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Experimental, analytical and numerical investigation of non-linearity of SOI diode temperature sensors at extreme temperatures

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ABSTRACT

This paper presents the performance of a silicon-on-insulator (SOI) p+/p-well/n+ diode temperature sensor, which can operate in an extremely wide temperature range of 80 K to 1050 K. The thermodiode is placed underneath a tungsten micro-heater which is embedded in a thin dielectric membrane, obtained with a post-CMOS deep reactive ion etching process. Analytical and numerical models are used to support experimental findings. Non-linearity, sensitivity and methods for their reduction and enhancement, respectively, are investigated in detail.

1. Introduction

Temperature is undoubtedly one of the most measured physical parameters, not only in science and technology but also in the everyday life. Some applications where the temperature needs to be measured accurately are as follows: meteorology, agriculture, automotive, medical, process industries, cryogenics, and consumer electronics. In order to satisfy many different requirements, in terms of temperature range, sensitivity, accuracy, linearity, frequency response, cost and dimensions, a wide variety of temperature sensors have been developed. An extensive review is given by Childs et al. [1]. Traditionally, thermometers are divided into electrical (thermocouples, thermistors, resistance temperature detectors, diodes and IC temperature sensors) and non-electrical (e.g. mechanical thermometers based on the thermal expansion of a substance) sensors, depending on the nature of their output. As electronics is now wide spreading, electrical sensors have started being significantly more employed than non-electrical ones, given their easier system integration. In the last two decades, the request for low cost CMOS compatible temperature sensors has exponentially increased, given the opportunity to embed the temperature sensor in the IC itself [2] or other sensing devices and the high reproducibility and yield characteristic to CMOS technology [3,4].

Some examples of other sensors requiring temperature sensors are listed in Table 1. Such sensors not only require their hot element temperature to be monitored and controlled in order to improve their accuracy but also ambient temperature to be monitored for compensation purposes. Ambient temperature compensation is often mandatory in many other types of sensors (not included in Table 1). Moreover, chip temperature monitoring and over-temperature protection circuits are embedded in complex ICs in order to prevent thermal failure. However, some of the applications afore mentioned require a temperature sensor which can withstand temperatures much higher than the CMOS maximum junction temperature (150 °C for standard CMOS and 225 °C for SOI). For many reasons diodes are the perfect candidates for temperature measurements in such applications: (i) they can be extremely small, (ii) they do not offer a thermal bridge between hot and cold zones, (iii) they are 'quite' linear, (iv) they have a wide range and (v) their sensitivity can be significantly enhanced by putting them in an array form.

Few studies focused on diodes performance at high temperature. Sakurano et al. [5] claim, that due to the reverse bias leakage current of the p–n junctions, bulk Si ICs cannot operate at temperatures higher than 150 °C. They propose a work function based SOI

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Table 1
List of sensors requiring integrated temperature sensor.

Sensor	Working temperature range [°C]
Chemoresistive gas sensors [13]	200–400
Thermal conductivity gas sensors [14]	>150
Humidity sensors [6,15]	>200
Pellistors [16]	200–600
Thermal flow sensors [17]	>200
Infrared emitters [18]	>400
Infrared detectors [19]	<200

temperature sensor, which can operate up to 250 °C. Kimura et al. [6] present an SOI thermodiode which can cover a very wide temperature range, from −200 °C to 500 °C. The diode is forward biased in the range −200 °C to 150 °C and reverse biased in the range 150 °C to 500 °C. The issue associated with this driving method is related to the leakage current, which is very low, and thus difficult to measure, and varies a lot from wafer-to-wafer (due to the variation of the carrier lifetime and the surface leakage currents). Further concerns are related to the diode driving current. As pointed out by Shwarts et al. [7], an increase in the driving current in order to increase the linear range of the diode, causes not only a reduction in the diode sensitivity but also an increase in the error associated to the measurement, due to the self-heating of the diode.

Our group has already shown that is possible to fabricate a thermodiode that can operate at record temperatures for silicon [8]. The diode performance was theoretically and experimentally investigated. Good agreement between experiments, simulations and analytical results was obtained. The linear dependence of the diode forward bias voltage on the temperature was maintained up to 615 °C, and trade-off between sensitivity and working range was shown. The piezo-junction effect was shown to be negligible (up to 300 °C) by comparing a diode embedded in the membrane with a reference diode placed on the substrate [8]. The thermodiodes have also shown to be fairly reliable after 100 h DC continuous operation at 500 °C and highly reproducible within the same wafer, wafer-to-wafer and lot-to-lot [9]. More recently, we also show that our SOI thermodiode can work in an extremely wide working temperature range (−200 °C to 700 °C) and that the self-heating effect can be neglected [10].

