DEVELOPMENT OF MICROSTRIP GAS CHAMBERS FOR RADIATION DETECTION AND TRACKING AT HIGH RATES
FINAL STATUS REPORT

Presented by F. Sauli at the LHCC open meeting, March 13, 1996*

1. INTRODUCTION

Micro-Strip Gas Chambers (MSGCs) have attracted a lot of interest since their introduction by A. Oed [1] due to many promising features: good position accuracy and two-track resolution, high rate capability and low cost. However, medium and long-term stability problems have been met at high radiation rates attributed to substrate charging up and modifications, and ageing due to gas polymerization. To co-ordinate the research on MSGC by various groups, many of them working on tracking devices for the LHC experiments, a proposal for research on micro-strip gas chambers was submitted to the DRDC and approved by the Research Board as RD-28 on June 30, 1992. After three years of collaboration, we can consider the generic R&D on MSGCs to be essentially completed; various groups are however continuing their development in the specific environment and with the constraints of the experiments or applications making use of the new detectors. The full length of the Status Report with a full list of collaborating physicists, institutions and all references can be found in Ref. 2.

2. THE MICRO-STRIP GAS CHAMBER

The basic micro-strip gas chamber (Fig. 1) consists of alternating thin metal strips, anodes and cathodes, typically 10 and 100 μm wide respectively, laid on an insulating support at a distance (pitch) of a few hundred microns. An upper drift electrode, at negative potential, delimits the sensitive gas volume where electrons are released by ionizing radiation. The back side of the support plate can also have a field-defining electrode; in some cases (for very thin substrates) the back-plane can be segmented in readout strips for two-dimensional localization. In the case of low resistivity substrates, the back plane electrode has no effect on the operation of the chamber and can be suppressed. Applying proper potentials to the electrodes, an electric field builds up such that electrons released in the drift space are collected and multiplied when reaching the anodes.

MSGCs have very promising features:

- proportional gains over 10^4 ;
- position accuracy for x-rays and perpendicular minimum ionizing particles of the order of 30 μm rms ;
- rate capabilities above 10^6 $mm^{-2}s^{-1}$;
- energy resolutions (10.7% FWHM for 5.9 keV X-rays).

Some stability problems were however met from the very beginning: gain modifications due to substrate polarization and charging up, and permanent deterioration (ageing) during sustained irradiation. The physical parameters used in manufacturing and to operate the detectors (substrate material, metal of strips, gas mixture and purity) appear to play a dominant role in determining the long-term stability of operation of the devices; the situation is complicated by the interdependence of the various parameters.

3. CHOICE OF THE SUBSTRATE AND HIGH RATE OPERATION

The choice of the substrate material is crucial to obtain a stable operation of the detector. The major properties to be considered are:

- Good surface quality and metal adhesion properties;
- Excellent surface rigidity to hold high voltage gradients;

- Moderate surface or bulk resistivity to limit surface charging up processes;

- Small support thickness and density to reduce multiple scattering and photon conversions, particularly in view of their use as tracking detectors for particle physics experiments;

- Long-term stability of performances in harsh operating conditions;

- Low cost and high reliability, particularly important parameters in view of a massive use in tracking detectors, embedded in set-ups with very limited accessibility.

Most commercially available insulators with good surface quality have a very high resistivity, above 10^{16} Ω cm, and an ionic type conductivity; it has been found by many groups that this results in operating instabilities of the MSGCs immediately after power on and during irradiation. These effects are attributed to the modification of the electric field by substrate polarization following the application of the potentials on electrodes, and to charging up of the insulator between strips due to the accumulation of electrons and ions, produced in the avalanches, on the surface of the support.

The initial decrease of gain at power on and the bizarre field-dependent behavior of the rate capability, first reported by the CERN group, have been confirmed by the NIKHEF and RAL groups. It is clearly a consequence of polarization effects on the dielectric inducing a time-dependent modification of the field map. While for moderate radiation fluxes use of high resistivity supports can be considered acceptable, and in fact has been adopted for example for the HERMES experiment, the behavior shown can obviously be a source of serious operating instabilities at higher rates.

Another, longer term modification of gain in MSGCs made on boro-silicate glass and exposed to high radiation fluxes has been reported: during sustained irradiation with X-ray sources realized to study the ageing properties of the chambers, a local decrease of gain is observed, recovering however with time towards the original after removal of the source. One should keep in mind that this long-term, recoverable gain modification overlaps to and can be confused with the permanent ageing due the formation of polymers in the gas; it can only be identified in runs realized in very clean conditions, analyzing the gain behavior after stopping the irradiation.

