An amorphous silicon photodiode array for glass-based optical MEMS application

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***Abstract*—A highly sensitive photo-detector array deposited on a glass substrate with an optional integrated optical filter have been presented. The active element is a vertically integrated hydrogenated amorphous silicon photodiode featuring a dark current of less than 1e-10 A/cm^2 for -3V polarization and a maximal quantum efficiency of 80% near 580 nm. The prototype was encapsulated and successfully tested optically. It has a fill factor of only 44% which, however, can be easily increased to 90% using flip-chip bonding to an integrated electronic circuit for signal conditioning. The sensor is bio-compatible and can be integrated with other glass-based and glass compatible micro-fabricated devices such as optical, micro-fluidic, lab-on-a-chip, chemical and biological devices in which photo-detection is a desired feature.**

I. INTRODUCTION

Photo-detection is used in many fields of research and serves, e.g., for drug screening and fluorescence imaging in life sciences and for particle detection with scintillate materials in material research. In general, these applications involve the use of commercially available photo-detectors which suffer from a number of disadvantages like modest sensitivity due to limited fill factor and the inability to be integrated into MEMS devices. Although a lot of effort has been made to incorporate photonic devices into microsystems to improve their functionality, a variety of integrated photonic detectors for specific function have also recently been demonstrated [1]. The development of a photo-detection system being compatible with various MEMS technologies would form an ideal platform for the fabrication of integrated measurement systems for many different applications. Current approaches in the field of opto-electronic sensors tend to miniaturize the imaging system by using small-pixel CMOS/CCD detectors [2], micro-PD/LED arrays [3] or thin film on ASIC (TFA) technology based on the deposition of a photo-sensitive layer on top of a read out integrated circuit [4], [5].

The development of optofluidic devices based on the integration of optics and microfluidics to achieve novel functionalities shows the importance and the impact of photonic detection in such integrated devices [6]. Microfluidics is a promising technology and is in rapid progress in different domains. It brings the advantages of small volumes of fluids, small waste and small numbers of cells to biological systems. Recent developments in microfluidic technology have made it possible to control light by integrating optical components such as optical switches [7], tunable lenses [8], and optical sensors on the same chip [9]. On the other hand, the use of elastomers and development of related microfabrication techniques allowed the rapid development of compact analysis systems over the past few years like, e.g., pumps [10], valves [11] and channels useful for chemical sensing and biological diagnostics in microfluidics system [12]. These opportunities provide powerful tools to realize more effective sensors by combining high sensitivity integrated photonic detectors with other MEMS, microfluidic and lab-on-a-chip devices. In the context of biochemical sensors, fluids can be used to transport otherwise difficult to handle nanostructures, cells and molecules having specific optical properties into sensitive photonic device. Manipulations of cells and micro/nano particles in this environment using a variety of opto-microsystems have recently been demonstrated. Combining these different technologies with photonic sensors have produced all kinds of innovative devices suitable to manipulate micro/nano particle such as optical trapping [13], optoelectrowetting [14], optical and optoelectronic tweezers [15].

Miniaturization of the read out optical system in fluorescence based detection sensor is a further desirable feature. Fluorescent tagging is one of the most frequently used methods to detect labeled target molecules and can also be used as an amplifier for weak signal. In this field of research, fluorescence detection systems have been developed which cover applications such as lab-on-a-chip [16], microchip capillary electrophoresis [17] and micro-spectrometers [18]. Moreover, in applied particle physic, radiation dosimetry and particle detection is a central feature of several applications

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including human health in medical diagnostics [19], space applications [20] and fundamental physic of particle research [21]. All of these applications require very high spatial resolution, efficiency of light detection, gain and optimized signal-to-noise ratios.

A glass-based photo detector device which is compatible with most of the existing microfabricated sensors including the ones described above can lead to further miniaturization and, hence, to ultra-portable and reconfigurable measurement devices which offer lower power requirements and lower sensor costs. Moreover, by co-implementing additional types of microsensors, the range of possible applications of the devices can be expanded substantially.

