Simulation and Electrical Characterization of Lateral PIN SOI Gated Diodes for Temperature Sensing

Lucas Aguiar Salvador and Michelly de Souza
Department of Electrical Engeneering, Centro Universitário da FEI, S. B. Campo, SP, Brazil
lucasaguiarsalvador@gmail.com and michelly@fei.edu.br

Abstract— **This work presents a study of lateral gated PIN SOI, for use as temperature sensor. The data were collected through numerical simulations using the Atlas simulator and experimental. In the simulations a voltage variation between 1.0 V and -1.0 V has been applied, for temperatures in the range between 100K and 500K. For experimental data, gate voltage has been varied between -3.0 V and 3.0 V, for temperatures ranging from 90 K to 500 K. From the obtained curves, the sensitivity and linearity of the PIN diode as a temperature sensor has been extracted.**

Keywords— PIN diode, SOI Technology, Temperature Sensor, Electrical Characterization, Numerical Simulation.

I. INTRODUCTION

Semiconductor diodes are electronic devices, consisting of a P-type and a N-type semiconductors junction [1]. Given the linear relationship between voltage and temperature, when the current is kept fixed, they are often used as temperature sensors.

The PIN diode consists of a PN junction with an intrinsic region (in fact it is a weakly doped P-type region) [2], separating the two regions, represented in figure 1.

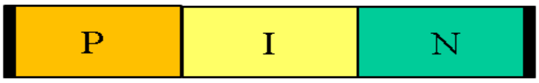

Fig. 1 - PIN diode.

The Silicon-On-Insulator (SOI) technology has become an important alternative to support the continuous reduction of dimensions faced by conventional CMOS technology implemented in silicon wafer. In this technology, a thin layer of insulation separates the active region from the components of the remainder of the substrate. Thus, the PN and PIN junctions can be implemented laterally, in a thin layer of silicon on buried oxide [3]. The figure 2 shows the transversal profile of a PIN diode implemented in SOI technology, with the dimensions used in this work.

In this study, a gate terminal was added over the intrinsic region to verify if the application of voltage, with potential induction of an electron channel (applying positive voltage) or hole (applying a negative voltage), has influence on the performance of the PIN diode working as a temperature sensor.

In figure 2, t_{Si} is the thickness of the silicon layer, t_{oxf} is the gate oxide thickness, t_{oxb} is the buried oxide thickness, LP is the length of the P+ region, Li is the intrinsic region length, and LN is the N+ region length.

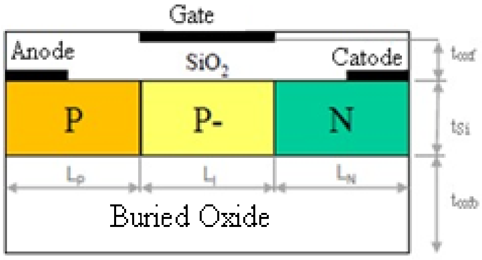

Fig. 2 - Schematic representation of the lateral PIN SOI used in the simulation and experimental parts.

II. NUMERICAL SIMULATIONS

Two dimensional numerical simulations were performed using Atlas software [4], to obtain the drain current curves of a PIN diode with gate voltage (V_G) between -1.0 V and +1.0 V, with steps of 250mV. The simulated diode features doping concentrations of $N_P=1\times10^{20}$ cm^3, $N_{P-}=1\times10^{15}$ cm^3, $N_N=4\times10^{20}$ cm^3, with the silicon layer thickness t_{Si} = 80nm, gate oxide thickness (t_{oxf}) of 31nm, and buried oxide thickness (t_{oxb}) of 400nm. This PIN diode presents a total length of 8µm, being a P+ region of length L_P = 1.5µm, an intrinsic region (actually, a lightly P- doped one) of L_i = 5µm and a N+ region of length L_N = 1.5µm. 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. It is worth mentioning that no optimization of model parameters has been made.

III. SIMULATION RESULTS

Figure 3 presents the relation between the diode current (I_D), as a function of the diode voltage (V_D), with V_G = 0V for temperatures ranging between 100 K and 500 K in linear scale. The same curve is presented in logarithmic scale in figure 4.

