Thin-Film Lateral SOI PIN Diodes for Thermal Sensing Reaching the Cryogenic Regime

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ABSTRACT

This paper presents the performance of lateral SOI PIN diodes for temperature sensing in the range of 100 K to 400 K. Experimental results indicate that PIN diodes can be used to implement temperature sensors with high accuracy in cryogenic regime, provided that a suitable temperature range is chosen for calibration. Numerical simulations using Atlas two-dimensional simulator were performed in order to confirm this hypothesis and extend the analysis, verifying the accuracy of the existing model.

Index Terms: PIN diode, Temperature Sensor, Low temperature, SOI.

1. INTRODUCTION

Forward biased semiconductor diodes are cheap and efficient temperature sensors and have been studied for this purpose since the sixties [1-4]. These devices show several advantages over other types of thermometers, mainly resistive thermometer devices, such as lower cost and high sensitivity over a wide temperature range [1, 4]. Diode thermometers are based on the fact that, under constant forward current, the voltage across the junction increases while decreasing the temperature.

Although basic PN junctions are the most popular type of diodes in use, PIN diodes present quasi-linear voltage versus temperature characteristics that make them a good alternative for temperature sensing at low power. The almost linear dependence of the forward voltage versus temperature over a wide temperature range eases the calibration of this kind of thermometer [3]. A PIN diode is a PN junction that is separated by an intrinsic (I) region [5]. In practice, however, the intrinsic region corresponds to either a P-type or N-type region with low doping level.

In this work an analysis of the performance of lateral SOI PIN diodes for temperature sensing reaching the cryogenic regime, from 100 K up to 400 K is presented. The effect of bias current change on the sensitivity of the sensors is also addressed. The present analysis is performed through experimental data and two-dimensional numerical simulations in order to evaluate the PIN diodes behavior. A simple model accounting for some diode nonlinearity is used to select the temperature range that must be used for calibration to increase accuracy in the temperature extraction.

2. PIN DIODES CHARACTERISTICS AND MEASUREMENT SETUP

Lateral PIN diodes with multifingers were implemented in a SOI fully depleted CMOS technology featuring silicon film thickness, t_{Si}, of 80 nm, and buried oxide thickness, t_{oxb}, of 390 nm [6]. The thin film ‘intrinsic’ (actually a P-type lightly doped region), P and N doping concentrations were about 1×10^{15} cm^{-3}, 1×10^{20} cm^{-3} and 4×10^{20} cm^{-3}, respectively. The length of the intrinsic region, L_i, was varied from 5 to 100 μm, with different widths, W. Figure 1 presents the schematic cross-section of one finger of the SOI PIN diodes under study. Table I presents the dimensions (intrinsic length and width) of the measured devices.

With the aim to evaluate the behavior of PIN diodes as temperature sensor, the devices were measured for temperatures (T), ranging from 100 K up to 400 K. The experimental anode voltage (V_D) measured as a function of the applied bias current (I_D) curves have been obtained with an Agilent 4156C Semiconductor Parameter Analyzer and the temperature has been controlled by using the Variable Temperature Micro Probe System from MMR Technologies, which features a temperature control accuracy of ± 0.01 K [7].

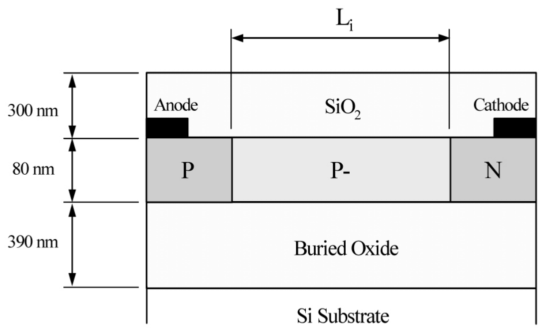

Figure 1. Schematic cross-section of one finger of the thin-film lateral SOI PIN diode under study.

Table I. Intrinsic length (L_i) and Width (W) of the measured PIN diodes.

Intrinsic Length, L_i (μm)	Width , W (μm)
5	758
7	564
10	570
100	83

3. EXPERIMENTAL RESULTS

Figure 2 presents the experimental forward bias current normalized by device width (I_D/W) vs. V_D curves measured at different temperatures for devices with L_i=7 and 100μm.

