IOSR Journal Of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 12, Issue 5 Ser. III (Sep. – Oct 2020), PP 53-56
www.Iosrjournals.Org

A note to support the correctness of the model for temperature dependence of Fowler-Nordheim tunnelling current in a MOS device

Dr. Ravi Kumar Chanana
Self-Employed Independent Researcher, Greater Noida, India.
Corresponding author: Dr. Ravi Kumar Chanana

Abstract: *In a MOSFET device in inversion, the oxide voltage must be corrected by the experimental band bending at the oxide/semiconductor interface instead of the theoretical band bending. Following this premise, the conduction band barrier height in n-channel 4H-SiC MOSFET device in inversion is found to reduce from 2.92 eV with the oxide voltage corrected by the theoretical band bending to 2.816 eV with the oxide voltage corrected by the experimental band bending at 298K, close to the confirmed model value of 2.79 eV at 298 K. This example can be extended to barrier heights at other temperatures also in the device where the oxide voltage was originally corrected by the theoretical band bending. The barrier heights with the oxide voltage corrected by the experimental band bending is expected to match with the model values at all temperatures and thus support the model for the temperature dependence of the Fowler-Nordheim tunnelling current in a MOS device proposed by the author in an earlier study.*

Keywords: *Band bending, MOSFET, Silicon Carbide, Temperature, Tunnelling.*

Date of Submission: 15-10-2020 Date of Acceptance: 31-10-2020

I. Introduction

This note corroborates the model for temperature dependence of Fowler-Nordheim tunnelling current in a metal-oxide-semiconductor (MOS) device through the calculation of the conduction band (CB) barrier height in a 4H-SiC MOS device at room temperature of 298 K at which the correct and confirmed value is known. The oxide voltage is calculated by subtracting the experimental band bending at the oxide/semiconductor interface of the metal-oxide-semiconductor field-effect-transistor (MOSFET) device in inversion from the gate voltage in place of subtracting the theoretical band bending from the gate voltage. The device has a gate oxide of 53 nm thickness [1]. The barrier height thus obtained is 2.816 eV and very closely matches with the confirmed barrier height of the model at 298 K of 2.79 eV [2]. It is to be noted that the barrier height comes down to this value of 2.816 eV from 2.92 eV by correcting the oxide voltage by the experimental band bending. There could be small errors in calculations which are mentioned later. The barrier heights at other temperatures are also expected to match with the model values by using the experimental band bending with the MOSFET biased in inversion [2].

II. Theory

Fowler-Nordheim carrier tunnelling current equation through a MOS device in accumulation or inversion is given by [2-8]:

$$J = AE_{ox}{}^{2}\exp(-B/E_{ox}) \qquad (1).$$

Here, A and B are constants given as follows:

$$\begin{aligned} A &= \frac{e^3 m}{16\pi^2 \hbar m_{ox}\phi_0} \\ A &= 1.54x10^{-6}\,\frac{m}{m_{ox}}\frac{1}{\phi_0}\cdots A/V^2 \end{aligned} \qquad (2)$$

$$B = \frac{4}{3}\frac{(2m_{ox})^{1/2}}{e\hbar}\phi_0^{\ 3/2}$$

$$B = 6.83x10^7\left(\frac{m_{ox}}{m}\right)^{1/2}\phi_0^{\ 3/2}\cdots V/cm \qquad (3).$$

In the above constants A and B, e is the electronic charge in Coulombs, m is the free electron mass in Kg, m_{ox} is electron mass in the oxide in Kg, $\hbar$ is the reduced Planck's constant, ϕ_0 is the electron barrier height in eV, and B is called the FN tunnelling slope constant at a particular temperature in Kelvin, and E_{ox} is the oxide field in V/cm. Equation (1) models the current-voltage characteristics through the amorphous thermal silicon dioxide at high electric field E_{ox}.

The oxide voltage in a metal-gated MOS device in accumulation is corrected only by the measured flatband voltage [5], whereas the oxide voltage in a metal-gated MOSFET device in inversion should be corrected by the experimental band bending at the oxide/semiconductor interface [7, 8]. The oxide voltage for the MOSFET in inversion corrected by the theoretical band bending is given as [1]:

$$V_{ox} = V_g - (V_{fb} + \psi_s) \qquad (4).$$

Here, V_g is the gate voltage, V_{fb} is the flatband voltage and ψ_s is the surface band bending in the semiconductor at the oxide/semiconductor interface in inversion which is equal to twice the bulk potential in the semiconductor given by:

$$\psi_b = \frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right) \qquad (5).$$

Here, n_i is the intrinsic carrier concentration in the semiconductor which for 4H-SiC is 10^{-8}/cm^3 at 298 K and N_A is p-type doping which is typically 10^{17}/cm^3 in 4H-SiC.

