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Ultra-high temperature (> 300 °C) suspended thermodiode in SOI CMOS technology

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ABSTRACT

This paper reports for the first time on the performance and long-term stability of a silicon on insulator (SOI) thermodiode with tungsten metallization, suspended on a dielectric membrane, at temperatures beyond 300 °C. The thermodiode has been designed and fabricated with minute saturation currents (due to both small size and the use of SOI technology) to allow an ultra-high temperature range and minimal non-linearity. It was found that the thermodiode forward voltage drop versus temperature plot remains linear up to 500 °C, with a non-linearity error of less than 7%. Extensive experimental results on performance of the thermodiode that was fabricated using a Complementary Metal Oxide Semiconductor (CMOS) SOI process are presented. These results are backed up by infrared measurements and a range of 2-D (dimension) and 3-D simulations using ISE and ANSYS software. The on-chip drive electronics for the thermodiode and the micro-heater, as well as the sensor transducing circuit were placed adjacent to the membrane. We demonstrate that the thermodiode is considerably more reliable in long-term direct current operation at high temperatures when compared to the more classical resistive temperature detectors (RTDs) using CMOS metallization layers (tungsten or aluminum). We also compare a membrane thermodiode with a reference thermodiode placed on the silicon substrate and assess their relative performance at elevated temperatures. The experimental results from this comparison confirm that the thermodiode suffers minimal piezo-junction/piezo-resistive effects.

1. Introduction

Temperature sensors are one of the fastest growing segments in sensors' market. An integrated temperature sensor for thermal management is a core component in power hungry circuits that tend to operate close to the maximum junction temperature. In such systems, accurate monitoring of the junction temperature is mandatory to optimize the integrated circuits (ICs) performance while maintaining high reliability. Most of the Complementary Metal Oxide Semiconductor (CMOS) processes now target higher junction temperatures to allow increased packing density of transistors, better cost-performance value and more powerful processing. Maximum junction temperatures in bulk CMOS ICs have moved from a conservative level of 125–150 °C [1–4] and even to 175 °C. By using copper or tungsten, which are more resistant to electro-migration, some of these processes can potentially move to 200 °C, provided that they address issues like latch-up and low cross-talk, and overcome reliability problems such as negative bias temperature instability (NBTI), time dependent dielectric breakdown (TDDB), etc. Furthermore, the additional use of silicon on insulator (SOI) technology in ICs not only suppresses the latch-up but also minimizes the leakage currents. It also provides an excellent vertical and lateral isolation and thereby allows a further increase in the maximum junction temperatures to 225° or potentially even 250 °C. Such ICs can be of use in automotive electronics, power supplies, motor control or other power systems.

The silicon thermodiodes (i.e. silicon diode temperature sensors) have been reported in the past for diverse applications. These applications include, for example, temperature measurement for cryogenic applications [5–11], flow sensing [12–15], liquid–vapour interface and liquid level point sensing in hydrogen [16], humidity sensing [17–19], pH sensing [20], vacuum sensing [21], PC temperature monitoring [22], thermometry [17,23–25], thermal characterization of thermally conductive underfill for flip-chip packaging [26], pure gas and gas mixtures' thermal conductivity monitoring [27], temperature-compensation of piezo-resistive stress sensors [28], MEMS bolometers [29], infrared (IR) detectors [30] and IR focal plane arrays [31], etc.

Although most of these applications require maximum junction temperature below 200 °C and more often below 150 °C, yet there are some emerging silicon-based sensors for which accurate

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and reliable temperature monitoring is essential at very high temperatures (i.e. up to 500 °C), well beyond the junction temperatures of standard ICs. The examples of such applications are smart micro-calorimeters [32], resistive gas sensors [33,34] and sensors used in automotive engines, exhausts, etc. Such smart sensors use membrane technologies for thermal isolation of the sensors (e.g. micro-calorimeters) that typically operate at 400 or 500 °C. As a result, while the active sensing element (e.g. gas sensitive layer) suspended on a very thin dielectric membrane would operate at high temperatures for optimal sensing, the on-chip electronics can still operate very close to the ambient temperature. For such sensors, accurate monitoring of the temperature at the hot-spot of the membrane is absolutely essential to enhance the sensor sensitivity and selectivity (as it is the case in gas sensors) and last but not least, for reliability assessment. To meet the challenge of temperature monitoring in these sensors, there is a need for IC/CMOS temperature sensors that can provide accurate temperature measurement, are small in size, high in sensitivity, and reliable in performance beyond 300 °C. To the authors' knowledge, there have been very few reports [5,35–37] on IC temperature sensors that can operate at such high temperatures.

In this paper we will report on the use of a membrane thermodiode operating at temperatures well beyond 300 °C [38]. Linearity is preserved up to 500 °C and the maximum temperature, beyond which the saturation current becomes comparable with the drive current of the thermodiode, is around 600 °C. We demonstrate for the first time that at very high temperatures, the membrane thermodiode offers better reliability than equivalent metal resistive temperature detectors (RTDs) using CMOS metals such as aluminum or tungsten while maintaining very high linearity. Furthermore, we have seen no evidence of piezo-junction/piezo-resistive effect in the suspended thermodiode, which would otherwise limit the operation of silicon-based resistive sensors at very high temperatures.