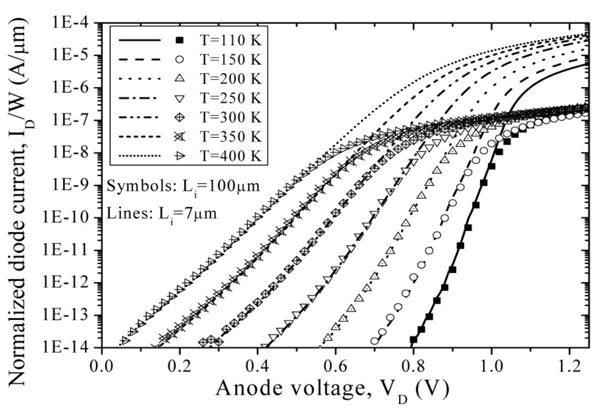

Figure 2. Normalized forward diode current (I_D/W) as a function of the applied voltage (V_D) for different intrinsic lengths and temperatures.

The presented results indicate that the curves of lateral SOI PIN diodes with different intrinsic lengths present similar slope under low injection condition. However, as the forward voltage is increased, the current of the diode with longer L_i becomes smaller than the shorter device, due to the larger resistance associated to the intrinsic region. As the resistance increases, the slope of the I_D/W vs. V_D curve is reduced, limiting the I_D/W range in which the diode can be used as temperature sensor (exponential part of the curve) with high sensibility and therefore, accuracy.

From I_D vs. V_D curves, as those shown in Figure 2, at constant I_D/W, the V_D vs. T curves of all measured devices have been extracted and are presented in Figure 3. For this analysis the current has been considered higher than 100pA/μm, since for lower I_D/W values the ideality factor of the curves presented in Figure 2 suffers an increase.

From these results one can note that the V_D vs. T curves approach a linear behavior in a wide temperature range, and the curves obtained at different I_D/W converge at 0 K to a value close to the bandgap voltage of silicon (around 1.19 V - 1.2 V), in agreement to the theory. In addition, it is possible to note

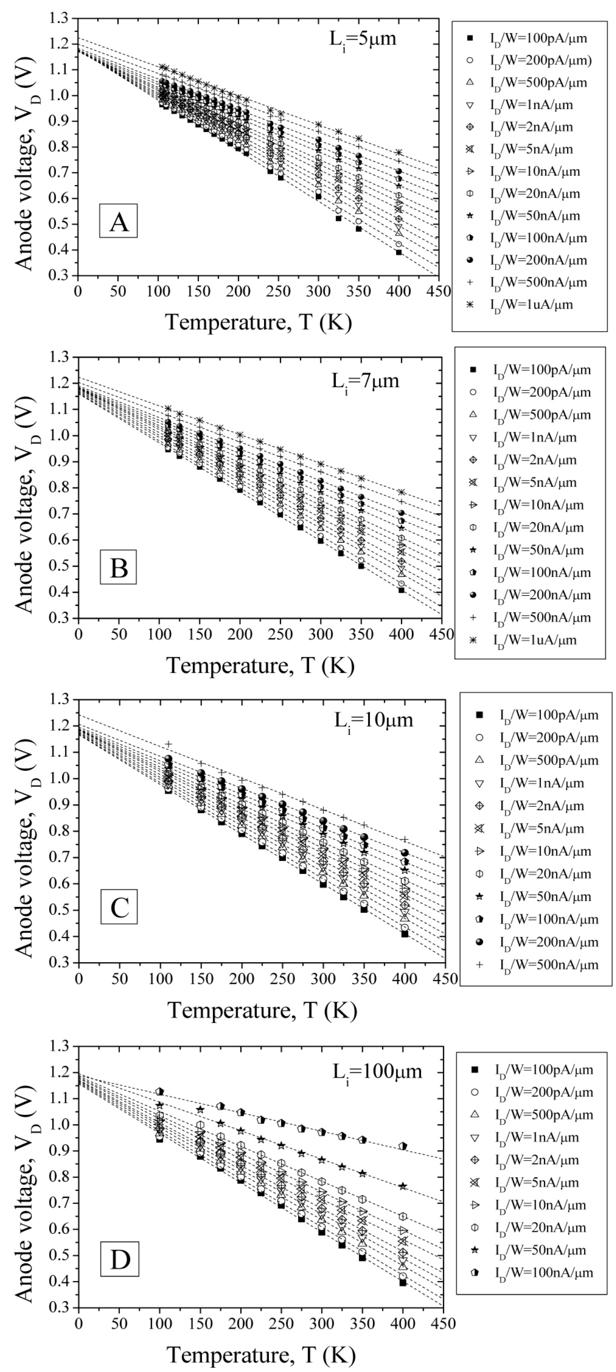

Figure 3. V_D vs. T curves for SOI lateral PIN diodes for different bias currents, I_D/W, and intrinsic lengths: (A) L_i=5 μm; (B) L_i=7 μm; (C) L_i=10 μm and (D) L_i=100 μm.

that for a given range of I_D/W, all devices present similar V_D vs. T curves, independent on the length of the intrinsic region. Table II presents the slope of the linear fitting of V_D vs. T curves shown in Figure 3, which represents a rough approximation of the sensor sensitivity.

