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Short Communication

Design and fabrication of bulk silicon-based temperature sensor[†]

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Abstract

This paper presents the design and fabrication of a bulk silicon temperature sensor based on the characteristic that resistivity of lightly doped silicon increases linearly with temperature. The sensor was fabricated on silicon wafer and two ohmic contacts taken across the sensor. The front contact was of a few micrometers in diameter and the back contact covers the whole counter surface of the sensor. A special technique of resistance measurement was used, which was based on the difference in size between the electrodes. The fabricated sensor has good repeatability, sensitivity and linear response with temperature in the range of –50° C to 150°C. Apart from these qualities, it is CMOS compatible, lightweight, small in size and comparatively cheaper than other temperature sensors.

Keywords Sensor, temperatures, silicon.

1. Introduction

Temperature measurement is required in applications ranging from industrial processes and space to biomedical instrumentation.Various types of temperature sensors have been developed and used for a variety of applications. These include resistance thermometers, thermistors, thermocouple and *p-n* junctions. The principal characteristics of temperature sensors are precision, linearity, sensitivity, repeatability, long-term stability, calibration procedures and dimensions.

In the temperature range of –273°C to 3000°C, thermocouples are the most versatile,[1] whereas metal resistance thermometers can be employed for temperatures from –273°C to 1000°C. Both types of sensors suffer from low sensitivity. Thermistors are usable over a range of –50°C to 150°C and exhibit good sensitivity. However, their resistance-temperature characteristic is exponential. In this range, one may employ a bulk silicon temperature sensor. Temperature coefficient of resistance (defined as the change in resistance per unit resistance at 0°C per degree rise of temperature) and sensitivity of this type of sensor can be much larger than metal thermometers and comparable with thermistors. Also, it is light in weight, small in size, much cheaper than other temperature sensors and can be integrated with signal processing chip.

2. Theory

Resistivity of *n*-doped bulk silicon is given by SZe[2]

$$\rho = 1/(\mu_e n_e e) \tag{1}$$

where e is the charge of electron (C), n_e, the free electron density (cm^{-3}) in silicon, μ_e the mobility of electron (cm^2/V-s) in silicon and ρ the resistivity (Ω cm) of silicon. Both μ_e and n_e are the

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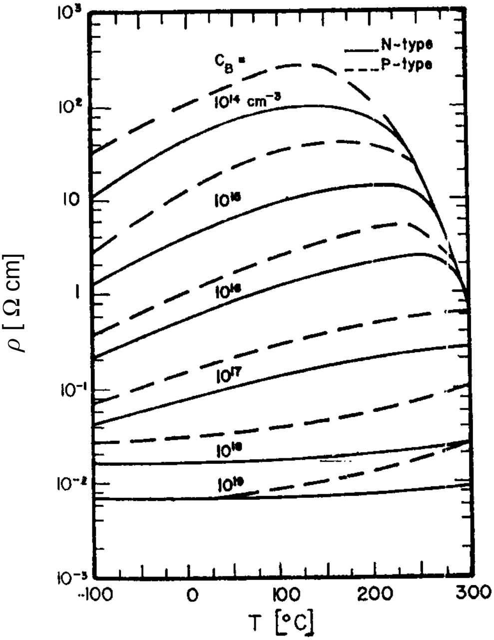


FIG. 1. Resistivity vs temperature plot of Si at various doping concentrations.

