{m}$ implantation layer whose conductivity is 10^5 times higher than the bulk substrate. Plots A, B, E and F are calculated using the dielectric solution, and so are time $t = 0$ conditions. Plots C, D, G and H are conductive solutions (time $t = \infty$). The differences between these plots will be discussed in the next section.

4.2 Field Variation with Substrate Charging

The process by which the electric field lines above and below the substrate surface change over time (and ultimately approach equilibrium) due to currents flowing in the substrate is commonly referred to as *substrate charging*. Such currents can result simply from the potential bias applied to the substrate by the peripheral electrodes or from avalanche created charge landing on the exposed surface of the substrate. To avoid confusing these two entirely different mechanisms, the latter is referred to as *high rate charging* and will be dealt with in the next section.

As discussed above, electric field configuration in a GMD changes from the moment of voltage turn on (where it resembles the dielectric solution), and approaches an equilibrium (where it resembles the conductive solution). The equilibrium condition is characterized by the absence of field lines striking the substrate-gas interface from below. That is, no lines cross this boundary. Examine the case for the untreated substrate shown in Figure 4.2. Plot A is the dielectric solution, and clearly both anode→cathode and backplane→cathode lines cross the boundary. Plot C is the conductive solution; here, a region of steady state negative charge has built up along the boundary. The charge has the effect of sourcing field lines in the gas and repelling field lines in the substrate.

Fig. 4.2: Electric field plots for $V_b = V_a$. Other conditions: A) unimplanted, dielectric solution; B) implanted, dielectric solution; C) unimplanted, conductive solution; D) implanted, conductive solution.

Figure 4.3: Electric field plots for $V_b = V_c$. Other conditions: E) unimplanted, dielectric solution; F) implanted, dielectric solution; G) unimplanted, conductive solution; H) implanted, conductive solution.

Now anode→cathode lines travel entirely within the substrate, near the surface. It is interesting that even though the field configuration in the substrate in plots A and C are different, the gas configuration remains remarkably similar. One would not expect to see much of a change in gas gain over time with this print (at low flux.).

The situation is not the same for an implanted print, shown in plots B and D. Whereas there appears to be no difference between implanted and unimplanted at turn on (plots A and B), the electric field configuration in the gas is different at equilibrium (plot D). Note that although it appears that some field lines touch the gas-substrate interface from below in this conductive solution, in fact these lines take a sharp turn at the bottom of the $2\text{ }\mu\text{m}$ implantation layer and head for the appropriate electrode. At steady state there appears to a region of negative charge build-up and another of positive charge build-up for the implanted print. Some field lines start and end on these regions, and do not involve the electrodes at all. Looking at plots B and D, one might expect to see a change in gain with time for the implanted print. However, in most cases the degree of implantation is such that this equilibrium is approached quite rapidly, and this change may not be observed in practice.

The ideas discussed above apply equally well to the $V_b = V_c$ cases given in Figure 4.3. Again, the time $t = 0$ solutions for both the untreated and implanted cases (plots E and F) are the same, and show lines crossing the substrate-gas boundary near the cathode strips. The equilibrium solution for the untreated print (plot G) is similar above the boundary to the $t = 0$ solution. In this case a region of positive steady state charge appears to have developed at the boundary. Again, large differences in the gas configuration are seen in the implanted, equilibrium solution (plot H). In fact, it is with the application of some back-plane voltage that one sees the enormous difference between unimplanted and implanted prints (plots G and H). The field lines around the anode are highly concentrated in plot G, forming a high field, and thus high gain region. These

same field lines appear to be spread out onto the substrate in plot H. In effect the region of steady state negative charge formed at the boundary near the anode increases the *effective width* of the anode. The spreading of field strength that results makes for significantly lower gain than in the untreated case. However, it is also clear that many of the field lines originating at the anode in plot G end up on the substrate surface, and will likely carry avalanche charge to this boundary, contributing to the high rate charging discussed in the next section. Thus, there is a compromise to be made between high gain and gain stability at high flux.

4.2.1 Backplane Effects

Examine the differences between the $V_b = V_a$ solutions in Figure 4.2 and the $V_b = V_c$ solutions in Figure 4.3. For the untreated substrate (plots C and G), there is a pronounced difference in field strength around the anode in the gas. A higher gain is expected when backplane potential is applied. The implanted solutions (plots D and H), on the other hand, have identical field configurations in the gas — backplane voltage seems to have no effect on implanted prints. It is often said that the implantation layer *shields* the electric field from the backplane potential. These observations are borne out experimentally: untreated prints have a strong backplane dependence of gain, whereas highly implanted prints see little or no backplane effect (see Figure 3.5).

There is a class of prints, however, that exhibit a so-called transient backplane effect. That is, a change in backplane voltage produces an immediate change in gain, followed by a slower return to the original gain (see Figure 3.6). This behaviour is typical of GMDs constructed on high resistivity ion-implanted substrates, with resistivities somewhere between untreated and normally implanted substrates. The field plots shown in Figures 4.2 and 4.3 do not give a picture of the field configuration during this transitory time. However, it is possible to have a qualitative understanding of this process.

First consider the untreated case. Imagine the print is at equilibrium with $V_b = V_a$ (plot C). At time $t = T_0$ the backplane voltage is changed to $V_b = V_c$. The system is no longer in equilibrium, and the steady state negative charge build up begins to dissipate — it is fairly quickly absorbed by the nearby anode. It will take some time to establish the positive charge region of plot G, and in the mean time, the electric field configuration must look something like plot E. However, since there is relatively little difference in gain between cases E and G, the gain will appear to quickly reach its new value and stay there.

