

# CMOS TEMPERATURE SENSORS - CONCEPTS, STATE-OF-THE-ART AND PROSPECTS

Florin Udrea, Sumita Santra, Julian W. Gardner\*

Engineering Department, University of Cambridge, 9 JJ Thomson Avenue, Cambridge CB3 0FA, UK  
Tel: +44 (0)1223 748319; Fax: +44 (0)1223 748348, E-mail: fu10000@hermes.cam.ac.uk

\*School of Engineering, University of Warwick, Coventry CV4 7AL, UK

***Abstract**—The paper reviews the state-of-the-art in IC temperature sensors. It starts by revisiting the semiconductor theory of thermodiodes and thermotransistors, continues with the introduction of IC temperature sensors, the concepts of VPTAT – Voltage Proportional To Absolute Temperature and IPTAT (Current Proportional To Absolute Temperature) and discusses the possibility of use of parasitic bipolar transistors as temperature sensors in pure CMOS technology. The next section demonstrates the very high operating temperature of a ‘special’ thermodiode, well beyond the typical IC silicon junction temperature. This is achieved with a diode embedded in an SOI CMOS micro-hotplate. A discussion on the temperature limits of integrated temperature sensors is also given. The final section outlines the prospects of IC temperature sensors.*

## 1. INTRODUCTION

Temperature sensors are one of the fastest growing fields in the sensors market because of the abundance of applications where temperature must be monitored and controlled, including personal computers, mobile phones, gaming consoles, automobiles, medical equipments, process industries, nuclear plants, within different sensors and many others. A large variety of temperature sensors have been developed to match these widely varying technical and economic requirements of these applications. Discrete temperature sensors in the form of resistive temperature detectors (RTDs) (e.g. platinum thermometer), thermocouples (e.g. bimetallic layer) and thermistors (e.g. metal oxides) have been extensively used in the industries and laboratories over the last many decades. These temperature sensors are fairly accurate and can be used in wide range of temperatures (~ up to 2000 °K). However, in the last couple of years CMOS temperature sensors have become increasingly popular because of rapid steady growth of Integrated Circuit (IC) industry and the necessity of effective thermal

management in the power hungry circuits. Again, steady improvement in the semiconductor process technology is driving the upper temperature limit of circuit operation from 125°C to 200°C or even 250°C in the case of ICs fabricated in Silicon On Insulator (SOI) process technology. Moreover, the new generation of CMOS compatible micro-hotplates often require much higher temperatures (between 200 and 600°C) of operation, where the heating portion is kept isolated from on chip circuit area by surrounding dielectric. This kind of structure is useful in high temperature gas sensors [1-6] or shear stress sensors [7-8] where accurate on chip temperature measurement and control is extremely important. Silicon based RTDs, diodes and transistors are currently used as the best temperature sensors for IC compatibility. Temperature sensors are also necessary in other sensors, such as flow sensors [9], pressure sensors [10-11], IR detectors [12-14], humidity sensors [15-16] etc. Cryogenic operation of ICs [17-19] is also another important use for CMOS temperature sensors. In this application not only that the sensor has to endure very low temperatures, but also there are situations when it is immersed in a strong magnetic field and/or a radio frequency field.

The basic and most accurate CMOS temperature sensor is the silicon *p-n* junction diode (i.e. thermodiode). The silicon bipolar junction transistor (BJT) can also be used as a temperature sensor when operated in a diode configuration (base and collector shorted). Extensive work on BJT temperature sensors has been carried out by a group of Delft University [20-22]. Often temperature sensors are integrated with smart processing circuits to form IC temperature sensors [23-26], because temperature measurement alone is not sufficient. The temperature reading must be interpreted properly and processed so that appropriate

actions can be taken to counteract any unwanted temperature fluctuations.

This paper will review the concepts of different CMOS temperature sensors (thermiodiode, BJT, MOS transistor as BJT etc). The paper also describes the state-of-the-art smart IC temperature sensor. The detail analysis of a thermiodiode (with low reverse saturation current), which has the potential to use for high temperature measurement ( $>300^\circ\text{C}$ ), will also be discussed. The paper concludes with a discussion of the future prospects of CMOS temperature sensors.

## 2. THERMIDIODE

The application of diodes and transistors as modulating thermal sensors was first proposed in 1962 by McNamara [27]. A clear description of the operation of diodes and transistors as thermal sensors has been given in Meijer [20]. Potential advantages of thermiodiodes over other types of thermal sensors include their compatibility with IC technology and low manufacturing cost. It is well known that the diode forward voltage decreases linearly with temperature when driven by a constant forward current. This property is exploited to use it as a temperature sensor.

