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Metal-Insulator-Semiconductor Characterization by Fowler-Nordheim Carrier Tunnelling Currents Through MOS Devices

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ABSTRACT

In this research article, characterization of a Metal-Oxide-Semiconductor (MOS) device fabricated on 4H-SiC semiconductor is performed by the Fowler-Nordheim (FN) carrier tunnelling currents through the devices in accumulation and having metal gates. The technique was earlier named by the author as BOEMDET. The unknown SiO_2 bandgap, the carrier effective masses in the oxide, and the conduction band (CB) and valence band (VB) offsets are determined simply from the known FN carrier tunnelling current Slope constants, the experimental bandgap of 4H-SiC, and the longitudinal electron effective mass in (0001) oriented 4H-SiC semiconductor. Three nonlinear simultaneous equations of slope constants are reduced to two with two unknowns of CB and VB offsets. Trial and error method is employed starting with a guess value of the CB offset. After several iterations, the CB and VB offsets are determined accurately that satisfy the two simultaneous equations. The unknown oxide bandgap and the carrier effective masses in thermal SiO_2 are obtained further once the CB and VB offsets are known.

Keywords: Mass-Energy equivalence, MIS characterization, 4H-SiC, MOS device, Fowler-Nordheim tunnelling.

INTRODUCTION

Metal-Insulator-Semiconductor (MIS) characterization technique using the FN current-voltage (I-V) characteristics of a MOS device was performed on 5-10 nm thermal silicon dioxides (SiO2) on Si (100). The technique was given the name of BOEMDET by the author as the 'Band Offset and Effective Mass Determination Technique'. The technique finds the CB and VB offsets, the unknown bandgap of the oxide insulator, and the electron and hole effective masses in the oxide insulator, simply from the known Slope constant values obtained from the FN plots on the MOS devices. Many applications of the technique were also listed [1-5]. A new discovery in the year 2022 has made it possible to characterize a MOS device fabricated on the 4H-SiC (0001) oriented and Si-terminated semiconductor by this technique. The new discovery is the application of the universal mass-energy equivalence relation dE/E = dm/m to the semiconductors and insulators. This relation is able to relate the intrinsic Fermi energy level Ei in the semiconductor to its longitudinal electron effective mass that further facilitates to perform this characterization on MOS devices fabricated on 4H-SiC semiconductor. This research paper presents the application of the above technique on MOS devices on 4H-SiC semiconductor, where prior knowledge of the oxide masses or the oxide bandgap is absent. It shows how it can be an alternative technique to the internal photoemission (IPE) method of finding band offsets in a MOS device [6-7].

THEORY

FN electron or hole tunneling currents occur at high electric fields across the oxide in a MOS device. It is described by the current-voltage characteristic equation on the device [8-9]:

$$\frac{J}{{E_{ox}}^2} = A \exp\left(-\frac{B}{E_{ox}}\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

where J is the current density in A/cm^2, E_{ox} is the oxide electric field in V/cm, and A and B are constants defined as:

$$A = \frac{e^3 m}{16\pi^2 \hbar m_{ox} \phi_0} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

$$A = 1.54\ x\ 10^{-6} \frac{m}{m_{ox}} \frac{1}{\phi_0} \dots\dots \left(\frac{A}{V^2}\right)$$

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

$$B = 68.3 \left(\frac{m_{ox}}{m}\right)^{1/2} {\phi_0}^{3/2} \dots\dots \left(\frac{MV}{cm}\right)$$