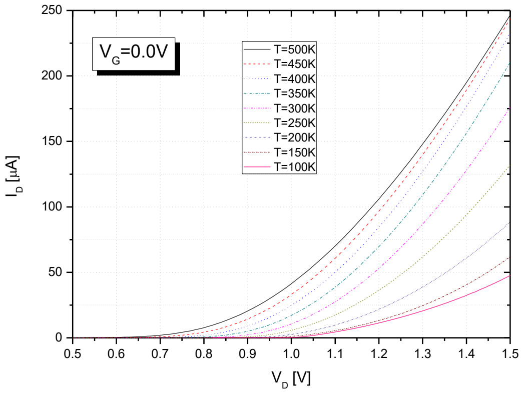

Fig. 3 – Simulated I_D x V_D curve for a SOI PIN diode with L_i=5µm and temperatures varying between 100 K and 500 K with V_G = 0 V.

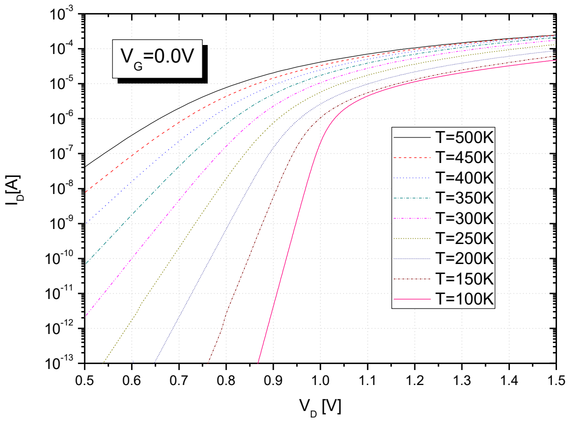

Fig. 4 - Simulated I_D x V_D (log scale) curve for a SOI PIN diode with L_i=5µm and temperatures varying between 100 K and 500 K with V_G = 0V.

To use the PIN diode as a temperature sensor, the almost linear relation between the voltage and the temperature is used. For this reason, it is necessary to analyze the relation V_D x T at different constant current levels. For this analysis, I_D of 100nA, 10nA, 1nA and 100pA have been considered and the results are presented in figure 5.

The sensitivity of the temperature sensor is given by the slope of the mean line formed by the points of the V_D x T curve. And it can be seen in figure 5, that the curve is more inclined to the current of 100 pA, what characterizes the greater sensitivity of the diode when applying smaller currents.

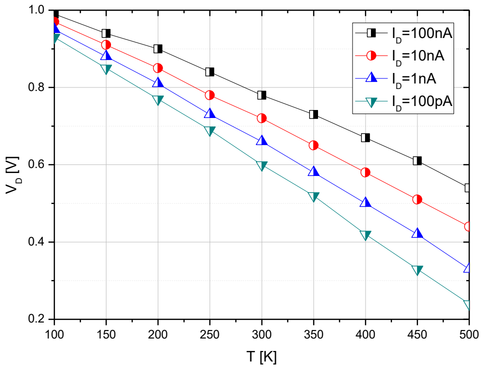

Fig. 5 – V_D x T curves, extracted from simulated data, at different current levels.

As can be seen in the presented curve, the V_D vs T curve is close to a straight line, increasing V_D as the temperature is reduced. In this work the coefficient of determination R^2 [5] was used to evaluate the linearity of the sensor. This coefficient is related to the best linear fit to the simulated points. With R^2 one can analyze the linearity of the simulated temperature sensor.

The slope of the I_D vs V_D graph translates the sensitivity of the sensor when translating temperature to voltage. The table I shows the extracted values of slope (S) and the R^2 coefficient for several values of gate voltage (V_G) and bias current (I_D).

It can be noticed that the sensitivity was not affected by the change of the gate voltage in the bias range used in the simulations. On the other hand, smaller bias current increases sensitivity, without worsening linearity.

Table I - Slope and R^2 coefficient to different currents.

