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Development in the Design and Performance of Gas Avalanche Microdetectors (MSGC, MGC and MDOT)

Hyo-Sung Cho
Physics Division

December 1997

Ph.D. Thesis

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**Development in the Design and Performance of Gas Avalanche
Microdetectors (MSGC, MGC and MDOT)**

Hyo-Sung Cho

Ph.D. Dissertation

Department of Nuclear Engineering
University of California, Berkeley

and

Physics Division
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

Fall 1997

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Development in the Design and Performance of Gas Avalanche
Microdetectors (MSGC, MGC and MDOT)

by

Hyo-Sung Cho

B.S. (Seoul National University) 1986

M.S. (Seoul National University) 1988

A dissertation submitted in partial satisfaction of the
requirements for the degree of

Doctor of Philosophy

in

Engineering-Nuclear Engineering

in the

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of the

UNIVERSITY OF CALIFORNIA, BERKELEY

Committee in charge:

Doctor John A. Kadyk, Cochair

Professor Jasmina L. Vujic, Cochair

Professor Victor Perez-Mendez

Professor Kam Biu Luk

Fall 1997

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by

Hyo-Sung Cho

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Abstract

Development in the Design and Performance of Gas Avalanche Microdetectors (MSGC, MGC and MDOT)

by

Hyo-Sung Cho

Doctor of Philosophy in Engineering-Nuclear Engineering

University of California, Berkeley

Doctor John A. Kadyk, Cochair

Professor Jasmina L. Vujic, Cochair

There has been continuing development of generic classes of microstrip gas chambers (MSGCs), microgap gas chambers (MGCs) and microdot gas chambers (MDOTs) at Lawrence Berkeley National Laboratory (LBNL) over the past few years, to improve such detectors beyond their present capabilities, to produce detectors suitable for use in current or upcoming experiments, and to allow a basis for new R&D developments which may incorporate these detectors as part of the system. All of these new detectors are collectively referred to as "*gas avalanche microdetectors*".

The MSGC, which was motivated by the pioneering work of A. Oed, has many attractive features, especially excellent spatial resolution ($\sim 30 \mu\text{m}$ rms at normal incidence) and high rate capability ($\sim 10^6 \text{ mm}^{-2}\cdot\text{s}^{-1}$). Moreover, the MGC seems to have certain advantages over the MSGC in speed, stability and simplicity, and the MDOT has larger gain ($>10^4$) and the intrinsic advantages of two-dimensional readout. Because of these attractive properties, they have received a great deal of attention for nuclear and high energy physics experiments, medical X-ray imaging and many other fields requiring radiation detection and measurement.

However, the gas avalanche microdetectors have not yet reached the state-of-the-art in which reliable detectors can be designed and built for the demanding experiments. Therefore, the main concern of this dissertation is to investigate the operating characteristics and design criteria of the gas avalanche microdetectors for a stable and safe operation, focusing on their possible problems.

Other interests include the use of a thin ($\sim 200\text{ }\mu\text{m}$) columnar cesium iodide (CsI) layer coupled to gas avalanche microdetectors, to improve the space and time resolutions, and the detection efficiency by eliminating the sensitivity to the angle of incident particle. This idea also provides the additional advantage that it may be possible to reduce the gain (and operating voltage) of these gas microdetectors, thus reducing the risk of sparking. All of these are important for significant improvement of the operation of the gas avalanche microdetectors.

Committee in charge:

John A. Kadyk, Cochair

Jasmina L. Vujic, Cochair

Victor Perez-Mendez

Kam Biu Luk

Handwritten signatures of John A. Kadyk and Jasmina L. Vujic, each written over a horizontal line.

*To my family, and
to the memory of my grandmother*

Table of Contents

Chapter 1 Introduction	1
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Chapter 2 Overview of Gas Avalanche Microdetectors

2.1 Introduction	5
2.2 Device Structure	7
2.2.1 Microstrip Gas Chamber (MSGC)	7
2.2.2 Microgap Gas Chamber (MGC)	10
2.2.3 Microdot Gas Chamber (MDOT)	11
2.3 Fabrication Technique	12
2.3.1 Conventional (or Standard) Technique	13
2.3.2 Lift-off Technique	15
2.4 Test and Measurement System	16
2.4.1 Radiation Source	16
2.4.2 Gas Media	16
2.4.3 Electronics for Signal Processing	20
2.5 Two-Dimensional Readout	21
2.5.1 Readout Schemes for 1-D Strip Array	21
2.5.2 Readout Schemes for 2-D Pixel Array	25
2.6 Possible Problems	26
2.6.1 Polarization Effect	27
2.6.2 Surface Charging Effect	28
2.6.3 Aging Effect	30
2.6.4 Spark Damage Effect	32
2.7 Applications to Research	33
REFERENCES	

Chapter 3 Microstrip Gas Chambers (MSGCs) with Conductive Surface Coating of Doped Amorphous Silicon Carbide (a-Si:C:H)

3.1 Introduction	40
3.2 Conductive Surface Coating of Doped A-Si:C:H	41
3.2.1 Basic Features of Amorphous Silicon	42
3.2.2 Deposition Method	47

3.2.3 Application of Amorphous Silicon to Conductive Surface Coating	48
3.3 Experimental Procedures	52
3.3.1 Device Fabrication	52
3.3.2 General Considerations	55
3.4. Results and Discussion	56
3.4.1 Gain vs. Time	56
3.4.2 Gain vs. Anode Voltage (V_a)	57
3.4.3 Gain vs. Backplane Voltage (V_b)	60
3.4.4 Gain vs. Drift Voltage (V_d)	61
3.5 Summary	68
REFERENCES	

Chapter 4 Microgap Gas Chambers (MGCs) Fabricated with Selected Anode Strip Metals

4.1 Introduction	72
4.2 Device Fabrication	74
4.3 Performance Tests	77
4.3.1 Experimental Procedures	77
4.3.2 Results and Discussion	80
4.4 Accelerated Aging Tests	95
4.4.1 Aging Phenomena	95
4.4.2 Analysis of Aging	97
4.4.3 Experimental Procedures	99
4.4.4 Results and Discussion	103
4.5 Spark Damage Tests	112
4.5.1 Description of Tests	112
4.5.2 Results and Discussion	114
4.6 Summary	129
REFERENCES	

Chapter 5 Microdot Gas Chambers (MDOTs) with Amorphous Silicon Carbide (a-Si:C:H) Overcoating

5.1 Introduction	135
5.2 Defocusing Effect of the Readout Stripline	137

5.3 Device Fabrication	139
5.4 Results and Discussion	142
5.4.1 Count Rate vs. Drift Voltage (V_d)	143
5.4.2 Gain vs. Anode Voltage (V_a)	149
5.4.3 Gain vs. Drift Voltage (V_d)	152
5.4.4 Gain vs. Time	153
5.5 Summary	154
REFERENCES	

Chapter 6 Columnar Cesium Iodide (CsI) Drift Plane Layer for Gas Avalanche Microdetectors

6.1 Introduction	158
6.2 Principle and Fabrication	159
6.2.1 Operating Mechanism	159
6.2.2 Deposition Method	163
6.3 Experimental Procedures	165
6.4 Results and Discussion	166
6.4.1 Electron Multiplication Factor	166
6.4.2 Detection Efficiency	171
6.5 Summary	172
REFERENCES	

Chapter 7 Summary	175
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Chapter 1 Introduction

The next generation of experiments in high energy physics will require detectors capable of operating at very high particle detection rates. The commonly used multiwire and drift chambers have reached their limits in spatial resolution and rate capability in many of the proposed experiments. This hand-wound technology is rather mature, so that there seems to be not much room for substantial improvement in their performance.

At the present time, detectors based upon silicon crystals, called the silicon strip detectors[1], are the best candidates for operating in very high flux environments, such as the inner tracking detectors for LHC or B-factory experiments. However, such detectors are difficult to build, and generally can only be produced in sizes that are quite small relative to the sensitive region to be covered. In addition, since they require a minimum thickness of crystalline silicon to provide a detectable signal, the detectors introduce a significant amount of material in the path of the particles, resulting in interactions and multiple scattering and thus degrading the measurements made by subsequent detectors (e.g. tracking and calorimetry). They are also rather vulnerable to radiation damage compared with, for example, wire chambers, which have been successfully tested up to accumulated doses in excess of several megarads[2].

In recent years, there has been a major breakthrough in the development of gas avalanche detectors, which was motivated by the pioneering work of A. Oed in 1987. He proposed a new alternative technology, called the microstrip gas chamber (MSGC)[3], wherein the anode wires of the multiwire proportional chamber are replaced by very thin parallel metallic anode strips patterned on an insulating substrate, using microelectronics technology. The introduction of the MSGC has drastically changed the field of gas avalanche detectors, and has led to further developments, such as the microgap gas chamber (MGC)[4] and the microdot gas chamber (MDOT)[5]. All of these new detectors are collectively referred to as "*gas avalanche microdetectors*". These gas

microdetectors have shown very promising features in spatial resolution, timing and rate capability, which may allow them to have many potential applications in high energy and nuclear physics experiments, astrophysics, medical X-ray imaging and many other fields requiring radiation detection and measurement. Their introduction is certainly the most important development in the field of gas avalanche detectors made in the last decade.

However, these microdevices have not yet reached a level of maturity that will be needed for the most demanding experiments, even though they have clearly demonstrated many improvements over wire chamber technology. The main concern of this dissertation is to investigate the operating characteristics and the design criteria of these gas microdetectors for a stable and safe operation, focusing on their possible problems.

In chapter 2, a brief and general description of the gas avalanche microdetectors is presented, including device structure, fabrication technique, test and measurement system, two-dimensional readout schemes, and possible problems with this technology. Applications to research are also discussed in the last section of this chapter.

In chapter 3, a new technique is described, involving the use of doped amorphous silicon carbide ($a\text{-Si:C:H}$) as a conductive surface coating. This coating is deposited during MSGC fabrication to eliminate problems associated with charge accumulation on the insulating surface. Performance of the detectors made in this way is discussed. Some necessary background information on the amorphous silicon coating material is also given briefly.

An investigation of the effects of different anode metals upon detector performance and reliability is described in chapter 4. Several MGCs were fabricated with different anode metals and tested to study the effects of these metals upon gain, resistance to radiation damage (aging), and spark damage. Although the aging and spark damage tests have been performed with MGCs, the results are expected to be similar for MSGCs. $A\text{-Si:C:H}$ has also been used as an insulating support pedestal for the anode strip in MGCs, in an attempt to achieve larger gain by using a thicker insulating layer.

A discussion of MDOTs is presented in chapter 5. MDOTs have the intrinsic advantage of two-dimensional ("*pixel*") readout of every particle detected, thereby reducing occupancy and tracking confusion in high flux environments. In addition, MDOTs achieve a larger gas gain than what can be obtained from MSGCs or MGCs. However, there is an influence of the anode readout stripline on the field in the drift region, leading to some defocusing of the drifting electrons from the anode dots, and consequent loss of sensitive region. To eliminate this effect, the same technique of the conductive surface coating of doped a-Si:C:H has been used, by which the readout region is isolated electrically from the drift region. Measurements of the defocusing effect and other effects of the conductive coating on the performance of the MDOTs are reported.

In chapter 6, a new technique, using a thin ($\sim 200\text{ }\mu\text{m}$) layer of columnar cesium iodide (CsI) on the drift plane, is described. This CsI layer acts as an efficient source of electrons produced by secondary emission resulting from passage of incident particles. In addition, electron multiplication within the columnar layer, as in a micro-channel plate, occurs when an appropriate potential is applied. This localization and increase in the number of drifting electrons is expected to lead to substantial improvements in space resolution, time resolution and efficiency. More importantly, it eliminates the existing angular dependence of these parameters, a significant improvement in the operation of gas avalanche microdetectors. The measurements of signal enhancement due to the columnar CsI layer, and detection efficiency with respect to the incident particle angle, are presented and discussed.

All of the significant findings and results in gas avalanche microdetectors are summarized in chapter 7.

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Chapter 2 Overview of Gas Avalanche Microdetectors

2.1 Introduction

The proportional counter[1] invented in late 1920s is a single wire chamber, in which a very thin anode wire is stretched axially at the center of a cylindrical cathode. Figure 2.1 (a) shows a schematic structure of the proportional counter. The electric field in such a geometry is inversely proportional to the radius from the center of the anode wire, resulting in an intense field very close to the anode wire and a relatively weak field elsewhere. The proportional counter relies upon the phenomenon of the electron avalanche. In this process, the number of electrons produced by ionization of gas molecules is greatly increased by the avalanche, and the amplification of a signal by the avalanche is called “*gas gain*” (this process is discussed in more detail in section 2.2.1). Although the primary electrons, created by an incident particle along its track, travel different distances from their origins before reaching the anode wire, they contribute equally to the output signal, since the avalanche occurs very close to the anode wire, thus maintaining proportionality between the energy deposited within the gas and the amplitude of the output signal. The term “*proportional*” refers to a regime of electric field strength and gas pressure ($\sim 10^4$ - 10^5 V/cm for gases at atmospheric pressure) in which the total charge eventually collected at the anode wire is proportional to the charge represented by the primary ionization. For this reason, the proportional counter can be used for energy spectroscopy.

In 1968 G. Charpak invented the multiwire proportional counter (MWPC)[2,3] as a position-sensitive radiation detector, and was awarded the Nobel Prize in physics in 1992 for his invention and development of this radiation detector, underlining the importance of the development of new detectors for progress in science. As shown in Fig. 2.1 (b), a MWPC consists of a set of thin, parallel, and equally spaced anode wires, being

Fig. 2.1 Schematic structures of (a) the proportional counter and (b) the multiwire proportional counter. V_0 is the anode-cathode voltage, r_a is the anode wire radius, r_b is the cathode inner radius, and r is the radius from the center of the anode wire.

symmetrically sandwiched between two cathode planes. Each anode wire acts as an independent proportional counter, thereby allowing spatial resolution of the order of half the wire spacing. Due to its position-sensing capability and other good features, the MWPC has been widely used in the fields of nuclear and high energy physics, medical X-ray imaging and astrophysics for the last two decades.

Nevertheless, the MWPC, at least in its standard design, has two major limitations which are crucial for future experimental requirements: (a) the spatial resolution in the direction orthogonal to the anode wire plane is limited by the wire spacing and (b) the rate capability is limited by the anode-cathode gap; both of these distances are of the order of a millimeter or a few millimeters. In order to overcome these two limitations, we must reduce the anode wire spacing, thus improving the spatial resolution as well as reducing the incoming flux per wire. And also reducing the anode-cathode distance will shorten the ion collection time, thus improving the rate capability. However, for spacings less than those mentioned above ($\leq 1\text{mm}$), the MWPC becomes difficult to operate due to unavoidable electrostatic instabilities of the anode wires. Thus, a fundamental change in the detector design is required in overcoming these limitations.

In this chapter, new designs and concepts, based on an alternative technology, are introduced: microstrip gas chambers (MSGCs), microgap gas chambers (MGCs) and

microdot gas chambers (MDOTs). In section's 2.2 and 2.3, the structure and fabrication technique of these microdevices are described. In section's 2.4 and 2.5, the measurement system and two-dimensional readout schemes are presented. In section 2.6, the possible problems with this new technology are discussed. Applications to research are also described in the last section.

2.2 Device Structure

2.2.1 Microstrip Gas Chamber (MSGC)

At the 1st London Conference on Position-Sensitive Detectors in 1987, A. Oed first suggested the use of photolithographic techniques with submicron accuracy in detector fabrication. This new type of detector is called the microstrip gas chamber (MSGC)[4-6], wherein the anodes, instead of being freely suspended in space as in the MWPC, are thin metallic strips firmly attached to an insulating substrate. Figure 2.2 (a) and (b) show the side view and the top view of the MSGC structure, respectively. The basic structure consists of alternating thin anode and cathode strips (typically 10 μm and 100 μm wide, respectively) which are laid on an insulating support, with a typically anode-to-anode spacing (called the "*pitch*") of a few hundred microns, with 200 μm a commonly used spacing. Such a small spacing would be impossible in conventional wire chambers. The drift electrode, negatively biased, defines one side of the sensitive gas volume in which primary ion pairs are released by an incident ionizing particle along its track. On the bottom of the substrate is a planar electrode, the backplane, for shaping the field lines, or, if made in the form of strips orthogonal to the anode strips, for the second coordinate of a two-dimensional readout. As shown in Fig. 2.2 (a), the electric field of the MSGC consists of two regions: (a) a drift region defined by the gas volume between the drift electrode and the microstrip plate, and (b) an amplification region defined by an array of

Fig. 2.2 Schematic structure of the MSGC: (a) from the side and (b) from the top. The electric field of the MSGC consists of two regions: a drift region and an amplification region.

anode and cathode strips, which is usually a small part of the drift region and quite close to the anode-cathode plane. The field lines between the drift electrode and the anode strips, and those between the cathode strips and the anode strips, concentrate on the thin anode strips, resulting in a very intense field here. Since the drift electrode is placed at relatively large distance from the anode strips (~a few millimeters above), compared with the neighboring cathode strips, it usually does not contribute as much to the intensification of the electric field as the cathode strips, but causes primary electrons to drift toward the anode strips: the contribution only depends upon the fraction of field lines coming from drift electrode or cathode strips, which is typically 30%/70%, respectively. For this reason, the neighboring electrodes to the anode strips are called the “cathode” strips, whereas the upper plane in the MWPC structure is called the “drift” electrode. A higher drift voltage is preferable for a larger gain, but it may be limited by the “dead zone” effect, as we shall discuss in section 3.4.4: in such a case, the drift field lines may end on the substrate surface or at the cathode, instead of at the anode, resulting in loss of signal from electrons drifting on these field lines. Therefore, it is important to

optimize the drift voltage, allowing field lines from the anodes to cover the entire gas drift region.

When an ionizing particle enters the gas volume, it creates primary ion pairs along its track, and the resulting electrons and positive ions drift along the field lines toward the anode strips and the drift electrode, respectively. While drifting, they are accelerated by the field, and undergo many collisions with the neutral gas molecules. Although the positive ions do not gain much energy between collisions due to their low mobility, the electrons, being much less massive, are easily accelerated and gain significant energy between collisions. When the field is sufficiently high ($>10^4$ V/cm for gases at atmospheric pressure), the electrons gain enough energy between collisions to ionize other gas molecules. The electrons released by such ionizations are also accelerated by the field, and contribute to further ionizations. As the electrons drift closer to the anode strips, where the electric field is stronger and the probability of ionization is higher, ion pairs are produced more readily. This process is called the "*avalanche formation*". This avalanche process starts near the anode strips, and ends when all of the electrons have been collected at the anode strips. On the other hand, most of the positive ions produced in the avalanche process move towards the neighboring cathode strips, which are much closer than the drift electrode. Their motion induces negative electrical signals on the anode strip toward which they travel, and positive signals on the other surrounding electrodes. The electrical signals can be read out from either the anode or the cathode strips, or even from the backplane if the substrate is sufficiently thin.

The greatly reduced anode-cathode distance, by the use of photolithographic technique, permits the fast collection of the ions produced in the avalanche process, together with a substantial improvement in spatial resolution ($< 30 \mu\text{m rms}$)[7], due to the large strip density. The rate capability is typically $\sim 10^6 \text{ mm}^{-2}\text{-sec}^{-1}$ [8,9], compared with $\sim 10^4 \text{ mm}^{-2}\text{-sec}^{-1}$ for the MWPC. The MSGC can be thought of as a miniaturized version of the MWPC, with improvements in spatial resolution and rate capability.

2.2.2 Microgap Gas Chamber (MGC)

In 1993 F. Angelini *et al.* proposed another version of the gas avalanche microdetector, called the microgap gas chamber (MGC) [10-13]. In the MSGC, the large insulating substrate surface exposed to the avalanche results in charge accumulation on the insulating substrate surface, thus leading to time and rate dependent gain instabilities[5]. This insulating surface is largely eliminated in the MGC design, as shown in Fig. 2.3. Its structure differs from that of the MSGC in that the anode strips are not coplanar with the cathode, but lie above the cathode on narrow insulating pedestals. This unique geometrical feature allows a separation distance of only a few microns between the anode strips and the cathode, rather than tens of microns as in the MSGC, and thus much stronger electric field exists between the electrodes ($\sim$ few MV/cm), resulting in a very high rate capability, nearly $\sim 10^7 \text{ mm}^{-2}\cdot\text{sec}^{-1}$. As might be expected, the quality of the insulating layer and the alignment of the strips in the fabrication process are crucial factors for the MGC performance. In addition, the MGC has no backplane, and normally a smaller fraction of electric field lines from the anode go to the drift electrode [10]. The

Fig. 2.3 Schematic structure of the MGC: (a) from the side and (b) from the top. Its structure differs from that of the MSGC in that the anode strips are not coplanar with the cathode, but lie above the cathode on narrow insulating pedestals.

MGC seems to have certain advantages over the MSGC in speed, stability and simplicity. It can be also thought of as a miniaturized version of the MWPC with highly asymmetric anode-cathode gaps.

2.2.3 Microdot Gas Chamber (MDOT)

In 1995 S. Biagi developed a new microdetector design, called the microdot gas chamber (MDOT), which is not a strip device like the MSGC or the MGC, but is capable of true two-dimensional (2-D) or “*pixel*” readout[14,15]. Figure 2.4 shows an example of the geometry of the MDOTs with an array of anode microdots surrounded by cathode grids: (a) from the side and (b) from the top. As noted in ref’s. 14 and 16, there is a substantial gain improvement in the MDOT chambers over the previous detectors, due to their electric field distribution: the electric potential near the anode microdot falls off as $1/r$, resulting in lower fields at the cathode, whereas the potential in the MSGC varies like a wire as $-\ln(r/R)$.

Fig. 2.4 An example of the MDOT structure with an array of anode microdots surrounded by cathode grids: (a) from the side and (b) from the top. The MDOT structure has intrinsic advantages of gas gain and two-dimensional readout.

Having a pixel rather than a strip geometry, these detectors have the intrinsic advantage of two-dimensional readout of every particle detected, reducing occupancy and therefore tracking confusion in high flux environments: it may be used either as a true two-dimensional device or may be connected as a microstrip device. However, in the latter case, it has been noted that there is an influence of the readout stripline potential on the field in the drift region, causing some distortion of the drift field and leading to defocusing of some drifting electrons, resulting in loss of signal[15]. This effect may be minimized by the use of "*floating rings*"[17]. As an alternative solution, a new approach has been tried by us: the isolation of the drift region from the amplification region by means of a conductive surface coating of doped a-Si:C:H[18]. The defocusing effect and other performance of the MDOTs with coating are reported in chapter 5.

2.3 Fabrication Technique

One distinct feature of the gas avalanche microdetectors is that they are fabricated using microelectronics technology which can produce highly uniform strips with submicron precision, eliminating the placement inaccuracy of the wires of the MWPC. The design and fabrication of our gas avalanche microdetectors has been done in the Microsystems Laboratory at LBNL and in the Microelectronics Laboratory of the University of California at Berkeley. These laboratories are equipped with standard facilities for microelectronics processing, including a mask generator, a wafer cleaning sink, high temperature furnaces for chemical vapor deposition (CVD) and thermal processing, a thin-film metallic coating system, photolithography station, plasma etcher, analytical and packaging tools, etc.

There are two techniques used in photolithography: the conventional or "standard" technique and the lift-off technique[19].

Fig. 2.5 Steps of the conventional or standard photolithographic process to fabricate MSGCs.