It is generally recognized and experimentally demonstrated that the use of a substrate with lower resistivity and electronic conductivity eliminates the initial polarization effects and the subsequent surface charging processes up to very high rates; in general one also obtains a more stable operation and a reduced ageing rate, if any. The best results in terms of long-term stability at high rates have been obtained with electron-conducting glass, with bulk resistivity in the range 10^9-10^{12} Ω cm, custom-made (the so-called Moscow glass developed by the BINP (Budker Institute of Nuclear Physics)-Novosibirsk), or commercial (S-8900 by Schott). Recently, the BINP group has reported the successful completion of the development of large size, thin electron conducting glass suitable for MSGC manufacturing; the first chambers realized on this glass are delivered at CERN for a long-term beam test set-up in the framework of the CMS tracking group development. The IP (Institute of physics)-Prague group has also developed electron-conducting glass and studied its morphological and electrical properties; Fig. 2 shows an example of measured temperature dependence of the volume resistivity of two types of glass, compared to the commercial Schott S-8900. MSGCs have been built on this glass and successfully operated.

Several methods of conditioning insulating supports to obtain the desired surface resistivity in the range 10^{14}-10^{15} Ω/square have been developed and tested by RD-28 co-operating institutions. In a natural extension of the methods developed in semiconductor industries, several studies of ion implantation or doping by diffusion have been used. The evolution of the gain under continuous irradiation measured with MSGCs manufactured on regular and ion-implanted D-263 glasses shows a much better behavior of the implanted plate;

there is however a small residual gain loss due to charging up or to some other surface-modifying mechanism.

Chemical Vapor Deposition (CVD) of thin diamond-like layers is a well known industrial technology, used both for hardening mechanical components or, more recently, to manufacture ionization detectors. The use of CVD diamond coatings to reduce surface resistivity was suggested long ago by the WIS group (Weizmann Institute of Sciences, Israel), but the standard method appeared not to be able to provide the high values of resistivity required. Recently, the CERN group has found a private research laboratory having this know-how, and able to provide thin coatings in the range 10^{12}-10^{14} Ω/square. The method (Low Pressure Plasma Assisted Chemical Vapor Deposition, LPCVD) is fast and cheap enough to be a valuable alternative to the use of semi-conducting glass, and allows to coat uniformly a wide range of materials over extended areas. For this particular run, the average value was $1.5 \pm 0.3\ 10^{15}$ Ω/square. Diamond coated plates have been extensively tested by the CERN group, and appear to be uniform and stable in the medium term. Large area (100x100 mm^2) MSGCs have been built on diamond-coated glass both with chromium and gold strips, and exhibit excellent rate capabilities as well as ageing properties. Fig. 3 shows the completely flat response of the chambers exposed to high rate x-ray fluxes, up to 2.10^6 counts $mm^{-2}s^{-1}$ at an avalanche size of about 10^5 electrons.

Direct deposition over an insulating support of an electron-conducting glass layer, obtained by sputtering bulk conducting glass, has been developed by the RAL (Rutherford Appleton Lab) group in collaboration with industry. Although promising results have been obtained in terms of rate capability and ageing properties of MSGCs manufactured on plates coated by S-8900 glass, the method has provided so far a fair uniformity of resistivity over extended areas, a known limitation of fixed-target sputtering. However, due to the moderate dependence of gain on surface resistivity, MSGCs manufactured on sputtered glass exhibit an acceptable gain uniformity and energy resolution; the rate capability is largely enhanced, a characteristic of the electron-conducting supports. The ageing behavior is also improved; work is in progress to improve the manufacturing by using larger area or mobile sputtering targets.

Other technologies for surface resistivity control by thin-layer coating have been explored. The LPI (Lebedev Physical Institute)-Moscow group has reported results obtained with ion-beam sputtering of semi-conducting glass and amorphous hydrogenated silicon, as well as low pressure chemical vapor deposition (LP CVD) of amorphous hydrogenated carbon. One characteristic property of some layers is a variation of the bulk resistivity with the electric field; the effect of this behavior on the operation of the detectors remains to be investigated. Moreover, a strong dependence of the resistivity from the light conditions has been observed, particularly for the amorphous silicon layers, another feature requiring thorough investigation.