I_D [A]	V_G[V]	S [mV/K]	R^2 [-]
100n	-1	-1,11	0.99710
	0	-1,12	0.99639
	1	-1,11	0.99615
10n	-1	-1,33	0.99791
	0	-1,33	0.99905
	1	-1,33	0.99905
1n	-1	-1,53	0.99892
	0	-1,54	0.99870
	1	-1,54	0.99845
100p	-1	-1,73	0.99865
	0	-1,73	0.99876
	1	-1,74	0.99799

From the obtained results, it can be noticed that in the initially simulated gate voltage (V_G) range, it was not possible to notice any significant change in the behavior of the gated SOI PIN diode as a temperature sensor when the gate voltage is varied. Therefore, the gate voltage range has been increased and is presented for V_D = 750 mV and T = 300 K in figure 6. From this result, one can note that there is a small current change for larger absolute V_G values.

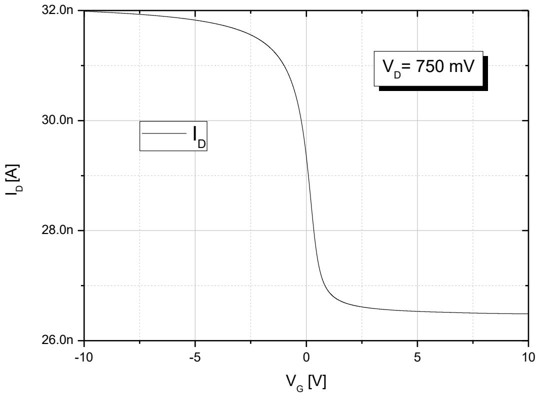

Fig. 6 – Simulated I_D x V_G at V_D = 750 mV and T = 300 K

IV. EXPERIMENTAL RESULTS

To perform the experimental part of the work, a Low Temperature Micro Probe (LTMP) associated to temperature controller K20, from MMR Technology has been used. This setup is able to set the desired temperature with precision of ± 0.05 K. The Semiconductor Parameter Analyzer Keithley 4200 SCS has been used to obtain the I_D vs V_D curves at different gate voltages, ranging between -3.0 and 3.0 V. The curves measured at V_G = -3.0 V and 3.0 V are presented in figures 7 and 8, respectively. One can see the decrease of conduction voltage as the temperature is increased. Also, a change in the I_D vs V_D slope is observed.

The figures 9 and 10, presents I_D vs V_D curves in logarithmic scale measured at different gate voltages and temperatures of 90K and 500K, respectively.

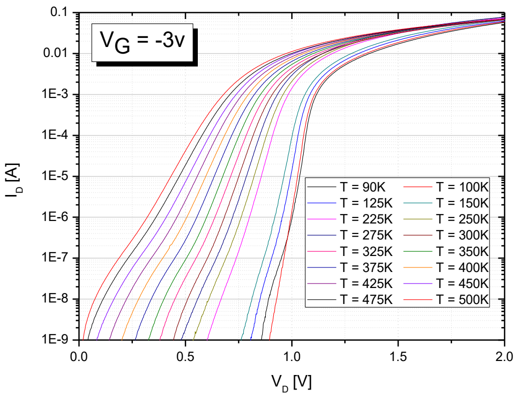

Fig. 7 – Experimental I_D x V_D curves in logarithmic scale at different temperatures, and V_G = -3.0 V.

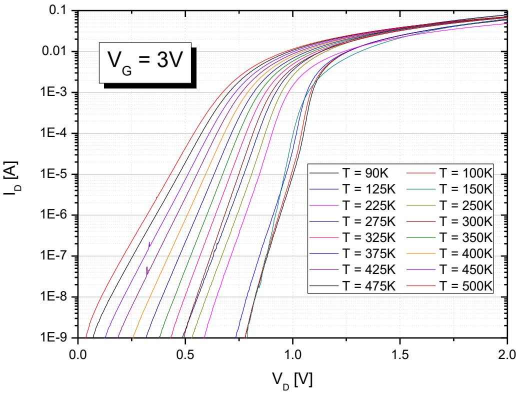

Fig. 8 – Experimental I_D x V_D curves in logarithmic scale at different temperatures, and V_G = 3.0 V.

