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Electron diffusion current after ionisation of thermal silicon dioxide in a MOS device forms the Fowler-Nordheim electron tunnelling current showing wave-particle duality of electrons

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Abstract: *Electrons and holes are created exponentially due to ionisation in the oxide of the metal-oxide-semiconductor device when Fowler-Nordheim tunnelled electrons accelerate towards the anode without colliding. The ionisation begins at the FN onset field as shown in the previous study. It is now further shown, that the electron diffusion current after ionisation of thermal silicon dioxide in a metal-oxide-semiconductor device forms the FN electron tunnelling current. An average electron density of about $10^{11}/cm^3$ exists in the oxide conduction band before ionization, with the average electron energies of 3 to 5 eV at oxide fields greater than 5 MV/cm. The research paper demonstrates wave-particle duality of electrons for the FN electron tunnelling current in a MOS device.*

Keywords: *Diffusion, metal-oxide-semiconductor, ionization, silicon carbide*

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I. Introduction

The Fowler-Nordheim (FN) electron tunnelling current density equation is originally derived by first finding the transmission or escape probability of electrons through a triangular potential barrier. This is done by treating electron as a wave and solving the second order Schrodinger's time-independent wave equation in one dimension after applying the JWKB approximation valid for a slowly varying potential with position. The Schrodinger's equation relates the total energy of the electron to the potential barrier. The equation for the current density is then derived by integrating the electron current density crossing the energy space [1-3]. In the present research study, the electron is treated like a particle. The present study is continued from the previous one, where it was shown that the ionization in the silicon dioxide of the n-4H-SiC MOS device begins at the FN onset field by the accelerated electrons which have not collided in the oxide after tunnelling in from the cathode [4]. The trajectory of the electrons is a near straight line when the applied electric field is of the order of 1MV/cm, with the mobility of electrons determined to be $20cm^2/V$-s in the oxide [5]. The author further shows that the FN electron tunnelling current in the device is formed by the diffusion current of the electrons created due to ionization of the oxide. Thus, for the FN electron tunnelling current in a MOS device, wave-particle duality of electrons is demonstrated. The diffusion current is foundational to the electric arc between two electrodes where the air molecules get ionized due to the high electric field, or the current from the tip of the scanning tunnelling microscope (STM) where again the air between the tip and the scanned material atoms is ionised. The diffusion current could also be said to be similar to the diffusion current of a forward-biased p-n junction, where the majority carriers diffuse to the other side of the junction due to the concentration gradient at a reduced barrier voltage at the junction. In the MOS device, electrons as the majority carriers are created upon ionization of the oxide starting at the FN onset field [4]. It is to be noted that wave-particle duality of electrons was first demonstrated when the Bohr's model of the atom was improved as the quantum mechanical model in 1925with DeBroglie's wavelength.

In the author's previous research paper the concept of ionization in the semiconductors was related to the onset field for FN carrier tunnelling current in a MOS device and it was shown that the ionization in the oxide begins at this field. This relation enabled the determination of the mean free path of electrons in the thermal silicon dioxide on silicon as about 3.2 nm [4, 6]. Direct tunnelling of electron occurs through this 3.2 nm thick oxide from cathode to anode without interacting with the oxide. About 0.5 nm to 1 nm thick SiO_2 is used as an interlayer in the present high-K metal gate (HKMG) CMOS technology mainly to keep the interface trap density low. The other applications of tunnel oxide are introduced in the author's earlier study. The passivated emitter solar cells and MIS tunnel transistors and contacts are few of these applications [7]. The Passivated Emitter and Rear Cell (PERC) families have increased solar cell efficiency to greater than 25 % [8-9]. A novel approach in PERC solar cells is to enhance carrier selectivity by adding positive or negative charges to the rear contact [10]. Adding positive charges would enhance the cathode field for electron tunnelling and adding negative charges will enhance the anode field for hole tunnelling [11-12]. It is however to be noted that such thin oxide growth of 1 to 2 nm requires the use of lower temperatures which causes the charge densities in the oxide or oxide/semiconductor interface to be high of the order of low $10^{12}/cm^2$.

II. Theory

The fundamental concept of avalanche breakdown in a p-n junction is discussed well in the book by Muller and Kamins with M. Chan [13]. It is shown than the change in the carrier density with position equals the ionization coefficient multiplied by the initial number of carriers in the semiconductor. That is given as:

$$\frac{dn}{dx} = \alpha n \qquad (1).$$

Here, α is the ionization coefficient for electrons or holes having the unit of cm^{-1}, and n is the initial density of carriers at a position x having the unit of cm^{-3}. α is given as [13]:

$$\alpha = KE \exp\left(-\frac{BB}{E}\right) \qquad (2).$$

Here again, K is a proportionality constant having the unit of V^{-1}, E is the average electric field in V/cm that accelerates an electron in the oxide and is taken hereto be E_{ox}/ϕ_0 for the MOS device. It has a minimum value of 2MV/cm at the FN onset oxide field of 5.5 MV/cm in the n-4H-SiC MOS device having ϕ_0 of 2.8 eV [4], and (-BB/E) is the probability that a carrier has not collided in the distance d necessary to gain adequate energy [13]. BB is $E_1/\lambda q$ as given in [13]. Using the above equations (1) and (2), the diffusion current, say for electrons, can be defined as [14]:

$$J_n = qD_n \frac{dn}{dx}$$
$$J_n = q\left(\frac{kT}{q}\mu_n\right)\left(KE \exp\left(-\frac{BB}{E}\right)(n)\right) \qquad (3).$$

