IOSR Journal of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 10, Issue 6 Ver. II (Nov. – Dec. 2018), 50-57
www.iosrjournals.org

Polysilicon and Metal-Gated N-Channel Grounded Si Mosfets As Devices To Characterise MIS Structures By The BOEMDET Technique

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Abstract: *The Si/SiO_2/poly-Si and Si/SiN/Al MIS structures have been characterized by biasing the FETs in strong inversion at Fowler-Nordheim (FN) fields. The gate tunnelling electron current and the substrate hole current due to anode hole injection over the anode barrier versus gate voltage characteristics of the FETs are used for this characterisation. The conduction band offset (CBO) and the valence band offset (VBO) determined for the Si/SiO_2/poly-Si device are 3.2 eV and 4.6 eV. The bandgap of the oxide is found to be 8.9 eV, and the electron and hole effective mases in the oxide are determined to be 0.42m and 0.58m respectively. The CBO and VBO of the Si/SiN/Al device are found to be 1.7 eV and 2.3 eV respectively, the bandgap of SiN is 5.1 eV, and the electron and hole effective masses in SiN are 0.44m and 0.56m, where m is the free electron mass. These values are correct to one decimal place for the offsets and bandgap and two decimal places for the effective masses.*

Keywords: *band offsets, bandgap, effective mass, FN-tunnelling,, metal-insulator-semiconductor*

Date of Submission: 04-01-2019 Date of acceptance: 21-01-2019

I. Introduction

MOSFETs in inversion, having thin oxides of 5 to 10 nm operate with FN injected electrons from the Si substrate into the oxide conduction band. The transport of electrons in the thin oxides is quasiballistic with the average electron energy, $E_{av} = q(\Delta V)$ [1]. They reach the polysilicon anode with an average energy greater than 5 eV in the oxide conduction band (CB), and cause impact ionisation creating hot holes. These hot holes go over the anode barrier of 4.6 eV into the oxide valence band (VB). Some of them get trapped into the oxide creating positive charge [1]. The hot holes follow the FN type exponential dependence as they drift through the oxide after coming into the oxide valence band [2-3]. The evidence for over the anode barrier hole transport is provided by the fact that for all the thin oxides of 5 to 10 nm, the hole injection in the oxide valence band occurs at the same gate voltage of 7.8 V [1] to 7.85 V [3]. The voltage correction factor of 1.06 V when added to this gate voltage [6, 9], makes the oxide voltage 8.86 V to 8.91 V, which is the bandgap of the oxide in terms of energy as 8.9±0.1 eV. So the holes are into the valence band at 8.86 V to 8.91 V from the gate, and drift through the oxide in the quasiballistic mode when the average electron energy is above 5 eV in the oxide CB. It is worth noting that the electron injection is at 5.7 V in the CB, which is 7.85-1.06-1.1 V [3].

The gate tunnelling electron current and the substrate hole current versus the oxide voltage characteristics are utilised to characterise the MIS structure, giving electron and hole barrier heights, bandgap of the oxide and the electron and hole effective masses in the oxide using the FN based Band Offset and Effective Mass Determination Technique (BOEMDET) [4-9]. Consider Fig.1 below showing the energy-band diagram of an n^+ polysilicon gated n-channel MOSFET which is grounded. It can be observed in the energy-band diagram that the positive bias at the polysilicon anode is V_G and the negative bias on the Si cathode is 0 V, or gnd. Also, the electron conduction is from CB of Si to CB of polysilicon by FN-tunnelling resulting in the conventional current from CB of polysilicon to CB of Si. The hole conduction is from VB of polysilicon to VB of Si over the hole barrier for thin oxides of 5 to 10 nm resulting in the conventional current in the same direction, as holes are positive charges. So, for both electrons and holes, the conventional current is from polysilicon to Si.

