A UV light photo-detector based on a MicroGap Chamber with single electron response

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Abstract

A MicroGap Chamber (MGC) used as a fast UV light detector with single electron sensitivity is presented. The detector has a semitransparent or reflective CsI photocathode, 100-200 μm anode pitch and 2-D capability. It works with gas mixtures based on DME and light noble gases at atmospheric pressure. A gas gain $>10^6$ has been achieved with a two-stage gas amplification ($G > 10^2$ in the drift region and $G \approx 10^4$ in the strip region). The use of light noble gases, like Neon, has brought to a sensible reduction of VUV light output (hence photon feedback) during electron multiplication in gas. Due to the very thin gap (5 μm) a very large fraction of the avalanche charge is quickly delivered to the fast amplifier (20 ns peaking time) thus improving the single electron detection capability of the MGC. Because of its higher gain the MGC with a semitransparent CsI photocathode provides a better single electron detection efficiency ($>90\%$) than the MGC with a reflective photocathode. This latter, vice versa, has a higher quantum efficiency and a faster response.

Experimental results on gas gain, drift properties, positional sensitivity and single electron detection efficiency are reported.

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Abstract

A MicroGap Chamber (MGC) used as a fast UV light detector with single electron sensitivity is presented. The detector has a semitransparent or reflective CsI photocathode, 100-200 μm anode pitch and 2-D capability. It works with gas mixtures based on DME and light noble gases at atmospheric pressure. A gas gain $>10^6$ has been achieved with a two-stage gas amplification ($G > 10^2$ in the drift region and $G \approx 10^4$ in the strip region). The use of light noble gases, like Neon, has brought to a sensible reduction of VUV light output (hence photon feedback) during electron multiplication in gas. Due to the very thin gap (5 μm) a very large fraction of the avalanche charge is quickly delivered to the fast amplifier (20 ns peaking time) thus improving the single electron detection capability of the MGC. Because of its higher gain the MGC with a semitransparent CsI photocathode provides a better single electron detection efficiency ($>90\%$) than the MGC with a reflective photocathode. This latter, vice versa, has a higher quantum efficiency and a faster response.

Experimental results on gas gain, drift properties, positional sensitivity and single electron detection efficiency are reported.

1. Introduction

The possibility of coupling modern gas detectors, like the MicroStrip Gas Chamber (MSGC) and the MicroGap Chamber (MGC), to efficient light or charged particle convertors for the detection of UV photons, low energy X-rays or minimum ionizing particles, has recently arisen a wide interest in the scientific community.

Low pressure MSGCs equipped with such convertors have been built by Anderson et al. and Breskin et al.[1,2], while a MSGC with a reflective photocathode working at atmospheric pressure has been introduced by Zeitelhack et al.[3]. Though in both cases reasonably good performances have been obtained there are still some limitations. Low pressure detectors have the disadvantage that they are not very easy to build. They must

be leak tight and equipped with thick windows. The main drawback coming from MSGCs with a reflective photocathode is the rather large geometrical inefficiency (40÷50%) of the photocathode itself. Indeed, the null or even repelling electric field on the wide insulating area between anode and cathode strips prevents to collect the photoelectrons from almost half of the detector area. The MGC, which is a full metal device, has on the contrary a geometrical inefficiency of only few percents ($\sim 2.5\%$ for a MGC with $5\text{ }\mu\text{m}$ anode width and $200\text{ }\mu\text{m}$ pitch).

The detection of UV radiation, which means efficient response to single electrons, implies large gains in gas-filled detectors. Recent experimental results have shown the possibility to reach such high gains with a MGC by using mixtures of light noble gases and DME at atmospheric pressure [4]. Because light noble gases are much more difficult to excite than heavy noble gases, like Argon or Xenon, the VUV light output during the multiplication mechanism is strongly reduced. For this reason the detector can operate free from photon-feedback breakdown even at very high gain in the strip region ($>10^4$). Furthermore the very thin gap (few μm) typical of the MGC internal structure, allows to collect a large amount of avalanche charge in very short time ($\sim 20\text{ ns}$) thus improving the capability to efficiently detect single electrons even when working with fast electronics.