2.3.1 Conventional (or Standard) Technique

The conventional (or standard) photolithographic technique used to manufacture a typical MSGC is illustrated in Fig. 2.5:

- (a) Substrate cleaning: the substrate is chemically cleaned to remove particulate matter on the surface as well as any traces of organic, ionic, and metallic impurities. The substrate can be glass, plastic, or silicon/quartz wafer as long as it has smooth surfaces.
- (b) Metal layer formation: a thin metal layer is deposited onto the substrate by means of sputtering or evaporation.
- (c) Photoresist application: the metal-plated substrate is coated with a thin layer of photoresist. The surface must be clean and dry to ensure good photoresist adhesion.
- (d) Soft baking: a soft baking is used to improve adhesion and to remove solvent from the photoresist.

Fig. 2.6 Edge profiles by (a) the wet etching and (b) the dry etching. The wet chemical etching tends to be isotropic, etching equally in all directions, and can produce undercut and nonuniform strips. In contrast, the dry etching (or plasma etching) is anisotropic, and can obtain a better uniformity and a rounded-off cross section of the edges of the strips.

(e) Mask alignment: a mask reproducing a desired strip pattern is placed over the substrate.

(f) Exposure to UV light: the photoresist is exposed to a UV light through the mask, wherever the metal is to be removed. Any photoresist which has been exposed to UV light is washed away with an alkaline solution, leaving bare metal in the exposed area.

(g) Hard baking: a hard baking is used to harden the unexposed photoresist and improve its adhesion to the metal.

(h) Etching: the metal layer unprotected by the hardened photoresist is removed by immersion in acid baths (wet etching) or by exposure to chemically active ions (dry or plasma etching). Figure 2.6 shows edge profiles by (a) the wet etching and by (b) the dry etching. The wet chemical etching tends to be isotropic, etching equally in all directions, and may produce undercut and nonuniform strips. In contrast, the dry etching tends to be anisotropic, and can yield better uniformity and rounded-off cross section of the strip edges. In principle, the dry etching process produces strips of high quality in terms of uniformity and edge profile.

(i) Photoresist removal: the remaining photoresist is stripped off from the substrate surface by either acetone or O_2 plasma to obtain the final microstrip plate.

Fig. 2.7 Steps of the lift-off photolithographic process to fabricate MSGCs. The lift-off technique is preferable, in principle, since the procedure does not depend upon the ability to etch the metal species, and it is less aggressive for the substrate, because no metal etching step is involved in this technique.

2.3.2 Lift-off Technique

The lift-off technique used to manufacture a typical MSGC is illustrated in Fig. 2.7. First, photoresist is spread over the substrate (glass, in this example). Then it is exposed to the UV light source through a mask and developed, revealing a negative structure of the MSGC. A metal layer is deposited over the entire substrate surface by sputtering or evaporation. Finally, the photoresist is removed with a solvent, removing the unnecessary metals placed on the photoresist. The lift-off technique is preferable, in principle, since the procedure does not depend upon the ability to etch the metal species, and it is less aggressive for the substrate, because no metal etching step is involved in this technique.

2.4 Test and Measurement System

The system we normally used for testing conventional gas avalanche detectors is illustrated in Fig. 2.8. It consists of a radiation source, a gas for detector operation, and electronics for signal processing, such as a preamplifier, a shaping amplifier and a pulse height analyzer.

2.4.1 Radiation Source

For low rate measurements, an ^{55}Fe radioisotope has been used as an X-ray source: it provides X-rays of only one energy, and a convenient half-life, 2.7 yr. After the K-shell electron capture by the iron nucleus, it decays directly to the nuclear ground state of its daughter, ^{55}Mn , emitting 5.9 keV X-rays. For high rate measurements, or for aging test runs, a small X-ray tube with a copper transmission target has been used, providing a maximum X-ray energy of ~ 8 keV and count rates up to $\sim 5 \times 10^5$ counts/mm²/sec[20].

2.4.2 Gas Media

Proper choice of the operating gas is rather critical in the gas avalanche microdetectors, more than in the MWPC, due to the very small interelectrode spacings and amplifying structures: this is because certain electrical breakdown processes are suppressed by absorption of photons in the gas (the so-called “quenching” behavior). Many efforts have been made to optimize several parameters of the gas for specific purposes, including ionization density, avalanche gain, drift velocity, transverse diffusion, etc.[21,22]. In X-ray detection, several processes can cause the absorption of the photons. For low energy X-rays ($E < \sim 50$ keV) photoelectric absorption is the dominant process. As the cross section for photoelectric absorption depends on the atomic number, Z , as Z^4 to Z^5 , it is important to use high Z material as a detection

Fig. 2.8 A conventional detection system applied to a single gas detector. It typically consists of a radiation source, a filling gas, and electronics for signal processing.

medium. The gases with the highest Z are the noble gases (e.g. neon, argon, krypton and xenon). The choice within the noble gases is then dictated by a high specific ionization. Excluding the expensive xenon or krypton (also slightly radioactive) for economic reasons, the choice falls naturally on neon or argon. Table 2.1 shows some properties of several gases used commonly in gas avalanche detectors. In this table, the total number of ion pairs is conveniently expressed by:

$$n_t = \frac{\Delta E}{W_i}$$

where ΔE is the total mean energy loss in the gas volume, and W_i is the mean energy for electron-ion pair creation. The addition of other gases to the noble gases can affect their W_i values due to the Penning effect, in which the energy of the metastable states of a noble gas atom is transferred to the atoms or molecules of another component gas that becomes ionized (i.e. it has an ionization potential less than that of the metastable state).. The number of primary ion pairs per unit length, n_p , is given experimentally at standard temperature and pressure (STP), and is roughly linearly dependent on the average atomic number of the gas mixture. Energy loss and ion pairs per unit length are given at atmospheric pressure for minimum ionizing particles.

For large gain and safe operation, it is necessary to add some amount of quenching gases (e.g. CH_4 , C_2H_6 , DME ($\text{C}_2\text{H}_6\text{O}$), CO_2 , etc.). These gases, typically hydrocarbons, are polyatomic and thus have many vibrational and rotational degrees of freedom, giving them large cross sections for absorbing UV photons emitted from the recombination of ions and de-excitation of atoms during the avalanche process. Otherwise, the emitted UV photons, if they excite other atoms or strike the cathode surface, can induce additional, undesirable, electron emission that may result in delayed spurious avalanches. A good quenching gas does not readily ionize or emit photons as a result, but rather de-excites by fragmentation or collision processes. As an example, the highly flammable gas,

Table 2.1 Properties of several gases, where E_{ex} is excitation potential, E_i is ionization potential, W_i is effective average energy to produce one electron-ion pair, dE/dx is reduced energy loss, n_p is average number of primary ionizing collision per unit length, and n_t is total number of ionization.

Gas	Z	A	ρ (g/cm ³)	E_{ex} (eV)	E_i (eV)	W_i (eV)	dE/dx (keV/cm)	n_p (pairs/cm)	n_t (pairs/cm)
He	2	4	1.66×10^{-4}	19.8	24.5	41	0.32	4.2	8
Ne	10	20.2	8.39×10^{-4}	16.67	21.56	36.3	1.56	12	43
Ar	18	39.9	1.66×10^{-3}	11.6	15.7	26	2.44	23	94
Kr	36	83.8	3.49×10^{-3}	10.0	13.9	24	4.60	22	192
Xe	54	131.3	5.49×10^{-3}	8.4	12.1	22	6.76	44	307
CO ₂	22	44	1.84×10^{-3}	5.2	13.7	33	3.01	35.5	91
CH ₄	10	16	6.70×10^{-4}	9.8	15.2	28	1.48	25	53
C ₂ H ₆	18	30	1.26×10^{-3}	8.7	11.7	27	1.15	41	111
i-C ₄ H ₁₀	34	58	2.49×10^{-3}	6.5	10.6	23	5.93	84	195
DME	26	46	1.90×10^{-3}	6.4	10.0	23.9	3.9	55	160

dimethylether (DME), has properties which make it a very effective quencher for use in the gas microdetectors. It also has a high primary ionization density ($\sim 55 \text{ cm}^{-1}$ at STP) and a moderately high total ionization density ($\sim 160 \text{ cm}^{-1}$)[21]. Therefore, the argon or neon mixed with DME is a very promising gas mixture, and has already been used successfully in the gas avalanche microdetectors[23,24]. In our measurements, we have used gas mixtures of Ar-methane (90/10), Ar-ethane (50/50), Ar-DME(50/50), Ne-DME(70/30) and DME (100). The operating properties of these gas mixtures are compared in chapter 4.

2.4.3 Electronics for Signal Processing

High voltages are applied to the electrodes by high voltage power supplies (Bertan, Associate Inc.) through a protection resistor of $1.2 \text{ M}\Omega$, and a preamplifier (Tennelec TC170) is connected to the readout electrode through a coupling capacitor of 1000 pF . The primary purpose of the preamplifier is to convert the charge produced in the detector by the avalanche process to a voltage pulse, and to provide an optimized coupling between detector output and the rest of the signal processing electronics. It is also necessary to minimize any noise source, and hence the preamplifier should be located as close as possible to the detector and very well shielded against ambient electrical noise sources: the preamplifier should contribute an intrinsic noise level small compared the detected signals. Such a charge-sensitive preamplifier is used to produce a voltage output proportional to the signal charge.

The main function of the shaping amplifier (TranLamp) is to shape the output pulse of the preamplifier and to provide some additional amplification. It is composed of a high and low pass filter network, and produces a short pulse, avoiding pulse pile-up of a subsequent signal on the tail of a preceding pulse; this is especially important in the case of large detection rates.

The pulse height analyzer (PCA3, Oxford Inc.) is basically a combination of an analog-to-digital (ADC) converter and an addressable memory, which records and stores pulses according to their amplitude. The memory contains the distribution of pulse amplitudes by channel number, which is proportional to the amplitude. The distribution of pulses in the channels is therefore an image of the distribution of the energies of the incident particles, or energy spectrum.

2.5 Two-Dimensional Readout

Position-sensitive detectors have been an essential tool in a variety of applications, including medicine, molecular biology, astrophysics, etc. Although the X-ray films are still frequently used in many applications, especially in medical imaging, due to their excellent spatial resolution and easy coverage of large sensitive areas, their applications are limited by narrow dynamic range, low contrast and, more importantly, lack of real-time imaging capability.

The configuration of position-sensitive detectors based upon the gas avalanche microdetectors can provide the possibility of real-time imaging processing with very good spatial resolution, high rate capability and high efficiency. These properties make the gas avalanche microdetectors very attractive for applications in which accurate position determination is needed in high rate environments (e.g. X-ray diffraction experiments with synchrotron radiation). The microdetector structures for imaging are often classified into one-dimensional strip arrays and two-dimensional pixel arrays.

2.5.1 Readout Schemes for 1-D Strip Array

Although gas microstrip devices (i.e. MSGCs or MGCs) were invented as one-dimensional detectors, it is possible to introduce a second coordinate, for two-dimensional readout, by suitably patterning strips on the backplane or the cathode. As

illustrated in Fig. 2.9 (a), the backplane in the MSGC can be divided into strips, orthogonal to the front electrode strips on the rear side of the insulating substrate, so that induced signals could be collected for the second coordinate information.

However, it is known that the amplitude of the induced signal on the backplane is generally small, unless the substrate is quite thin, leading to a poor signal-to-noise ratio for the induced signal. Figure 2.10 shows the ratio of the charge induced on the backplane (Q_b) to the charge induced on the front cathode strips (Q_c) as a function of substrate

Fig. 2.9 Configuration of microdetector structures with an one-dimensional strip geometry for two-dimensional readout: (a) MSGCs, (b) MGCs and (c) MDOTs.

Fig. 2.10 The ratio between the charge induced on the backplane (Q_b) and the charge induced on the front cathode strips (Q_c) as a function of substrate thickness.

thickness, for a MSGC having 10 μm wide anode strips, 60 μm wide cathode strips and a 200 μm wide pitch[25]. Signals on the backplane are less than 50% of the signals on the front cathode strips with a substrate of 50 μm glass thickness. Thus, the substrate must be very thin to obtain a sufficiently large induced signal amplitude. In addition, since the signal on the backplane is induced through the nonmetallized part of the substrate, it is screened by the front cathode strips. Therefore, the induced signal on the backplane strips will depend not only on the thickness of the insulating substrate, but also on the gap between the anode and cathode strips[26,27].

In Fig. 2.9 (b), the separation of the anodes and cathodes in two different planes, in the MGC design, makes it easy to achieve two-dimensional readout. The cathode plane which is separated from the anode strips by insulating strip layers of a few μm thickness is also divided into strips orthogonally to the anode strips, leading to anode and cathode signals having nearly the same amplitude [28]. The MDOT has a pixel rather than a

Fig. 2.11 Schematics of readout schemes for one-dimensional strip array: (a) direct readout method and (b) delay line (or resistive line) readout method.

strip geometry, but may also be used as a microstrip-like device, as illustrated in Fig. 2.9 (c). Two readout schemes for one-dimensional strip geometry, often used for two-dimensional position determination, are illustrated in Fig. 2.11.

(a) Direct readout method

A direct readout of all strips is possible by connecting each strip to its own data acquisition line. This method gives very fast readout, but is expensive due to the large number of readout channels of electronics. Therefore, it is more efficient to use interpolating readout methods such as the delay line (or resistive line) readout methods[29-32].

(b) Delay line (or resistive line) method

Each strip for each of the coordinates is connected to one cell of a delay line (or a resistive line), the ends of which are the inputs to the preamplifiers. Position is determined by the difference of signal arrival times at two amplifiers for the delay line

readout, and by the ratio of charge division for the resistive line readout. For the delay line scheme, each output signal at the ends of the delay lines is first amplified and shaped by NIM standard electronics modules. The event position is then digitized by CAMAC time-to-digital converter modules, and coupled together to define an (x,y) memory address. The signal of the anode strips may deliver its energy spectrum, i.e., an analogue signal.

2.5.2 Readout Schemes for 2-D Pixel Array

More sophisticated readout schemes are required, by nature, for true two-dimensional detectors, and a hypothetical design is discussed here. It would be ideal to connect every pixel to its own data acquisition line: then every pixel sends signals through its own data line to a linear array of amplifier chips located either at the top or bottom edge of the detector array. This method gives very fast readout speed but it requires a large number of signal processing components. Also since the data lines are numerous and become quite closely spaced as the pixel size becomes smaller, a practical size limit is soon reached. Hence, a more realistic readout scheme is needed.

Alternative designs are shown in Fig. 2.12: instead of the direct readout of each pixel, they are read out by individual switching thin film transistors (TFTs) or diodes onto readout lines[33,34]. The pixel array can be read out line by line, by sending an enable or gating signal to the TFT or the switching diode in that line: the x-coordinate is determined by the time of the gate pulse and the y-coordinate is given by a column index. The charge in the elements in the tagged line can be readout by some integrated circuit with multiple inputs (such a device has been developed at Lawrence Berkeley National Laboratory[35]).

Fig. 2.12 (a) TFT readout scheme and (b) diode readout scheme. The pixel array can be readout line by line, by sending an enable signal to the TFT or the switching diode in that line.

2.6 Possible Problems

Even though the operation of the gas avalanche microdetectors is based on the same principle of the gas proportional detectors, their unique structures give rise to new effects, and some characteristics of their behaviors have not yet clearly been understood. In this section, four important effects affecting their performance are identified.

2.6.1 Polarization Effect

Polarization effect is observed inside the volume of a glass substrate commonly used in the MSGC. It is a consequence of the nature of ionic conduction in glass. Figure 2.13 shows the migration of alkali ions (e.g. Na, K, etc.) under the influence of an electric field. After applying high voltages to the electrodes, the alkali ions around the anode strips migrate toward the cathode strips through the bulk, resulting in the increase of the resistivity of the glass substrate. Figure 2.14 shows the variation of the leakage current with time after applying an anode voltage of 700 V to ten ganged anode strips of the MSGC having a Pyrex glass substrate. It decreased by an order of magnitude within five minutes. Thus, it is necessary to wait for a short time after the high voltage is switched on to allow the detector to come to a new electrostatic equilibrium. This effect is reversible by changing the polarity of the electric field, and can be avoided by the proper choice of a substrate without ionic conductivity.

Fig. 2.13 Schematic diagram of the migration of alkali ions: (a) fresh substrate, (b) migration of alkali ions and (c) polarized substrate.

Fig. 2. 14 Leakage current variation with time just after applying a voltage of 700 V to ten ganged anode strips of the MSGC having a Pyrex glass substrate.

2.6.2 Surface Charging Effect

In the MSGC, the effect of charge accumulation on the substrate surface adds to the causes of gain variation. As shown in Fig. 2.15, some ions created from the avalanche can reach the substrate surface along the electric field lines which fall onto the substrate rather than onto the cathode strips, resulting in the buildup of surface charge. These charges then modify the original electrostatic field configuration, leading to a decrease in gain, and simultaneously prevent further charging of the same charges, leading to decrease of charging rate. They can also be neutralized by an electrical conduction through a substrate having non-zero conductivity. By the competition of these two mechanisms of charging and conduction, a new dynamical equilibrium state is set, depending upon the count rate and substrate conductivity[36]. Figure 2.16 shows the initial time dependence of the gas gain for a MSGC having a Corning 7059 glass substrate with a resistivity of about $10^{14} \Omega\text{-cm}$. The gas gain decreased by about 22%

Fig. 2.15 Schematic diagram showing the mechanisms of charge accumulation on the substrate surface and electrical neutralization by the leakage current.

Fig. 2.16 Initial dependence of the gas gain for a MSGC having a Corning 7059 glass substrate whose bulk resistivity is about $10^{14} \Omega\text{-cm}$.

from the initial value to a new equilibrium value. This effect can be classified as a recoverable, local, and short-term phenomenon. Since this effect is entirely due to the presence of the insulating substrate, it depends on the electrical properties of the substrate surface. Thus, this surface charging effect can be minimized by using an electronically conductive substrate (e.g. Pestov glass or Schott S8900 glass)[37,38], by lowering the

surface resistivity of high resistivity substrate (e.g. ion implantation, thin film deposit, etc.)[39,40], or by choosing the operating conditions properly, particularly of the backplane potential[41,42]. On the contrary, in the MGC, it is thought that the surface charging effect can be neglected due to its intrinsic structure having virtually no insulating substrate exposed to the avalanche.

2.6.3 Aging Effect

Another source of gain variations is an effect of radiation-induced damage. It is an old and commonly encountered problem in all gaseous detectors, and may seriously limit their useful lifetime.

During their operation, molecules of the gas are broken up in the avalanche, producing various reactive species, primarily neutral radicals and ions, that may undergo a large number of plasma chemical reactions, leading to a modification of the electrode surface[43]. Very simply, radicals are atoms or molecular fragments with unattached chemical bonds, and may be either charged or neutral. For example, molecular fragments can recombine as much larger molecules (i.e. polymerize), leaving deposits on the electrode surface in certain situations so as to destroy the operation of the detectors:

In similar ways, much heavier, less volatile polymers can form and deposit on electrodes (the dot “•” represents an unattached bond). Figure 2.17 shows a photograph taken with a scanning electron microscope (SEM) of a MGC having nickel anode strips with deposits, after irradiation during an aging test in a dirty test vessel, which caused aging due to

Fig. 2.17 Photograph taken with a scanning electron microscope (SEM) of a MGC having nickel anode strips with deposit during an aging test in a dirty test vessel.

certain pollutants. The degradation of the electrode surfaces by deposits causes various undesirable phenomena, including loss of gain, loss of gain uniformity and energy resolution, excessive and self-sustained currents, sparking, etc. The generic term “aging” is used to describe all forms of performance degradation. Aging can be considered as a side effect of the amplification (or avalanche) process of the gaseous detectors, and can be described as a nonrecoverable, local, and long-term phenomenon. This effect is generally more severe in the gas avalanche microdetectors than in the conventional wire chambers, when normalized to the charge transfer per anode length, partly due to the smaller effective area of the electrodes exposed to the avalanche formation, and partly because the microdetectors generally operate at lower gain, both effects leading to a larger polymer deposition per unit charge transfer. Since aging is very sensitive to the purity and nature of the filling gas, outgassing of the constructing materials, and the metal used for the electrodes[44-46], special precautions must be taken for systematic aging studies.

2.6.4 Spark Damage Effect

It has been known that the maximum gas gain of gas avalanche microdetectors (MSGCs or MGCs) is typically limited to 10^4 by the onset of electrical breakdown. Several groups have studied the breakdown mechanisms in MSGCs, and suggested the hypothesis that the breakdown is triggered by an increase in the number of avalanches initiated by electrons released at the cathode edge by UV photon absorption, field emission or ion bombardment[47-52]. However, V. Peskov *et al.* have experimental evidence that the maximum gain in MSGCs is limited by streamers propagating along the substrate surface, that these are self-quenched over a very limited voltage region, and that sparks form when the streamer bridges the anode-cathode gap[53,54]. From these investigations, it has been suggested that in order to suppress the streamers and hence increase the maximum gain before breakdown in MSGCs, the amplification region should be concentrated in a narrow region around the anode strips, and that the gas gain elsewhere, especially near the cathodes, should be maximally suppressed. This could be done by reducing the anode width, by increasing the pitch, and by developing designs which use optimally shaped cathodes (e.g. MDOT chambers).

Nevertheless, it is quite difficult to guarantee the complete suppression of sparks in present gas microdetector designs. The gas avalanche microdetectors are much more vulnerable to spark damage than are conventional wire chambers, because their electrodes, especially the anode strips, have a smaller cross sectional area, leading to a larger ratio of ohmic heating power to mass (I^2R/mass) per unit length, and the sparking is generally more localized, causing the heating of the electrode to be more concentrated. These effects lead to a larger temperature increase for the gas microdetectors than for the wire chambers, for an equal discharge energy. Figure 2.18 shows an example of an anode strip destroyed by a discharge, with a MGC having 1 μm thick aluminum anode strips, when the spark energy was supplied by 1000 pF capacitor charged to 440 V. The discharge energy is stored in the overall system capacitance. It is thus important to

Fig. 2.18 An example of a strip destroyed by sparking when the spark energy was supplied by 1000 pF capacitor charged to 440 V. The tested detector was a MGC having 1 μm thick aluminum anode strip.

consider the effects of the read-out scheme, the operating voltage and the electrode geometry that minimize the total capacitance. With such precautions, it may be possible to avoid serious spark damage with judicious choices of strip metals. With respect to spark damage, the chosen metal should have a high melting point, a high heat capacity, and a suitable electrical resistivity[55].

2.7 Applications to Research

Although the gas avalanche microdetectors have distinct advantages over other types of gas detectors, the possible problems described in the previous section must be resolved before reliable detectors can be designed and built for demanding experiments.

One of the principal requirements for a stable and safe operation is that the gas gain be high enough to provide a good signal-to-noise ratio for detecting minimum ionizing

particles, and to give a sufficient safety margin between the operating voltage and the appearance of sparking. The gas gains of MSGCs and MGCs are substantially less than for conventional wire chambers in the avalanche mode. This is due to the smaller distance scale available for the avalanche development and less quenching of UV photons by the gas, also a consequence of smaller interelectrode spacing. In MGCs, it is possible to increase the gas gain by increasing the thickness of the insulating pedestal that supports the anode strips, increasing the avalanche distance. The gas gain is larger in MDOTs than in MSGCs or MGCs, because the electric field intensity near the cathode edge is smaller for a given anode field intensity, a consequence of the detector geometry; this results in a reduction of the vulnerability to sparking (or, equivalently, increasing the maximum gain). Our efforts to achieve larger gas gain are presented in chapter's 4 and 5.

