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Integration of amorphous silicon balanced photodiodes and thin film heaters for biosensing application

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Abstract

This work presents the development and testing of an integrated system for on-chip detection of thermochemiluminescent biomolecules. The activation energy of the reaction is provided by a transparent structure of thin film heaters deposited on one side of a glass substrate. Light, passing through the substrate, reaches an array of amorphous silicon differential structure deposited on the opposite side of the glass substrate. The structure is designed to perform differential current measurements between a light-shielded diode, whose current is sensitive only to temperature, and a photosensor, sensitive to both incident light and temperature. The device therefore balances the thermal variations of the photodiode current and reduces the dark-current noise. These features make the presented system very appealing as highly miniaturized micro-analytical devices for biosensing applications.

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Keywords: amorphous silicon; balanced photodiode; thin film heater; lab-on-chip; thermochemiluminescence.

1. Introduction

Lab-on-chip systems [1] have gained great consideration by the scientific world, thanks to their potentiality to accomplish bio-chemical analysis in shorter times and with smaller reagent volumes with respect to standard laboratories [2]. In these systems, detection and quantification generally rely on optical techniques that are

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characterized by very high sensitivity [3]. In order to increase the compactness of the Lab-on-Chip system [4] without reducing the sensitivity performances, different approaches are investigated: (i) organic [5] and inorganic [6] thin film photodiodes, providing on-chip detection, have been proposed as alternatives to cooled CCD camera or CMOS imagers; (ii) thin film resistors [7] are utilized as substitutes of external bulky metal blocks to furnish the energy for the thermal treatment of the sample. Furthermore, from a bio-chemical point of view, bioluminescence and chemiluminescence approaches [8] are investigated as substitutes of fluorescence based systems. Recently, thermochemiluminescent nanoparticles have been proposed as labels for optical detection, particularly suited for Lab-on-Chip systems, as it provides high signal-to-noise ratio and reagentless trigger of the chemical luminescence process, which requires only heat [9]. Among inorganic thin film materials, a-Si:H photosensors present high quantum efficiency (from 0.4 to 0.8 in the visible range) and low dark current (around 10^{-10} A/cm² at small reverse voltage) [10]. These optoelectronic features coupled with the low deposition temperature, which implies the possibility to use different kind of substrates as glass or plastic, make a-Si:H photosensors appealing device for on-chip detection of biomolecules. However, thermal treatment of the analyte would alter the current flowing through the photodiode [11]. Indeed, under reverse bias conditions, temperature determines an exponential variation of the diode current, which is indistinguishable from changes due to the thermochemiluminescence.

In this framework, this work presents the fabrication, on the same glass substrate, of an array of amorphous silicon differential photodiodes [12] and thin film heaters for on-chip detection and thermal treatment of biomolecules. The thin-film heaters, deposited on one side of the glass substrate, provide the activation energy for thermochemiluminescent phenomena, while the differential pair of diodes, deposited on the opposite side of the substrate, detects the thermochemiluminescence rejecting at the same time thermal variations of the diode current.

2. Device structure and operation

A cross section of the system structure is shown in Fig. 1. The glass substrate hosts, on the upper side, a thin film of Indium-Tin Oxide (ITO), which acts as heater and, on the bottom side, an a-Si:H differential photodiode, constituted by a pair of p-type/intrinsic/n-type stacked structures. The two diodes are identical, but one is shielded from the incident light with a metal electrode. When a solution drop containing the thermochemiluminescent compound is spotted on the ITO, in correspondence of the differential photodiode, the thermal energy provided by the heater activates the thermochemiluminescence. The induced radiation reaches both diodes, but only the light impinging on the unshielded diode will be revealed. As the two diodes of the balanced structure are at the same temperature, the thermal variations of the dark current will be compensated.

This behavior is illustrated in Fig. 2, which represents the equivalent electric circuit of the differential diode connected to a current-to-voltage amplifier. I_{ph} is the photocurrent induced by the thermochemiluminescence, I_{t1} the dark current of the unshielded diode and I_{t2} the dark current of the blind (metal shielded) diode. As the two diodes of the balanced structure are at the same temperature, the thermal variations of the dark current will be compensated and I_{diff} will be identical, in ideal conditions, to I_{ph} .

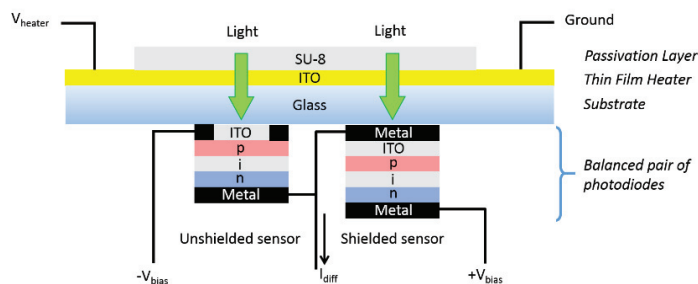


Fig. 1. System structure.

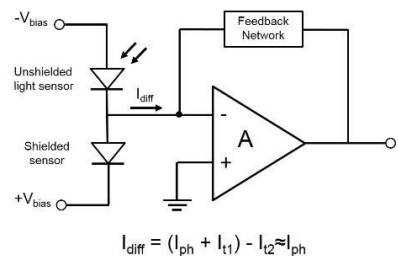


Fig. 2. Equivalent electrical circuit of the differential photodiode.