These results have driven us to design, build and test a UV light sensitive MGC with single electron response. As photon convertor a very thin layer of CsI has been chosen. Two different CsI photocathode configurations were tested: the *semi-transparent* photocathode and the *reflective* photocathode. Gas gain, single electron detection efficiency and position sensitivity have been studied for both cases.

2. The detector

A schematic view of the UV sensitive MGC* with two different depositions of the CsI photon convertor layer is shown in Fig.1a) and 1b). Basically the MGC structure is the same for both configurations: $1\text{ }\mu\text{m}$ thick aluminum self-aligned anode and cathode strips separated by a $5\text{ }\mu\text{m}$ thick insulator (the micro-gap), with a pitch of $100\text{ }\mu\text{m}$ for the reflective and $200\text{ }\mu\text{m}$ for the semi-transparent photocathode. The strip's width is $5\text{ }\mu\text{m}$ and the active area $25.6 \times 25.6\text{ mm}^2$.

The entrance window, 3 mm above the detection plane, is made of a quartz substrate (2 mm thick) onto which a $60\text{ }\text{\AA}$ thick Chromium layer or an aluminum mesh of $100\text{ }\mu\text{m}$ pitch (Fig.2) were alternatively deposited to define a drift cathode. For both kinds of drift cathode the measured transmission coefficient as a function of the UV wavelength is shown in Fig.3. The light transmission coefficient is slightly higher for the drift electrode equipped with the fine mesh.

* made by CSEM (Neuchatel, SWITZERLAND)

According to Fig.1 two different operational configurations for the UV photon conversion were adopted:

the *semi-transparent* photocathode, in which a 100 Å thick layer of CsI was homogeneously evaporated onto the Cr layer or the fine mesh under high vacuum conditions at $T \approx 60^\circ\text{C}$, and

the *reflective* photocathode, in which the same thickness of CsI was evaporated onto the MGC anode-cathode Al structure.

After evaporation the photocathodes were immediately enclosed under vacuum in a stainless steel flange for transport. The total time of exposure to air was only few minutes.

CsI has been chosen for its high quantum efficiency for UV photons, which has been widely demonstrated in literature [5,6,7,8,9], and because it is rather insensitive to air exposure and compatible with normal pressure operation.

The gas mixture used in the tests was Ne-DME (70/30 or 80/20). At the moment we are not yet well equipped for the precise measurement of the UV transmission coefficient of this mixture and of the CsI quantum efficiency at the high electric field values used in the tests. It has been extensively demonstrated in laboratory measurements [6,9] that gas and electric field play an important role in the determination of the CsI photoemission properties.

The choice of Neon as main filling gas is due to the high gain obtained recently by working with MGCs filled with gas mixtures based on light noble gases (Neon, Helium) at atmospheric pressure. As shown in Fig.4 very high gains in the strip region, up to $2.7 \cdot 10^4$, have been reached working with voltages considerably higher (490 V maximum) than those commonly allowed with Argon or Xenon based mixtures. This large gain is obtained using relatively small percentages of quencher (30% or less DME). This could be explained with the strong depression in Ne and He mixtures of UV photon feedback. The excitation potentials of Ne and He (16.6 eV and 19.8 eV respectively) are much higher than the excitation and ionization potentials of other, heavier, noble gases (for instance, 11.6 and 15.7 eV of Argon) and much higher than the ionization potential of the quencher (10 eV for DME). Being He and Ne rather difficult to excite, very little UV light is produced in these mixtures during the avalanche process. Furthermore, the presence of long-lived metastable states in light noble gases favours the channelling of the energy from the excited atom to a quencher molecule (Penning effect) [10] and thus a partial recovery of the energy spent into excitation of the noble gas. The result of this energy transfer is the ionization of the quencher molecule without re-emission of UV photons.

3. The experimental set-up

A schematic drawing of the experimental set-up is shown in Fig. 5. The chamber is illuminated with UV photons from a hydrogen discharge lamp (A) which is mounted on a rotating micrometer to align the spark that takes place between the electrodes with the direction of the strips of the MGC. A first quartz lens (B) and an adjustable diaphragm (C) allow to obtain a parallel beam which is then focused onto the entrance window (diameter of the spot varying from 1 to 5 mm) by a second quartz lens (D). Beyond this lens a series of filters* allows to reduce the UV intensity down to single photon counting at $\lambda=200 \pm 15$ nm. With no filters the intensity of the UV beam is such that the chamber can efficiently operate in ionization regime.