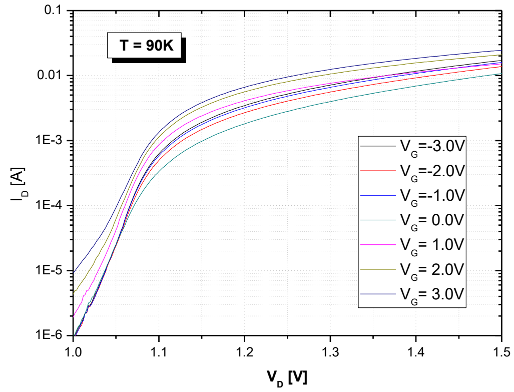

Fig. 9 – Experimental I_D x V_D curves in logarithmic scale at different gate voltages, and T = 90 K.

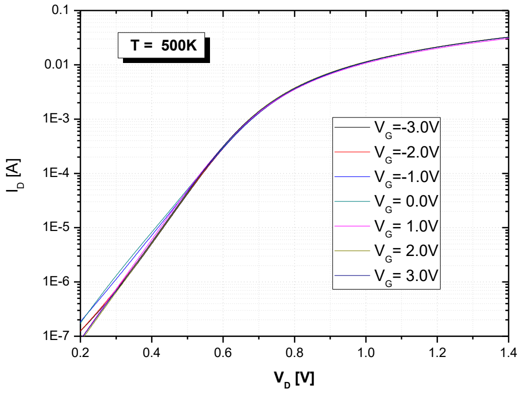

Fig. 10 – Experimental I_D x V_D curves in logarithmic scale at different gate voltages, and T = 500 K.

For the use of the PIN diode as a temperature sensor, the almost linear relation between its voltage and temperature is used when considering a constant current. The analysis was performed using the I_D x V_D curves previously seen, extracting the relation between V_D x T at different current levels, 100 μA, 10 μA, 1 μA, 100 nA and 10 nA.

The figures 11 and 12 present the results obtained for the voltage of the diode as a function of temperature, with different current bias levels, considering the gate voltages of -3.0 V and 3.0 V, respectively.

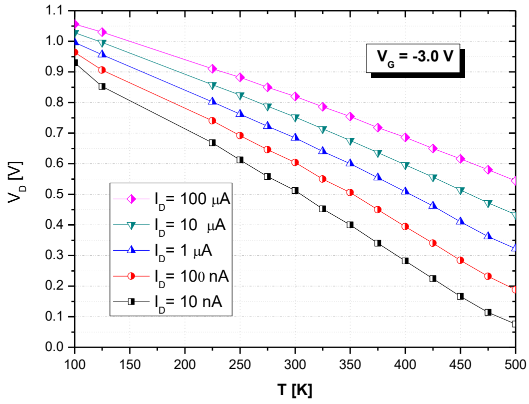

Fig. 11 – V_D x T curves, extracted from experimental data, at different current levels, and V_G=-3.0 V.

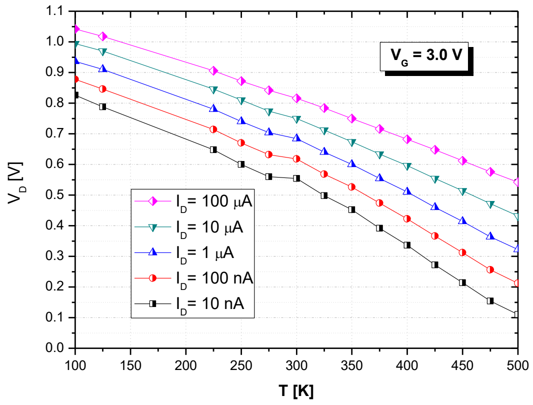

Fig. 12 – V_D x T curves, extracted from experimental data, at different current levels, and V_G=3.0 V.

The results show that, for a fixed current level, the reduction of the temperature promotes the increase of the voltage in the diode. In addition, the smaller the bias current, higher the voltage variation for the same temperature range.

In the moment when higher gate voltages are applied, the sensibility of the PIN diode is affected, changing the slope of the curves, as shown in figure 12.