Here in the constants A and B, e is the electronic charge as 1.602 x 10^{-19} Coulombs, m is the free electron mass as 9.11 x 10^{-31} Kg, $2\pi\hbar$ is the Planck's constant as 6.626 x 10^{-34} Joule-Hz^{-1}, m_{ox} is the electron or hole effective mass in the oxide, ϕ_0 is the electron barrier height from the oxide CB to the semiconductor CB that can be represented by ϕ_e, or hole barrier height from the semiconductor VB to the oxide VB that can be represented by ϕ_h, at the oxide/semiconductor interface. Furthermore, it has been shown by the author in his earlier studies that the intrinsic Fermi energy level E_i in the SiO_2 of the MOS device is aligned to the E_i in the semiconductor due to charge neutrality and that the universal mass-energy equivalence relation dE/E = dm/m relates E_i to the longitudinal electron effective masses in the oxide or the semiconductors [7]. In this relation, dE is the differential potential energy from E_i to the oxide or semiconductor CB, E is the oxide or semiconductor bandgap as the total potential energy for electrons with reference to the VB at zero energy, dm is the differential mass as the electron effective mass in the materials, and m is the free electron mass. Based on the above, m_{ox}/m in the oxide can be written as $\left(\frac{\phi_e + x}{E_g}\right)$ or $\left(\frac{\phi_h + y}{E_g}\right)$ representing dE/E = dm/m for electrons and holes in the oxide. Here, x is the differential potential energy for the electrons in the semiconductor from E_i to the semiconductor CB and y is the differential potential energy for holes in the semiconductor from E_i to the semiconductor VB. The bandgap for thermal silicon dioxide is E_g and the bandgap for the semiconductor is equal to $(x + y)$. The Slope constants B_e and B_h for the electron and hole tunneling currents can now be written as follows:

$$B_e = 68.3\ x\ \left(\frac{\phi_e + x}{E_g}\right)^{1/2}\ (\phi_e)^{3/2} \dots\dots \left(\frac{MV}{cm}\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots (4)$$

$$B_h = 68.3\ x\ \left(\frac{\phi_h + y}{E_g}\right)^{1/2}\ (\phi_h)^{3/2} \dots\dots \left(\frac{MV}{cm}\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots (5)$$

$$E_g = \phi_e + \phi_h + z \dots\dots (eV) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$

Here in equation (6), $z = (x + y)$is the semiconductor bandgap in eV. The FN plots of $\Delta\ln(J/E_{ox}^2)$ versus $\Delta(1/E_{ox})$ provides the Slope constants. They are very sensitive to the oxide voltages as they are in the exponential terms. The oxide voltage corrections, the formulas of which are mentioned in the author's earlier study have therefore to be applied precisely [8-9].

The MOS devices on n- and p-type Si (100) and n- and p-type 4H-SiC (0001) oriented semiconductors with metal gates are considered for the current-voltage/capacitance-voltage (I-V/C-V) based MIS characterization, where the FN electron or hole tunneling currents are observed at high electric fields across the oxide with the MOS devices in accumulation. The nMOS device in accumulation will exhibit FN electron tunneling current from the cathode as the dominant current in a two-terminal MOS device, provided the electron barrier at the cathode is smaller than the hole barrier at the anode. Similarly, the pMOS device in accumulation will exhibit FN hole tunneling current as the dominant current from the anode in a two-terminal MOS device, provided the hole barrier at the anode is smaller than the electron barrier at the cathode. The 4H-SiC semiconductor is considered for the characterization of thermal SiO_2 because 4H-SiC has a wide experimental bandgap of 3.234 eV causing the hole barrier at the anode of the pMOS device in accumulation to be small at about 2.91-2.92 eV as compared to the electron barrier with the SiO_2 conduction band at the Au cathode of 4.2 to 4.4 eV causing FN hole tunneling current to be dominant. This is not possible with Si because the hole barrier with Si is 4.6 eV at the anode and the electron barrier is smaller for most metals including Au, causing the electron current to be dominant in the two terminal MOS device. However, Si can be used with all other high-K oxides such as HfO_2 having smaller bandgaps causing the hole barrier at the Si anode of the pMOS device in accumulation to be small to observe FN hole tunneling current.

