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Silicon diode temperature sensors – A review of applications

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Abstract

Most of the variables measured in scientific investigations or engineering applications depend, by varying degrees, on temperature. This necessitates the simultaneous measurement of temperature along with the variable of interest in order to perform high fidelity temperature compensated measurements. Silicon diode based temperature sensors (or silicon thermodiodes) have the advantages of being low cost, having an absolute temperature measurement capability as well as providing the option of on-chip integration with electronics circuits and a wide temperature measurement range. Leveraging these advantages, engineers and scientists have used silicon thermodiodes in numerous and diverse applications. This paper identifies the common temperature measuring techniques, and focuses on the use and advantages offered by silicon diodes operated as temperature sensors in different drive modes. Finally it explores the published literature for summarizing the application areas where such sensors have been utilized successfully in recent years.

1. Introduction

Temperature is one of the most important and commonly measured physical quantities. Consequently, temperature sensors cover the largest segment of the sensor market by volume [1]. Many of the physical phenomena being sensed and measured (e.g., humidity, pressure, flow, stress and gas concentration) have some temperature dependence and therefore, need to be compensated for temperature variations. Major applications of temperature sensors are thus focused at sensing temperature for thermal compensation.

With ongoing advancements in CMOS (Complementary Metal Oxide Semiconductor) and micro-fabrication technology in recent years, requirements for smaller size, lower power consumption, wider temperature ranges and on chip sensor-electronics integration have challenged the conventional temperature measurement techniques. To fulfill these stringent requirements, silicon diodes and transistors are increasingly being used as temperature sensors.

The silicon p-n junction diodes are the most accurate CMOS temperature sensors and many researchers in a wide variety of applications have used them for sensing temperature, mainly due to their accuracy, compatibility with IC (Integrated Circuit) technology and low manufacturing costs [2].

When the base and collector of a Silicon BJT (Bipolar Junction Transistors) are shorted, it can be operated as a diode and used as a temperature sensor. A number of researchers have instead used diode connected BJTs for temperature sensing because in a diode-connected BJT, the effect of material, geometric and process variations associated with diode manufacturing process are removed. Moreover, some CMOS design kits only offer the option of a diode-connected BJT and not a stand-alone diode. Significant research on diode-connected BJTs has been reported by a research group at Delft University [3-5]. Similarly, diode-connected metal–oxide–semiconductor field-effect transistors (MOSFET) are also used for temperature sensing though their nonlinear response has been a limiting factor [2]. However, on-chip temperature measurements with improved linearity [6, 7], layout area, current consumption and sensitivity to thermal variations [7, 8] of diode-connected MOSFETs, as compared to the ones based on BJTs, have recently been reported.

Section II of the paper identifies various temperature sensing techniques. Utilization and advantages of silicon diodes operated as temperature sensors are discussed in section III. In section IV, various biasing techniques that are best suited for silicon thermodiodes in particular situations are elaborated. Finally, a detailed review of silicon diode temperature sensors focusing on application areas where they have been successfully utilized by researchers are highlighted.

2. Temperature Sensing Techniques

There are a variety of techniques employed for sensing temperature which utilize diverse physical phenomenon like thermal expansion [9], thermoelectricity [10], fluorescence [11], etc. Selection of any of these techniques depends upon specific requirements or constraints. For example, a sensor may be required to establish direct contact with the environment of which the temperature is being measured, or on the contrary, it may not be desirable at all for the sensor to have any contact with the environment.

From the point of view of the relative position of the sensor and the environment, temperature measuring systems may be divided into three main categories: invasive, semi-invasive and non-invasive [9, 12, 13]. Each of these categories has distinct characteristics and limitations. Invasive temperature measurement systems have a direct contact with the environment of which the temperature is being measured. Examples of such systems include the common liquid-in-glass thermometers, gas thermometers, thermoelectric devices like thermocouples, electrical resistance devices like platinum resistance temperature detectors and thermistors, and semiconductor devices. Semi-invasive temperature measurement systems enable remote observation like change of colour for temperature detection. Thermonic liquid crystals, thermographic phosphorus and heat sensitive paints are a few examples of semi-invasive techniques. The non-invasive temperature measurement systems have no contact with the environment of interest. Examples of such systems include infrared thermography, absorption and emission spectroscopy and acoustic thermography.

Detailed elaborations on theoretical background, advantages and limitations of each category may be found elsewhere [9, 12].

Out of all the techniques available for sensing temperature, selection of the best suited technique depends on various factors like the required accuracy, range, response time, size, cost, fabrication limitations, robustness, electrical circuit simplicity, integration requirements etc. An excellent overview of the techniques generally employed for sensing temperatures along with a comprehensive guide highlighting different merits and demerits of each technique is given by Childs et al. [9]. Similarly, Altet et al. [12] and Blackburn [13] have consolidated various measurement techniques for temperature sensing in ICs. A comparison between resistance temperature detectors (RTDs) and diodes for chip temperature measurements, in the context of techniques used for reducing uncertainty and errors during measurements, is presented by [14]. More recently, Udrea et al. [2] have reviewed state of the art in IC temperature measurements with special focus on CMOS technology.

3. Use and Advantages of Silicon Diode Temperature Sensors

Diodes can be used for temperature sensing due to the strong temperature dependence of their forward bias voltage drop. Many different semiconductor materials have been reported in literature for diode temperature sensors (silicon, germanium and selenium are some examples). Exploiting this behaviour of silicon diodes, their earliest use as temperature sensors was reported by Harris [15] and McNamara [16]. In recent years, interest in using silicon diodes as temperature sensors was further fuelled by a number of merits associated with them. Most importantly, they (a) have a very low cost

[2, 9], (b) exhibit a simple voltage temperature relationship over a wide range (4.2 to 888 K) [17-21], (c) can be integrated with the electronics on the same chip [2, 9], (d) measure absolute temperature, and (e) exhibit reasonable sensitivity (around 2.5 mV/K) and accuracy (of the order of ±50 mK after calibration) [9]. In addition, the performance deterioration associated with self-heating can be taken care of by operating silicon thermodiodes at very low currents [2, 9]. Careful calibration is, however, required for measurements in cryogenic range, and noise reduction techniques should be adopted to avoid ac component in constant current supply. More recently, a number of CMOS and discrete MEMS (Micro Electro Mechanical Systems) sensors [22-28] have used the thin silicon layer of a commercially available silicon on insulator (SOI) process to implement thermodiodes. A survey of these SOI based diode temperature sensors can be seen in [27].

Silicon thermodiodes can be easily integrated with on chip electronics such as micro controllers, signal processing circuits and A/D converters. Various on-chip circuit arrangements like band-gap reference circuit commonly referred to as ‘1.2V reference’ circuit, voltage proportional to absolute temperature (VPTAT) and current proportional to absolute temperature (IPTAT) have been reported in the literature. Udrea et al. have provided details of such circuits in [2].

4. Drive Modes Used for Silicon Diode Temperature Sensors

Silicon thermodiodes are used for temperature measurement in two different modes: (a) constant current mode, and (b) constant voltage mode.

4.1. Constant Current Mode

Constant current mode is the most widely used drive mode for silicon thermodiodes, where the diode is operated at constant forward current. In such condition, the voltage drop across the diode is quite linearly proportional to the absolute temperature of the device over a relatively wide temperature range. The diode behaviour drastically changes for temperatures lower than 30 – 40 K (the voltage increases sharply) and at high temperatures (around 600 K where the voltage saturates). Typical forward voltage sensitivity of a diode is shown in Figure 1, while detailed mathematical description of diode as temperature sensor in constant current mode is given in [2].

The ideal behaviour of a diode is described by the Shockley ideal diode equation, often referred as diode law. Mathematically it is represented by:

$$I = I_s \left(e^{(qV/kT)} - 1\right) \qquad (1)$$

Where I is the diode current, I_s is the reverse bias saturation current, q is the electron charge, V is the voltage across the diode, k is the Boltzmann's constant, and T is the absolute temperature.

The reverse saturation current I_s is also temperature dependent and can be expressed as:

$$I_s \cong KT^r e^{(-qV_g/kT)} \qquad (2)$$

where, V_g is the extrapolated energy gap at absolute zero temperature. Here, the terms K, r and V_g are independent of temperature T. The constant K depends on the geometric factors like width of p-n junction in diode, while r is a process dependent parameter and has a value ~ 3.5 for silicon.

For I>>I_s, equation (1) can be rewritten as:

$$I = I_s e^{(qV/kT)} \tag{3}$$

In order to get a relation in terms of forward voltage V, Equation (3) and (2) can be combined to obtain the following expression:

$$V = V_g + \frac{kT}{q}(ln\, I - ln\, K - r\, ln\, T) \tag{4}$$

The above relation shows that at constant current, the forward voltage drop is almost a linear function of temperature. For most practical purposes, this relation can be expressed as:

$$T = A + BV \tag{5}$$

Equation (5) forms the basis of the constant current method for sensing temperatures with the help of diodes. Constants A and B are determined experimentally by driving the diode at constant current and calibrating it for the target temperature range.