Another requirement is the stability in short-term and long-term operation. The surface charging effect in MSGCs is well known as a source of short-term instabilities, and has been eliminated using a conductive surface coating of doped amorphous silicon carbide ($a\text{-Si:C:H}$), as reported in chapter 3. As a long-term instability source, the aging effect due to radiation-induced damage, i.e., from polymerization and deposition effects, is one of the most important outstanding issues, and has been studied systematically in chapter 4 primarily as functions of gas composition and anode strip material.

The other important requirement is the robustness with respect to sparking. We began systematic spark damage studies before the vulnerability to spark damage emerged as a serious problem in full-scale experiments in Europe. This issue, in conjunction with aging, is probably the most critical design problem remaining as an obstacle to more widespread use of the gas avalanche microdetectors. A series of systematic measurements of spark damage on several anode metals of MGCs is presented in chapter 4.

Other interests include pixellated gas avalanche detectors (i.e. MDOTs), which would have the intrinsic advantages of two-dimensional readout and gas gain, and the use of a thin ($\sim 200\text{ }\mu\text{m}$) layer at the drift plane of columnar cesium iodide (CsI) that acts as

an efficient source of electrons produced by secondary emission due to the incident particle, and as an electron multiplier, in order to improve the space and time resolutions, and detection efficiency with respect to the angle of the incident particle. All of these are important for a significant improvement of the operation of the gas avalanche microdetectors. These topics are presented in chapter's 5 and 6, respectively.

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Chapter 3 Microstrip Gas Chambers (MSGCs) with Conductive Surface Coating of Doped Amorphous Silicon Carbide (a-Si:C:H)

3.1 Introduction

The MSGC[1-5], using microelectronics technology, is an extension of the basic concept of the multiwire proportional chamber (MWPC) to regimes of better spatial resolution ($\sim 30 \mu\text{m rms}$) and higher rate capability ($> 10^6 \text{ mm}^{-2}\cdot\text{sec}^{-1}$). These promising features may allow it to have many potential applications in high energy physics and nuclear physics experiments[6], medical X-ray imaging[7] and many other fields requiring radiation detection and measurement[8,9]. The introduction of the MSGC, and related gas microdetectors, is a major development of gas avalanche detectors in the last decade.

However, the first attempts to use this kind of detector encountered serious problems of time- and rate-dependent gain instabilities. At first, the insulating substrate of the MSGC was supposed to have just a mechanical supporting role without any influence on the detector performance. But, as described in section 2.6.2, it has turned out that for high rate operation it is important to reduce the amount of charge accumulation on the insulating substrate, because these charges cause distortion in the electrostatic field and result in gain variations[10-12]. This effect is entirely related to the electrical properties of the insulating substrate. If the resistivity of the substrate is too high, the charges accumulated on the substrate would not be readily removed by electrical conduction; if it is too low, large leakage currents might occur, resulting in excessive noise and heating. Therefore, the proper choice of the substrate conductivity is a crucial factor for a stable MSGC operation.

Most common glass substrates available commercially, with good surface quality, have an ionic conductivity and very high resistivity, which results in gain instabilities just

after power is applied and during initial irradiation. This is attributed to the polarization and the surface charging effects of the insulating substrate, respectively. According to the experimental results obtained so far[10,13,14], substrates with surface resistivity in the range of 10^{12} - 10^{16} $\Omega/\square$ achieve the design requirements just discussed. A large effort has been made to find substrates of the surface resistivity in the range mentioned above. Some groups have reported success in using electronically conducting glass with low bulk resistivity in the range of 10^9 - 10^{12} $\Omega\cdot\text{cm}$ (e.g. Pestov glass or Schott S8900 glass)[15-18], while other groups used ion implantation to change the surface condition[19,20]. However, a more attractive solution may lie in conductive surface coating for the same purpose: thin film of Ge[21], Ni/Cr[22], lead glass[16], Pestov glass[23,24], amorphous carbon[25,26], amorphous silicon[27], or diamond[28].

In this chapter, a new alternative technique to other surface treatments of substrates involves the use of doped amorphous silicon carbide (a-Si:C:H) as a conductive surface coating material. The performance of detectors made in this way has been tested. Gas gain was measured with respect to several operating parameters such as time, anode voltage (V_a), backplane voltage (V_b) and drift voltage (V_d). In section 3.2, some necessary background information on the amorphous silicon and its application to surface coating are described. In section's 3.3 and 3.4, the experimental procedures and the results are presented, respectively. The summary of this chapter is given in section 3.5.

3.2 Conductive Surface Coating of Doped A-Si:C:H

As mentioned in the previous section, the appropriate surface resistivity can be achieved by using a substrate of low bulk resistivity. However, instead of reducing the resistivity of the entire substrate, it is possible to limit the conductive region to a very thin surface layer of the substrate by appropriate surface treatments such as ion implantation or deposit of conductive layer. These techniques minimize the current needed to eliminate

Fig. 3.1 Cross sections of typical MSGCs (a) overcoated or (b) undercoated with doped amorphous silicon carbide (a-Si:C:H).

the effects of surface charging, and the associated noise and heating effects. A thin conductive layer also reduces the electric field strength near the edges of the electrodes, helping to prevent sparking. Moreover, it could be helpful against aging, because the interaction of the gas and the substrate is minimized[29]. Among the appropriate surface treatments, the ion implantation is much more expensive and time-consuming than a thin film coating process, and charging up with electrons on the insulating substrate during implantation makes it difficult to control the uniformity and dosage of implanted ions accurately[4].

As an alternative technique, we have recently developed a method to coat a conductive layer with doped amorphous silicon carbide (a-Si:C:H) in the fabrication of MSGCs, either before (undercoated) or after (overcoated) the electrodes have been metalized. Figure 3.1 shows the cross sections of typical MSGCs (a) overcoated or (b) undercoated with this material. Doped a-Si:C:H film works well, because its resistivity can be easily controlled over a wide range by doping and is stable with time. In addition, it is radiation-hard, and a large area can be coated at relatively low cost[29].

3.2.1 Basic Features of Amorphous Silicon

One of the main features of amorphous silicon, compared with crystalline silicon, is its disordered atomic structure. As shown in Fig. 3.2, the atomic structure of the

Fig. 3.2 Atomic configuration of amorphous silicon. Crystalline silicon has a diamond structure, while the amorphous silicon is represented by a random network model.

amorphous silicon is represented by a continuous random network[30], while the crystalline silicon has a diamond structure. According to this model, the amorphous silicon retains a short-range order in the atomic structure with nearly identical bond length and angle as in the crystalline silicon. Consequently, its overall material properties are similar to those of the crystalline silicon. On the other hand, it lacks the long-range order due to small deviations in the bond length and angle, resulting in its inherent structural defects. The elementary defects in the amorphous structure are the coordination defects, when an atom has too many or too few bonds, and voids between clusters. The broken bonds, called dangling bonds, are the most important defects in amorphous silicon, because they control the Fermi energy level, E_f , and thus the electrical properties. The dangling bonds are also a source of charge carriers which are released in a strong electric field[31]. These defects can be reduced by the hydrogenation process, by which the dangling bonds are terminated (by hydrogen atoms), enhancing the electrical and mechanical properties of the amorphous silicon. An atomic hydrogen concentration of about 10% in the deposition gas is known to be optimum for making a “device-quality”

Fig. 3.3 Energy band diagrams of (a) crystalline silicon and (b) amorphous silicon, where E_v is the energy at the top of the valence band and, E_f is the Fermi energy and E_c is the energy at the bottom of the conduction band.

material[32]. Figure 3.3 shows the energy bands of (a) crystalline silicon and (b) amorphous silicon, where E_v is the energy at the top of the valence band, E_f is the Fermi energy and E_c is the energy at the bottom of the conduction band. In the amorphous silicon, conduction and valence bands are not well defined. Instead, “*mobility edge*” in non-crystalline solids was suggested by N. Mott[33]. At $T = 0$ K, electrons above the mobility edge (called the free electrons) have a finite mobility, while electrons below the mobility edge (called the trapped electrons) have zero mobility, and similarly for the holes. At a given temperature, there is a dynamic equilibrium of trapping and detrapping process of free carriers and trapped carriers. The energy difference between the mobility edges is called the mobility gap, and is about 1.7-1.9 eV in amorphous silicon. As shown in Fig. 3.3 (b), each edge has a deeply penetrating band tail in the forbidden gap due to the lack of long range order in the random network and there is a high density of gap states that originate from the dangling bonds. The average energy state of the dangling bonds is located at the middle of the forbidden gap, and the density of states has a broad

Table 3.1 Physical properties of crystalline silicon and hydrogenated amorphous silicon.

Properties \ Silicon	Crystalline	Amorphous
Structure	Diamond	Random network
Interatomic distance (Å)	2.35	2.35 ± 0.07
Bond angle (°)	109.47	109 ± 10
Density (g/cm ³)	2.3	~2.25
Dielectric constant	12.0	~11.8
Resistivity (Ω·cm)	$< 10^5$	$> 10^9$
Electron mobility (cm ² /V/sec)	1350	1 ~ 2
Hole mobility (cm ² /V/sec)	480	0.004 ~ 0.007
Band gap energy (eV)	1.12 (indirect)	1.7~1.9 (direct)

peak which is often simulated as a Gaussian shape with a width of a few tenths of eV. The fundamental physical properties of crystalline silicon and amorphous silicon are summarized in Table 3.1.

Another important feature of the amorphous silicon (a-Si:H) is substitutional doping. Amorphous silicon has been known for a long time, but it has only attracted attention as an electronic material since Spear and LeComber reported in 1975 that substitutional n- or p-type doping was possible by adding phosphine (PH₃) or diborane (B₂H₆) to silane (SiH₄) gas. Figure 3.4 shows the variation of the conductivity at room temperature, σ_{RT} , of the n- and p-type doped a-Si:H films measured by them. The conductivity of undoped a-Si:H sample is about 10^{-9} (Ω·cm)⁻¹ (see Fig. 3.5). The addition of small quantities of phosphine or diborane to the deposition gas results in changes in the room-temperature conductivity by more than a factor of 10^6 . The change in conductivity is explained by a shift of the Fermi energy in the energy band due to the introduction of dopants. It should be mentioned that the bulk resistivity of the a-Si:H can be affected by strong electric field. Figure 3.5 shows the dependence of the a-Si:H bulk resistivity on electric field applied across 20 μm thick layer[34]. For electric field in the range of 10^4 -

Fig. 3.4 Variation of the room-temperature dc conductivity of a-Si:H films doped by the introduction of phosphine and diborane into the deposition gas (Spear and LeComber 1975).

Fig. 3.5 Electric field dependence of the bulk resistivity for hydrogenated amorphous silicon. For the electric field in the range of 10^4 - 10^5 V/cm, the bulk resistivity decreases in more than two orders of magnitude.

10^5 V/cm, the bulk resistivity decreases by more than two orders of magnitude.

3.2.2 Deposition Method

Amorphous silicon is deposited most commonly by the method of Plasma Enhanced Chemical Vapor Deposition (PECVD), which is known to produce the best quality thin films with lowest defect density compared with other methods (e.g. sputtering, evaporation, chemical vapor deposition). A schematic diagram of a typical PECVD system is illustrated in Fig. 3.6. In this method, silane gas (SiH_4) diluted with hydrogen is fed into a vacuum chamber, and is then decomposed by hydrogen stripping into SiH_n^- ($n = 1-3$) by a radio-frequency induced glow discharge that creates a weakly ionized plasma. The SiH_n^- ions diffuse into the substrate, and form a Si-Si network by chemical reactions assisted by the heat provided from a filament underneath the substrate. During the deposition process hydrogen gas is evolved from the surface, and removed by the vacuum pump together with the excess gas. Deposition conditions such as gas flow rate, gas pressure, rf power density and substrate temperature play a critical role in determining the quality of films and growth rate. The deposition process described above is grossly

Fig. 3.6 Schematic diagram of a typical PECVD system for doped a-Si:C:H film deposition.

simplified, and the actual physical and chemical reactions are extremely complex. More detailed information on amorphous silicon deposition may be found elsewhere[30].

3.2.3 Application of Amorphous Silicon to Conductive Surface Coating

A-Si:H is widely used in industry as a photosensitive material, and was recently used by P. Savard *et al.*[27] as a conductive surface coating in MSGCs. However, as shown from this previous work, the intrinsic a-Si:H film showed variations in its surface resistivity and in gas gain with the backplane voltage (V_b). Since a thin ($\sim 1.7 \mu\text{m}$ thick) SiO_2 was used as an insulating layer between the backplane and the other electrodes, their device behaved like a MOSFET. This effect is attributed to the undepleted charge carriers of the dangling bonds in the a-Si:H, and can be minimized by making the insulating layer thick enough. Furthermore, a significant decrease in the surface resistivity can result from the UV light generated in the gas avalanche. A consequence of the light sensitivity of the a-Si:H is an increase of the leakage current during the gas avalanche, and this affects the pulse amplitude. We measured the light sensitivity of MSGCs with a $0.1 \mu\text{m}$ thick a-Si:H film on Corning 7059 glass substrate. The surface resistivities in darkness and in the incandescent light (600 lux illumination intensity) were about 10^{16} and $10^{13} \Omega/\square$, respectively: the surface resistivity decreased by three orders of magnitude due to the ambient light. We considered it important to suppress the light sensitivity of the a-Si:H to achieve reliable performance of the detectors when using this material as a surface coating.

In order to accomplish this, two strategies have been carried out in our research: carbon alloying and boron doping of a-Si:H. Carbon is one of the best candidates for alloying because it is in the same column in the periodic table with silicon. Addition of carbon to silicon is known to reduce the light sensitivity due to the increased optical bandgap, and to increase the resistivity due to the combined effect of reduced carrier mobility and the reduced number of carriers participating in electrical transport [35]. The

Fig. 3.7 Surface resistivity in darkness and the light response factor of a-Si:C:H measured as a function of CH₄ content in the process gases, where the light response factor is defined as the ratio of the conductivity in the incandescent light (600 lux illumination intensity) to the conductivity in darkness.

optical band gap of the carbon alloy of a-Si:H (i.e. a-Si:C:H) prepared from SiH₄-CH₄ (50/50) gas mixture is 1.9-2.3 eV vs. 1.7-1.9 eV for intrinsic a-Si:H. The electron drift mobility of a-Si:C:H films having a band gap of 1.7-1.9 eV are 1-3 orders of magnitude lower than that of intrinsic a-Si:H. Figure 3.7 shows the surface resistivity in darkness and the light response factor of the a-Si:C:H measured as a function of CH₄ content in the process gases. The light response factor is defined as the ratio of the conductivity in the incandescent light (600 lux illumination intensity) to the conductivity in darkness. By varying the CH₄ content, the surface resistivity in darkness can be increased to about 10¹⁸ Ω/□, out of the suitable range for conductive coatings, while the light response factor decreases by two or three orders of magnitude.

In order to suppress the light sensitivity further and to compensate the increased surface resistivity, boron doping has been performed. In practice, the resistivity of the n-

type, as shown in Fig. 3.4, varies abruptly with a small change in the amount of dopant in the gas phase, and the results are hardly reproducible. P-type doping by boron leads to more controlled results, and is preferred to n-type doping by phosphine. For the doped a-Si:C:H, an approximate expression for the overall conductivity is expressed as:

$$\sigma_{\text{overall}} = q\mu (N_{\text{int}} + N_{\text{ext}}) \quad (3-1)$$

where q is the electrical charge, μ is the charge carrier mobility, N_{int} is the number density of intrinsic charge carriers excited by light, and N_{ext} is the number density of extrinsic charge carriers introduced by doping. From the above equation, if the extrinsic carriers contribute predominantly to electrical conduction (i.e. $N_{\text{int}} \ll N_{\text{ext}}$), the overall conductivity will not be significantly affected by light. Figure 3.8 shows our measurements of (a) the surface resistivity in darkness and (b) the light response factor as a function of boron doping concentration for a-Si:C:H containing 50% and 70% CH₄. Both the light response factor and surface resistivity in darkness decrease with the boron doping concentration. With a doping concentration of 560 ppm, the a-Si:C:H prepared from SiH₄-CH₄ (30/70) gas mixture did not show any variation in surface resistivity at the given illumination condition.

Moreover, the doping technique can shorten the equilibrium time of the surface resistivity, since most charge carriers are released from the dopant states, which are much shallower than the dangling bond states. Figure 3.9 shows the time dependence of the surface resistivities for intrinsic a-Si:H and heavily doped a-Si:C:H layers (with 70% CH₄ and 560 ppm B₂H₆). These curves are normalized to their equilibrium values. It took several hours to reach the equilibrium leakage current for the intrinsic a-Si:H coating, but less than 10 minutes for the heavily doped a-Si:C:H film. Although our coating was 0.1 μm thick, by varying this thickness, the light response factor and surface resistivity could be optimized independently. Consequently, the light response factor and the equilibrium

(a)

(b)

Fig. 3.8 (a) Surface resistivity in darkness, and (b) light response factor as a function of boron-doping concentration for a-Si:C:H containing 50% and 70% CH_4 . Both the surface resistivity and light response factor decrease with the boron doping concentration.

Fig. 3.9 Time dependence of the surface resistivity for an intrinsic a-Si:H coating film and for a heavily doped (70% CH₄ and 560 ppm B₂H₆) a-Si:C:H layer, where the curves are normalized to their equilibrium values.

time of the surface resistivity can be successfully minimized, while the surface resistivity is controlled in the range of 10^{12} - $10^{16} \Omega/\square$.

3.3 Experimental Procedures

3.3.1 Device Fabrication

In order to construct and operate MSGCs successfully, it is important to choose substrate material suitable for both fabrication and operation. From the point of view of detector fabrication, the substrate should have good surface quality, good metal adhesion properties and low cost. From the operational point of view, the substrate should have a moderate surface or bulk resistivity to minimize surface charging at high rates, and should be thin and have low density and low atomic number, Z , to minimize multiple scattering and photon conversion probability. These latter properties are of importance for

Fig. 3.10 Schematic cross section of a typical MSGC undercoated with 0.1 μm thick a-Si:C:H (not to scale). A chromium layer of 0.2 μm thickness was metalized onto a 800 μm thick plate of Corning 7059 glass, using sputtering deposition.

particle tracking and for minimizing backgrounds. In this research, Corning 7059 glass of an 800 μm thickness has been used. This glass is readily available commercially and has a smooth surface.

Several MSGCs having Corning 7059 glass substrate and different conductive surface coatings have been fabricated at LBNL: bare glass, thin conductive films of pure a-Si:H, undoped a-Si:C:H (with 50 or 70% CH_4), lightly doped a-Si:C:H (with 70% CH_4 and 200 ppm B_2H_6), and heavily doped a-Si:C:H (with 70% CH_4 and 560 ppm B_2H_6). Figure 3.10 shows a schematic cross section of a typical MSGC with undercoating. Figure 3.11 shows photographs of a MSGC taken with an optical microscope from the top, showing the detail of each end of the strips. A chromium layer of 0.2 μm thickness was deposited onto the Corning 7059 glass, using sputtering technique. Alternating anode and cathode strips were patterned with two different detector pitches, using standard photolithography and metal lift-off techniques. One design had anodes of 5 μm width, cathodes of 95 μm width and a pitch of 200 μm . The other design had anodes of 5 μm width, cathodes of 195 μm width and a pitch of 300 μm , thereby keeping the spacing

(a)

(b)

Fig. 3.11 Photographs taken with an optical microscope of a typical MSGC showing: (a) the end of the anode strips and (b) the end of the cathode strips.

between the electrode edges fixed at 50 μm . The active areas of these detectors were 1.5x2.0 cm^2 and 2.0x2.0 cm^2 , respectively. A layer of a-Si:C:H, undoped or doped, of 0.1 μm thickness, was undercoated (or overcoated) on the entire substrate surface, using Plasma Enhanced Chemical Vapor Deposition (PECVD). The carbon content and boron doping concentration in the a-Si:C:H layer were controlled by changing the relative flow rates of CH_4 and B_2H_6 in the process.

3.3.2 General Considerations

The absolute gas gain was determined by measuring the current and count rate simultaneously, using the known number of ion pairs produced per event (~ 230) in Ar-ethane (50/50) gas mixture with an ^{55}Fe source:

$$G = \frac{I_{\text{aval}} (\text{A})}{(230 \text{ e}^-)(1.6 \times 10^{-19} \text{ C/e}^-)(R \text{ sec}^{-1})} \quad (3-2)$$

where, G is the absolute gas gain, I_{aval} is the measured avalanche current (i.e. cathode current minus leakage current), and R is the count rate. At the same time, the pulse height spectrum was also calibrated with respect to gas gain.

All detectors to be tested were mechanically bonded to printed circuit boards using an epoxy. Since the ionization from the primary electrons created by the incident X-ray is spread over several strips in the gas drift region, and the transverse spread of the drifting electrons caused by diffusion leads to an even broader avalanche, anode strips were connected in groups of ten to collect nearly all the charge produced in each event (see Fig. 4.4 (a) and (d)). All cathode strips were connected together, and through a picoammeter to ground. Before being mounted inside a gas-tight test vessel, all detectors were baked at 100 $^{\circ}\text{C}$ for several hours inside a vacuum oven to remove any residual moisture. For all tests, the anode strips were biased through a 1.2 $\text{M}\Omega$ protection

resistor. The anodes were also capacitively coupled (with 1000 pF) to a charge-sensitive preamplifier and a shaping amplifier. The cathode strips were kept at ground potential. The drift electrode, made of a thin stainless steel mesh, was located 4 mm above the substrate surface. The backplane consisted of a thin layer of gold deposited on the other side of the glass plate. The entire chamber assembly was mounted inside the gas-tight test vessel. Gas was conducted through copper tubing at atmospheric pressure for a period of at least half a day before starting tests. This helped to remove residual air and moisture inside the test vessel. The gas flow rate was typically about 20 sccm. It is important to make the test vessel gas-tight because oxygen in air is electronegative, resulting in loss of drifting electrons, as well as decreasing the avalanche gain, and may, in other ways, affect performance (e.g. causing aging effects).

3.4 Results and Discussion

The gas gain was measured using an Ar-ethane (50/50) gas mixture and an ^{55}Fe source (~ 0.2 mCi), which emits 5.9 keV X-rays. In this section, the behavior of the gas gain is presented with respect to several operating parameters such as time, anode voltage (V_a), backplane voltage (V_b) and drift voltage (V_d).

3.4.1 Gain vs. Time

Figure 3.12 shows the initial time dependence of the gas gain for the conductive coatings discussed in section 3.3.1. All tested detectors had a 200 μm pitch. For the bare glass and undoped a-Si:C:H (50 or 70% CH_4) coating, the gas gain decreased about 25% from the initial value to a new equilibrium gain value. This short-term gain instability is due to surface charging, resulting from an excessively high surface resistivity. For the pure a-Si:H coating, the gas gain decreased in the first 20 minutes and then increased somewhat in the next 10 minutes. For the doped (lightly or heavily) a-Si:C:H coating,

Fig. 3.12 Initial time dependence of the gas gain for various conductive surface coatings. No charging phenomenon has been detected on MSGCs with either lightly doped or heavily doped conductive surface coating.

there was no noticeable change of the gain over the approximately one and one-half hour time period. Therefore, no charging phenomenon has been detected on MSGCs with either lightly doped or heavily doped conductive surface coating.