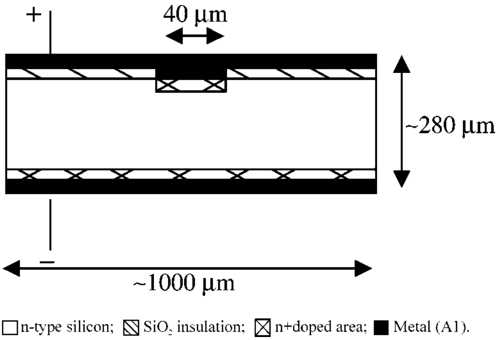
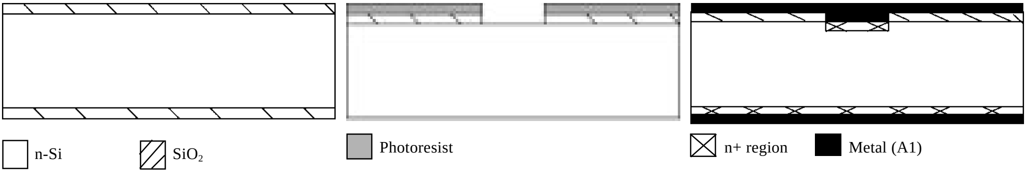


FIG. 2. Cross-section of bulk silicon temperature sensor.

functions of temperature and doping concentration. Extremely low-doped bulk silicon material shows a different mechanism of resistivity. At low temperatures (<−100ºC), the thermal energy in the crystal is not sufficient to ionize all the donor impurity present. Some electrons are 'frozen' at the donor level and free electron concentration is less than the donor concentration.[2] As the temperature is further increased, the free electron concentration approaches the same as the donor concentration over a temperature range of –100ºC to 150ºC.

Free electron mobility is also a function of temperature and doping concentration.[2] For lightly doped samples (e.g. the sample with doping of 10^{14}–10^{15} cm^{-3}), the lattice scattering dominates, and the mobility decreases as the temperature increases. For heavily doped samples, the effect of impurity scattering is most pronounced at low temperatures. Therefore, mobility increases as the temperature increases. For a given temperature, the mobility decreases with increasing impurity concentration, because of enhanced impurity scattering.

In short, at lower doping (10^{15} cm^{-3}) the concentration of free electron is almost constant and electron mobility decreases with temperature in the range of –50ºC to 150ºC. Therefore, resistivity increases with temperature in this range. Figure 1 shows the resistivity vs temperature curve of silicon in the extrinsic region at different doping concentrations.[3] In this region, resistivity of the lightly doped sample increases with temperature whereas the resistivity of heavily doped sample is almost constant. This is because of the different scattering mechanisms at different doping concentrations at a given temperature. The plot of resistivity vs temperature on the linear scale at doping concentration of around 10^{15} cm^{-3} is linear in the temperature range of –50ºC to 150ºC. This linear increase in resistivity with temperature is exploited for bulk silicon-based temperature sensor.



(a) Oxidation on *n*-type <100> silicon wafer.

(b) Lithography and oxide etching.

(c) Phosphorus diffusion and metallization.

FIG. 3. Fabrication steps for bulk silicon temperature sensor.

3. Design

The mechanism described above was used practically to design the bulk silicon temperature sensor. A special technique of resistance measurement was implemented based on differences in size between the electrodes used for measurement.[4] Figure 2 shows the basic layout of such a sensor made by using microelectronic technology. In this sensor, one electrode is only a few micrometers in diameter, while the other covers the whole back surface of the semiconductor piece.[5] In accordance with the geometry of the sensor shown in Fig. 2, the resistance of the sensor is given by

$$\mathrm{R} = (\rho/2\pi)\int_{ro}^{\propto} r^{-2}\,dr = \rho/2\pi r_o = \rho/\pi \mathrm{d} \qquad (2)$$

where R is the resistance of the sensor, r_o and d are the radius and diameter of smaller electrode, respectively. Since the radius of curvature r_o is very small (40 μm) the spreading resistance would

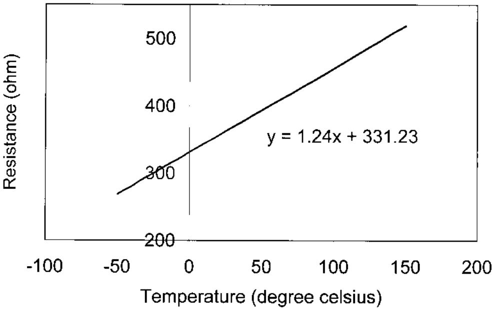


FIG. 4. Resistance vs temperature plot of the sensor.