Now consider the implanted print in plot D. When the backplane voltage is changed, again the equilibrium is disturbed, and the field configuration quickly resembles plot F. However, the gain in plot F is significantly higher than in plot H, and during the return to equilibrium, the gain will be inflated. Since the gains in plots D and H are the same, the gain will ultimately return to its original value, and so this inflated gain is transient. In fact, one would expect to see a transient backplane effect for *all* implanted prints. But, remember that the relaxation time for a print is in inverse proportion to the conductivity as per equation (4.10). For heavily implanted prints, the return to equilibrium is likely fast enough that the transition is not measurable in practice.

4.3 Field Variation with High Particle Flux

4.3.1 Effect of Avalanche Deposited Charge

During normal operation of a GMD, a great deal of free charge propagates through the gas volume. While it may not be correct to say that the gas is conductive in the normal sense, this charge movement has the same result, with the added complication that both negative and positive species (electrons and ions) are free to move. Ideally, charge movement in the GMD gas volume would occur only between the metal electrodes: electrons formed in the avalanche above the anode

would be immediately absorbed by the anode, and the ions that remain would drift to either the cathodic strips or the drift plane where they would be neutralized. In practice however this is not generally the case. In the conductive solution, the build-up of charge along the substrate surface between the electrodes results in electric field lines starting or ending on this surface. This means that free charge in the gas volume may end up drifting onto the substrate. These electrons and ions do not remain *stuck* to the substrate surface as some have suggested. Remember that the substrate surface is in an *equilibrium current* condition. The arrival of additional charge from the gas will disturb this equilibrium temporarily, and for a while a net current will appear to flow into or out of the interface region. Ultimately, however, the offending charge will be neutralized and the equilibrium reestablished.

The situation changes, however, when the chamber is operating with a steady rate of new avalanches. Imagine that each avalanche shows a small area of the substrate surface with a measurable amount of free charge. The equilibrium is disturbed, and substrate currents begin to flow to counter this effect. If the next avalanche comes before equilibrium can be reestablished, it will appear as though equation (4.9) is violated; a net current is constantly flowing to the interface. As a simplification, the constant discrete arrival of charge due to each avalanche can be thought of as a continuous charge arrival, or current, impinging on the substrate surface at that point. The situation can be modeled by placing a small current source at the surface. From the point of view of the electrostatic modeler, this can be accomplished by imposing a Neumann condition on the substrate to gas interface; that is,

$$-\frac{dV}{dn} = \mathcal{E} = \frac{J}{\sigma} = \text{Area} \frac{I}{\sigma} \quad (4.11)$$

A new steady state solution will arise, in which current arriving at the interface from the gas side is countered by equal substrate currents. Of course, since the amount of equilibrium charge build-up on the gas to substrate interface will

change under these conditions, one cannot expect the E-field distribution above the substrate to remain the same before and after this current source is switched on. In turn, since the amount of charge arriving at the substrate at that point may be a function of this E-field distribution, it is clear that some kind of iterative solution may be required.

4.3.2 Mechanism of Charge Transport to the Substrate

Electron and ion drift in the gas will proceed in much the same fashion as electron conduction in a dielectric. The charged particles will accelerate in the direction of the electric field and travel some distance before impacting with a gas molecule. If the mean distance traveled at each step is sufficiently small, the particles will essentially follow the static E-field lines from one place to another in the gas volume. We can use this to trace the path of electrons and ions through the gas volume of a GMD from their starting positions in the avalanche region above the anode.

Consider the GMD half-cell (gas only) shown in Figure 4.4. If we assume all field lines in this region begin at the anode, and if we place some positively charged particles in the region immediately above the anode, we can determine how many of those particles end up on the substrate, the cathode or the drift electrode by counting the number of field lines ending up on each of these regions.

An easy way to count up field lines is to use Gauss' law,

$$\oiint \vec{D} \cdot d\vec{A} = Q \quad (4.12)$$

and especially its two dimensional form,

$$\oint \epsilon \vec{E} \cdot d\vec{n} = Q_e \quad (4.13)$$

Consider the contour integral shown in Figure 4.4 which runs entirely within the

Figure 4.4: A GMD half-cell showing the Gaussian contour integral

gas. The lines running from the middle of the anode or cathode to the drift electrode have no field lines crossing them due to symmetry. If we assume there is no net free charge in the gas volume, this leaves

$$\int E_{\text{anode}}^y dx + \int E_{\text{substrate}}^y dx + \int E_{\text{cathode}}^y dx - \int E_{\text{drift}}^y dx = 0 \quad (4.14)$$

In fact, under some conditions there is a region of the substrate within a distance x_p of the anode where *positive* charge has built up at the boundary. In this region electric field lines start rather than end on the substrate surface. If the total width of the substrate from anode to cathode is x_s , then we can rewrite the above equation,

$$\int E_a^y dx + \int_0^{x_p} E_s^y dx = \int E_d^y dx - \int E_c^y dx - \int_{x_p}^{x_s} E_s^y dx \stackrel{\text{def}}{=} V_t \quad (4.15)$$

The situation is shown graphically in Figure 4.5. Here, the gas volume in the half-cell is broken down into 3 distinct regions, separated by electric field lines. Positive ions in region A end up at the drift electrode, ions in region B arrive at the cathode strip electrode, and those in region C wind up on the substrate surface. Electrons in these regions end up either on the anode strip or on the

Figure 4.5: Charge collection regions in a GMD half-cell

substrate surface on the left side of x_p . Of course, the actual size of these regions near the anode vary with the field configuration and may not be exactly as shown, but can be calculated by means of Gauss' theorem as discussed above. In fact, for a GMD with a thin conductive layer (such as an io^- -implanted print) the width d_{bot} shown in the diagram may be larger than the anode width.