3.4.2 Gain vs. Anode Voltage (V_a)

The gas gain was measured as a function of anode voltage at a fixed drift field of 2.5 kV/cm, using an Ar-ethane (50/50) gas mixture. As shown in Fig. 3.13, the gas gains of the MSGCs having conductive surface coating were lower at a given anode voltage, whereas the maximum applied voltages limited by sparking were higher than those of the MSGC having the bare glass. This result is primarily due to the more uniformly graded potential distribution, which makes the electric field around the cathode and anode strips less concentrated. Among the conductive surface coatings, the undoped a-Si:C:H (70% CH₄) gave the highest maximum gas gain of 8100, whereas the heavily doped a-Si:C:H

Fig. 3.13 Gas gain measured as a function of anode voltage at a fixed drift field of 2.5 kV/cm, for various conductive surface coatings, using a gas mixture of Ar-ethane (50/50). All tested detectors have a 200 μm pitch. The maximum voltages and gains were limited by electrical discharge.

gave the lowest one of 2900, lower by a factor of 2.8, at an anode voltage of 620 V. As pointed out in ref. 36, the ratio of the surface conductivity to the insulating substrate bulk conductivity, R_{σ} , is a crucial parameter for the gas gain. A large value of R_{σ} decreases the gas gain, because it reduces the electric field strength at the anode strip. Figure 3.14 shows the gas gain as a function of R_{σ} at an anode voltage of 620 V for different coatings.

Figure 3.15 shows the effect of the cathode width on the gas gain, using the MSGC having the heavily doped a-Si:C:H layer. Two cathode widths of 95 and 195 μm were tested, while the anode width and the electrode spacing were fixed at 5 and 50 μm , respectively. The gas gain corresponding to the 195 μm wide cathode was higher by a factor of 1.9 than that of the 95 μm wide cathode at an anode voltage of 600 V. Simulations performed by S. Schmidt *et al.* also demonstrated that the gas gain goes up for larger cathode width[36]. This is because the wider cathode makes the electric field

Fig. 3.14 Gas gain measured as a function of R_s at an anode voltage of 620 V and a drift field of 2.5 kV/cm for various conductive surface coating, where R_s is defined as the ratio of the surface conductivity to the insulating substrate bulk conductivity.

Fig. 3.15 Effect of the cathode width on the gas gain, using the MSGC having heavily doped a-Si:C:H layer. Two cathode widths of 95 and 195 μm were tested, while the anode width and the electrode spacing were kept constant at 5 and 50 μm , respectively.

on the anode strips more intense. Although a wider cathode is preferable for a larger gain, the width of the cathode strips may be limited by requirements on the position accuracy.

The energy resolution in MSGCs is somewhat better at the same gain than that in conventional wire chambers. For example, the energy resolution of a wire proportional counter typically ranges from 15-20% FWHM, using an Ar-based gas mixture and an ^{55}Fe source[37,38]; the lower end of this range is not easily achieved. On the other hand, for MSGCs, an energy resolution of 16% FWHM at an avalanche gain of 1000 was reported by A. Oed, using an Ar-methane (90/10) gas mixture and an ^{55}Fe source[2]. The energy resolutions we measured were 13.4, 15.2, 14.1 and 15.6% FWHM for MSGCs having bare glass, undoped a-Si:C:H, with 50 and 70% CH_4 , and heavily doped a-Si:C:H coatings, respectively, at a gain of about 1000, using an Ar-ethane (50/50) gas mixture and an ^{55}Fe source. These results indicate that there is, at most, a small loss of energy resolution due to the coating.

3.4.3 Gain vs. Backplane Voltage (V_b)

Figure 3.16 shows the effect of the backplane voltage on the gas gain. A more negative voltage on the backplane tends to increase the gas gain, since this results in additional field lines at the anode. This effect was more apparent for the bare glass and undoped a-Si:C:H (70% CH_4), while it was almost completely absent for the doped (lightly or heavily) a-Si:C:H layer. The pure a-Si:H layer showed a slight dependence on the backplane voltage, but its dependence was not as significant as reported by P. Savard *et al.*[27]. This is because our insulating substrate is much thicker (~470 times) than theirs, and the influence of the backplane electrode on the field configuration at the substrate surface is relatively weak. The MOSFET effect mentioned in section 3.2.3, by which the surface resistivity and gas gain change with the backplane voltage, can be minimized by using a thick enough insulating substrate and large enough conductivity, using the doping techniques. The thin conductive layer not only plays a desirable role by

Fig. 3.16 Gas gains measured as a function of backplane voltage for various conductive surface coatings. The thin conductive layer on the electrodes screens the effect of the backplane potential on the avalanche, allowing the backplane to be omitted altogether.

suppressing the surface charging effect, but it also screens the effect of the backplane potential on the avalanche, allowing the backplane to be omitted altogether.

3.4.4 Gain vs. Drift Voltage (V_d)

Figure 3.17 shows the gas gain measured as a function of drift voltage. The gas gain increased as the drift voltage became more negative, since a more intense drift field enhances the field in the avalanche region. However, the increase in the drift field is not without other consequences: an increasing number of drift field lines terminate on the substrate surface rather than on the anode strips, resulting in an inactive region or “*dead zone*”. Moreover, more ions from the avalanche go back to the drift electrode, rather than traveling to the cathode strips, leading to a larger charge collection time and hence loss of rate capability. In order to study this effect quantitatively, we have simulated the drift

Fig. 3.17 Gas gain measured as a function of drift voltage for various conductive surface coatings. The gain increased as the drift voltage became more negative, since a more intense drift field enhances the field in the avalanche region.

electric field lines for our MSGC detector geometry, using the Maxwell program package[39]. Figure 3.18 shows the simulation results that give the fraction of drift field lines to the substrate surface as a function of drift field strength, (a) for two different anode voltages of 500 and 600 V, at a pitch of 200 μm , and (b) for three different pitches of 200, 300 and 400 μm , keeping the anode and cathode strip widths fixed at 5 and 95 μm , respectively, at an anode voltage of 600 V. The dead zone, where the drift field lines end at the substrate surface, is larger for the lower anode voltage and the larger pitch. For the 200 μm pitch, it begins to grow at drift fields of 15 and 20 kV/cm for the anode voltages of 500 and 600 V, respectively. For the pitches of 200, 300, 400 μm , the dead zone begins to grow at drift fields of 20, 10 and 7.5 kV/cm, respectively, with a fixed $V_a = 600$ V. For a 400 μm pitch, the dead zone at a drift field of 9 kV/cm is predicted by the program to be about 15% of the total detector area. Figure 3.19 shows the drift field lines for two different drift fields of 5 and 15 kV/cm, at an anode voltage of 600 V and a pitch

Fig. 3.18 Simulation results that give the fraction of drift field lines to the cathode as a function of drift field strength, (a) for two different anode voltages of 500 and 600 V, at a pitch of $200\text{ }\mu\text{m}$, and (b) for three different pitches of 200, 300 and $400\text{ }\mu\text{m}$, respectively.

of 300 μm . Figure 3.20 shows the drift field lines for two different anode voltages of 500 and 600 V, at a drift field of 15 kV/cm and a pitch of 300 μm . Figure 3.21 shows the drift field lines for two different pitches of 200 and 400 μm , at an anode voltage of 600 V and a drift field of 15 kV/cm. Although this effect is probably small for most operation regimes of MSGCs, it can be much more significant in microgap gas chambers (MGCs)[40].

(a)

(b)

Fig. 3.19 Drift field lines for two different fields of (a) 5 and (b) 15 kV/cm, at an anode voltage of 600 V and a pitch of 300 μm .

Fig. 3.20 Drift field lines for two different anode voltages of (a) 500 and (b) 600 V, at a drift field of 15 kV/cm and a pitch of 300 μm .

(a)

(b)

Fig. 3.21 Drift field lines for two different pitches of (a) 200 and (b) 400 μm , at an anode voltage of 600 V and a drift field of 15 kV/cm.

3.5 Summary

Using boron-doped a-Si:C:H as a conductive surface coating, it has been shown that optimum surface conductivity can be achieved in microstrip gas chambers (MSGCs) to prevent charge accumulation on the substrate surface. The surface resistivity was successfully controlled in the range of 10^{12} – 10^{16} $\Omega/\square$ and the light sensitivity was almost completely suppressed by carbon alloying and boron doping.

We have studied the performance of the detectors having several different conductive surface coatings, by measuring the gas gain as a function of time, anode voltage (V_a), backplane voltage (V_b) and drift voltage (V_d). For the heavily doped (with 70% CH_4 and 560 ppm B_2H_6) a-Si:C:H coating of $\sim 2 \times 10^{12}$ $\Omega/\square$, a gas gain of 2900 and an energy resolution of 16% FWHM were achieved in an Ar-ethane (50/50) gas mixture. No charging effect was detected, and the effect of the backplane voltage was almost completely suppressed. Computer simulations indicated that significant dead zone, where the drift field lines end at the substrate surface, can occur when large drift fields are used in an attempt to achieve larger gas gain. This effect is larger for lower anode voltages and wider pitches.

A thin, doped, a-Si:C:H film is a conductive surface coating that works well, and is an attractive alternative to other surface treatments of the substrate, because its resistivity can be easily controlled over a wide range by doping and is stable with time. Large area can be coated at relatively low cost. A-Si:C:H is also expected to have great resistance to radiation damage as a result of its amorphous structure.

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Chapter 4 Microgap Gas Chambers (MGCs) Fabricated with Selected Anode Strip Metals

4.1 Introduction

The microgap gas chamber (MGC)[1-5] is, potentially, a microdetector with improved performance over the microstrip gas chamber (MSGC): it has shown intrinsic short-term gain stability against surface charging, and faster charge collection time, resulting in higher rate capability ($\sim 10^7 \text{ mm}^{-2}\cdot\text{sec}^{-1}$)[1], than for the MSGC ($\sim 10^6 \text{ mm}^{-2}\cdot\text{sec}^{-1}$). Its unique structure allows a separation distance of only a few microns between the anode strips and the cathode, and operates with very strong electric field between these electrodes ($\sim$ a few MV/cm). Therefore, as can be imagined, the quality of the insulating layer and the alignment of the strips in the fabrication process are crucial factors for MGC performance capability.

Silicon dioxide (SiO_2) has been commonly used as the insulating layer material for MGCs. However, the maximum gas gain before sparking is limited by the anode-cathode spacing, only 2 μm in the original design, which is not large enough to permit full development of an avalanche. Therefore, a means of achieving a larger gain in the MGCs is by increasing the thickness of the insulating layer[2]; this may also improve the signal-to-noise ratio due to the decreased internal capacitance of the detector. Since a high quality SiO_2 layer is difficult to make thicker than about 2 μm because of the small deposition rate ($\sim 0.5 \mu\text{m/hr}$), and due to the problem of forming stress-free and pinhole-free films[6], insulating layer materials other than SiO_2 have been investigated. One such material that we have used is hydrogenated amorphous silicon carbide (a-Si:C:H). It can be deposited at a rate of about 2.3 $\mu\text{m/hr}$ and has a resistivity of $10^{12}\text{-}10^{13} \Omega\cdot\text{cm}$, comparable with SiO_2 . Two MGCs having 2.3 and 4.6 μm thick a-Si:C:H layers have been built and tested to study the effect of different insulator thicknesses upon gas gain.

Other critical issues in gas avalanche microdetectors (MSGCs or MGCs) are two essential mechanisms of permanent damage: aging and sparking. These topics are probably the most critical design problems remaining as obstacles to more widespread use of these detectors. Gas avalanche microdetectors have been found to show long-term gain instabilities under sustained irradiation, leading to irreversible damage resulting in permanent gain decrease and electrical discharges. These radiation-induced damage (i.e. aging) effects are usually the result of polymer formation on the electrodes, and are a direct consequence of the avalanche process. They must be overcome for long-term operation. The aging effects in the gas avalanche microdetectors are generally more severe than in conventional wire chambers, when normalized to charge transfer per electrode length, partly due to the smaller effective area of the electrodes exposed to the avalanche, and partly due to being operated at relatively lower gain; both of these effects lead to a larger polymer deposition. In addition, aging could be in part due to the substrate material, an effect not present in wire chambers.

The gas avalanche microdetectors are also more vulnerable to spark damage by discharge than are wire chambers, because their electrodes, especially the anode strips, have a smaller cross sectional area, leading to a larger ratio of ohmic heating power to mass (I^2R/mass) per unit length. The sparking is also generally more localized, causing the heating of the electrode to be more concentrated. These effects lead to a larger temperature increase for gas avalanche microdetectors than for wire chambers, for an equal electrical discharge energy.

Since the aging and spark damages are very sensitive to metal used for anode strips[7,8], several MGCs have been fabricated with selected anode strip metals, including aluminum, gold, nickel, chromium, titanium/tungsten (10%/90%) and tungsten (100%), and these have been tested in a few selected gas mixtures to study their performance. In section 4.2, device fabrication for these tests is described. In section 4.3, the results are given on the behavior of gas gain with respect to several parameters, such

as anode voltage (V_a), drift voltage (V_d), insulating layer thickness, and stability over extended operating periods. In section 4.4, the aging effects are studied primarily as functions of gas composition and anode strip metal. In section 4.5, the spark damage effects are presented to compare the relative sensitivity of each selected anode metal to failure, over a range of electrical discharge energies. These results are summarized in section 4.6. Most of the results for aging and spark damage tests given in this chapter are expected to be qualitatively similar for MSGCs. This is especially true for the spark damage tests, where the vulnerability depends primarily on the metal used, the anode cross sectional area and the energy in the discharge.

4.2 Device Fabrication

Several MGCs have been fabricated with selected anode strip metals of aluminum, gold, nickel, chromium, titanium-tungsten (10%/90%) and tungsten (100%), to study systematically the properties of gas gain, aging, and spark damage by electrical discharge. Detectors were fabricated in the Microsystems Laboratory of LBNL, starting with a low resistivity silicon substrate ($\sim 3 \text{ m}\Omega\cdot\text{cm}$). A two micron SiO_2 insulating layer was deposited onto the silicon substrate using low-pressure chemical vapor deposition (LPCVD), and the oxide was densified at 900°C for 30 minutes in a nitrogen atmosphere to enhance the electrical and mechanical properties. The Al, Cr, Ti/W and W anode strips and their insulating layers were patterned by wet chemical etching, while the Au and Ni anode strips were patterned by lift-off technique and their insulating layers defined using a freon-based plasma etching technique (see section 2.3). The widths of the anode strip and SiO_2 insulating layer were 9 and 19 μm , respectively. The pitch was 200 μm and the active area was $1.0 \times 1.0 \text{ cm}^2$. The geometry of all MGCs used in these tests is identical, and is described in Fig. 4.1. Figure 4.2 shows photographs taken by a scanning electron microscope (SEM) of the MGCs having (a) gold and (b) chromium anode strips, indicating that the dry etching produces strips of higher quality in terms of uniformity and

Fig. 4.1 (a) Schematic diagram of the cross section and (b) a photograph taken with a scanning electron microscope (SEM) showing the top view of the MGC. The left side of (b) shows wire-bonding pads of anode strips on the SiO₂ layer, and the right side shows the strips of the anode and SiO₂ insulating pedestal on the silicon cathode.

edge profile than the wet etching, as described in section 2.3.1.

A-Si:C:H was also used as an alternative insulating layer material to SiO₂, in an attempt to make a thicker high quality insulating layer; it has a similar resistivity but a larger deposition rate, and is more easily processed, compared with SiO₂. However, the

(a)

(b)

Fig. 4.2 Photographs taken by a scanning electron microscope (SEM) of the MGCs having (a) gold anode strips patterned by plasma etching and (b) chromium anode strips patterned by wet etching. The dry etching produces strips of high quality in terms of uniformity and edge profile.

light sensitivity of the a-Si:C:H could have an adverse effect on the gas gain[9]. As pointed out in ref. 10, when the conductivity of the insulating layer increases, electric fields are more concentrated around the edge of the insulating layer, rather than at the anode strip. This field configuration is undesirable for the gas gain. As shown in section 3.2.3, the light sensitivity of the a-Si:C:H decreases with the CH₄ content of the PECVD gas, due to the increased optical band gap of the material, while the dark resistivity increases with the CH₄ content due to the combined effect of reduced carrier mobility and the number of carriers participating in electrical transport[11]. Therefore, in order to suppress the light sensitivity and the leakage current, layers of a-Si:C:H having 2.3 and 4.6 μm thicknesses were prepared in a SiH₄-CH₄ (10/90) PECVD gas mixture. The measured light response factor and the dark resistivity were about 2.4 and more than $10^{13} \Omega\cdot\text{cm}$, respectively, where the light response factor is defined as the ratio of the conductivity in the ambient light (600 lux incandescent illumination intensity) to the conductivity in darkness. Then an aluminum layer of 1.0 μm thickness was deposited onto the a-Si:C:H layer by sputtering. The patterning was done by standard photolithography and reactive ion etching (RIE) techniques. The widths of the anode strip and the a-Si:C:H insulating layer were 10 and 20 μm , respectively. The pitch was 200 μm and the active area of the detector was $1.5 \times 2.0 \text{ cm}^2$.

4.3 Performance Tests

4.3.1 Experimental Procedures

Figure 4.3 shows a test station equipped with an X-ray generator and a clean stainless steel test vessel. Positive high voltage, V_a , was applied to the anode strips through a $1.2 \text{ M}\Omega$ protection resistor, the preamplifier being connected to the anode strips through a 1000 pF coupling capacitor. Current was measured between the cathode (silicon wafer) and ground ($V_c=0$). The drift electrode was normally held at $V_d = -1000 \text{ V}$

Fig. 4.3 Test station equipped with an X-ray generator and a clean stainless steel test vessel mounted with the chamber assembly.

except when drift voltage was varied to measure gain changes. All detectors to be tested were mechanically bonded to ceramic boards using an epoxy that is known from previous tests to be safe with respect to possible effects upon aging[12]. Ten anode strips were wire-bonded together to each gold lead-out strip on these boards to collect all of the charges produced in the avalanche. Figure 4.4 shows the shapes of ^{55}Fe pulse height spectra measured with respect to the number of ganged anode strips, at $V_a = 420\text{ V}$ and $V_d = -1000\text{ V}$, using a gas mixture of Ar-ethane (50/50). The comparison of the spectra from single anode strip and from group of ten anode strips indicates clearly that the size of primary electron distribution is large enough to be shared between neighboring channels. Detectors were baked at $100\text{ }^{\circ}\text{C}$ for several hours inside a vacuum oven to remove any residual moisture before mounting into a clean test vessel. The drift electrode was a stainless steel mesh located 4 mm above the cathode. The entire chamber was mounted inside a carefully cleaned, gas-tight, stainless steel test vessel. Gas was conducted through electropolished stainless steel tubing at atmospheric pressure for a

Fig. 4.4 Shapes of ^{55}Fe pulse height spectra measured with respect to the number of ganged anode strips, at $V_a = 420$ V and $V_d = -1000$ V, using a gas mixture of Ar-ethane (50/50). The comparison of the spectra from single and ten anode strips indicates clearly that the size of primary electron distribution is large enough to be shared between neighboring channels.

period of at least half a day before starting tests, to remove any residual air and moisture inside the test vessel. In all cases, the leakage current of a new, unused, MGC was very small, typically much less than 0.1 nA, and usually could be neglected for the purposes of all tests.

4.3.2 Results and Discussion

(a) Gain vs. Anode Voltage (V_a)

Gain measurements with respect to anode voltage, V_a , are shown in Fig's. 4.5-4.7 for five gas mixtures and three anode metals: (a) gas mixtures of Ar-methane(90/10), Ar-ethane (50/50), Ar-DME (50/50), Ne-DME (70/30) and DME (100), and (b) anode metals of aluminum, nickel and chromium. All tested MGCs had 2.0 μm thick SiO_2 insulating layer, and the drift field intensity was 2.5 kV/cm for all measurements. Gain measurements of MGCs with all metals are expected to be the same, for the same gas mixture. However, there are some differences in the gas gains, estimated to be as much as 20%, among these three devices, for the same gas mixture, and this is probably due to small unavoidable differences in fabrication of MGCs.

As shown in Fig's 4.5-4.7, the gas gains primarily depend on the composition of the gas. Table 2.1 shows some properties of several operating gases commonly used in gas avalanche detectors. The MGCs give a larger gain at a given anode voltage than would be obtained with the MSGCs (e.g. ~ 1500 for the MGCs, while < 400 for the MSGCs at $V_a = 420$ V, using a gas mixture of Ar-ethane (50/50)), and are even able to operate at low voltages for which the MSGCs would not yet produce a measurable gas gain. For all tested gas mixtures except Ar-methane(90/10), the maximum gains, which are limited by sparking, were in the range of 2000 to 4000. This is consistent with earlier measurements by the Pisa group with the same geometry [1,2]: 2800 with Ar-DME (50/50), 3000 with Ne-DME (70/30) and 3800 with DME (100). In Fig. 4.5, the maximum gain was about

Fig. 4.5 Gas gains measured as a function of anode voltage, V_a , for gas mixtures of Ar-methane (90/10), Ar-ethane (50/50) and Ar-DME (50/50), using a MGC having Al anode strips. All tested MGCs had a $2.0 \mu\text{m}$ thick SiO_2 insulating layer, a $200 \mu\text{m}$ pitch, and the drift field intensity was 2.5 kV/cm .

Fig. 4.6 Gas gains measured as a function of anode voltage, V_a , for gas mixtures of Ar-ethane (50/50), Ar-DME (50/50) and DME (100), using a MGC having Ni anode strips. The drift field intensity was 2.5 kV/cm .

Fig. 4.7 Gas gains measured as a function of anode voltage, V_a , for gas mixtures of Ar-ethane (50/50), Ar-DME (50/50) and Ne-DME (70/30), using a MGC having Cr anode strips. The drift field intensity was 2.5 kV/cm.

five times larger for Ar-DME (50/50) than for P-10. P-10 does not “quench” well (absorb photons emitted from avalanche), and a larger maximum gas gain is achieved with a larger fraction of, and more effective, quenching gas; this is especially important in MGCs due to the extremely small spacing between the anode strips and the cathode. In Fig’s. 4.6 and 4.7, the maximum gain was largest using DME (100), the best quenching gas, and was about 30% larger for Ne-DME (70/30) than for Ar-DME (50/50). Note, however, the somewhat different fraction of DME in these two gas mixtures. A possible explanation of the larger gas gain using the neon-based gas mixture is a smaller yield of lower energy photons than when using the argon-based gas mixture[3,13]. As shown in Table 2.1, the ionization and excitation potentials of Ne (21.6 and 16.7 V, respectively) are much higher than those of Ar (15.7 and 11.6 V, respectively). Moreover, the large difference between the ionization potential of DME and the ionization and excitation potentials of Ne favors the channeling of the energy transferred from the electric field to

the drifting electrons, into ionization of the DME molecules rather than into ionization or excitation of Ne. These properties effectively suppress the production of UV-light produced in the avalanche process by excitation of the noble gas component, which is thought to initiate harmful electric breakdown.

Figure 4.8 shows the ^{55}Fe pulse height spectra for Ar-ethane (50/50), Ar-DME (50/50) and Ne-DME (70/30) gas mixtures at $V_a = 380$ V and $V_d = -1000$ V, and for DME(100) at $V_a = 400$ V and $V_d = -1000$ V. Relative energy resolutions of 14.1, 13.5, 15.9 and 14.8% FWHM were achieved at gas gains of 750, 1060, 690 and 920, respectively: the estimated errors on these FWHM values are less than 1%. The positions of the full energy peak and the escape peak of ^{55}Fe source are explained by the transmission probabilities of these gases. Figure 4.9 shows the fractional transmission in a 4 mm thickness of these gases at 0.5 atmosphere (corresponding to a partial pressure in a 50/50 mixture). Discontinuities of these curves are caused by the gas absorption edges[14]. The response of the detector is a measure of number of electrons generated by the ionization energy loss of the stopping photoelectrons produced by incident X-rays. Since the energies of photoelectrons are directly related to the X-ray energy, photon energy can be identified from the position of corresponding full energy peak of the pulse height spectrum. The response function for low energy X-rays can be complicated by several effects related to characteristic X-rays generated by interaction of the primary radiation within the detectors. The most significant involves the characteristic K-series X-rays which usually follow the photoelectric absorption of the primary radiation in the filling gas. Because the corresponding energy can be relatively large (e.g. K_α X-ray energy is 2.97 keV for Ar), this X-ray may escape from the gas without further interaction. A corresponding escape peak will then appear in the response function which lies below the full energy peak by an amount equal to the characteristic X-ray energy.