Table II. Slope of V_D *vs.* T curves shown in Figure 3.

I_D/W	Approximated sensitivity (mV/K)			
	L_i = 5µm	L_i = 7µm	L_i = 10µm	L_i = 100µm
100 pA/µm	1.97	1.88	1.89	1.89
200 pA/µm	1.88	1.82	1.83	1.84
500 pA/µm	1.78	1.74	1.76	1.76
1 nA/µm	1.70	1.69	1.70	1.70
2 nA/µm	1.63	1.63	1.64	1.64
5 nA/µm	1.53	1.55	1.56	1.54
10 nA/µm	1.46	1.49	1.49	1.46
20 nA/µm	1.40	1.43	1.43	1.34
50 nA/µm	1.31	1.34	1.34	1.09
100 nA/µm	1.25	1.27	1.28	0.71
200 nA/µm	1.19	1.21	1.22	-
500 nA/µm	1.14	1.14	1.18	-

As demonstrated by the results presented in Table II, the slope of V_D vs. T curves of all diodes increases when decreasing the forward current, as the effect of parasitic resistances is less pronounced. This result is in agreement to the data reported in ref. [8], which presents temperature sensors implemented with PN bulk diodes. For the longest intrinsic region (L_i=100 µm), the decrease of I_D/W observed in Figure 2 can be seen through a significant decrease of the V_D vs. T slope. In this case, the resistance of the intrinsic region becomes important, and for I_D/W values larger than 20nA/µm the result starts diverging from the slope of diodes with shorter L_i. For this reason and aiming to increase the studied bias current range, a more detailed analysis will focus on the shortest available intrinsic region (L_i=5µm).

Despite this linear-like characteristic, according to ref. [9], the temperature dependence of a PIN diode voltage is not strictly linear. This can be clearly seen in Figure 4, which presents the sensitivity, i. e. $|dV_D/dT|$, of the PIN diode with L_i=5µm at different I_D/W. As mentioned before, the sensitivity of the diode increases when decreasing the forward current.

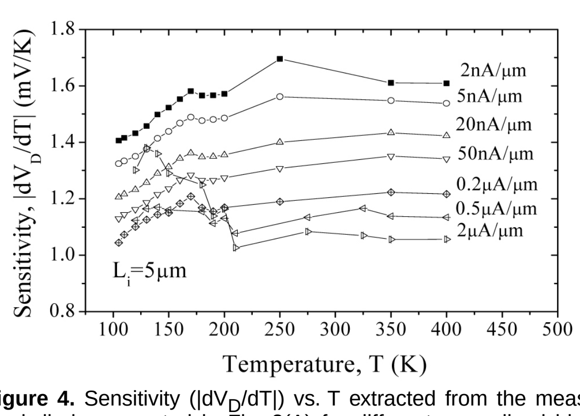

Figure 4. Sensitivity ($|dV_D/dT|$) vs. T extracted from the measured diode presented in Fig. 3(A) for different normalized bias current (I_D/W).

According to the presented curves, the temperature lowering causes the sensitivity to reduce for smaller applied bias current. On the contrary, for higher bias current values, the sensitivity suffers an increase at reduced temperatures. As the current is increased, the sensitivity tends to a constant value in the entire T range, close to 1.2mV/K, which in this case happens for I_D/W between 0.2 and 0.5 µA/µm. After this point, further I_D/W increase leads to a rise of the sensitivity for T<200 K. A similar tendency was observed for the other diodes.

Following ref. [9], at constant bias current, the temperature dependence of the forward voltage of PIN diodes can be expressed as

$$V_D(T) = V_{g0} - \frac{T}{T_r}\left[V_{g0} - V_D(T_r)\right] - \eta v_T \, ln\left(\frac{T}{T_r}\right) \quad (1)$$

where V_{g0} is the extrapolated bandgap voltage to 0 K, which is confirmed by the results presented in Figure 3, η is a process-dependent parameter, v_T is the thermal voltage (kT/q) and $V_D(T_r)$ is the diode anode voltage at the reference temperature, T_r. The last term in eqn. (1) accounts for non-linearity in V_D(T) characteristic, caused by some V_{g0} dependence on the temperature, which is more noticeable at low temperatures [9].

