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Modelling and Simulation of the Thermal Behaviour of the Offset Voltage of Piezoresistive Pressure Sensors

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Abstract: Based on the phenomena of displacement of the majority carriers in silicon and based on the assumption that each piezoresistor of a silicon pressur sensor has its own temperature coefficients (TCRs of the first and second order), this study gives an explanation on the existence of the offset volage in the piezoresitif pressure sensors and its thermal behaviour. Using different models of majority carriers mobility in silicon, this study presents a new formula for the first and the second temperature coefficient α and β in function of doping concentration N (cm^{-3}).On the other hand, this new presentation enable us to present the thermal behaviour of piezoresistive pressure sensors in function of 2 parameters namely the doping concentration N (cm^{-3}) and temperature T (°C) then we report the effect of the temperature on the offset voltage.

Key words: Offset voltage, pressur sensor, temperature coefficient, doping concentration

INTRODUCTION

A major problem associated with piezoresistive pressure sensors is their cross to temperature. The influence of temperature is manifested as a change in the span and offset sensor output, silicon resistor is realized by microelectronic techniques using ion implantation technique and the study of its thermal behaviour presents fundamental interest. In this research, which is closely related to Boukabache and Pons (2002) this last studied the effects of doping concentration on the first and second order Temperature Coefficients of Resistance (TCRs), he has used three models of majority carries mobility in silicon and in our work we added another model of mobility (Masetti *et al*., 1983) we present a new formula of theses two thermal coefficients, α and β of a silicon resistor, where we present their relationship only in function of the doping concentration N (cm^{-3}). Finally we present an analytical expression of resistance of the silicon resistor and we have established the expression of the thermal variations of the offset voltage.

INFLUENCE OF TEMPERATURE

At temperature T, the thermal variation of resistance of silicon can be evaluated by the following expression (Shirousu and Sato, 1982).

$$R\,(T) = R\,(T_0)\,(1+\alpha(T-T_0)+\beta\,(T-T)^2) \qquad (1)$$

Where $R\,(T)_0$ is the value of the resistance at the reference temperature T_0; α and β are the temperature coefficients of the first and second power of T, respectively.

Many studies (Boukabache *et al*., 2000; Stankevic and Simkevicius, 1998) use theses two coefficients α and β. In particular the first coefficient has been studied by Bullis *et al.* (1968) he has found it in experiment and presents the influence of doping concentration while the other study of these two coefficients have been reported by Boukabache and Pons (2000) where he used three models of mobility for presenting the influence of doping concentration on these two coefficients.

EFFECT OF DOPING ON THE TWO TEMPERATURE COEFFICIENTS

The resistance value of a semiconductor bar is:

$$R = \rho L/S \qquad (2)$$

Where L,S and ρ are its length, surface and resistivity, respectively. By neglecting the dimensional variations compared to those of resistivity, the thermal variations of resistance is (Boukabache and Pons, 2002)

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$$\Delta R/R_0 = \Delta\rho/\rho_0 \quad (3)$$

Where R_0 and ρ_0 are the values of resistance and resistivity at temperature T_0, respectively. The comparison of (2) and (3) leads to:

$$\Delta\rho/\rho_0\,(T) = \alpha\,(T-T)+\beta\,(T-T_0) \quad (4)$$

However, in the case of a P-doping with N concentration, the resistivity can be approximated by:

$$\rho \approx \frac{1}{\left(q\mu_p N\right)} \quad (5)$$

Where q and μ_P are elementary charge and the holes mobility, respectively.

We have used different hole mobility models (Masetti *et al.*, 1983; Klaassen, 1992; Arora *et al.*, 1982; Dorckel and Leturcq, 1981) by introducing equations giving μ_P as a function of N_A, we obtain, for each value of concentration, a coefficient for T and another for T^2. By identification with (4), coefficient α and β can be easily found. This method has been repeated for different concentrations between 10^{17} cm^{-3} and 10^{20} cm^{-3} (Boukabach and Pone, 2002).

