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N-channel 4H-SiC MOSFET device on $(11\overline{2}0)$ oriented epitaxial surface

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Abstract: *This research study demonstrates that a higher surface field-effect mobility of electrons can be obtained in a n-channel 4H-SiC-MOSFET device by fabricating it on the $(11\overline{2}0)$ epitaxial surface. The article also gives a method to find the properties of a MOS device on any parabolic semiconductor, given the transverse and longitudinal electron effective masses in the semiconductor and its bandgap, without fabricating the MOS device. Finally, the study also highlights a significant scientific concept of physics that, the electron effective masses in semiconductors and insulators are not only related to the mobility through drift velocity, but are also related to the intrinsic Fermi energy below the conduction band of the semiconductor through the relation dE/E equals dm/m, where dE is the differential kinetic energy of the moving electron, E is the semiconductor bandgap, dm is the effective mass of the electron in the material and m is the free electron mass.*

***Keywords*:** *Metal-Oxide-Semiconductor, Silicon Carbide, Intrinsic Defects*

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I. Introduction

The MIS characterization can lead to the determination of the intrinsic Fermi level E_i, in the semiconductor bandgap. The differential energy dE from E_i to the semiconductor conduction band (CB) determines the longitudinal effective mass in the semiconductor by using the relation dE/E equals dm/m. Here, E is the semiconductor bandgap, dm is the effective mass in the semiconductor and m is the free electron mass [1-3]. If the MOS device is fabricated on the transverse surface, then the MIS characterization will lead to the transverse effective mass in the semiconductor. This becomes a new method of determining the electron effective masses in a parabolic semiconductor. Alternatively, if the transverse and longitudinal effective masses in a parabolic semiconductor are determined correctly, by say the cyclotron resonance method [4], then the E_i in the semiconductor bandgap can be easily determined using the relation dE/E equals dm/m. The intrinsic defects density in the semiconductor can then be found using the equation of charge neutrality in the semiconductor [1-2]. In this article, the properties of a 4H-SiC-MOS device such as, conduction band offset (CBO), the Fowler-Nordheim (FN) onset electric field, and the oxide electric breakdown field along with the intrinsic defect density in 4H-SiC are all determined starting with the known transverse and longitudinal electron effective masses in 4H-SiC semiconductor as 0.42m and 0.297m and its experimental bandgap of 3.23 eV, without even fabricating the MOS device.

II. Theory

The main properties of a MOS device are; the conduction and valence band offsets at the oxide/semiconductor interface, the FN onset field in the amorphous oxide (thermal SiO_2 in the present case) that is a measure of the leakage current in the oxide, oxide electrical breakdown strength, the intrinsic defects density in the semiconductor that indirectly determines the surface field-effect (FE) mobility in the MOSFET. By adding the electron affinity of the thermal SiO_2 of 0.9 eV [5], to the CBO of the semiconductor/oxide interface or the metal/oxide interface, one can also determine the electron affinity of the semiconductor or the work function of the metal for the given surface and ambient conditions. The band offsets can be determined from the known position of E_i from the CB of 4H-SiC by comparing it to the E_i in the SiO_2. E_i can also help in determining the intrinsic defects density in the semiconductor [1-2]. 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 the oxide as 2 MV/cm with confirmation by the author's study [6-7]. The FN onset field can therefore be found once the CBO is known. Two points on the high field region of the FN electron tunneling current versus voltage characteristics can be used to find the tunneling slope constant B for the current and the dielectric breakdown field strength in MV/cm. One point can be the (10^{-8} to 10^{-10} A/cm^2, FN onset field in

MV/cm) and the second point can be the (10^{-4} A/cm^2, E_{bkdn} in MV/cm). The 10^{-4} A/cm^2 current density is assigned as the breakdown current density in thick oxide of say 40 nm. This is described in the author's earlier studies [8-10]. Thus, the main properties of a MOS device can be found without fabricating the MOS device.