Equation (1) has been solved using the least-square solution [10, 11] for the system with two unknown variables (V_{g0} and η), for each T_r, to find the set of parameters that minimizes the sum of squared errors. The model parameters, V_{g0} and η, obtained from the fitting of eqn. (1) to the experimental data of Figure 3(A) are presented in Figure 5 as a function of the bias current, I_D/W, with T_r=170 K, which provided best model fitting for the whole measured temperature range. As shown in this figure, V_{g0} values are close to the bandgap voltage up to I_D/W≅100 nA/µm. In the same range of bias current, η lies close to 2.4, which is in agreement to the data reported by Tsividis [9] for bulk PN diodes from different processes.

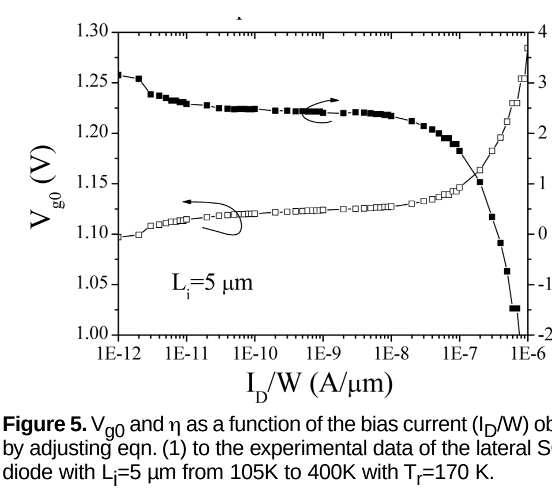

Figure 5. V_{g0} and η as a function of the bias current (I_D/W) obtained by adjusting eqn. (1) to the experimental data of the lateral SOI PIN diode with L_i=5 µm from 105K to 400K with T_r=170 K.

The error in the temperature extraction (ΔT) has been obtained by calculating the difference, ΔV_D, between the measured ($V_{D,measured}$) and modeled ($V_{D,model}$) V_D vs. T curves, which is then converted in temperature by using the sensitivity. The resulting ΔV_D and ΔT vs. T curves are presented in Figure 6, for the diode with L_i=5 μm under different bias currents. It is worthwhile mentioning that similar tendencies and values were obtained for diodes with other intrinsic lengths.

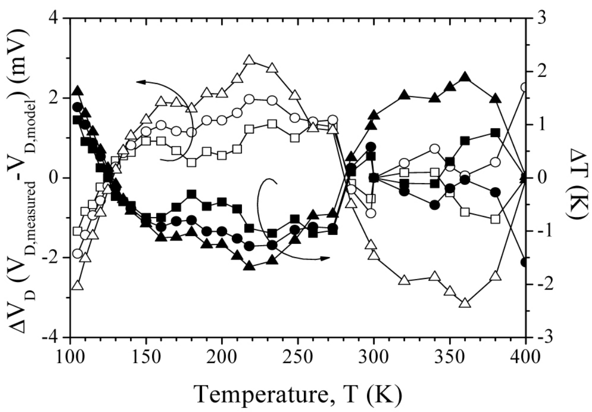

Figure 6. V_D and T errors extracted by adjusting eqn. (1) to the experimental data of the lateral SOI PIN diode with L_i=5 μm from 105 K to 400 K with T_r=170 K, for different bias currents (I_D/W): 1nA/μm (■,□), 10 nA/μm (•,○) and 100 nA/μm (▲,Δ).

From the extracted error curves presented in Figure 6 one can observe that the error is smaller than 2 K if the sensor were meant to be used in such a wide temperature range and biased up to 100 nA/μm. These results show that SOI PIN diodes are good temperature sensors not only at high temperature, as demonstrated in ref. [12], but also at cryogenic temperatures. The bias current reduction promotes an increase of accuracy and the error can be as low as 1 K for I_D/W < 10 nA/μm. Similar errors, in the order of 2 K, have been presented in ref. [13] for temperature sensing from 50 K up to 300 K using bulk PN diodes biased at 100 μA qualifying these lateral SOI PIN diodes as temperature sensors compared with the literature.

Despite the presented temperature inaccuracy may be smaller than 2 K in the entire studied temperature range, it is important to mention that the presented values of ΔT result both from the measurement setup and/or temperature stability and from the error imposed by the model adjustment to the measured data. In order to evaluate whether it is possible to accurately model the temperature sensor behavior in a wide temperature range, decorrelating both sources of inaccuracy and avoiding any possible lack of accuracy in the measurement setup, numerical simulation results were used and are presented in the next section.