For calibration purposes the UV light from the lamp can be reflected by a simple quartz mirror (E) onto a photomultiplier tube (F) which measures, independently, the incident photon rate. The intensity of the beam was very stable during the tests.

A picture of the detector mounted on the printed circuit board is shown in Fig. 6. The outline of 8 large cathode strips is visible through the semitransparent window. The anode strip structure at 100 μm pitch is not visible.

According to the photocathode configuration under test, the MGC can operate in two different gas amplification regimes: i) single step mode, i.e. with proportional multiplication only around the thin anode strip for the *reflective* case and ii) two-step mode, i.e. with modest amplification ($G \approx 10\div 100$) also in the drift region [11], for the *semi-transparent* case. The total gain, $G_T = G_{\text{drift}} \times G_{\text{strip}}$, is tunable from a few 10^4 to 10^6 or even more. Due to the rather modest gain in the drift region, no instability or sparking has been observed. This mode of operation is, instead, rather sensitive to changes in temperature. The electronic chain used to read-out individually the anode signals comprises of a fast hybrid preamplifier (Laben 5231) mounted near the detector, a remote shaping amplifier and line receiver (Laben 5185) and a 12 bit ADC. The gain of the electronic chain was calibrated using a pulser and an input capacitor of known value.

A photograph of the anode signals produced by single photoelectrons is shown in Fig. 7. One should note the fast shaping time of the signals, which have ~ 20 ns peaking time. The wide spread in time and amplitude visible in the picture are due respectively to the duration of the light pulse, ~ 100 ns, and to the fluctuations of the gas gain.

4. The experimental results

The operation of the MGC with semitransparent CsI photocathode in two-step mode is shown in Fig. 8a. The collected charge is plotted at several anode-cathode voltages (V_{a-c}) as a function of the drift voltage ($V_{\text{drift}} - V_{a-c}$). In this mode a large variety of gas gains

* produced by ORIEL corp. (Stratford, USA)

can be reached because of the possibility to switch on the multiplication mechanism, separately or at the same time, in the strip and in the drift region. As shown in Fig. 8a for values of V_{drift} in the range 500 V÷2500 V, i.e. before multiplication in the drift volume, we observe a large increase of the collected charge for increasing $V_{\text{a-c}}$, even starting from very small values of $V_{\text{a-c}}$. This is a clear effect of gain only in the region around the strips. At higher drift fields, > 8 kV/cm for these mixtures, there is gas gain also in the drift region. Moreover, as it can be inferred by the increase of the slope in the upper curves of Fig. 8a between 500 and 2500 V, the increase of the drift field affects also the proportional gain in the small region around the anode-cathode strips.

Constant gain curves obtained with different settings of the potential at the drift cathode and at the strip cathode are plotted in Fig. 8b. The figure shows how the same gain can be reached with very different choices of working conditions.

The effect of the two-step and single-step amplification mechanism are compared in Fig. 9. The amplitude of the signals from one anode strip and from the sum of three neighbouring strips have been plotted as a function of the anode-cathode voltage, at two different values of V_{drift} : just under ($V_{\text{drift}}=2400$ V) and well above ($V_{\text{drift}}=3400$ V) the threshold of multiplication in the drift region. In Fig. 9 it is clearly visible not only the large increase in the overall gain due to the contribution of the drift gain, but also the difference in amplitude between single strip signal and signal of the sum, due to the spread of the charge over few strips when the multiplication takes place also in the drift space.

In the semitransparent photocathode configuration the photons converting in the CsI layer originate electrons all at the same depth in the chamber, i.e. at the convertor surface. The photoelectrons then travel the same path length before initiating the avalanche process at the collecting anode strip. By measuring the time lag between the trigger, which is supplied by the discharge lamp, and the anode signal we could measure the drift velocity in the mixture Ne-DME (70/30) as a function of the drift field for different values of $V_{\text{a-c}}$ (Fig. 10). The saturation of the drift velocity was reached at $E_{\text{drift}} > 3$ kV/cm. The highest drift velocity ($\cong 6$ cm/ μ s) was obtained by applying only 5 V between anode and cathode strips. Ne-DME are rather fast gas mixtures at this value of drift field.