The oxide voltage for the MOSFET in inversion corrected by the experimental band bending is given as [7-8]:

$$V_{ox} = V_g - (V_T + \frac{Q_d}{C_i}) \qquad (6).$$

Here, V_T is the experimental threshold voltage that can be seen from the specification sheet of the commercial MOSFET device [1], Q_d is the depletion charge per unit area in the device in inversion, and C_i is the insulator (oxide) capacitance per unit area in the device. The depletion potential Q_d / C_i can be calculated. In an n-channel MOSFET device, V_T is positive and Q_d is negative. The depletion charge per unit area Q_d for a grounded MOSFET is given as:

$$Q_d = -\sqrt{2q\varepsilon_0\varepsilon_r N_A \psi_s} \qquad (7).$$

Here, the relative dielectric constant ε_r for SiC is 9.7. Equation (6) should be used with the MOSFET in inversion in place of equation (4). The oxide field is then simply oxide voltage divided by the oxide thickness.

III. Results and Discussion

In the experimental research paper by O. Avino Salvado et al., the CB barrier height in the 4H-SiC MOSFET is determined to be 2.92 eV at 298 K using the correction in the oxide voltage by the theoretical band bending [1]. This gives the slope constant B of 220.84 MV/cm using equation (3). The calculations below replace the theoretical band bending by the experimental band bending and show that the barrier height becomes nearly equal to the model value of 2.79 eV at 298 K thus corroborating the model. The basic parameter values for the calculations are tabulated in Table I, and the calculated parameters are tabulated in Table II below.

Table I. Basic parameters used in calculation of slope constant and band bending in the MOSFET device.

m_{ox}	d (nm)	ψ_s (V)	Q_d (Coul/cm^2)	C_i (F/cm^2)	V_T (V)	V_{fb} (V)
0.42m	53	2.98	28.617 x 10^{-8}	6.5 x 10^{-8}	3.3	-5 with Al gate.

Table II. Calculated slope constant, depletion potential and band bending in the MOSFET device.

B (MV/cm)	Q_d / C_i, (Volts)	Experimental band bending $V_T + (Q_d / C_i)$, (Volts)	Theoretical band bending $V_{fb} + \psi_s$, (Volts)	Theoretical minus experimental band bending, (Volts)
220.84	-4.40	-1.10	-2.02	-0.92

If the theoretical band bending is replaced by experimental band bending, then to calculate the oxide voltage,

$$V_{ox} = \{V_g - (V_{fb} + \psi_s)\} + (V_{fb} + \psi_s) - (V_T + Q_d / C_i)$$

$$V_{ox} = \{V_g - (V_{fb} + \psi_s)\} + (theoretical - \exp erimental) bandbending$$

$$V_{ox} = \{V_g - (V_{fb} + \psi_s)\} + (-0.92)$$

Thus, 0.92 V more has to be subtracted from the gate voltage if the experimental band bending replaces the theoretical band bending at the oxide/semiconductor interface in the particular 4H-SiC MOSFET device in inversion. This converts to 0.173 MV/cm oxide field for the 53 nm oxide. In the calculation of the slope constant from the current-voltage data at high oxide fields in a device as seen from equation (1),

$$B = \Delta \ln(J / E_{ox}{}^2) / \Delta(1 / E_{ox}) \qquad (8).$$

Here, it is observed that the term in the natural logarithm is "compressed" and so does not cause much change in the slope constant. The denominator causes significant change and it is shown next how it affects the slope constant. Two high oxide fields of 6 MV/cm and 7 MV/cm are taken and the change in $1/\Delta(1/E_{ox})$ is calculated.