Over-coating, covering an existing MSGC structure with a thin resistive layer, has also been tried by several groups. Intrinsically simpler, since it avoids possible adhesion problems that can be met when manufacturing the chamber, the acceptance of an over-coat solution depends however on the long-term stability of the thin layer, that acts as interface between the gas and the electrodes and can be damaged by the electron and ion currents, as well as by the reactivity of the various molecular species present in the avalanche. Promising results have been reported by the TRIUMF group using several metals, sputtered in argon over standard MSGCs made on Kapton. As already reported in previous studies, the best results have been obtained with nickel; although evolving with time, the value of resistivity appears to stabilize after a month or so from fabrication. The rate capability of chambers over-coated (or passivated, in the author's language) is excellent demonstrating that in the short term the presence of the layer above (as against below) the conductors has a similar role in preventing surface charging up. In several long-term irradiation exposures, the group has demonstrated also stability of operation up to large collected charges. Less promising results have been reported by the CERN group, observing a systematic degradation of all over-coated structures tested so far when subjected to long-term irradiation.

Continuing its work on advanced thin-film coating technologies, the INFN-Legnaro group has developed a new deposition method to prepare polyimide over- or under-coatings in order to reduce the surface resistivity. Using a vapor deposition polymerization, the group has been able to produce thin polymer layers of accurately controlled thickness; uniformity within a few percent over 80 mm has been demonstrated. The method has been used to realize the passivation of the ends of strips in a MSGC, in order to prevent the well known problem of discharges.

4. MSGC OPERATION

Operating parameters and features of MSGCs such as gas gain, space and energy resolution, signal characteristics, noise and discharge rate have been studied by varying gas mixtures, working potentials, geometrical parameters like the gap, pitch, width of the electrodes, support thickness and potential of the back electrode (if present). In general, the best results in terms of gain and stability of operation have been obtained using mixtures of argon-DME, neon-DME and CO_2-DME in comparable percentages, or pure DME. Other gases used within the collaboration include mixtures with CF_4, a gas known to prevent or even cure ageing processes in multi-wire chambers; some doubts persist however on the effects in the long term of the etching properties of CF_4, as well on the production of electro-negative long lived free radicals in the avalanches.

In an extended study that included, aside from the experimental measurements, also the development of a model for the appearance of discharges, the CERN and BINP groups have analyzed the optimum geometry of MSGC allowing to reach high stable gains. Fig. 4 shows a set of gain curves measured with MSGC plates having identical geometry (7 µm anodes and 200 µm pitch), and different cathode strip widths; an optimum seems to be reached for a width close to 90 µm, a "filling" ratio (metal to insulator) of around 50%. A detailed study of the single electron noise spectra close to the maximum gain seems to confirm the hypothesis that discharges are triggered by an increase in the number of avalanches initiated by electrons released at the cathode edge by ion bombardment or field effect. In view of the strong dependence of the electron emission probability on the electric field and on the work function of the metal used for cathodes, one would expect a large variation in the maximum gain safely reached depending on the manufacturing technology (affecting the detailed shape of the edges) and perhaps the nature of the electrodes. Indeed, maximum gains reached in practice vary from less than a thousand to more than 10^4; the comparison is however often difficult because of the tendency by various groups to only quote relative gain values. Fig. 5 shows a comparative set of absolute gain measurements in different gas mixtures, recently realized by the WIS group in a search for non-flammable alternatives to the most popular choices.

A critical test for the quality of MSGCs is their behavior in presence of heavily ionizing radiation, such as the one generated by neutron-induced reactions at LHC. Recoil protons or activation gamma can easily release in the gas several hundred keV, as against the few keV produced by minimum ionizing particles. The CERN-BINP-MSU groups have observed that in presence of heavily ionizing tracks (α particles from an ^{241}Am source) the maximum safe operating gain is reduced. The CERN-BINP groups have started a systematic investigation on the maximum gain attainable in MSGCs made with chromium and gold strips on electron-conducting substrates and with various operating gases.

The dependence of gain on temperature, another factor affecting the stability of operation, has been studied by the CRN-Strasbourg group. The variation is small, and can be attributed to the change in the gas density. For detectors manufactured on conductive substrates, a change in resistivity with temperature induces another element of variation; as most electron conducting glasses have a negative temperature coefficient, one would expect (equal being the operating voltage) the gain to decrease with temperature, an opposite trend from the one due to the gas itself.