Looking at Figure 4.5, imagine the GMD response to the passage of a single charged particle. By far the majority of initial ionization would be contained in region A. The ions created by this process would end up at the drift electrode, and are of little consequence. The primary electrons, on the other hand, head down towards the anode and will be responsible for starting the avalanche process. The bottom of region A is very narrow, and in the absence of diffusion all the primary electrons would be collected at the bottom of this *drift bucket*. In this case, the avalanche would be almost entirely confined to this region, and all of the ions formed in the avalanche would be forced all the way back to the drift electrode. The advantage afforded by the nearby cathode strip would be lost. In

addition, only in the case that the drift bucket were wider than the anode would any electrons be absorbed by the substrate rather than the anode.

Fortunately, electrons have a rather large mean free path in a gas and diffusion must be considered. Fang et al. [29] point out that it is difficult to estimate diffusion in this geometry. Because of the large geometric conversion factor (the ratio of the widths d_{top} and d_{bot} shown in Figure 4.5) and the large field near the bottom of the bucket, they point out that the transverse diffusion is expected to be much less than in a homogeneous field. Fang et al. estimate the diffusion to be

$$\sigma_{diff} = \sigma'_{diff} \sqrt{\frac{d_{bot}}{d_{top}}} \quad (4.16)$$

where σ'_{diff} is the transverse diffusion for an electron drifting over the same distance in a homogeneous field equal to the field above the anode. They give a value of $\sigma'_{diff} = 19 \mu m$ for an Ar/CH₄ (90/10) mixture.

Because of transverse diffusion, the avalanche cloud may extend over into regions B and C. This has the consequence of not only distributing more electrons to the substrate rather than the anode, but means that ions are collected by the cathode strip electrode and possibly the nearby substrate. Of course, the field strength over the substrate near the anode is expected to be quite a bit less than the anode field, and so primary electrons that diffuse enough to make it there will likely produce less secondary ionization. This effect must be considered when determining the quantity of free charge available in each of the three regions.

4.3.3 The Iterative Method

Most electrons and ions in the gas volume are produced in pairs (or nearly so) during an avalanche in the vicinity of the anode. These avalanches begin when an electron, freed during ionization of the gas by an incident high energy particle, enters this avalanche region. Thus, the total number of electron-ion pairs produced per second in the gas volume is a function of the rate of incident par-

Figure 4.6: Factors affecting high rate performance of a GMD and how they relate to each other.

ticle arrivals, the total ionization produced by each particle, and the number of pairs produced in a single avalanche (gas gain). We can imagine two currents, an electron and an ion current sourced in the avalanche region. These currents (really currents per unit length) are distributed to either one of the three metal electrodes (where they disappear) or the substrate surface (where they continue as substrate currents) in a way commensurate with the ideas discussed above.

Presumably a steady state condition now arises in which charged particles pass at a constant rate through the gas and are converted or neutralized at the substrate boundary. The resulting substrate currents are sourced by the three electrodes at the periphery of the medium. However, this steady state solution is difficult to derive since the gas to substrate currents have the effect of changing the E-field configuration which in turn modify the gas to substrate currents. Figure 4.6 illustrates the problem. It is clear from the diagram that the only way to arrive at a solution such that this system is self-consistent is iteratively.

At first glance it would seem that once a flux of incident particles had been specified, an estimate of the gas gain as calculated from the E-field map inside the gas volume would be necessary at each step in the iterative process. In fact, it is possible to avoid this complication by fixing the total amount of current (both

ion and electron) to be distributed at each step rather than the incident particle flux. The E-field configuration must then be consulted only to determine the quantity of current arriving at each point along the substrate. The application of this new current has the effect of changing the E-field configuration, and so the process continues until a convergent solution is reached. At this last stage an estimate of the total gas gain can be made. Working backwards, the total incident particle flux corresponding to this solution can be calculated as

$$\Phi = \frac{I_{tot}}{G n_p d_{top} e} \quad (4.17)$$

where I_{tot} is the total current (per unit length) to distribute as fixed during the iteration, G is the estimate of the gas gain, n_p is the mean total ionization of the incident particle, d_{top} is half of the chamber pitch, and e is the electronic charge.

4.3.4 Description of the Computer Model

In order to solve for the steady state E-field configuration for a GMD operating at various particle fluxes, a computer program was devised capable of performing the iterative process described above. The backbone of this model was an electrostatic modeling package called POISCR, which is part of CERNLIB [30]. This package was capable of solving for the electric field configuration in a GMD half-cell for the conductive case. It used a finite-element technique, and was controlled through a series of input files which could be modified by an external program between runs. This external program, called GFLUX, was designed to examine the output of POISCR, make decisions about the parameters of the next iteration, and launch POISCR again with these new parameters.

For simplicity the surface of the (two dimensional) substrate between anode and cathode was divided into a number of small elements. Each of these elements could become a surface current source, the total strength of which (in A/m) being specified by GFLUX. At each stage of the iteration, GFLUX would integrate the

y-component of the electrostatic field above each of the three electrodes and each of the substrate elements, yielding the following values:

$$\begin{aligned} V_d &= \int E_d^y dx \\ V_a &= \int E_a^y dx \\ V_c &= \int E_c^y dx \\ V_s(i) &= \int_{x_i}^{x_i + \Delta x_i} E_s^y dx \end{aligned}$$

where the integration paths are along the Gaussian contour shown in Figure 4.4.