4.2. Constant Voltage Mode

The other mode, in which thermodiodes can be biased, is the constant voltage mode. For detailed mathematical description of diodes used as temperature sensors in constant voltage mode, [29] may be referred. In constant voltage mode thermodiodes can be operated either in forward bias or reverse bias. A brief outline of both modes is given below.

4.2.1. Forward Bias: Recall that for a given forward bias voltage $V > 0.1$, the diode current I>>I_s. Thus equation (1) can be rewritten as:

$$I = I_s e^{(qV/kT)} \tag{3}$$

Rearranging equation (4) to get a relation between current I and temperature T:

$$ln\, I = \frac{q(V-V_g)}{kT} + ln\, K + r\, ln\, T \tag{6}$$

or

$$ln\, I = S\frac{1}{T} + ln\, K + r\, ln\, T \tag{7}$$

where

$$S = q\,\frac{(V-V_g)}{k} \tag{8}$$

Neglecting the last nonlinear term in equation (7), we obtain proportionality between $\ln I$ and ${}^{1}/_{T}$ [2, 30]. The slope S of the line of $\ln I$ versus ${}^{1}/_{T}$ represents the temperature sensitivity. The temperature sensitivity S can be varied by changing applied voltage V in accordance with equation (8).

4.2.2. Reverse Bias: The p-n diodes can also be operated at constant voltage in reverse biased mode [24, 29, 30]. Since in reverse bias, the current through diode I is the same as reverse saturation current I_s hence we have

$I = I_s$.

We also know from equation (2) that reverse saturation current I_s is given by

$$I_s \cong KT^r e^{(-qV_g/kT)} \qquad (2)$$

Thus as seen in case of constant voltage mode in forward bias (equation (7)), we get a linear relationship between $\log I$ and $1/T$ in the reverse biased constant voltage mode as well [30].

5. Applications of Silicon Diode Temperature Sensors

The desire for careful and accurate temperature monitoring for efficient performance of various systems has led to use of silicon diode temperature sensors in a wide range of applications in recent times. These applications of silicon thermodiodes can be grouped into four broad categories in various engineering fields. These are; (a) thermodiodes for temperature compensation e.g. for stress, pH and pressure sensors, (b) thermodiodes for stand-alone cryogenic and high temperature measurements, (c) thermodiodes for temperature monitoring and feedback e.g. gas sensing, IC and chip temperature monitoring, flow sensing and monitoring of thermal conductivity of gases, and (d) thermodiodes for sensing parameters other than temperature e.g. IR detection, liquid level sensing and humidity sensing. A brief description of some of the important application areas where silicon thermodiodes have been employed for temperature sensing is given below, while a summary is given in Table 1.

5.1. Stress Sensors

Stress is one of the most important parameters for the monitoring and verification of the "health" of any mechanical structure. Repetitive stress cycles, also known as fatigue, and excessive stresses can cause failure of the structure. In order to calculate stress, strain is measured in the structure which then helps in calculating stress using Hook's Law. Knowledge of stresses not only helps in preventing structural failure, but also in validating the analytical / numerical models. Various techniques (optical, capacitive, piezoelectric, piezoresistive and frequency shift phenomena) have been utilized for sensing stresses [31]. Piezoresistive stress sensors are one of the most common and widely used stress sensors [32]. While discussing the sources of variation in piezoresistive stress sensor output, Slattery et al. [32] identified temperature among the factors to which piezoresistors are highly sensitive. It is known that temperature variations, as low as 0.25 ºC, result in serious deviations in experimental results when compared to stresses obtained from non-temperature compensated stress formulae [33]. In order to compensate for the dependence of piezoresistors on temperature, a number of researchers have used silicon diodes on their piezoresistive stress sensors for temperature compensation [33, 34]. These stress sensors use p and n-type piezoresistors as sensing elements, thus a p-n junction diode becomes the most logical and simplest choice for temperature sensing. Furthermore, in contrast to thermocouples which sense relative temperature between the two junctions, the thermodiodes are absolute temperature sensors and can be used as stand-alone sensors. Successful use of thermodiodes embedded in SOI wafers for decoupling of temperature information from piezoresistive elements of stress sensors has been demonstrated [35].

5.2. Pressure Sensors

Pressure sensors are widely used for a variety of industrial, laboratory and domestic applications. They employ different techniques for conversion of mechanical signal (pressure) to an electrical signal. However, in most cases, these sensors lack linearity and sensitivity. This is mainly because of the noise generated by piezoresistors due to temperature fluctuations [36]. On-chip temperature sensors are essential to provide thermal feedback for temperature compensation of the measured pressure. Silicon diodes provide the best possible solution for temperature measurement and compensation of pressure sensors, because of the simplicity of circuit design and ease of on-chip integration. One such example is a resonant beam pressure sensor [37], where temperature measurement and compensation was done by an on-chip silicon diode temperature sensor. The resonant frequency of the beam (the pressure sensing element) is affected by properties such as Young's Modulus, density and dimension of the beam and the internal stresses. Thus addition of materials like metals, for realizing thermocouples or RTDs for sensing beam temperature drastically affects the resonant frequency of the single crystal silicon beam. However, a simple p-n junction diode embedded at the end of the beam has the least overall effect on the beam's frequency and thus the accuracy of the sensor. A pressure sensor that utilizes three silicon diodes for temperature measurement and compensation, reported by Kimura et al. [25] is shown in Figure 5.

5.3. Cryogenic Applications

Temperature is the most important parameter in cryogenic applications. In contrast to measurements in normal ranges, temperature measurements in cryogenic range require utmost care and efforts. Thermodiodes are perfectly suitable for cryogenic applications due to their ability of on-chip integration, low power consumption, simplicity of required instrumentation, relatively large signal output, and wide operation range [38]. However, alongside the advantages, self-heating in thermodiodes needs careful attention for their use in extremely low temperatures. There are a number of examples where researchers have used diodes for sensing temperatures in cryogenic ranges [21, 39-42]. Operation of CMOS circuitry in cryogenic temperatures ($T < 100K$) is generally witnessed in satellites for high performance radiation detection. Hamlet et al. [26] have successfully demonstrated use of diode temperature sensor for sensing temperatures of CMOS circuitry at cryogenic temperatures. Similarly, de Souza et al. [43] have utilized thermodiodes for temperature sensing in the temperature range of 100K to 400K. Boltovets et al. [20] have also proposed silicon thermodiodes for measuring temperature in cryogenic range (2-600 K) and concluded that the sensors (schematic diagram shown in Figure 8) demonstrated high thermal sensitivity and linearity in 30 to 600 K range. Dynamic behaviour of the silicon thermodiodes along with long term stability (12 months) has also been reported by Vepřek and Strnad [44].

5.4. High Temperature Measurements

In general, the maximum temperature required to be measured by silicon thermodiodes is around 150 – 200 ºC. It is worth mentioning here that maximum temperature of the thermodiode is not limited (to 200 °C) due to any physical capability of the thermodiode. Rather it is restricted by the IC processes and normal operating range of ICs. Thermodiodes integrated on chip usually measure the chip temperature, and the maximum operating temperature for bulk silicon CMOS is limited to 150 ºC. SOI technology increases this limit to around 200 ºC. Hence, the thermodiodes are generally not required to measure temperature beyond IC limiting temperature. However, there are certain applications (e.g. gas sensing using micro hot plates), where the sensing elements need to be operated at temperatures as high as 700 °C or above, which is way beyond the IC limiting temperatures. In such cases, the heated elements (or micro hot plates) are thermally isolated from the on-chip circuitry by embedding them on membranes (e.g. Figure 3, Figure 9 and Figure 10). Membranes are thin dielectric structures which significantly reduce the conduction heat transfer from the hot-plates to the substrate where the circuitry is accommodated. Silicon thermodiodes have been used by some researchers to provide thermal feedback to accurately control the heater temperature, thus improving the overall performance of the sensors. Examples of such applications involving high temperature measurements include gas sensors [22, 23, 45], humidity sensors [29], and calorimeters [46]. More recently, [17, 19, 27, 47] have demonstrated a silicon thermodiode which, when operated in constant current mode, can not only work up to 850 ºC, but also down to -200 °C, covering the widest temperature range ever reported in the literature. Figure 11 represents the long term stability test results achieved for the thermodiodes reported by [19].

