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Properties of a Gallium Nitride MOS device

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Abstract: *This research study characterizes a GaN MOS device theoretically for the properties of the conduction band offset, Fowler-Nordheim onset field, the oxide leakage current density at low oxide electric fields, the electrical breakdown strength, the intrinsic Fermi energy level in GaN and its intrinsic defects density. These properties match with the experimentally observed values. It utilizes the universal mass-energy equivalence relation dE/E equals dm/m that relates to the properties of the MOS device with the given longitudinal electron effective mass and the bandgap of GaN. The study also shows that the Coulomb-scattering limited peak surface field effect mobility in an n-channel wurtzite GaN MOSFET can be obtained with only a fabricated GaN MOS device. The universal mass-energy equivalence relation, first discovered by the famous scientist Albert Einstein, is manifested in semiconductors and insulators and can significantly facilitate new materials research.*

Keywords: *MOS device, GaN Semiconductor, Intrinsic Defects, Mobility, FN-Tunnelling*

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I. Introduction

The author has demonstrated through his earlier studies on Si (100), 4H- and 3C-SiC and (100) oriented crystalline Diamond, that the properties of a Metal-Oxide-Semiconductor (MOS) device on any parabolic semiconductor can be found theoretically given the longitudinal and transverse electron effective masses in the semiconductor and its bandgap [1-4]. This conclusion was based on the electron or hole particle physics concept of universal mass-energy equivalence given by the equation dE/E equals dm/m, that relates to the properties of the MOS device with the thermal silicon dioxide as an insulator. In this equation, dE is the differential kinetic energy of the electron when excited into the semiconductor conduction band (CB) from the intrinsic Fermi energy level in the semiconductor or the differential potential energy of the electron from the intrinsic Fermi energy level to the semiconductor CB. E is the semiconductor bandgap as the total potential energy of the electron with reference to the valence band (VB) at zero potential energy. The dm in the above relation is the differential mass as the electron effective mass and m is the free electron mass. The above is capsulated in the author's earlier study [5]. The mass-energy equivalence relation $E=mc^2$, was first discovered by Albert Einstein as a conclusion of his special theory of relativity in 1905 and is briefly discussed earlier by the author [5]. It is shown that the relation when having a moving body of relativistic mass m and relativistic energy E is differentiated, it gives the above universal mass-energy equivalence relation. The kinetic energy of an electron or hole moving in a silicon crystal has also been shown to possess the same property under a changing thermal energy [5]. The equation is valid for a changing kinetic or potential energy of particles such as electrons or holes in materials as well. In the present case of GaN MOS device, the materials are GaN as semiconductor and amorphous SiO_2 or Oxide/Nitride/Oxide stack as insulator. The determination of the intrinsic Fermi energy level is also elaborated in an author's earlier study, where it is shown that the intrinsic Fermi energy level E_i of the thermal oxide at 3.75 eV from the oxide conduction band, aligns with the E_i in the semiconductor for the electron effective mass in the oxide at 0.42m due to charge neutrality [6-7]. The above relation of dE/E equals dm/m can then be used to find the electron effective mass in the semiconductor with the known differential energy dE through MIS characterization and the semiconductor bandgap. This calculation has been performed for the (0001) oriented wurtzite GaN in another submission to this conference. The longitudinal electron effective mass determined in (0001) oriented wurtzite GaN is about 0.2m for both the A and L- conduction valleys [6-7, 8]. The longitudinal electron effective mass in zincblende GaN can also be shown to be about the same at 0.2m. Theoretically determined longitudinal electron effective mass and the transverse mass in GaN is also about 0.2m. The heavy-hole mass in GaN becomes 0.8m as the longitudinal electron effective mass for one conduction valley and the heavy-hole mass add up to be equal to free electron mass. This is because dE/E gives the electron mass and (E-dE)/E gives the hole mass that adds to m as the free electron mass. The hole devices such as the p-channel MOSFETs in GaN will therefore be inefficient with the high hole mass value of 0.8m providing low field-effect surface mobility and consequently low drain current. However, NMOS technology can flourish in GaN.