The equations (4), (5), and (6) are generalized equations applicable to MOS devices on both Si and 4H-SiC semiconductors. The values of x, y, and z will be different depending on whether Si is used or 4H-SiC is used for the fabrication of the MOS devices. Consider Si (100) first. The longitudinal electron effective mass in the [100] direction in Si (100) is 0.49m for one conduction valley out of two and the bandgap of Si is 1.12 eV at 300 K temperature. Substituting these values in the universal mass-energy equation of dE/E = dm/m gives the differential potential energy or the position of E_i below the Si CB as dE = 0.49 x 1.12. This equals 0.5488 eV which can be rounded to 0.55 eV. Thus, x = 0.55, y = 0.57 and z = 1.12 eV for Si semiconductor. Consider (0001) oriented and Si-terminated 4H-SiC semiconductor next. The longitudinal electron effective mass in the [0001] direction in 4H-SiC is 0.297m and the bandgap of 4H-SiC is 3.234 eV, giving the dE = 0.297 x 3.234 =0.96 eV from the universal

mass-energy relation. This is the position of E_i below the 4H-SiC CB. Thus for 4H-SiC, x = 0.96, y = 2.274, and z = 3.234 eV. Now, the equations (4), (5) and (6) can be used either with the MOS devices fabricated on Si (100) or with the MOS devices fabricated on (0001) oriented 4H-SiC.

Few limitations and cautions are to be highlighted while using the above technique of MIS characterization. First, the oxides should be amorphous with negligible bulk traps so as to exhibit FN carrier tunneling currents at high electric fields across the oxides or other wide bandgap semiconducting materials such as h-BN or AlN that can act as insulators. Second, the oxide voltage corrections for the MOS devices in accumulation are simpler and more accurate than devices having polysilicon gates. Polysilicon depletion occurs at polysilicon gates when the voltage is applied and the depletion voltage has to be corrected. This requires additional voltage correction that can cause possible errors. Third, silicon dioxides and aluminium oxides, grown or deposited have large bandgaps and can be characterized with MOS devices on 4H-SiC semiconductor that will exhibit small hole barriers at the anode of the pMOS devices. The other insulating materials having lower bandgaps can use MOS devices on Si to get a small hole barrier at the anode of the pMOS devices. Finally, the oxide thickness has to be very precise within 1 nm and should be thick of about 20 to 40nm at least to tolerate errors in oxide thickness, and the FN Slope constants B_e and B_h obtained from the FN plots of $\Delta\ln(J/E_{ox}^2)$ vs. $\Delta(1/E_{ox})$ from the I-V characteristics of the MOS device should be of high accuracy. Here Δ represents 'change in value'.

RESULTS AND DISCUSSIONS

The CB and VB band offsets at the thermal SiO_2/semiconductor interface, the electron and hole effective masses in the SiO_2, and the bandgap of the oxide are determined by FN carrier tunneling currents through MOS devices in accumulation. The devices are fabricated on the n-type and p-type 4H-SiC semiconductor oriented in the (0001) direction and Si-terminated. The I-V and C-V measurements on 4H-SiC MOS devices having a 40 nm oxide yielded the electron and hole tunneling FN Slope constants B_e and B_h from the FN plots to be 206 MV/cm and 258 MV/cm [8-9]. The hole tunneling Slope constant was later modified to 259 MV/cm after including two lower field raw data points on the FN plots. So, B_e = 206 MV/cm and B_h = 259 MV/cm are utilized in the characterization. Substituting the above values in equations (4), (5), and (6) and rearranging them yields two equations below as:

$$9.097 = \left(\frac{\emptyset_e + 0.96}{\emptyset_e + \emptyset_h + 3.234}\right) x\,(\phi_e)^3 \ldots\ldots \left(\frac{MV}{cm}\right)^2 \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$14.380 = \left(\frac{\emptyset_h + 2.274}{\emptyset_e + \emptyset_h + 3.234}\right) x\,(\phi_h)^3 \ldots\ldots \left(\frac{MV}{cm}\right)^2 \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Notice that for 4H-SiC, x=0.96, y=2.274, and z= 3.234 as described above in the theory section, and E_g is substituted in equations (4) and (5). The two non-linear simultaneous equations (7) and (8) have two unknowns $\emptyset_e$ and $\emptyset_h$ that can be solved for, either by a computer program or by trial and error starting with a guess value for $\emptyset_e$. The trial-and-error method is adopted