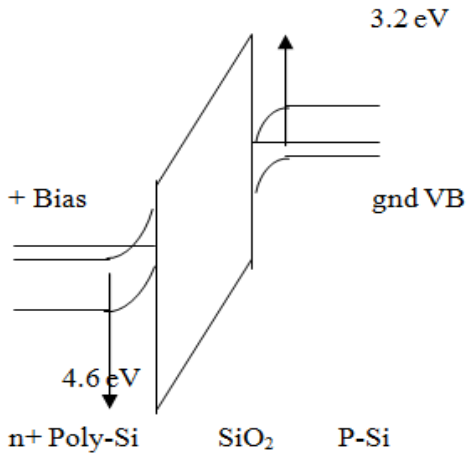

Fig.1. Energy band diagram of a n-channel Si MOSFET device in inversion.

The threshold voltage of a MOSFET is given by:

$V_T \approx V_{fb} + V_{sinv} - Q_d/C_i$, (1)

where V_T is the experimental threshold voltage, V_{fb} is the flatband voltage, V_{sinv} is silicon surface potential in inversion which is twice the bulk potential, Q_d is the depletion charge and is negative for n-channel MOSFET because of acceptor ions of the p-substrate and C_i is the insulator capacitance [10].

$V_T + Q_d/C_i \approx V_{fb} + V_{sinv}$ (2)

Now, the left side is experimental band bending of the silicon substrate and the right side is theoretical band bending in the silicon substrate. The left hand side is larger than the right hand side and should be used for the band bending in silicon [6, 9]. The experimental V_T is extrapolated from the MOSFET with fully formed channel due to electron inversion layer of about a 100nm. The theoretical V_T is the right hand side of the equation when the channel is at the onset of inversion. The MOSFET is at a high field region when V_{poly} depletion is maximum and equal to its bandgap value, say 0.97V with 5 x 10^19 Phosphorous atoms doping /cm^3, or 0.9 V with 10^20 P atoms doping/cm^3 or even 0.844 V with 1.5 x 10^20 P atoms doping/cm^3. The bandgap of polysilicon decreases from 1.12 eV due to band gap narrowing [11].

II. Theory

Fowler-Nordheim (FN) electron and hole tunnelling has been observed in Si and SiC MOS devices and in organic light emitting diodes [4, 5, 12-17]. The FN equation models the current-voltage characteristics across a MOS device at high fields. It is given by the classical equation [4]:

$$\frac{J}{E^2} = A\exp\left(\frac{-B}{E}\right)\ldots\ldots(3);$$

where J is the current density across the MOS device in A/cm^2, E is the oxide electric field in V/cm, and the pre-exponent A and the slope constant B are given by:

$$A = \frac{e^3 m}{16\pi^2 \hbar m_{ox} \phi_0}\ldots\ldots(4)$$

$$A = 1.54x10^{-6}\frac{m}{m_{ox}}\frac{1}{\phi_0}\ldots\ldots(A/V^2)$$

$$B = \frac{4}{3}\frac{(2m_{ox})^{1/2}}{e\hbar}\phi_0^{3/2}\ldots\ldots(5)$$

$$B = 6.83x10^7\left(\frac{m_{ox}}{m}\right)^{1/2}\phi_0^{3/2}\ldots\ldots(V/cm)$$

In A and B constants, e is the electronic charge, m is the free electron mass, m_{ox} is the electron or hole mass in the oxide, $2\pi\hbar$ is Planck's constant and ϕ_0 is the electron or hole barrier height expressed in electron volts. A plot of ln(J/E^2) versus 1/E, called an FN plot, gives the value of the slope constant B, from which $(m_{ox}/m)^{1/2}\phi_0^{3/2}$ product can be obtained. Then, with a known effective mass, ϕ_0 can be calculated, and with

a known ϕ_0, the effective mass in the oxide can be calculated. The slope constant B is very sensitive to the oxide field as it is in the exponential and therefore precise determination of the oxide field is absolutely critical in the evaluation of the tunnelling parameters. The ln (J/E^2) term is relatively much less sensitive to the oxide field as it is in the natural logarithm. The slope constant B can be independently used to determine the carrier effective masses, band offsets at the insulator-semiconductor surface and the insulator bandgap, without the knowledge of band offsets from photoemission spectroscopic measurements. This however is possible on the silicon substrate, where the grown or deposited dielectric film forms an abrupt interface and the intrinsic Fermi level of silicon lies very near the middle of its bandgap after the growth or deposition of the film due to negligible intrinsic defects in the silicon substrate. The slope constants for electron current B_e, and for the hole current B_h, can be obtained from the current-voltage characteristics of an n-channel MOSFET.