Using these four models of majority carries mobility in silicon (Masetti *et al.*, 1983; Klaassen, 1992; Arora *et al.*, 1982; Dorckel and Leturcq, 1981) we present the evolution of the first and second temperature coefficients as well as the relationship existing between each of α and β and the doping concentration N. This definition allows us to present the relationship between the resistance R (T) and the 2 parameters T and N. By using the values of α and β in interpolation program, we obtain equations relating those two coefficients of temperature in function of the doping concentration N and we have found a 4th degree logarithmic regression function.

The expressions giving these variations are as follow:

$$\alpha(N) = A+B\log(N)+C\log^2(N)+D\log^3(N)+E\log^4(N) \quad (6)$$

$$\beta(N) = A'+B'\log(N)+C'\log^2(N)+D'\log^3(N)+E'\log^4(N) \quad (7)$$

Where A, B, C, D, E and A', B', C', D', E' are constants of the function of α and β and N is the doping concentration of the silicon resistor.

We have reported in the Table 1 and 2 the 5 constants of α and β using the four models.

We are now able within this model represent the variations of α and β in function of the doping concentration N. and the results are shown in the Fig. 1 and 2.

For α (Fig. 1):

- Between 3×10^{18} cm^{-3} and 4×10^{18} cm^{-3} curve (iv) has a minimal value approximately 480 ppm/°C.
- Curves (ii), (iii) and (iv) are relatively close to one another (except curve (iv) for doping higher than 2×10^{19} cm^{3}).
- Until 2×10^{19} cm^{-3} the values of α for the curve (i) are higher than the values obtained for the three curves (ii), (iii) and (iv) and its value becomes minimal from 4×10^{19} cm^{-3}.
- The existence of a value minimal of α is remarkable in the 3 models (ii),(iii) and (iv).

For β (Fig. 2):

- Curves (i), (iv) and (ii) have a possibility of passing by the zero, so in this case β = 0.
- Curves (ii), (iii) and (iv) show a monotonous decrease until a doping concentration of approximately 10^{19} cm^{-3} with doping.
- The curve (iii) takes high values compared to the other curves.

Table 1: Constants of α

Coefficients of α Models of mobility	A	B	C	D	E
Arora	-705288.03348	386396.02481	-49263.53998	2384.2094	-39.93215
Klaassen	-2.00231E7	4.44985E6	-369115.63611	13550.44074	-185.808
Dorckel and Leturcq	-1.20717E7	2.54514E6	-199158.06738	6847.66465	-87.14671
Masetti	9.6924E6	-2.2322E6	192222.54016	-7326.19557	104.20675

Table 2: Constants of β

Coefficients of β Models of mobility	A’	B’	C’	D’	E’
Arora	-53982.9634	11605.05634	-932.6115	33.21372	-0.4424
Klaassen	-12589.238008	2644.78304	-205.54902	7.00987	-0.08853
Dorckel and Leturcq	140978.75194	-30622.58872	2492.26207	-90.06064	1.21907
Masetti	-68178.19235	14731.11556	-1187.46977	42.33521	-0.56337