4. TWO-DIMENSIONAL NUMERICAL SIMULATIONS

Two-dimensional numerical simulations of lateral SOI PIN diodes were performed using Atlas software [14]. All devices were simulated considering a steep transition of the doping concentration at the boundary of P, intrinsic and N regions and using the same technological parameters as the experimental samples (t_{Si}= 80 nm, t_{oxb}= 390 nm, N_A= 1×10^{20} cm^{-3}, $N_{intrinsic}$= 1×10^{15} cm^{-3} and N_D = 4×10^{20} cm^{-3}). However, in order to maximize the bias current range and avoid the influence of the series resistance, PIN diodes were simulated for shorter intrinsic region lengths of 1, 2 and 5 μm. In all the cases, the width is 1 μm.

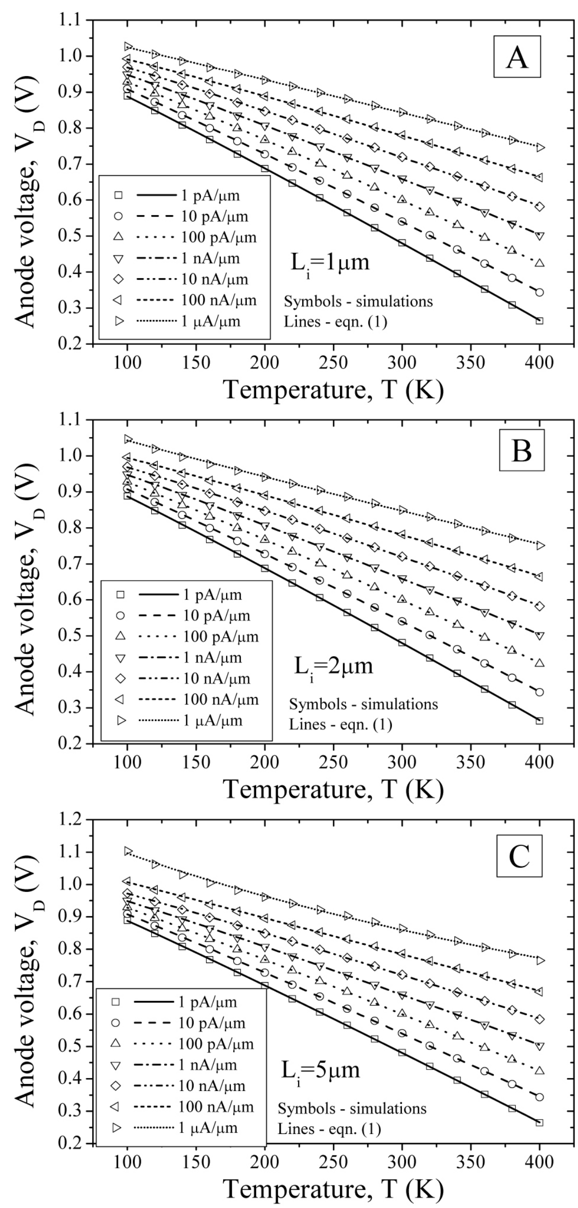

Figure 7. Simulated and modeled V_D as a function of the temperature of PIN diodes with L_i = 1 μm (A), 2 μm (B) and 5 μm (C) by using eqn. (1) for different current bias.

Physical models accounting for mobility dependence on velocity saturation and doping concentration, bandgap narrowing, Auger and SRH recombination, doping-dependent lifetime and incomplete carrier ionization for the lightly doped region were included in the simulation files. The lattice temperature, which would affect the behavior of SOI devices due to self-heating, has not been considered in the simulations, since it has shown to be negligible in the analyzed voltage-current range. In addition, no optimization of model parameters has been made, which is beyond the scope of this analysis and may affect the quantitative results but does not affect the qualitative analysis.

From the simulated diode characteristics, V_D vs. T curves for temperatures ranging between 100 K and 400 K, with step of 10 K were obtained. Figure 7 presents the resulting V_D vs. T curves of PIN diodes with L_i= 1 µm (A), 2 µm (B) and 5 µm (C) at different bias current values. In the same graphs the curves obtained by the fitting of eqn. (1) to the simulated data are presented as lines.