A. Modification of the FN slope constant equations for devices on silicon

It has been observed from a recent report of Ultraviolet photoemission and Inverse photoemission spectroscopic experiments on 2nm dry thermal SiO_2 [18], that the conduction and valence band offsets from the intrinsic silicon Fermi level are 3.8 eV and 5.1 eV respectively, and the bandgap of SiO_2 is 8.9 eV [19-21]. Taking the ratios of these values as 3.8/8.9 and 5.1/8.9 gives the electron and hole effective masses in the SiO_2 of 0.427m and 0.573m respectively. Within the experimental error of ±0.1 eV in the measurements of band offsets, the masses can be valued as 0.42m and 0.58m as reported earlier [4-9]. This ratio describes the ratio of the photo-emitted electron or hole kinetic energies during photoemission into the oxide conduction and valence bands as $\frac{0.5m_{ox,e}v^2}{0.5(m_{ox,e}+m_{ox,h})v^2}$ which equals $\frac{m_{ox,e}}{m}$, thus giving the ratio of electron effective mass to the sum of electron and hole effective masses. Here, v is the drift velocity of the electron or hole in the oxide. The sum of the electron and hole effective masses equals the free electron mass for the amorphous insulators [5], and therefore the band offsets to insulator bandgap ratio equals the relative carrier effective masses. Thus, the relative electron and hole effective masses $\frac{m_{ox,e}}{m}$ and $\frac{m_{ox,h}}{m}$ can be written as $\frac{(\phi_e+0.55)}{E_g}$ and $\frac{(\phi_h+0.57)}{E_g}$ when the insulator is grown or deposited on Si<100> or Si<111> surface. Here, ϕ_e is the electron band offset from silicon conduction band to oxide conduction band and ϕ_h is the hole band offset from the silicon valence band to insulator valence band and 0.55 and 0.57 eV are added respectively to coincide the band offsets from the intrinsic Fermi level of silicon. The intrinsic Fermi level E_i of silicon is given by:

$$E_i = \frac{E_c + E_v}{2} + \frac{kT}{2}\ln\left[\frac{N_v}{N_c}\right] \ldots\ldots(6)$$

where E_c is the bottom of the conduction band, E_v is the top of the valence band, N_c is the effective density of states in the conduction band, and N_v is the effective density of states in the valence band. N_c for silicon equals 2.8 x $10^{19}/cm^3$ and N_v equals 1.04 x $10^{19}/cm^3$ at 300K temperature [22]. Evaluating the above equation gives the position of intrinsic Fermi level of silicon about 0.01 eV above the middle of the silicon bandgap. Thus 0.55 eV is added to ϕ_e and 0.57 eV is added to ϕ_h for the conduction and valence band offsets from the intrinsic Fermi level of silicon. If B_e and B_h are the electron and hole tunnelling slope constants, then the slope constant equations can be written as below:

$$B_e = 6.83x10^7\left(\frac{m_{ox,e}}{m}\right)^{1/2}\phi_e^{3/2} \ldots(7)$$

$$B_h = 6.83x10^7\left(\frac{m_{ox,h}}{m}\right)^{1/2}\phi_h^{3/2} \ldots(8)$$

Substituting for $\frac{m_{ox,e}}{m}$ and $\frac{m_{ox,h}}{m}$, the equations become

$$B_e = 6.83x10^7\left(\frac{\phi_e + 0.55}{E_g}\right)^{1/2}\phi_e^{3/2}\ldots(9)$$

