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Development of polysilicon devices for microfluidic thermal instrumentation

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ABSTRACT

In microfluidics applications such as biology and chemistry, for which lab-on-chip and microreactors have been developed, the temperature control through a microchannel is of first interest. In this paper, we present a simple and generic technology for thermal sensing applications based on the fabrication of polysilicon diodes that can be implemented either on silicon, fused silica or silicon carbide substrates. Thermal sensitivities were characterized and as a first experimental approach a dedicated set-up was developed for the temperature measurement of a water flow through a SU-8 microchannel.

1. Introduction

Integration of thermal instrumentation is important for various microfluidics applications (lab on chip, gas sensors, chemical microreactors, ...). Generally, defined devices are used to detect the temperature and its variations as well as for thermal actuation. The thermal sensor selection depends on the expected thermal sensitivity, the temperature range to be measured, the sensor size and the fabrication cost. It is also preferable to integrate the sensor with the microsystem fabrication. Various technological approaches have been developed for the precise and localized control of temperature. Among these, a few are interesting for chemical and biochemical microsystems: one can note the modification of the electrical resistance of a material and the thermal dependence of the electrical parameters of a semiconductor junction.

Resistive sensors are the most common found in the literature due to easy fabrication and a linear variation of resistances with temperature: different materials have been used (metal, polysilicon, ...) and processed on different substrates (silicon, silicon on insulator (SOI), dielectric membrane, glass, porous silicon, ...) with different designs (see Table 1 in Ref. [1]). In general, platinum and doped-polysilicon are mostly used for heaters fabrication because of their thermal stability (TCR of about $38 \times 10^{-4}\,{}^{\circ}C^{-1}$ for pure platinum) and good thermal conductivity [2].

Tin oxide (SnO_2) gas sensors are the most developed, often with resistive platinum heater on a SiO_2/Si_3N_4 membrane formed by silicon bulk etching for reducing power consumption: operating temperatures of 600 °C can be achieved and dissipated power of 50 mW at 300 °C [3]. Most recent technologies employed suspended membranes maintained by micro bridges [4–8]: in Ref. [5] a lower consumption of 6 mW at 300 °C is measured with a driving circuit in CMOS technology. Micro hotplates have also been developed on polyimide membranes, more robust and more adapted to the integration of metal-oxide layers [9].

For lab on chip applications, platinum resistances are largely used as heaters and thermal sensors, often fabricated on glass wafers and embedded within micro channels which are made with SU-8 epoxy resist [10] or micromachined into silicon by dry etching [11].

Some works have shown Tungsten-based SOI micro hotplates fabrication based on a commercial CMOS process [1]: it offers ultralow DC power consumption at high temperatures (12 mW at 600 °C), fast transient time (as low as 2 ms rise time to 600 °C), low cost and circuit integration [1].

First developed for integrated circuits, polysilicon is largely used for micro electromechanical structures as mechanical and sacrificial layer, but also as heater material for SnO_2 sensors: thermal performances are comparable with platinum ones. It allows size reduction and easy integration of both gas sensing and electronic

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IC areas. However, these structures operating at high temperatures (400–600 °C) are confronted with a temporal drift of the material resistance thus rendering the associated instrumentation critical, thus necessitating a regular calibration. This phenomenon can be neglected at lower temperatures (<100 °C) as encountered for lab-on-chip applications.

Electrical properties of silicon can be interesting for the fabrication of thermal sensing elements: in works reported in Ref. [12], the micro heater is a p-channel or n-channel MOSFET on SOI and the thermal sensor is a forward biased PN diode. An array of 32 × 32 diodes with an area of 8 mm × 8 mm is proposed in Ref. [13] with polysilicon heaters embedded on silicon and located around the diodes to control the temperature of the device: at 10 μA, each diode shows a thermal sensitivity of −2.2 mV/°C, to be compared to the values obtained for standard E or K-type thermocouples, in the order of 40–50 μV/°C. Only 64 interconnections pads are needed to measure the temperature in 1024 points instead of 1025 interconnections if thermal resistances are used. Diodes are particularly adapted to local temperature measurement, which is of primary interest for microfluidics applications. However, in that work, heating source and sensing element are dissociated thus making the device area larger. In the same way these structures are developed only on silicon substrates: this can be a limiting factor for some microfluidics applications for which glass substrates are often required.

In this context, we have developed a technology based on polysilicon material consisting to the ion implantation of localized N^+-doped regions through a P^+-doped polysilicon layer resulting in an association in series of P^+N^+ diodes successively biased in forward and reverse modes. For high doping levels, the P^+N^+ junction behaves as a Zener diode. Depending on electrical current levels, we have demonstrated that these diodes are able to operate both in thermal sensing or thermal actuating modes [14]. The thermal sensing zone is localized only at the P/N junction and to make a temperature detection into micrometric channels becomes possible.

In this paper we present the fabrication process and the electrical characterization of polysilicon diodes designed to obtain high thermal sensitivities at current levels of 1 μA and bias voltages lower than 5 volts to facilitate the implementation of the electrical instrumentation setup.

