SOI Diode Temperature Sensor Operated at Ultra High Temperatures – A Critical Analysis

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Abstract— This paper investigates the performance of diode temperature sensors when operated at ultra high temperatures (above 250°C). A low leakage Silicon On Insulator (SOI) diode was designed and fabricated in a 1 µm CMOS process and suspended within a dielectric membrane for efficient thermal insulation. The diode can be used for accurate temperature monitoring in a variety of sensors such as microcalorimeters, IR detectors, or thermal flow sensors. A CMOS compatible micro-heater was integrated with the diode for local heating. It was found that the diode forward voltage exhibited a linear dependence on temperature as long as the reverse saturation current remained below the forward driving current. We have proven experimentally that the maximum temperature can be as high as 550°C. Long term continuous operation at high temperatures (400°C) showed good stability of the voltage drop. Furthermore, we carried out a detailed theoretical analysis to determine the maximum operating temperature and explain the presence of nonlinearity factors at ultra high temperatures.

I. INTRODUCTION

This paper reports on the performance of a Silicon On Insulator (SOI) diode with tungsten metallisation as a temperature sensor for operation at ultra high temperatures (> 300°C). The silicon p+/n/n+ junction diode was designed in a SOI CMOS process and embedded in a thin silicon/oxide membrane with a ring type resistive tungsten micro-heater. The structure was used as part of a resistive nanomaterial based gas-sensor and its response to gases at relatively low temperatures (< 250°C) have been reported elsewhere [1]. Interestingly it can be exploited in other CMOS compatible sensors that need to operate at higher temperatures (> 250°C) or high temperature environments: e.g. pellistors or automotive engines, exhausts etc.

In this paper we analyse in detail the behaviour of an SOI diode temperature sensor when operated well beyond its normal operating temperature. The diodes were heated up by the resistive micro-heater up to 780°C. It was found that the diode forward voltage vs temperature (*V*-*T*) plot remains linear up to 550°C, with a non-linearity error of less than 7%. To the authors' knowledge [2-4] this is the first study in the literature of a Si diode used as a temperature sensor above 400°C. The *V*-*T* characteristic plot becomes nonlinear above 550°C. Extensive simulations and analytical calculations were carried out to match the experimental results and explain the non-linearity factors at high temperatures.

II. DESIGN AND FABRICATION

The silicon diode was designed and fabricated in a 1.0 µm SOI CMOS technology with triple metallization layers. High temperature (tungsten) metallization was used for contacts to the two terminals of the diode (metal2), build the micro-heater (metal1) and form the top electrodes for sensing (metal3). The micro-heater and the temperature sensors are embedded in a larger membrane formed by Deep Reactive Ion Etching (DRIE) of the silicon substrate with the buried oxide acting as an etch-stop. An optical microscope picture of the top view of the fabricated device is shown in Fig. 1. The diode was placed at the centre of the membrane to enable accurate temperature measurement. The diode has a circular shape (diameter 30 µm) to match the heater (diameter 24 µm) and the membrane (diameter 300 µm).

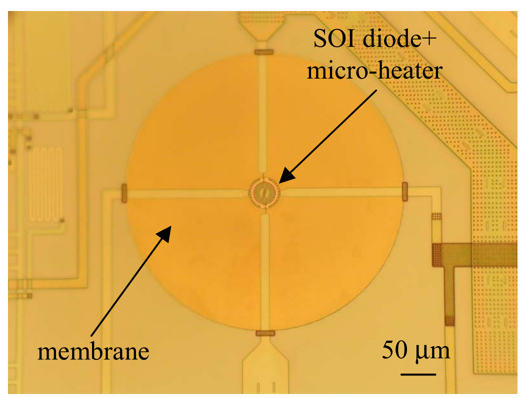

Figure 1. Fabricated micro-hotplate with embedded SOI diode temperature sensor

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III. Measurement And Characterisation

The micro-heater embedded in the membrane is used as a heat source. It was first calibrated with a high precision computer control hot chuck with 1°C resolution.

The silicon diode can be used as a temperature sensor when it is driven (in the forward bias mode) by a constant current source. It is well known that the diode forward voltage decreases linearly with temperature. To avoid self-heating but still provide a high ratio between the forward-bias (i.e driving) current and the reverse saturation (i.e. leakage) current, the maximum drive current was selected as 65 µA. The forward voltage across the diode was measured at different temperatures up to 780°C. To verify the repeatability of the results, the experimental characterization of the SOI diodes was first carried out on several devices across one wafer and then for several CMOS wafers. We concluded that the results are highly reproducible, in spite of the very high temperature of operation. This was encouraging and demonstrated a reliable SOI CMOS process.