Fig. 11 shows both the trigger (upper trace) and the anode signal (lower trace). At small values of the drift field and, correspondingly, at rather low value of the drift velocity, the small prompt anode signal due to the photoelectrons created directly at the Al cathode strip (used as low Q.E. photocathode) is distinguishable from the much higher signal due to the photoelectrons extracted from the CsI layer deposited on the entrance window and delayed by the drift time.

When working with the reflective photocathode the electrons are created, on the contrary, very close (< 50 μ m) to the anode strips. They are collected and immediately multiplied in the region of high field around the anode strips. In this configuration the

drift cathode potential was set equal to the cathode strip potential, so no field, and therefore no gain, was settled in the drift volume. A comparison of the signal amplitude between the reflective and the semitransparent photocathode as a function of V_{a-c} is done in Fig. 12. When the semitransparent photocathode was used, the amplification in the drift field was also switched off ($G_{drift}=1$) by lowering the drift potential to 2400 V. The higher signal amplitude obtained with the reflective photocathode can be explained partly by the difference in quantum efficiency, which is considerably lower for the semitransparent photon convertor, and partly by the difference of path length in the amplification region of the photoelectrons which provides a larger gain for electrons created at the back cathode.

The positional sensitivity of the MGC with reflective photocathode has been studied illuminating the detector with a high photon flux (≈ 300 electrons/spark). Histograms of the event charge distribution and of the center of gravity of such distributions, for a 200 μm shift of the chamber, are shown in Fig. 13 and 14 respectively. The r.m.s. of the centroid distributions is 20 μm . This value is an upper limit of the overall positional sensitivity. It includes also the spatial uncertainty of the spark position in the discharge lamp.

To study the single photon counting capability of the MGC with the reflective photocathode the light intensity has been attenuated by increasing the number of filters at the entrance window. For each set of filters we measured the total charge in the biggest cluster and in the whole chamber (Fig. 15). After 8 filters the cluster has the dimension of one strip only and no further appreciable reduction in the cluster charge is observed. This means that the collected charge is generated by only one primary photoelectron. The noise level (r.m.s.) and the background level when the light was switched off are also plotted in Fig. 15.

In Fig. 16 the number of clusters in the full chamber is plotted as a function of the light intensity. The decrease of this number indicates that the detector is counting a lower and lower number of photons. At the minimum photon flux (12 filters) we evaluate on 32 strips 0.6 photoelectrons per event, on average. The background with light off was 10% of this value.

The distributions of the total charge in the whole chamber at various photon fluxes are shown in Fig. 17. The figure refers to a MGC with a reflective photocathode operating at $V_{a-c}=475$ V and null drift field, filled with a Ne-DME (70/30) mixture. The shape of the charge spectrum is well reproduced by a Monte-Carlo simulation which makes the convolution of a Poisson distribution for the number of photoelectrons ($\mu=\langle N^0 \rangle e^-$) with an exponential distribution for the gas amplification of each electron. The probability function taken to describe the avalanche size at high gains is $P(q) = q_{mean}^{-1} \exp(-q/q_{mean})$, with q and q_{mean} respectively total and average charge detected by the fast amplifier. The best fit to the experimental data, obtained with this Monte-Carlo, is superimposed on the