The ideal current  $I$  voltage  $V$  equation of a  $p$ - $n$  junction diode is given by

$$I = qA \left( \frac{D_p}{L_p} p_n - \frac{D_n}{L_n} n_p \right) \left( e^{\frac{qV}{kT}} - 1 \right) = I_s(T) \left( e^{\frac{qV}{kT}} - 1 \right) \quad (1)$$

where  $D_n$  and  $D_p$  are the diffusivity of the electrons and holes respectively,  $L_n$  and  $L_p$  are diffusion length for the electrons and holes respectively. The saturation current  $I_s$ , constant at a particular temperature  $T$ , is related to the junction area  $A$  and different junction parameters.  $n_p$  and  $p_n$  are the minority carrier in  $p$ -type and  $n$ -type respectively at equilibrium, they can be expressed as:

$$n_p = \frac{n_i^2}{N_a}, p_n = \frac{n_i^2}{N_d} \quad (2)$$

where  $n_i$  is intrinsic carrier concentration in the semiconducting material.

$n_i$  has a very strong dependence on temperature [28]

$$n_i^2 \propto T^3 e^{-\frac{qV_g}{kT}} \quad (3)$$

In the case of forward conduction at low temperatures (below  $300^\circ\text{C}$ ), equation (1) becomes

$$I = I_s \exp(qV/kT) \quad (4)$$

From equations (1) and (2) we can see that the diode saturation current is proportional to  $n_i^2$ , and the saturation current can be expressed as

$$I_s = CT^\eta e^{-\frac{qV_g}{kT}} \quad (5)$$

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. In the above equation,  $\eta$  ( $\text{Si} \sim 3.5$ ) is a process dependent parameter.

The voltage across the diode is (from equation (1))

$$\begin{aligned} V &= \frac{kT}{q} \ln \left( \frac{I}{I_s(T)} + 1 \right) \\ &= \frac{kT}{q} \ln \left( \frac{I}{I_s(T)} \right) + \frac{kT}{q} \ln \left( \frac{I_s(T)}{I} + 1 \right) \end{aligned} \quad (6)$$

Using equation (5) and (6) the voltage can be expressed as

$$V = V_g - \frac{kT}{q} \eta \ln T + \frac{kT}{q} \ln \frac{I}{C} + \frac{kT}{q} \ln \left( \frac{I_s(T)}{I} + 1 \right) \quad (7)$$

To develop the equation for  $V$ , equation (7) is written at two temperatures, an arbitrary temperature  $T$  and a specified reference temperature  $T_r$  (keeping the current constant).

$$\begin{aligned} V &= \left( V_g + \frac{\eta k T_r}{q} \right) - \frac{V_g + \frac{\eta k T_r}{q} - V(T_r)}{T_r} T \\ &+ \frac{\eta k}{q} \left( T - T_r - T \ln \frac{T}{T_r} \right) + \frac{kT}{q} \ln \left( \frac{I + I_s(T)}{I + I_s(T_r)} \right) \end{aligned} \quad (8)$$

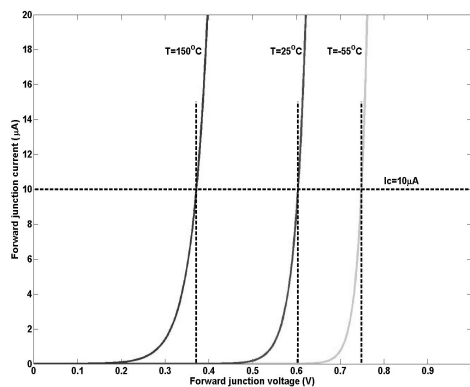
Therefore, the voltage across the diode is the sum of a constant term (first term), a term proportional to absolute temperature (second term) and two nonlinear terms. Neglecting the two nonlinear terms the temperature gradient can be expressed as

$$\frac{dV}{dT} = - \left[ V_g + \frac{\eta k T_r}{q} - V(T_r) \right] \frac{1}{T_r} \quad (9)$$

For silicon, taking  $V(T_r) \cong 0.6\text{V}$  at  $300^\circ\text{K}$  the bandgap,  $V_g = 1.14\text{V}$ , the temperature gradient of the diode can be calculated as  $-2.1\text{ mV}/^\circ\text{K}$ . In

practice this varies from  $-1.2$  to  $-2.2$  mV/°K depending on the forward driving current (as  $V(T_f)$  is not constant and varies with the forward current as given by equation (1), technology, the physical parameters of the junction and the geometry). The lower absolute value of this coefficient (i.e.  $-1.2$  mV/°K) is generally expected when the forward current is higher leading to higher forward voltage  $V(T_f)$  and the junction exhibits parasitic series resistances.

