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A second look at the derivation of the average oxide fields in a charged metal-oxide-semiconductor device

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

Abstract: *A simplified understanding of a charged metal-oxide-semiconductor (MOS) device is developed by a second look at the derivation of the average oxide fields in the device. The distortion in the oxide field due to charges is removed by subtracting and adding the flatband voltage from the applied voltage to make the field at the cathode and anode uniform as before without charges that results in the centroid at half the thickness of the oxide for the uniform oxide field.*

Keywords: *Metal-Oxide-Semiconductor, Anode, Cathode*

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I. Introduction

An electron is a fundamental particle of nature as a fermion in the Standard Model of particles with a charge of 1.602x 10^{-19} Coulombs, a free electron rest mass of 9.11 x 10^{-31} Kg, a spin of ±½, and a lifetime of about 6.6 x 10^{28} years. The motion of the electron in different materials such as semiconductors and insulators constitute the conductivity effective masses in the materials which may depend on the direction in a crystal as well, resulting in mobility relation through drift velocity as given in Chapter 1 of the textbook by Muller and Kamins with Mansun Chan [1]. The MIS characterization with thermal silicon dioxide as the insulator, has led to the determination of Si-and C-face conduction band offsets in 4H-SiC MOS devices as 2.78 (2.79 or 2.8) eV and 2.92 eV, and the conductivity effective masses of electron and hole in the thermal SiO_2 as 0.42m and 0.58m, where m is the free electron mass [2-4]. A technique called BOEMDET has been invented that determines the band offsets and effective masses of electron and hole in other high-K amorphous oxides also, having negligible bulk defects so as to be called a non-leaky oxide. The electron and hole effective masses in the thermal SiO_2 of 0.42m and 0.58m have also been determined by using a Si-MOSFET in inversion without any Nitrogen at the interface and having vastly different band offsets at the oxide/Si interface than at the oxide/4H-SiC interface. The hole effective mass of 0.58m in thermal SiO_2 has been confirmed by a Japanese research group of Nemoto et al. using a 4H-SiC MOS device [5-9].

In the present article, the derivation of the average oxide fields across a MOS device in accumulation is discussed again. It is shown through the geometry of the fields that the distorted cathode and anode field due to the flatband voltage represented by a sheet of positive or negative charges in the oxide can again be made uniform as before without the presence of charges, by subtracting and adding the flatband voltage from the applied voltage V, and thus give the centroid of the charge distribution at half the thickness of the oxide as a consequence. This centroid position represents uniform distribution of charges before the distortion of the uniform electric field.

II. Theory

The derivation of average oxide field across a MOS device in accumulation is being discussed again in the present article. A simple structure of metal-gated metal-oxide-semiconductor (MOS) in accumulation is shown in Fig.1 below with oxide of thickness d between cathode and anode. A uniform sheet of positive charge is shown at a distance a, from the cathode that causes the distortion in the uniform field F=V/d. The field at the cathode is enhanced and the field at the anode is reduced [4, 10-11]. A sheet of negative charges in the oxide would cause the field at the cathode to reduce and the field at the anode to enhance. The cathode field E_1, and the anode field E_2 derivation using Gauss's law has been presented in the earlier study by revisiting Klein's study of 1972 [4, 10-11]. The derivation for the average oxide field for electron tunnelling from the cathode and hole tunnelling from the anode had been left for the reader to derive in the earlier study [4]. The earlier study was extended by presenting the derivations of the average oxide fields for carrier tunnelling [11]. It is to be noted that the I-V characteristics across the MOS device in accumulation has originated in the works of the Irishman, J. S. Townsend in the early 20th century [12], when he was doing research at Oxford on electricity in gases. He afterwards had become a British citizen. He had shown that the electrons in the gases after ionization multiply exponentially. This observation later on developed into the Fowler-Nordheim electron tunnelling current through the MOS device, and it has now been shown by the author to be the diffusion current of electrons resulting from ionisation of the thermal oxide at high electric fields across the MOS device in accumulation [3-4, 13]. The gases at low pressure were acting as the dielectric then, which in the MOS device is replaced by amorphous SiO_2. The hole tunnelling can be observed at the solid-solid interface but cannot be observed in the vacuum.