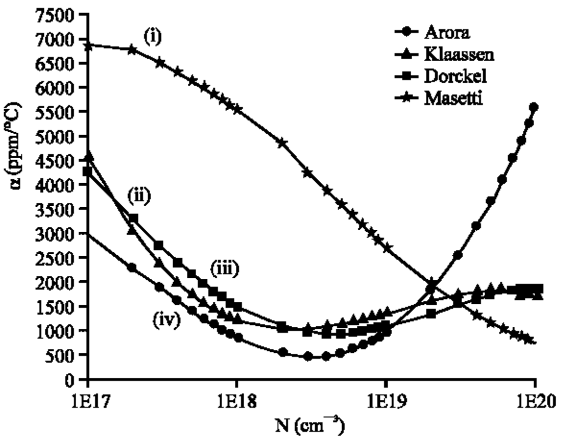

Fig. 1: Variations of α in function of the doping concentration *N*

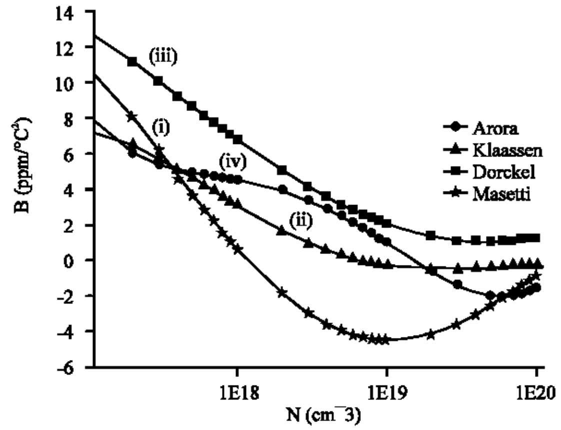

Fig. 2: Variations of β in function of the doping concentration *N*

Comparing our results with those obtained in Boukabache and Pone (2002) we notice the following points:

- The first coefficient α is identical.
- We have obtaining the same variation of β using the 3 models of mobility, except there is a shift of value using a model of Klaassen and Dorckel.

Introducing the 2 formulas (6) and (7) in expression (1) we represent a new formula for R (T):

$$R\,(T) = R\,(T_0)[1+(A+B\log(N)+...+E\log^4(N))(T-T_0)]+ (A'+B'\log(N)+...+E'\log^4(N))(T-T^0)^2] \qquad (8)$$

So, the relative resistance is given by this equation:

$$\frac{R(T)-R(T_0)}{R(T_0)} = (A+B\log(N)+...+E\log^4)(T-T_0)+ (A'+B'\log(N)+...+E'\log^4(N))(T-T_0)^2 \qquad (9)$$

