Transactions on Engineering and Computing Sciences - Vol. 11, No. 6
Publication Date: December 25, 2023
DOI:10.14738/tecs.116.15906.
Chanana, R. V. (2023). The Discovery of the Universal Mass-Energy Equivalence Relation in Materials Having a Bandgap. Transactions on Engineering and Computing Sciences, 11(6). 19-23.
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The Discovery of the Universal Mass-Energy Equivalence Relation in Materials Having a Bandgap

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ABSTRACT

This article describes how the discovery of the universal mass-energy equivalence relation came about and tabulates the possible high, medium and low voltage Metal-Oxide-Semiconductor-Field-Effect-Transistors (MOSFETs) from different semiconductors which could be n-channel or p-channel devices. Some points are to be considered for the tabulated MOSFETs which are enlisted. The universal mass-energy equivalence relation is given as dE/E = dm/m where, E is the energy and m are the mass. The article is published elsewhere but the author feels the need to widen publicity.

Keywords: MOSFETs, Intrinsic defects, Semiconductors, Effective Mass, Tunnelling.

INTRODUCTION

The above discovery was made by the author during his research period from 2014 to 2021 on Metal-Insulator-Semiconductor (MIS) characterization with thermal silicon dioxide (SiO_2) as the insulator. It then took the form of electron and hole effective mass determinations in thermal SiO_2 and further a generalized band offset and effective mass determination technique named BOEMDET is concretized in the year 2023. This article reviews the research on the MOS devices utilizing the mass-energy equivalence relation and tabulates the possible MOSFETs that can be made out of many semiconductors in the present and future. One key outcome of the above discovery is that the properties of a MOS device can be found theoretically without having to fabricate the device, given the longitudinal electron effective mass in the semiconductor and its bandgap. This will save a lot of time, money and effort in this research area of MIS characterization.

THEORY

Five properties of a MOS device are: the conduction and valence band offsets at the oxide/semiconductor interface, the electron and hole effective masses in the oxide, the Fowler-Nordheim (FN) onset field in the amorphous oxide that is a measure of the leakage current in the oxide, oxide electrical breakdown strength, and the total intrinsic defects density in the semiconductor that indirectly determines the surface field-effect (FE) mobility in the MOSFET. These properties of a MOS device can be found theoretically starting with the known bandgap of the semiconductor and its longitudinal electron effective mass.

RESULTS AND DISCUSSIONS

The discovery mentioned above resulted from research studies in the years 2014 to 2021. Starting in 2014, the total intrinsic defects density N_{id} per cm^3 in semiconductors were

determined by adding the N_{id} term to the formula for charge neutrality in doped semiconductors. The intrinsic Fermi energy level in doped semiconductors E_i in eV was identified by the aligned E_i in thermal SiO_2 of an MIS device with the SiO_2 as an insulator. This alignment is due to charge neutrality. Since the electron effective mass in SiO_2 having a bandgap of 8.93 eV is 0.42m, therefore the position of E_i in SiO_2 is given by 8.93 x 0.42 = 3.75 eV below the oxide CB. If from the MIS characterization, one finds the conduction band offset (CBO) at the oxide/semiconductor interface then, the E_i in the semiconductor can be found by subtracting the CBO from 3.75 eV. Substituting E_i in the charge neutrality equation for a semiconductor gives the N_{id}, given the intrinsic carrier density and the bandgap in the semiconductor [1]. Results of N_{id} in Si, SiC polytypes, and Diamond semiconductors were found this way and corroborated with results in the scientific literature of N_{id} found by other methods [1]. Results of N_{id} on many other semiconductors were also found from the band offsets at the oxide/semiconductor interface. In some interfaces, the oxide was ALD Al_2O_3 with the E_i as 2.65 eV, and in others it was the thermal SiO_2 having an E_i of 3.75 eV. Reordering and corrections of the N_{id} data was performed in the subsequent research study [2]. One particular data of 2017 on 4H-SiC triggered the finding of the relationship between the E_i in the semiconductor and its bandgap. It was observed that the E_i in 4H-SiC of 0.97 eV below the CB when divided by the bandgap of 4H-SiC of 3.26 eV gave the relative longitudinal electron effective mass in 4H-SiC oriented in the [0001] direction. This was confirmed from the archival data on 4H-SiC band structure from the Ioffe Institute in Russia. Research continued further with this data at the back of the mind. In 2021, the linear model for the variation of semiconductor bandgap with high temperature was being studied [3]. To see the effect of the change in thermal energy on the mass of the electron in Silicon, the kinetic energy formula of $E = 0.5mv^2$ was differentiated which resulted in the relation of $dE/E = dm/m$. From this relation, the change in the electron mass due to a change in 400 K of temperature was found to be 9.2 %. It was also observed that the mass-energy equivalence relation has been discovered first by Einstein as $E = mc^2$ for relativistic masses m. Differentiating his relation once gives the same formula of $dE/E = dm/m$, meaning that the relation is a universal mass-energy equivalence relation applicable to other energy transformations also such as Nuclear and Chemical energies. It suddenly clicked that the same formula can be applied to the materials having a bandgap with the 0.297 data of 4H-SiC at the back of my mind. In semiconductors, dE is the differential potential energy from E_i to the CB of the semiconductor, E is the bandgap of the semiconductor as the total potential energy of the electrons, dm is the differential mass as the longitudinal electron effective mass in the semiconductor and m is the free electron mass. This fitted into the 4H-SiC data of 0.297 as dm/m. The discovery was made and was applied to Si (100) also where the longitudinal electron mass for one conduction valley was known to be 0.49m and the bandgap being 1.12 at 300 K gave dE as 0.55 eV below the Si CB. The above finding was elaborately studied on Si (100) MOS device and 4H-SiC MOS device and it was found that all the parameters of a MOS device can be found without fabricating the devices [4-5]. Further research papers were published finalizing the electron and hole effective masses in thermal SiO_2 as 0.42m and 0.58m respectively utilizing the above universal mass-energy equivalence relation [6-8]. A generalized band offset and effective mass determination technique called BOEMDET was put forth where the oxide bandgap and the electron and hole effective masses in the oxide are unknown and they are determined using the above technique with only the known slope constants of the Fowler-Nordheim (FN)

