Characterization of Amorphous Silicon Based Microchannel Plates with High Aspect Ratio

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Abstract— Microchannel plates (MCPs) fabricated out of hydrogenated amorphous silicon offer a promising alternative to conventional lead glass ones. Progress in the fabrication process has allowed for detectors with higher aspect ratios, which significantly increases the multiplication factor with respect to previous generations. The current work focuses on the characterization procedure where multiplication factor and general detector performance were examined. For this, a specifically designed photoelectron source was used that allows measuring the gain value in the quasi steady-state regime. The current generation of amorphous silicon MCPs showed for the first time gain values in excess of 100. Using an electron beam induced current technique the electrical properties of the sample detectors were analyzed and localized charging effects were observed. The effect of the tilt angle between the electron source and the detector surface was also investigated.

Keywords— Amorphous Silicon, Characterization, EBIC, Microchannel Plates

I. INTRODUCTION

AMORPHOUS silicon based microchannel plates (AMCP) are electron multipliers used for particle detection. They offer unique advantages with respect to conventional lead glass MCPs and can potentially overcome some of their limitations. Monolithic detectors can be realized by fabricating the AMCPs directly on top of the readout electronics, which greatly enhances the spatial and temporal resolution of the detector. Bulk resistivity of the amorphous silicon layer can be changed by several orders of magnitude, which can lead to a faster charge replenishment in comparison to lead glass MCPs. Finally, the micromachining processes allow for a more facile and more flexible fabrication process. The typical structure of microchannel plates is shown in Fig.1. Three electrodes are included in the stack: the top electrode, where bias voltages of up to 500V can be applied, an intermediate electrode, to evacuate the leakage current through the stack, and the bottom electrode where the signal is collected. Both the intermediate and bottom electrodes were kept at ground potential and separated by a 2 μm thick hydrogenated amorphous silicon layer, called a decoupling layer. An incoming particle that needs to be detected will hit the wall of one of the channels, causing the release of secondary electrons. These secondary electrons are then accelerated through the channel by the applied electric field, colliding several more times with the

Fig. 1. Schematic view of the AMCP architecture (left). A bias voltage of up to 500V can be applied at the top electrode. An intermediate electrode is used to evacuate the leakage current through the stack. Cross-sectional SEM images of the top of an AMCP, showing the current channel geometries, and of the bottom layers are shown on the right. Image taken from [1].

channel walls, each time causing the release of more secondary electrons. Recent examples of AMCPs have a channel diameter between 4- 6 μm and show a maximum gain factor of 104.

The Eberhardt model [2,3] is used to describe the multiplication gain of the AMCPs. This model describes the behavior of microchannel plates as if they were discrete electron multipliers with a fixed number of dynodes. The gain is then given by

$$G = \delta_1 \delta^{n-1} = \delta_1 \cdot \left(\frac{V}{n \cdot V_c} \right)^{k(n-1)} \quad (1)$$

with the bias voltage V , the number of collisions inside one channel n , and the secondary emission coefficient δ . Since the secondary emission coefficient strongly depends on the energy of the incoming particle, the yield for the first collision δ_1 is expected to be different from the following collisions inside the channel. V_c is the first crossover potential and k is a constant coefficient that relates to the curvature of the secondary emission function. Optimization of the fabrication process has allowed the realization of detectors with high aspect ratios [4]. As the multiplication gain of AMCPs increases with the number of electron impacts in the channels and the yield of secondary electrons per impact, high aspect ratio AMCPs are expected to show gain values that are significantly higher than those of the previous generations [5]. In this paper, we report on the characterization of AMCPs with aspect ratios up to 13.6. The multiplication gain was determined using a specifically

designed setup, to test the detection of electrons under conditions similar to possible applications of the detectors. The electrical properties of the AMCPs were examined by the use of a second setup that was based on the electron beam induced current (EBIC) technique.

II. METHODS

For the development and characterization of the AMCPs, dedicated chip-like test structures were designed. Each structure contained 23 individual detector areas of three different sizes. The chip was then bonded to a double-sided interface board for the electrical connections. One of the most important characterization parameters is the multiplication factor of the MCPs. To determine this gain value, a characterization setup composed of an illumination source, a vacuum vessel, a gold photocathode and a rotatable support rod was used. The setup is schematically shown in Fig. 2.