5.5. Gas Sensors

Detection of toxic and combustible gases with the help of inexpensive, portable and reliable gas sensors is important in automobile, mining, environmental and many other applications. The target gas is detected by a gas sensing layer with embedded heating arrangements. The sensing materials used in gas sensors are sensitive to different gases at specific temperatures, requiring accurate temperature control of the sensor elements for reliable gas sensing. The operating temperature is generally achieved with the help of resistive heaters embedded in the sensor while thermal feedback is provided by a temperature sensor. SOI CMOS based thermodiodes have been utilized by Maeng et al. [22] for sensing temperature for a smart gas sensor system in ubiquitous sensor networks. The specific requirements of having miniaturised battery-powered sensors capable of operating for long time, being fully integrable with CMOS circuits, operating at high temperatures and producing high quality repeatable results are distinctly handled by using SOI CMOS thermodiodes(an example of which is shown in Figure 2). Similarly, [23, 28, 45, 48, 49] have also used silicon diodes for temperature control of micro hot-plates used in their gas sensors. One such diode temperature sensor embedded on a micro hotplate [23] is shown in Figure 3.

5.6. IC and Chip Temperature Measurement

Temperature on the surface of integrated circuits and silicon chips is an important parameter as it influences the performance and reliability of the devices installed on it. It also provides a thermal map of the IC which helps in understanding heat transfer state between various elements of the IC structure. Accurate thermal information can help in design improvements for optimum performance of such devices. Similarly, electronic circuits used in harsh environments (e.g. aerospace, automotive, well-logging, nuclear and geothermal applications) generally face extreme temperatures, thus temperature sensing and control becomes imperative. IC temperature sensors are also used to characterise the performance of analogue circuits, for instance RF circuits, embedded in the same chip. Use of silicon thermodiodes as absolute temperature sensors for IC temperature measurements is preferred due to their predictability, linearity and stability over a wide range. For these reasons, many researchers [24, 50] have reported the use of silicon diodes for temperature measurement of ICs, while a survey has also been carried out by Altet et al. [12]. Huque et al. [24] have reported an on-chip SOI thermodiode for temperature monitoring and control intended to safeguard against excessive die temperature in the engine compartment of automobiles. The schematic diagram of the low power diode temperature sensor circuit proposed is shown in Figure 4.

5.7. Flow Sensing

Flow sensing is a broad measurement category encompassing parameters such as flow rate, velocity, flow direction, turbulence and wall shear stress etc. These sensors are used in a variety of applications including industrial process feedback and control, automotive and aerospace industry, fluid dynamics experimentation and biomedical instrumentation. Thermal flow sensors based on convective heat transfer from sensing element to the fluid flow are the most common types of flow sensors [51]. Such sensors require accurate measurement of flow and heating element temperature for optimum performance. Again due to simplicity of the electrical circuit and ease of on chip integration, silicon thermodiodes are among the best choices for researchers. Examples include utilization of thermodiodes for flow velocity and turbulence intensity measurements by Lofdahl et al. [52, 53]. Silicon chips designed by Lofdahl et al. were used and compared with hot wire anemometer. However, unlike the hot wires, temperature feedback was not taken from the wire resistance. Instead, two silicon diodes were used to provide feedback of both the sensor chip and the flow temperatures. Diodes were particularly useful because the on-chip heater resistance would not have given correct chip temperature in case of hot wires, whereas diodes embedded on the sensor chip away from the heater gave better chip and flow temperature feedbacks. In a similar example, Kersjes et al. [54, 55] have utilized a pair of thermodiodes for sensing flow rate as well as flow velocity. The chip is designed for invasive blood velocity measurements and uses hot film anemometry. Thus for constant heating power of the polysilicon heater, the temperature difference between two locations of the thermodiodes is used for measuring fluid flow. Once the thermodiodes are operated at constant forward bias, the difference between their voltages is proportional to their temperature difference. Hence a very simple arrangement of the two diodes results in measurement of their differential temperature.

Another frequently used sensing principle in flow sensors is surface fence. Unlike flow sensors based on thermal principle, these fall in the category of direct flow measurement sensors. These sensors incorporate a fence probe on the surface. The fence is deflected due to the flow and this deflection is measured with the help of piezoresistors embedded in the fence probe. Since the piezoresistors embedded in the fence have significant dependence on flow / fence temperature, thus their output has to be compensated for temperature changes. Again thermodiodes are commonly used for sensing flow and fence temperature that is subsequently used for temperature compensation in piezoresistors. A wall shear stress sensor with two thermodiodes used for temperature compensation of piezoresistors has been reported by [56].

5.8. Infra-Red (IR) Detectors

Human vision is limited to the visible spectrum of light. However, IR detectors extend this vision beyond red into the infra-red region. IR detectors have found immense utilization not only in military applications, but also commercial uses like night vision enhancements for drivers [57], fire detection [58], fault diagnostics [59] and security systems [60].

Silicon diodes have proven to be a potential low cost technique for IR detection [61]. This is mainly because of the fact that IR detectors need vacuum packaging and cryogenic cooling to ensure high detectivity and fast response. Thermal IR detectors can operate at room temperature without the need of an expensive cooler. However, loss of the thermal signal associated with conduction losses reduces detectivity and response time. On the other hand, a cleverly designed micromachined diode that is thermally isolated, does not need vacuum packaging or cryogenic cooling to have comparable detectivity and response time. An array of such thermodiodes is connected to form pixels thus making them an excellent low cost alternative to conventional IR detectors. Examples of such arrangements have been demonstrated by [61-65] while one such device [61] is shown in Figure 6.

5.9. Humidity Sensors

Humidity sensors have diverse applications including climate control, agriculture, storage, military as well as domestic applications. Among others, an investigated humidity sensing mechanism is based on the different thermal conductivity of air and water vapour at high temperature. Kimura and Kikuchi [29] reported that the change in thermal conductivity of humid air at different temperatures has a linear relation with water content in the air. Their humidity sensor was fabricated using a micro heater and a thermodiode. The same technique was used by Okcan and Akin [66], but instead of micro heater, two thermally isolated thermodiodes were utilized. The proposed design, as shown in Figure 7, has the advantage of monolithic integration with readout circuitry, linear response and low hysteresis. Wu et al. have also reported an integrated temperature and humidity sensor based on silicon diode [67].

5.10. Miscellaneous Sensors

Besides the key application areas discussed above, thermodiodes have also found their application in less common areas like liquid level / liquid vapour interface sensing [68], pH sensing [69] and sensing of thermal conductivity of gases [48]. This proves the efficacy of thermodiodes and their popularity among the researchers as the sensor of choice for temperature monitoring.

6. Conclusion

This paper gives a brief account of temperature sensing techniques and the reasons for the widespread use of silicon diodes as temperature sensors. The analytical equations that govern behaviour of silicon thermodiodes when operated in constant current and constant voltage mode have been briefly discussed. Various application areas like gas sensing, IC temperature measurement, stress sensing, pressure sensing, IR detection, humidity sensing, cryogenic regime temperature sensing, high temperature sensing, flow sensing, liquid level detection, pH sensing and monitoring thermal conductivity of gases, in which researchers have preferred using silicon thermodiodes for temperature monitoring and control, have been reviewed. For the convenience and quick reference of the interested readers, key specifications and performance attributes of silicon thermodiodes used in different applications have been comprehensively summarized and presented in tabular form. The paper will serve as a quick reference for the readers interested in exploring the diode temperature sensors and their applications reported in the literature during the last two decades.

