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Amorphous silicon photosensors for on-chip detection in digital microfluidic system

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ABSTRACT

In this paper we present the integration, on a single glass substrate, of amorphous silicon photodiodes with an electrowetting-on-dielectric (EWOD) system as a technological demonstrator for achieving a compact, stand alone Lab-on-Chip (LoC) system. The EWOD system comprises a thin film of indium tin oxide (ITO) acting as actuation electrodes and a 1 μm-thick polydimethylsiloxane (PDMS) layer acting as both insulation and hydrophobic layer. The a-Si:H photosensors are ITO/p-type/intrinsic/n-type/metal stacked structures, aligned with the transparent EWOD electrodes, to detect optical signals generated inside (or modulated by) the liquid droplets handled by the digital microfluidic system.

The fabrication process has been designed and performed taking into account the compatibility of all the technological steps of the photosensor and EWOD structures fabrication. The successful integration has been demonstrated checking the correct geometry of EWOD electrodes and measuring the optoelectronic performances of the a-Si:H photosensors at the end of the system fabrication. The correct operation and potentiality of the presented device has been assessed monitoring a photodiode current when a water droplet is moved forward and backward over the EWOD electrodes aligned with the photosensors.

1. Introduction

Lab-on-Chip (LoC) systems are miniaturized devices able to perform biomolecular analysis based on microfluidic network [1]. They take advantage of the miniaturization to reduce sample and reagent volumes, of the diffusion-limited kinetic to achieve faster reactions [2] and of the high parallelism to increase analysis throughput. These features lead also to a reduction of the analysis cost and of the environmental pollution.

The main shortcomings of the today LoCs are the limited miniaturization due to the lack of on-chip detection and the need for macro-to-micro interconnections for the fluidic handling. Both of these drawbacks lead to Chip-in-a-Lab system rather than true LoC device [3]. Although examples of on-chip detection [4,5] or microfluidic handling performed without interconnections between the microfluidic chip and external fluid [6] have been presented, none of the commercial available LoC or devices resulting from laboratory research combines the two on-chip features monolithically [7,8].

The reported on-chip detections have been performed integrating in the LoC device microelectrical sensors, based on the use of silica nanowires [9], impedimetric [10], surface acoustic wave [11], magnetic nanoparticles [12] and microantenna technologies, or photosensors [13] based on organic and amorphous silicon technologies. In particular, hydrogenated amorphous silicon (a-Si:H) photosensors [14,15] are appealing for LoC applications because, thanks to their low deposition temperature (around 200 °C), can be deposited on the substrate materials (silicon, glass) usually employed for the fabrication of microfluidic devices. Furthermore they present excellent optoelectronic characteristics such as high quantum efficiency (from 60% to 90% in the visible range) and low dark current (below 10^{-10} A/cm^2 at small reverse voltage). For these reasons, different research groups have already applied a-Si:H photosensors in labeled [16–18] and label-free [19,20] biomolecule detection techniques such as stimulated fluorescence detection [21], optical absorption measurements [22] and chemiluminescence detection [23–25].

On the other hand, the electrowetting-on-dielectric (EWOD) technique is able to handle very small fluid quantity [6] (down to picoliter) varying the contact angle of an electrically conductive liquid droplet placed on a hydrophobic surface by means on an external electric field [26–28]. This variation determines the change of the droplet shape that leads to fluidic operations

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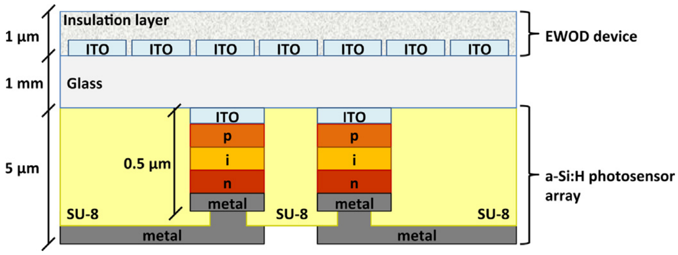

Fig. 1. Cross section of the LoC, showing the detailed structure of the EWOD device and the a-Si:H photosensors. The area of the EWOD electrodes is 1.5 mm × 1.5 mm or 2 mm × 2mm, while the area of the a-Si:H photodiode is 2.5 mm × 2.5mm or 3 mm × 3 mm, respectively.

as movement, mixing, splitting and dispensing from a reservoir [29].

Herein, we present the fabrication and characterization of a device, which integrates on a single glass substrate both on-chip detection, through amorphous silicon photosensors, and on-chip microfluidic handling, through EWOD. This technological demonstrator opens a route toward a true Lab-on-Chip system, avoiding external optics to focus the light toward a CCD camera as well as interconnections toward pumps or syringes.