(a)

(b)

(c)

(d)

Fig. 4.8 ^{55}Fe pulse height spectra for (a) Ar-ethane (50/50), (b) Ar-DME (50/50) and (c) Ne-DME (70/30) gas mixtures at $V_a = 380$ V and $V_d = -1000$ V, and for (d) DME (100) at $V_a = 400$ V and $V_d = -1000$ V. Relative energy resolutions of 14.1, 13.5, 15.9 and 14.8% FWHM were achieved at gas gains of 750, 1060, 690 and 920, respectively.

(a)

(b)

Fig. 4.9 Fractional transmission in a 0.4 cm thickness of (a) Ar and Ne and (b) Ethane and DME, at 0.5 atm (corresponding to a partial pressure in a 50%/50% gas mixture). The discontinuities of these curves are caused by the gas absorption edges.

(b) Gain vs. Drift Voltage (V_d)

Figure 4.10 shows gain measurements with respect to the drift voltage. Characteristically, the gain increases almost linearly as $|V_d|$ is increased, i. e. V_d is made more negative, since a more intense drift field enhances the field in the avalanche. For a fixed anode voltage of 400 V, the gain increases by a factor of 1.4 as V_d is changed from -1000 V to -2800 V.

However, as explained in section 3.4.4, for sufficiently large drift field, some of the drift field lines are directed toward the cathode instead of toward the anode strips, with the increase of the drift voltage, resulting in inactive region or “dead zone”[15,16]. We have also simulated the drift field lines for our MGC detector geometry, using the MAXWELL program package (see also section 3.4.4). Figure 4.11 shows simulation results that give the fraction of the drift field lines to the cathode as a function of drift

Fig. 4.10 Relative gas gain as a function of drift voltage (V_d), at a fixed anode voltage of 400 V. Characteristically, the gas gain increases almost linearly as $|V_d|$ is increased, since a more intense drift field enhances the field in the avalanche.

Fig. 4.11 Simulation results that give the fraction of drift field lines to the cathode as a function of drift field strength, (a) for three different anode voltages of 300, 400 and 450V, at a pitch of $200\ \mu\text{m}$, and (b) for two different pitches of 100 and $200\ \mu\text{m}$, at an anode voltage of 400 V. The dead zone, where the drift field lines end at the cathode, is larger for a lower anode voltage and a wider pitch.

Fig. 4.12 Fraction of drift field lines reaching the cathode as a function of cell (or granularity) density in MAXWELL, for a drift field of 7 kV/cm, an anode voltage of 400 V and a pitch of 200 μm .

field strength, (a) for three different anode voltages of 300, 400 and 450 V, at a pitch of 200 μm , and (b) for two different pitches of 100 and 200 μm , at an anode voltage of 400 V. The dead zone, where the drift field lines end at the cathode, is larger for a lower anode voltage and a wider pitch. With a 200 μm pitch, the dead zone begins to grow at drift fields of 3.5 and 5.5 kV/cm for $V_a = 300$ and 450 V, respectively. With $V_a = 400$ V, it begins to grow at drift fields of 15 and 4.5 kV/cm for the pitches of 100 and 200 μm , respectively. For a 200 μm pitch and $V_a = 300$ V, the dead zone at a drift field of 5 kV/cm is predicted to be about 7% by the program.

In order to see the effect on these results of different cell (or granularity) sizes in MAXWELL, we calculated the drift field lines as a function of cell density, for a drift field of 7 kV/cm, an anode voltage of 400 V and a pitch of 200 μm . With increasing cell density, the smoothness of the field lines increased, but the fraction of field lines reaching the cathode remained almost the same, as shown in Fig. 4.12.

The dead zone effect is much more significant in MGCs than in MSGCs for most operation regimes (cf. Fig. 3.18), mainly due to their different geometries, and partly due to being operated at a lower anode voltage. Figure 4.13 shows drift field lines for MGCs having two different drift fields of (a) 3.5 and (b) 7.5 kV/cm, at an anode voltage of 400 V and a pitch of 200 μm . Figure 4.14 shows drift field lines for MGCs having two different anode voltages of (a) 400 and (b) 450 V, at a drift voltage of 5.5 kV/cm and a pitch of 200 μm . Figure 4.15 shows drift field lines for MGCs having two different pitches of (a) 100 and (b) 200 μm , at a drift field of 7.5 kV/cm and an anode voltage of 400 V. For clarity, most field lines whose termination on the anode strip is unaffected by changing V_d are omitted in these figures.

(a)

(b)

Fig. 4.13 Drift field lines for MGCs having two different drift fields of (a) 3.5 and (b) 7.5 kV/cm, at an anode voltage of 400 V and a pitch of 200 μm .

(a)

(b)

Fig. 4.14 Drift field lines for MGCs having two different anode voltages of (a) 400 and (b) 450 V, at a drift field of 5.5 kV/cm and a pitch of 200 μm .

(a)

(b)

Fig. 4.15 Drift field lines for MGCs having two different pitches of (a) 100 and (b) 200 μm , at a drift field of 7.5 kV/cm and an anode voltage of 400 V.

(c) Gain vs. Time

Figure 4.16 shows short-term gain stability against surface charging, for tested anode metals (note the expanded vertical scale). It was derived from the ^{55}Fe (~ 0.2 mCi) source spectra measured in a gas mixture of Ar-ethane (50/50), at an anode voltage of 380 V. Over an hour test period, there was no significant evidence of gain variation, except for aluminum, where a slight gain decrease was observed. Aluminum oxidizes readily, and may have formed a thicker aluminum oxide layer during the test period. This stability against gain change due to insulator charging is thought to be primarily due to the very little insulating surface exposed to the radiation source and avalanche. It is emphasized that no conductive coating is required for MGCs, as necessary for MSGCs, to maintain stability against charge build-up.

Fig. 4.16 Short-term gain stability against surface charging, for tested anode strip metals (note the expanded vertical scale). Over an hour test period, there was no significant evidence of gain variation, except for aluminum, where a slight gain decrease was observed. Aluminum oxidizes readily, and may have formed a thicker aluminum oxide layer during the test period.

(d) Gain vs. Insulator Thickness

Gain measurements with respect to the anode voltage, V_a , are shown in Fig. 4.17 for two different thicknesses of insulating layers: 2.3 and 4.6 μm thick a-Si:C:H layers. The gains were measured at a fixed drift field of 2.5 kV/cm, using a gas mixture of Ar-ethane (50/50) and an ^{55}Fe source. As shown in Fig. 4.17, the MGC with the 4.6 μm thick a-Si:C:H insulating layer gave a larger gain than the one with the 2.3 μm thickness, at a given anode voltage. We believe that this result is primarily due to the larger gas amplification volume allowed by the increased thickness of the insulating layer. At an anode voltage of 420 V, a gas gain of 2000 and an energy resolution of 17% FWHM were achieved from the MGC having the 4.6 μm thickness; this gain is larger by a factor of 1.4 than that obtained with the 2.3 μm thick layer at the same voltage. This was the

Fig. 4.17 Gain measurements as a function of anode voltage for two different insulating thicknesses. The gas gain obtained using the MGC with a 4.6 μm thick a-Si:C:H insulator was larger by a factor of 1.4 than for one having a 2.3 μm thickness, at an anode voltage of 420 V.

maximum achievable gain before sparking in the MGC having the 4.6 μm insulator, while the other MGC, with the 2.3 μm insulator, achieved a larger gas gain, 3200, before sparking. We believe that the gain of the 4.6 μm detector was limited by misalignment of the electrodes, which was seen under an optical microscope, and we expect to be able to achieve larger gains with improved fabrication techniques.

4.4 Accelerated Aging Tests

4.4.1 Aging Phenomena

Aging, the performance degradation of the detectors by exposure to radiation, is one of the most serious problems encountered with all gas detectors, limiting their useful lifetime. There are several different manifestations of the aging phenomena, typically including loss of gain, loss of gain uniformity and energy resolution, excessive and self-sustained current, sparking, etc. Any or all of these may occur in the use of the detectors in a radiation environment. These detrimental effects can all be caused by coating of electrode surface by polymer formed in the avalanche plasma. There is an enormous number of chemical reactions that can potentially occur in the avalanche plasma. The avalanche breaks up gas molecules and creates reactive species (e.g. radicals and ions) as well as electrons, that may undergo a large variety of reactions leading to modification of the electrode surfaces (e.g. chemical reaction with the electrode surface material, polymerization, etc.). Table 4.1 summarizes the classes of reactions by which reactive species can be formed in the plasma environment, including collisions of neutral species with electrons, photons and heavy particles. The generic molecule AB is used to represent any molecular species; $A\cdot$ (or $B\cdot$) represents any neutral species with one or more unpaired electrons (i.e. neutral free radicals), which are chemically very reactive and an important ingredient in polymer formation; M represents a third body (e.g. molecule, ion, or atom) that can transfer energy or momentum in a collision; $h\nu$ represents a photon.

Table 4.1 Reactions that form reactive species in the avalanche plasma. AB represents any molecular species. A $\cdot$ (or B $\cdot$) represents any neutral species with one or more unpaired electrons (i.e. neutral free radicals). M represents any third body (e.g. molecule, ion or atom) that can transfer energy in a collision, and $h\nu$ represents a photon.

Electron impact:	$e + AB \longrightarrow A\cdot + B\cdot + e$ $e + AB \longrightarrow A^+ + B^- + e$
Photodissociation:	$h\nu + AB \longrightarrow A\cdot + B\cdot$ $h\nu + AB \longrightarrow A^+ + B^-$ $h\nu + AB \longrightarrow e^- + A^+ + B\cdot$
Photoionization:	$h\nu + AB \longrightarrow (AB)^+ + e^-$
Heavy particle collisions:	$M + AB \longrightarrow A\cdot + B\cdot + M$ $M + AB \longrightarrow A^+ + B^- + M$

These processes can occur in gas phase or on a surface. Obviously, the chemistry occurring in the avalanche plasma is extremely complex, and thus virtually impossible to be described completely. There are a large number of factors that may potentially affect aging, including gas composition and especially gas impurities, chamber construction materials, radiation dose rate, avalanche gain, etc.[17,18]. Only with careful and directed analysis, is it possible to describe qualitatively the dominant chemical reactions that cause aging. Aging effects occur on both the anode and the cathode, but with very different consequences.

(a) Anode Aging

Anode aging results from the modification of the anode surface, and is manifested typically as loss of gain and of gain uniformity. This modification may be caused by coating of anode surface by a polymer formed in the avalanche plasma or, if the anode surface is chemically active, it may also be caused by a corrosion or oxidation process that can form insulating layers, or in other ways degrade the surface[9]. The loss of gain

can arise by reduction in the effective anode potential due to the negative charge accumulation on the insulating layer, reducing the field strength at the anode and thus the gain. Loss of gain uniformity is also commonly observed along the anode length, because the coating, or the surface charge accumulation is nonuniform.

(b) Cathode Aging

Cathode aging is usually the result of a thin insulating deposit again caused by the polymerization processes discussed above. Positive ions drifting to the cathode collect on these deposits, and produce a strong dipole field across the insulating layer. Ultimately, with sufficient charge accumulation, the field becomes intense enough to draw electrons from the cathode by field emission, and many of these electrons will enter the gas volume, and initiate further avalanches. When this process reaches a critical level, it becomes self-sustaining, and a discharge or electrical breakdown occurs: this process is the so-called "*Malter effect*"[19]. This level of critical field is of the order $\sim 10^7$ V/cm. The field-emitted electrons can more successfully penetrate the Malter or insulating layer than can the positive ions, and some of them will neutralize the positive charge. Many electrons, however, will enter the gas, drift to the anode, and produce more positive ions, which then drift to the cathode and enhance the strength of the dipole field and the field emission of electrons. This positive feedback ultimately leads to a self-sustained discharge and generally renders the detector inoperable.

4.4.2 Analysis of Aging

(a) Parametrization

For the analysis of the aging tests, it is conventional to characterize the aging by parameterizing the aging rate as the normalized rate of gain decrease, R :

$$R = -\frac{1}{G} \frac{\Delta G}{\Delta Q} = -\frac{1}{I} \frac{\Delta I}{\Delta Q} \quad (4-1)$$

where R is the normalized rate of gain decrease, usually taken to be in units of %/C/cm, G is the gain, Q is the charge transfer per unit strip length, and I is the corresponding current. Changes in the gain can be inferred from changes in the current because the two are linearly related. The strip length in this case refers to the irradiated portion of the strip that actually collects charge. The transferred charge is calculated by integrating the current. As an example of a high intensity experiment, the transferred charge of 100 mC/cm corresponds to the radiation dose expected at a radius of 40 cm for minimum ionizing particles at an LHC experiment (e.g. ATLAS or CMS) in 10 years of operation at full luminosity[20-23]. As a scale, to give some sense of the aging rate, various aging levels in wire chambers were classified by J. Kadyk as: $R < 10$, “negligible”; $10 < R < 100$, “moderate”; $100 < R < 500$, “large”; $R > 500$, “extremely rapid”[17].

(b) Pressure and Temperature Correction

During the aging tests, current and/or pulse height is monitored to determine the gas gain. However, even in the absence of aging these can change due to changes in temperature, pressure, and in the case of current monitoring, the X-ray flux. In order to remove the ambient-induced variations, it is necessary to correct the measurements for changes in gas pressure and temperature when analyzing data, since the gas gain depends upon the gas density, which, in turn, is a function of pressure, P , and absolute temperature, T . For example, pressure changes are normally the result of prevailing weather patterns, while temperature changes are mainly diurnal. The current for each sample record number, n , is corrected according to the following formula:

$$I_n' \text{ (corrected)} = \frac{I_n \text{ (measured)}}{(c_n)^\alpha}; \quad c_n = \frac{P_0 T_n}{P_n T_0} \quad (4-2)$$

Here α is the density dependence of gas gain, and is found to be small ($0 < \alpha < 1$) in the aging tests we have done with gas avalanche microdetectors (cf. wire chambers, where $4 < \alpha < 7$, typically). The correction factor, c , is calculated assuming ideal gas behavior, and P_0 and T_0 are the initial pressure and temperature for each aging test.

4.4.3 Experimental Procedures

(a) Setup

For a systematic study of aging effects, we have built a test station, which includes a clean test vessel, an X-ray generator and a data acquisition and monitoring system. Figure 4.18 shows a schematic drawing of the test station, indicating electrical connections to and gas flow through the apparatus used for these tests.

Shown in the photograph of Fig. 4.3, the clean test vessel is a cylindrical stainless steel container with gas and signal feed-throughs, where the detector assembly can easily be mounted on a stainless steel support. A thin (~ 0.005 inch) transparent mylar window was made and glued on the top of the container to allow visual observation and irradiation by low energy X-rays, using the epoxy Epotek E505: this epoxy is known as one which does not seem to cause aging effects[12]. Two cover plates were sealed to the main body of the vessel with clean copper gaskets. High voltages are provided and signals are extracted, using vacuum-grade metal-ceramic feed throughs. The gas inlet and outlet are connected to the gas system with electropolished stainless steel tubes. All parts were chemically cleaned in an ultrasonic bath for an hour using isopropanol alcohol and then baked for several hours at 100°C before assembly. Special precautions were taken to make our test vessel clean, gas-tight, and, as nearly as possible, free of plastics and organic materials.

In order to age the detectors in a convenient length of time (1-2 weeks), a small X-ray tube with a copper transmission target has been used, providing a maximum energy of

Fig. 4.18 A schematic drawing indicating electrical connections to and gas flow through the apparatus used for aging tests.

about 8 keV X-rays[24]. The size of the irradiated area was collimated to a 1.6 mm diameter, and an area of 2.0 mm². The gases used in these tests were carried to the clean test vessel from gas cylinders through a stainless steel tubing, and, when necessary, were filtered to remove mainly oxygen, water vapor, or halogenated impurities. The exhaust of the test vessel passes through a rotameter and an electronic flowmeter, and then to a vent manifold, which ultimately exhausts to the atmosphere. Barometric pressure and gas temperature were also monitored so that corrections for variations in the gas gain caused by changes in the gas density could be made (a negligible pressure drop occurs between the test vessel and the exhaust).

The outputs of the electronic gas flowmeters, thermistors, barometer and high voltage power supplies are analog signals that are digitized by the digital multimeter (DMM), and then these measurements and the picoammeter readings were collected by a computer at programmed intervals, and stored onto a hard disk memory. The computer is also used to plot the current with respect to collected charge or time, and to fit this curve to determine the aging rate. Communication between the instruments and the computer occurred via a general purpose interface bus (GPIB), the IEEE 488 standard.

(b) Procedures

The MGCs being tested were mounted just under the X-ray generator. Low gas gain (usually ~500) was used for these tests to prevent sparking in the high X-ray flux. The current density corresponding to the detector charge collected was typically about 10-20 nA/mm² for the gains used. This corresponded to a count rate of about 1.0×10^5 /mm²/sec. Pulse height spectra were taken, using an ⁵⁵Fe source (~0.2 mCi), through the same collimated aperture; the count rate was about 1.0×10^2 /mm²/sec. These spectra were taken at least at the beginning and end of aging runs, to look for degradation of resolution as well as for gain shifts: the peak position is a measure of gain, and the peak width is a measure of uncertainty of the gain. However, the primary measurement of gain changes

Table 4.2 Aging test results of the various anode strip metals with selected gas mixtures. The results are listed in the order in which the tests were done. The quoted values of aging rates in this table refer to asymptotic values near the end of the aging run.

Testing Order	Anode Metal	Gas Mixture	Gas Gain	Charge Transfer (mC/cm)	Aging Rate (%/C/cm)	Comments
1	Al	Ar/Ethane	560	10.0	3100	severe aging
2	Al	Ar/DME	100	2.4	2500	discharges
3	Au	Ar/DME	500	15.0	60	no aging
4	Au	DME	500	6.0	2300	contaminated
5	Au	Ar/Ethane	520	22.0	-30	no aging
6	Ni	Ar/Ethane	540	20.0	150	some aging
7	Ni	DME	520	5.0	5900	contaminated
8	Ni	Ar/DME	500	30.0	-30	no aging
9	Cr	Ar/DME	500	22.0	64	no aging
10	Cr	DME	480	3.2	2900	badly contaminated
11	Cr	Ar/Ethane	510	16.0	2500	
12	Ti/W	Ar/Ethane	250	16.0	-57	no aging

came from observing the current vs. integrated charge transfer. The leakage current for MGCs is usually very small (< 0.1 nA), as there is no conductive coating needed to remove charge build-up as would be the case for MSGCs. Therefore, the change in measured current can generally be regarded as a consequence of gain change, although occasionally aging caused a slight leakage current increase: this was subtracted in deriving the aging rate. The aging was measured by frequent sampling of the current, which was plotted and analyzed with respect to charge transfer per cm of anode strips irradiated. Current is assumed to be proportional to gain, since the X-ray flux is held constant and the leakage current is negligible. Aging effects were studied primarily as functions of gas composition and anode strip material, and are summarized in Table 4.2, where the results of the tests are listed in the order in which they were done. The values of R quoted in this table refer to asymptotic values near the end of the aging run. Typical

systematic uncertainties in the results are not well known, but are estimated to be of the order: $|\Delta R| \sim (100-200)$. In these tests, we have used three different gas mixtures of Ar-ethane (50/50), Ar-DME (50/50) and DME (100). It is known that ethane (C_2H_6) and DME (C_2H_6O) are good quenchers with argon, and help increasing also the number of primary and total ion pairs per cm for a given density[25-27]. Especially, DME is a very effective quencher, and also has a high linear ionization density ($n_p \sim 55$ and $n_t \sim 160$ ion pairs/cm), a low drift velocity and a low electron diffusion constant[28]; these are all properties which make it a good choice for use in high resolution drift chambers (e.g. vertex detectors).

4.4.4 Results and Discussion

(a) For Aluminum Anode Strip

As shown in Table 4.2, the aluminum anode strip was severely aged in both Ar-ethane (50/50) and Ar-DME (50/50): the measured aging rates were 3100 and 2500 %/C/cm, respectively. These results are usually explained by the high chemical activity (e.g. oxidation) of aluminum. Figure 4.19 (a) shows the aging curve of a MGC having aluminum anode strips at a gain of 560, using a gas mixture of Ar-ethane (50/50). The aging was also characterized using pulse height spectra as measured with an ^{55}Fe source, at $V_a = 360$ V and $V_d = -1000$ V. As shown in Fig. 4.20, the initial gain and energy resolution were about 560 and 15% FWHM, whereas those after the exposure of 9.6 mC/cm were about 470 and 18% FWHM. The shape of the spectrum after that exposure had slightly degraded: the width had significantly increased. The gain decreased substantially, and the aging rate based upon the pulse height of the main ^{55}Fe peak spectra was about 1.7×10^3 %/C/cm, considerably less than that found from the current decrease. The fact that the degradation in the shape of the spectrum is small may be explained by a thin, uniform coating of aluminum oxide (Al_2O_3), or possibly a very

(a)

(b)

Fig. 4.19 Aging curves of the MGC having aluminum anode strip with (a) Ar-ethane (50/50) at a gain of 560 and (b) Ar-DME (50/50) at a gain of 100. The measured aging rates were 3100 and 2500 %/C/cm, respectively.

Fig. 4.20 ^{55}Fe pulse height spectra (a) before and (b) after the exposure of 9.6 mC/cm . The shape of the spectrum after that exposure was still good, even though the gain decreased substantially, and the aging rate based upon the pulse height spectra was about $1.7 \times 10^3 \text{ \%}/\text{C/cm}$.

uniform polymer coating on the anode strips. This could decrease gain without affecting gain uniformity significantly. The sudden increase of the current near the beginning of the test is a result of a discharge, which seemed not to repeat. Unexpectedly, there was a sudden and small decrease of the current near 8 mC/cm , and we guess that this may have been caused by a small unintentional decrease in bias voltage. At the end of the test, the X-ray tube was turned off for about four hours and then turned on again. The current did not recover to the initial value but to the “aged” value before turnoff, a clear evidence of permanent damage.

Figure 4.19 (b) shows the aging curve of a MGC with aluminum anode strips at a gain of 100, using a gas mixture of Ar-DME (50/50). The measured aging rate was $2500 \text{ \%}/\text{C/cm}$. Near the beginning of the test many microdischarges were observed, indicating an insulating deposit on the cathode (i.e. Malter discharges). As the aging continued, the discharges diminished, possibly due to the Al_2O_3 insulator which becomes thick enough

discharges diminished, possibly due to the Al_2O_3 insulator which becomes thick enough to inhibit the discharges-such as epoxy passivation on ends of cathode strips, or possibly due to the self-passivation effect of the growing insulating layer. Here the self-passivation effect means that as aging goes on, the insulating deposit on the cathode grows, reducing the electric field intensity across itself, which makes it more difficult to pull electrons from the cathode, resulting in less discharges with time.

(b) For Gold Anode Strip

On the other hand, the gold anode strip did not show significant aging in either Ar-ethane (50/50) or Ar-DME (50/50). One test using DME (100) gave a rapid aging with the gold strips, but at this time the DME was thought to have been contaminated by using a nearly empty bottle of DME. It is known from previous studies of aging using DME in wire chambers that serious aging begins when the DME bottle is nearly empty[29].