Fig. 1 shows the diode  $I$ - $V$  forward characteristics of a silicon thermodiode at different temperatures. The voltage drop decreases with increase in temperature for the same current level.



**Fig. 1.**  $I$ - $V$  forward characteristics of a thermodiode at different temperatures. The forward voltage drop varies from 0.6 V at room temperature (25 °C) to 0.75 V at  $-55$  °C and 0.37 V at  $+150$  °C.

When the diode is used as a temperature sensor it is best to operate it at relatively low forward currents/low power to avoid self-heating, the influence of the series resistances, and to increase the sensitivity to values closer to  $-2.2$  mV/°K. To further increase the sensitivity, one can use either two or more diodes in series or, if possible, an on-chip analogue amplifier.

The useful temperature range for the diode is typically between  $-100$  to  $250$ °C, however to preserve accurate linearity and be compatible with typical IC junction temperatures, the scale is generally restricted to  $-55$  to  $150$  °C for a bulk silicon process and  $-55$  to  $200$  °C for SOI. Over this limited temperature range, thermodiodes offer a low cost way of measuring temperature to a reasonably good accuracy.

### 3. THERMOTRANSISTORS

The voltage between the base and emitter of the transistor,  $V_{BE}$ , is temperature-dependent with a relationship similar to the diode expression. In fact a thermodiode can be simply obtained by short-circuiting the base to the collector of the transistor and the only active junction is that formed between the base and emitter diffusion regions. Often in an IC, the diodes are made of bipolar transistors with the base and collector connected together. A more sophisticated and considerably more accurate method to measure temperature with one diode is to apply first a high forward bias current  $I_{C1}$  to its terminals and then, secondly, a low forward bias current  $I_{C2}$ . The difference in the voltage drop  $\Delta V_{BE}$  now only depends upon the ratio of these two currents rather than the geometrical or material factors. Writing the well-known equation from (4) for two values of the current  $I_{C1}$  and  $I_{C2}$  and, knowing that the saturation current is the same, one can find a relationship between the voltage drop difference and temperature ( $I_{C1} \gg I_{C2}$  and  $N = I_{C1}/I_{C2}$ ):

$$\Delta V_{BE} = (V_{BE1} - V_{BE2}) = \frac{kT}{q} \ln\left(\frac{I_{C1}}{I_{C2}}\right) = \frac{kT}{q} \ln(N) \quad (10)$$

In this way one removes all the material/geometrical/process variations related to the diode manufacturing process.

Bipolar transistors (BJTs) with superior performance are commonly met in analogue, mixed-signal or RF processes. Lateral bipolar transistors or the parasitic substrate transistors can also be used as thermotransistors in CMOS technology.

The generation of  $\Delta V_{BE}$ , the base-emitter voltage drop difference can be carried out in several ways (Fig. 2)

(i) Using one transistor and applying two different emitter currents (with a known ratio  $N$ ) at different times through a switch (note that the base current is negligible and the emitter current is approximately equal to the collector current).

(ii) Using two identical transistors (placed side by side) and operated with two constant currents in their emitters with a known current ratio  $N$ .

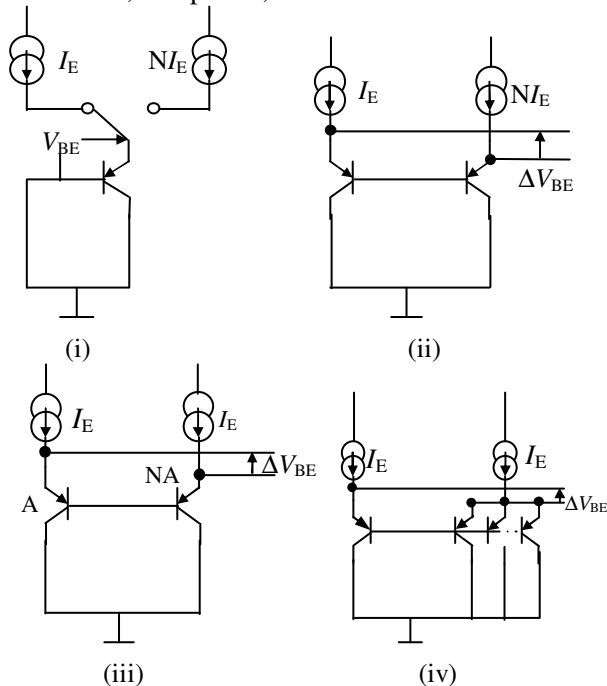
(iii) Using two identical constant current sources driving two transistors that sit side by side, the two transistors having different areas with a ratio  $N$ .

