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EXTRACTION OF TRAP-ASSISTED TUNNELING PARAMETERS BY GRAPHICAL METHOD IN THIN n-Si/SiO$_2$ STRUCTURES

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Trap-assisted tunneling in hydrogen implanted thin n—Si/SiO2 structures have been investigated. The distance between nearest traps and energy position in the energy gap of the deep levels, responsible for this mechanism, have been extracted by graphical calculations. These results have been compared to the data counted up by numerical calculations.

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1. Introduction

Trap generation both at the interface and in the oxide layers, generated by high electrical fields [1], or during technological operations as ion beam implantation [2], plasma treatment [3], etc. cause tunneling currents in these structures. Analyses of trap-assisted tunnelling in SiO$_2$ layers consider two transport mechanisms: Fowler-Nordheim trap emission [4-6]- electrons tunnelling from the occupied traps in SiO$_2$ energy gap to the SiO$_2$ conduction band; and inter-trap tunneling-electrons tunnel from occupied traps to the nearest unoccupied ones.

In our previous investigation of hydrogen implanted n-Si/SiO$_2$ structures [7] Fowler-Nordheim trap emission cannot explain the conduction through these dielectric layers and inter-trap mechanism is considered in the study of trap-assisted tunneling currents trough these dielectric layers. By using the equation, describing inter-trap tunneling model, the distance between the nearest traps and the energy position of traps in SiO$_2$ energy band gap have been calculated.

The purpose of this work is to present a simplified graphical model, which gives a convenient way of calculating the parameters extracted by inter-trap tunneling mechanism.

2. Experimental

SiO$_2$ layers with 60 nm thicknesses were formed on n-Si (100) substrates by dry thermal oxidation at 850 ^{o}C [8]. For the analysis were used hydrogen implanted Si/SiO$_2$ structures from the SiO$_2$ side with implantation energy 1.6 keV and doses 10^{15} cm^{-2}.

MOS capacitors were formed by vacuum thermal evaporation of aluminium dots on the SiO$_2$ surface through a metal mask and continuous Al film on the silicon backside.

For analysis of trap-assisted mechanism and calculation of the parameters extracted by inter-trap tunneling were used current-voltage (I-V), measurements at temperatures 300 K and 77 K.

3. Results and discussion

In the case of inter-trap tunneling mechanism the probability factor, P$_d$, when applied voltage V decreases the electron energy barrier for electron tunnelling between the nearest traps along the voltage, in the WKB approximation is given by the equation [9]:

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$$P_d = \exp\left[-\frac{2(2m*q)^{1/2}\varphi_t^{1/2}w}{\hbar}\right]\exp\left[\frac{(2m*q)w^2V}{\hbar d\varphi_t^{1/2}}\right] \tag{1}$$

When the voltage increases the energy barrier for an electron tunnelling in the opposite direction from the occupied deep level to the next nearest unoccupied one (against the applied voltage), the probability factor for this tunnelling P_{up} is similar to P_d. In this case P_{up} is given by the:

$$P_{up} = \exp\left[-\frac{2(2m*q)^{1/2}\varphi_t^{1/2}w}{\hbar}\right]\exp\left[-\frac{(2m*q)w^2V}{\hbar d\varphi_t^{1/2}}\right] \tag{2}$$

The electron current density is described by the equation:

$$J = \frac{q\nu}{w^2}\frac{(P_d - P_{up})}{2} \tag{3}$$

Substituting (1) and (2) in (3) the equation for current density is:

$$J = \frac{q\nu}{w^2}\exp\left(-\frac{2(2m^*q)^{1/2}\varphi_B^{1/2}w}{\hbar}\right)\sinh\left(\frac{(2m^*q)^{1/2}w^2V}{\hbar d\varphi_B^{1/2}}\right) \tag{4}$$

Where J [A/m^2] is current density, $q = 1.610^{-19}$ [C] is elementary charge, $\nu = 10^{13}$ [s^{-1}] is electron attempt to escape frequency, V is the gate voltage [V], d [m] is the SiO_2 thickness, $m^* = m^e/2$ [kg] is effective electron mass, $m_e = 9.10910^{-31}$ [kg] is electron mass, $\hbar = 1.05410^{-34}$ [Js] is reduced Planck constant, w [m] is the distance between the nearest traps, φ_B [V] is the barrier height,

In accumulation regime applied voltage decreases the energy barrier and the probability for electron tunnelling along the electrical field prevail over the tunneling in the opposite direction ($P_d > P_{up}$) and the expression for current density is:

$$J = \frac{q\nu}{w^2}P_d \tag{5}$$

so

$$J = \frac{q\nu}{w^2}\exp\left(-\frac{2(2m^*q)^{1/2}\varphi_B^{1/2}w}{\hbar}\right)\exp\left(\frac{(2m^*q)^{1/2}w^2V}{\hbar d\varphi_B^{1/2}}\right) \tag{6}$$

After logarithmic transformation of (6):

$$\ln(J) = \ln(q\nu) - 2\ln(w) - \frac{2(2m^*q)^{1/2}}{\hbar}\varphi_B^{1/2}w + \frac{(2m^*q)^{1/2}w^2}{\hbar d\varphi_B^{1/2}}V \tag{7}$$