Various other studies have been reported concerning the effect on MSGC substrate and metals of high radiation levels. The CRN-Strasbourg group has systematically investigated the effect of radiation in boro-silicate glass analyzing the density of radiation-induced defects in the bulk with the Electronic Para-Magnetic Resonance method.

The UC-London-RAL groups have studied the effect of neutron irradiation on MSGC, both experimentally and theoretically. Exposing a MSGC made on S-8900 glass to an intense neutron beam at the ISIS spallation facility at RAL, the authors have measured the induced energy spectra and compared with Monte-Carlo simulations. A more extensive work estimating the contribution of the major neutron-induced reactions has been presented at the Lyon workshop and suggests a considerable contribution to background noise of the various processes; the choice of materials for MSGC manufacturing, of the strip's metal and of operating gas may play a critical role in the background levels, and should be thoroughly investigated by the LHC groups.

Several alternatives are possible for the metal used for the strips, depending on the manufacturing technology: aluminum, chromium and gold are the most common choices. Various arguments have been proposed in favor or against each choice, such as the conductor resistivity and the long-term ageing behavior; the final choice depends on the expected operating conditions and on cost considerations. The CERN-BINP group has investigated in detail the properties of MSGCs made with chromium, a good choice in terms of the excellent quality of the photolithography and low costs, but limited to relatively short strip lengths due to signal attenuation, and possibly more sensitive to ageing in presence of pollution .

5. AGEING

Ageing, or fast degradation of the performance of the detectors during irradiation, is the most serious problem encountered with MSGCs and has been extensively studied experimentally. Permanent damage of the plates has been associated with the production in the avalanches of polymeric compounds, sticking to the electrodes or to the insulator, and perturbing the counting action and inducing discharges. MSGCs have been found to be particularly prone to ageing, possibly because of the small effective area used for charge multiplication; some gases (hydrocarbons) induce very fast ageing, while others like dimethylether (DME) and carbon tetra fluoride (CF_4) allow extended lifetimes.

A careful selection of the operating gas and materials used in manufacturing appears mandatory to guarantee survival of the devices in a high radiation environment. A systematic study of outgassing properties of various materials considered as construction elements for chambers has been performed with the CERN RD-10 set-up, which includes an X-ray long-term irradiation facility and gas monitoring system (a combined mass spectrometer-gas chromatograph). The set-up allows to make long-term exposures to radiation with continuous monitoring of currents, pulse heights and physical conditions both in the test chamber and in a monitor counter; materials under test can be an integral part of the chamber construction, or introduced in a “reaction” box in the gas line. Similar set-ups for studying long-term operation of detectors under sustained irradiation have been built at LIP-Coinbra and LPPE-Mons.

A systematic investigation of ageing under sustained irradiation has been performed by several groups within the collaboration using MSGC plates manufactured on various substrates and operating conditions. In optimal laboratory conditions, a long-term survival without degradation up to a collected charge above 100 mC cm^{-1} has been demonstrated, corresponding (at an avalanche size of $2 \cdot 10^5$ electrons) to a radiation dose for minimum ionizing particles of 10 MRad, or more than 10 years of LHC operation at maximum luminosity. One example is provided in Fig. 6, obtained with a chamber made with chromium strips on electron-conducting glass, and using as construction materials those recommended by previous outgassing studies.

The majority of ageing tests is realized, for practical reasons, exposing the detector to a high intensity X-ray flux, and accelerating the experiment taking as normalization factor the total collected charge per unit length of strips. It has been found however by the CERN group that, at least when using boro-silicate glass supports, use of excessively large radiation rates (current densities) results in an optimistic estimate of the ageing rate. This is illustrated in Fig. 7, result of a set of measurements realized in different positions on the same plate at several values of flux. While no gain modifications appear at high current densities, substantial ageing is seen at the lower values. While the exact mechanism of this behavior is not clear, the observation invalidates some previous measurements realized at excessive current densities and casts a general doubt on the adequacy of accelerated ageing tests. Based on this observation, the group recommends to use, for the systematic tests, current densities not exceeding 10 nA mm^{-2}, an acceleration factor of 20 compared to LHC rates; a final verification at rates closer to real would however seem mandatory.