(iv) Using one constant current source driving one transistor and an identical current source driving  $N$  identical transistors in parallel that sit side by side.

Fig. 2 shows schematic circuits that are able to generate  $\Delta V_{BE}$  using  $p-n-p$  transistors. A similar implementation is possible using  $n-p-n$  transistors and constant current sources attached to the collector terminals.

#### 4. IC TEMPERATURE SENSORS

Integrated circuit (IC) or smart temperature sensors is a new class of thermal sensors that has emerged in the last decade and is now one of the main driving forces in sensor development. The field was initially driven by automotive electronics but has now moved into lower power, higher volume products such as mobile phones, LCD TVs, computers, and PDAs.



**Fig. 2.** Generation of  $\Delta V_{BE}$ : (i) using a single transistor, a switch and two different current sources, (ii) using identical transistors and two current sources with different currents, (iii) using identical current sources and two transistors with different emitter areas, and (iii) using identical current sources and a combination of multiple identical transistors. A combination of these techniques is also possible.

Such sensors monitor the temperature in CPUs, batteries, power ICs, motherboards, hard disc drives, in essence everything that is exposed or produces heat. Moreover, unlike any other thermal sensors, the IC temperature sensors can

be directly embedded into the heat source to detect with high precision the hotspot temperature. Virtually all the CPUs today have an on-chip thermodiode (or thermotransistor) that can be connected remotely to a temperature sensor which measures accurately the silicon temperature, rather than package temperature. They also react instantly to temperature changes (as the thermal impedance from the heat source to the sensing element is extremely small and certainly negligible when compared to the junction to ambient thermal impedance). The IC temperature sensor can send signals to a cooling fan or lower the clock frequency, change the duty cycle or stop momentarily the clock when a safe limit of temperature is exceeded. New IC temperature sensors are fully programmable, and contain a smart controller. Not only do they allow the set up of the safe temperature limits, the hysteresis cycle but they can also decide on the best combination of fan speed/clock-stalling/duty cycle change to respond to overheating. The IC temperature sensors today have an overwhelming impact in increasing the system reliability and improving performance without resorting to over-designed, expensive cooling hardware, or running at a reduced performance, based on the worst-case scenario for the heat dissipation.

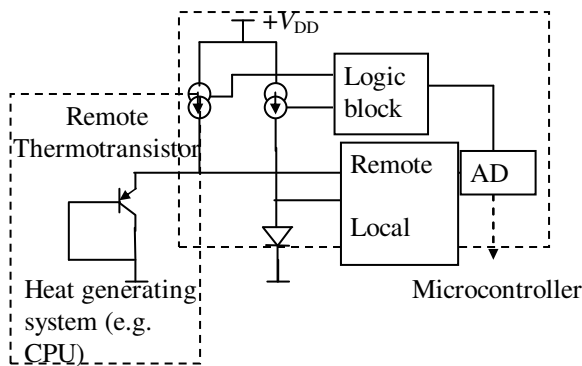
Comprehensive articles and application notes describing the benefits of IC temperature sensors are freely available on the web. A nice example is 'IC temperature Sensors - Find the hot spot' [29].

IC temperature sensors differ from the more traditional resistive or thermocouple sensors in several ways. They are cheaper, easy to integrate and they generally do not need cold-junction compensation or complex, linearization circuits. They can measure both the absolute and differential temperature, easily. They have a very low thermal mass and they can have a fast transient response, especially when the sensing element (thermodiode) is fully buried within the heat source. In addition, the IC temperature sensors benefit from on-chip associated electronics, such as signal processing circuits and smart controllers. These advantages make them easily the most attractive class of temperature sensors. Nevertheless they have limited range of operation (typically  $-55^{\circ}\text{C}$  to  $+150^{\circ}\text{C}$ ) and their

accuracy, while in most cases acceptable, is below that of platinum RTDs.