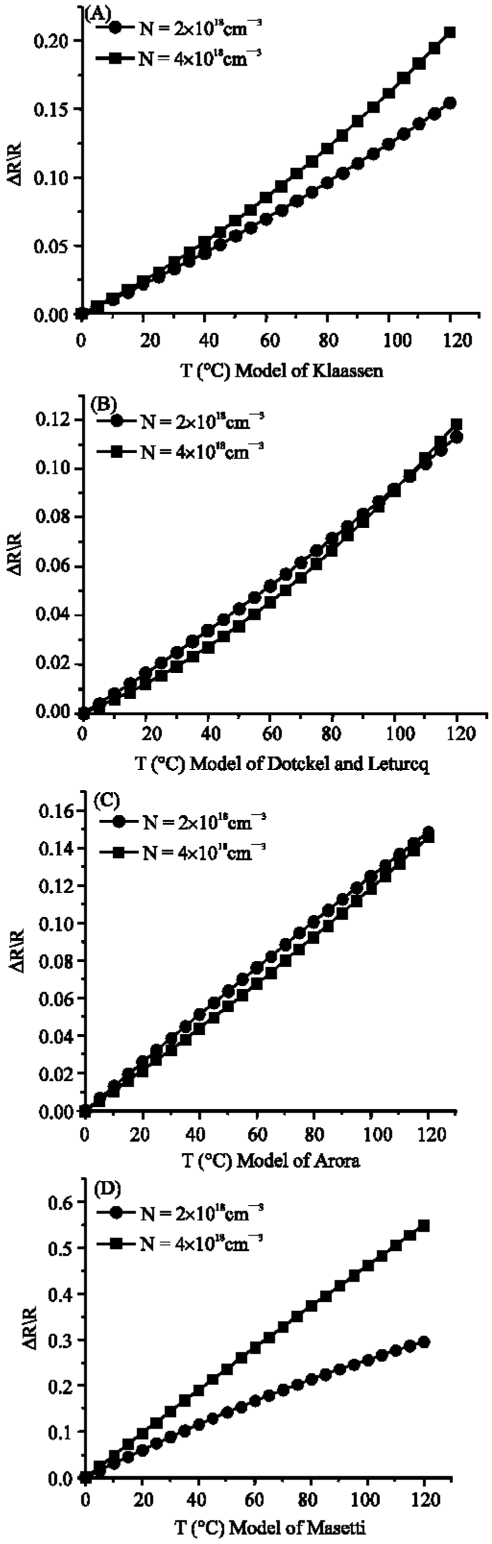

Fig. 3 : A thermal variation of the relative resistance using four models of mobility and N like a parameter (2× 1018 cm^{-3} and 4×1018 cm^{-3})

We have presented in Fig. 3a thermal variation of resistance using N like a parameter (2×10^{18} cm^{-3} and $4\times10^{18}cm^{-3}$).

We notice that:

- In the four models the thermal variation of resistance increases in function of temperature.
- In the two models of (Dorckel and Arora) the value of it is weak compared to the other models (Klaassen and Masetti).
- The doping concentration influences in a different way in the four models.

OFFSET VOLTAGE

Connecting the four piezoresistors in a Wheatstone bridge (Fig. 4).

The thermal variation of the output voltage is:

$$\Delta(T)=V_0\left[\frac{R_1(T_0)R_2(T_0)}{\left(R_1(T_0)+R_2(T_0)\right)^2}\left[(\alpha_1-\alpha_2)T+(\beta_1-\beta_2)T^2\right]\right]$$

$$-V_0\left[\frac{R_3(T_0)R_4(T_0)}{\left(R_3(T_0)+R_4(T_0)\right)^2}\left[(\alpha_3-\alpha_4)T+(\beta_3-\beta_4)T^2\right]\right]\quad(10)$$

Where:

- V_0 is the supply voltage of the Wheatstone bridge.
- α and β are temperature coefficients (i = 1, 2, 3, 4).
- $R_I(T_0)$(i = 1, 2, 3, 4) are the value of the piezoresistor at the reference temperature.

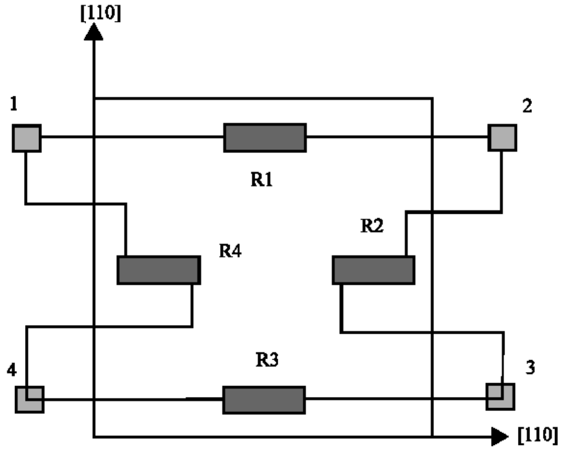

Fig. 4 : Implantation of the piezoresistors on the top of the silicon membrane

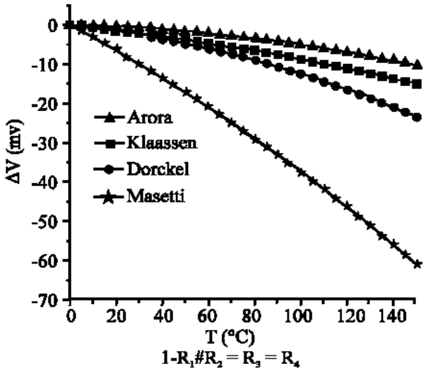

Fig. 5: Variations of ΔV in function of temperature using the cas where one of four piezoresistors (R_1) different from the others and N = 2×10^{18} cm^{-3}