In order to calculate the strengths of the surface current sources $I_s(i)$ for the next iteration, GFLUX used the following criteria:

- A value for d_{bot} in equation (4.16) was generated according to,

$$\int_0^{d_{bot}} E^y dx = V_d \quad (4.18)$$

where the integration path starts at the middle of the anode and continues along the gas to substrate interface.

- The total avalanche width d_{av} was calculated using equation (4.16). That is,

$$d_{av} = d_{bot} + 19\mu m \sqrt{\frac{d_{bot}}{d_{top}}} \quad (4.19)$$

- To parameterize the varying gas gain across the avalanche region, the region was divided into sub-regions j , each with integrated E^y values of $V(j)$. The fraction $f^-(j)$ of the total current I_{tot} being generated over sub-region j was estimated by,

$$f^-(j) = \frac{V(j)^n}{\sum_j V(j)^n} \quad (4.20)$$

where n was a free parameter in the model. Setting $n = 0$ would eliminate

this extra parameterization. However, the best results were achieved with $n = 4$.

- The electrons generated over the sub-regions corresponding to the anode strip were eliminated. Those beyond the anode strip were used to calculate substrate currents. If sub-region j corresponded in physical location to substrate current element i , then a current contribution of $I_{tot}f^-(j)$ was added to $I_s(i)$. That is,

$$I_s(i) = -I_{tot} \sum_j f^-(j), \quad j \text{ coincident with } i \quad (4.21)$$

- The ion current was distributed by following the field lines from the avalanche using Gauss' Law. Figure 4.7 shows the technique graphically. The top two lines show the cumulative V values (integrated E^y) and the fraction of total current f^- for the regions j near the anode. The third line shows the cumulative V values for the drift electrode, cathode and substrate elements near the cathode (the total number of substrate elements is given as N). The bottom line shows the fractions f^+ of the total ion current distributed to each of these regions k , given by

$$f^+(k) = \sum_j f^-(j) \frac{\|V(k) - V(j)\|}{V(k)} \quad (4.22)$$

where $\|V(k) - V(j)\|$ represents the amount of overlap between $V(k)$ and $V(j)$ on the cumulative graphs shown in the Figure.

- Once the fraction $f^+(k)$ of the total ion current arriving at each substrate element k was determined, the remainder of the substrate current elements could be assigned trivially:

$$I_s(i) = I_{tot} f^+(i) \quad (4.23)$$

2 of/de 2

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
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Figure 4.7: Representation of the analytic technique for distributing ion currents.

- The new values of $I_s(i)$ were underrelaxed to speed convergence. That is,

$$I_s^{new}(i) = I_s^{old}(i) + \alpha [I_s(i) - I_s^{old}(i)] \quad (4.24)$$

where α is the underrelaxation parameter with $0 < \alpha \leq 1$.

Armed with the new values of $I_s(i)$, POISCR calculated the new electric field configuration and the iterations proceeded until convergence was reached. Each such convergence represents a point on a gain versus rate plot as described in the previous section.

4.3.5 Results from the Computer Model

Figure 4.8 shows the changes in gas gain as a function of rate of incident X-rays for three different levels of ion-implantation as generated by the computer model. The ratio of conductance of the $2 \mu\text{m}$ implantation layer to the bulk substrate is taken to be 10, 100 and 10^4 for the high, medium and low resistance prints, respectively. The first thing to notice is that the print with near bulk resistive properties has a much higher gas gain at low rates than the implanted prints. This is due to the *spreading out* of the field lines close to the anode in implanted prints, as discussed previously. As the incident rate is increased, the following trends are observed: the bulk resistive print begins to loose gain, the highly implanted print sees no gain change, and the print in between actually sees a rise in gas gain. Remember that these values were derived by estimating the gas gain from the field configuration of a converged solution — an imprecise step at best. The abscissa values in the Figure are only approximate. For instance, the effects as generated by the model are not as pronounced as are usually observed experimentally, and they occur at lower rates. Convergence at higher rates became difficult, due likely to round off error and other such effects. However, the predicted trends are quite similar to some of the observations discussed in section 3.2, and may shed

Figure 4.8: Rate effects from computer model.

some light onto the changes that occur in a GMD when exposed to high levels of radiation. Observations from the model are discussed below.

For a bulk conductive print, with high surface resistivity, the *drift bucket* is small and confined to the middle of the anode. This is actually a low field region and does not produce much gain. Diffusion carries some primary electrons to the anode edges where the field is much higher and a large fraction of the ions are produced there. The field lines from the anode edge carry most of these ions to the cathode strips, but a few find their way to the surface of the substrate close to the cathode (i.e. some cross region B into region C i.e. Figure 4.5). The build up of steady state positive charge in this area has the effect of widening region B, providing a limit to the amount of ion current that can cross over to region C. In

effect, the field lines that were crowded around the anode edge become spread out onto the surrounding substrate. This also has the consequence of lowering the gas gain. The effect becomes more pronounced at higher rates, and is commonly referred to as *high rate charging*. It should be pointed out that a carefully chosen set of electrode voltages could place region C far enough away from the anode that this effect would not be seen until much higher rates.