### A. Remote Sensing

Remote sensing of the temperature is one of the most exciting applications of the IC sensors. One can mount a remote thermodiode (or thermotransistor) inside the same package or, in best case, inside the same piece of semiconductor as that of a system that generates heat. Such a system can be a micro-processor, a power integrated circuit or a battery operating near its maximum junction temperature. The rest of the IC temperature sensor does not need to make direct thermal contact to the system but can be mounted away from it. Instead, the IC sensor can measure both the temperature of the heat-generating system using the  $\Delta V_{BE}$  method applied to the remote thermodiode (or thermotransistor) and the temperature of its own package. The IC sensor also contains an A/D converter, logic blocks that switch the constant current sources and read-out circuitry. The IC temperature sensor can send signals to a micro-controller as to optimize the electro-thermal performance of the system for best performance



**Fig. 3.** Remote sensing of temperature using a thermotransistor embedded in a heat generating system (such as silicon CPU), an IC temperature sensor and a microcontroller.

without exceeding the maximum junction temperature.

Fig. 3 shows schematically how the remote sensing of the temperature is carried out.

### B. Bandgap Reference

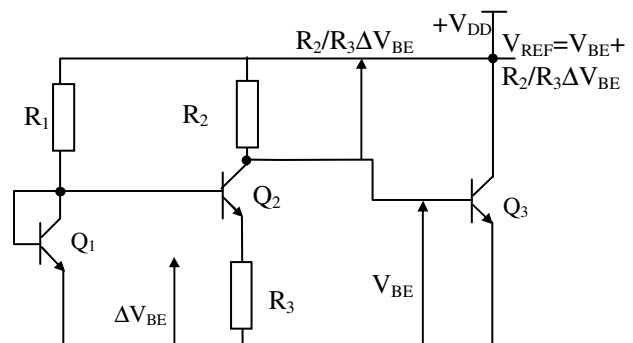
The basic cell of advanced IC temperature sensors is a bandgap circuit. The bandgap circuit provides a reference voltage that is equal

to the extrapolated energy-bandgap voltage in silicon at zero temperature, 1.205 V. For this reason the circuit is also referred to as the ‘1.2 V reference’. A reference voltage can have a zero-temperature coefficient, by adding up the voltage drop across the base-emitter of a transistor  $V_{BE}$  to a voltage drop that is proportional with  $\Delta V_{BE}$ . The former has a negative temperature coefficient which exactly cancels out the positive temperature coefficient of the latter.

One of the bandgap reference circuits is shown in Fig. 4. [30].

### C. Vptat And Iptat

Interestingly, the bandgap voltage circuit can be easily turned into a VPTAT (Voltage Proportional To Absolute Temperature) sensor. In Fig. 4 one can monitor the voltage drop across the resistor  $R_2$ , as this voltage is directly proportional to the absolute temperature and is amplified by  $R_2/R_3$ . A second stage amplifier can be used to further amplify this voltage if required. Summing this voltage to  $V_{BE}$  and adjusting the values of  $R_2$  and  $R_3$  one can obtain a stable reference voltage  $V_{REF}=1.2V$ .



**Fig. 4.** Widlar cell provides an output reference voltage that is independent of the temperature.

An IPTAT (Current Proportional To Absolute Temperature) is a constant current generator that varies linearly with the absolute temperature.

### D. CMOS Sensors

Advanced CMOS technologies, such as Bi-CMOS or BCD (Bipolar CMOS DMOS), also contain bipolar structures, but standard CMOS that is applicable to the largest market of integrated circuits does not normally feature such transistors. One idea is to use the variation of the MOSFETs on-state with temperature. This

variation is characterized by two parameters: the degradation of the mobility with temperature and the decrease in the threshold voltage with temperature. The first is more evident at higher currents while the second is dominant when the gate voltage is very close to the threshold voltage. Unfortunately both variations are highly non-linear (especially the mobility with temperature) and they tend to vary severely from technology to technology and from one device to another. Fortunately in standard CMOS, there are two types of parasitic bipolar transistors. Firstly there are the lateral n-p-n or p-n-p transistors which are in parallel with the n-channel MOSFET and p-channel MOSFET, respectively. These transistors are normally inhibited by reverse-biasing (or zero biasing) their base-emitter junctions, but can be used by making the MOS gate inactive and forward-biasing their emitter/base junction. Secondly, there are the substrate parasitic transistors (n-p-n in p-well CMOS technology or p-n-p in n-well CMOS technology). Generally it is accepted that the substrate transistors are more suited for use as thermotransistors because they exhibit a 'more' ideal behaviour and have lower sensitivity to stress. Wang and Meijer [31], Pertjis *et al.* [32] also showed that in spite of a reduced gain, such transistors, display similar performance to that of standard bipolar transistors when used as temperature sensors.

