Fabrication and Characterization of High Aspect Ratio Amorphous Silicon Based Microchannel Plates

S. Frey, M. Beygi, J. Löffler, C. Ballif, N. Wyrsch

Abstract–**This contribution focuses on the fabrication and characterization of microchannel plates made of hydrogenated amorphous silicon (AMCPs). Flexible fabrication processes and the semi-conducting nature of amorphous silicon could give these detectors the advantage of superior temporal and spatial resolution over conventional lead glass based microchannel plates (MCPs). The current work focuses on the fabrication and characterization of high aspect ratio devices. The multiplication gain was measured under continuous illumination of UV light using a customized setup. Through optimization of the micro-engineering processes, devices with high aspect ratios up to 25 were realized which resulted in a multiplication factor of ~1500 for this new generation of AMCPs. This high gain, coupled with the AMCPs remarkable temporal and spatial resolution make them a promising alternative for various applications such as detectors for positron emission tomography.**

I. INTRODUCTION

AMORPHOUS silicon based microchannel plates (AMCPs) offer a promising alternative to conventional lead glass microchannel plates. In addition to boasting a facile and flexible fabrication process, the AMCP's main advantage lies in the possibility to fabricate monolithic detectors by growing the AMCPs directly on top of the readout electronics, which greatly enhances temporal and spatial resolution of the detectors. With the optimization of the micromachining processes involved in their fabrication [1,2], detectors with aspect ratios of up to 25 and channel diameters between 1.6 µm and 3 µm have been realized. AMCPs can cover a broad range of applications that depend on high spatial and temporal resolution including time-of-flight positron emission tomography (TOF-PET) scanners. Since the image quality of a PET scanner is directly tied to the detection accuracy of the annihilation-photon's arrival time, timing resolution becomes a key factor in improving TOF-PET scanners. Modern scanners use silicon photomultipliers (SiPMs) as a photodetector due to their high photon detection efficiency and low timing jitter [3]. However, the main drawbacks of SiPMs are the dead-space around the cells and their relatively high dark noise component [4]. AMCPs are an attractive alternative as they provide superior spatial resolution via monolithic integration, and a minimal dark count rate that only depends on the spontaneous emission rate of the photocathode. In the present paper, we report on the fabrication and characterization of a new generation of AMCPs with channel diameters down to 1.6 µm and aspect ratios up to 25. The multiplication gain was determined using a customized setup that measured the produced electrons under continuous illumination.

II. AMCP FABRICATION PROCESS

The details of our AMCP fabrication process have been elaborated by A. Franco [5] and J. Löffler [6] and are only briefly summarized in this section. A schematic representation of the full AMCP architecture as well as a cross section image of a finished detector are shown in Fig. 1. A grounded intermediate electrode is used to evacuate the leakage current through the stack. It is separated from the bottom pads where the signal is collected by a 2 µm thick amorphous silicon decoupling layer. In comparison to earlier generations of AMCPs, this intermediate electrode consists of a thin chromium layer (50 nm) instead of a microcrystalline silicon (µc-Si) one, which is pattered before the deposition of the main layer made out of hydrogenated amorphous silicon (a-Si:H). This modification is expected to decrease or fully prevent previously observed charging effects at high incoming electron fluxes [7]. One of the most critical steps is the deposition of a thick a-Si:H layer (40- 100 µm) by plasma-enhanced chemical vapor deposition (PECVD). During the growth of this layer, the deposition parameters have to be precisely controlled to prevent hydrogen accumulation and keep the intrinsic stress as low as possible. Afterwards, a thin chromium layer (20 nm) is sputtered on top of the a-Si:H layer and patterned by a lithography step. This Cr layer serves both as a top electrode and as a hard mask for the etching of the channels. The channels are then fabricated by deep reactive ion etching (DRIE) process. Lastly, by tuning the etching parameters, channels with diameter of 1.6 µm and aspect ratios up to 25 are feasible. As a final step in the fabrication, a few devices are coated by atomic layer deposition (ALD) with either alumina (Al_2O_3) or magnesium oxide (MgO) to increase the secondary emission yield per collision and hence the final multiplication gain of the devices [8].

Manuscript received December 01, 2021. This work was supported by the Swiss National Science Foundation (SNSF) under the Sinergia project on MEMS based Gamma Ray Detectors for Time-of-Flight Positron Emission Tomography (Grant number: 177165). All authors are with the Photovoltaics and Thin-Film Electronics Laboratory, Institute of electrical and microengineering (IEM), École Polytechnique Fédérale de Lausanne (EPFL), Neuchâtel, Switzerland (Correspondence: samira.frey@epfl.ch).