It appears that, together with the purity of the gas system, dominant factors in determining ageing rate are the nature of the support and the metal used for the strips; the strength of the drift field also seems to play a role. The NIKHEF group, using D-263 glass, has observed a clear improvement replacing aluminum with copper, gold and nickel for the strips. It is suspected that long-term modifications or charging-up of the boro-silicate glass play a role in explaining the observed behavior. This is confirmed by the observed recovery from "ageing"; one could speculate that the different ageing rates for different metal could be due, at least in part, to the different surface conditions of the plates, an outcome of the manufacturing process. The dominant role of a moderate surface resistivity in determining the gain stability is demonstrated by measurements realized by the same group on a MSGC manufactured on D-263 sputtered with S-8900 electron conducting glass, showing a much better performance up to several mC cm^{-1}.

The RAL group has also systematically investigated the role of metals and supports on the ageing rates. The large difference in ageing rate was measured on two MSGCs manufactured in aluminum and gold on electron-conducting glass. The same group has recently reported the good ageing properties of detectors made on boro-silicate glass, sputtered with a thin layer of low resistivity S-8900 glass; gold strips behave considerably better than aluminum and allow to reach the 100 mC cm^{-1} benchmark with a moderate 10% gain loss .

Measurements realized by the CERN group on chambers manufactured on diamond coated glass have also confirmed the dominant role of the low substrate resistivity in determining ageing behavior. A detector made with chromium strips and irradiated at moderate current density (9 nA mm^{-2}) could reach 80 mC cm^{-1} without gain deterioration . It should be noted that the measurement was realized with a standard gas system set-up, without the strict cleanliness requirements of the dedicated laboratory of the same group.

6. RD-28 MAJOR ACHIEVEMENTS AND CONCLUSIONS

In the three years since the approval of the RD-28 project, the collaboration has expanded from the original number of 40 proponents to 170 physicists and engineers from 40 institutions. A large number and variety of prototype MSGCs have been manufactured and successfully tested in the laboratory and in beams; some have been incorporated in experiments and have already contributed to the improvement of the results. It has been demonstrated that a reasonably good operation at moderate rates can be obtained with supports made on commercially available boro-silicate glass, such as D263, that can be obtained in a wide range of thicknesses, and confirmed that intrinsically more stable operation can be obtained with chambers made on slightly conductive supports. The development of special electron-conducting thin glass, with bulk conductivity in the range 10^9 to 10^{12} Ω cm, and of various surface conditioning methods to reduce resistivity to around 10^{15} Ω/square has been successfully completed; a new technology for diamond-like coating seems to be particularly successful.

The conditions necessary to guarantee the lifetime of the detectors at high radiation rates suitable for the LHC experiments have been determined, with integral collected charges in accelerated laboratory tests exceeding 100 mC cm^{-1}, equivalent to ten years of operation in vertex detectors at LHC. The major role of using low resistivity substrates in reducing the ageing rate has been established.

The operating characteristics of the MSGCs have been experimentally measured and predicted using computer simulations, developed to better understand some properties of the detectors and allow the optimization of their design.

Basic manufacturing techniques have been investigated and tested in view of establishing the criteria for a cost effective large scale production; while gold remains the best choice material for the strips, due to its low resistivity and better resistance to ageing, the alternative choice of chromium (an intrinsically cheaper and better known technology) has undergone careful investigations to clarify the size limitations due to the resistivity of the metal, and the possible enhancement of ageing processes.

Various readout schemes and highly integrated electronics circuits, originally developed for solid state detectors to be used at LHC, have been tested, both at the basic level and on detectors operating in realistic conditions; analysis of the data aimed at improving the time resolution has suggested the best strategy for bunch crossing identification.

Special devices have been successfully developed, such as thin plastic MSGCs for transition radiation detectors, plates with non-parallel (keystone) geometry, very thin layer detectors for two-dimensional readout, photon-sensitive and scintillating chambers. Charge multiplication with MSGCs in liquid xenon has been demonstrated.

Micro-strip gas chambers are now integral constituents of several present and future detectors, such as HERMES and CMS; the teams involved in the basic research are now integral part of those experiments.

The members of the RD-28 collaboration consider the generic research on micro-strip gas chambers to be successfully completed, and do not request therefore a continuation of the project. The present is therefore the final status report of the RD-28 collaboration.

REFERENCES

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[2] F. Sauli, RD-28 Status Report: CERN/LHCC 96-18, LDRB Status Report/RD-28, February 14, 1996.

* The Status Report was considerably shortened by editor (J.V.) for the puposes of the ICFA Bulletin.