Figure 4.21 (a) and (b) show the aging curves of a MGC having gold anode strips using gas mixtures of Ar-DME (50/50) and Ar-ethane (50/50), respectively, at a gain of about 500 in each case. The aging rate for the Ar-DME (50/50) gas mixture measured after the initial transient behavior was 60 %/C/cm, which is lower by a factor of about 40 than that obtained with aluminum in the same gas mixture. For the Ar-ethane (50/50) gas mixture, the rate was -30 %/C/cm, indicating no aging. This reduction in aging is thought to be because gold is chemically quite inert and is not oxidized in the avalanche process.

Figure 4.22 shows the aging curve of a MGC having gold anode strips with the impure DME, and the measured aging rate was 2300 %/C/cm at a gain of 500. In subsequent aging tests, the contamination of DME became progressively more severe, but at this point had not yet seriously contaminated the clean test vessel. The contamination of the test vessel, we believe, increased after each use of the DME, and became especially severe only when the DME gas bottle became empty (i.e. no liquid DME remained).

(a)

(b)

Fig. 4.21 Aging curves of the MGC having gold anode strip with (a) Ar-DME (50/50) and (b) Ar-ethane (50/50), at a gain of about 500 in each case. The measured aging rates, respectively, were 60 and -30 %/C/cm, indicating no aging.

Fig. 4.22 Aging curve of the MGC having gold anode strips with the contaminated DME at a gain of 500. The measured aging rates was 2300 %/C/cm.

(c) For Nickel and Chromium Anode Strips

Subsequent aging tests with Ni and Cr anode strips show that there was still no evidence of aging with Ar-DME (50/50) even in the presence of some contamination of the test vessel by impure DME. All DME tests (test's 4, 7 and 10 in Table 4.2) resulted in severe aging because the DME was contaminated. The measured aging rates in the progressively contaminated DME were 2300, 5900 and 2900 %/C/cm for Au, Ni and Cr, respectively.

Figure 4.23 shows the aging curves for Ni anode strips with gas mixtures of (a) Ar-ethane (50/50) (test 6) and (b) Ar-DME (50/50) (test 8), and Fig. 4.24 (a) shows the aging curves for Cr anode strips with Ar-DME (50/50) (test 9). The corresponding aging rates are 150, -30 and 64 %/C/cm, consistent with no aging. Near the end of test 9, some microdischarges were observed, indicative of deposits. The next two tests resulted in severe aging, which is evidence of contamination of the test vessel, as shown in Fig. 4.24

(a)

(b)

Fig. 4.23 Aging curves of the MGC having nickel anode strip with (a) Ar-ethane (50/50) and (b) Ar-DME (50/50), at a gain of about 500 in each case. The measured aging rates were 150 and -30 %/C/cm, respectively.

(a)

(b)

Fig. 4.24 Aging curves of the MGC having chromium anode strip with (a) Ar-DME (50/50) and (b) Ar-ethane (50/50), at a gain of about 500 in each case. The measured aging rates were 64 and 2500 %/C/cm, respectively.

(b), inconsistent with earlier Ar-ethane tests. This result, we believe, is due to contamination from the previous DME run.

(d) For Titanium/Tungsten (10%/90%) Anode Strip

Finally, the test vessel was completely cleaned, and new aging tests were begun. The first of these was using titanium/tungsten (10%/90%) for the strip material, and as indicated in Fig. 4.25, this gave a quite good aging result: $R = -57\%/\text{C}/\text{cm}$, consistent with no aging. This metal was used because it was easily available, since it is frequently used in microprocessing technologies. As we will see in the next section, it is also of interest because of its strong resistance to spark damage.

Fig. 4.25 Aging curve of the MGC having Ti/W anode strips with a gas mixture of Ar-ethane (50/50) at a gain of 250. The measured aging rates was $-57\%/\text{C}/\text{cm}$, consistent with no aging.

4.5 Spark Damage Tests

4.5.1 Description of Tests

These spark damage tests are intended to provide estimates of limits of electrical discharge energies to avoid disabling damage. The tests have been done over a range of energies, and for a variety of anode strip metals, to determine the failure modes and relative robustness with respect to sparking. The optimization of strip design is constrained by the requirement of a minimum conductivity along the strip, to prevent excessive signal loss in the readout. The value used in this investigation corresponds to a maximum strip resistance of $500 \Omega/\text{cm}$ [30]. All tests were done using MGCs, though the results should be equally applicable to MSGCs. As shown in Fig. 4.26, the anode strips were connected in groups of ten, biased, and, for most of the tests, coupled to an external capacitor, while the cathode was kept at ground potential. In all of these tests, an Ar-ethane (50/50) or Ar-DME (50/50) gas mixture was used at atmospheric pressure. Sparking always occurred at nearly the same voltage, 440V, independent of metal and gas mixture. The electrical discharge energy is stored in the overall system capacitance,

Fig. 4.26 Schematic diagram of the electrical connection for spark damage tests. The anode strips were connected in groups of ten, biased, and, for most of the tests, coupled to an external capacitor, while the cathode was kept at ground potential.

Fig. 4.27 Capacitance of anode strips to ground measured in air, as a function of the number of anode strips ganged together, for a MGC having a conventional geometry.

which includes capacitances of ganged anode strips to ground, an external capacitor (if used), and cabling. It is important to consider a readout scheme, an operating voltage, an electrode geometry, and an appropriate metal to avoid the spark damage. In principle, the electrical discharge energy can be limited by reading out anode (or cathode) strips at ground potential, thus avoiding a coupling capacitor, and by reading out only one, or at most a few strips ganged, minimizing the internal capacitance. Figure 4.27 shows the measured capacitance of anode strips to ground as a function of the number of anode strips ganged together, for a MGC having the geometry used here. The capacitance per strip has been determined to be about 2.6 pF/cm from the slope of the graph. Increasing the thickness of the insulating layer also decreases the internal strip capacitance, and may have advantages of larger gas gain and higher signal-to-noise ratio. With such precautions, and others, it may be possible to avoid serious spark damage, depending upon the choice of the anode strip metal. With regard to spark damage, the strip metal

should have a high melting point, a high heat capacity, and a suitable electrical resistivity. If the electrical resistivity is too high, propagation of the signal will be degraded, while if it is too low, the strip may be damaged (melted) due to large peak ohmic heating (I^2R). In Table 4.3, some important physical properties of several anode strip metals are listed. In these spark damage tests, several different external capacitances have been used, from zero (i.e. internal capacitance only, ~30 pF) up to 4000 pF, in order to determine the failure point of the anode strip metals. The spark damage was assessed using optical and scanning electron microscope (SEM) photographs, and by measuring leakage current before and after sparking.

Table 4.3 Physical properties of several anode strip metals.

Properties \ Metals	Al	Au	Ni	Cr	W	Ti/W
Density (g/cm ³)	2.70	19.3	8.9	7.2	19.3	-
Melting Point (°C)	660	1064	1453	1857	3410	2600
Boiling Point (°C)	2467	2808	2732	2672	5660	-
Resistivity(m Ω -cm)	2.65	2.27	6.03	12.9	5.28	70.0
Heat Capacity (J/g/K)	0.903	0.129	0.446	0.449	0.135	-
Heat Conductivity (W/cm/K)	2.37	3.18	0.909	0.939	1.73	-
Work Function(eV)	~4.2	~5.2	~5.2	4.5	~4.7	-

4.5.2 Results and Discussion

(a) For Aluminum Anode Strip

Spark damage tests with aluminum anode strips of 0.5 or 1.0 μm thickness have been done, using several external capacitors of zero, 100, 200, 470 and 1000 pF. Figure's 4.28 and 4.29 show the photographs taken with a SEM of aluminum anode strips damaged by sparking, indicating a strong correlation between the damage and the

Fig. 4.28 SEM photographs of aluminum anode strip (a) before the sparking tests, and damaged by sparking with external capacitors of (b) zero ($1.0\text{ }\mu\text{m}$ thick) and (c) 100 pF ($0.5\text{ }\mu\text{m}$ thick).

(a)

(b)

(c)

Fig. 4.29 SEM photographs of 0.5 μm thick aluminum anode strips damaged by sparking, with external capacitors of (a) 200, (b) 470 and (c) 1000 pF. The thickness of the strip in (c) was 1.0 μm .

electrical discharge energy. As indicated in Table 4.3, the electrical resistivity of aluminum is small and its melting point is low. Evidently, from Fig's. 4.28 and 4.29, spark damage by melting, or even evaporation of the strips, has occurred. As shown in Fig. 4.29, the spark damage of the aluminum strips with external capacitors greater than 200 pF was catastrophic, breaking the strip and sometimes shorting out and disabling the detector. In Fig. 4.28 (b), even when the external capacitor was disconnected, there was noticeable damage after sparking, but the detector was still operational: the damage was significant but less serious, and was distributed in a regular pattern along the anode strip, perhaps caused by the multiple sparking.

(b) For Au, Ni, Cr and Ti/W (10%/90%) Anode Strips

As alternatives, other anode strip metals more robust than Al have been tested, such as Au, Ni, Cr and Ti/W (10%/90%). Figure's 4.30-4.34 show their anode strips damaged by sparking, with external capacitors of 1000, 2000 and 4000 pF. These photographs also show a strong correlation between the damage and the electrical discharge energy, and a large variation in damage between different anode strip metals for the same electrical discharge energy.

As shown in Fig's. 4.30 and 31, the spark damage to the 0.25 μm thick Au anode strip was more severe than to one with 0.5 μm thickness. In Fig. 4.30 (b) and 4.31 (b), the Au anode strip of 0.25 μm thickness was broken with an external capacitance of 2000 pF, whereas the Au anode strip of 0.5 μm thickness was damaged but still continuous. Although Au is somewhat preferred as a strip metal for purposes of aging and electrical conductivity, it does not have good sparking characteristics, since there was a large leakage current induced during nearly all of the Au tests (~ 3 nA, compared with ~ 0.01 nA initial leakage), probably due to evaporation of Au.

As shown in Fig's. 4.32-4.34, the spark damage to the Ni, Cr and Ti/W anode strips was much smaller than to the Al or Au anode strips. For these metals, even with an

(a)

(b)

(c)

Fig. 4.30 SEM photographs of 0.25 μm thick gold anode strips damaged by sparking, with external capacitors of (a) 1000 pF, (b) 2000 pF and (c) 4000 pF.

Fig. 4.31 SEM photographs of 0.5 μm thick gold anode strips damaged by sparking, with external capacitors of (a) 1000 pF, (b) 2000 pF and (c) 4000 pF.

Fig. 4.32 SEM photographs of 0.25 μm thick nickel anode strips damaged by sparking, with external capacitors of (a) 1000 pF, (b) 2000 pF and (c) 4000 pF.

(a)

(b)

(c)

Fig. 4.33 SEM photographs of 0.5 μm thick chromium anode strips damaged by sparking, with external capacitors of (a) 1000 pF, (b) 2000 pF and (c) 4000 pF.

(a)

(b)

(c)

Fig. 4.34 SEM photographs of 0.25 μm thick Ti/W anode strips damaged by sparking, with external capacitors of (a) 1000 pF, (b) 2000 pF and (c) 4000 pF.

Table 4.4 Damage effects of several anode metals due to sparking.

Anode strips: all 9 μm wide (thickness indicated)

* The thickness of Al anode strip was 1.0 μm

Strip Damage (SD): % width remaining [SD | SL]

Surface Leakage current increase (SL): nA
(SL measured at $V_a = 400\text{ V}$; if less than 0.1 nA :~0)

Capacitance (pF)	Al (0.5 μm)		Au				Cr (0.5 μm)		Ni (0.25 μm)		Ti/W (0.25 μm)		W (0.55 μm)	
			(0.25 μm)	(0.5 μm)	(0.5 μm)	(0.5 μm)								
0	95*	~0	-	-	-	-	-	-	-	-	-	-	30	~ μA
100	60	~0	-	-	-	-	-	-	-	-	-	-	-	-
200	40	~0	-	-	-	-	-	-	-	-	-	-	-	-
470	0	~0	-	-	-	-	-	-	-	-	-	-	-	-
1000	0*	shorted	35	0.58	50	~0	80	~0	75	~0	80	~0	60	~ few μA
2000	-		0	2.85	25	0.21	40	~0	50	~0	65	~0	0	
4000	-		0	0.88	0	0.53	40	~0	12	~0	55	~0	-	

external capacitance of 4000 pF, none of the strips were broken by sparking. Leakage current increase after sparking was not observed with these metals. The detectors remained operational after sparking, even in the case of Fig. 4.33 (c). Cracks in the chromium strips seen in Fig. 4. 33 are due to internal stress resulting from the fabrication, and were apparent even before the sparking tests. We believe that the good performance exhibited for the Ni, Cr, and Ti/W anode metals is mainly due to their higher melting points and higher electrical resistivity. The damage effects of the tested anode strip metals due to sparking is summarized in Table 4.4.

However, metals having a high electrical resistivity may experience excessive signal degradation, and an investigation has been done recently to achieve both a low resistivity and relative insensitivity to spark damage using unalloyed tungsten for the strip metal.

(c) For Tungsten (100%) Anode Strips

In the previous systematic studies of spark damage on a variety of anode metals used in fabrication of MGCs, One metal alone, titanium/tungsten suffered very little damage, even at the largest discharge energy, about 350 μJ (4000 pF). The good performance exhibited there could be due partly to the very high melting point of tungsten in this alloy, which consists of 90% tungsten, and due partly to a current limitation resulting from its relatively large resistivity ($\sim 70 \mu\Omega\cdot\text{cm}$). However, this large resistivity precludes its use on gas avalanche microdetectors of larger sizes: anodes having such a high resistivity would cause an excessive signal loss. Thus, we have undertaken the fabrication of MGCs with unalloyed tungsten, which has an electrical resistivity in bulk of about $5.3 \mu\Omega\cdot\text{cm}$ and a melting point of 3410°C , in the search for a metallization that will be both highly robust against sparking and yet have sufficiently low resistivity to permit larger sizes of detectors ($\sim 25 \text{ cm}$ [31]).

Before fabricating the MGCs with tungsten anode strips for spark damage tests, we deposited tungsten layers of three different thicknesses ($3000\text{\AA}$, $7500\text{\AA}$ and $1.0 \mu\text{m}$) on glass samples using a sputtering technique, in order to measure the sheet resistance and the strip resistance for each of these layers. It was soon evident that adherence of the tungsten to the glass substrate required a thin adhesion layer (initially $\sim 100\text{\AA}$) of titanium /tungsten. The measured sheet resistances for these layers were, respectively, 0.68, 0.27 and $0.15 \Omega/\square$, values corresponding to about three times what would be calculated from the tungsten volume resistivity ($\rho_v = \sim 5.3 \mu\Omega\cdot\text{cm}$) using the known layer thickness. Such a result is commonly known to result from deposition processes. Based upon the measured sheet resistances given above, the anode strip resistances are expected to be 756, 300 and $167 \Omega/\text{cm}$ for $9 \mu\text{m}$ wide anode strips, as shown in Fig. 4.35. The latter two values are compatible with the $500 \Omega/\text{cm}$ requirement we have adopted.

Thicker anode strip is preferable for less signal attenuation and is also more robust against sparking[32]. However, with thicker strips, it is more difficult to vacuum-clamp a

Fig. 4.35 Measured and calculated (based upon the tungsten volume resistivity, $\rho_v = \sim 5.3 \mu\Omega\cdot\text{cm}$) resistances of the $9 \mu\text{m}$ wide anode strips. The dashed line corresponds to our assumed strip resistance requirement, $\leq 500 \Omega/\text{cm}$.

substrate sufficiently flat for processing, due to the larger stress. Thick tungsten deposition is known to have a large internal stress, either compressive or tensile, depending upon the sputtering parameters, especially the gas pressure. It is also known that the volume resistivity of the deposited tungsten depends upon the gas pressure used during the deposition process[33]. In order to measure the dependence of the internal stress and resistivity upon the deposition pressure, we deposited a tungsten layer of about $5500\text{\AA}$ thickness on glass samples, using four different sputtering deposition pressures: 6, 10, 14 and 20 mTorr of argon. We also deposited an underlayer of titanium/tungsten of about $500\text{\AA}$ to insure better adherence of the tungsten ($100\text{\AA}$ was found to be insufficient). Figure 4.36 shows the measured electrical resistivity and internal stress of the sputtered tungsten films as a function of deposition pressure: these parameters are very sensitive to the deposition pressure, as well as other parameters, and, as shown in Fig. 4.36, there is a sharp compressive-tensile transition which may be related to the

Fig. 4.36 Measured electrical resistivity and internal stress as a function of deposition pressure. The stress was determined by measuring substrate curvature.

microstructure of the film. Based upon the above test results, we have fabricated MGCs with two different anode thicknesses on a low resistivity ($\sim 3 \text{ m}\Omega\cdot\text{cm}$) silicon substrate, which is used as the cathode: (a) a $7500\text{\AA}$ thick tungsten anode, deposited at 3 mTorr and (b) a $5500\text{\AA}$ thick tungsten anode, deposited at 10 mTorr. We have used a gas mixture of Ar-ethane (50/50) at atmospheric pressure in these sparking tests.

First, we performed spark damage tests with the MGCs of $7500\text{\AA}$ thick tungsten anodes. The stress induced in this film was compressive and estimated to be more than $2.8 \times 10^9 \text{ Pa}$, based upon a measurement of the substrate curvature. The sheet and strip resistances were $0.27 \text{ }\Omega/\square$ and $300 \text{ }\Omega/\text{cm}$, respectively. Figure 4.37 shows an SEM photograph of the $7500 \text{ \AA}$ thick tungsten anodes, damaged by sparking with an external capacitor of 4000 pF. Sparking occurred at nearly 440 V. With this spark energy, only 30-40% of anode strip width ($\sim 4 \text{ }\mu\text{m}$) was melted, but the strips broke and curled up at a short distance from the sparks. With smaller external capacitances, the strip exhibited less

Fig. 4.37 Scanning electron microscope (SEM) photograph of 7500 Å thick tungsten anode strips, damaged by sparking with an external capacitor of 4000 pF. The anode strips broke and curled up at a short distance from the sparks, probably due to some combination of thermal shock, large internal stress of the film and insufficiently thick Ti/W adhesion layer.

melting, but a crack was always observed near the sparks. These effects are presumably due to some combination of thermal shock, large internal stress of the film and insufficiently thick Ti/W adhesion layer (~ 100 Å).

In order to minimize the internal stress of the sputtered tungsten films, we decreased the film thickness to 5500 Å and increased the deposition pressure to 10 mTorr. The measured internal stress of this film was compressive and about 1.4×10^9 Pa. The sheet and strip resistances were measured, respectively, as about $0.42 \Omega/\square$ and $467 \Omega/\text{cm}$, values that are still compatible with our requirement. Figure 4.38 shows optical microscope photographs of the 5500 Å thick tungsten anodes, damaged by sparking with external capacitors of (a) zero, (b) 1000 and (c) 2000 pF. In these cases, sparking occurred at nearly 500 V. In Fig. 4.38 (c), the tungsten anode strip was discontinuous after sparking with an external capacitor of 2000 pF. Even with no external capacitor, there was noticeable damage, but no loss of strip continuity (Fig. 4.38 (a)). With an

(a)

(b)

(c)

Fig. 4.38 Optical microscope photographs of the $5500\text{\AA}$ thick tungsten anode strips, damaged by sparking with external capacitors of (a) zero (i.e. internal capacitance only, $\sim 30\text{ pF}$), (b) 1000 and (c) 2000 pF. Only in (c) did the strip become discontinuous.

external capacitor of 1000 pF, the strip was more severely damaged but still continuous. The breaking and peeling off of the strip, as seen with the 7500 Å anodes, was not observed with these 5500 Å anodes, even at the largest discharge energy. This might be explained by the smaller internal stress of the film and thicker adhesion layer of Ti/W (~500 Å) used. After sparking, none of the detectors were operational any more, because of large leakage currents (~few μA , compared with ~0.01 nA initially). Such an increase in leakage current had not been seen in the previous tests of other metals, except for gold (section 's (a) and (b)). The photographs in Fig's. 4.37 and 4.38 show clearly that some melting, and perhaps evaporation of tungsten has occurred due to large peak ohmic heating (melting point = 3410°C, boiling point = 5660°C for tungsten), and probably this has also occurred on the silicon (melting point = 1410°C, boiling point = 2355°C for silicon): the deposits resulting from the evaporation of either material could explain the increase in leakage current. At this time, it is not clear if the leakage current increase is due to the sputtering of tungsten or silicon, or both, but it did not occur in previous tests using Ti/W (10%/90%) strips having higher resistivity, and thus less intense ohmic heating.

4.6 Summary

Microgap gas chambers (MGCs) fabricated with various anode strip metals, Al, Au, Ni, Cr, Ti/W (10%/90%) and W (100%) onto 2 μm thick SiO_2 insulating layers, have been used to study the properties of gas gain, aging and spark damage. These MGCs achieved the expected maximum gas gains of about 3000 to 4000 in DME-based gases. Computer simulations indicate that significant dead zone can occur when the drift field is increased in an attempt to achieve larger gain. There was no noticeable change in the gas gain over an hour time period for any of these anode metals, except aluminum, demonstrating short-term gain stability against surface charging. A-Si:C:H has been used to make thicker high quality insulating layers in MGCs. The gas gain obtained using the

MGC with the 4.6 μm thick a-Si:C:H insulator was larger by a factor of 1.4 than that with the 2.3 μm thickness, at an anode voltage of 420 V. A maximum gas gain of 3200 was obtained with the 2.3 μm thickness in a gas mixture of Ar-ethane (50/50).

Accelerated aging tests have been performed primarily as functions of filling gas composition and anode strip material. Aging did not occur at the level of the present tests ($Q=15\text{-}30\text{ mC/cm}$) for any anode metal except aluminum, using Ar-ethane (50/50) or Ar-DME (50/50). The overall aging results are summarized in Table 4.2.

It is difficult to eliminate sparking and still achieve sufficiently large gas gain, especially since heavily ionizing particles can enhance the sparking probability. As a possible solution to the spark damage problem, we have investigated electrode metal themselves which are both highly robust against sparking and yet have sufficiently low resistivity to permit larger sizes of detectors without excessive signal loss. Our systematic studies of spark damage on a variety of anode metals (e.g. aluminum, gold, nickel, chromium, titanium/tungsten (10/90) and unalloyed tungsten) used in the fabrication of MGCs showed that there is a large range in the susceptibility of these anode metals to damage from sparking. Aluminum was very easily damaged, and its anode strips were broken by sparks of relatively low energy, while other anode metals such as, gold, nickel, chromium, and titanium/tungsten were more robust by varying degrees. One metal, gold, was found to be relatively resistant to strip breakage, but large increases of leakage current occurred due to sparking, a phenomenon not observed with the other metals except for unalloyed tungsten. The spark damage is also generally small, even for aluminum, if the internal capacitance to ground is kept small, and for metals having a high melting point and a high electrical resistivity. However, the high resistivity of the metal precludes its use on the gas avalanche microdetectors of the larger sizes due to excessive signal loss. Thus, we have undertaken the fabrication of MGCs with unalloyed tungsten, which has a relatively low electrical resistivity in bulk of $\sim 5.3\text{ }\mu\Omega\text{-cm}$ and a high melting point of 3410°C . The spark damage of tungsten anodes was severe, and even

with no external capacitor, there was noticeable damage. After sparking, the tungsten detectors were not operational due to large leakage current: this is due to the large peak ohmic heating which occurs with low resistivity anode metals. The silicon cathode was also severely damaged by the sparking. It is not known at present whether the increase in the leakage current is due to the sputtering of tungsten or silicon, or both. The principal limitation seen in these measurements is the leakage current increase rather than melting, and further work would be needed to understand its source. If the silicon is responsible, then perhaps tungsten deposited on a non-conductive substrate may serve as a suitable cathode. The results of spark damage tests are summarized in Table 4.4. With respect to spark damage, aluminum, gold and unalloyed tungsten were "*poor*", nickel was "*good*", and chromium and titanium/tungsten were "*very good*".