After performing a linear extrapolation of the experimental data presented in the graphics, one can evaluate the sensitivity (S) and the coefficient (R^2), which determines how close the mean line is to the points.

The sensitivity of the temperature sensor, given by the slope of the mean line formed by the points of the curve V_D x T given in the figures 11 and 12, simulated with different gate voltages, the sensor sensitivity values were extracted. The slope of the mean line and the coefficient of determination are presented in table II.

The sensitivity increases with the reduction of the current, which can be seen through the curve, which shows larger V_D variation with temperature for smaller currents.

Table II - Slope and R^2 coefficient extracted from experimental curves, for different current levels.

I_D [A]	**V_G [V]**	**S [mV/K]**	**R^2 [-]**
100 µ	-3	-1,27	0.99636
	0	-1,29	0.99729
	3	-1,24	0.99682
10 µ	-3	-1,48	0.99799
	0	-1,51	0.99564
	3	-1,39	0.99450
1 µ	-3	-1,67	0.99785
	0	-1,72	0.99336
	3	-1,51	0.98938
100 n	-3	-1,91	0.99716
	0	-1,88	0.99180
	3	-1,63	0.98397
10 n	-3	-2,09	0.99589
	0	-2,00	0.98940
	3	-1,75	0.98081

Based on the analysis in the graphics and with the aid of the coefficient R^2, we can see that for the currents of 1 µA, 100 nA and 10 nA, in the 3.0 V graphic, the slope is kept between 100 K and 275 K, making a linearity transition and restarting a new slope between 300 K and 500 K. That is the reason why R^2 decreases for smaller bias current and larger gate bias.

Due to this characteristic, a new linearization was performed for these two steps, thus obtaining table III. One can note that R^2 closer to the unity has been attained when taking two different ranges of temperature. It has been observed that for smaller bias current, larger sensitivity for temperature sensing above room temperature.

Table III - Slope and coefficient R^2 for V_G=0.0 V and V_G=3.0 V for two T ranges, extracted from experimental data.

T [K]	-	100 to 275		300 to 500	
I_D [A]	**V_G [V]**	**S [mV/K]**	**R^2 [-]**	**S [mV/K]**	**R^2 [-]**
1 µ	0	-1,58	0.99903	-2,01	0.99743
	3	-1,30	0.99658	-1,83	0.99925
100 n	0	-1,73	0.99786	-2,24	0.99725
	3	-1,37	0.99693	-2,06	0.99875
10 n	0	-1,81	0.99156	-2,43	0.99738
	3	-1,46	0.99622	-2,27	0.99868

V. CONCLUSION

This work presents an analysis of gated PIN diodes for temperature sensor. Based on obtained results it was possible to see that when applying a voltage variation on the PIN gate (V_G) between -3.0 V and 3.0 V, the higher the voltage applied and the lower the current (I_D), higher is the sensitivity (S) of the sensor, and it maintain its good linearity (R^2).

In addition, when we apply a temperature range (T) from the room temperature to higher temperatures, as 500 K, we can perceive a higher sensitivity (S) of the component.

ACKNOWLEDGMENT

The authors acknowledge Centro Universitário FEI for the financial support and available structure.

REFERENCES

[1] Sedra, Adel S.; Smith, Kenneth C. Microeletrônica. São Paulo: Access Intelligence, 1995.

[2] de Souza, Michelly; Rue, Bertrand; Flandre, Denis; Pavanello, Marcelo A. Thin-Film Lateral SOI PIN Diodes for Thermal Sensing Reaching the Cryogenic Regime. Journal Integrated Circuits and Systems, Vol 5, no. 2, p. 160-167 (2010).

[3] Pereira, Guilherme N; de Souza, Michelly. Simulação e Análise de Sensores de Temperatura com Diodos Laterais PIN SOI com a Configuração PTAT. VII Simpósio de Iniciação Científica, Didática e de Ações Sociais da FEI (2017).

[4] ATLAS User's Manual, SILVACO, 2011.

[5] Nagelkerke, N. J. D., Biometrika, v. 78, pp. 691-692, 1991.