III. Results and Discussion

The transverse and longitudinal electron effective masses in 4H-SiC semiconductor are 0.42m and 0.297m, and its bandgap is 3.23 eV. The electric field in the thermal SiO_2 having negligible bulk defects is oriented in the [11$\bar{2}$0] direction for the MOS device fabricated on the (11$\bar{2}$0) surface. The intrinsic Fermi level E_i, is located at 0.42 x 3.23 eV = 1.35 eV below the CB of 4H-SiC, given that the relative energy equals relative mass of a moving electron from the expression dE/E equals dm/m [1-3]. The CBO of the oxide/semiconductor interface is 3.75-1.35 eV = 2.4 eV and the FN onset field in the oxide is 2 x 2.4 = 4.8 MV/cm. This is because the minimum field for electron heating in the oxide is 2 MV/cm, which is FN onset field divided by the CBO with 1 eV as the minimum energy needed to see vacuum emission of hot electrons. The FN onset field in the MOS device is thus 2 MV/cm-eV x CBO, as presented above to be 4.8 MV/cm [6-7]. 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 4H-SiC of the oxide/semiconductor interface. 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 [1-2]. 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 40nm, given that two points on the Fowler-Nordheim (FN) current-voltage (I-V) characteristics at high fields are (10^{-8} A/cm^2, 4.8 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 166 MV/cm, and from the second point, the E_{bkdn} can be calculated to be 6.3 MV/cm. E_i, located at 1.35 eV from the 4H-SiC CB and close to the mid-bandgap of 1.62 eV translates to a small intrinsic defect density, N_{id} of 10.5/cm^3 [1-2]. The surface field-effect (FE) electron mobility for the MOSFET can be known from the I-V/C-V based characterization of a pair of n-MOS and p-MOS device only, by finding the border trap density (D_{bt}) and the interface trap density (D_{it}), followed by a comparison to a Si-MOSFET with known surface mobility and total interface defect density. This is possible because the FE surface mobility is inversely proportional to the total interface traps density in the device, and the Hall electron mobilities in Si and 4H-SiC are comparable [11]. The oxide electric field should thus be directed in the higher effective mass direction of the semiconductor giving lower N_{id}. This direction also gives lower FN onset field in the MOS device, but the minimum oxide field required with the MOSFET in the ON state is only 2 MV/cm as the electron heating threshold in the oxide. The lower effective mass direction [0001] can thus give larger mobility, as the oxide electric field and electron flow are directed perpendicular to each other.

If the oxide electric field is oriented in the [0001] direction by fabricating the MOS device on the (0001) surface, then with the given electron effective mass of 0.297m in the [0001] direction of 4H-SiC (heavy-hole mass becomes 0.703m), the E_i will be located at 0.297 x 3.23 eV = 0.96 eV below the 4H-SiC CB. The CBO at the oxide/SiC interface will be 3.75-0.96 = 2.79 eV and the FN onset field in the oxide will be 2 x 2.79 = 5.58 MV/cm. The oxide will exhibit an electrical breakdown field of about 7.8 MV/cm for a 10^{-4} A/cm^2 current density for a thick oxide of say 40 nm, given that two points on the FN I-V characteristics at high fields are (10^{-9} A/cm^2, 5.6 MV/cm) and (10^{-4} A/cm^2, E_{bkdn} in MV/cm). From the first point, slope constant B can be calculated as 206 MV/cm, and from the second point, the E_{bkdn} can be calculated to be 7.8 MV/cm. The position of E_i in the 4H-SiC at 0.96 eV below the 4H-SiC CB means that, there is a much larger density of intrinsic defects N_{id}, as the Fermi level is away from the mid-bandgap of 1.62 eV [12]. The calculated N_{id} in the [0001] direction is 1.1 x 10^{14}/cm^3 [1-2].

It is inferred from the above theoretical analysis corroborated with experimental evidence that, if the mobility in the 4H-SiC-MOSFET, fabricated on the (11$\bar{2}$0) epi-surface called the a-face, is attempted to be increased by orienting the electron flow in the lower effective mass [0001] direction, then the leakage current in the oxide is increased by lowering the FN onset field to 4.8 MV/cm. The breakdown strength of the oxide is also reduced from 7.8 MV/cm to 6.3 MV/cm [13-14]. Since the oxide field is to be kept ideally around 2 MV/cm as the electron heating threshold in the SiO_2 with the MOSFET device in the ON state, therefore an attempt to increase the mobility is justified by fabricating the n-channel MOSFET on the (11$\bar{2}$0) surface. The properties of a Wurtzite GaN MOS device can be found similarly. Wurtzite GaN has an indirect bandgap of 5.1 eV, and the same transverse and longitudinal electron effective mass of 0.186m. The heavy-hole mass becomes 0.814m. The properties of a Si (100) MOS device have been reported by the author recently on similar lines as this article [15]. In truth, the properties of a MOS device on any parabolic semiconductor can be found similarly without fabricating it.

One thing can be said for sure about the surface FE mobility in MOSFETs. The interface states density at the oxide/semiconductor interface is a continuum of states in the bandgap. A larger bandgap will have a larger total number of interface states, resulting in lower surface FE mobility in the FET. Thus, 4H-SiC-

MOSFET with a 4H-SiC bandgap of 3.23 eV will exhibit a lower mobility than a Si-MOSFET with the Si bandgap of 1.12 eV at 300K, given that Hall electron mobilities in the semiconductors are comparable.

IV. Conclusions

It is concluded from the above research study that, if a 4H-SiC-MOSFET device is fabricated on the (11$\bar{2}$0) epitaxial surface rather than on the (0001) surface, then a higher surface FE mobility of electrons in the n-channel MOSFET can be obtained. However, the FN onset field is reduced to about 4.8 MV/cm from 5.6 MV/cm exhibiting higher leakage current in the oxide. 4H-SiC semiconductor has a reduced N_{id} of only 10.5/cm^3 in the [11$\bar{2}$0] direction. No correlation is found between N_{id} and the FN onset field in the MOS device on different semiconductors. As the minimum electric field in the oxide is to be kept ideally at 2 MV/cm as the electron heating threshold in the oxide, therefore fabricating the MOSFET on the (11$\bar{2}$0) surface is justified and technologically and economically advantageous.

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