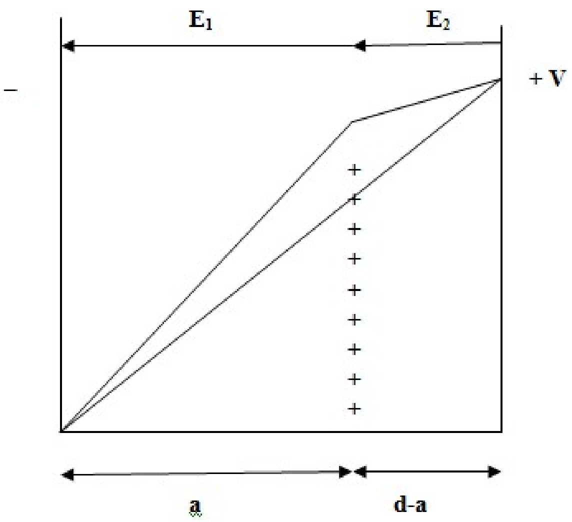

Fig. 1. A MOS device in accumulation having an oxide of thickness d with a uniform sheet of positive charge at a distance a from the cathode causing enhancement of the cathode field E_1 and reduction of the anode field E_2.

III. Results and Discussion

Consider electron tunnelling from the cathode of a MOS device having positive charges in the oxide at a distance a, from the cathode. The oxide thickness is d and the applied voltage across the device is V and $0<\sigma<1$. Let X be the gate bias for which the cathode field $E_1=F$, where F is the applied field across the device without charges in the oxide. Then,

$$X= E_1a + E_2(d-a) \qquad (1)$$
$$E_1=E_2 + \sigma F \qquad (2)$$
$$E_2=E_1-\sigma F$$
$$E_2=F - \sigma F$$
$$X=Fa + (F-\sigma F)(d-a)$$
$$X=aF + dF - aF - \sigma F(d-a)$$
$$X=dF - \sigma F(d-a)$$
$$X=dV/d - (\sigma V/d)(d-a)$$
$$X=V - \sigma V((d-a)/d) \qquad (3).$$

Similarly, consider hole tunnelling from the anode of a MOS device having positive charges in the oxide at a distance a, from the cathode. The oxide thickness is d and the applied voltage across the device is V and $0<\sigma<1$. Let X be the gate bias for which the anode field $E_2=F$, where F is the applied field across the device without charges in the oxide. Then,

$$X=E_1a + E_2(d-a) \qquad (4)$$
$$E_1=E_2 + \sigma F \qquad (5)$$
$$E_1=F + \sigma F$$
$$X= (F + \sigma F)a + F(d-a)$$
$$X= aF + a\sigma F + dF - aF$$
$$X= dF + a\sigma F$$
$$X= dV/d + \sigma Va/d$$
$$X= V + \sigma Va/d \qquad (6).$$

The field distortion and its removal by subtracting and adding the flatband voltage is discussed further by observing the geometry of cathode and anode field. The Fig.2 below presents the uniform field F for the uniform distribution of charges by CDO. The uniform field F=V/d, where V is the voltage at point C of the anode with respect to the cathode at point O. CAO represents the distortion of the field F due to the sheet of positive charges ADH extended on the X-axis that divides the thickness of the oxide (d) into (a) and (d-a). AO represents the field E_1 and CA represents the field E_2 as in the Fig. 1. When E_1 equals the field F without charges for the electron tunnelling from the cathode represented by DO, then ED represents E_2 parallel to CA, and the (σV(d-a)/d) has to be subtracted from V as shown in the formulation above. When E_2 represented by CA equals the field F without charges for the hole tunnelling from the anode, then BA becomes parallel to CD, and AO represents E_1. Now, (σVa/d) is added to V as shown in the formulation above. Under these two conditions the side AD is common to the two parallelograms ABCD and ACED. Therefore, BC equals CE which are the addition and subtraction to and from the voltage V, making them equal. From this equality, it can be inferred that a=d/2 as the centroid for a uniform distribution of charges having a uniform field F represented by CDO. BC and CE now form the magnitude of the flatband voltage V_{fb} equal to σV/2 when W_{ms} is included, and are equal to AD. Flatband voltage is the voltage that is subtracted or added from the applied voltage V to obtain uniform distribution of charges in the oxide as before the charges were present. Here again, $0 < \sigma < 1$. The distorted field at the cathode and anode due to the positive charge sheet at (a) distance from the cathode, is made uniform by subtracting and adding the flatband voltage from the applied voltage V, thus giving the centroid at a=d/2 for the uniform field F without charges.