As previously indicated in the experimental results, the V_D vs. T curves of lateral SOI PIN diodes are not affected by the length of the intrinsic region, if low current bias is applied. On the other hand, at higher current levels, the increase of the intrinsic length makes the diode voltage to increase at low temperatures, due to the larger resistance associated to this region. This effect is clearly seen in Figure 8, which presents the sensitivity, extracted from the simulated V_D vs. T curves. As shown by these curves, at low bias current, all diodes present the same sensitivity in the whole temperature range. In addition, the increase of the bias current causes the sensitivity of diodes with different intrinsic lengths to depart at low temperatures. The longer the intrinsic region (and consequently, the series resistance), larger is the sensitivity increase in the cryogenic regime.

Figure 9 presents the values of V_{g0} and η, obtained from the adjustment of eqn. (1) to the simulated data of PIN diode with L_i= 1µm, 2µm and 5 µm. From the presented curves one can note that the parameters extracted from simulated and experimental data (Figure 5) present the same tendency and similar values. As shown in this figure, V_{g0} and η are virtually constant except for larger values I_D/W. In this condition, both parameters lose their physical meaning. This effect becomes more pronounced as L_i increases and is associated to the fact that the model used to fit the simulated curves does not consider the series resistance associated to the intrinsic region, thus failing to reproduce the diode behavior in the bias condition where the resistance becomes important.

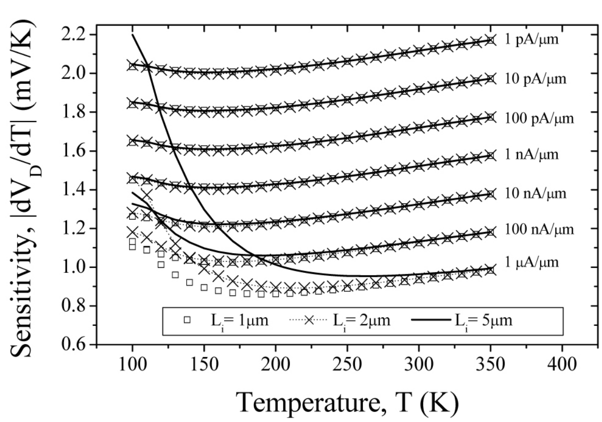

Figure 8. Sensitivity ($|dV_D/dT|$) vs. T extracted from the numerical simulation of PIN diodes with L_i = 1 µm, 2 µm and 5 µm for different current biases.

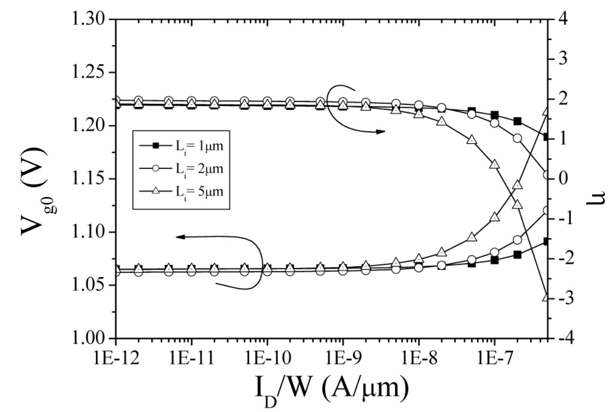

Figure 9. V_{g0} and η values as a function of the normalized bias current (I_D/W) obtained by adjusting eqn. (1) to the simulated data of the lateral PIN diode with different intrinsic lengths.

Through the difference between simulated and modeled V_D vs. T curves (Figure 7), and using the sensitivity presented in Figure 8, the error in the temperature extraction (ΔT) has been obtained and is presented in Figure 10 for the simulated PIN diodes with L_i=1µm and 5µm.

Considering that in the numerical simulations there is no sources of temperature inaccuracy as may exist in the measurement setup, the exact PIN diodes temperature is known and any error in the V_D (and hence, T extraction) comes from the model used to describe the sensor behavior. Therefore, this 'intrinsic' error may be used to evaluate how accurate is the model in describing the V_D vs. T characteristic. From the presented curves it is possible to note that for low values of I_D/W, both diodes present similar error for the extracted temperature and may be smaller than 1 K in the entire temperature range, for bias current values up to approximately 1nA/µm. As the current is increased, the already mentioned influence of the series resistance associated to the intrinsic length becomes more important and results in a increase of the error in the extracted temperature for the diode with L_i=5µm in comparison to the one which features shorter L_i.