### E. Analogue, Digital And Pulse Width Modulator (PWM) IC Temperature Sensors

Analogue temperature sensors available either as VPTAT with gains between 6-20 mV/°C, or as IPTAT with gains of 1-10 μA/°C are very common. Their accuracy varies from 0.5 % to about 2%.

Recently, more sophisticated temperature sensors with digital output have been developed. Such sensors can more easily communicate with a microcontroller.

Pulse width modulator (PWM) temperature sensors are based on an output signal that has a mark-space ratio dependent on the temperature. This can be obtained by using a VPTAT and a type of voltage to frequency converter.

## 5. CMOS TEMPERATURE SENSORS OPERATING BEYOND 250°C

SiC diodes can, in principle, go up to 800°C as the  $n_i$  is almost 18 orders of magnitude smaller than in silicon (at 300°K) [33] (shown in Fig. 5). However, their incompatibility with IC technology makes them of little use in practical applications.

Interestingly, what limits the application of silicon thermodiodes to temperatures beyond 250°C is not their physical limits, but more often the reliability of the IC process and the normal operation of the IC.

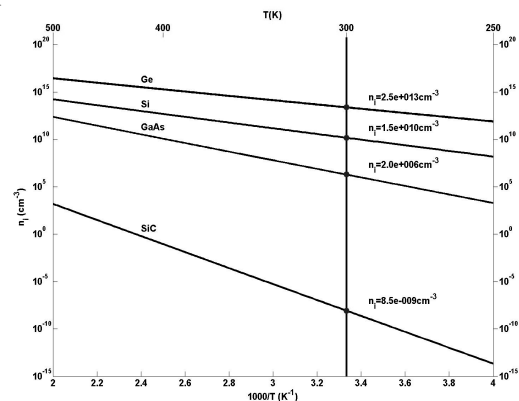
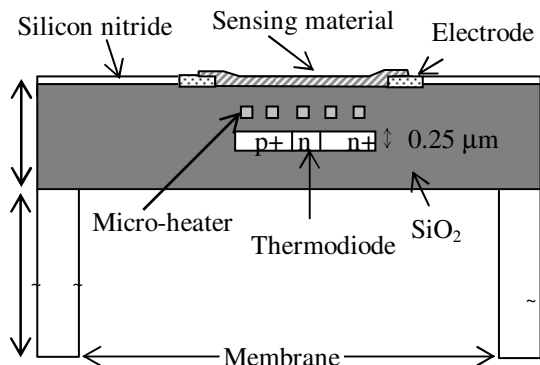


Fig. 5. Variation of the carrier concentration  $n_i$  with  $1/T$  for silicon, germanium, GaAs and silicon carbide (4H SiC). The plot is linear with a gradient proportional to the bandgap.

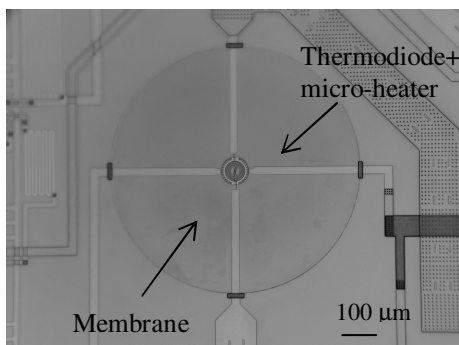
The junction temperature is often limited by electromigration (EM) of metal contacts, latch-up in circuits, reliability of the wire bonds, reliability of the package, or effects like ionic contamination. At high temperatures, the performance of CMOS devices deteriorates substantially and parasitic effects such as substrate injection or short-channel effects are exacerbated.

However there are situations where the integrated electronics operates below the junction temperature (e.g. 150°C), while a part of the smart sensor operates at much higher temperatures (e.g. 150-600°C). Temperatures sensors up to 400°C have been investigated in [34-35], but beyond this level, there is very little reported in the literature. CMOS micro-hotplates can often go beyond 300 °C (e.g. microcalorimeters) and for this reason it would be interesting to see what is the actual temperature limit for a thermodiode or a thermotransistor.