The medium resistivity implanted print has a much larger drift bucket, and secondary ionization is likely to occur not only over the anode but over the substrate as well. Recall that for an implanted print, the effective anode (where field lines start) extends beyond the physical anode. In this case, secondary electrons are absorbed by the substrate and a steady state build-up of negative charge develops near the anode. The response of the field configuration is to limit this current by moving the field lines away from the substrate and onto the anode. That is, region A shrinks in favour of region B. This compacting of field lines has the effect of raising the gas gain. These prints have the rather odd behaviour of a gain increase with rate. One might assume that at higher rates the drift bucket would become sufficiently small that this increase would reach an upper limit, and that furthermore one might see a gain drop due to the high rate charging effect discussed above. Experimentally, these prints experience a rise and then a drop-off in gain as rate increases (see Figure 3.9). However, it does not appear that this will happen in the model. It is therefore surmised that this experimental drop-off is due to effects not considered here — space charge for instance.

The highly implanted, low resistivity, print also has a large drift bucket. However, because of the highly conductive nature of the implantation layer, much larger electron currents can be absorbed by the substrate near the anode without any significant steady state charge build-up. Because of this, no change in gas gain is seen over a large range of incident rates. One might expect that eventually the currents would be large enough to produce a gain increase, but at that point

such effects as space charge may have imposed other limits to the gas gain.

As discussed previously, the computer model as currently configured has the ability to point out trends and gives some explanation for the shape of rate effect curves. In this sense, the model is qualitatively useful. However, it fails to provide quantitatively accurate results. For instance, the high rate charging effect is expected to be more dramatic than the model allows. This might be due to such phenomenon as tertiary ionization (avalanche) in the high field region of cathode edge. Additional ions formed over the substrate through this process would advance the gain loss at lower rates, but are not considered in the model. Also, the details of avalanche formation are not included in the model and might prove to be very important. Avalanche simulations [31] have indicated that a single avalanche can cover a large area and is not confined to a small region as suggested in the present model. Effects such as photon emission during the avalanche might spread the extent of the ionization even further. Finally, the present model considers only those primary electrons formed in region A of Figure 4.5. While this represents the majority of the deposited charge, it may be that ionization in the other regions have important consequences. This is the basis for the ideas of Fang, et al. [29] in their discussion of rate effects.

A more general method of simulating rate effects would be to employ a Monte-Carlo technique which would include all the phenomenon discussed above and be able to track large number of ions and electrons after an avalanche to estimate gas to substrate currents. The results of the Monte-Carlo would be fed into an electrostatic modeling program for the next iteration. In fact, Bellazzini and Spezziga [32] have done precisely this in a recent paper. The involved process of iteration means that on average 30 days are needed to reach convergence. While the present method is much faster, it obviously lacks the precision of the Monte-Carlo technique.

Chapter 5

Applications

The Gas Microstrip Detector can detect both charged particles and X-ray energy photons. These two abilities lend themselves naturally to a number of interesting applications. The GMD is foreseen as an excellent cost effective device for tracking charged particles at the next generation of high luminosity particle accelerators, such as the Large Hadron Collider (LHC) at CERN. The GMD's X-ray detection ability has sparked an interest in exploring the possibility of using this device as a replacement for photographic film in medical imaging applications. These two potential applications will be examined in this chapter.

5.1 Particle Physics Applications

Gas Microstrip Detectors are currently part of the design of two experiments (CMS and ATLAS) proposed for construction at the LHC at CERN. The ATLAS detector is a general purpose proton-proton detector slated for operation at the startup of the accelerator, early in the next century [33]. The focus of the experiment is the origin of mass at the electroweak scale, and so the detector is optimized for the Standard Model Higgs search. Detailed studies of top quark decays and Supersymmetry searches will also be possible. These physics goals

require high energy and high luminosity. The LHC will provide both of these with center of mass energy of 14 TeV and luminosity up to $1.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

Figure 5.1 shows a cutaway view of the ATLAS detector. The inner detector is the closest layer to the beam interaction point. It is surrounded by electromagnetic and hadron calorimeters, with muon detectors enveloping the outside. The “paddle-wheel” structures are the air core superconducting toroid magnets. Two forward calorimeters complete the detection system. The complete detector will measure approximately 20 meters in diameter, 35 meters in length, and weigh 6 kT. The Gas Microstrip Detectors are used for tracking in the inner detector.

Figure 5.2 depicts the inner detector in detail. It occupies a cylindrical cavity 1.15 meters in radius and 6.80 meters in length. A magnetic field of 2 T is provided within the detector by a thin superconducting solenoid about its circumference. The 1 mm thick, 5 cm diameter beam pipe runs along the axis of the detector. The innermost tracking system is the semiconductor tracker (SCT). The crowded inner region of the SCT is occupied by a silicon pixel detector. This is surrounded by silicon strip detectors in a barrel configuration. GaAs strip detectors are used in the higher fluence forward region of the SCT due to the superior radiation tolerance of this material. In the forward region a transition from barrel to disc geometry is made. Gas Microstrip Detectors (or Microstrip Gas Chambers MSGCs — as they are sometimes called) are foreseen as the high granularity tracking detectors in this region. GMDs are chosen over silicon strip and other detectors in this large area region because of their low cost per channel and low material usage, which helps minimize multiple scattering. They are mounted on several wheels as shown in the Figure. Transition radiation trackers (TRT), comprised of straw tubes are used at high radius where track density is reduced. These straw tubes are also used as an inexpensive means of low precision multiple track measurements which aid in track identification [34].

The specifications for the inner detector require 6 precision hits and 36 straw tube hits over the whole acceptance range. In the forward region up to four of

Figure 5.1: The ATLAS detector (air toroid option).