2. Device operation and fabrication

The proposed device is fabricated on a 5 cm × 5 cm glass substrate. Its cross section is reported in Fig. 1. The top side of the glass holds the EWOD device, while the bottom glass side hosts the a-Si:H photosensor array. The structure of the EWOD device is constituted by transparent electrodes, covered by an insulating layer, aligned with the photosensors.

The presence of the liquid droplet over an electrode can cause a variation of the light impinging on the photodiode due to:

a. light generated inside the droplet due to chemiluminescent reactions or excitation of labeled or naturally fluorescent molecules.
b. optical absorption of an external radiation in label-free detection systems.

The light variation induces a variation of the photocurrent, flowing through the photosensor, which is related to the type and concentration of analyte inside the liquid droplet.

The area of the electrodes and the distance between them must be designed taking into account the size of the liquid droplet to move. The EWOD structure of our prototype has been designed to move a liquid drop of 2 μl.

On the opposite surface of the glass substrate, the area of the photosensors and the distance between them must be designed to maximize the detection of the radiation coming from the drop aligned with the sensor, and minimizing the inter-site crosstalk. The fraction of the emitted radiation impinging on the photodiode is related to the viewing angle of the sensor with respect to the droplet and can be calculated by geometrical considerations [30].

The fabrication procedure of the LoC has been designed and optimized to keep the functional compatibility of the different technological steps. In particular, the fabrication process starts with the deposition and patterning of the EWOD electrodes, proceeds with the deposition and patterning of the a-Si:H photosensor array and ends with the deposition of a polydymethylsiloxane (PDMS) layer. During the deposition of the a-Si:H sensors, the EWOD electrodes have been protected with a cured photoresist layer, in order to avoid any effect of the reagents used during the photolithographic and wet etching steps.

The fabrication process of the entire LoC requires 5 masks (reported in Fig. 2): one for the EWOD device and 4 for the a-Si:H photosensor array. Markers on both sides of the glass allow the alignment between the microfluidic device and the detection unit.

2.1. EWOD device

An indium tin oxide (ITO) layer deposited by magnetron sputtering is the material for the EWOD electrodes. Its deposition time is 15 min, which, taking into account the growth deposition rate of our sputtering system, leads to an estimated thickness of 180 nm. The need for transparent electrodes comes directly from the operation of the proposed system, where the presence of the droplet over the electrode modulates the light impinging on the photosensor. From transmittance measurement, we found that the ITO transmittance is greater than 80% for wavelength longer than 425 nm [31]. The ITO film has been patterned with mask #1 reported in Fig. 2, showing two linear arrays of 7 electrodes. The area of the electrodes is 1.5 mm × 1.5 mm and 2 mm × 2 mm for the upper and bottom array, respectively. In both arrays the distance between electrodes is 60 μm.

The electrodes are covered by a PDMS layer (Rhodorsil RTV 90700 from Siliconi Padova, Italy) deposited by spin-coating. The procedure for the PDMS deposition starts with the mixing of the two components of the elastomer in 1:1 ratio and degassing in a gentle vacuum for 2 min to remove the air bubbles. Subsequently, the PDMS is poured on the glass and spin coated with a two-step process: 5 s at 500 rpm and 30 s at 6000 rpm. The elastomer is then cured at 110 °C for 20 min. From measurement performed with interferometer equipment (Fogale from Nanotech) we found that the PDMS thickness is 1.3 μm.

In our EWOD device, the PDMS film acts both as dielectric and hydrophobic layer [32]. We found that the breakdown electric field is greater than 2 MV/cm allowing an actuation voltage greater than to 200 V. The contact angle, measured in a sessile drop experiment, is 104° at zero Volts confirming the layer hydrophobicity.

An electronic board generates the voltages for the electrode activation to achieve droplet movement, and includes a circuit, which detects the presence of the droplet over the electrodes comparing the discharge time of the electrode capacitance with respect to a calibrated time value. Details of the electronic board can be found in [29].

2.2. a-Si:H photosensor array

ITO/a-SiC:H p-type/a-Si:H intrinsic/a-Si:H n-type/metal stacked structures have been deposited and patterned to be aligned with the EWOD electrodes.

The photodiodes have been fabricated with the following technological steps:

a. deposition by magnetron sputtering of a 180 nm-thick ITO layer, which acts as transparent bottom contact of the diodes;
b. patterning of the ITO layer by dry etching process, aligning the markers of mask 2 with markers of mask 1 on the other side of the glass;
c. covering with kapton tape of the ITO markers to allow the subsequent alignments;
d. deposition by plasma enhanced chemical vapor deposition (PECVD) of the a-Si:H stacked structure p-type/intrinsic/n-type. The deposition parameters of the PECVD process are reported in Table 1. In particular, the p-type layer is a-SiC:H film grown in a mixture of silane and methane (and diborane) to obtain the high energy gap need for the window layer [33]. Furthermore, the selected deposition temperature and time of the intrinsic region ensure that the thickness and energy gap fulfill the requirements