7. Acknowledgments

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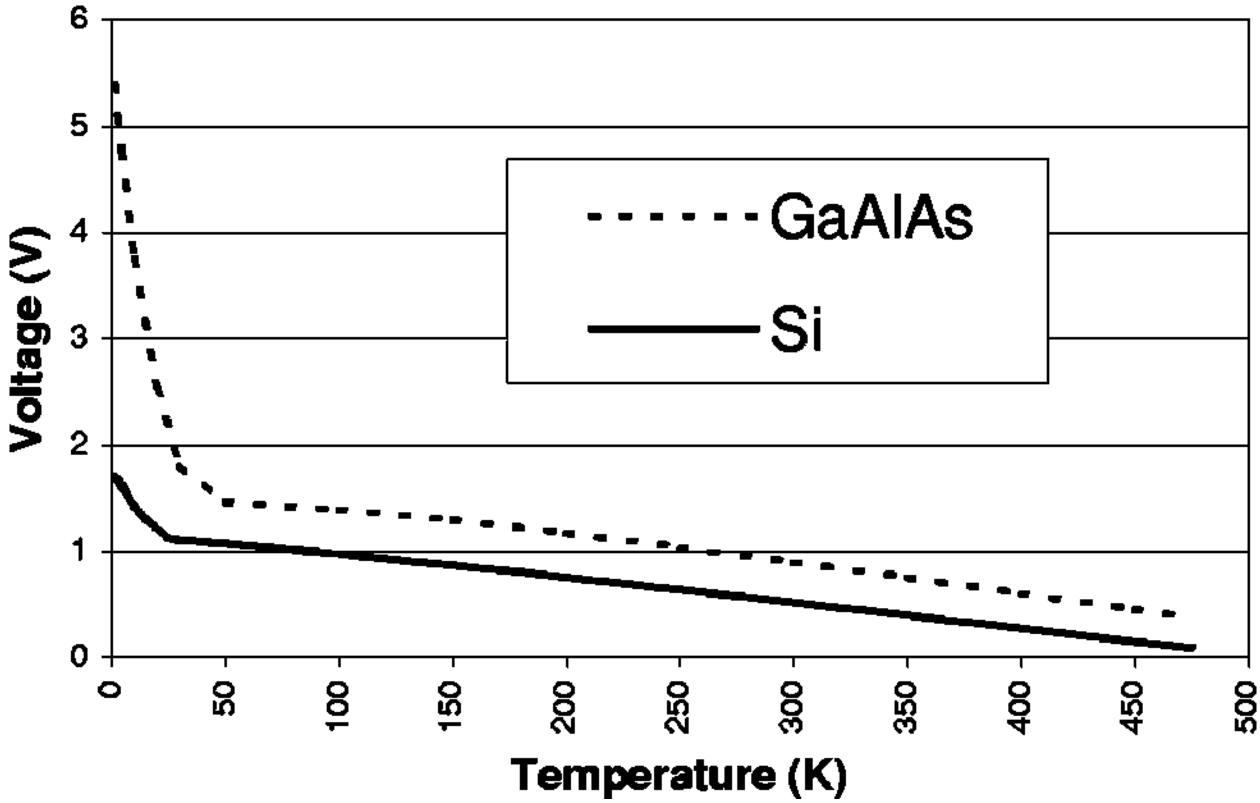
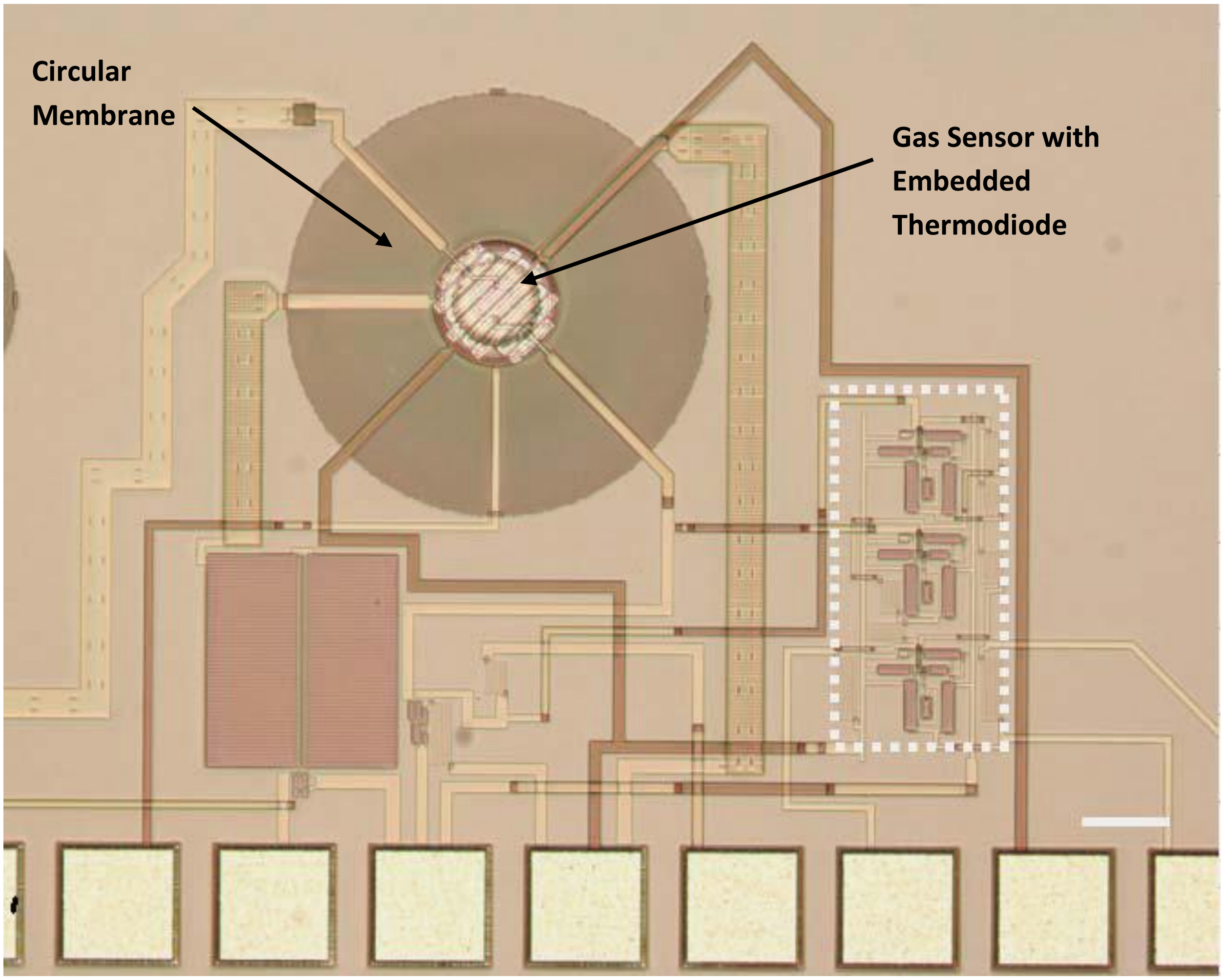


Figure 1. Typical forward voltage and temperature relationship of semiconductor diode operated in constant current mode [9].



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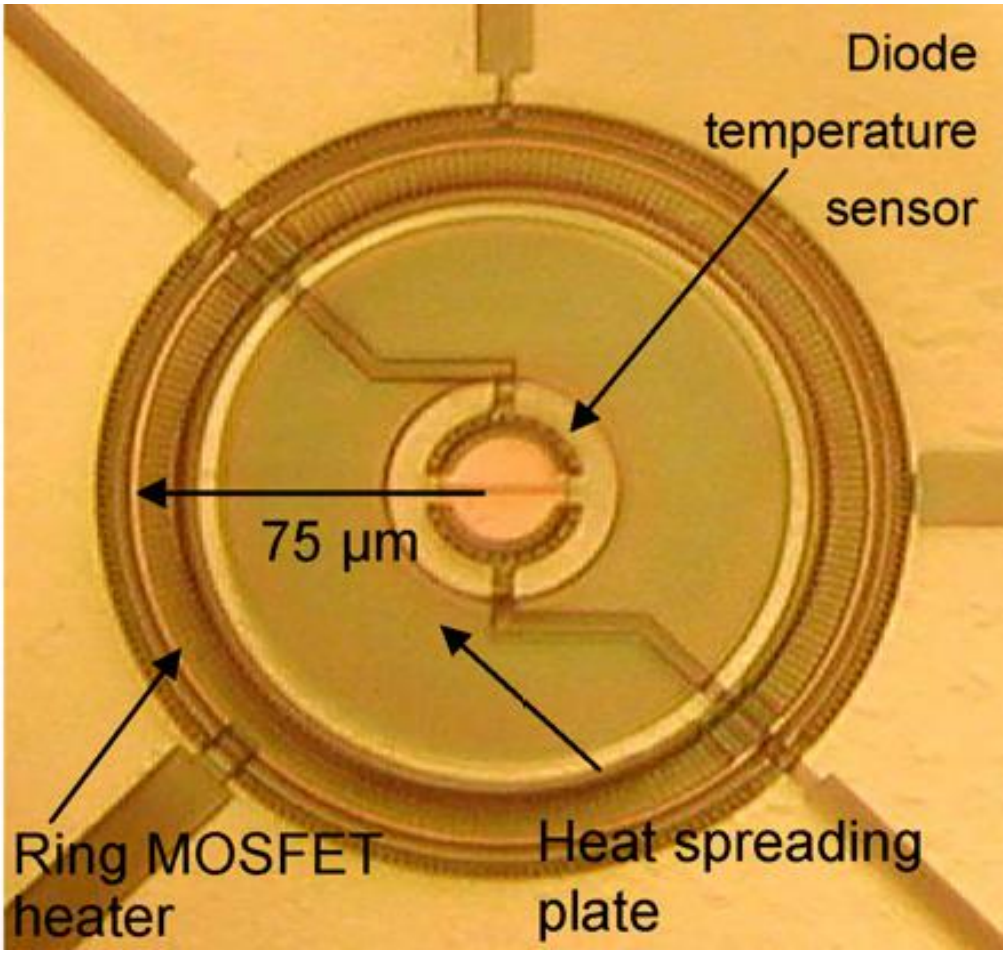