Figure 6 (a) shows a micro-hotplate as part of smart gas sensors [36-37] made using SOI membrane technology. The micro-hotplate is embedded in a thin membrane ( $\sim 5 \mu\text{m}$ ) containing a silicon island (with a thickness of  $\sim 0.25 \mu\text{m}$ ) where a thermodiode is placed to monitor accurately the temperature of the micro-hotplate. The top view of the fabricated micro-hotplate along with the diode temperature sensor is shown in Fig. 6(b). The micro-hotplate is heated by a resistive heater made of tungsten. At high temperatures (e.g. 200- 500°C), the gas reacts with the sensitive layer (placed above the heater) and changes its resistance. Tungsten is CMOS compatible and can be employed instead of Al as a CMOS metal to avoid electro-migration and allow much higher temperature of operation. Here, it is additionally used as a heater. Since no electro-migration, no latch-up and no package issues are present, the micro-hotplate can run well beyond the junction temperature, being ultimately limited by the accuracy of the thermodiode, mechanical stress and aging.



a)

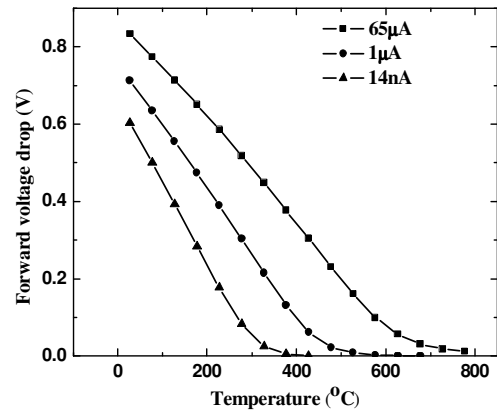


b)

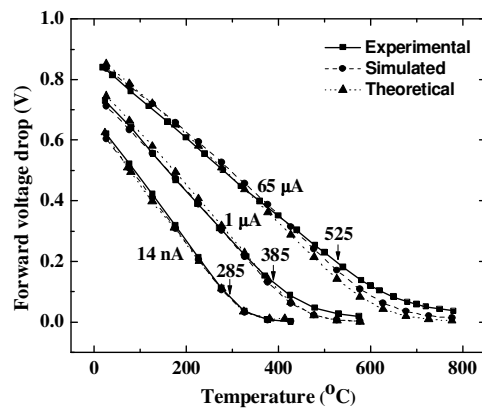
**Fig. 6.** (a) Cross sectional view of micro-hotplate (drawing not to scale) (b) Fabricated micro-hotplate with diode temperature sensor.

The forward voltage vs temperature ( $V-T$ ) plot of the thermodiode at three driving currents is shown in Fig. 7. The slope of the thermodiodes is found to be  $-1.3 \text{ mV}/^\circ\text{C}$  at  $65 \mu\text{A}$  current and operate linearly up to  $550^\circ\text{C}$ . The reason for this linear operation up to  $550^\circ\text{C}$  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 saturation current. The linearity maintained up to high temperatures is due to the very low value of the reverse saturation current,  $I_s$ . If we further increase temperature it was found that the slope becomes nonlinear.

Extensive finite element simulations in 'Sentaurus Device' and theoretical calculations were carried out to match the experimental results and explain in detail the thermodiode temperature characteristics. Experimental, numerical and analytical calculations are all in excellent agreement which is shown Fig. 8. The full equation of the forward voltage drop in a thermodiode function of the temperature  $T$  is given in equation (8).



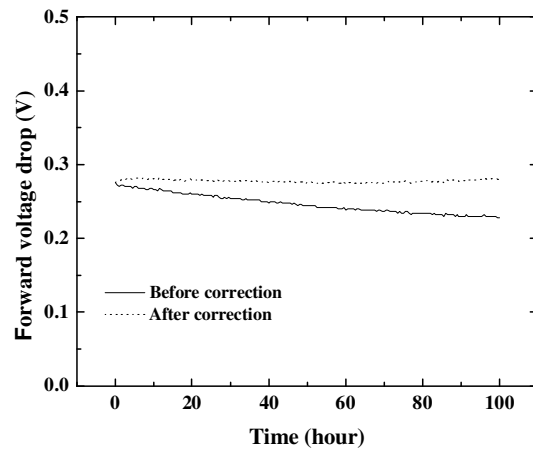
**Fig. 7.** Voltage vs temperature plot of a Si diode at different driving current.