experimental spectra of Fig. 17. The shape of the charge distribution changes drastically going from a rather high statistics of photoelectrons emitted (~ 20) in the chamber (the Gaussian shape of Fig. 17d), to few photoelectrons (~ 2) when many filters are used (Fig. 17a). In this latter case it is distinguishable in the spectrum the exponential component due to a single photoelectron plus a peak corresponding to a second photoelectron detected. The disagreement between experimental data and Monte-Carlo prevision in Fig. 17d is due essentially to the fact that no cross-talk effect has been taken into account in the simulation. This effect becomes significant only for events where many strips are hit. The condition of single photon detection, reached at this very low light intensity, is clearly visible in Fig. 18a. The experimental conditions are the same of Fig. 17 but now the histogram refers to the charge collected by a single strip (strip hit probability $\ll 10^{-2}$) and not to the total charge in the chamber. The shape of the distribution is a pure exponential as it is well evidenced by the same plot in semi-logarithmic scale (Fig. 18b). Figs. 18 and 19 refer to different gain values: $\sim 1 \cdot 10^4$ ($V_{a-c}=475$ V) and $\sim 1.7 \cdot 10^4$ ($V_{a-c}=495$ V), respectively. The single electron detection efficiency, defined as the integral of the probability function $P(q)$ from a $3\sigma_{\text{noise}}$ cut ($\sigma_{\text{noise}} \sim 4400$ e $^-$) to infinity $\epsilon_{1e^-} = \int_{3\sigma_{\text{noise}}}^{\infty} P(q) dq$, is $\epsilon_{1e^-} = 25\%$ at $V_{a-c}=475$ V ($q_{\text{mean}} \sim 9100$ e $^-$) and $\epsilon_{1e^-} = 40\%$ at $V_{a-c}=495$ V ($q_{\text{mean}} \sim 15000$ e $^-$). No significant deviation from the exponential law is observed in the curves at high values of avalanche charge. This means that onset of secondary ionization processes due to photon feedback is negligible.

The charge distribution from a single strip obtained with a MGC equipped with a semi-transparent photocathode is shown in Fig. 20 for two different operating conditions. The gas mixture is still Ne-DME but with a little higher (85%) percentage of Neon. Fig. 20a refers to a working condition in which amplification takes place mainly in the drift region. The drift field is $E_{\text{drift}} \sim 12$ kV/cm while the anode-cathode voltage is $V_{a-c}=50$ V. In this case the charge spectrum for a single electron departs from the exponential distribution showing a maximum at small pulse heights. The distribution is fitted well by a Polya function:

$$P(q) = N \left(\frac{q}{q_{\text{mean}}} \right)^{b-1} e^{-b \left(\frac{q}{q_{\text{mean}}} \right)}$$

with N a normalisation factor and b a parameter ($b=1.246$).

The single electron detection efficiency with a cut at $4.5\sigma_{\text{noise}}$ was $\epsilon_{1e^-} = 96\%$ at a gain $\sim 3.6 \cdot 10^5$. Fig. 20b refers to the case in which amplification takes place essentially in the strip region, but with a non negligible contribution (~ 60) from the drift region. The operating voltages are: $V_{a-c}=400$ V and $V_{\text{drift}}=3300$ V ($E_{\text{drift}} \sim 9$ kV/cm). The charge distribution from a single electron is best fitted by a pure exponential that gives as

detection efficiency, at $4.5\sigma_{\text{noise}}$ threshold, the value $\epsilon_{\text{le-}} = 92\%$. The gain has been estimated from the fit to be $\sim 3 \cdot 10^5$.

The good agreement between experimental data and Monte-Carlo for some typical on-line distributions in the case of a reflective photocathode is shown in Fig. 21.

5. Discussion and conclusions

The coupling of UV photocathodes to the MGC has been successfully demonstrated. This makes possible to detect UV light with $20 \mu\text{m}$ positional sensitivity and 2-D imaging capability. The possibility to reach a high gain in safe conditions using gas mixtures based on light noble gases and DME at atmospheric pressure allows to choose the most suitable operating regime for the detector according to the photocathode configuration adopted. With the *reflective* photocathode, the chamber has shown to work efficiently in single-step mode with null drift field, while the two-step mode, i.e. amplification also in the drift region, is better suited for the *semitransparent* photocathode. In particular with the latter kind of photocathode very high gains ($\gg 10^5$) and very high detection efficiency ($>90\%$) have been obtained. In this configuration the detector is, nevertheless, still sensitive to charged particles, a feature which is not desirable in applications like RICH detectors or extended air shower detectors. This aspect is overcome in the MGC equipped with the reflective photocathode. Since the chamber can operate with null drift field, it is practically blind to ionizing tracks. Furthermore, even if the gain is limited to few 10^4 with detection efficiencies lower than in the other configuration, it has a higher quantum efficiency (Q.E.). The Q.E. could be further enhanced by a very strong field at the cathode surface. A field-enhancement of the CsI Q.E. has been observed and intensively studied by the RD-26 collaboration [12]. An increase in Q.E. of a factor varying from 1.5 to 25 for wavelength in the range of 160 to $> 200 \text{ nm}$ has been measured by this collaboration at a cathode field $\approx 500 \text{ kV/cm}$. By reducing the MGC anode pitch it will be possible to create a very intense electric field at the photon convertor surface (Fig. 22). This unique feature of the MGC provides a simple and elegant way to fully exploit this phenomenon. MGCs with $50 \mu\text{m}$ pitch will soon be tested in our laboratory. We are also trying to increase the Q.E. of the reflective photocathode by increasing the thickness of the CsI layer. At this scope we have already built and tested a MGC with a reflective photocathode of $300 \text{ \AA}$ and $5 \mu\text{m}$ anode-cathode gap, in which, however, early sparking has prevented to reach high gains. To overcome this limitation a set of MGCs with a thicker insulation layer ($10\div 12 \mu\text{m}$) and strips made of gold have been manufactured. On these detectors different thicknesses of photosensitive coatings will be tried. The use of MGCs with gold strips will decrease the UV sensitivity of the electrode structure.