II. Theory

The knowledge of the properties of the MOS device on a parabolic semiconductor are essential to be known in order to predict its efficient and reliable operation in integrated circuits. Five properties of CB and VB offsets, intrinsic Fermi energy level E_i and intrinsic defects density N_{id}, Fowler-Nordheim (FN) onset electric field, leakage current in the oxide at low electric fields, and the electrical breakdown strength of the oxide can be determined theoretically, without fabricating and experimentally characterizing the MOS device, simply with the known longitudinal and transverse electron effective masses in the semiconductor and the semiconductor bandgap [1-4]. The MOS device however, has to be fabricated and experimentally characterized for the oxide/semiconductor interface states density and the border trap density in the oxide near the semiconductor CB by the current-voltage (I-V) and capacitance-voltage (C-V) methods to determine the field-effect surface mobility of the MOSFET device which is primarily limited by Coulomb scattering [9]. It is emphasized that the characterization of the fabricated MOS device is sufficient to provide reasonable estimates of surface mobility in the MOSFET device without having to fabricate and characterize a MOSFET transistor.

III. Results and Discussion

The properties of the GaN MOS device that can be calculated theoretically are considered first. The longitudinal and transverse electron effective mass in (0001) oriented GaN is about 0.2m (0.218m in the L-conduction valley) as introduced earlier in the introduction section of this article. Given the bandgap of the wurtzite GaN from the L-conduction valley to be 4.35 eV, the intrinsic Fermi energy level E_i can be calculated to be 0.218 x 4.35 = 0.95 eV from the GaN CB using the relation dE/E equals dm/m. Here, dm/m is 0.218 and E is 4.35 eV giving dE as 0.95 eV from the GaN CB. The E_i for SiO_2 that aligns to the E_i in GaN is 3.75 eV. Therefore, the CB offset from the oxide CB to the GaN CB is calculated to be 3.75-0.95 = 2.8 eV. The threshold for electron heating in the amorphous SiO_2 is 2MV/cm-eV, where 1 eV is the energy to create hot electrons in vacuum [10-11]. Multiplying this value to the CBO gives the FN onset field in the MOS device to be 5.6 MV/cm as shown in earlier studies also [1-2]. The theoretical value of the slope constant B for the FN tunnelling electron current can now be decided using the formula [12-14]:

$$B = 68.3\, x \left(\frac{m_{ox}}{m}\right)^{1/2} x(\emptyset_0)^{3/2} \dots\dots MV/cm \qquad (1).$$

Here, electron effective mass m_{ox} for SiO_2 is 0.42m and the oxide/semiconductor interface barrier height $\emptyset_0$ is found above theoretically as 2.8 eV. These values give the theoretical slope constant B as 207.4 MV/cm. The FN electron current density for this B and an FN onset field of 5.6 MV/cm found above will be about 3.5 x 10^{-9} A/cm^2 theoretically [12-14]. The oxide will exhibit a breakdown field of about 7.6 MV/cm for a 10^{-4} A/cm^2 current density for thick oxide of say 40 to 100 nm, given that two points on the FN current-voltage (I-V) characteristics at high fields are (3.5 x 10^{-9} A/cm^2, 5.6 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 207.4 MV/cm, and from the second point, the E_{bkdn} can be calculated to be 7.6 MV/cm [12-14]. Experimentally also, the low field leakage current density is about 2 x 10^{-9} A/cm^2 in a GaN MOS device having 20 nm thick plasma-enhanced chemical vapour deposited (PECVD) SiO_2 annealed at 800^{o}C in dry oxygen for 30 minutes. The PECVD oxide after annealing shows a breakdown electric field of around 8 MV/cm which compares well to the theoretically obtained value of 7.6 MV/cm for a 10^{-4} A/cm^2 current density [15]. The data can be observed in Fig.2 of the reference [15]. The theoretical calculations therefore predict quite accurately the experimentally observed properties of the GaN MOS device, although the low oxide field current density is lower than the theoretical prediction indicating presence of border traps [9]. The FN onset field is not very clear for this experimental GaN MOS device. Another experimental study on GaN MIS device with Oxide/Nitride/Oxide as the gate insulator with 24 nm equivalent oxide thickness (EOT) instead of only amorphous SiO_2 shows a FN onset field of about 6 MV/cm close to the theoretically predicted 5.6 MV/cm with a low-field oxide leakage current density of about 10^{-9} A/cm^2 that is lower than the theoretical value calculated above of 3.5 x 10^{-9} A/cm^2, again indicating the presence of border traps at 25.8 x 10^{11}/cm^{2}eV [9]. These can be observed in Fig.10 of reference [16]. The breakdown electric field of the ONO insulator is much higher at 11 MV/cm for a 10^{-4} A/cm^2 current density [16]. There are some positive charges giving a flatband voltage of -1.8 V. The positive charges enhance the electric field at the cathode [17-18]. The oxide voltage will therefore have to be reduced to obtain the field without charges [18]. The oxide breakdown field would be about 10 MV/cm instead of 11 MV/cm. This becomes closer to the theoretically predicted value of 7.6 MV/cm keeping in mind that the insulator is not SiO_2 but an ONO layer. The intrinsic defect density N_{id}, in the wurtzite GaN semiconductor for an E_i of 0.95 eV from the CB has been calculated before as 2.7 x