Figure 5.2: The ATLAS inner detector.

these precision space points are provided by the Gas Microstrip Detectors. Each point must have a resolution of $40\text{ }\mu\text{m}$ per plane in ϕ and 1.44 mm in r . A radial, or *krystoned* strip arrangement is used to achieve the high precision ϕ measurement. The r measurement is accomplished by using three detector layers at each wheel position; a radial, ϕ , layer and two stereo layers, u and v , set at a small angle ($\pm 1^\circ$), as shown in Figure 5.3. This triple layer arrangement guarantees at least two hits per track for each wheel, enabling space point reconstruction. Each detector has a $200\text{ }\mu\text{m}$ anode pitch and has an active area of $10\text{ cm} \times 10\text{ cm}$. The u and v planes are assembled together with a common drift plane. The detectors are staggered to minimize overlap of dead areas, and mounted on a series of 10 mm thick carbon fibre discs or wheels as shown in Figure 5.4, sandwiched between layers of the TRT. There are 24 small wheels and two full wheels at the far end of the detector. All together, approximately 1.47 million GMD signal channels are expected.

The hostile environment within the inner detector imposes some stringent requirements on the performance of the GMDs. Charged particle fluxes of up to $10^4\text{ mm}^{-2}\text{ s}^{-1}$ are expected, and the detectors must operate at this flux without serious loss of gain or efficiency. Operation without performance loss for integrated flux of up to 100 mC per cm of strip length, corresponding to 10 years of LHC operation, is expected. The detector must also be free of degradation due to neutral background radiation of up to 400 kGy . Several candidate substrates are under consideration, including semiconducting glass, SiO_2 substrates, and treated Upilex.

In order to properly associate a GMD hit with a particular LHC bunch crossing, a maximum drift time of 2 LHC interbunch times (50 ns) is required. This can be accomplished by using a 2.8 mm drift gap and an argon/DME (50/50) gas mixture with electron drift velocity of $53\text{ }\mu\text{m/ns}$ for a 10 kV/cm drift field [25]. About 20 primary electrons are liberated by a minimum ionizing particle in this configuration. Other gas mixtures are also under consideration. Hit de-

Figure 5.3: The GMD detector module showing three GMD layers. The U/V double plane is in front with the ϕ plane behind.

tection and bunch assignment is the function of the readout electronics. Two readout schemes are currently proposed. The “RD20” scheme uses an amplifier with a long ($\tau = 45$ ns) shaping time, which has the advantage of low noise and low power consumption. The resulting signal must be passed through a high pass digital filter to resolve the bunch time. The “Fastplex” scheme uses a fast rise time ($\tau = 15$ ns), long decay time amplifier. The signal is passed through a double correlated sampling (DCS) system, which subtracts samples taken at successive beam crossing times and looks for large differences. A comparison of the strengths of these two schemes for GMD readout is given in [35].

At this stage in the development of the ATLAS detector, many decisions remain about the nature of the GMDs used in the experiment. Choice of substrate, counting gas, and readout scheme have not yet been finalized. These choices will need to be made shortly, so that sufficient time remains for construction of the

Figure 5.4: The GMD mounting wheel.

Figure 5.5: A GMD mammography imaging system.

system before the first beams in year 2003. Overall, GMDs remain an excellent choice for robust, low cost precision tracking in the ATLAS inner detector.

5.2 Medical Imaging Applications

GMDs have been considered for use in medical X-ray imaging applications as a replacement for the widely used screen-film image receptor. Mammography is a principle area of interest because of the soft X-rays used in that process, which means that GMD efficiencies remain high. Because the GMD has only a 1D resolution, the image would need to be scanned by introducing a slit between the X-ray source and the object. A conceptual imaging system is shown in Figure 5.5. The detector is shaped in a curved geometry with radius centered at the X-ray source. This geometry prevents parallax errors. Plastics are seen as the substrate of choice for this arrangement because of the ease of constructing such a curve [36].

GMDs have several advantages over screen-film imagers. Screen-film has a limited dynamic range, and contrast must be set before the image is taken and is then fixed. A compromise which allows for the variation in X-ray intensity from the thickest to the thinnest part of the object may not allow the sensitivity needed to detect subtle changes in intensity, such as those that might occur in the vicinity of a tumor. The GMD by comparison has a much higher dynamic range, with several 10^4 counts per pixel. In addition, contrast could be adjusted by the operator to examine localized intensity changes after the image is taken.

The GMD is a photon counter, whereas film is an energy-integrating detector. For this last type of detector, the *detected quantum efficiency* at low spatial frequencies is given by

$$\text{DQE} = \eta \frac{\langle E_d \rangle^2}{\langle E_d^2 \rangle} \quad (5.1)$$

where η is the probability of photon interaction (quantum efficiency) and E_d is the distribution of possible energies deposited in the detector per photon interaction [36]. This last factor is significantly less than unity in practice. The GMD, on the other hand, counts all photons with equal weight, meaning that $\text{DQE} = \eta$ for this device. The target for detection efficiency (η) in the GMD for 18 keV mammographic X-rays is 70%. This is accomplished by using high pressure (~ 7 bar) Xe as the counting gas. This means that the DQE for the GMD is significantly better than is possible for a screen-film system. Since $\text{DQE} = \text{SNR}_{\text{image}}^2 / \text{SNR}_{\text{input}}^2$ where SNR is signal to noise ratio and $\text{SNR}_{\text{input}}^2 = N_{\text{input}}$, the number of photons detected per pixel, improved DQE translates into better image quality for the same dose (or equivalently, lower dose for the same image quality).