3. Fabrication and characterization of the structure

The technological steps for the integration on the same glass substrate of the thin film heater and the a-Si:H differential photodiodes have been optimized taking into account the deposition temperatures of the thin film materials and the etching procedures needed to define the device geometries. As a result of the optimization process, the sequence and main parameters of the fabrication steps are the following:

- Thermal evaporation and patterning of a stack Cr/Al/Cr (300Å/1500Å/300Å) and ITO (1500Å) layers acting as bottom electrode;
- Sputtering and patterning ITO (1500Å) layers acting as window layer for the unshielded diode;
- Deposition of the p-i-n a-Si:H layers by Plasma Enhanced Chemical Vapor Deposition (PECVD);
- Thermal evaporation of a metallic film (500Å-thick Cr film) acting as top contact and patterning of the sensors;
- Deposition of a passivation layer (SU-8 3005) and its patterning for the via-hole definition;
- Sputtering of a Ti-W metal layer film (500Å) and its patterning for definitions of the electrical connections;
- Spin coating of a SU-8 3005 layer and its patterning for the final passivation of the sensors;
- Sputtering of ITO (2000Å) film and patterning to define the heater geometry;
- Evaporation of a stack Cr/Al/Cr (300Å/1500Å/300Å) and patterning to define the heater electrical pads;
- Spin coating of a SU-8 3005 layer and its patterning for the final passivation of the heater.

A picture of the fabricated device is shown in Fig. 3. The left part of Fig. 3 is the glass side hosting the differential photodiodes, organized as an array of arranged in 5×6 array structure with: 20 differential diodes where each diode has a 1800×1800μm² active area; 10 differential diodes where each diode has a 800×800μm² active area. The right part of Fig. 3 is instead the glass side where are defined the thin film heaters. They are arranged as six lines aligned with the columns of the photodiode array. The region aligned with each differential structure is made only in ITO, while the other regions are stacked structures of ITO and Cr/Al/Cr layers. In this way, heating is limited to the area above the differential photodiode, where the heater resistance is higher.

Taking into account our previous works [12], where we have demonstrated the effectiveness of the differential structure in rejecting the common mode signal due to temperature variations, in this work we focus on the successful integration of the a-Si:H photosensors and the thin film heater. Characterization of the correct operation of the a-Si:H photosensors is inferred from Fig. 4, which reports the current-voltage curves of the single diodes of one differential structure. The blue symbols refer to the blind diode, while the red circles refer to the unshielded device. We observe that both curves present the typical diode behaviour (exponential in the forward bias region and almost constant at reverse voltage) and a very good symmetry between the two diodes. Furthermore, from measurements of the spectral response, we found that, for each differential structure, the quantum efficiency of the shielded diode is at least three orders of magnitude lower than the quantum efficiency of the photodiode. Testing of the fabricated heaters has been performed, instead, by powering one column of the heater at 230mA and monitoring the temperature distribution with an infrared camera (FLIR A325). From results reported in Fig. 5, we see that the thermal power is confined on the area above the differential structure with a quite uniform temperature distribution. Indeed, the average temperature inside the white zone, defined by the grey circle, is 83.6°C with a standard deviation equal to 1.3°C. This temperature satisfies the biological requirements for thermochemiluminescence experiments [9].

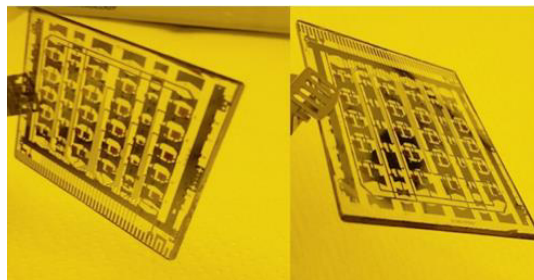


Fig. 3. Fabricated device.

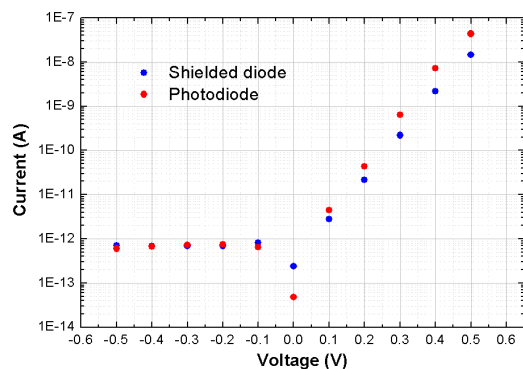


Fig. 4. Current-Voltage characteristics measured in dark conditions for the blind diode (blue circles) and the photodiode (red circles).

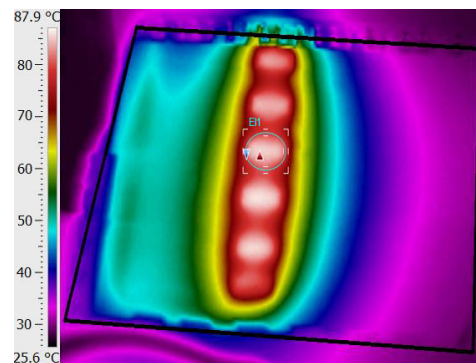


Fig. 5. Temperature distribution over a column of the heater biased at 230mA. The white regions correspond to the ITO zone.

4. Conclusions

This work has reported the successful integration, on the same glass substrate, of an array of a-Si:H differential photodiodes and thin film heaters for the on-chip detection and thermal treatment of biomolecules. The fabrication steps have been optimized taking into account the compatibility of the different microelectronic technologies and in particular the deposition temperatures and the etching procedures of the thin film materials. The correct operation of both the a-Si:H diodes and the thin film resistors have been experimentally demonstrated.

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