$10^{15}/cm^3$. This defects density is about 25 times higher than that in 4H-SiC and can be a major disadvantage when compared to 4H-SiC [7]. It can cause premature breakdown at junctions making GaN MOS devices suitable for only lower voltages [19]. The thermal conductivity in GaN is also three times lower compared to that in 4H-SiC at about 1.3 $Wcm^{-1o}C^{-1}$ that also makes it compatible with lower voltage operation. Overall, the theoretical predictions of the properties of the MOS device are comparable to the experimental observations. The author's view is that small differences between the theory and experiment are due to the imperfections in experiments. Previous similar studies by the author have more precise agreement between the theory and experiment [1-2].

The property of surface field-effect mobility of the n-channel GaN 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 GaN MIS device with the ONO layer as insulator. Utilizing the equation (4) in the author's earlier study gives the mobility of about 45 cm^2/V-s for the ONO based MIS device having total interface state density of about 30 x $10^{11}/cm^2eV$ [9, 16]. 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 oxide/semiconductor interface traps. In another two experimental studies by the same authors Huang et al. [20-21], the net effective fixed oxide charge density in the MOS device having 65 nm PECVD oxide was found to be 1.45 x $10^{12}/cm^2$ that constitutes the border trap density. The oxide/semiconductor interface trap density being two orders lower makes the total trap density remain at 1.45 x $10^{12}/cm^2eV$. 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 97 cm^2/V-s by using the equation (4) of the reference [9]. During comparison, the bulk Hall mobilities in Si and GaN should be comparable which they are. W. Huang and co-researchers obtain a peak field-effect mobility of 104 cm^2/V-s in their experimental research on GaN n-channel MOSFET having a thick PECVD oxide of 65 nm [21]. It can be observed that as the oxide thickness increase from 20-24 nm to 65 nm, the mobility increased from 45 cm^2/V-s to 97-104 cm^2/V-s because of reduction in the total interface trap density. An oxide thickness of about 100 nm is necessary for an oxide displacement current density to be same as that predicted theoretically at 3.5 x 10^{-9} $A/cm^2$and substantially reduce the near-interface (border) traps to provide higher mobility, possibly greater than 104 cm^2/V-s [9]. 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. Thus, the experimental determination of mobility from the MOS device alone, can be accurate.

IV. Conclusions

Theoretical prediction of the properties of a GaN MOS device is performed with the given longitudinal electron effective mass of 0.218m in the L-conduction valley and the bandgap of GaN of 4.35 eV, utilizing the universal mass-energy equivalence relation that relates to the properties of a MOS device. The prediction is overall quite accurate and matches with the experimentally observed properties of the GaN MOS device. Theoretically, the CBO is 2.8 eV, the FN onset field is 5.6 MV/cm, the oxide leakage current is about 3.5 x 10^{-9} A/cm^2 at low oxide electric fields, the electrical breakdown strength is 7.6 MV/cm and the intrinsic defect density N_{id}, in wurtzite GaN is 2.7 x $10^{15}/cm^3$. Experimentally, the Coulomb-scattering limited surface field-effect mobility can be up to about 100 cm^2/V-s as the peak value in n-channel GaN MOSFETs and it can be obtained by characterizing only a fabricated GaN MOS device without the need for a MOSFET. About 100 nm oxide thickness is necessary for the oxide displacement current density of 3.5 x 10^{-9} A/cm^2 that will match with the theoretical prediction of current density at the FN onset field of 5.6 MV/cm and substantially reduce near-interface (border) traps to reduce the total interface trap density. The theoretical properties of MOS devices on (0001) oriented 4H-SiC and GaN are the same. An oxide thickness of about a 100nm could reduce the total interface trap density in the (0001) oriented 4H-SiC device also by reducing near-interface (border) traps and provide surface field-effect mobility in the n-channel lateral MOSFET of greater than 50-65 cm^2/V-s. A major disadvantage of GaN when compared to 4H-SiC is a 25 times higher intrinsic defects density and about three times lower thermal conductivity that favors lower voltage operation of GaN MOS devices.

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