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An analytical two-dimensional model for circular spreading-resistance temperature sensor based on thin silicon film

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Abstract

An analytical two-dimensional model is developed to explain the minority-carrier exclusion effect in circular spreading-resistance temperature (SRT) sensor fabricated on thin silicon film. The model can be used to show the relation between minority-carrier exclusion length and maximum operating temperature of the sensor under different bias currents and different doping levels. Comparison is made between the proposed model and the conventional one-dimensional model used for similar sensors with rectangular shape. Experimental results show that the new model is more accurate than the one-dimensional model for predicting the characteristics of the circular SRT sensor.

Keywords: Minority-carrier exclusion; Two-dimensional model; Temperature sensor; Silicon film

1. Introduction

Currently, there is a strong demand for electronic devices that can operate over a wide temperature range, such as those in the high-temperature portions of cars and aircrafts. Moreover, this demand is further increased by the development of high-fidelity sensors and control circuits used in space rockets, nuclear reactors and geothermal power generators. High-temperature sensors based on wide-bandgap semiconductors such as diamond and SiC have also been investigated in attempts to produce electronic devices operating reliably even at high temperatures [1–3]. However, it takes long time for wide-bandgap semiconductor sensors to become practical devices. Therefore, the development of high-temperature sensors based on the commonly used silicon and related technologies still continues.

Normally, devices based on silicon can only work below the intrinsic temperature of 250 °C due to excessive thermal generation of electron and hole pairs at high temperatures [4]. However, by introducing the spreading-resistance structure, the maximum operating temperature (T_{max}) of silicon temperature sensors can be increased. The first spreading-resistance temperature (SRT) sensor was introduced in 1982 [5] and commercialized in 1983 [6]. The structure of this SRT sensor is vertical as shown in Fig. 1(a). Silicon temperature sensors based on this spreading-resistance principle can work at temperatures from −65 to 300 °C. Later on,

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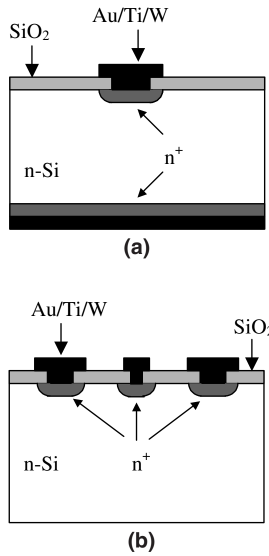

Fig. 1. Cross-sectional structure of (a) vertical SRT sensor, (b) lateral SRT sensor.

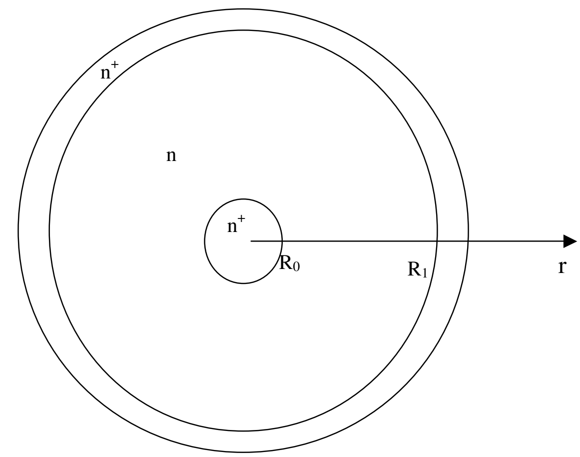

Fig. 2. Top view of two-dimensional lateral SRT sensor.

in't Hout and Middelhoek raised T_{max} of SRT sensors to 400 °C [7]. Moreover, they used the minority-carrier exclusion effect to explain the principle of spreading resistance from a physical view point and developed a one-dimensional model to accurately explain the characteristics of the vertical SRT sensors [7,8].

Recently, the lateral SRT sensor shown in Fig. 1(b) was studied. T_{max} of these SRT sensors ranges from 300 to 450 °C with substrate material used including bulk Si, thick-film silicon on insulator (SOI) and thin-film SOI [9–12]. Besides high working temperature, the lateral SRT sensor can be easily integrated into a microchip due to its planar structure. The lateral SRT sensor has an n^+ circle at the center surrounded by an n^+ ring. When a voltage is applied between the inner circular electrode and the outer ring electrode, a current flows radially from the inner circle to the outer ring. Although the old one-dimensional model can be used to approximately explain the circular sensor, a two-dimensional minority-carrier exclusion model is necessary to provide a more accurate description.

2. The exclusion effect

Fig. 2 is the top view of the sensor in Fig. 1(b). Since the electron concentration of the n^+ circle is much higher than that of the n region, the hole concentration of the n^+ circle is much lower than that of the n region. When an electric field is applied along the *r* direction, minority carriers (holes) flow from the n^+ circle to the n^+ ring while majority carriers (electrons) move in the opposite way. Near the inner n^+n high–low junction, holes in the n region are extracted by the electric field faster than those supplied by the n^+ circle due to the hole-concentration difference, and hence holes in the n region near the junction are reduced. If the electric field is strong enough, the hole concentration near the junction will be lowered to nearly zero even at high temperatures, and hence the electron concentration can be restored to the doping level due to the condition of space-charge neutrality. In other words, minority-carrier exclusion happens in a region next to the n^+ circle where thermally generated minority carriers are effectively removed. Since the extrinsic carriers dominate the electrical conduction, the resistance of the sensor is same as that before thermal generation due to high temperatures. This is why T_{max} of the sensor can be extended to higher values. Since the minority-carrier concentration does not really go to zero when exclusion occurs, a parameter α is used to define the extent of exclusion. The exclusion region starts when the minority-carrier concentration is reduced to αN_d, where N_d is the doping level of the n region. When electric field or current density is higher, more holes are extracted from the n region, resulting in longer exclusion region, and hence higher T_{max}.

3. Two-dimensional model

In order to construct a two-dimensional model for the sensor, the current in the vertical direction is assumed to be zero, like the case in the thin-film SOI sensor. R_0 is the radius of the n^+ circle, R_1 is the inner radius of the n^+ ring and *r* represents the distance from the center. Since the perimeter of circle is different along the *r* direction, the current density decreases in the same direction. As a result, current (*I*) instead of current density (*J*) is used to set the operating condition of the sensor.

The semiconductor transport equations based on the drift-diffusion model are given by