$$1/\Delta(1/E_{ox}) = \{1/(1/6 - 1/7)\} = 42\,.$$

Subtracting 0.173 MV/cm from both the fields gives;

$$1/\Delta(1/E_{ox}) = \{1/(1/5.827 - 1/6.827)\} = 39.781$$

The new corrected slope constant becomes;

$$B = 220.84x(39.781/42) = 209.17 MV/cm\,.$$

The conduction band barrier height calculated from this slope constant of 209.17 MV/cm using equation (3) and the electron effective mass in the oxide as 0.42m now becomes 2.816 eV, which reduces from 2.92 eV and becomes almost same as the confirmed value of 2.79 eV. The important point is to note the effect of using the experimental band bending in place of the theoretical band bending that cures the difference in the barrier heights. Two main sources of error could be the oxide thickness which needs to be within ±1 nm for a thick oxide of say 53 nm, and small changes in the numerator of equation (8) due to change in the oxide fields. The results and discussions above clearly support the model for the temperature dependence of FN tunnelling currents in the MOS devices proposed by the author in the earlier study [2]. It is based on the application of the equipartition theorem for energy in the thermal silicon dioxide where classical Maxwell-Boltzmann distribution is shown to be applicable [9-11].

IV. Conclusions

It is concluded that the oxide voltage in a MOSFET device in inversion must be corrected by the experimental band bending instead of the theoretical band bending at the oxide/semiconductor interface. All the barrier heights in the experimental study by O. Avino Salvado et al. at different temperatures are expected to match the barrier heights of the model values from the proposed model of the temperature dependence of FN tunnelling currents in a MOS device by the author in an earlier study, thus corroborating the proposed model. The model is based on the application of equipartition theorem for electron energies in the oxide which agrees with the Maxwell-Boltzmann distribution of non-interacting electron particles in a dilute semiconductor like the amorphous thermal silicon dioxide.

References

[1]. O. Avino-Salvado, B. Asllani, C. Buttay, C. Raynaud, H. Morel, “Extraction of the 4H-SiC/SiO_2 barrier height over temperature”, IEEE Trans. On ED, 2020;67(1):63-68.

[2]. R.K.Chanana, “A simple model for temperature dependence of the Fowler-Nordheim carrier tunnelling current through the oxide in a metal-oxide-semiconductor device in accumulation or inversion”, IOSR-J. Appl. Phys., 2020;12(4):29-34.

[3]. Z.A. Weinberg, “On tunneling in metal-oxide-silicon structures”, J. Appl. Phys., 1982;53(7):5052-5056.

[4]. R.K. Chanana, K. McDonald, M. Di Ventra, S.T. Pantelides, L.C. Feldman, G.Y. Chung, C.C. Tin, J.R. Williams, R.A. Weller, “Fowler-Nordheim hole tunneling in p-SiC/SiO_2 structures”, Appl. Phys. Letts., 2000;77(16):2560-2562.

[5]. R.K. Chanana, “Determination of hole effective mass in SiO_2 and SiC conduction band offset using Fowler-Nordheim tunnelling characteristics across metal-oxide-semiconductor structures after applying oxide field corrections”, J. Appl. Phys., 2011;109:104508.

[6]. R.K. Chanana, “Determination of electron and hole effective masses in thermal oxide utilizing an n-channel silicon MOSFET”, IOSR J. Appl. Phys., 2014;6(3):1-7.

[7]. R.K. Chanana, “N-channel silicon MOSFET as a device to characterize MIS structures by the BOEMDET technique”, IOSR J. Appl. Phys., 2015;7(4):17-25.

[8]. R.K. Chanana, “Polysilicon and metal-gated n-channel grounded silicon MOSFETs as devices to characterize MIS structures by the BOEMDET technique”, IOSR J. Appl. Phys., 2018;10(6):50-57.

[9]. D.J. DiMaria, T.N. Theis, J.R. Kirtley, F.L. Pesavento, D.W. Dong, S.D. Brorson, “Electron heating in silicon dioxide and off-stoichiometric silicon dioxide films”, J. Appl. Phys., 1985;57(4):1214-1238.

[10]. M.V. Fischetti, D.J. DiMaria, S.D. Brorson, T.N. Theis, J.R. Kirtley, “Theory of high-field electron transport in silicon dioxide”, Physical Review B, 1985;31(12):8124-8142.

[11]. S.M. Sze, “Carrier Transport Phenomenon” in “Semiconductor Devices, Physics and Technology”, John Wiley and Sons, Toronto, 1985:30-69.

Dr. Ravi Kumar Chanana. “A note to support the correctness of the model for temperature dependence of Fowler-Nordheim tunnelling current in a MOS device.” *IOSR Journal of Applied Physics (IOSR-JAP),* 12(5), 2020, pp. 53-56.