II. PROPOSED DEVICE AND FABRICATION

A. *Proposed device*

Our proposed approach consists of a photo-detection system which permits the samples to be positioned close to the detectors. Photodiodes are deposited on the back of a Quartz substrate where the front can be used for fabrication of any MEMS sensor which is in need of photo-detection. The samples are in contact with the glass surface and the emitted photons are sensed by the underlying photodiodes. An optional highly selective dielectric optical filter can be integrated between the glass substrate and the photodiodes in order to permit wavelength delimited measurement of photon emission. The advantage of this approach is its inherent simplicity and a high sensitivity due to maximal optical aperture and fill factor.

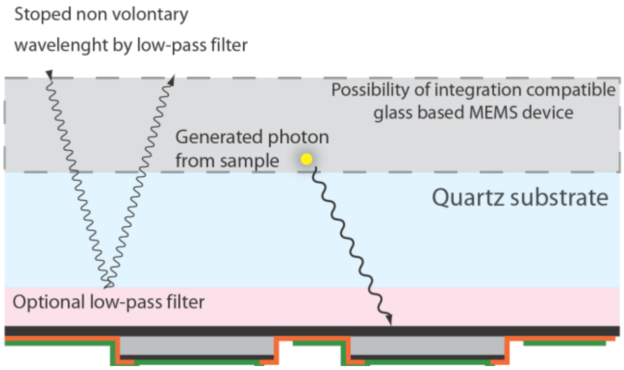

Figure 1. Cross-sectional view of the proposed sensor device which is based on a 500 µm thick Quartz substrate. Photosensitive layers (ZnO/a-Si:H/ZnO) form individual pixels which are connected to the output by Ti/Pt metal conductors.

This device represents an ideal platform for other MEMS application in which photon detection is required. Different pixel shapes and sizes from a few micrometers to several centimeters can be patterned easily for each specific application in order to maximize sensitivity and efficiency of photon detection. In addition to offer biocompatibility and transparency, the glass substrate also permits to fabricate additional structures like, e.g. cavities and channels by using conventional glass etching techniques [22]. If required by a specific application, the glass thickness can be reduced in order to minimize the distance between generation and detection of photons. The feasibility of direct bonding of Si bulk devices to the glass [23] and the good sealing properties of the majority of polymers [24] used in research renders this device a versatile platform for integration with other MEMS device.

B. *Fabrication*

In this study, PIN photodiodes were chosen for the detection of photons originating from particles and cells. The photodiodes consist of a p-i-n junction with an intrinsic region in the middle. The deposited photodiodes were realized in hydrogenated amorphous silicon (a-Si:H). It is an alloy of silicon with around 10% (atomic) hydrogen and offers several significant advantages; low deposition temperature (around 200°C), high resistance to radiation [25], and mechanical properties close to c-Si. Being issued from the solar cell research, they show excellent characteristics in terms of quantum efficiency (as high as 80% between 500 and 600 nm), low dark current (1e-10 A/cm^2 for -3V polarization) [26].