2. Thermodiode design, fabrication and on-chip circuitry

In chemical sensor, the micro-hotplate (MHP) is a region of the sensor placed on a thin dielectric membrane, which contains a micro-heater. The temperature in this region is quasi-uniform and considerably higher than that outside the membrane. We designed our MHP to contain a tungsten micro-heater and placed the drive and signal processing electronics outside the membrane. For accurate monitoring of the MHP temperature we have placed a thermodiode, which we refer to as the membrane thermodiode, right in the centre of the membrane under the MHP. An additional thermodiode is placed outside the membrane to monitor the junction temperature of the IC chip (which in our case, where the IC power consumption is negligible when compared to that of the sensor, is often close to the ambient temperature). A schematic cross-section of the membrane thermodiode, a reference thermodiode and the CMOS electronic cells are shown in Fig. 1. The MHP, SOI thermodiode was designed in Cadence 5.0 software. The Cadence layout of the thermodiode is shown in Fig. 2(a). The diameter of the diode was ~34 μm. Note that the shapes of both the membrane and the MHP are chosen to be circular to minimize the mechanical stress at the membrane edge.

The thermodiodes integrated micro-hotplates were fabricated using a commercial 6 inch 1.0 μm SOI CMOS process. This process features a 0.25 μm active silicon layer, a 1.0 μm buried oxide layer and triple high temperature metallization based on tungsten. The use of tungsten metallization allows operation of the MHP at high temperatures (up to 700 °C). The tungsten layer was used for the resistive micro-heater (metal 1 layer), contacts of the two terminal diodes (metal 1, 2 layer) and interdigitated electrodes (metal 3 layers). These interdigitated electrodes are used specifically for gas sensing material's resistance measurement. After CMOS fabrication, the wafers underwent a single deep reactive ion etching (DRIE) back-etch step at a separate micro electrical mechanical systems (MEMS) foundry to form the thin oxide–nitride membrane (ca. 5 μm) in specific areas. The details of the micro-heater design and characterization have been reported elsewhere [39]. An optical microscope picture of the fabricated MHP (with the membrane thermodiode and micro-heater) is shown in Fig. 2(b). The diameter of the membrane on which micro-heater and thermodiode are embedded at its centre, is 300 μm. As already mentioned, a reference thermodiode was placed on the silicon substrate to monitor the ambient temperature and also assess the piezo-junction effect. The structure of the reference thermodiode is identical to that of the membrane

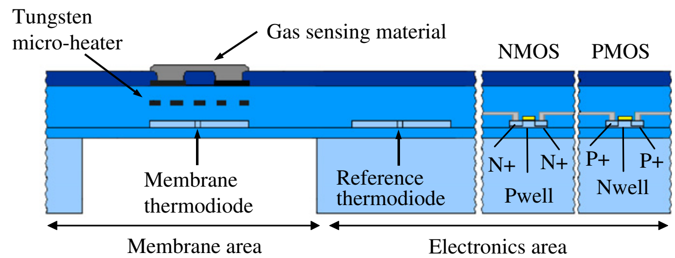

Fig. 1. Cross-sectional view of membrane thermodiode, a reference thermodiode and the CMOS electronic cells.

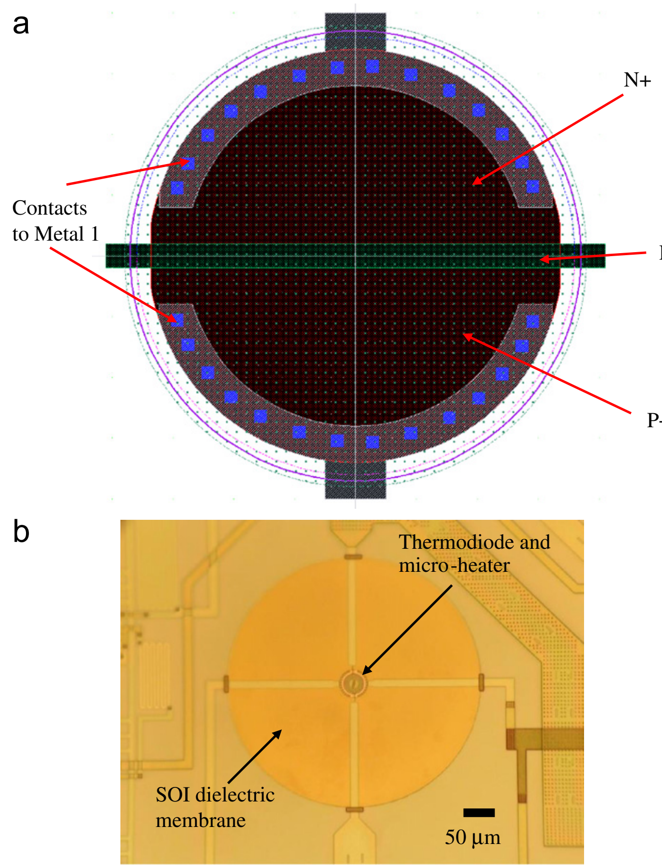

Fig. 2. (a). Cadence layout of the SOI p+/p/n+ thermodiode with diameter of 34 μm. (b). The optical micrograph of a fabricated micro-hotplate with SOI thermodiode temperature sensor embedded under the hotplate, within the oxide membrane.