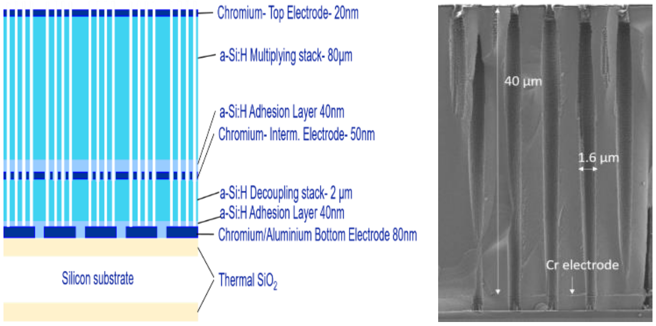

Fig. 1. Left: Schematic representation of the AMCP structure. The samples are fabricated on a silicon substrate with a thermal silicon oxide on top to isolate the bottom anodes. A 50 nm thick chromium intermediate electrode is used to evacuate the leakage current through the stack and is separated from the bottom anodes by a 2 µm thick decoupling layer. The multiplication of the electrons takes part in the main a-Si:H layer that can be between 40-100 µm in thickness. Finally, the top electrode consists of a 20 nm thick chromium layer. Right: Cross-section image of the fabricated AMCPs. The channels have a diameter of 1.6 µm and a channel length of 40 µm resulting in an aspect ratio of 25.

III. GAIN CHARACTERIZATION

To characterize the AMCPs dedicated chip-like test structures were designed. Each structure contained 16 individual sensors with areas of three different sizes. These chips were then bonded to a double-sided interface board for the electrical connections and placed into a vacuum chamber. To measure the multiplication gain of the AMCPs, a gold photocathode was placed on top of the chips and a mercury lamp (λ=254 nm) was used as a continuous UV illumination source. The details of the characterization setup can be found in [5].

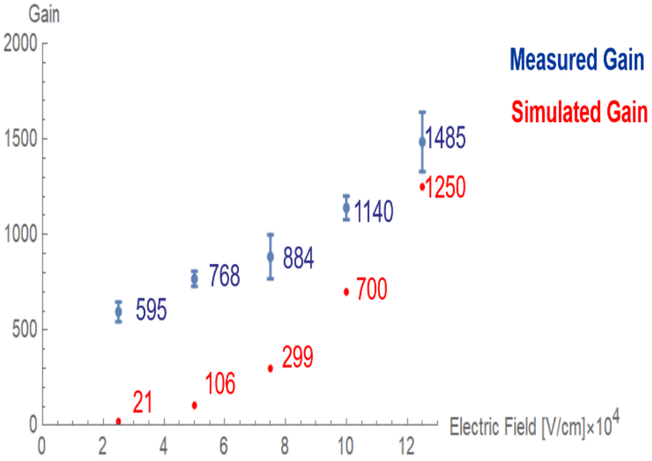

Fig. 2. Measured multiplication gain as a function of the applied electric field and the simulated values for comparison. The measured device had channel diameters of 1.6 µm and a main channel length of 40 µm, resulting in an aspect ratio of 25.

The electron multiplication in the channels was then measured for different electric fields applied between the top and intermediate electrode of the AMCPs. The a-Si:H layer can withstand an electric field of over 12.5×10^4 V/cm, which is larger than the maximum value usually applied in conventional MCPs. Previous generations of AMCPs with low aspect ratios have shown a maximum gain factor of ~100 for a field of 5.5×10^4 V/cm and an aspect ratio of 13.6 [7]. The gain has been proven to increase with increasing aspect ratio [1]. For this last generation, the maximum channel gain for a detector with aspect ratio of 25 (1.6 µm channel diameter and 40 µm channel length) was measured to be 1485 for an applied E-field of 12.5×10^4 V/cm. The expected gain for this channel geometry was additionally simulated using a Monte Carlo model presented in [9]. The measurement of the multiplication gain as a function of the applied electric field as well as the simulated values can be seen in Fig. 2. For a strong electric field of 12.5×10^4 V/cm the simulation underestimates the expected gain by ~16%. However, the difference between the simulation and the measurement results becomes much more apparent for lower fields. This means that the model for the low energy collisions may need to be slightly improved to better fit the experimental data. A possible explanation of the relatively high gain at low applied biases could lie in the surface morphology of the channel walls. Due to the etching process the inside of the channels are relatively rough which could be beneficial for the secondary electron emission. Further measurements have to be conducted to better understand the exact physical processes. In a second characterization measurement, the influence of the energy of the first collision on the total gain was investigated. The measurement is shown in Fig. 3.