$$B_h = 6.83x10^7\left(\frac{\phi_h + 0.57}{E_g}\right)^{1/2}\phi_h^{3/2}\ldots(10)$$

$$E_g = \phi_e + \phi_h + 1.12\ldots\ldots(11)$$

The equations (9), (10), and (11) form three non-linear simultaneous equations with three unknowns that can be solved with a simple MATLAB software program or by trial and error for a given B_e and B_h values. This evaluation will result in the values of ϕ_e , ϕ_h and E_g. Following this evaluation, the band offsets from the intrinsic silicon Fermi level can be obtained. Further, the carrier effective masses and the unknown bandgap of the insulator can be determined. This technique of characterizing an MIS structure is called BOEMDET by the author [7, 8]. The character of an MIS structure can thus be described by the below mentioned Table as:

ϕ_e	ϕ_h	E_g	m_e	m_h

B. Calculation of the corrected Slope constants B_e and B_h

The corrected oxide voltages can be calculated as given in the above analysis. The slope constant B given in equation (5) is determined from the I-V characteristics using equation (3). First $\Delta ln\,(J/E^2)/\Delta\,(1/E)$ is calculated by taking at least two points on the I-V characteristics in the FN regime at high fields utilizing the applied gate voltage. This yields the uncorrected B. Next, the corrected B is calculated by dividing $\Delta ln(J/E^2)$ by$\Delta(1/E)$, with E obtained from the corrected oxide voltages corresponding to the same current density J as for the uncorrected B. It can be observed that $\Delta\ln (J/E^2)$ can be evaluated as $\Delta\ln (I/V^2)$ in the numerator without causing any error. This means that the area of the device can be ignored. However, the oxide thickness needs to be exact as it appears in the Δ (1/E) term in the denominator. A report highlights the importance of exact oxide thickness [23].

C. Polysilicon depletion voltage

Consider an$^+$ polysilicon gated n-channel MOSFET having substrate doping of $10^{16}/cm^3$ and a substrate bias of -1 V. The device has an experimental threshold voltage of 1.25 V, extrapolated from the MOSFET with the fully formed inversion channel of about a 100 nm as given in Fig.43 of reference 24[6, 24]. The depletion charge Q_d at the threshold voltage V_T is given by the equation

$$Q_d = -\sqrt{2q\varepsilon_s N_A(2\psi_b + V_{BS})} \qquad (12).$$

Here ε_s is the permittivity of Si, N_A is the silicon substrate doping, V_{BS} is the substrate bias, and ψ_b is the silicon bulk potential. If the MOSFET is grounded, then $V_{BS} = 0$. The equation for the insulator capacitance C_i is given as;

$$C_i = \frac{\varepsilon_0\varepsilon_r}{d} \qquad (13).$$

Here ε_0 is the free space permittivity, ε_r is the relative permittivity of the insulator which is 3.9 for SiO_2, and d is the thickness of the oxide. When the threshold voltage of the MOSFET having 50 nm oxide is 1.25V, Q_d/C_i is the voltage drop across the oxide and is calculated to be -1.09 V with no polysilicon depletion. Now, if no parameter of the device changes except reduction of the oxide thickness to 8.5 nm [2], then the Q_d/C_i at 1.25 V reduces to -0.19 V in magnitude. The change in Q_d/C_i goes into polysilicon depletion voltage of 0.9 V [6]. One can now consider a MOSFET having a substrate doping of $10^{17}/cm^3$ and an oxide thickness of 25 nm. This will give a threshold voltage of about 1 V with no polysilicon depletion, as can be seen in Fig.41 of the reference [24]. For this device, the change in Q_d/C_i when the oxide thickness reduces from 25 nm to 4 nm or 5.6 nm or 7.7 nm gives the polysilicon depletion voltage, which are calculated and presented in the Table I below [3, 24, 25]. It can be observed that for a given doping of the substrate of $10^{17}/cm^3$, Δ (Q_d/C_i) decreases with increasing thickness of thin oxides of 5 to 10 nm. This can be observed in columns 8, 9, and 10. The calculated and experimental values of polysilicon depletion voltages match very closely as can be seen in columns 8 and 9.