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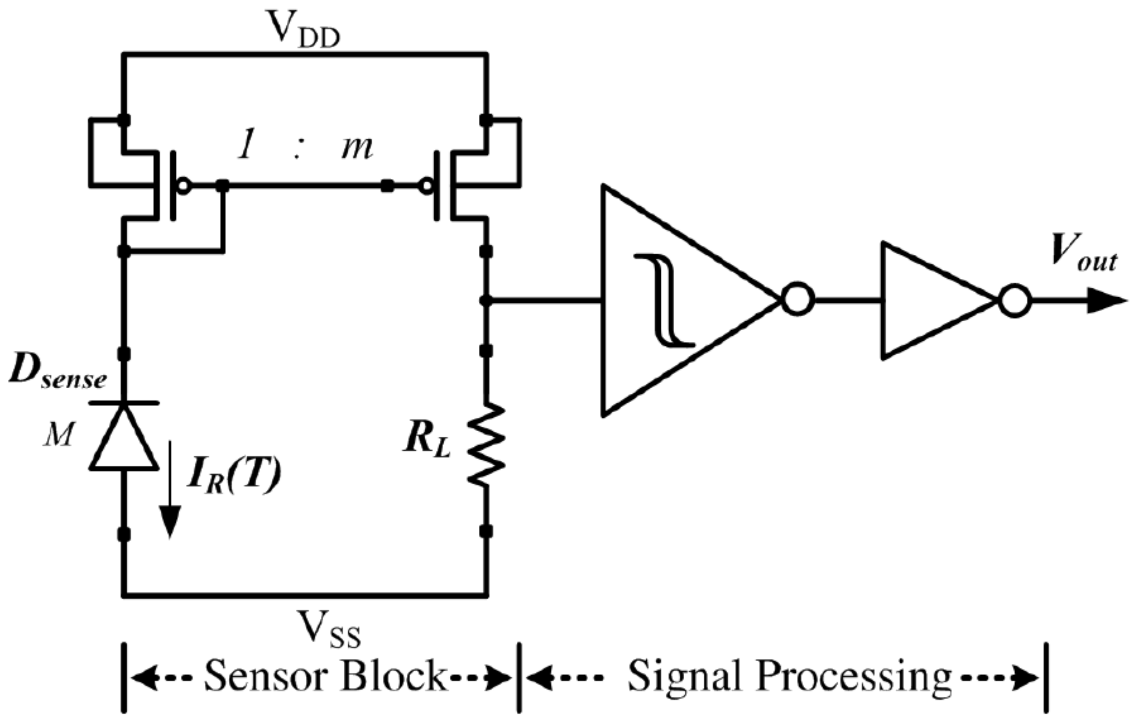

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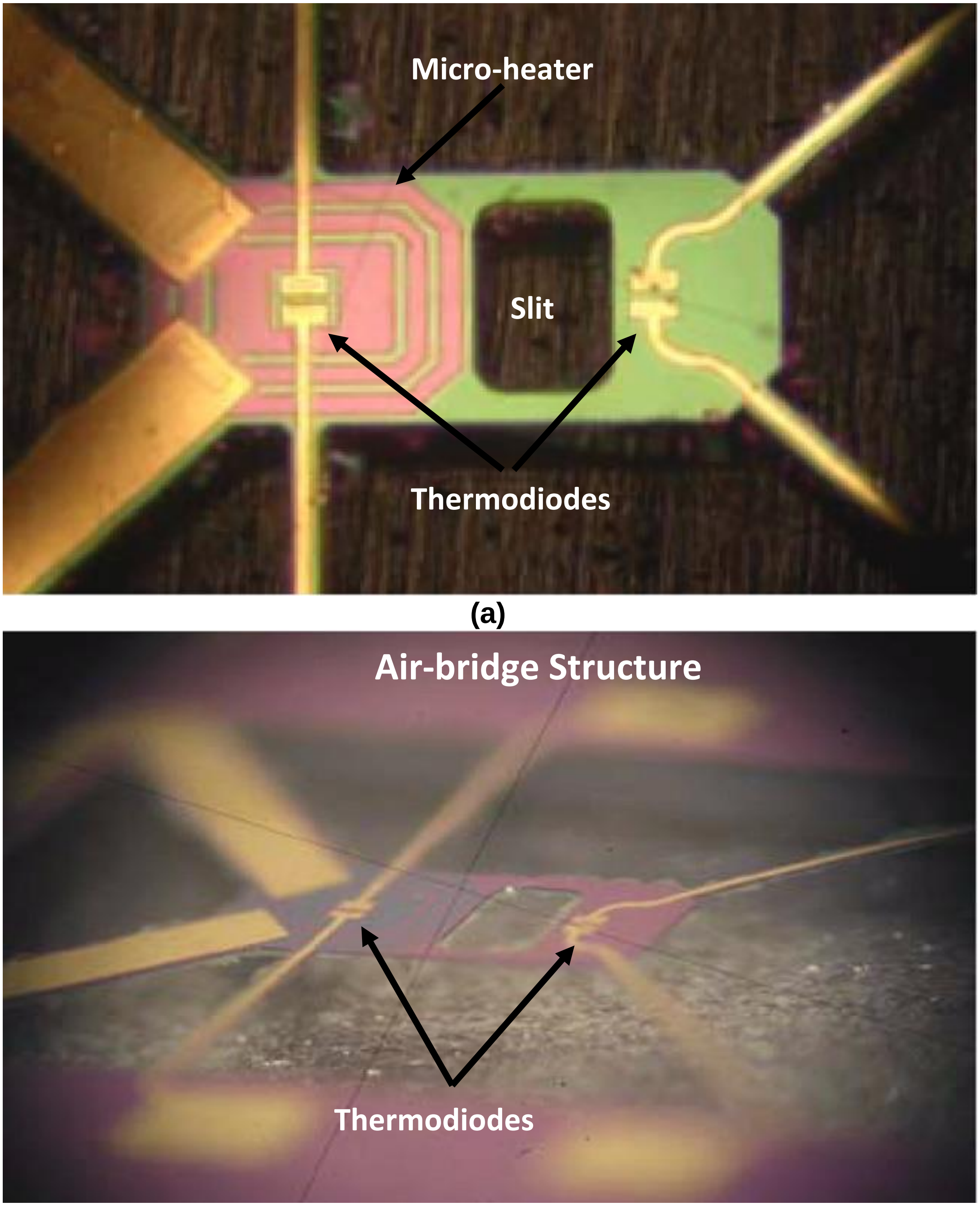

(b)

Figure 5. Micrographs of thermodiodes used in thermal vacuum sensor; (a) Top view (b) Oblique view [25].Third diode temperature sensor (not visible in the figure) is formed on SOI substrate for sensing ambient temperature.

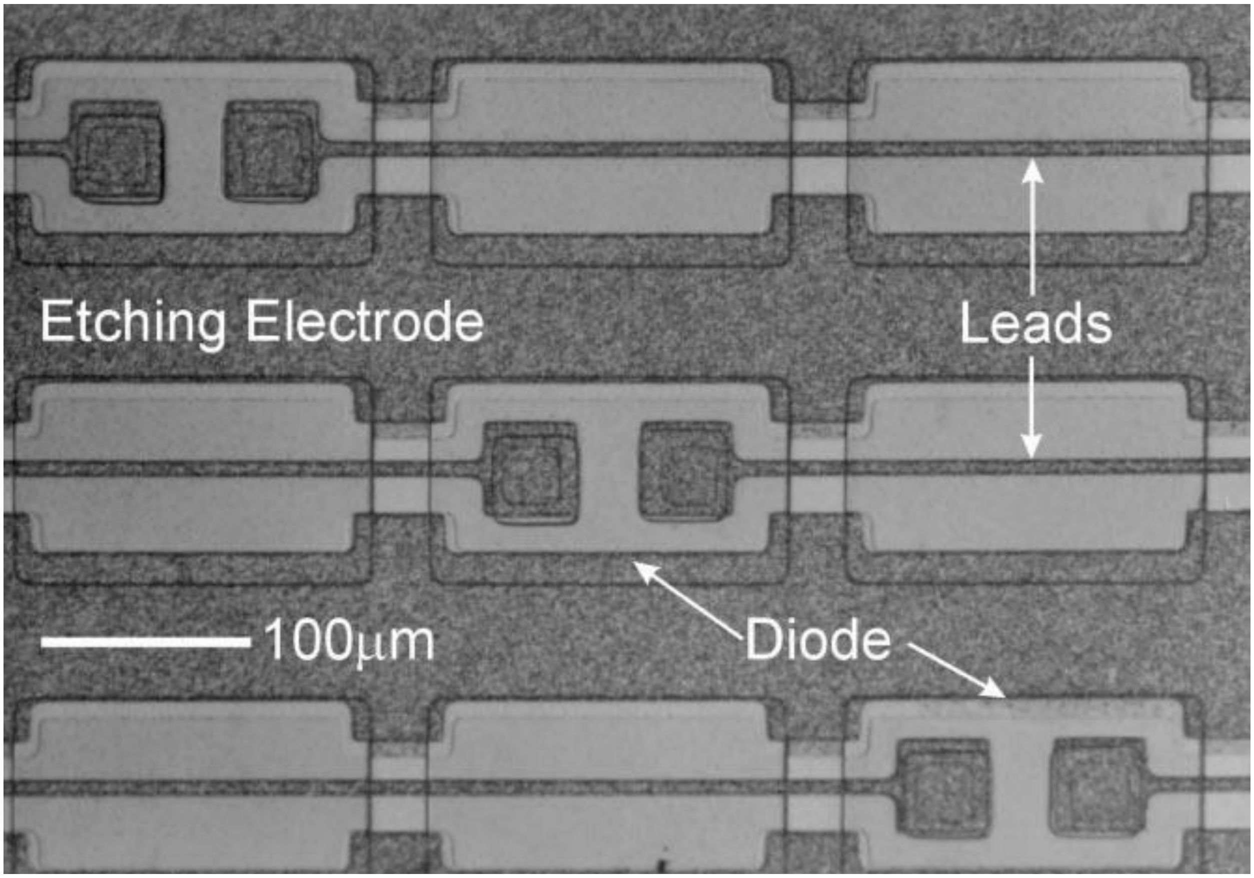

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Figure 6Photograph of MISIR (micromachined isolated silicon diode for IR detection) [61].