A. Temperature Measurement

The forward voltage vs temperature plot is given in Fig. 2. The slope was found to be −1.3 mV/ °C when driven with a constant current of 65 µA. The diodes were driven using currents ranging from 14 nA to 65 µA. It was found that the *V-T* slope and the maximum operating temperature depends significantly on the driving current and the characteristic becomes nonlinear at high temperatures (>550°C).

B. IR Camera Measurement

The temperature distribution across the surface of the membrane was measured using an infrared camera (Quantum Focus Instruments Infrascope II). The maximum temperature allowed by the IR equipment was only 250°C. The temperature is relatively uniform over the heater area while it decreases rapidly beyond that, across the rest of the membrane as shown in Fig. 3. We therefore can assume that the temperature is constant within the heated area; hence there are no temperature gradients within the SOI diode.

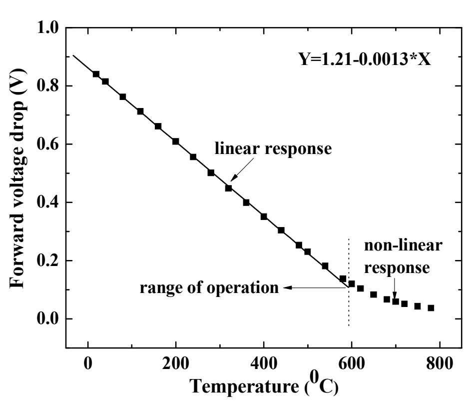

Figure 2. Forward voltage drop vs temperature plot of Si diode driven with a forward current of 65 µA

The SOI diode was operated at 300°C and 400°C for 100 hours continuously to check its long term stability (the drift in the voltage drop when supplied with a constant current). The maximum deviation was found to be 5°C and 7°C respectively at those temperatures (as shown in Fig. 4). This was slightly unexpected, but on a more detailed analysis revealed that this change was not predominantly due to the changing of the diode parameters, but due to the change in the electrical resistance of the tungsten micro-heater. Accounting for this change in the temperature, the drift in the diode output voltage was found to be only ~1°C.

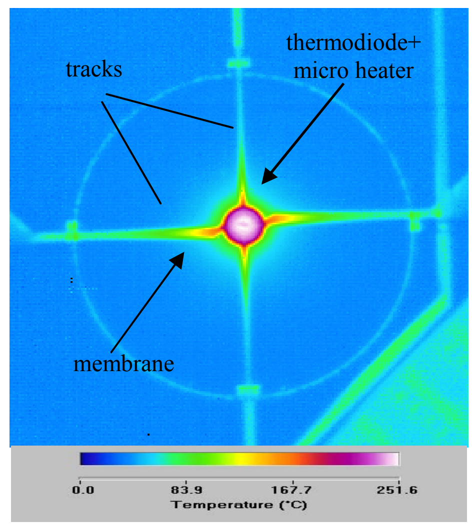

Figure 3. IR measurements of the microhotplate at 250°C. Note that the temperature profile is more accurate in the heater area as beyond this the dielectric membrane is transparent to IR

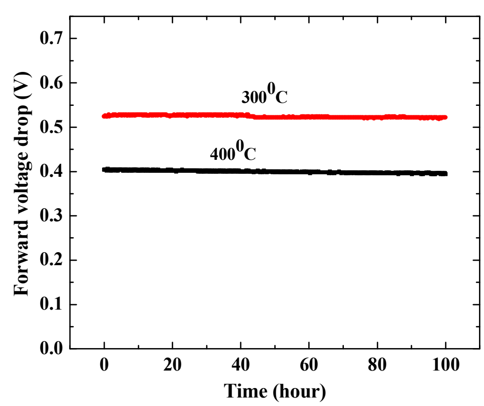

Figure 4. Long-term (continuous) testing of the SOI diode at 300°C and 400°C for 100 hours