carrier tunneling currents through the n-type and p-type MOS devices in accumulation with the devices having metal gates [8]. Furthermore, possible MOSFETs on many semiconductors were researched on utilizing the universal mass-energy equivalence relation [4-5, 9-16]. The possible MOSFETs are tabulated in Table 1 below.

Table 1: Possible MOSFETs from different semiconductors having small, wide, and ultra-wide bandgaps

Semiconductor	Bandgap (eV)	Electron effective mass m_e. Hole mass $m_{h=}$ m-m_e	Position of E_i (eV) from the mass-energy equivalence equation dE/E=dm/m	CBO at the oxide/semi-interface = 3.75-E_i in semiconductor 3.75 eV = E_i in SiO_2	VBO at the oxide/semiconductor interface = 8.93-E_g-CBO	High (H), Medium (M), or Low (L) Voltage MOSFETs	n- or p-channel MOSFET
Si	1.12	0.49m	0.55	3.2	4.6	L and M	Both
4H-SiC	3.23	0.297m (0001)	0.96	2.785	2.915	H	n-FET
3C-SiC	2.38	0.062m (anomaly)	0.148	3.60	2.95	L and M	n-FET
Wurtzite GaN	4.7 (A-Valley)	0.202m	0.95	2.80	1.43	L and M	n-FET
1L-MoS_2	1.8	0.48m	0.864	2.886	4.24	L	Both
Bilayer Graphene	0.25	0.04m	0.01	3.74	4.94	L	n-FET
2H-GeC	2.5	? say 0.3m	0.75	3.00	3.43	M	n-FET
3C-GeC (Material does not exist yet)	1.8?	0.043m (possible anomaly)	0.0774	3.67	3.46	M	n-FET
Beta-Ga_2O_3	4.8	0.27m	1.3	2.45	1.68	H	n-FET
Diamond	5.5	0.43m	2.37	1.38	2.03	H	p-FET
Wurtzite AlN	6.28	0.33m	2.07	1.68	0.97	None	Too leaky

Points to consider in the Table 1 above:

1. The E_i in SiO_2 is found by using the universal mass-energy equivalence relation dE/E = dm/m. For SiO_2, E is 8.93 eV as the oxide bandgap and the relative electron effective mass dm/m = 0.42 giving dE as 0.42 x 8.93 = 3.75 eV. This is the position of E_i in SiO_2 below the oxide conduction band (CB).
2. If the hole effective mass in the semiconductor is large then an efficient p-channel FET cannot be made. The hole effective mass is m-electron effective mass. For example, the electron effective mass in Si for one conduction valley at 300 K is 0.49m. So, the hole effective mass is 0.51m. It is complementary. So, an efficient p-FET on GaN is not possible as the hole mass is 0.8m which is large and will provide low mobility of holes in the channel.
3. Fowler-Nordheim (FN) onset field in the oxide is 2 x CBO (or VBO) given in MV/cm, because the threshold for electron heating in the oxide is found to be 2 MV/cm-eV, where 1 eV is the energy required to create hot electrons in vacuum.
4. It can be observed that if one knows the bandgap of the semiconductor and the electron effective mass in the longitudinal direction of the field, then one can determine if a MOSFET is possible without fabricating the device.
5. There is an anomaly in the cubic 3C-SiC semiconductor that the electron effective mass in [100] direction for one valley as measured by the cyclotron resonance is 0.34m in place of 0.062m as obtained from the band offsets. This is possibly because of a high

density of defects of the order of $10^{33}/cm^3$ observed in 3C-SiC due to stacking faults that slows down the electron during the cyclotron experiment. This anomaly may exist in 3C-GeC semiconductor also if the material is ever created which does not exist yet.

6. For GaN, the position of E_i is 0.95 eV below the CB of GaN. Depending on the bandgap of the satellite valley, the effective mass may vary around the value of 0.2m for wurtzite GaN.

CONCLUSION

The above research and review enlist several possible MOSFET devices that can be made on different semiconductors having small, wide, and ultra-wide bandgaps in the present and future. The above knowledge will have to be supplemented with further experimental research on a chosen MOS device. This experimental research is presently on-going.

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