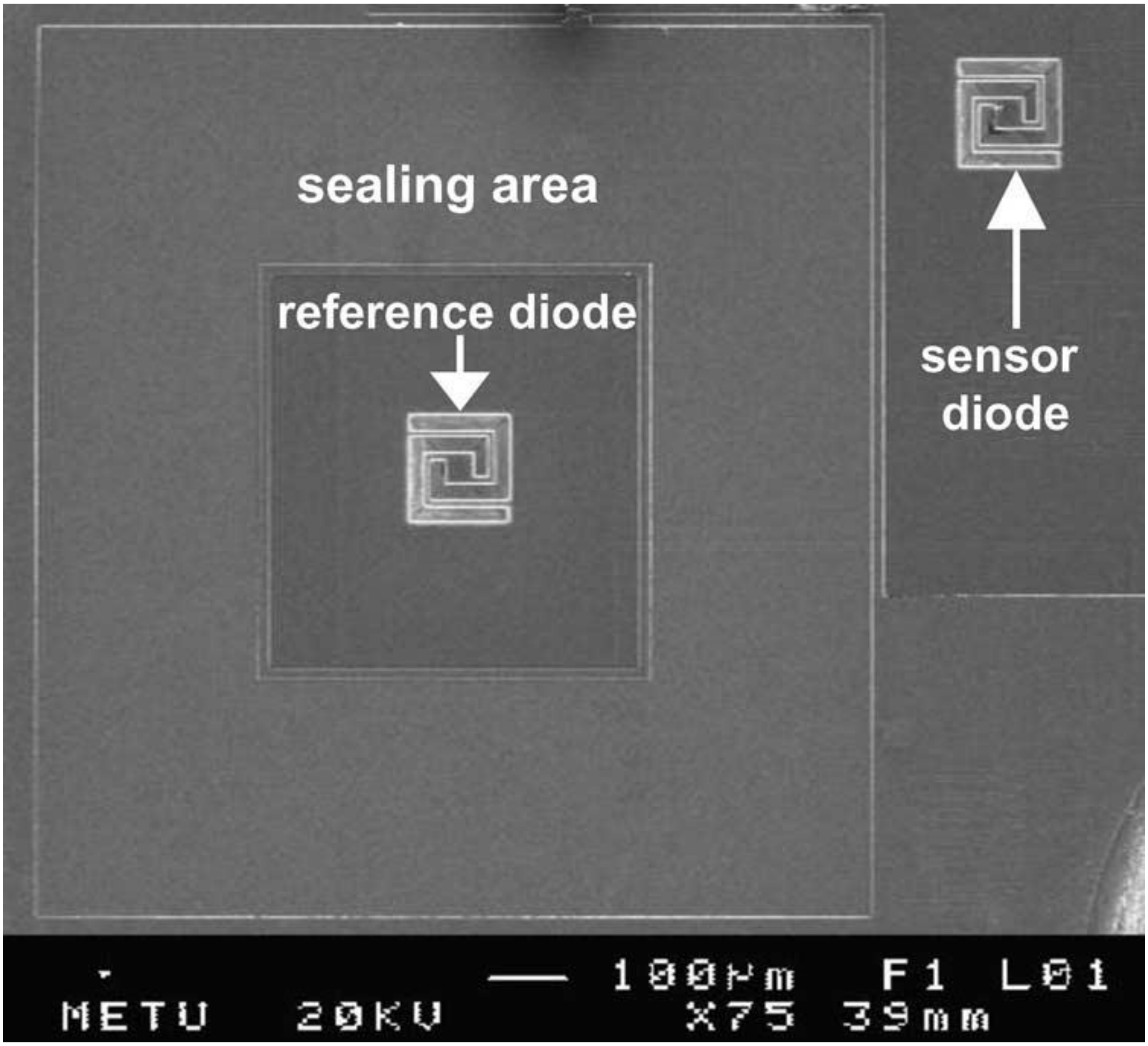


Figure 7. SEM pictures of reference and sensor silicon diodes in humidity sensor chip [66].

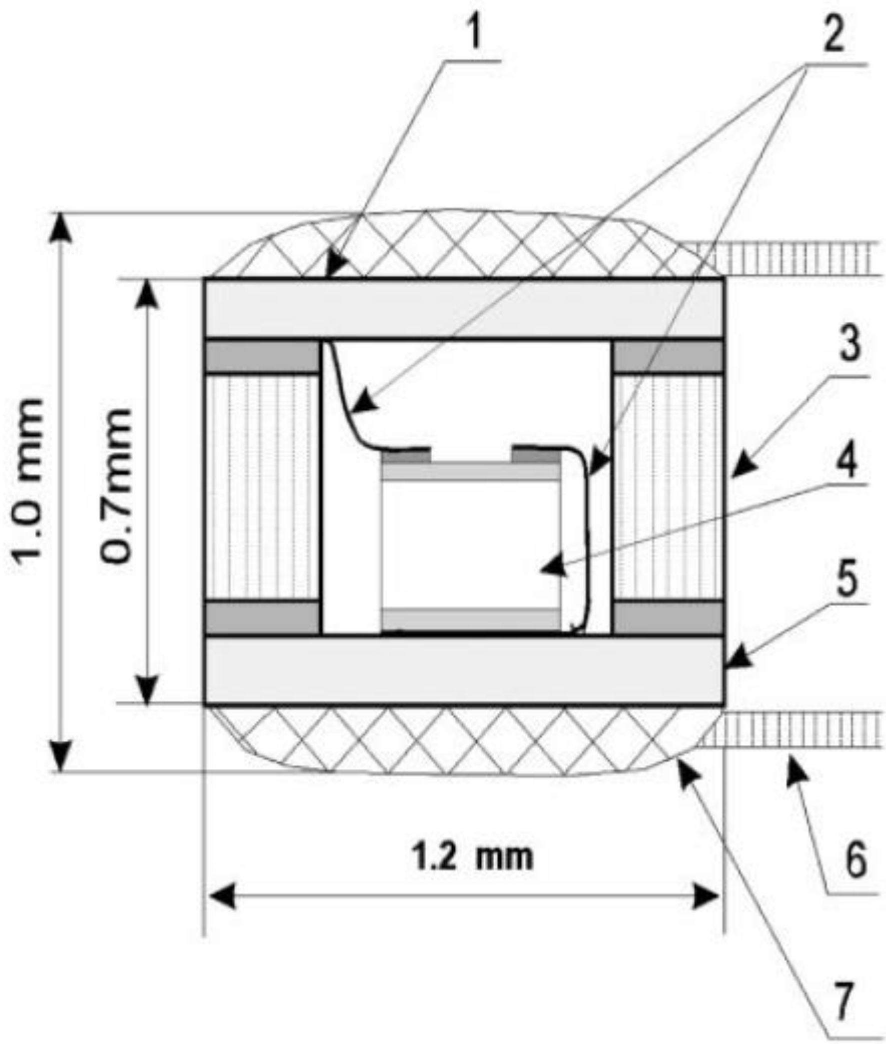
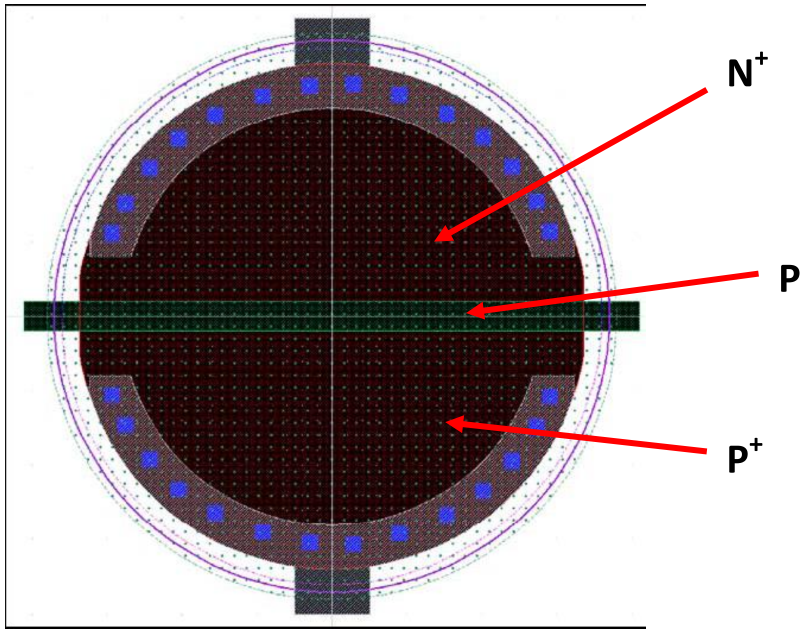


Figure 8. Cryogenic diode temperature sensor design by [20]. (1) and (5) copper discs, (2) gold strip, (3) corundum cylinder, (4) temperature sensitive element (thermodiode) (6) copper wire, (7) tin.