The electron diffusion coefficient is D_n, given by the Einstein's relation as [14]:

$$D_n = \frac{kT}{q}\mu_n \qquad (4).$$

The mobility of electrons in the thermal SiO_2 is μ_n, determined as $20cm^2/V\text{-}s$ [5], k is the Boltzmann constant in J/K, T is the temperature in Kelvin and q is the electronic charge in Coulombs. kT/q equals 0.0259 V at the room temperature of 298K.

The electron drift velocity in SiO_2 is determined to be equal to the thermal velocity of electrons as 10^7 cm/s [15]. This velocity can be used to determine the density of electrons or holes in the MOS device before the ionization begins at the FN onset field with the known low-field leakage current observed in a MOS device in accumulation. The formula for the drift velocity is given as:

$$J_{nn} = qn\mu_n E_{ox} \qquad (5).$$

Here, $\mu_n E_{ox}$ can be replaced by the saturation velocity, v_{th} equal to 10^7 cm/s, giving the formula:

$$J_{nn} = qnv_{th} \qquad (6).$$

The average kinetic energy of an electron in thermal SiO_2 can be calculated by using the formula:

$$E_n = (1/2)m_n {v_{th}}^2 \qquad (7).$$

By taking electron effective mass in thermal SiO_2, m_n to be 0.42m, where m is the free electron mass, E_n can be calculated to be equal to 11.94 meV.

III. Results and Discussion

The initial electron density n before ionization in SiO_2 begins is determined using equation (6) with the known low-field electron current density in the n-4H-SiC MOS device in accumulation as 10^{-9} A/cm^2 [11-12]. The n is calculated to be $6.25 \times 10^2/cm^3$. Next, from the diffusion current equation (3), the constant K is determined for this n at the oxide onset field of FN tunnelling of 5.5 MV/cm [4] as 1.78 x 10^{17} V^{-1} with the (-BB/E) in equation (3) replaced by (-B/E_{ox}) as shown in [4], and given that the slope constant B is 206 MV/cm [11]. Following equation (3) gives:

$10^{-9} = q(0.0259x20)K(2x10^6)[\exp\{(-206/2.8)/(5.5/2.8)\}](6.25x10^2)$. The value of K is thus obtained.

The general equation for diffusion current density in A/cm^2 J_n, for varying oxide electric field beyond the FN onset field of 5.5 MV/cm with this value of K at the FN onset field can now be given by the equation (3) as:

$$J_n = 9.220x(E_{ox}/2.8)\exp[(-B/2.8)/(E_{ox}/2.8)] \quad (8).$$

E_{ox} is the oxide field without charges.

$$I_n = J_n xA \quad (9).$$

Here, A is the C-V dot area which is 9.1 x 10^{-4} cm^2 [16].

$$I_n = 8.390x10^{-3}x(E_{ox}/2.8)\exp[(-B/2.8)/(E_{ox}/2.8)] \quad (10).$$

I_n is the diffusion current in Amperes. Using equation (10), I_n is calculated and tabulated below in Table I at five different fields.

When one observes the low field leakage current in the n- and p-type 4H-SiC MOS devices in accumulation in the author's earlier collaborative study [11-12], the currents are 8 x 10^{-13} A for the n-type device and 8 x 10^{-12} A for the p-type device. The oxide capacitance in accumulation is 78 pF for the 40 nm oxide having a C-V dot area of 9.1 x 10^{-4} cm^2. The observed current in the n-type device is one order lower because the near interface traps, the density of which is given as D_{NIT} and the interface traps, the density of which is given as $D_{it,}$ are trapping electrons and reducing the current. The D_{NIT} is calculated to be 23.5 x 10^{11}/cm^2 eV at 300K near conduction band (CB) of n-4H-SiC and the D_{it} is calculated to be 6 x 10^{11}/cm^2 eV , both after NO annealing [16-17]. The traps constitute negative charge in the oxide when filled with electrons with the MOS device biased in accumulation, which otherwise are neutral after NO annealing and give negligible flatband voltage [16-17]. The equivalent voltage induced by this charge is given as:

$$V_{IT} = \frac{q(D_{NIT} + D_{it})}{C_{ox}} \quad (11).$$

Here, V_{IT} is the voltage due to electrons trapped in the near-interface traps and the interface traps, having a total density of 29.5 x 10^{11} per cm^2, and C_{ox} is the oxide capacitance per unit area for a 40 nm oxide having a relative dielectric constant of 3.9. V_{IT} equals 5.47 V. It needs to be remembered that these are not fixed charges, but are interface traps that act as capacitance and provide an ac conductance which equals to frequency multiplied by capacitance at low frequency, thereby adding resistance to the oxide resistance and reducing the low-field leakage current without changing the slope of the FN plot of the MOS device. The negative charges due to trapped electrons reduce the field at the cathode for electron tunneling [12]. Therefore, the calculated current in Table I for say 27.53 V without charges is compared to the observed current in the device with charges at 33.00 V after adding 5.47 V due to the negative trapped electrons.