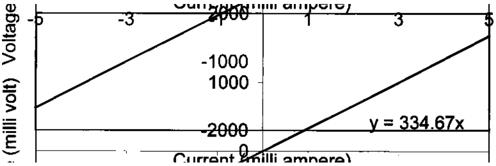


FIG. 5. I–V Characteristic of the sensor at 0°C.

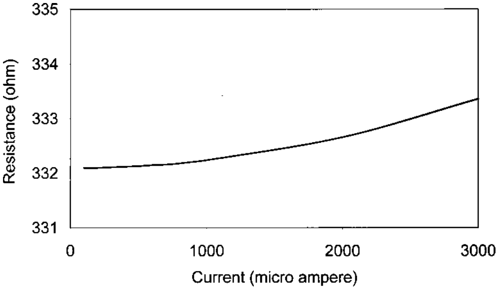


FIG. 6. Resistance vs current plot of the sensor at 0°C.

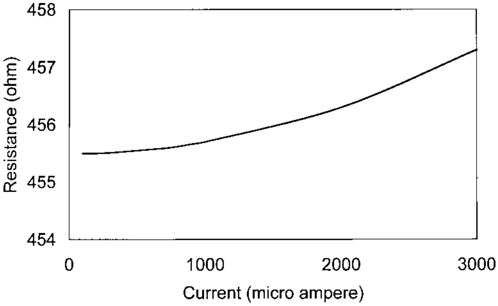


FIG. 7. Resistance vs current plot of the sensor at 100°C.

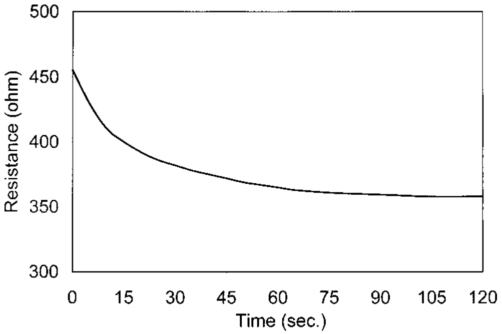


FIG. 8. Transient response of the sensor in air.

have attained higher values. *n*+/*n* contact[4] was made by phosphorus diffusion to form an ohmic contact between the metal and the semiconductor.[4]

4. Fabrication

The sensor was fabricated using microelectronic technology. The major fabrication steps are given in Fig. 3.

5. Results and discussion

Temperature vs resistance plot (Fig. 4) shows that the resistance of the temperature sensor increases linearly from 268 to 519 ohm with increase in temperature from –50ºC to 150ºC. Resistance value at a particular temperature was found to be the same in all the measurements. This shows that the fabricated sensor has a good repeatability. Temperature coefficient of resistance and sensitivity of the sensor were found to be $3.76\times10^{-3}\,K^{-1}$ and 1.24 Ω/K, respectively.

Figure 5 shows that current vs voltage (I–V) characteristic of the sensor is perfectly linear indicating the contact between the metal and the semiconductor is perfectly ohmic,[4] even at low current.

Figures 6 and 7 show a slight increase in the resistance of the sensor with increase in temperature. This is due to self-heating of the sensor. This variation in resistance was found to be slightly more at higher temperature as compared to lower temperature as expected. These figures also show that the change in resistance is negligible up to 1 mA. After that, the increase in resistance is slightly higher. Hence, the operating current of the sensor should be less than 1 mA.

Transient response time of the sensor in air was calculated by the transient response characteristic (Fig. 8). Response time and t_{90} time of the sensor was 18 and 55 s, respectively, and the time taken by the sensor to reach its final value was 115 s in air, and less than 1 s in water.

6. Conclusion

The fabricated sensor has good repeatability, sensitivity and linear response with temperature in the range of –50ºC to 150ºC. It is also light in weight, small in size, and comparatively cheaper than other temperature sensors.

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