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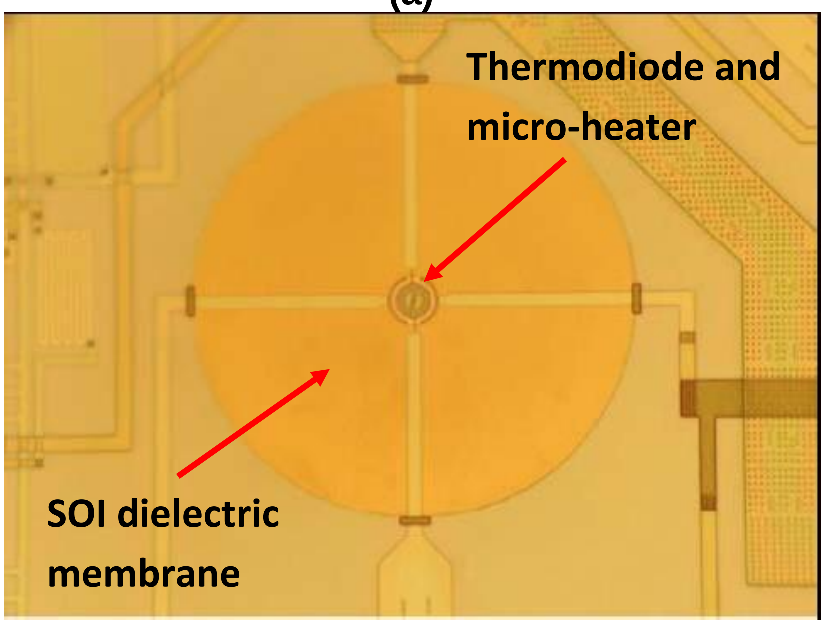
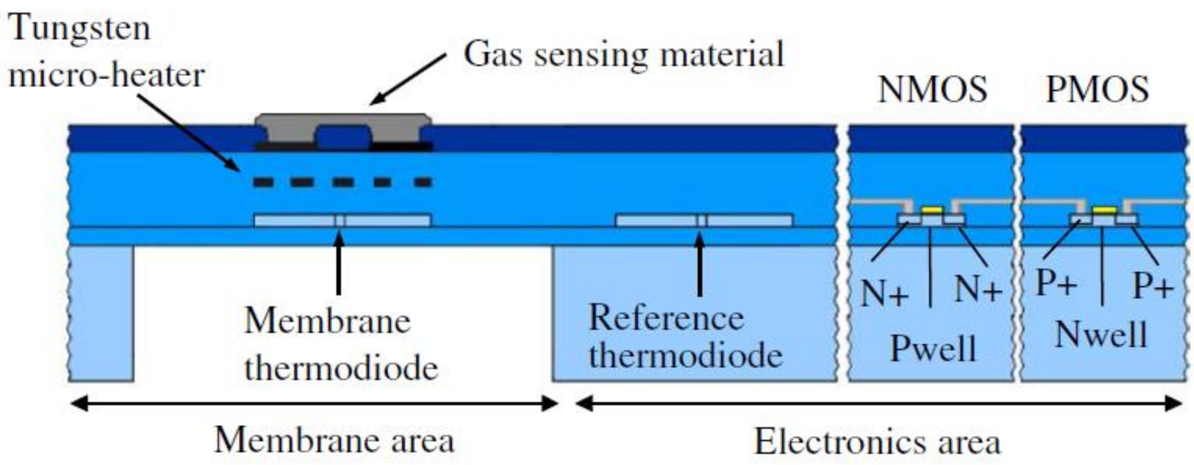
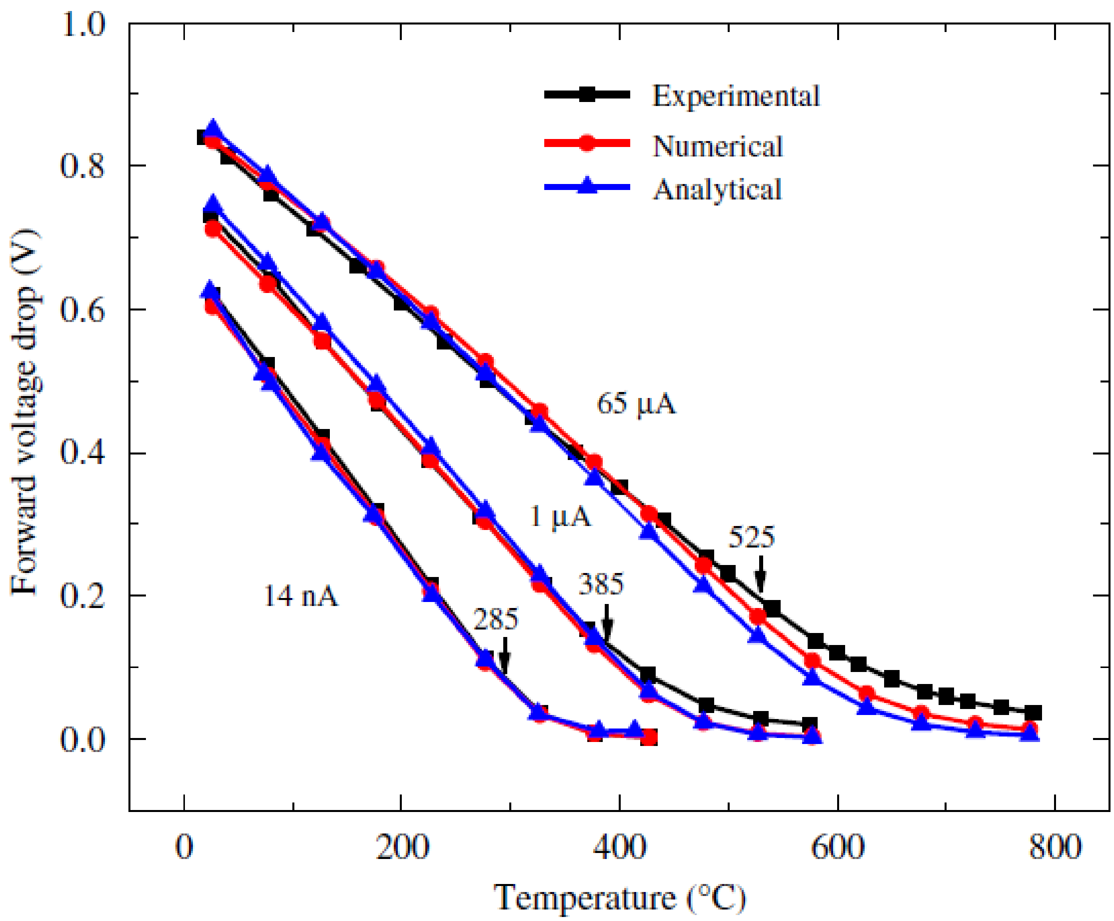


(b)

Figure 9. (a) Cadence layout of the SOI p+/p/n+ thermodiode with 34µm diameter. (b)The optical micrograph of a fabricated micro-hotplate with SOI thermodiode temperature sensor embedded under the hotplate within the oxide membrane [27].



(a)



(b)

Figure 10. Thermodiode designed by [27] for high temperature measurements. (a) Cross sectional view of membrane thermodiode, reference thermodiode and CMOS electronics cells, (b) Comparison of experimental, numerical and analytical calibration curves of the thermodiode.