C. Simulation and Theoretical Investigation

Extensive numerical simulations were carried out using ANSYS and ISE TCAD. The ANSYS simulation shows that the temperature distribution over the heater area is almost uniform which is consistent with the IR measurements. The ISE TCAD was used to simulate the *V-T* plot of our device. The standard diode equation for *p-n* diode is

$$I=I_s(T)(\exp(qV/kT)-1) \quad (1)$$

where I_s is saturation current, V is voltage drop across the diode, k is the Boltzmann's constant. The saturation current is expressed by the following equation

$$I_s=C\sqrt{T}\, n_i^2 = CT^{\eta}\exp(-(qV_g/kT)) \quad (2)$$

where C is a constant that includes the density of states, effective masses of electrons and holes, carrier mobility, doping density, recombination life time, junction area etc. η is a process dependent parameter (Si ~ 3.5), V_g is the extrapolated bandgap voltage at 0°K, n_i is the intrinsic carrier concentration in the semiconducting material. n_i has a very strong dependence on temperature given by the following formula:

$$n_i^2 \propto T^3 \exp(-(qV_g/kT)) \quad (3)$$

From (1), the voltage across the diode is

$$V=(kT/q)\ln(I/I_s(T)+1)$$
$$=(kT/q)\ln(I/I_s(T)) + (kT/q)\ln(I_s(T)/I+1) \quad (4)$$

Using (4) and (2) the voltage can be expressed as

$$V=V_g-(kT/q)\,\eta\ln T+(kT/q)\ln I/C + (kT/q)\ln(I_s(T)/I+1) \quad (5)$$

To develop the equation for V, the (5) is re-written for two temperatures, namely an arbitrary temperature T and a specified reference temperature T_r (keeping the current constant).

$$V = (V_g+\eta kT_r/q) - (V_g+\eta kT_r/q - V(T_r))T/T_r$$
$$+ \eta k/q\,(T - T_r - T\ln T/T_r) + kT/q\ln(I+I_s(T)/I+I_s(T_r)) \quad (6)$$

Therefore, the voltage across the diode is the sum of a constant term (first term), a term proportional to the absolute temperature (second term) and two nonlinear terms. Neglecting the two nonlinear terms the temperature gradient can be expressed as:

$$\mathrm{d}V/\mathrm{d}T = -(V_g + \eta kT_r/q - V(T_r))/T_r \quad (7)$$

At 300°K, V_g = 1.14 V, $V(T_r)$ = 0.85 V at 65 µA, the temperature gradient of the diode can be calculated as −1.3 mV/°K, which is the same as that determined from the experimental results.

In Fig. 5 we have plotted the experimental, simulated and theoretical data. The simulated and theoretical graphs are again in excellent agreement with experimental data.

IV. Discussion

The first non-linear term in (6) increases with temperature. However, this non-linear effect can be removed by using two driving currents with a known ratio for the same diode or by using the same current into two diodes of different areas with a given ratio. Nevertheless, it is very difficult to compensate the last nonlinearity term of (6). In Fig. 6 we have plotted the last non-linear term at 65 µA. It was found that the contribution of this non-linearity is negligible at low temperature. Its nonlinear behaviour becomes prominent at high temperatures (above 550°C). The reason for this linear operation up to 550°C is due to the use of a thin active silicon layer (i.e. SOI layer) with a very low volume of the depletion region. This results in a very low value of reverse saturation current (i.e. leakage during reverse bias), I_s ~ few fA. Hence, the increase in nonlinearity is directly caused by an increase in the saturation current at high temperatures (from (2) & (3)) which in turn is due to the rapid increase in the intrinsic carrier concentration. The intrinsic carrier concentration increases exponentially with temperature (e.g. at 27°C n_i is 9.5×10^9cm^{-3} and at 650°C n_i is 1.49×10^{17}cm^{-3}). At high temperatures, the saturation current is comparable or even higher than the driving current and the consequence of this is that the last term dominates over the other terms of (6). As a result the total resultant *V-T* plot becomes severely nonlinear as shown in Fig. 6. It was also found that the high temperature nonlinearity occurs at lower temperatures for lower driving currents. This is expected as the saturation current becomes dominant over the driving current at a lower temperature level. One can define the maximum operating temperature as the threshold temperature for the on-set of voltage-temperature nonlinearity. This can be calculated numerically by using the theory of nonlinear conduction in semiconductors [5], which relates the 'threshold' of the on-set of a nonlinear effect to the cancellation of the third derivative. As mentioned above, the nonlinearity of the *V-T* characteristics in our case comes from the presence of the last term in (6). The third derivative of this term can be calculated using Matlab and equate it to zero (other methods, such as, defining a maximum RMS error relative to a linear function can also be used). An example of the shape of the third derivative of the last term of (6) w.r.t temperature is shown in Fig. 7 for a 65 µA driving current. The maximum operating temperatures at 65 µA, 1 µA and 14 nA are 608, 445 and 327°C, respectively. The driving current vs. the maximum operating temperature is plotted in Fig. 8. An empirical exponential function can be fitted through points to relate the maximum operable temperature to the operating forward-bias current:

$$T_{max} = T_0 + A_1\times(1-\exp(-I/t_1)) + A_2\times(1-\exp(-I/t_2)) \quad (8)$$

where T_0, A_1, t_1, A_2, t_2 are constants. The values of these constants are 284.78, 142.07, 8.549E-8, 192.17, 1.65E-5, respectively.

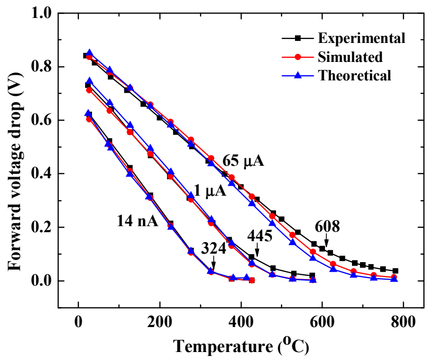

Figure 5. Experimental, theoretical and simulated *V-T* plot. One can see that there is reasonably good agreement between experimental data, finite element simulations and analytical calculations.

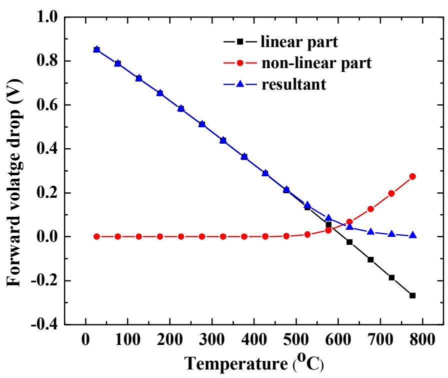

Figure 6. The Effect of the nonlinear term on the total voltage drop function of the temperature.

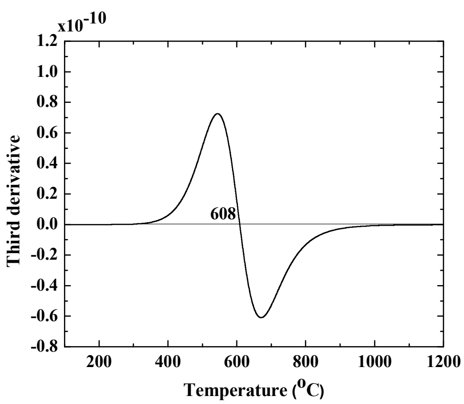

Figure 7. The third derivative of the nonlinear term of the diode voltage vs temperature equation for a driving current of 65 µA

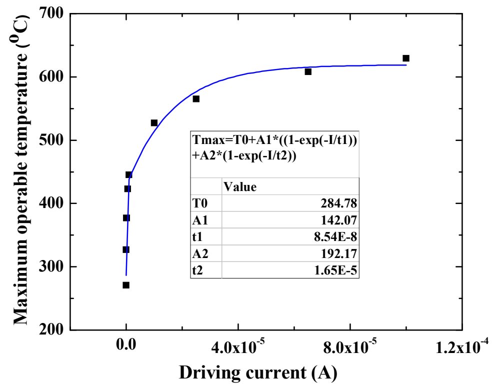

Figure 8. The maximum operable temperature of SOI diode for different driving currents

V. CONCLUSIONS

In this paper we have reported upon the performance of an SOI diode at ultra high temperatures (>250°C). The simulated and theoretical data are both in good agreement with the experimental results. We have demonstrated an SOI diode, embedded in a silicon/oxide membrane that can be used as a temperature sensor up to 550°C. The linearity maintained up to this high temperature is due to the very low reverse saturation current, I_s. It was found that performance of the diode deteriorates beyond these temperature levels due to a rapid increase in the diode saturation current. A long term, continuous operation at 400°C shows that the diodes are fairly reliable and the maximum deviation found was 1-2 mV corresponding to approximately ~1°C over a period of 100 hours.

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