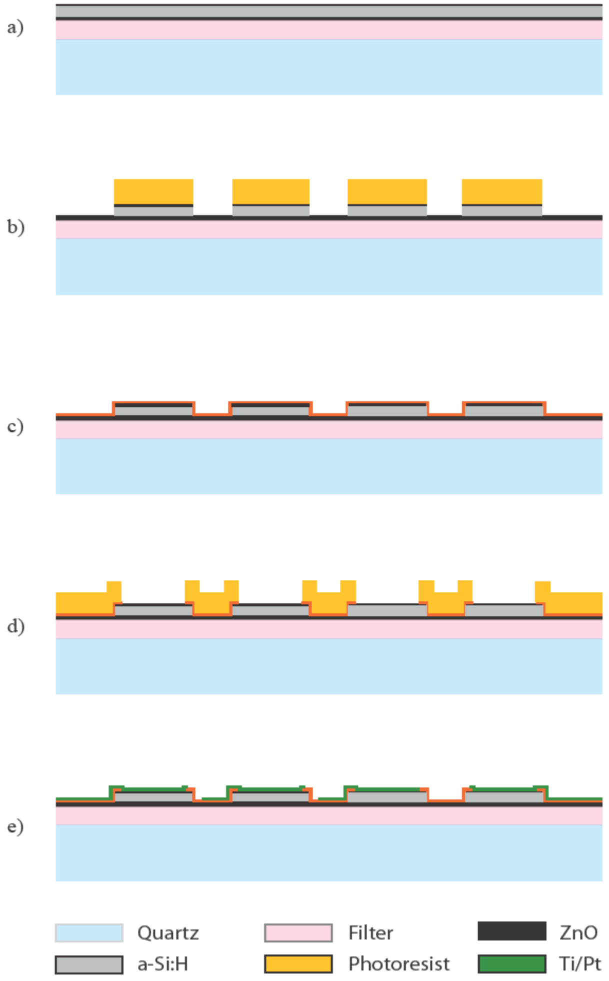

Figure 2. (a) Deposition of the dielectric optical filter composed of multiple layers of Ta_2O_5/SiO_2 (performed by MSO-Iena) is followed by photodiode deposition by PVLAB-EPFL ; (b) Photolithography for pixel definition following by Zno wet etching and a-Si:H dry etching; (c) Deposition of SiO_2 passivation layer by sputtering at low temperature; (d) Photodiode back side pattering and silicon oxide dry etching; (e) Ti/Pt deposition by lift-off photolithography and removal of remain mask.

Photodiodes were fabricated based on in-house methods and facilities of PVLAB at EPFL (VHF PE-CVD: very high frequency Plasma Enhanced Chemical Vapor Deposition). A 1 µm thickness ZnO transparent oxide layer was deposited on the dielectric filter and served as common anode for photodiodes. A 1 µm a-Si:H layer (the photodiode) was then deposited, followed by a 150 nm thick layer of ZnO for electrical contact with additional metal layers. The photodiode patterning was done by a combination of wet and dry etching for the different layers. A 2 µm positive photoresist was coated and patterned on top of ZnO. Through the opening windows on the mask, the thin ZnO layer was etched away by using diluted HCL (1:200). The a-Si:H layer was etched away with SF_6 by ICP techniques. The photoresist was removed and plasma oxygen treatment served to clean the surface. Once the photodiodes were patterned, a 200 nm passivation Silicon dioxide layer was sputtered on top of the photodiodes in order to create an electrical isolation layer. By using conventional photolithography and dry etching techniques, the Silicon dioxide was etched away on the back side of each pixel. A Ti/Pt (20 nm/100 nm) metal connection layer was deposited by lift-off techniques to make a connection between the back of each photodiode and the external pads.

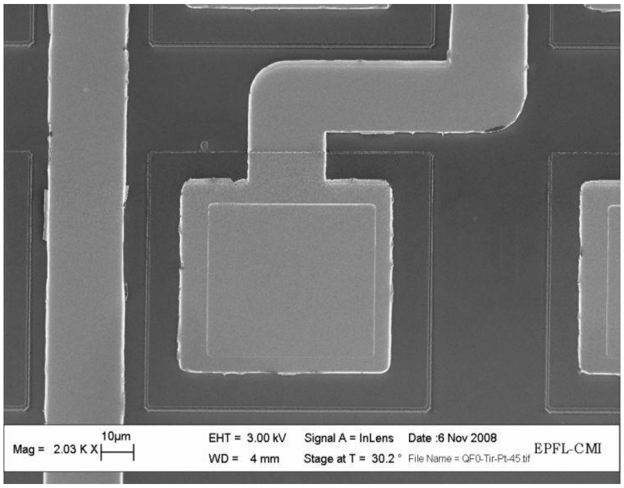

Figure 3. Patterned photodiode is connected by a sputterd Ti/Pt metal layer to external pad.