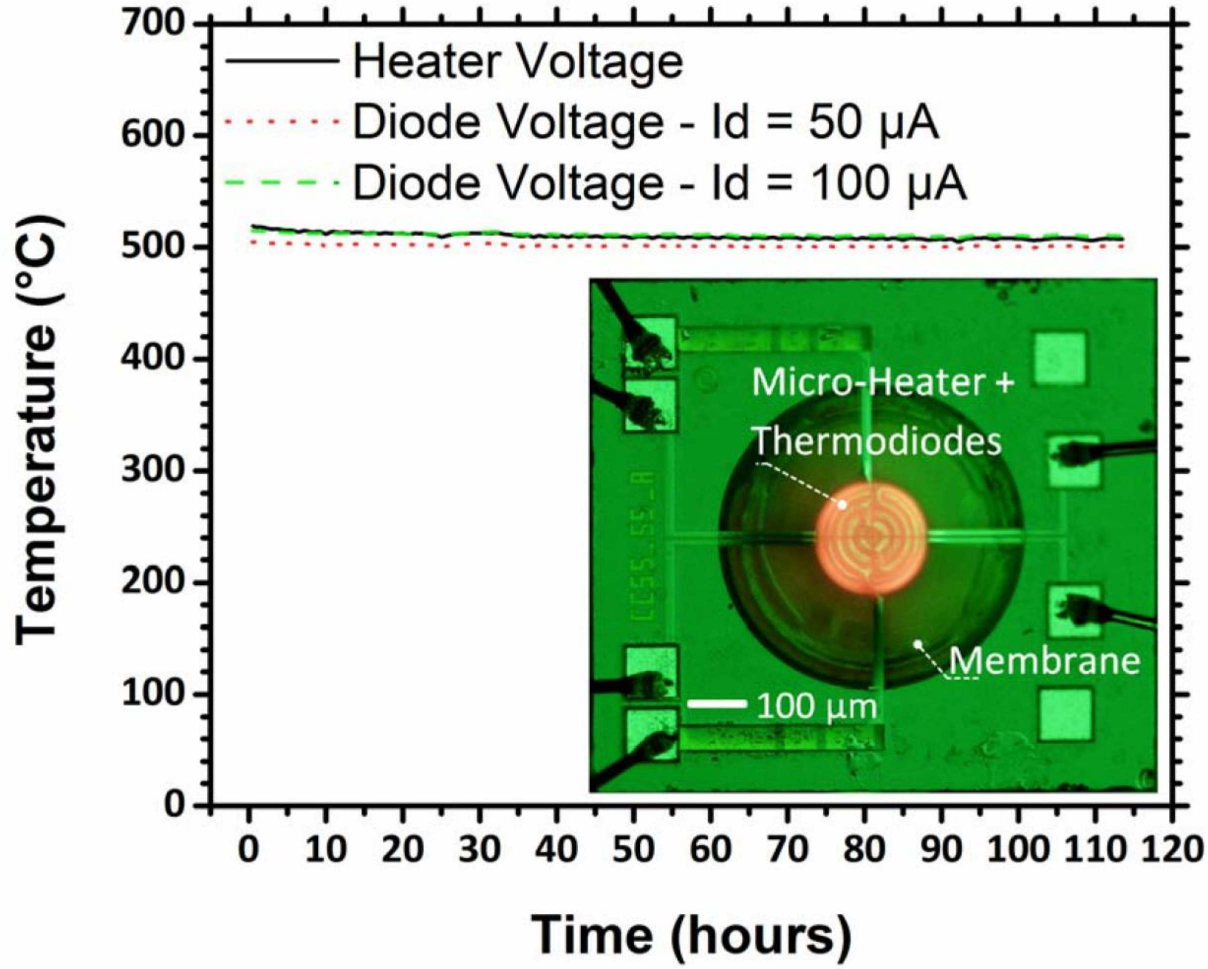


Figure 11. Results showing long-term stability of the thermodiode reported by [18] at high temperatures. The thermodiode is embedded under the micro heater. Inset: micro-hotplate chip with micro-heater glowing when operated at high temperature.

Table 1. Details of silicon and SOI based diodes used as temperature sensors in various applications

Application	Temperature Range	Diode Drive Mode	Technology	Sensitivity	Diode Size	Chip Size(mm)	Ref
Gas Sensing	Upto 600 ºC	Constant current (ΔV between two sensors)	SOI CMOS	-	Dia < 75 µm	-	**[22]**
	Upto 550 ºC	Constant current (ΔV between two sensors)	SOI CMOS	-1.2 ± 0.005 mV/K @ 65 µA drive current	18 µm	4 × 4	**[23]**
	Upto 700 ºC	-	SOI CMOS	-	-	-	**[45]**
	Upto 220 ºC	Constant current	SOI CMOS	-1.95 ± 0.005 mV/K @ 10 µA drive current	-	5 × 5	**[49]**
IC / Chip Temperature Measurement	Upto 200 ºC	Reverse Bias (Leakage Current < 15 nA)	SOI CMOS	-	-	-	**[24]**
	0 to 150 ºC	Forward Bias	Silicon	-	-	12 × 12	**[70]**
Stress Sensing	-40 to 150 ºC	-	Silicon	-	-	5 × 5	**[33]**
	Upto 220 ºC	Constant Current	SOI	-1.2 mV/K @ 100 µA	-	-	**[35]**
Pressure Sensing	-40 to 125 ºC	-	Silicon	-	-	-	**[37]**

	25 to 85 ºC	Constant Voltage	SOI CMOS	N/A	-	3 × 2.5	**[25]**
IR Detector	-	Constant Current	Silicon CMOS	-2 mV/K	40 × 40 µm	6.5 × 7.9	**[63]**
	25 to 37 ºC	Constant Current	Silicon CMOS	-2.0 mV/K @ 20 µA 2.35 mV/K @ 1 µA 1.7 mV/K @ 100 µA	40 × 40 µm	-	**[62]**
	-	Constant voltage	Silicon	-	-	-	**[61]**
	-	Constant Current	SOI	~-1.3 mV/K for single diode -6.5 mV/K for five diodes in series and -12.3 mV/K for ten diodes in series @ 50 µA	5 µm wide	-	**[65]**
Humidity Sensing	-200 to 500 ºC	Constant Voltage forward bias for lower temperatures (-200 to 150 ºC) and reverse bias for higher temperatures (150 to 500 ºC)	SOI CMOS	-	100 × 100 µm	-	**[29]**
	150 to 250 ºC	Constant Current	Silicon CMOS	-1.3 mV/K @ 100 µA -1.6 mV/K @ 60 µA	~100 × 100 µm	1.65 × 1.90	**[66]**

Cryogenic Applications	4.2 to 300 K	Constant Current	SOI CMOS	-	-	-	**[26]**
	100 K to 400 K	Constant Current	SOI CMOS	0.7 – 1.97 mV/K @ 5-100 µA	5 × 758 µm 7 × 564 µm 10 × 570 µm 100 × 83 µm	-	**[43]**
	2 to 600 K	Constant Voltage	Silicon	-1.8 mV/K @ 10 µA	350 × 350 µm	Dia =1.2 Length = 1.0	**[20]**
	10 to 300K	Constant Current	Silicon	-1.41 to -21.8 mV/K			**[39]**
	4.2 to 300 K	Constant Current	Silicon	> 2 mV/K		2 × 2	**[41]**
	5 to 255 K	Constant Current	Silicon		0.5 × 0.3 mm	2 × 3	**[42]**
	4.2 to 600 K	Constant Current	Silicon	< 2.5 mV/K			**[21]**
	1.5 to 380 K	Constant Current	Silicon	> 2.2 mV/K			**[44]**
High Temperature Applications	25 to 780 ºC	Constant Current	SOI CMOS	-2.2 mV/K @14 nA -1.3 mV/K @ 65 µA	Dia ~ 34 µm	-	**[27]**

	-200 to 500 ºC	Constant Voltage. Adjustable forward bias for lower temperatures (-200 to 150 ºC) and reverse bias for higher temperatures (150 to 500 ºC)	SOI CMOS	-	100 × 100 µm	-	**[30]**
	22 to 780 ºC	Constant Current	SOI CMOS	-1.3 mV/K @ 65 µA	Dia = 80 µm	-	**[17]**
	-200 to 850 ºC	Constant Current (100 µA)	SOI CMOS	-1.1 mV/K for Aj=5 µm^2 -1.2 mV/K for Aj=56.5 µm^2 -1.3 mV/K for Aj=142 µm^2	-	1 × 1	**[18]**
Flow Sensing	5 ºC (above ambient)	Constant Current (ΔV between two sensors)	Silicon CMOS	2 mV/K	-	1 × 5	**[54]**
	11.5 ºC (above ambient)	Constant Current (ΔV between two sensors)	Silicon CMOS	2 mV/K	-	4 × 5	**[55]**
	~ 50 ºC (above ambient)	-	Silicon	-	-	1.6 × 0.4	**[52]**

	-	Constant Current	SOI	-2 mV/K	-	5.2 × 7.5	**[56]**
Liquid Level Sensing	N/A	Constant Current	Silicon	N/A	3.2 × 1.9 µm		**[68]**
pH Sensing	5 - 55 ºC	Constant Current	Silicon CMOS	-1.51 mV/K			**[69]**
Thermal Conductivity Sensing		Constant Current	Silicon	-2.5 mV/K			**[48]**

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