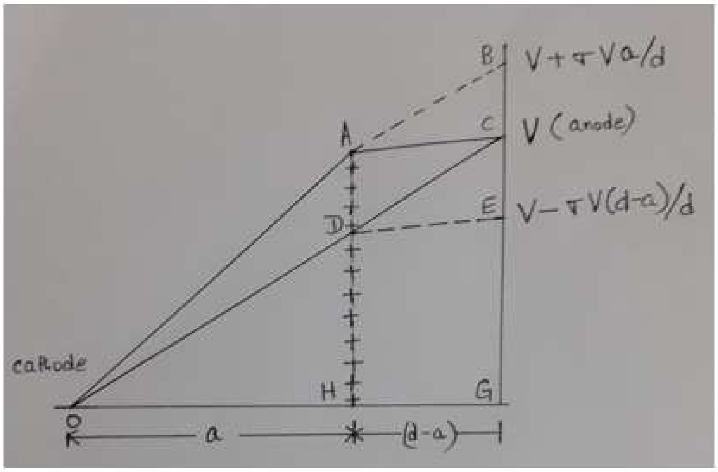

Fig.2. The Fig.1 represented under the condition of electron and hole tunnelling from the cathode and anode.

The flatband voltage is thus equal to AD in Fig.2, and is given at a distance (a)=(d/2) from the cathode as:

$$V_{fb} = \sigma Va/d$$
$$V_{fb} = \sigma V/2 \qquad (7).$$

In a MOS device, the flatband voltage is given as:

$$V_{fb} = W_{ms} - (Q_f + Q_{ot} + Q_{mo} + Q_{it})/\, C_{ox}. \qquad (8).$$

Here, Q_f, Q_{ot}, Q_{mo}, and Q_{it} represents the fixed oxide, oxide trapped, mobile ionic, and interface trapped charge densities in Coulombs/cm^2. C_{ox} is the oxide capacitance in Farads/cm^2, and W_{ms} is the metal-semiconductor work function difference in Volts. Q_{it} becomes part of the V_{fb} when the interface trap density is very high, of the order of 10^{12} cm^{-2}eV^{-1} or greater. Therefore, V_{fb} obtained from the C-V measurements, that includes the effect of all the above charges and W_{ms} has been used in the calculations of oxide voltages and average oxide fields, F_{av}. A negative measured value of V_{fb} on the C-V curve signifies net positive charges in the MOS device including W_{ms}, and a positive measured value of V_{fb} on the C-V curve signifies net negative charges in the MOS device including W_{ms}. So, the voltage across the oxide for electron tunnelling from the cathode from equation (3) is now given as:

$$V_{ox} = |V| - |V_{fb}|. \qquad (9)$$

The average field across the oxide in the MOS device having positive charges in the oxide, for electron tunnelling from the cathode is now given as:

$$F_{av} = (|V| - |V_{fb}|)\, /\, d \qquad (10).$$

The voltage across the oxide for hole tunnelling from the anode from equation (6) is given as:

$$V_{ox} = |V| + |V_{fb}|. \qquad (11).$$

The average field across the oxide of a MOS device having positive charges in the oxide, for hole tunnelling from the anode is now given as:

$$F_{av} = (|V| + |V_{fb}|)/d \qquad (12).$$

The derivations of the average field across the oxide for the two cases of electron and hole tunnelling having positive charges in the MOS devices are presented above with the average fields given by equations (10) and (12). Similar derivations of the average oxide fields can be performed for electron and hole tunnelling in the MOS devices having negative charges in the devices. The oxide voltages for all four cases have already been presented in the author's earlier study and further unified in one equation [3-4, 14].

IV. Conclusions

A second look at the derivation of the average oxide fields in a MOS device having charges in the oxide leads to a simplified understanding of how the distortion in the uniform field due to the presence of charges that represent the flatband voltage is corrected by subtracting and adding the flatband voltage from the applied voltage, resulting back into a uniform field at the cathode and anode as before without the presence of charges.

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