Table I. The calculated diffusion currents in the n-4H-SiC MOS device having oxide without charges compared to the raw observed FN electron tunnelling current in the same device having oxide with charges.

Device	The oxide with charges means the oxide with traps		The oxide without charges means the oxide without traps		
	Applied Voltage (Volts)	Raw Observed FN tunnelling Current (A)	V_{ox} (Volts) Appl. Voltage minus 5.47 V	E_{ox} from V_{ox} (MV/cm)	Diffusion current I_n (A) calculated using equation(10) with B=206MV/cm.
n-4H-SiC MOS device in accumulation having 40 nm thick oxide and Mo gate. Ref. [11-12].	29.00	2.475 x 10^{-11}	23.53	5.8825	1.074 x 10^{-11}
	30.00	6.149 x 10^{-11}	24.53	6.1325	4.728 x 10^{-11}
	31.00	1.640 x 10^{-10}	25.53	6.3825	1.827 x 10^{-10}
	32.00	4.200 x 10^{-10}	26.53	6.6325	6.474 x 10^{-10}
	33.00	1.013 x 10^{-09}	27.53	6.8825	2.068 x 10^{-09}

It can be observed from the Table I that the calculated diffusion current is nearly the same with the same order of magnitude as the raw observed FN tunneling current, corroborating the diffusion current model for the FN electron tunneling current in the n-4H-SiC MOS device. It is to be noted that the raw observed FN electron tunneling currents at 29 V and 33 V can be used to confirm the slope constant B of the FN plot of the n-4H-SiC MOS device to be 206.5 MV/cm by calculating {$\Delta\ln(I/V^2)$ / $\Delta(1/E)$} for the 40 nm thick oxide where the C-V dot area can be ignored but not the thickness [18]. This slope constant is same as the B used for calculating the diffusion current. For the increased resistance in the oxide due to traps there is an increased voltage for the same current when the traps store electronic charge. The additional oxide resistance comes from the ac conductance due to traps. Therefore, the oxide without charges means the oxide without traps having reduced oxide resistance corresponding to the reduced oxide voltage without charges. The slope constant B thus remains the same. The thickness of the oxide does not change as the near-interface traps are in the oxide near the n-4H-SiC CB and the interface traps are at the oxide/SiC interface. The above discussion falls in line with the concept of voltage being proportional to resistance for constant current. A similar analysis can be performed for the FN hole tunneling current in the p-4H-SiC MOS device. The hole mobility has been shown to be negligibly low by Hughes [19], although the observed hole tunneling current is comparable to the electron tunneling current [11-12].

From an earlier study by DiMaria, Fischetti and Tierney [20], it is observed that the average electron energy in the oxide conduction band during FN electron tunneling in a MOS device is about 1 eV at 2MV/cm anode field to 5 eV at 10 MV/cm anode field. At the FN onset field in the oxide of n-4H-SiC MOS device of 5.5 MV/cm [4, 16], the average energy of the electrons is about 3 eV [20]. The number of electrons can be calculated by dividing this 3 eV energy by the energy of one electron in the oxide of 11.94 meV found from equation (7) above. It gives 251 electrons. The average density of electrons is further calculated to be 6.9 x $10^{10}/cm^3$ for the MOS device having 40 nm thick oxide and a C-V dot area of 9.1 x 10^{-4} cm^2. This is the initial average density of electrons in the oxide when the ionization begins at the FN onset field. It is corroborated by Mourou (Nobel) and co-researchers, where they calculated the same initial electron concentration of about $10^{11}/cm^3$ in a laser induced breakdown study of silicon dioxide [21]. The rate of ionization in semiconductors is still under research.

It is also inferred from the previous study [4] and the present study that ideally, electron heating in the oxide which starts at about 2MV/cm oxide electric field or ionization which starts at the FN onset field should not be allowed in a working MOSFET device for enhanced reliability, that is, the oxide electric field should be ideally kept below 2 MV/cm in a working MOSFET device.

IV. Conclusions

The electron diffusion current after ionization in the thermal silicon dioxide of a MOS device forms the FN electron tunneling current. The density of electrons in the oxide conduction band is of the order of $10^{10}/cm^3$ to $10^{11}/cm^3$ as an initial average electron concentration at the onset of ionization with the average energies of 3 to 5 eV at greater than 5 MV/cm fields. Ideally, the oxide electric field in a working MOSFET should be less than 2 MV/cm for enhanced reliability. The research paper shows wave-particle duality of electrons for the FN electron tunneling current in a MOS device, invoking causality.

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