Heat conduction through a silicon substrate being a limiting factor because of its high thermal conductivity, we have investigated the capability to fabricate these polysilicon diodes on fused silica wafers of lower thermal conductivity (K_{TH} = 1.5 W/m K instead of 150 W/m K for silicon) but also on silicon carbide (SiC) wafers ($K_{TH\text{-}SiC}$ of about 200 W/m K). Because of its transparency, fused silica is interesting for observation of fluidics flows while SiC can be applied to harsh environments due to its high chemical resistance. The performances in terms of measured thermal sensitivities are presented for each developed device. First microfluidics experiments are described proving that this technology is promising for microfluidic thermal instrumentation.

2. Fabrication process

2.1. Polysilicon diodes development

The fabrication process presented in this paper is a generic one because it can be implemented onto various host substrates. It is based on the development of P^+N^+ diodes implemented through a polysilicon layer. The different technological steps are described in Fig. 1. First a 1 μm-SiO_2 passivation layer is obtained by wet thermal oxidation if conducting substrates are chosen. A 0.5 μm-polysilicon layer is then deposited by LPCVD (Low Pressure Chemical vapor Deposition) at 605 °C during 60 min. P-doping of the poly-Si layer is performed over the full wafer by Boron ion implantation at 50 keV with a 5×10^{14} cm^{-2} dose to obtain a doping level about 10^{19} cm^{-3} (Fig. 1.1), value which is a trade-off between the Zener voltage and the resistive conduction through this layer. The next step is the delimitation of the active poly-Si zones by CF_4-dry etching (Fig. 1.2). N^+-zones are defined by localized implantation of phosphorous, at 50 keV with a 2×10^{16} cm^{-2} dose (10 times the Boron's one to compensate the P-doping) leading to a 2×10^{20} cm^{-3} N-doping (Fig. 1.3). The active zones are then encapsulated by a 20 nm-Si_3N_4 cap layer prior to the implantation annealing at 950 °C during 1 h (Fig. 1.4). Electrical contact apertures are defined by Si_3N_4 dry etching (Fig. 1.5) followed by 0.6 μm-AlSi metallization (Fig. 1.6). After a wet etching of AlSi pads (Fig. 1.7) and electrical contacts annealing (400 °C – 1 h – N_2H_2), devices are passivated with a 0.5 μm PECVD (Pressure Enhanced Chemical Vapor Deposition) SiO_2 layer to prevent the $I(V)$ characteristics dispersion due to leakage currents. Finally, a SiO_2 dry etching defines the apertures over the contact pads (Fig. 1.8). An example of the obtained device is shown in Fig. 2a for a surface area of 200 μm × 200 μm: one can see the contrast between the different N^+ and P^+ zones.

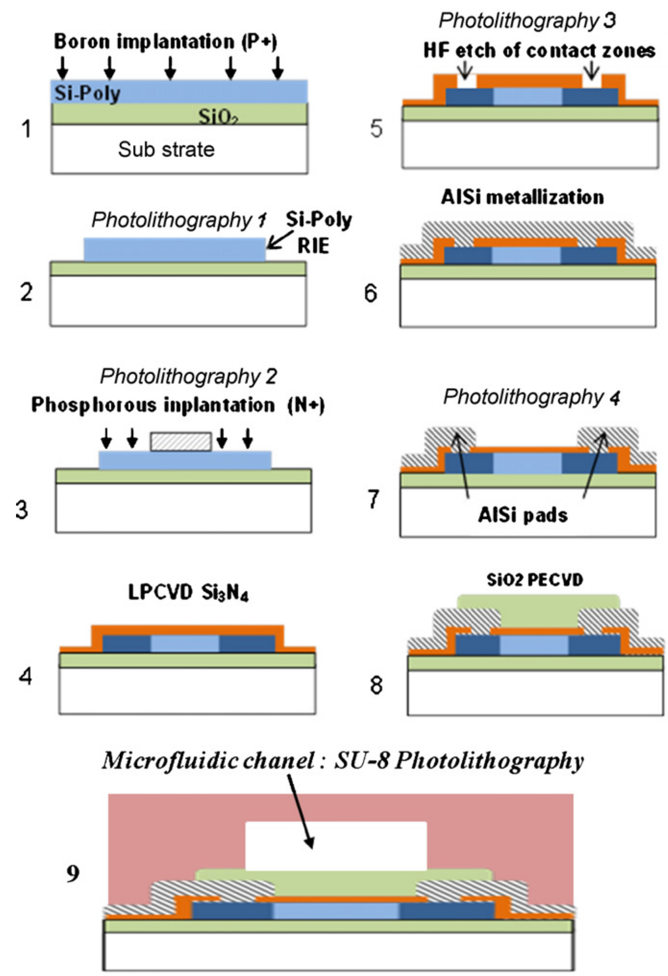

Fig. 1. Schematic cross sectional view of polysilicon PN diodes fabrication steps.

2.2. Implementation of the microfluidic part

In order to investigate the sensors capability for temperature measurement in microfluidics operating conditions, we have to perform the integration of a fluidic circuit on top of the devices as schematized on Fig. 1.9. To do that, after the polysilicon diodes