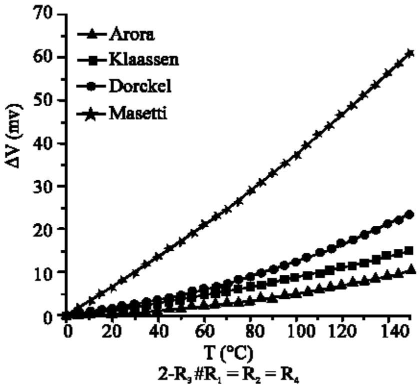

Fig. 6: Variations of ΔV in function of temperature using the cas where one of four piezoresistors (R_3) different from the others and N = 2×10^{18} cm^{-3}

We can take (Boukabache *et al*., 2000):

$$\frac{R_1(T_0)R_2(T_0)}{\left(R_1(T_0)+R_2(T_0)\right)^2}=\frac{R_3(T_0)R_4(T_0)}{\left(R_3(T_0)+R_4(T_0)\right)^2}\approx0.25\quad(11)$$

Introducing the expressions (6) and (7) of α and β in the expression of offset voltage (10) we obtained it variation directly as function of the doping concentration N and in this case we can see it influence in the offset voltage, in our study we take two values N = 2×10^{18} cm^{-3} and N = 4×10^{18} cm^{-3}.

Figures (5), (6), (7) and (8) shows us a non linear variation of the offset voltage, thus it's very remarkable that in the case of N = 2×10^{18} cm^{-3} the thermal behaviour of the offset voltage varies approximately from 0 to 70 mv and from 0 to 45 mv for the doping N = 4×10^{18} cm^{-3}.

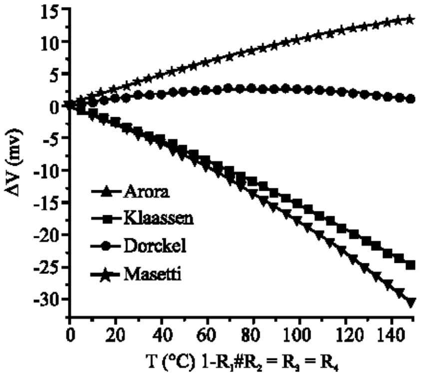

Fig. 7: Variations of ΔV in function of temperature using the cas where one of four piezoresistors (R_1) different from the others and $N = 4\times10^{18}$ cm^{-3}

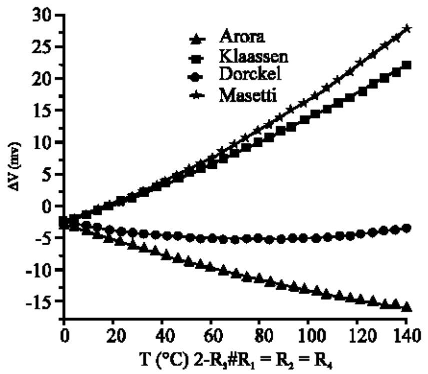

Fig. 8: Variations of ΔV in function of temperature using the cas where one of four piezoresistors (R_3) different from the others and $N = 4\times10^{18}$ cm^{-3}

CONCLUSION

The theoretical aspects of the thermal variations of the offset voltage of silicon piezoresitive pressure sensors have been developed by assuming that there exists a difference in the doping concentration of the four piezoresistors constituting the Wheatstone bridge. The numerical model of α and β obtained in this work allowed us to obtain a new formula for these two coefficients of temperature. Then using the interpolation program we obtained the variations of these two coefficients in function of the doping concentration N only.

With these formulas we can obtain usually a thermal variation of the offset voltage only in function of two parameters, temperature T and doping N. This new method for driving α, β in function of N, ΔN in function of N and T should be of interest to people working in the field of sensors where we they can easily extract the numerical values of the two coefficients α and β and use them in the formula of the offset voltage.

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