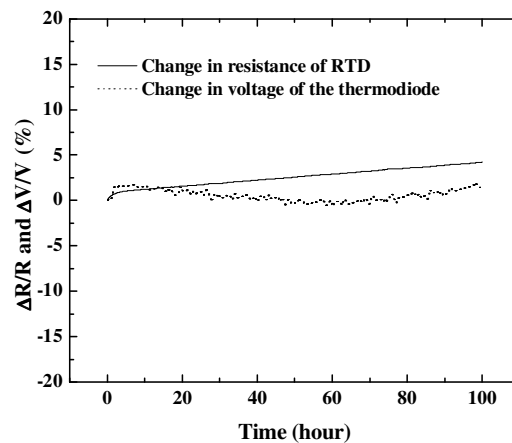
**Fig. 8.** Experimental, theoretical and simulated  $V-T$  plot.

The contribution of the non-linear terms is negligible at low temperature. However at high temperatures (e.g.  $> 550^{\circ}\text{C}$ ) the saturation current increases because of the rapid growth in the intrinsic carrier concentration. The intrinsic carrier concentration increases exponentially with temperature (e.g. at  $27^{\circ}\text{C}$   $n_i$  is  $1 \times 10^{10} \text{ cm}^{-3}$  and at  $650^{\circ}\text{C}$   $n_i$  is  $1.49 \times 10^{17} \text{ cm}^{-3}$ ). At very 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 equation (8)). As a result the  $V$ - $T$  plot of the thermodiode becomes severely non-linear as shown in Fig. 7. As expected the high temperature nonlinearity occurs earlier for lower driving forward currents. This is expected because in that case the saturation current becomes dominant over the driving forward current at a lower temperature level. Therefore to extend the temperature range of a thermodiode a substantial driving forward current is needed. Nevertheless, as already mentioned, a too high forward current is undesirable because of the self-heating effect, as well as the effect of the parasitic resistors. In addition the sensitivity (the slope of the  $V$ - $T$  curve) is decreased at higher current levels as can also be seen in Fig. 7.

The long term stability (the drift in the voltage drop when supplied with a constant current) of the thermodiodes was checked by operating them at  $500^{\circ}\text{C}$  for 100 hours using the tungsten heater on the membrane. The tungsten heater was operated using a fixed constant current while the diode was driven at current of  $65 \mu\text{A}$ . The maximum deviation in the diode voltage over this time period was  $48 \text{ mV}$  ( $\sim 40^{\circ}\text{C}$ ). Details investigation showed that this change was not due to the deterioration of the diode, but due to the change in resistance of the tungsten heater (Fig. 9), which caused a corresponding change in the actual temperature. Accounting for this change in the temperature, the drift in the diode output voltage is  $1\text{-}2 \text{ mV}$  ( $\sim 1^{\circ}\text{C}$ ) (Fig. 9). The relative change comparison between  $\Delta R/R$  (for tungsten) and  $\Delta V/V$  (for thermodiode) shown in Fig. 10 confirms that the performance of the diode temperature sensor is more reliable than that of the tungsten RTD, which might suffer from electro migration or mechanical stress effects.



**Fig. 9.** Reliability test of thermodiode at  $500^{\circ}\text{C}$ . The first curve (solid line) is the measured voltage drop across the diode. The second curve (dotted line) has been corrected by taking into account the slight temperature change (due to the change in heater resistance) to more accurately represent the diode characteristic.



**Fig. 10.** Relative change in tungsten resistance and diode voltage with time.

## 7. PROSPECTS

The future for IC temperature sensors is very promising. The market in IC temperature sensors alone is estimated at over 700 million dollars and is expected to grow to over 2 billion dollars in less than 5 years. They account for about 15% of the total sensor market. This is remarkable given, that their general research profile is quite low compared to other categories of smart sensors such as IC pressure, accelerometer or chemical sensors. The IC temperature sensor field is ahead of many other categories of sensors in terms of revenue growth (with a CAGR estimated in excess of 10%) with a continuous expansion in new fields. The temperature sensors perform real-time thermal management in virtually all IT products, such as PCs,

notebooks, power supplies, computer peripherals and industrial equipment. As the price and the volume of electronics is going down with the frequency going up and the packages becoming cheaper and smaller naturally leading to a superlinear increase in the power density, the need for accurate temperature control is no longer desirable but mandatory!

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