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Fig. 1 - Schematic view of the UV sensitive MGC with two different depositions of the CsI photon convertor layer: a) semitransparent, b) reflective photocathode.

Fig. 2 - Drift cathode made of an Al mesh of 100 μm pitch.

Fig. 3 - Transmission coefficient of the entrance window for two configurations of the drift cathode as a function of the UV wavelength.

Fig. 4 - The gain of the MGC as a function of the anode-cathode voltage for various mixtures of DME and light noble gases (He,Ne).

Fig. 5 - Schematic drawing of the experimental set-up.

Fig. 6 - Photograph of the detector mounted on the printed circuit board.

Fig. 7 - Photograph of the anode signals produced by single photoelectrons.

Fig. 8a - The collected charge in a MGC with semitransparent photocathode as a function of $V_{\text{drift}} - V_{a-c}$ for various V_{a-c}

Fig. 8b - Curves of constant gain for different settings of V_{a-c} and V_{drift}

Fig. 9 - The single and two step gas multiplication in a MGC with semitransparent CsI photocathode.

Fig. 10 - The drift velocity in Ne-DME (70/30) as a function of the drift field for different values of V_{a-c} .

Fig. 11 - Photograph of the trigger signal (upper trace) and of the anode signal (lower trace).

Fig. 12 - Comparison of the signal amplitude between the reflective and the semitransparent photocathodes as a function of V_{a-c} .

Fig. 13 - Event charge distribution before (■) and after (□) a 200 μm shift of the chamber.

Fig. 14 - Distributions of the center of gravity of the total charge of the event.

Fig. 15 - The total charge in the biggest cluster and in the whole chamber as a function of the number of filters.

Fig. 16 - The number of clusters in the full chamber as a function of the number of filters.

Fig. 17 a b - Total charge distributions in a MGC with reflective photocathode at different photon fluxes. (Experimental ■ and Monte-Carlo • data).

Fig.17 c d - Total charge distributions in a MGC with reflective photocathode at different photon fluxes. (Experimental and Monte-Carlo data).

Fig. 18a b - Charge distribution from a single strip of a MGC equipped with a reflective photocathode. $V_{a-c} = -475 \text{ V}$. (Experimental $\blacksquare$ and Monte-Carlo $\bullet$ data).

Fig. 19a b - Charge distribution from a single strip of a MGC equipped with a reflective photocathode. $V_{a-c} = -495 \text{ V}$. (Experimental ■ and Monte-Carlo ● data).

Fig. 20a - Charge distribution from a single strip of a MGC with semitransparent photocathode. $V_{\text{drift}} = -3550\text{ V}$, $V_{\text{a-c}} = -50\text{ V}$.

Fig. 20b- Charge distribution from a single strip of a MGC with semitransparent photocathode. $V_{\text{drift}} = -3300\text{ V}$, $V_{\text{a-c}} = -400\text{ V}$.

Fig. 21 - On-line distributions () with superimposed the Monte-Carlo prediction (•) for the case of a MGC with reflective photocathode detecting few electrons.

Fig. 22 - The electric field at the cathode in a MGC for several anode pitches.