Table I. Polysilicon depletion voltage shown as $\Delta (Q_d/C_i)$ for MOSFETs having different substrate doping and oxide thickness. Two experimental values are compared with the calculated values.

1	2	3	4	5	6	7	8	9	10
Substrate doping, N_A, Ref.6,24	Q_d for MOSFET with 50 nm oxide and -1 V substrate bias (Coul/cm^2)	C_i for 50 nm oxide (F/cm^2)	Q_d/C_i for 50 nm oxide (V)	Q_d/C_i for 8.5 nm oxide (V)	$\Delta(Q_d/C_i)$ for 8.5 nm oxide with 50 nm oxide (V)				
10^{16}/cm^3	-7.55 x 10^{-8}	6.9 x 10^{-8}	-1.09	-0.19	0.9				
Substrate doping, N_A, Ref.24,	Q_d for MOSFET with 25 nm oxide and grounded substrate	C_i for25 nm oxide	Q_d/C_i for 25 nm oxide	Q_d/C_i for 4 nm oxide	Q_d/C_i for 5.6 nm oxide	Q_d/C_i for 7.7 nm oxide	$\Delta(Q_d/C_i)$ for 4 nm oxide with 25 nm oxide	$\Delta(Q_d/C_i)$ for 5.6 nm oxide with 25 nm oxide	$\Delta(Q_d/C_i)$ for 7.7 nm oxide with 25 nm oxide
10^{17}/cm^3	-1.66 x 10^{-7}	1.38 x 10^{-7}	-1.20	-0.19	-0.27	-0.37	1.01	0.93	0.83
Experimental values of Polysilicon depletion potential (V), Ref. 25							1.1 (measured from the published article)	0.91	

D. Oxide voltage derivation

In this article, the oxide voltage derivation is based on looking at how the electron and hole energies vary on the anode and cathode side when the MOSFET is biased in strong inversion at high FN fields. This approach is valid for thin oxides of 5 to 10 nm where the transport thought the oxide is quasiballistic and the average electron energy is related to the oxide voltage as $E_{av} = q\ (\Delta V)$ [1]. On the anode side, the electron energy to cross the CB is reduced by polysilicon depletion, so the voltage is reduced by V_{poly}, the voltage becomes V_G-V_{poly}, and the hole energy to cross the VB is increased by polysilicon depletion, so the voltage is increased by V_{poly}, the voltage for hole conduction becomes V_G+ V_{poly}. On the cathode side, the electron energy to cross the CB is increased by silicon band bending, so the voltage is increased by $V_T + Q_d/C_i$, from zero, and the hole energy to cross the VB is decreased by silicon band bending, so the voltage is decreased by the same amount from zero. So, the voltage is + ($V_T + Q_d/C_i$) for electron conduction, and - ($V_T + Q_d/C_i$) for hole conduction. The oxide voltage V_{ox} is the difference of the two voltages, that is, voltage at the anode minus the voltage at the cathode. So, V_{ox} for electron conduction is (V_G-V_{poly}) – (+(V_T+Q_d/C_i)), and V_{ox} for hole conduction is (V_G+V_{poly}) – (-($V_T + Q_d/C_i$)). Finally,

$$V_{ox} = V_G - (V_{poly} + V_T + Q_d/C_i) \quad (14)$$

for electron conduction, and

$$V_{ox} = V_G + (V_{poly} + V_T + Q_d/C_i) \quad (15)$$

for hole conduction.