In this paper we experimentally, analytically and numerically investigate the performance of SOI thermodiodes. In particular, we focus on their non-linear behaviour at high temperature, showing what it is due to and methods for its minimization.

2. Design and fabrication

Several different chips (1 mm × 1 mm) comprising a microheater with one or more thermodiodes underneath have been designed using the CADENCE Virtuoso design platform and fabricated in SOI CMOS technology at a commercial foundry (Figs. 1 and 2). High temperature tungsten metallization has been used for the Si p+/p-well/n+ diode contacts and as resistive material for the microheater. Tungsten has been chosen due to its very high melting point (>3400 °C) and lower susceptibility to electromigration when compared to aluminium. The microheater has a circular multi-ring structure accurately designed to provide a highly uniform temperature distribution. The diode and the microheater are embedded in a ≈5 μm thick SiO_2 circular membrane, released by a post-CMOS Deep Reacting Ion Etching (DRIE) process step in the same foundry. During this fabrication step, the buried oxide layer (BOX) acts as an effective etch-stop. The DRIE process allows the realization of nearly vertical side-walls, permitting aggressive miniaturization. The circular design of the membrane allows the stress to be more uniformly distributed, compared to the square design where the stress is concentrated at the membrane corners.

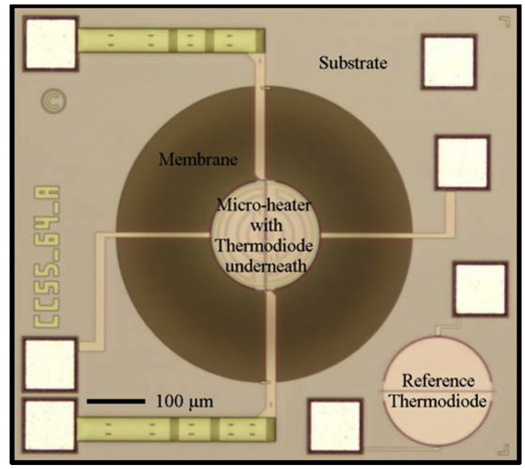

Fig. 1. Optical picture of a fabricated typical microhotplate with suspended thermodiode on the membrane (underneath the heater) and reference thermodiode on the substrate. The chip (1 mm × 1 mm) features a 600 μm diameter membrane and a 200 μm diameter heater.

This improves significantly the diaphragm mechanical robustness. The membrane thermally isolates the microheater from the substrate, allowing temperatures in excess of 1000 K to be reached in the heater area. Moreover, on-chip electronics can be integrated on the same die, outside the membrane, so that it will not be affected by the very high heater temperature. For ambient temperature monitoring, the presence of a reference thermodiode (identical to the suspended thermodiode) on the substrate is almost mandatory in most of the applications. Si_3N_4 is used for the passivation layer.

3. Experimental

In order to characterize the thermodiodes between 80 K and 1050 K, the calibration was split into two steps, low temperature (80–250 K) and high temperature (273–1050 K) measurements. Low temperature measurements (80–250 K) were done at chip level at 10^{-6} mbar. A cryogenic probe system (Suss MicroTech PMC200), equipped with a commercial Si-diode (DT670) for accurate temperature monitoring of the samples holder, was used for the measurements. Low pressure in the chamber can induce stress on the membrane and piezo-junction effect can influence the forward bias diode voltage drop. By comparing the diode voltage drop at 10^{-6} mbar and atmospheric pressure (at room temperature), it was concluded that low pressure in the chamber does not affect the diode characteristic. Furthermore, the actual temperature of the suspended diode might slightly differ from the temperature of the substrate in direct contact with the chuck, due to thermal isolation offered by the membrane. For this reason, the voltage drop across the diode embedded on the membrane was compared with the reference diode positioned on the substrate and no significant difference was observed.

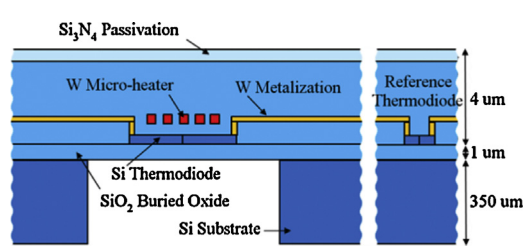

Fig. 2. Schematic cross-section (not to scale) of microheater, suspended thermodiode and reference thermodiode.