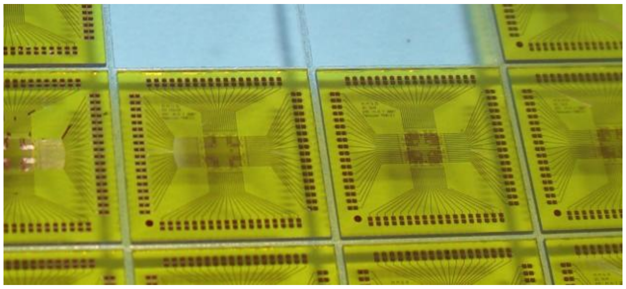

Figure 4. diced device (each wafer contained 32 devics).

The detectors feature a modest fill factor of 44% because of the space required for the metal connection lines. This number could be easily increased to ≥ 90% by using flip-chip and high density solder bump techniques [27]. Each wafer contains 32 devices of 100 mm^2 each. They were separated by wafer dicing and packaged for a biological application.

C. *Packaging*

The fabricated device is glued by EPOXY resin to a specially designed PCB serving as mechanical support and providing external electronic connection. A thermal treatment at 150°C was done before connecting the devices to the pads of the PCB via wire bonding. A glass container was finally fixed by biocompatible glue to the system to form the culture chamber. Fig. 5 shows an overall view of the packaged system.

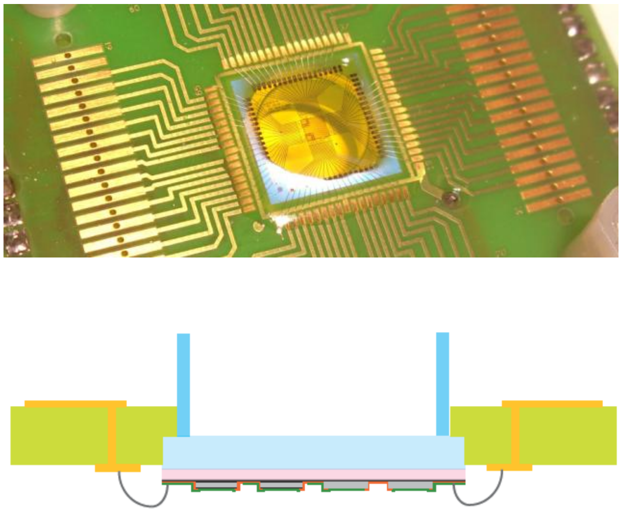

Figure 5. Photodetector packaging.

III. EXPERIMENTAL RESULTS

Relative quantum efficiency was measured to verify optical filter functionality and the efficiency of photodetection by the pixels. Relative QE was measured for four different pixel sizes (20 µm x 20 µm to 80 µm x 80 µm). Fig.6. shows the measurements for two pixels (80 µm x 80 µm) with and without optical filter. The interference filter serves to block undesired wavelengths from reaching the photodiodes which is an important requirement for applications such as fluorescence imaging. The integrated optical filter exhibited excellent properties: high attenuation (>99.99%) outside and high transmission (>90%) within the pass-band. Each device had approximately 40% of functional pixels which performed highly similar. Non-functional pixels were in most cases due to discontinuities of metal deposition on the PD step layer. This problem will be solved by using solder bump connections in the next generation of devices. For optical tests, the devices were encapsulated and bonded to a PCB which in turn was connected to an external electronic circuit. A spectrometer was used to measure absorption spectra between 350 nm and 800nm. Due to small pixel dimension in the range of several tens of microns, the spot size of the excitation light was not small enough to cover the surface of only one pixel. Therefore, relative quantum efficiency was measured and normalized.