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Chapter 5 Microdot Gas Chambers (MDOTs) with Amorphous Silicon Carbide (a-Si:C:H) Overcoating

5.1 Introduction

Since A. Oed introduced the first microstrip gas chamber (MSGC), there has been noticeable progress in the detector design to achieve reliable, two-dimensional position-sensitive detectors. As described in section 2.5, two-dimensional readout has been realized by suitably segmenting the backplane in the MSGC[1-4] or the cathode in the MGC[5,6], orthogonal to the anode strips, so that induced signals could be collected for the second coordinate information (see Fig. 2.9). However, none of these microstrip detectors represents a true two-dimensional (or pixel) device.

In 1995 S. Biagi *et al.* developed a new microdetector design, called the microdot gas chamber (MDOT)[7], which consists of a matrix of adjacent metal rings (the cathodes) with an anode dot in each center. Figure 5.1 shows examples of MDOTs in which columns of anode dots are connected together for convenience of readout: (a) top view with a circular cathode, (b) top view with a hexagonal cathode, and (c) side view. The MDOT is not a strip device like the MSGC or the MGC, but a pixel device capable of true two-dimensional readout. In addition, recent measurement of the MDOT has yielded maximum gas gain of at least 4×10^4 [8,9]: this is several times larger gain than can be expected from other types of gas avalanche microdetectors which have strip geometry. Therefore, the MDOT has the intrinsic advantages of gain and two-dimensional readout of every particle detected, reducing occupancy and therefore tracking confusion in high flux environments.

However, the MDOT has encountered a new design problem which is caused by the readout stripline: defocusing of the drift field lines by the interference of the readout stripline potential as it perturbs the field in the gas drift region. In this chapter, a new

Fig. 5.1 Examples of MDOTs: (a) top view with a circular cathode, (b) top view with a hexagonal cathode, and (c) side view. For convenience of readout, columns of anode dots are connected together, giving a strip configuration.

approach to a solution of this problem is presented. Section's 5.2-5.4 describe and discuss, respectively, the defocusing effect of the readout stripline, the fabrication of the MDOT chambers, and the experimental results. The summary of this chapter is given in the last section.

5.2 Defocusing Effect of the Readout Stripline

The MDOT may be used either as a true two-dimensional (or pixel) device or may be connected as a microstrip device (see Fig. 5.1). However, in the latter case, it was noted that there was an influence of the readout stripline on the field in the gas drift region, as illustrated in Fig. 5.2. The potential of the readout stripline causes distortion of the drift field lines, leading to defocusing of the drifting electrons from the anode dots, and consequent loss of sensitive region[10]. An inactive region (dead zone) will be created in the gas drift region, where some of the drifting electrons will be directed toward the readout stripline (below the insulating surface), instead of toward the anode dots, leading to loss of detection efficiency. The addition of "*floating rings*" in a later design modification may minimize that effect[10,11], as indicated in Fig. 5.2. Also shown in this figure are drift field lines which may go to the cathode, if the drift field is sufficiently strong. Figure 5.3 shows an optical microscope photograph of a MDOT with a hexagonal cathode and one-floating ring. The floating ring improves the electric field profile in the gas avalanche region, and may be helpful in reducing the dead zone.

In this chapter, another approach to a solution of this problem is presented: the isolation of the readout region from the gas drift region by means of a thin conductive surface coating on the insulating surface. When detector surface is coated with a thin layer of sufficient conductivity, the region of the readout stripline becomes electrically isolated from the gas drift region, so that the number of defocused drift field lines is reduced. R. Bouclier *et al.* also reported a similar screening effect on the backplane

Fig 5.2 Defocusing effect of the readout stripline. In this geometry, the readout stripline acts to attract some of the drift field lines, hence misdirecting them from the anode dots to the readout stripline below the insulating surface.

Fig. 5.3 Optical microscope photograph of a MDOT with a hexagonal cathode and one-flooding ring. The floating ring improves the electric field profile in the gas avalanche region, and may be helpful in reducing the dead zone.

potential, produced by the surface current of the conductive surface coating layer in the MSGC[12,13]. In our case, a thin ($\sim 0.1 \mu\text{m}$) layer of boron-doped amorphous silicon carbide (a-Si:C:H) has been deposited over the entire detector surface using the PECVD technique. We have performed such a coating on pixel detectors of our own design, which are microdot gas chambers having a square geometry (SMDOTs; see Fig. 5.4). We have investigated the effect upon the defocusing and other detector performance by comparing uncoated and coated SMDOTs.

5.3 Device Fabrication

The devices have fabricated on quartz wafers using standard photolithography processes. Figure 5.4 shows a schematic structure, and Fig. 5.5 is an optical microscope photograph of the SMDOT fabricated by us. The square geometry was employed for its simplicity in mask layout. We have fabricated SMDOTs having two different pitches: 100 and 200 μm . For the 200 μm pitch, the anodes were $20 \times 20 \mu\text{m}$ squares and the cathode grid was 80 μm in width. For the 100 μm pitch, the anodes were $10 \times 10 \mu\text{m}$ squares and the cathode grid was 30 μm in width. For purpose of a simple test, several anode dots (e.g. 16 in the 200 μm pitch and 40 in the 100 μm pitch) were grouped together and connected to an individual readout bonding pad. Future detectors could have each anode dot connected to an individual readout line. The active area of the whole detector was $0.8 \times 0.8 \text{ cm}^2$.

A 0.2 μm thick chromium layer was deposited onto the quartz substrate, and was patterned as a readout stripline, using RF sputtering and lift-off techniques. A 7.5 μm thick a-Si:C:H insulating layer was prepared using a gas mixture of $\text{SiH}_4\text{-CH}_4$ (10/90), with the PECVD technique. Square holes ($10 \times 10 \mu\text{m}$ for the 200 μm pitch and $5 \times 5 \mu\text{m}$ for the 100 μm pitch) were made through the a-Si:C:H insulating layer by the reactive-ion etching (RIE) technique. Then anode dots and cathode grid were defined with 0.2 μm thick aluminum or chromium, by RF sputtering and lift-off techniques. Finally, 0.1 μm

Fig. 5.4 Schematic structure of the SMDOT: (a) side view and (b) top view. The overcoating layer is 0.1 μm thick p-doped a-Si:C:H having a bulk resistivity of $2 \times 10^8 \Omega \cdot \text{cm}$, and the insulating spacer is 7.5 μm thick intrinsic a-Si:C:H having a bulk resistivity of $8 \times 10^{12} \Omega \cdot \text{cm}$. Shown in the inset are the 4x4 anodes grouped together in a 200 μm pitch.

Fig. 5.5 Optical microscope photograph of the SMDOT having a 200 μm pitch: this detector has 20x20 μm square anode dots, 80 μm wide cathode grid, and 0.8x0.8 cm^2 active area. For purpose of a simple test, sixteen (4x4) anode dots were grouped together and connected to an individual readout bonding pad.

thick boron-doped a-Si:C:H (with 70% CH_4 and 200 ppm B_2H_6) was deposited over the entire detector surface as a conductive surface coating.

We have used the a-Si:C:H film in the fabrication of the SMDOT, both as an insulating layer and, when properly doped, as a conductive surface coating[14-17]. The bulk resistivity of the 7.5 μm thick insulating spacer was about $8 \times 10^{12} \Omega \cdot \text{cm}$, and that of the 0.1 μm thick conductive surface coating layer was about $2 \times 10^8 \Omega \cdot \text{cm}$. As pointed out in ref. 18, the readout region can be quite effectively isolated electrically from the drift region, if the ratio of the bulk resistivities of the insulating layer and the conductive surface coating layer, $\rho_{\text{insu}}/\rho_{\text{surf}}$, exceeds 10^4 . In our case, this ratio is about 4×10^4 , which should be sufficient to decrease the defocusing effect of the readout stripline. Figure 5.6 shows the leakage current measured in darkness as a function of anode voltage, using the SMDOT having a 200 μm pitch (uncoated and coated): it was always much less than 1

Fig. 5.6 Leakage current of the SMDOT having a 200 μm pitch (uncoated and coated), measured in darkness as a function of anode voltage. The resistivity of the surface coating was about $2 \times 10^8 \Omega\text{-cm}$.

nA. The thick ($\sim 7.5 \mu\text{m}$) insulating spacer kept the leakage current low, and a relatively high voltage could be applied to the electrodes: the breakdown voltage for the SMDOT having a $7.5 \mu\text{m}$ thick insulating spacer was around 600 V, whereas it was below 440 V for the MGC having a $2 \mu\text{m}$ thick spacer (see Fig. 4.5).

5.4 Results and Discussion

For all tests, the cathode grid was held at ground potential while the anodes were biased through a $1.2 \text{ M}\Omega$ protection resistor and read out through a 1000 pF coupling capacitor to a charge-sensitive preamplifier and a shaping amplifier. The drift electrode was made of a thin stainless steel mesh and located 4 mm above the detector surface. The SMDOTs had pitches of 100 and $200 \mu\text{m}$, and were tested with an ^{55}Fe source ($\sim 0.2 \text{ mCi}$) using a gas mixture of Ar-ethane (50/50). Biagi's circular MDOTs having a $100 \mu\text{m}$

pitch, with and without the floating ring, were also tested, and the results were compared with those of the SMDOTs.

5.4.1 Count Rate vs. Drift Voltage (V_d)

One way to characterize the defocusing effect of the readout stripline may be to use a radioactive source, and measure the count rate variation with respect to the drift voltage. As the drift voltage is increased, a larger fraction of drift field lines will be defocused, i.e. drawn toward the insulating surface above the readout stripline, or possibly toward the cathode rather than toward the anode dot, resulting in the decrease of count rate. Even though not established quantitatively, the extent of the count rate variation with the drift voltage should at least be some measure of the size of the dead zone.

Figure's 5.7 and 5.8 show, respectively, the count rates measured as a function of drift voltage for SMDOTs having 100 and 200 μm pitches (uncoated and coated), and for MDOTs having either none or one-floating ring (uncoated and coated, 100 μm pitch). For all detectors except the SMDOT having the 100 μm pitch (uncoated), the count rate increased sharply at first and then decreased gradually with the drift voltage. The weak field behavior is probably explained by the lack of field in the drift region to collect ionization, and for strong fields, a potential well may be created by the readout stripline, causing drifting electrons to be drawn toward it rather than to the anode; in both cases, this results in a significant loss of count rate. We parameterized the defocusing effect, by measuring the ratio of the count rate between its peak value and the value at a drift voltage of -1000 V, $R_{\text{peak}}/R_{1000\text{V}}$, and a summary of the results is given in Table 5.1. The defocusing effect of the readout stripline was, as expected, more severe for the SMDOTs having a wider pitch, and the conductive surface coating appears to be effective in reducing the size of the dead zone, whereas the addition of one floating ring had a much smaller effect on the count rate variation with V_d . It is to be emphasized, however, that these measurements do not necessarily give a quantitative measure of the defocusing

Fig. 5.7 Count rate variation of the SMDOTs with the drift voltage. The defocusing effect of the readout stripline was more severe for detectors having wider pitch, as expected, and the conductive surface coating appears to be effective in reducing the dead zone.

Fig. 5.8 Count rate variation of the MDOTs having either none or one floating ring (uncoated and coated, 100 μm pitch) with the drift voltage. The conductive surface coating appears to be more effective in reducing the dead zone than the addition of one floating ring.

Table 5.1 The ratio of the count rate between the peak value and the value at a drift voltage of -1000 V, $R_{\text{peak}}/R_{1000\text{V}}$, for the SMDOTs and Biagi's MDOTs.

SMDOT				Biagi's MDOT (100 μm pitch)			
100 μm pitch		200 μm pitch		no floating ring		one floating ring	
uncoated	coated	uncoated	coated	uncoated	coated	uncoated	coated
2.5	1.4	3.6	2.2	4.4	2.9	3.8	3.0

effect.

However, the count rate variation was still observed with the overcoated detectors, although the conductivity of the surface coating was expected to be sufficient to screen the influence of the readout stripline to the gas drift region[18]. There might be factors other than the influence of the readout stripline, which may contribute to the overall count rate variation, such as the defocusing of the drift field lines to the cathodes. This has been observed in the previous simulations of the dead zone for the MSGC and MGC geometries (see section's 3.4.4 and 4.3.2, respectively). Moreover, a recent measurement of the count rate variation for the MGC shows a similar variation at small drift fields. The MGC has been rather well investigated by computer modeling, and no defocusing of the drift field is expected where this variation is observed at low field, indicating that at least one other mechanism than discussed is responsible for the count rate variation. However, when used as a qualitative probe, this method does appear to be sensitive to the size of the inactive regions.

We have also simulated the drift field lines for the uncoated SMDOT detector having a 200 μm pitch, using the 3-D Maxwell program package. Figure 5.9 shows the drift field lines in three-dimension view, for two drift voltages of (a) -500 and (b) -2000 V, at a fixed anode voltage of 520 V. Figure 5.10 shows the drift field lines arriving at the surface of the SMDOT, which was mapped on the x-y plane, for two drift voltages of (a) -500 and (b) -2000 V. All of the field lines are terminated near the anode dot, but a

Fig. 5.9 Drift electric field lines in three-dimension view, for two drift voltages of (a) -500 and (b) -2000 V, at a fixed anode voltage of 520 V. The anode dot is the upper-right corner of the x-y plane.

Fig. 5.10 The map of the drift field lines arriving at the detector surface, for two drift voltages of (a) -500 and (b) -2000 V, at a fixed anode voltage of 520 V. The anode dot and the readout stripline are outlined with the thick lines. The anode dot is the lower-right corner of the plot and the readout striplines extend from the anode dot to the top and the left.

Fig. 5.11 Simulation results of the SMDOT of a 200 μm pitch that give the fraction of drift field lines to the anode dot, the insulating surface, and outside of the pixel cell boundary, with the drift voltage, at an anode voltage of 520 V.

considerable fraction of the drift field lines are spread out above the readout stripline near the anode dot, indicating clear evidence of the insensitive region. At $V_d = -2000$ V, the drift field lines are spread out even further than at $V_d = -500$ V. Figure 5.11 shows the simulation results giving the fraction of the drift field lines reaching the anode, the insulating surface, and outside of the pixel cell boundary (spurious, resulting from insufficiently fine granularity in the simulation), as a function of drift voltage. For $V_d = -500$ V, about 26% of the drift field lines terminated on the anode dot and about 54% on the insulating surface; for $V_d = -2000$ V, about 6% on the anode dot and about 85% on the insulating surface. These simulation results support qualitatively the experimental results of the count rate variation with the drift voltage.

5.4.2 Gain vs. Anode Voltage (V_a)

Figure's 5.12 and 5.13 show the gain measurements with respect to the anode voltage, for the SMDOTs and the MDOTs, respectively. As shown in Fig. 5.12, the maximum gains of the SMDOTs having a 200 μm pitch, uncoated and coated, were 11700 and 9900, respectively. The gains of the SMDOTs having a 100 μm pitch, uncoated and coated, did not exhibit the normal exponential increase with V_a , and were limited to about 3000. As shown in Fig. 5.13, the MDOTs having a 100 μm pitch and a circular geometry gave much larger gains (~ 10000) than those of the SMDOTs having the same pitch. We conjecture that the effect on the gain of the radial asymmetry becomes quite significant as the detector dimension becomes smaller. The gains were not affected significantly by the floating ring, but were somewhat reduced by the overcoating. Compared with typical MSGCs with the same pitch, the microdot device exhibited much larger maximum gains (thus higher breakdown voltages), probably due to the reduced electric field intensity near the cathode edge. At a given anode voltage, the lower gains of the coated detectors than those of the uncoated detectors are primarily due to the more uniformly graded potential distribution, which makes the electric field around electrodes less concentrated. J.J. Florent *et al.* have shown by simulation that the peak electric field strength near the anode strip edge decreases roughly by 40% with a conductive layer in their MSGC structure[19].

Figure 5.14 shows ^{55}Fe pulse height spectra of (a) the SMDOT having a 200 μm pitch (coated) and (b) the MDOT having a 100 μm pitch and no floating (coated), both at an anode voltage of 480 V and a drift voltage of -1000 V. The spectrum shape of the SMDOT was much worse than that of the MDOT, probably because the electrode shape of the SMDOT is square rather than circular, resulting in the electric field nonuniformity in the avalanche region and a resulting gain nonuniformity. The energy resolution of the MDOT was about 18.2% FWHM at a gain of 1360.

Fig. 5.12 Gas gains of the SMDOT with a 200 μm pitch, measured as a function of anode voltage at a fixed drift voltage of -1000 V, using an ⁵⁵Fe source and a gas mixture of Ar-ethane (50/50).

Fig. 5.13 Gas gains of the MDOT with 100 μm pitch, measured as a function of anode voltage at a fixed drift voltage of -1000 V, using an ⁵⁵Fe source and a gas mixture of Ar-ethane (50/50).

(a)

(b)

Fig. 5.14 Pulse height spectra of (a) the SMDOT having a pitch of $200\text{ }\mu\text{m}$ and (b) the MDOT having a pitch of $100\text{ }\mu\text{m}$ and no floating ring, using a gas mixture of Ar-ethane (50/50). The spectrum of the SMDOT was much worse than that of the MDOT, probably because the electrode shape of the SMDOT is square rather than circular, resulting in an electric field nonuniformity.

5.4.3 Gain vs. Drift Voltage (V_d)

Figure 5.15 shows relative gains measured as a function of drift voltage at a fixed anode voltage of 560 V, using the SMDOTs having a 200 μm pitch (uncoated and coated). As the drift voltage became more negative, the gain decreased in the uncoated detector but increased in the coated detector. As we have seen earlier, the positive bias on the readout stripline misdirects some of the drift field lines toward it, instead of toward the anode dot. However, when the detector surface is overcoated with a thin conductive film, the overlayer plays a role to screen the effect of the readout stripline on the gas drift region, reducing the number of straying drift field lines. In this case, the gain increases with the drift voltage, since a more intense drift field enhances the field in the avalanche region, even though the fraction of drifting electrons going to anodes will decrease.

Fig. 5.15 Gas gains measured as a function of drift voltage at a fixed anode voltage of 560 V, using the SMDOT of a 200 μm pitch (uncoated and coated).

5.4.4 Gain vs. Time

Figure 5.16 shows the short-term gain stability with time, using the SMDOTs having a 200 μm pitch (uncoated and coated). The gain increased with time by about 10% and leveled off soon. The tendency of the initial gain increase with time is possibly explained as the charging by electrons of the insulating surface, created by the positively biased readout stripline[20]. Negative charging on the insulating surface increases the average field strength near the anode dots, yielding larger gain. The gain variation was smaller in the coated detector than in the uncoated detector, indicating that the conductive surface coating is also helpful to decrease the charging effect.

Fig. 5.16 Initial time dependence of the gas gain, at an anode voltage of 520 V and a drift voltage of -1000 V, using the SMDOT having a 200 μm pitch (uncoated and coated). The initial gain increase with time is possibly explained as the charging by electrons of the insulating surface, created by the positively biased readout stripline.

5.5 Summary

We have fabricated microdot gas chambers having a square geometry (SMDOTs) which have exhibited very high gains ($>10^4$), and represent a promising new detector design. The microdot gas chambers have the intrinsic advantages of two-dimensional readout and gas gain.

However, due to the existence of the readout stripline passing below the insulating surface, the drift field lines defocus from the anode dots, resulting in an insensitive region (dead zone). In order to reduce the defocusing effect, we have performed the surface coating of boron-doped amorphous silicon carbide (a-Si:C:H) on the SMDOTs, using the PECVD technique. The resulting bulk resistivity of the conductive overlayer was about $2 \times 10^8 \Omega \cdot \text{cm}$. We have investigated the effect upon the defocusing and other performance by comparing uncoated and coated SMDOTs. MDOTs having either none or one-floating ring have been also tested. Although the SMDOTs are simpler and less sophisticated than those of the MDOTs, they have shown comparable maximum gas gain: ~ 12000 for the uncoated SMDOT and ~ 10000 for the coated SMDOT. The defocusing effect was characterized by measuring the count rate variation with the drift voltage, and was also simulated using the 3-D MAXWELL computer program. According to our experimental and simulation results, the technique of the conductive surface coating appears to be effective in reducing the dead zone, but there are indications that a significant insensitive region still seems to be present after applying the coating. In the future, we hope to make more definitive measurements and to obtain a more detailed understanding through 3-D simulations.

The conductive surface coating onto the SMDOTs has also played important roles in detector performance: (a) it minimizes the effect of charge accumulation on the insulating layer surface, (b) it makes the electric field strength near the edges of the electrodes more uniform, helping to prevent electrical breakdown and thus resulting in

larger maximum gain, (c) it also weakly contributes to short-term gain stability with time, but (d) it reduces the gain somewhat at a given anode voltage.

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Chapter 6 Columnar Cesium Iodide (CsI) Drift Plane Layer for Gas Avalanche Microdetectors

6.1 Introduction

Gas avalanche microdetectors (MSGCs and MGCs) have many attractive features, especially very good spatial resolution and rate capability. However, it has been recognized for some time that these microdetectors perform more poorly for particles which are not incident normal to the plane of the detectors: this is due to distributed nature of primary ion pairs along the particle track. The degradation affects the space and time resolutions, and the efficiency[1-3]. In addition, the gains of such detectors are typically limited to 10^4 by the onset of electrical breakdown, and, for most designs, it is even difficult to reach this level. Furthermore, the potential damage due to sparking demands that detector operation be at a significantly lower voltage and gain than at the maximum. A low gain provides a poor signal-to-noise ratio for the detection of minimum ionizing particles, especially for inclined particle tracks, and hence will affect the detection efficiency.

To overcome these problems, it has been proposed that a thin cesium iodide (CsI) layer, functioning as a secondary electron emitter, be used as the drift plane, becoming the dominant source of primary ionization[4-7]. With this approach, the time resolution was improved by more than an order of magnitude, compared with the conventional MSGC operation, and no angular dependence of the efficiency was observed[6]. However, the efficiency for production of electrons by secondary emission using this technique was found to be unacceptably low for use in a detector. Therefore, the key to making the MSGC a viable device is to find an efficient secondary electron emitter[7].

In this chapter, we present a new technique which shows promise in achieving this goal: the use of a thin (~ 200 μm) columnar CsI layer added to the drift plane. This method is based on the same fundamental idea as in previous approaches, but uses a

“columnar” layer of CsI instead of a single (flat) layer, in order to provide a higher probability for secondary electron emission, and also to allow an electron multiplication mechanism within the layer as in the micro-channel plate[8]. The columnar CsI layer was developed for a previous medical imaging project funded by CRADA[9], and its performance was described in ref. 10. In section 6.2, the operating principle and the deposition method of the thin columnar CsI layer are described. In section’s 6.3 and 6.4, the experimental procedures and the results are presented and discussed, respectively. The summary of this chapter is given in the last section.