In practice, no more than 5 seconds must elapse during the entire scanning process in order to prevent distortion due to patient movement. This means that a very high instantaneous flux is used to achieve acceptable counting statistics in the GMD. Fluxes of $4 \times 10^7 \text{ mm}^{-2} \text{ s}^{-1}$ are expected, corresponding to a total patient dose of 100 mR [36] which is similar to the dose typically used in screen-

film imaging. This high flux capability for plastic GMDs has been demonstrated at 1 bar pressure, especially for the case of nickel oxide coated Upilex prints [13].

Resolution of the GMD image is determined in one direction by the slit width (about 100 μm) and in the other by centroid finding technique (assuming several anodes record a hit for each photon). A 200 μm pitch device is used, and a spatial resolution of 70 μm in the direction perpendicular to the anodes is expected. These resolutions are similar to those achieved by screen-film.

Digital mammography has distinct advantages over existing screen-film techniques. Several methods have been proposed, including use of silicon strips or CCD arrays. Due to its high DQE, low cost and longevity, the GMD is a particularly attractive alternative for digital breast imaging. The Carleton/CRPP groups intend to develop this application in the near future.

Chapter 6

Conclusion

In Gas Microstrip Detector technology is a marriage of many sciences. Microstructures, material science, electrostatics, gas physics, electronics and particle physics all play a fundamental role. The result is a device with increased positional resolution and several orders of magnitude better rate capability than existing gas chambers, while maintaining the cost effectiveness and robustness of that technology.

This thesis has given a flavour for many of the elements that go into GMD design and evaluation. In particular, GMD construction on plastic substrates was examined. Photolithography using wet etch or lift-off techniques has produced good quality prints on plastic using an optimized process. Using ion-implantation to reduce the surface resistivity, Upilex substrate GMDs have proven to operate without degradation in performance at X-ray fluxes of up to $10^6 \text{ mm}^{-2} \text{ s}^{-1}$. More highly resistive ion-implanted prints have demonstrated a gain increase with flux at low flux, as well as a transient backplane dependence.

Plastic GMDs have been evaluated in test beam environments. Results from these studies for $400 \mu\text{m}$ pitch gold on Upilex prints have shown particle detection efficiencies of 90% and timing resolution of 17 ns for slow gas and better than 10 ns for fast gas. The shapes of the timing distribution acquired in the test

beams were understood with the help of a Monte-Carlo simulation.

Operation of the GMD has been studied in the context of electric field diagrams. Much of the observed laboratory phenomena can be explained by examining these diagrams, including temporal gain variations, backplane effects, and effects of thin conducting (implanted) layers. An attempt to explain GMD gain variation with flux, particularly in the case of ion-implanted plastic prints, was made through the construction of a model of avalanche charge distribution. This iterative model was able to predict qualitatively the observed trends for bulk conducting, medium resistivity ion-implanted, and low resistivity ion-implanted prints. Although it leaves much room for expansion and improvement, the model was successful in demonstrating that this kind of technique can be used to study dynamic electric fields in a GMD, and in providing some explanation for the behaviours observed in the laboratory. Further work in this area will be possible, using the techniques outlined here as a foundation.

The next stage in GMD development will be the production of large area prints. It must be demonstrated that GMDs with active areas of 100 cm^2 or more can be made with few defects in a cost effective manner. Readout electronics tailored to GMD operation must also be developed. In the near future, GMDs will make the transition from objects of research to tools of research. With applications such as the ATLAS experiment and mammography, this technology is poised to play an important role in physics and medical science in the next century.

References

- [1] H. Geiger and W. Muller. Technische bemerkungen zum elektronenzahlrohr. *Physikalische Zeitschrift*, 30:489, 1929.
- [2] G. Charpak, R. Bouclier, T. Bressani, J. Favier, and C. Zupancic. The use of multiwire proportional counters to select and localize charged particles. *Nuclear Instruments and Methods in Physics Research*, 62:262–268, 1968.
- [3] A. Oed. Position-sensitive detector with microstrip anode for electron multiplication with gases. *Nuclear Instruments and Methods in Physics Research*, A263:351–359, 1988.
- [4] F. Angelini, R. Bellazzini, L. Bosisio, A. Brez, M. M. Massai, A. Perret, G. Spandre, and M. R. Torquati. A microstrip gas chamber with true two-dimensional array pixel readout. *Nuclear Instruments and Methods in Physics Research*, A323:229–235, 1992.
- [5] R. Bouclier, J. J. Florent, J. Gaudaen, G. Millon, A. Pasta, L. Ropelewski, F. Sauli, and L. I. Shekhtman. High flux operation of microstrip gas chambers on glass and plastic supports. *Nuclear Instruments and Methods in Physics Research*, A323:240–246, 1992.
- [6] J. E. Bateman and J. F. Connolly. Substrate-induced instability in gas microstrip detectors. Internal report, Rutherford Appleton Laboratory, 1992.