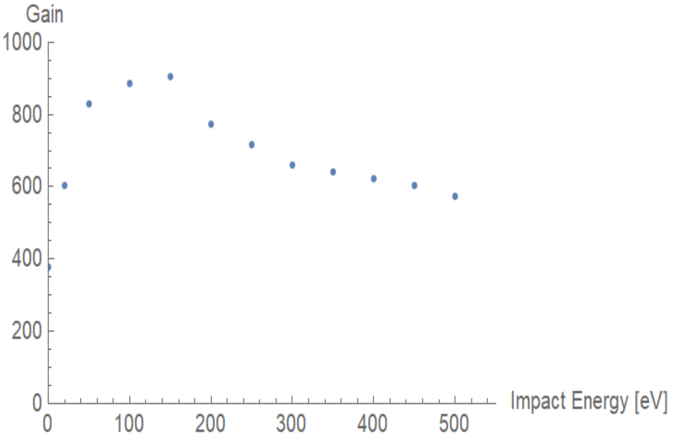

Fig. 3. Measured gain as a function of the energy of the incoming electrons. The measurement shows a maximum gain at a potential difference of 150 V between the photocathode and the AMCP. Measurements of the total secondary emission yield as a function of energy and angle showed a maximum closer to 200 eV [8].

It is observed that the gain reaches a maximum value when applying a bias of 150 V between the photocathode and the top electrode of the AMCP. Measurements from the total emission yield as a function of energy show a maximum closer to 200 eV [8]. This could mean that most of the incoming electrons collide further down the channels rather than at the opening, hence their energy at the collision point is already higher than just the potential difference between the photocathode and the AMCP. The optimum potential difference is likely to change when different wall coatings are going to be applied.

IV. DISCUSSION AND OUTLOOK

AMCPs with an aspect ratio of 25 and a multiplication factor of up to 1500 have been measured. By further improving the fabrication process, aspect ratios of up to 35 appear feasible. These high aspect ratios together with channel wall coatings of high secondary emission materials (Al_2O_3 and MgO) are expected to result in an electron gain of 8000-10000 according to simulations. Further characterization in the transient regime via a UV pulsed laser source will help to better understand charge replenishment of the detectors. Additionally, by adjusting the channel geometry to a more funnel shaped structure, the active area of the detectors will increase to a value over 90 %, which will be essential for their use in applications where single photon detection is necessary such as in TOF-PET scanners. Chip-level 3D integration of the AMCPs and the readout electronics is the subject of ongoing work that will be discussed in future publications.

ACKNOWLEDGMENT

The authors would like to thank the staff of the center of micronanotechnology (CMi) and the people from the Interdisciplinary Centre for Electron Microscopy (CIME) for their expertise and support in the fabrication process. Lastly, we would like to thank all members of the PV-lab for their continued support.

REFERENCES

[1] A. Franco, J. Geissbühler, N. Wyrsch, and C. Ballif, “Fabrication and characterization of monolithically integrated microchannel plates based on amorphous silicon,” Sci. Rep., vol. 4, no. August 2015, pp. 1–7, 2014.

[2] J. Löffler, C.Ballif, and N. Wyrsch. “Amorphous silicon- based micro-channel plate detectors with high multiplication gain,” Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., 2018.

[3] E. Roncali, S.R. Cherry,”Application of silicon photomultipliers to positron emission tomography,” Ann Biomed Eng 39:1358-1377, 2011.

[4] E. Berg, S.R. Cherry,”Innovations in Instrumentation for Positron Emission Tomography,” Semin Nucl Med 48:311–331, 2018.

[5] A.Franco, “Monolithic Particle Detectors based on Hydrogenated Amorphous Silicon,” Ph.D. dissertation, Institute of Microengineering, EPFL, Lausanne, Switzerland, 2014.

[6] J.Löffler, “Towards Single Photon Detection with Amorphous Silicon Based Microchannel Plates,” Ph.D. dissertation, Institute of Microengineering, EPFL, Lausanne, Switzerland, 2021.

[7] S.Frey, J. Löffler, C. Ballif, N. Wyrsch, “Characterization of Amorphous Silicon Based Microchannel Plates with High Aspect Ratio,” Conference Record, 2019 IEEE Nuclear Science Symposium and Medical Imaging Conference.

[8] J.Löffler, M.Belhaj, JJD. Leon, S.Frey, P.Wyss, J. Thomet, S. Nicolay, C. Ballif, N. Wyrsch, “A comprehensive analysis of electron emission from a-Si:H and Al2O3 at very low energies” *(unpublished).*

[9] J.Löffler, J. Thomet, S.Frey, M.Beygi, C. Ballif, N.Wyrsch, “Single photon detection with amorphous silicon-based microchannel plates: A Monte Carlo model” Nuclear Inst. and Methods in Physics Research, A *(submitted for publication).*