Fig. 2. Schematic drawing of the characterization setup. Light from the mercury lamp enters the vacuum vessel onto a gold photocathode. The photoelectrons are then multiplied inside the channels of the AMCP and the signal is collected at the bottom electrode. The supporting rod can be tilted up to 30°. Figure taken from [1].

A mercury lamp was used as an illumination source, which allows for gain measurements in the quasi-continuous regime. Future upgrades of the system will include a pulsed laser source for transient measurements. The light enters the vacuum vessel through a quartz window and a 10% filter onto a gold photocathode. The test structure was placed on the support rod that could be tilted from the outside. A thin aluminum plate with an opening (photoelectron screen) was used to shield the bonding pads from the collection of parasitic electrons. A voltage difference of 500 V was maintained between the photocathode and the top electrode of the AMCPs. Additionally, a mechanical chopper was placed between the lamp and the entrance window of the vessel to chop the light at a low frequency (<1 kHz). This was then used as a reference frequency input for a lock-in amplifier that reads out the signal. More details of the described setup can be found in [5]. The AMCP itself could be biased with a maximum of 500 V. The multiplication gain was then determined as the current variation (with biased and grounded photocathode), divided by the calibrated photoelectron current inside the channels. To obtain the input current flowing inside the channels, the photoelectrons arriving at the top electrode were measured and the current was divided by the open area ratio, assuming that only electrons that directly enter the channel contributed to the measured signal.

To examine the electrical properties of the fabricated devices an EBIC setup [6] was used. For this, the sample was placed in the chamber of a scanning electron microscope (SEM) and the electron beam was swept across the device. The induced current arriving at the bottom anodes of the AMCPs was then fed back to the SEM video board, over a current-to-voltage amplifier, to build a map of the sample. The map then showed the spatial distribution of the induced current intensity as a function of beam position. This provided a qualitative overview of the electrically active areas and allowed identification of the presence of possible fabrication defects and their effect on the detector performance. The devices could be biased inside the chamber with up to 300 V by the use of a high-voltage supply.

III. GAIN CHARACTERIZATION

The multiplication factor, i.e. gain, as a factor of the applied bias voltage was determined with the setup described in section II. Two measurements, one for a sample with an aspect ratio of 13.6 and one with 11.7, are shown in Fig. 3.

Fig. 3. Gain versus bias voltage for two samples with different aspect ratio, 13.6 and 11.7. A maximum multiplication factor of 104 could be measured for the 13.6 sample when biased with 500 V.

The curves clearly show the impact of the aspect ratio on the measured multiplication factor. Higher gain values for narrower and longer channels can only be explained when an avalanche process is taking place inside the channels. The results also demonstrate the ability of the a-Si:H layer to sustain large bias voltages, corresponding to an electric field of $7.5 \cdot 10^4$ V/cm.

The number of collisions inside a channel can be obtained from these measurements by the use of the gain definition given in Eq. (1). Applying a logarithm to both sides of the equation shows a log-linear dependence between the bias voltage and the measured gain.

$$\log G = k(n-1) \log V - k(n-1) \log V_c + \log \delta_1 \quad (2)$$

The number of collisions were extracted from linear regression curves by the use of Eq. (2) for all measured samples and a fit was done for the expected number of collisions for higher aspect ratios, shown in Fig. 4.

Fig. 4. Calculated number of collisions for 6 samples with aspect ratios between 6.0 and 13.6. A fit was done between the expected numbers of collisions per aspect ratio by assuming a linear dependence.

Lastly, a fit for the expected gain per collisions (resp. aspect ratio) could be created by the use of Eq. (1), shown in Fig. 5. This helps to give a rough estimation of the achievable gain values of amorphous silicon based MCPs based on feasible aspect ratios of around 30 formed by deep reactive ion etching. It should however be noted that it is not yet clear if the Eberhardt model can accurately describe the behavior of AMCPs.

Fig. 5. Gain per collisions based on the Eberhardt model. To achieve a gain of around 850, 11 collisions (with an aspect ratio of 22.5) are needed.

The fit produced a secondary emission coefficient of 1.9 for the collisions inside the channels. This rather high value, considering the expected low energies of the produced secondary electrons [7], could be the result of surface roughness produced by the deep reactive ion etching process.