6.2 Principle and Fabrication

6.2.1 Operating Mechanism

Figure 6.1 illustrates schematic diagrams (not to scale) of (a) a conventional MSGC and (b) a MSGC coupled with a thin columnar CsI layer at the drift plane as an efficient secondary electron emitter. In the conventional gas avalanche microdetectors, the space and time resolutions, although very good, are both limited by the extended distribution of ion pairs produced along the incident particle tracks. The drifting primary electrons arrive at different anode strips, in general, at different times compromising the time resolution. Furthermore, for inclined particle tracks, the ionization will be distributed over several anode strips, resulting in significant loss of spatial resolution. A way to avoid both of these problems is to produce the primary electrons predominantly from a very small region or “*point*” on the drift plane, rather than from along the incident particle tracks, in the gas drift region. The concentration of electron production in such a way allows primary electrons to be focused on a much smaller number of anode strips, improving the space and time resolutions, as well as the detection efficiency. More importantly, it eliminates the angular dependence of these parameters since the source is point-like. All of these are important for a significant improvement of the operation of gas avalanche

Fig. 6.1 Schematic diagrams (not to scale) of (a) a conventional MSGC and (b) a MSGC coupled with a columnar CsI secondary electron emitter at the drift plane.

microdetectors.

The new approach presented here uses the same fundamental idea as in previous attempts, but it differs from them in that the electrons are produced as a result of secondary emission from CsI, not as a single (flat) layer, but in a columnar structure forming a layer having a thickness of order 200 μm . As illustrated in Fig's. 6.1 and 6.2, the columnar structure provides a large number of surface crossings of the incident

Fig. 6.2 Thin columnar structure of CsI layer, which enhances the secondary electron emission efficiency, and provides an electron multiplication mechanism as in a micro-channel plate (not to scale). Substrate may be made very thin, and of other material than silicon.

particle on its path through the layer, leading to the much larger secondary electron yield. Although the secondary electron efficiency per surface crossing may be much less than 100% (and is of order 5-10%), the enhanced yield resulting from many surface crossings may result in a particle detection efficiency of nearly 100%. Furthermore, an appropriate potential difference across the columnar CsI layer causes it to act as an electron multiplier, amplifying the number of initial secondary electrons to produce a much larger number of electrons entering the gas drift region. However, the precise mechanism of this amplification is not yet established experimentally. Improvements in space and time resolutions are further consequences of this point concentration of electron production. The pulse amplitude is expressed as:

$$\text{Signal pulse amplitude} \propto [n_e (\text{CsI layer}) + n_e (\text{gas drift region})] \cdot G_{\text{gas}} \quad (6-1)$$

$$n_e (\text{CsI layer}) = n_e (\text{SEE}) \cdot G_{\text{column}} \quad (6-2)$$

Here n_e (CsI layer) is the number of electrons produced in the columnar CsI layer before entering the gas drift region and is expressed by Eqn (6-2); n_e (gas drift region) is the number of primary electrons produced in the gas drift region; n_e (SEE) is the number of electrons produced by secondary emission due to the incident particle, and G_{gas} and G_{column} are absolute gains in the gas avalanche region near the anodes and within the columnar layer, respectively.

More important, and crucial to the operation of this device, is the efficiency for the detection of the minimum ionizing particles with respect to the incident particle angle. Principally, the primary ionization (secondary emission) process, being a small number of independent events, obeys Poisson statistics. If n is the average number of primary electrons, the actual number k in one event will have a probability of:

$$P_k^n = \frac{n^k}{k!} e^{-n} \quad (6-3)$$

Thus, the detection efficiency (assuming that detection requires only one electron), ϵ , is expressed as:

$$\epsilon = 1 - P_0^n = 1 - e^{-n} \quad (6-4)$$

With the columnar CsI layer, the secondary electron efficiency will be much higher because of the many surface crossings, and, based upon published yields[6,11], should be adequate to provide a fully efficient detector over the complete range of the incident particle angles. For example, at an incident dip angle of 20° , the average number of secondary electrons expected from the 200 μm thick columnar CsI layer is about 3-4, and the loss in efficiency is about 3%, assuming 10% secondary electron efficiency per surface crossing. This is to be compared to the measured loss of efficiency for a conventional MSGC of about 40-60% at this angle[3].

6.2.2 Deposition Method

Figure 6.3 shows the vacuum evaporation setup for depositing the thin columnar CsI layer. During the vacuum evaporation process, CsI powder in a boat which is heated by a thermocouple vaporizes rapidly and condenses onto the substrates, releasing the latent vaporization heat and thus causing the substrate temperature to increase. To compensate this temperature increase, the substrate holder is cooled by a water tubing system. The Halogen lamp above the rotating substrate holder supplies the radiant heat to maintain the substrate temperature at 100-150 °C during the evaporating process. The chamber is pumped down initially to 10^{-6} Torr, and then argon gas is admitted into the chamber, which is maintained at about 5 mTorr during the process. The role of argon atoms is to modify the transport paths of the CsI vapors toward the substrate by scattering, which enhances the columnar structure of the CsI layer. Figure 6.4 shows

Fig. 6.3 Schematic setup of the evaporator for depositing the columnar CsI layer. By vacuum evaporation of the CsI in a low pressure argon atmosphere and rotating the substrate, the CsI layer tends to grow in well-defined columns.

(a)

(b)

Fig. 6.4 Scanning electron microscope (SEM) photographs of a 200 μm thick columnar CsI layer (a) from the side view and (b) from the top view. The columns of CsI are about 3 μm in diameter, and spaced apart with about 1 μm between wall surfaces. By the vacuum evaporation of the CsI in a low pressure argon atmosphere and the rotating substrate, the CsI layer tends to grow in well-defined columns due to its high crystallographic anisotropy.

scanning electron microscope (SEM) photographs of a 200 μm thick columnar CsI layer (a) from the side view and (b) from the top view. The columns of CsI are about 3 μm in diameter, and spaced apart with about 1 μm between wall surfaces. By the vacuum evaporation of the CsI in a low pressure argon atmosphere and the rotating substrate, the CsI layer tends to grow in well-defined columns due to its high crystallographic anisotropy[12].

6.3 Experimental Procedures

An experimental layout for measurements of the electron multiplication factor and the detection efficiency of the columnar CsI layer is shown in Fig. 6.5; voltages applied to the electrodes are defined there. A thin (~ 200 μm) layer of columnar CsI was placed on the outside surface of the drift plane, using a 5 mil thick kapton as a spacer. A collimated ^{90}Sr source (~ 0.3 mCi) was used to provide electrons as minimum ionizing particles. Two identical MSGCs were used for these measurements: the anode and cathode strips were patterned onto a 800 μm thick Corning glass substrate, and their widths were 5 and 95 mm, respectively. The pitch was 200 μm and the active area was 1.5×2.0 cm^2 . More detailed information on these detectors is found elsewhere[13]. In order to help insure that only electrons emitted from the ^{90}Sr source are detected by the top MSGC, a second MSGC (bottom) was mounted just under the top MSGC. After amplification, output signals from the bottom MSGC are fed into a discriminator and a gate generator. The gate output signals allow the pulse height analyzer to store only those pulses from the top MSGC that are coincident with events in the bottom MSGC. The gate output signals are also fed into a scaler to count the number of coincidence events. The gas gap between the drift plane and anode-cathode plane was either 2 or 4 mm for the top MSGC, while for the bottom MSGC it was fixed at 4 mm. In our measurements, we used a gas mixture of Ar-ethane (50/50).

Fig. 6.5 Experimental layout for measurements of the electron multiplication factor and the detection efficiency of the columnar CsI layer. Two identical MSGCs were used for coincidence measurements.

6.4 Results and Discussion

6.4.1 Electron Multiplication Factor

The electron multiplication factor due to the columnar CsI layer was measured as a function of the voltage applied across the CsI layer, $\Delta V_{\text{csi}} (= V_d - V_{\text{csi}})$, where V_d and V_{csi} are voltages applied to the drift plane and to the Si-substrate of the CsI layer. The electron multiplication factor due to the CsI layer is defined as the ratio of signal pulse amplitude produced when V_{csi} is turned on to that produced when the V_{csi} is turned off (i.e. $\Delta V_{\text{csi}} = V_d$), and is expressed as:

$$\frac{\text{PH (CsI)} + \text{PH (Gas)}}{\text{PH (Gas)}} \quad (6-5)$$

where, PH (CsI) is the signal pulse amplitude produced both by secondary emission due to the incident particle and by gas amplification within the columnar CsI layer, and PH (Gas) is that produced by gas amplification in the gas volume. We used two kinds of columnar CsI layers of 200 μm thickness: pure CsI and thallium-doped CsI (CsI(Tl)). Figure's 6.6 and 6.7 show oscilloscope traces and pulse height spectra of the ^{90}Sr source from the top MSGC coupled with the pure CsI layer, for (a) $V_{\text{csi}} = 0$ and (b) $V_{\text{csi}} = -1600$ V, at fixed anode and drift voltages of 460 and -200 V, respectively. The ^{90}Sr pulse height spectra measured from the top MSGC were gated by the bottom MSGC. The noise spectrum was also measured by removing the source from the detector; this was small, and was subtracted from the ^{90}Sr spectra. The output signal is not just CsI "noise", because the signal completely disappeared when the source was removed from the detector. These measurements indicate that electron multiplication subsequently occurs within the columnar CsI layer when it is activated, greatly enhancing signal pulse amplitudes over the conventional signal coming from the ionization in the gas drift region. As an estimate of the electron multiplication due to the CsI layer, we calculated the centroid of the ADC top 10%, $\tilde{x}$, from the measured ^{90}Sr spectra, and is defined as:

$$\tilde{x} = \sum_{i \geq 90\%} x_i y(x_i) / \sum_{i \geq 90\%} y(x_i) \quad (6-6)$$

Here x_i is the ADC channel number, and $y(x_i)$ is the corresponding number of counts in the measured ^{90}Sr pulse height spectra. In this calculation, we used only top 10% of the ^{90}Sr pulse height spectra in order to minimize certain spurious effects, such as those related to the very large multiple scattering of the β -particles at low energies (~ 1 MeV) in the CsI layer and detector substrate.

Figure 6.8 shows the estimated electron multiplication factor, based upon this calculation, of the pure CsI and CsI(Tl) layers as a function of $\Delta V_{\text{csi}} (=V_d - V_{\text{csi}})$. The thickness of each layer was 200 μm and the gas gap was 4 mm. A large electron

(a)

(b)

Fig. 6.6 Oscilloscope traces of the ^{90}Sr source from the top MSGC coupled with a pure CsI layer at $V_a = 460$ V and $V_d = -200$ V, for (a) $V_{\text{csi}} = 0$ and (b) $V_{\text{csi}} = -1600$ V, using a gas mixture of Ar-ethane (50/50). The gain and shaping time of the amplifier were 200 and 2 μsec , respectively. The CsI “signal” is not just “noise”, because the signal completely disappeared when the source was removed from the detector.

multiplication factor was measured by applying an appropriate potential across these thin layers (e.g. > 1300 V for the pure CsI, > 1900 V for the CsI(Tl)). Signal pulse amplitudes for the pure CsI layer were enhanced by more than a factor of 35 over the conventional signals coming from the gas drift region at $\Delta V_{\text{csi}} = 1500$ V, while for the CsI(Tl) layer, by more than a factor of 25 at $\Delta V_{\text{csi}} = 2200$ V. For higher values of ΔV_{csi} , the power on the

Fig. 6.7 Pulse height spectra of the ^{90}Sr source from the top MSGC coupled with a pure CsI layer of a $200\text{ }\mu\text{m}$ thickness at $V_a = 460\text{ V}$ and $V_d = -200\text{ V}$, for $V_{\text{csi}} = 0$ and -1600 V , using a gas mixture of Ar-ethane (50/50). The noise spectrum was measured by removing the source from the detector, and this was subtracted from the ^{90}Sr spectra.

Fig. 6.8 Electron multiplication factor due to the CsI layer with respect to ΔV_{csi} , based upon the top 10% centroid calculation from the measured ^{90}Sr pulse height spectra, using a pure CsI and a CsI(Tl) columnar layer of a $200\text{ }\mu\text{m}$ thickness.

Fig. 6.9 Electron multiplication factor due to the CsI layer for two different gas gaps of 2 and 4 mm with respect to ΔV_{csi} , using a pure CsI columnar layer of a 200 μm thickness.

CsI layer tripped off due to electrical breakdown between the Si-substrate of the CsI layer and the drift plane, which did not seem to harm the CsI layer: the CsI layer performance appeared to be the same after the breakdown. For a given ΔV_{csi} , the pure CsI gave a much larger electron multiplication factor than that obtained with the CsI(Tl), and was even able to operate at low voltages for which the CsI(Tl) would not yet be activated. This result suggests that the gain mechanism for the two different CsI layers are somewhat different.

Figure 6.9 shows the electron multiplication factor due to the CsI layer measured for two different gas drift gaps of 2 and 4 mm, with respect to ΔV_{csi} , using a pure CsI columnar layer of a 200 μm thickness. As expected, the reduced gas drift gap of 2 mm gave larger electron multiplication factor by about a factor of two than the 4 mm gap, at $\Delta V_{\text{csi}} = 1500 \text{ V}$. Reducing gas drift gap should lead to an even further significant improvement in spatial resolution, since the present limitation on the spatial resolution

Fig. 6.10 Efficiency for detection of the β -rays from the ^{90}Sr source measured with respect to the incident particle dip angle, using a pure CsI layer of a $200\text{ }\mu\text{m}$ thickness.

imposed by diffusion in the gas can be substantially decreased by reducing the electron drift distance. Similarly, there may be some improvement in time resolution due to a smaller drift region.

6.4.2 Detection Efficiency

Figure 6.10 shows the measurement of the efficiency for the detection of β -rays from the ^{90}Sr source with respect to the incident particle dip angle, using a $200\text{ }\mu\text{m}$ thick pure CsI layer. The efficiency was determined by measuring count rates of the top and bottom MSGCs in coincidence. The measured efficiency did not decrease significantly up to at least 30° , which suggests that electron production in the columnar CsI layer is large enough to insure nearly 100% efficiency, even though our measurement, using the ^{90}Sr β -source, is somewhat crude. For a precise measurement, it will be necessary to use a test beam, instead of the ^{90}Sr β -source, because of the effects of the very large multiple

scattering of the β -particles at these low energies (~ 1 MeV) in the CsI layer and detector substrate.

6.5 Summary

A thin (~ 200 μm) columnar CsI layer, as an efficient secondary electron emitter, has been added to the drift plane, in order to improve the space and time resolutions, and the detection efficiency, with respect to the angle of incident particles, for gas avalanche microdetectors. Another advantage of this method is that with the enhanced electron yield from the CsI layer, it may be possible to reduce the gain (and voltage) of the gas avalanche microdetectors, thus reducing the risk of sparking. All of these are important for a significant improvement of the operation of the gas avalanche microdetectors.

We estimated the electron multiplication factor due to the columnar CsI layer, which is defined as the ratio of signal pulse amplitude produced within both the CsI layer and the gas drift region to that produced within the gas drift region, for two different CsI layers (i.e. pure CsI and CsI(Tl) layers), and for two different gas drift gaps (i.e. 2 and 4 mm). The electron multiplication within the CsI layers subsequently occurred when they were activated, greatly enhancing signal pulse amplitudes over the conventional signal from the gas drift region, by more than a factor of 35 for the pure CsI, and by more than a factor of 25 for the CsI(Tl). As expected, reducing the gas drift gap to 2 mm gave a larger electron multiplication factor of the CsI layer, by about a factor of two, relative to the 4 mm gap, using a pure CsI columnar layer of a 200 μm thickness. Reducing gas drift gap should lead to an even further improvement in spatial resolution, since the present limitation on the spatial resolution imposed by diffusion in the gas can be substantially decreased by reducing the electron drift distance.

The efficiency for the detection of β -rays from a ^{90}Sr source was measured with respect to the incident particle dip angle. The detection efficiency did not change

significantly up to at least 30° , suggesting that electron production in the CsI layer is large enough to insure nearly 100% efficiency over a complete range of incident particle angles. For a more precise measurement, it will be necessary to use a test beam, instead of the ^{90}Sr β -source, to avoid effects of multiple scattering at the low energies available from β -sources. Measurements of the space and time resolutions were beyond the scope of these investigations and were not attempted, but are very important for the continuing study of this technique.

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Chapter 7 Summary

Interests in gas avalanche microdetectors such as the microstrip gas chamber (MSGC), the microgap gas chamber (MGC) and the microdot gas chamber (MDOT) have continued to increase, being aware of the potential of such detectors to solve the challenges imposed by the next generation of experiments, especially in nuclear and high energy physics, that require detectors capable of operating with very good resolutions at very high radiation detection rates. Although the principal activity in this area is still in Europe, there has been continuing development in the design and performance of these gas microdetectors at Lawrence Berkeley National Laboratory (LBNL) over the past few years. The objectives of this research were to improve the gas avalanche microdetectors beyond their present capabilities, to produce detectors suitable for use in current or upcoming experiments, and to allow a basis for new R&D developments which may incorporate these microdetectors as part of the system.

The MSGC, which was motivated by the pioneering work of A. Oed, has many attractive features, especially very good spatial resolution ($\sim 30 \mu\text{m}$ rms at normal incidence) and high rate capability ($\sim 10^6 \text{ mm}^{-2}\cdot\text{s}^{-1}$). Moreover, the MGC seems to have certain advantages over the MSGC in speed, stability and simplicity, and the MDOT has the intrinsic advantages of gain and two-dimensional readout. Because of these attractive properties, the gas avalanche microdetectors have received a great deal of attention for nuclear and high energy physics experiments, medical X-ray imaging and many other fields requiring radiation detection and measurement. Their introduction is certainly the most important development in the field of gas avalanche detectors made in the last decade.

However, although the gas avalanche microdetectors have distinct advantages over other types of detectors, they have not yet reached the state-of-the-art in which reliable detectors can be designed and built for the demanding experiments. Therefore, the main

concern of this dissertation was to investigate the operating characteristics and the design criteria of these gas microdetectors for a stable and safe operation, focusing on their possible problems such as : (a) sensitivity to the electrical properties of the substrate material (e.g. polarization and surface charging effects in the MSGC), (b) relatively low gain, compared with conventional wire chambers, (c) radiation-induced damage (aging), limiting their useful lifetime, (d) vulnerability to spark damage, etc.

Methods for obtaining stable and large gains in the gas avalanche microdetectors have been a continuing subject of investigation in this research. A new technique used in this work involved the successful use of doped amorphous silicon carbide (a-Si:C:H) as a conductive surface coating in the MSGC fabrication, to eliminate the effect of charge accumulation on the substrate surface without disturbing the operation of the detectors in any way. The doped a-Si:C:H film is a conductive surface coating that works well, and is an attractive alternative to other surface treatments of the substrate: its resistivity can be easily controlled over a wide range by doping, it is radiation-hard and stable with time, and a large area can be coated at relatively low cost.

Increasing gas gain is desirable for the safe operation of the gas avalanche microdetectors, which gives a sufficient safety margin between the operating voltage and the appearance of sparking, and also provides a good signal-to-noise ratio for the detection of minimum ionizing particles. In the MGC, it is possible to increase gain by increasing the thickness of the insulating pedestal that supports the anode strip, thus increasing the avalanche distance. Amorphous silicon carbide (a-Si:C:H) was also found to have useful application as an insulating pedestal material. It was shown that doubling insulator thickness increased gas gain by about 40%. Although somewhat less gain was achieved than with nearly equal thickness of SiO_2 , it was much easier to make thicker a-Si:C:H pedestals and thus achieve larger gain. Different types of insulating materials (e.g. polyimide, Si_3N_4 , etc.) deserve further study for optimum results. In the MDOT detector, it is also possible to increase gain by reducing electric field intensity near the cathode

edge for a given anode field intensity, thereby reducing the vulnerability to sparking (or equivalently, increasing the maximum gain): a gain of $\sim 10^4$ was achieved in a gas mixture of Ar-ethane (50/50), using our own MDOT design having a square geometry. The gas gain depends on gas composition, and there is the possibility that a larger gain may be obtained when a gas mixture with a larger fraction of, and a more effective quenching gas, is chosen.

Radiation-induced damage (aging) is one of the most important outstanding issues for a long-term reliable operation of the gas avalanche microdetectors. We have performed systematic aging studies to understand the factors influencing the aging, the results of which have become progressively better, as more and more understanding of aging has been obtained. Recent aging rates obtained by us appear almost as good as the best obtained elsewhere, although with much lower integrated doses ($Q = 15\text{-}30 \text{ mC/cm}$). The aging phenomena need to be more clearly understood, however, before there can be complete confidence in using these microdetectors as major components in high luminosity experiments.

Spark damage, in conjunction with aging, is probably the most critical design problem remaining as an obstacle to more widespread use of the gas avalanche microdetectors. We began the systematic spark damage studies before the vulnerability to spark damage emerged as a serious problem in full-scale experiments in Europe. Increasing gas gain is one possible approach to a solution of the spark damage problem, providing a sufficient safety margin between the operating and the breakdown voltages. As another possible approach, we have investigated electrode metals themselves which are both highly robust against sparking and yet have sufficiently low electrical resistivity to permit larger sizes of detectors without excessive signal loss. The results of spark damage tests showed that there was a strong correlation between the damage and the spark energy, and also a large variation in the damage between different anode metals tested. Among the metals commonly used, Al and Au were “*poor*”, Ni was “*good*”, and

Cr and Ti/W (10%/90%) were “*very good*” with respect to the spark damage. Unalloyed tungsten, which has a high melting point (3410°C) and a sufficient low bulk resistivity ($\sim 5.3 \mu\Omega\cdot\text{cm}$) for signal transmission on large detectors, was also severely damaged by sparking, due to large peak ohmic heating which occurs with low resistivity anode strips. Most of the results for the spark damage tests in this research, as well as for the aging tests, were obtained using MGCs, but similar results are expected for MSGCs. This is especially true for the spark damage tests, where the vulnerability depends primarily upon the metal used, the anode cross sectional area and the energy in the sparking.

Other allied interests included pixellated gas avalanche microdetectors (MDOTs), which have the intrinsic advantages of gain and two-dimensional readout, and the use of a thin columnar cesium iodide (CsI) layer added to the drift electrode for improvement of space and time resolutions, and detection efficiency, by eliminating the sensitivity to the angle of incident radiation. We fabricated MDOTs having a square geometry, which exhibited much more gain ($> 10^4$) than can be expected from other types of gas avalanche microdetectors having a similar pitch. However, due to the existence of the readout stripline passing below the insulating surface, a fraction of the drift field lines defocused away from the anode dots, resulting in an insensitive region (dead zone). To reduce this effect, a new approach was tried: the isolation of the readout region from the drift region by means of a conductive ($\sim 2 \times 10^{13} \Omega/\square$) surface coating of doped a-Si:C:H. This coating technique appears to be effective in reducing the dead zone, although a significant dead zone may still be present after applying the coating (further examination of this point is needed). In the future, we hope to make more definitive measurements and to obtain a more detailed understanding through 3-D simulations.

Finally, a new technique has been proposed to improve the space and time resolutions, and the detection efficiency by eliminating the sensitivity to the angle of incident radiation, for the gas avalanche microdetectors. This method used a thin ($\sim 200 \mu\text{m}$) columnar cesium iodide (CsI) layer, to provide a higher probability for secondary

electron emission, and also to allow an electron multiplication mechanism within the CsI layer. Another advantage of this method is that with the enhanced electron yield from the CsI layer, it may be possible to reduce the gain (and voltage) of the gas avalanche microdetectors, thus reducing the risk of sparking. Our measurement showed that the electron multiplication subsequently occurred within the columnar CsI layer when it was activated, greatly enhancing the signal pulse amplitudes over the conventional signal coming from the ionization in the gas drift region. For a precise measurement, it will be necessary to use a test beam, instead of the ^{90}Sr β -source, to avoid possibly important effects of multiple scattering at the low energies available from the ^{90}Sr β -source.

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY
ONE CYCLOTRON ROAD | BERKELEY, CALIFORNIA 94720

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