Higher accuracy may be achieved even for PIN diodes with longer intrinsic region by reducing the temperature range for which eqn. (1) is fitted [15]. With this purpose, eqn. (1) was fitted to the simulat-

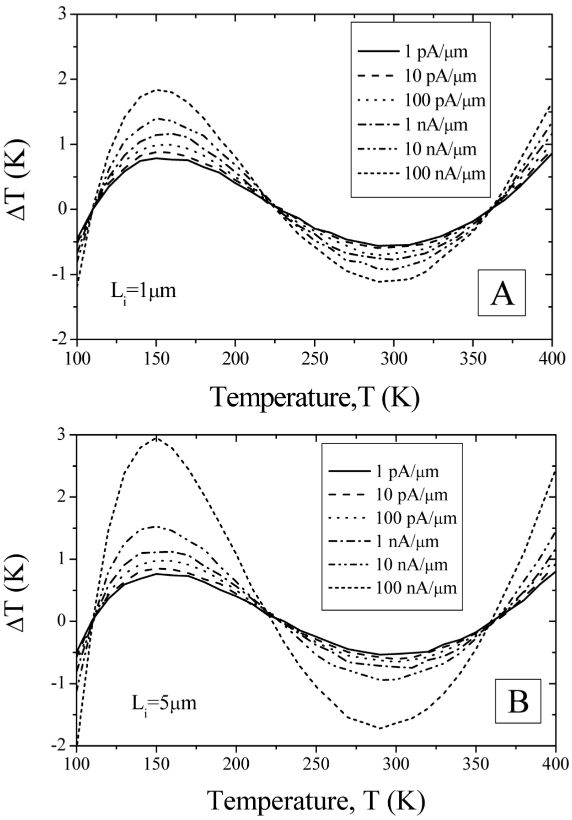

Figure 10. Temperature error extracted by modeling PIN diodes with L_i = 1 μm (A) and 5 μm (B) by using eqn. (1) for different current bias ranging from 1pA/μm to 100 nA/μm.

ed data at I_D/W=1 nA/μm varying the temperature range for the model fitting, thus limiting the sensor range of operation. The resulting V_{g0} and η values extracted for the diode with L_i=5μm are presented in Table III, as well as the approximate slope of the V_D vs. T curves and, for each temperature range, the reference temperature, T_r, for which the error is minimized. From the results of this table it is possible to note that the value of V_{g0} is not strongly affected by the selected temperature range (V_{g0}=1.0658 V ±0.025 V). On the other hand, depending on the temperature range, η can even assume fictitious values in order to match the simulated results.

The ΔV_D ($V_{D,simulated} - V_{D,model}$) curves as a function of the temperature, obtained from the model fitting conditions shown in Table III are presented in Figure 11: fixing the maximum temperature at 400 K and varying the minimum one (A), fixing the minimum at 100 K and sweeping the higher one (B) and taking different ranges around 250 K (C). The presented results indicate that the model loses accuracy with the temperature range increase.

Following the results shown in Table III, the average slope of V_D vs. T curves, which gives a roughly approximation of the sensor sensitivity, is in the order of −1.5 mV/K for I_D/W= 1nA/μm. Therefore, if one wants to describe a PIN diode with the simulated characteristics, for temperature

Table III. Extracted V_{g0}, η, T_r and linear slope of V_D *vs.* T curves for the simulated PIN diodes with L_i=5 μm for different temperature ranges, biased at I_D/W=1 nA/μm.

	T range [K]	V_{g0} [V]	η	T_r [K]	Slope [mV/K]
(A1)	100 .. 400	1.067	1.827	110	-1.48
(A2)	120 .. 400	1.057	2.247	130	-1.49
(A3)	140 .. 400	1.049	2.588	150	-1.49
(A4)	160 .. 400	1.041	2.895	170	-1.50
(A5)	180 .. 400	1.034	3.172	190	-1.51
(A6)	200 .. 400	1.028	3.412	210	-1.52
(B1)	100 .. 200	1.116	-1.559	140	-1.42
(B2)	100 .. 240	1.104	-0.599	160	-1.42
(B3)	100 .. 280	1.093	0.294	110	-1.43
(B4)	100 .. 300	1.089	0.568	110	-1.44
(B5)	100 .. 320	1.086	0.816	110	-1.45
(B6)	100 .. 360	1.080	1.247	110	-1.46
(C1)	120 .. 380	1.065	1.965	130	-1.48
(C2)	140 .. 360	1.059	2.201	150	-1.48
(C3)	160 .. 340	1.054	2.376	170	-1.47
(C4)	180 .. 320	1.050	2.517	240	-1.47
(C5)	200 .. 300	1.047	2.618	250	-1.47

sensing with accuracy of ± 0.5 K, the V_D difference between the simulated (or experimental) and modeled curves must be smaller than ±0.67 mV (indicated in Figure 11).