IV. ENERGY MEASUREMENT AND FIRST COLLISION DEPENDENCE

The maximum energy of the secondary electrons at the end of the channels was measured by applying a negative voltage difference between the intermediate and bottom electrode, as seen in Fig. 6. If this difference becomes larger than the energy of the electrons, they are not able to reach the anode anymore. This yielded a maximum energy of around 40 eV. The energy between each collision inside the channels was expected to be in a similar range.

Fig. 6. Measurement of the maximum energy of the secondary electrons at the end of the channels.

To determine the influence of the first collision energy on the total multiplication gain, the voltage between the photocathode and the top electrode of the AMCPs was altered between 0 V and -500 V. Seen in Fig. 7, the gain was observed to be at around 50% of its maximum value even when there was no voltage applied on the photocathode. This further demonstrates that there was a multiplication process taking place inside the channels. The gain value then increased and appeared to reach a maximum at around -500 V.

Fig. 7. Gain as a function of the first collision voltage. The voltage between the top electrode of the AMCP and the photocathode was altered between 0V and -500V to determine the influence of the energy of the first collision on the total multiplication gain.

V. EBIC MEASUREMENTS

The EBIC technique allows for a visual check of the quality of the fabricated samples. Fig. 8 shows the current arriving at the bottom anode decreased over time, as the sample was biased with 200 V and tilted by 8°. This decrease in the multiplication gain was most likely caused by localized charging of the decoupling layer. The incoming electrons collide with the isolation layer between the intermediate and bottom electrode. Due to the low conductivity of this layer, it becomes charged and decreases the applied electric field over the channels. This caused a drop of the multiplication gain in that area, resulting in a much lower induced current coming from the channels. This effect was more prominent with high input currents (over 1 nA) so the following measurements were conducted with much lower probe currents. A high conductivity intermediate electrode, as is planned for the next generation of AMCPs, could help to keep the multiplication gain constant for high input fluxes.

Fig. 8. EBIC image of the same area at the first scan (left) and the second scan (right). Bias voltage -200V, EHT 1.0 keV, Probe Current 1.5nA, Tilt 8°. The signal quickly disappeared, most likely due to localized charging effects.

The influence of the tilt angle on the multiplication factor was also examined by EBIC. If the AMCP was not tilted with respect to the electron beam, a brighter signal, corresponding to a higher induced current, was observed in a tiny annular area around each channel (Fig. 9).

Fig. 9. EBIC image of an untilted sample. Bias voltage -200 V, EHT 2.0 keV, Probe Current 120 pA. Induced current was higher only at the channel edges.

When the sample was tilted by 5°, the same area showed a brighter signal coming from the whole channel area (Fig. 10).

In both cases, a -200 V bias voltage was applied. This observation suggests that if there is no tilt angle between sample and electron source, most of the electrons will pass through the channels without colliding with the channel walls and hence not cause an avalanche (i.e. there is no multiplication). Since the AMCPs do not have a bias angle (in contrast to glass based ones), their axis is perpendicular to the sample surface. A tilt with respect to the incoming electrons should always be applied to achieve maximum gain values.

Fig. 10. EBIC image of a tilted sample. Bias voltage -200 V, EHT 2.0 keV, Probe Current 120pA, Tilt 5°. A brighter signal was observed inside the whole channel area.

VI. CONCLUSION AND OUTLOOK

The multiplication gain of amorphous silicon based microchannel plates was measured for various samples with aspect ratios between 6 and 13.6. The increase of the gain with higher aspect ratios and the fact that a gain was observed even with very low energies for the incoming particles was a clear proof of the multiplication process taking place inside the channels. By the use of the Eberhardt model, that describes MCP as if they were discreet electron multiplier, the number of collisions inside the channels could be extracted. This allowed for a rough estimation of the expected gain as a function of aspect ratio. The next series of fabricated AMCPs will feature aspect ratios of up to 30 with channel diameters of 2 µm and expected gain values of several thousands. This will further help to understand the relationship of the aspect ratio and the measured multiplication factor and check the validity of the Eberhardt model.

It was shown that a tilt angle between the particle source and the detector surface was necessary to achieve maximum gain values. In future measurements, the influence of this angle on the multiplication factor will be further investigated by measuring the induced current at different tilt angles. It should also be noted that this dependence might be different if the channel geometry is adjusted, e.g. to a more funnel-like shape. Funnel shaped channels would greatly increase the active area and therefore the detection efficiency of the detectors. This would allow for the use of AMCPs in applications with very low input fluxes.

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