here and is described next. The guess value of $\emptyset_e$ is taken as 2.0 eV. Substituting it in equation (7) yields $\emptyset_h$as negative. Since the equations have unique solutions with values belonging to the set of Real numbers as the band offsets and effective masses are positive Real values, therefore as a next step $\emptyset_e$ is increased to 2.5 eV. Substituting it again in equation (7) gives 0.207 eV for $\emptyset_h$. These values of $\emptyset_e$ and $\emptyset_h$ are substituted in equation (8) to give the right-hand side of the equation as 0.0037. This is very small compared to the left-hand side of 14.380. The $\emptyset_e$ is kept at 2.5 eV and $\emptyset_h$ is slowly increased to 2.9 eV which gives the right-hand side of equation (8) as 14.615 which is larger than the left-hand side at 14.380. So, $\emptyset_h$has to decrease to 2.88 eV now giving the right-hand side of equation (8) as 14.293 which is just below 14.380. If 2.89 was used for $\emptyset_h$, it would have given a larger value of 14.45 of the right-hand side than 14.380 on the left. Now, we go back to equation (7) and substitute 2.88 for $\emptyset_h$ and 2.5 for $\emptyset_e$ on the right-hand side yielding 6.276 which is smaller than the left-hand side of 9.097. This time now $\emptyset_e$is increased to 2.785 eV slowly to give the right-hand side of equation (7) as 9.0904 which is almost the same as the left-hand side of 9.097. We now look at equation (8) again and substitute 2.785 for $\emptyset_e$ and 2.88 for $\emptyset_h$to give the right-hand side as 13.835. This being smaller than 14.380, $\emptyset_h$ is increased to 2.915 eV to give 14.386 on the right-hand side of equation (8) which almost matches with the left-hand side at 14.380. Equation (7) has already matched with $\emptyset_e$ at 2.785. Thus, 2.785 and 2.915 eV are the final values of $\emptyset_e$and $\emptyset_h$ respectively. The difference between the two is 0.13 eV which is already confirmed [10]. With these final values of $\emptyset_e$and $\emptyset_h$, the electron effective mass in the thermal SiO_2 comes out to be 0.419m and the hole effective mass comes out to be 0.581m. These values can be rounded to be 0.42m and 0.58m. The unknown bandgap of SiO_2 comes out to be 8.934 eV from equation (6).

The MIS characterization using FN carrier tunneling currents uses only electrons having a maximum of 5 eV energy, whereas the internal photoemission (IPE) of electrons from the semiconductor VB requires 6 to 8 eV photons to determine the VB to oxide CB offsets or VB to vacuum emission energy. This FN technique of MIS characterization is a viable, simpler and accurate alternative to photoemission methods of band offset determinations such as IPE and XPS, keeping in mind the limitations and cautions mentioned above.

CONCLUSION

An accurate MIS characterization of MOS devices can be done with FN carrier tunnelling currents through them using either Si (100) or (0001) oriented 4H-SiC and Si-terminated semiconductors. The unknown bandgap of thermal SiO_2 determined by this method is 8.934 eV. The electron and hole effective masses in the thermal SiO_2 are 0.42m and 0.58m with the MOS devices fabricated on the 4H-SiC semiconductor. The CB offset comes out to be 2.785 eV and the VB offset comes out to be 2.915 eV. The technique uses only electrons as compared to IPE technique that used photons. It is a simple and accurate method of MIS characterization. Oxides with smaller bandgaps can use MOS devices fabricated on the Si (100) semiconductor surface.

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