From the presented curves, one can note that such precision in the modeled V_D can be achieved depending on the temperature range in which eqn. (1) is adjusted to the PIN diode curve. For instance, if one fixes the maximum temperature at 400K, the lowest temperature in which the model would be able to describe the sensor characteristic with inaccuracy smaller than ±0.67 mV is approximately 160 K for this simulated diode. On the other hand, if the model must fit the sensor characteristics for lower minimum temperatures (for instance, 100 K), it would be possible to extend the range up to around 270 K (Figure 11(B)), to achieve the temperature extraction accuracy of ± 0.5 K (V_D < ±0.67 mV). However, in this case, fictitious values of η must be used to match the simulated data. Nevertheless, if no extreme temperatures need to be used (in Figure 11(C), approximately between 150 K and 350 K) the model can describe the PIN diode behavior with good accuracy, keeping the physical meaning of η parameter (Table III).

According to this analysis, if the temperature range used in eqn. (1) is not adequately chosen it is clear that the expected temperature sensing error will be overestimated, since the model neglects some effects that may take place in these devices. On the other hand, with appropriate temperature range, the lateral SOI PIN diode demonstrated to be able to sense temperatures in a wide range, by fitting the diode curves using the existing model. However, the model parameters present no physical meaning for T<120 K, suggesting that some model correction to describe the PIN diode behavior may be needed in cryogenic regime.

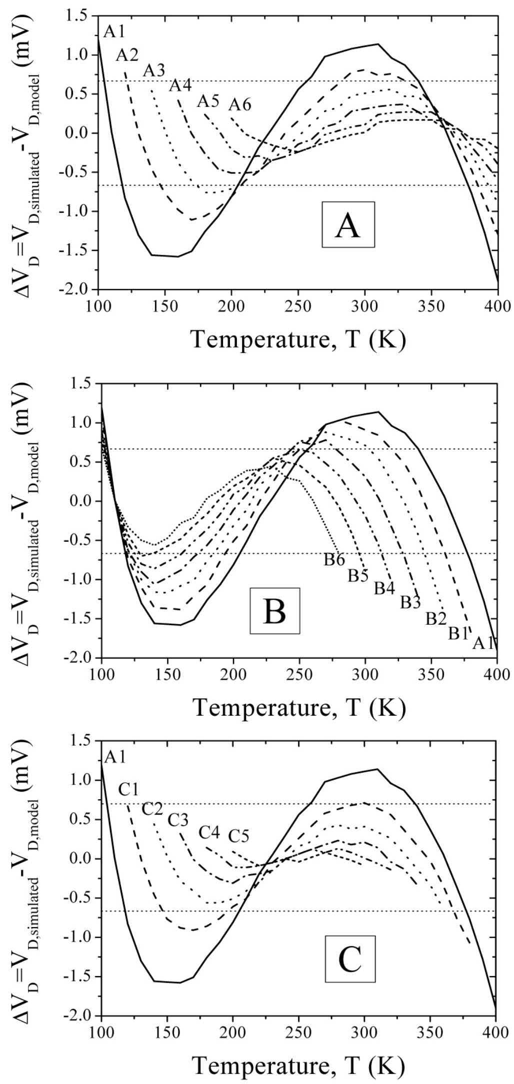

Figure 11. Extracted V_D error *vs.* T for the simulated diode with L_i=5µm and I_D/W=1nA/µm, fixing the maximum temperature at 400 K (A), fixing the minimum temperature at 100 K (B) and taking different temperature ranges around 250 K (C).

5. CONCLUSIONS

In this work the performance of thin-film SOI PIN diodes for the implementation of temperature sensors in a wide temperature range, reaching the cryogenics regime, has been presented. A simple analytical model for the diode voltage as a function of the temperature has been used to predict the error in the temperature extraction. Experimental results showed that PIN diodes may be suitable for the temperature sensing in a wide temperature range (from 100 K to 400 K), reaching high accuracy down to 100 K. Also, the shorter the intrinsic length, the larger the bias current range that may be used while maintaining good accuracy. Two-dimensional numerical simulations were performed and used to evaluate the ability of the existing model to describe the behavior of these diodes for thermal sensing purposes. It has been shown that, depending on the temperature range chosen for the operation of the sensor, the model can describe its behavior with good precision, providing high accuracy in the temperature extraction, by diminishing the error in the conversion of voltage into temperature. However, there is still room for improvement in the modeling of these devices, in order to accurately describe the behavior of sensors implemented with SOI PIN diodes for cryogenic temperatures sensing.

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