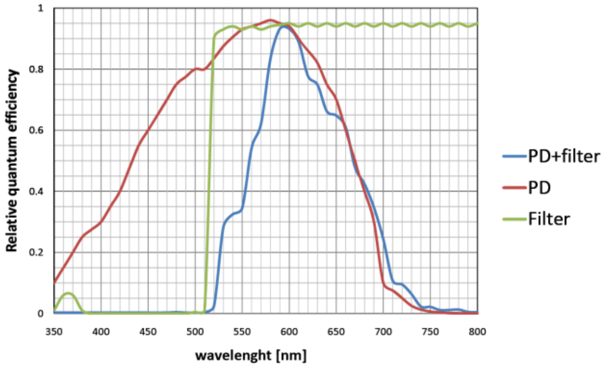

Figure 6. Relative quantum efficiency measured with and without filter, frequency response of deposited dielectric filter, provided by MSO-Jena.

TABLE I. PHOTODIDODE CHARACTERSTICS

Device parameters	*PD (80 µm x 80 µm)*	*condition*
Dark current	< 1e-10 A/cm^2	at -3V bias voltage
Maximum relative QE	~ 90%	near 580 nm
Fill factor	~ 44%	-
Filter cut-on frequency	525nm	-
Biocompatibility	Yes	-

IV. APPLICATIONS

As described above, devices with integrated optics are increasingly on demand because of the anticipation of a large market for portable devices, monitoring systems and instruments for medical diagnostics. Optical detection is a complementary tool to create more compact devices offering extended functionalities. In this respect, the proposed glass based lends itself ideally suited for integration with other MEMS devices because of its high optical transparency, the feasibility of high quality optical filter integration, the potentially high fill factor and the possibility to adapt the shape of the detectors to specific applications.

A. Mapelli et al. have developed a new type of scintillation particle detector with high spatial resolution and increased radiation hardness [28]. It consists of a single microfluidic channel designed to define a densely packed array of scintillating waveguides. A fraction of the scintillation light produced by the interaction of a particle with the liquid scintillator circulating in the microchannel is guided along one of the waveguides towards a photodetector. The devices have been fabricated by patterning high aspect ratio structures of the order of 20:1 in 200 micrometers thick layers of the SU-8 photoresist GM1075 from Gersteltec. The 10 micrometers wide structures are separated by 50 micrometers wide channels filled with a liquid scintillator. The 60 micrometers pitch of this novel microfabricated device is fully compatible with the dimensions of the a-Si:H photodiodes presented in this paper. A high spatial resolution microfluidic scintillation detector with integrated optical detection is currently under development. The compact design of such a device could be of interest for numerous applications such as X-ray imaging and *in situ* dosimetry in the medical or homeland security domain. Moreover the possibility to measure very close to the edge of the detector (up to a few micrometers) and the intrinsic radiation hardness of the device makes it particularly interesting for tracking particles in high energy physics experiments.

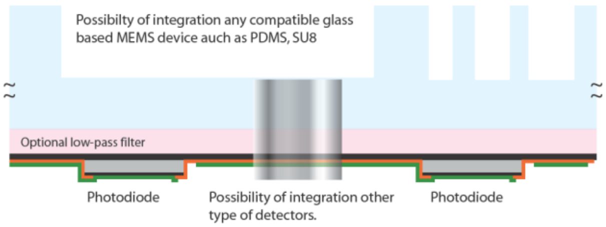

Figure 7. proposed device can be integrated with other MEMS sensor and also can be used as hybrid sensor by combing optical sensing with other detection technologies.

In addition, the proposed device can be used in the setting of a hybrid detector by integrating other types of sensors. Taken together, the high versatility regarding sensor integration and the possibility of a concomitant use of MEMS technology renders the device suitable for developing highly flexible sensing devices for solving specific and complex problems.

V. CONCLUSION

The concept and microfabrication steps of an optical photodetection system including optical filters for glass-based MEMS was presented. The system offers high photon detection sensitivity, potentially high spatial resolution and high biocompatibility. The fabrication technique can be used to construct, on the same structure, hybrid and high density detectors for multi-parameter, long-term measurement of biological preparations. The sensor is bio-compatible and can be integrated with other glass-based micro-fabricated devices such as micro-fluidics, chemical and biological devices in which photo-detection is a desired feature.

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