Plotting lnJ versus V (Fig. 1) and using the equation for graphical calculation of straight-line parameters in the accumulation regime:

$$\ln(J) = A + BV \tag{8}$$

A is the cross section of straight line with x-axis, B is the slope of the straight line Replace A and B in (2):

$$A = \ln(qv) - 2\ln(w) - \frac{2(2m^* q)^{1/2}}{\hbar}\varphi_B^{1/2} w \tag{9a}$$

$$B = \frac{(2m^* q)^{1/2} w^2}{\hbar d \varphi_B^{1/2}} \tag{9b}$$

After transformation for φ_B and w in (9a) and (9b) there is a system equation:

$$\varphi_B = \frac{(2m^* q) w^4}{(\hbar d B)^2} \tag{10a}$$

$$2\ln(w) + \frac{2(2m^* q)}{\hbar^2 d B} w^3 = \ln(qv) - A \tag{10b}$$

Separating (10b) in two parts:

$$2\ln(w) \tag{11a}$$

and

$$F = \ln(qv) - A - \frac{2(2m^* q)}{\hbar^2 d B} w^3 \tag{11b}$$

Cross section of the graphics (11a) and (11b) depending on w (Fig. 2) gives a solution for w in (10b). This value is substitutes in (5a) and determines the φ_B value.

The current density J of hydrogen implanted Si/SiO$_2$ structures with implantation energy 1.6 keV and dose 10^{15} cm^{-2} in accumulation regime, at 77 K is slightly higher than at 300 K (Fig. 1). This behaviour is typical for tunneling type mechanism [10].

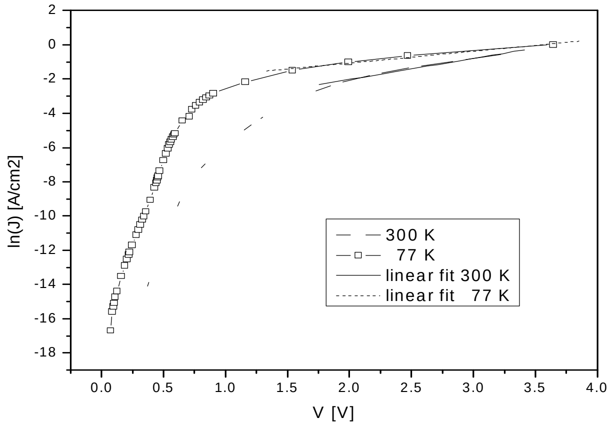

Fig. 1. Current density vs. V of hydrogen implanted Si/SiO2 structures with energy 1.6 keV and dose 10^{15} cm^{-2}.

In Table 1 are presented the parameters A and B extracted from the plot in Fig. 1, and calculated parameters: the distance between nearest traps w and the barrier height φ_B, corresponding to 300 K and 77 K in accumulation regime (ΔV).

Table 1.

T [K]	300	77
ΔV [V]	1.9 – 3.27	1.54 – 3.64
A	-4.472	-2.441
B	1.224	0.688
w [m]	4.36E-9	3.53E-9
φ_B [V]	0.879	1.198

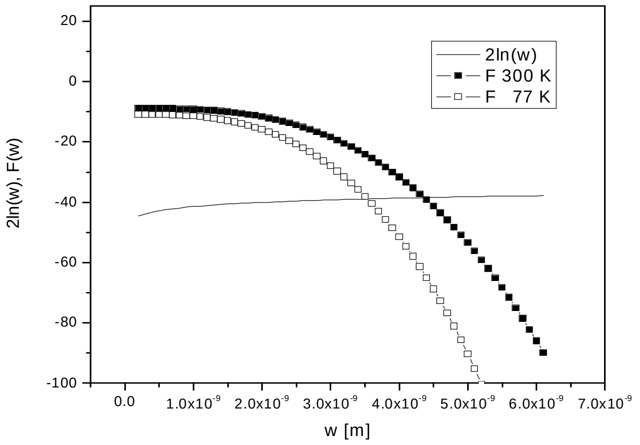

Fig. 2. Graphical calculation of w.

Substitution of calculated values of w and φ_B in equation (7) and comparison of calculated values of ln(J) to experimental ln(J) data gives good agreement between the experiment and graphical calculation of inter-trap tunneling parameters. Fig. 3 illustrates comparison of the experimental and calculated data of ln(J) at 300 K and 77 K, corresponding to the voltage in accumulation regime.

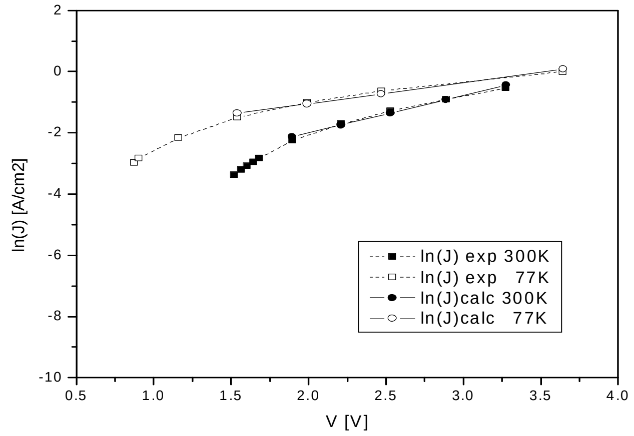

Fig. 3. Experimental and calculated data comparison of ln(J).

4. Conclusion

Graphical calculations of inter-trap tunneling parameters give alternative method for parameters calculating, extracted by inter-trap tunneling mechanism. Reducing the step dimension of w values around graphical cross section of (11a) and (11b) increases the w and φ_B accuracy.

Presented graphical method is applicable because of: 1) the equations (11a) and (11b) have only one solution and; 2) the functions 2ln(w) and F(w) are intersected at enough big angle, which is guarantee that both functions have simple common working-out.

Very good agreement between experimental and calculated data for ln(J) is an evidence, that the presented graphical method is a convenient and accurate instrument for calculation of inter-trap tunneling parameters.

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