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Theoretically Calculated Properties of a MOS Device on Gallium Oxide

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ABSTRACT

The properties of a MOS device on (100) oriented β-Ga_2O_3 semiconductor are determined theoretically utilizing the concept of physics that the carrier effective masses in materials are related to the intrinsic Fermi energy levels in materials by the universal mass-energy equivalence equation given as dE/E = dm/m, where E is the energy and m is the free electron mass. The known parameters of isotropic electron effective mass of 0.27m and the bandgap of 4.8 eV for β-Ga_2O_3 semiconductor are utilized to determine the properties of the MOS device along with the parameter of threshold for electron heating in SiO_2 as 2 MV/cm-eV.

Key words : Gallium Oxide, Mass-Energy equivalence, MOS device, Fowler-Nordheim Tunnelling.

1. INTRODUCTION

It has been shown by the author in his earlier studies that the Einstein's mass-energy equivalence given by the equation $E=mc^2$ is manifested in semiconductors and insulators. It has been shown that the electron and hole effective masses in parabolic semiconductors and insulators are related to the intrinsic Fermi energy level in the bandgap of the materials by the universal mass-energy equivalence relation dE/E equals dm/m, where dE is the differential potential energy from the intrinsic Fermi energy level to the conduction band of the material, dm is the differential mass as the effective mass of carriers in the materials, E is the bandgap of the semiconductor or insulator as the total potential energy of the electrons, and m is the free electron mass [1]-[2]. This universal equation is obtained by differentiating Einstein's equation once on both sides and is valid for all energy transformations and moving big or small masses [3]. In this research paper the above concept is utilized to determine the properties of a metal-oxide-semiconductor (MOS) device on β-Ga_2O_3 (100) oriented semiconductor theoretically. It is known that the MOS device is the heart of a metal-oxide-semiconductor field -effect transistor (MOSFET), the properties of which can determine the viability and reliability of a high or low voltage and high frequency power FET. β-Ga_2O_3 having an ultra-wide bandgap of 4.8 eV is found to be a viable semiconductor for a high voltage power FET.

2. THEORY

The current conduction through the SiO_2 insulator and the oxide/semiconductor interface properties are the two groups of properties of a MOS device which are interrelated [4]. The current-voltage characterization of a MOS device in accumulation or inversion gives the properties of low-field leakage current through the oxide insulator, the onset electric field for Fowler-Nordheim (FN) tunnelling current, and the tunnelling current at high electric fields across the oxide insulator that leads to the breakdown of the oxide. The oxide/semiconductor interface properties from the capacitance-voltage measurements give the oxide charge densities and the interface trap densities in the MOS device. These are well-studied properties and are elaborately discussed in an excellent 900 pages book on MOS Physics and Technology [5]. In this research paper, the properties based on current conduction are determined theoretically that identifies a reliable Gallium Oxide MOS device for a Power MOSFET. The oxide/semiconductor interface properties obtained by another research group are utilized to determine the surface field effect mobility in the FET channel. The isotropic electron effective mass for β-Ga_2O_3 has been determined theoretically and experimentally to be 0.27m [6]. The electron mobility in bulk Ga_2O_3 is estimated at 300 cm^2/V-s. It is low as compared to other power semiconductors such as SiC and GaN [7].

3. RESULTS AND DISCUSSION

The properties of the metal/SiO_2/Ga_2O_3 (100) MOS device with electron as a current carrier can be determined theoretically with the given electron effective mass of 0.27m and the bandgap of β-Ga_2O_3 as 4.8 eV. The MOS device fabricated on the Ga_2O_3 (100) surface and in accumulation with metal gate as the anode has the electric field in the thermal SiO_2 having negligible bulk defects oriented in the [100] direction. This results into Fowler-Nordheim (FN) electron tunnelling current through the oxide at high electric fields. The intrinsic Fermi level E_i, is located at 0.27 x 4.8 eV = 1.30 eV below the Conduction Band (CB) of Ga_2O_3, given that the relative energy equals relative mass of a moving electron or hole from the equation dE/E equals dm/m [1]-[3]. The CBO of the oxide/semiconductor interface is 3.75-1.30 = 2.45 eV and the FN onset field in the oxide is 2 x 2.45 = 4.9 MV/cm with electron as a current carrier. This is because the FN onset field divided by the CBO in a MOS device equals 2 MV/cm-eV as the electron heating threshold in the thermal SiO_2, where 1 eV is the energy to create hot electrons in vacuum. This has been found by direct observation of electron heating threshold in thermal SiO_2 as 2 MV/cm, with confirmation by the author's study. The FN onset field in the MOS device is thus 2 MV/cm-eV x CBO [8]-[9]. Therefore, the FN onset field for the electron carrier is 4.9 MV/cm as presented above. Here, 3.75 eV is the position of the E_i in SiO_2 from its CB and identifies the position of E_i in Ga_2O_3 for the oxide/semiconductor interface due to charge neutrality. The 3.75 eV equals 0.42 x 8.93 eV, where 0.42 is the relative electron effective mass in the oxide and 8.93 eV is the oxide bandgap [10]-[11]. The theoretical value of the slope constant B for the FN tunnelling electron current can now be decided using the formula [12]-[13]:

$$B = 68.3 \text{ x } (m_{ox}/m)^{1/2} \text{ x } (\Phi_0)^{3/2} \text{---(MV/cm) -- (1).}$$

Here, electron effective mass m_{ox} for SiO_2 is 0.42m and the oxide/semiconductor interface barrier height Φ_0 for electrons is found above theoretically as 2.45 eV. These values give the theoretical slope constant B as 169.744 MV/cm. This can be safely set equal to 170 MV/cm. The FN electron current density for this B and an FN onset field of 4.9 MV/cm found above will be about 3.24 x 10^{-8} A/cm^2 theoretically. The oxide will exhibit a breakdown field of about 6.3 MV/cm for a 10^{-4} A/cm^2 current density for thick oxide of say 25 to 100 nm, given that two points on the FN current-voltage (I-V) characteristics at high fields are (3.24 x 10^{-8} A/cm^2, 4.9 MV/cm) and (10^{-4} A/cm^2, E_{bkdn} in MV/cm). From the first point, FN slope constant B can be calculated as 170 MV/cm, and from the second point, the E_{bkdn} can be calculated to be 6.3 MV/cm [12]-[13]. E_{bkdn} is the breakdown electric field in the amorphous silicon dioxide. E_i, located at 1.30 eV from the Ga_2O_3 (100) CB translates to a very small intrinsic defect density, N_{id} as Ga_2O_3 has a very small intrinsic carrier concentration because of its large bandgap of 4.8 eV [10]-[11]. Thus, the electronic properties of intrinsic Fermi energy level E_i in the semiconductor on the (100) surface, Conduction Band Offset at the oxide/semiconductor interface, FN onset field in the SiO_2, leakage current density at the FN onset field in the SiO_2, and the Electric breakdown strength of the oxide are all determined for the MOS device theoretically, given the isotropic electron effective mass in the semiconductor Ga_2O_3 in the [100] direction of 0.27m and its bandgap of 4.8 eV, without even fabricating and characterizing the MOS device experimentally. However, the MOS device has to be fabricated and characterized for the interface properties that will lead to the determination of surface field-effect (FE) electron mobility in the MOSFET device channel.

The property of surface FE mobility of the n-channel Ga_2O_3 MOSFET transistor is considered next which are obtained from the fabricated n-MOS device in conjunction with the concept that the mobility is inversely proportional to the total interface trap density for a Coulomb-scattering limited mobility. This concept is applied on the Ga_2O_3 MIS device with the SiO_2 layer as insulator. Utilizing the equation (4) in the author's earlier study [14] gives the mobility of about 70 cm^2/V-s for the SiO_2 based MIS device having total interface state density of about 20 x 10^{11}/cm^{2}eV [15]. The combined densities of border traps or near-interface traps in the oxide near the semiconductor CB and the oxide/semiconductor interface traps constitutes the total interface trap density. They can be said to form two parallel capacitances, one due to the near-interface traps in the oxide and the other due to the traps at the oxide/semiconductor interface. The oxide/semiconductor interface trap density being much larger makes the total trap density remain at 20 x 10^{11}/cm^{2}eV. This, when compared to the Si MOS device as a control sample having a mobility of 140 cm^2/V-s for a 10 x 10^{11}/cm^2 eV total interface state density gives a mobility of 70 cm^2/V-s by using the equation (4) of [14]. Peak channel electron mobility of 80-90 cm^2/V-s have been obtained experimentally on Ga_2O_3 n-channel MOSFET [16]. The above calculation shows that the Coulomb-scattering limited mobility can be obtained with the concept of mobility being inversely proportional to the total interface state density with the total interface state density characterization of only the fabricated MOS device [14].

4. CONCLUSION

The MOS device on β-Ga_2O_3 semiconductor is found to possess reliable properties for a Power MOSFET as determined theoretically. A concerning parameter is the low bulk electron mobility in Ga_2O_3 of only about 300 cm^2/V-s. This may limit the achievable channel mobility of electrons in the power transistor.

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