- [7] J. E. Bateman and J. F. Connolly. Some results from a gas microstrip detector fabricated on Schott S-8900 glass. Internal report, Rutherford Appleton Laboratory, 1993.
- [8] A. Oed and P. Geltenbort. Substratum and layout parameters for microstrip anodes in gas detectors. *Nuclear Instruments and Methods in Physics Research*, A310:95-97, 1991.
- [9] R. Bouclier, J. J. Florent, J. Gaudaen, G. Million, L. Ropelewski, and F. Sauli. Microstrip gas chambers on thin plastic supports. *IEEE Transactions on Nuclear Science*, 39(4):650-653, 1992.
- [10] F. Angelini, R. Bellazzini, T. Lomtadze, M. M. Massai, R. Raffo, G. Spandre, and M. A. Spezziga. A thin, large microstrip gas chamber with strip and pad read-out. Internal report, Istituto Nazionale di Fisica Nucleare, 1993.
- [11] S. F. Biagi, J. N. Jackson, T. J. Jones, and S. Taylor. Initial investigations of the performance of a microstrip gas-avalanche chamber fabricated on a thin silicon-dioxide substrate. *Nuclear Instruments and Methods in Physics Research*, A323:258-262, 1992.
- [12] M. Salomon, J. Armitage, G. Chapman, M. Dixit, J. Dubeau, W. Faszer, L.A. Hamel, and G. Oakham. Passivation of gas microstrip detectors and stability of long term operation. *Nuclear Instruments and Methods in Physics Research*, 1994. To be published.
- [13] S. C. Taylor, J. C. Armitage, D. Batchelar, M. S. Dixit, J. Dubeau, P. G. Estabrooks, C. Henderson, D. Karlen, J. L. Muench, F. G. Oakham, M. Salomon, and G. C. Stuart. The operation of plastic MSGCs at high rates. Presented at the IEEE Nuclear Science Symposium, Norfolk, Va., 1994.
- [14] M. S. Dixit, F. G. Oakham, J. C. Armitage, J. Dubeau, D. Karlen, G. C. Stuart, S. C. Taylor, I. Shipsey, E. Johnson, and A. Greenwald. Gas mi-

- crostrip detectors on resistive plastic substrates. *Nuclear Instruments and Methods in Physics Research*, A348:365–371, 1994.
- [15] S. C. Taylor and J. C. Armitage. The effect of ion-implantation on the surface resistivity of polyimide film. Internal report, Carleton University Physics Department, 1992.
- [16] T. Hioki, S. Noda, M. Sugiura, M. Kakeno K. Yamada, and J. Kawamoto. Electrical and optical properties of ion-irradiated organic polymer Kapton H. *Appl. Phys. Lett.*, 43(1):30, 1983.
- [17] G. Marletta, S. Pignataro, and C. Oliveri. Correlation between the modification of the chemical structure and electrical properties of Ar-ion bombarded polyimide. *Nuclear Instruments and Methods in Physics Research*, B39:792–795, 1989.
- [18] N. Weste and K. Eshraghian. *Principles of CMOS VLSI Design: A Systems Perspective*. Addison-Wesley, 1985.
- [19] C. D. Kemshall, K. G. Beauchamp, and P. W. Benjamin. The attenuation of proportional counter pulses by RC amplifier time constants. *Nuclear Instruments and Methods in Physics Research*, 68:153–156, 1969.
- [20] R. C. Fernow. *Introduction to Experimental Particle Physics*. Cambridge University Press, 1986.
- [21] R.C. Weast ed. *Handbook of Chemistry and Physics*. Chemical Rubber Publishing Co., 66 edition, 1985.
- [22] CERN. *Short Introduction to the use of the H6 beam*, May 1993. DRAFT.
- [23] TRIUMF. *TRIUMF User's Handbook*, July 1987.

- [24] G. C. Stuart, J. C. Armitage, M. S. Dixit, J. Dubeau, P. G. Estabrooks, L. A. Hamel, J. P. Martin, T. D. Nichols, P. G. Oakham, M. Salomon, and S. C. Taylor. Fabrication and test beam operation of plastic MSGCs. *Nuclear Physics B, Proceedings Supplement*, 1994. To be published.
- [25] S. F. Biagi. A multiterm Boltzmann analysis of drift velocity, diffusion, gain and magnetic-field effects in argon-methane-water-vapour mixtures. *Nuclear Instruments and Methods in Physics Research*, A283:716-722, 1989.
- [26] G. C. Stuart, 1994. Private communication.
- [27] W. S. Anderson, J. C. Armitage, E. Dunn, J. G. Heinrich, C. Lu, K. T. McDonald, J. Weckel, and Y. Zhu. Electron attachment, effective ionization coefficient, and electron drift velocity for CF_4 gas mixtures. *Nuclear Instruments and Methods in Physics Research*, A323:273, 1992.
- [28] M. A. Plonus. *Applied Electromagnetics*. McGraw-Hill, 1978.
- [29] R. Fang, J. M. Brom, W. Geist, A. Michalon, J. L. Riester, and C. Voltolini. Charge accumulation at the interface between two dielectrics and gas gain variations of microstrip gas chambers. Internal report, Centre de Recherches Nucléaires, Université Louis Pasteur, 1994.
- [30] Poiscr. CERNLIB routine T604.
- [31] M. Matoba, T. Hirose, T. Sakae, H. Kametani, H. Ijiri, and T. Shintake. Three dimensional monte carlo simulation of the electron avalanche around an anode wire of a proportional counter. *IEEE Transactions on Nuclear Science*, 32(1):541-544, 1985.
- [32] R. Bellazzini and M. A. Spezziga. Electric field, avalanche growth and signal development in micro-strip gas chamber and micro-gap chamber. Internal report, Istituto Nazionale di Fisica Nucleare, 1994.

- [33] ATLAS letter of intent. CERN/LHCC/92-4, October 1992.
- [34] ATLAS technical design report, 1994. To be published.
- [35] J. Armitage, J. Dubeau, P. Estabrooks, G. C. Stuart, S. C. Taylor, M. Dixit, and G. Oakham. A comparison of readout schemes for MSGC's. Presented at the International Workshop on Micro-Strip Gas Counters, Legnaro, Italy, 1994.
- [36] M. S. Dixit et al., 1994. NSERC grant request proposal.

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