V_G becomes $V_G - V_{BS}$ if a substrate bias is applied. Here, $V_T + Q_d/C_i + V_{poly}$ is the correction voltage in the oxide voltage. $V_T + Q_d/C_i$ for all MOSFETs having different substrate doping and having thick and thin oxides vary in the range of 0.15 to 0.19 as can be observed in the Table II below, and can be reasonably taken as 0.2 V [3, 24, 26]. The calculated V_{poly} varies from 0.83 V for the device with 7.7 nm oxide to1.01 V for the device with 4 nm oxide for a given substrate doping of 10^{17}/cm^3 as shown in Table I above. If V_{poly} is taken as 0.9 V for the device having substrate doping of 10^{16}/cm^3 and with 8.5 nm thick oxide, then the voltage correction factor becomes 1.06 V [6]. The oxide voltage correction factor becomes 0.98 V (1.0 V) for the MOSFET having 7.7 nm oxide as shown in the Table II below. V_{poly} variation of 0.2 V introduces uncertainty in the calculation of FN slope constants because the current density through the MOSFET is exponentially related to the slope constant. Therefore, a MOSFET with metal gates will remove this uncertainty because there is no polysilicon. So, for a MOSFET with metal gates, a correction by 0.2 V for ($V_T + Q_d/C_i$) remains as the only correction and the variation in correction is very small, from 0.15 V to 0.19 V. The equation for oxide voltage for a grounded MOSFET with metal gates becomes:

$$V_{ox} = V_G - 0.2 \quad (16)$$

for electron conduction, and

$$V_{ox} = V_G + 0.2 \quad (17)$$

for hole conduction. V_T, Q_d, and C_i can also be determined for the sample FET which is being used for MIS characterisation to find the correction voltage instead of taking it as 0.2V.

Table II. Silicon substrate band bending in row 3 and the oxide voltage correction in row 5 presented for MOSFETs having different substrate doping and having thick and thin oxides.

S.No.	Voltages (V)	MOSFET with 50 nm oxide and -1 V substrate bias and N_A = $10^{16}/cm^3$, Ref.24	MOSFET with 5 nm oxide and -1 V substrate bias and N_A= 2.67 x $10^{17}/cm^3$, Ref.26	MOSFET with 5 nm oxide and no substrate bias and N_A=2.67 x $10^{17}/cm^3$, Ref.26	MOSFET with 7.7 nm oxide and no substrate bias and N_A=$10^{17}/cm^3$, Ref.3
1.	V_T	1.25	0.81	0.58	
2.	Q_d/C_i	-1.09	-0.62	-0.43	
3..	$V_T + Q_d/C_i$	0.16	0.19	0.15	0.15(expected)
4.	V_{poly}	0.90	0.93	0.93	0.83
5.	$V_T + Q_d/C_i + V_{poly}$	1.06	1.12	1.08	0.98

III. Results and discussion

Gate voltage versus current data has been taken from Rasras et al [3] for a n^+ polysilicon gated n-channel grounded MOSFET having 7.7 nm SiO_2 as the gate dielectric. It is biased in inversion as shown in Fig.1 giving gate tunnelling electron current and substrate hole current by anode hole injection over the anode barrier through the oxide at high FN fields at which the B_e and B_h slope constants are calculated followed by MIS characterisation. The oxide voltages have been determined for electron and hole conduction with the voltage correction factor given as 1 V in the Table II above. The determined data after characterisation is presented in the Table III-V below. It should be noted that there could be small errors in reading voltage and current data from a published article.

Table III. Calculated slope constants from gate tunnelling electron current and substrate hole current versus oxide voltage characteristics at high oxide fields in a n^+ polysilicon gated n-channel MOSFET having 7.7nm thick SiO_2 as gate dielectric and grounded substrate [3].

Current type	$V_1/V_{ox,1}$ (V)	I_1 (A)	$V_2/V_{ox,2}$ (V)	I_2 (A)	Slope constant, B_e and B_h, (MV/cm)
Gate tunnelling electron current	8.0/7.0	10^{-8}	10.0/9.0	10^{-5}	262
Substrate hole current over the anode barrier	8.0/9.0	10^{-12}	11.0/12.0	10^{-7}	512

Table IV. Calculated band offsets, band gap of SiO_2 and carrier effective masses in SiO_2

Electron Band Offset, ϕ_e (eV)	Hole Band Offset ϕ_h (eV)	Bandgap of SiO_2, E_g (eV)	Electron effective mass in SiO_2, m_e	Hole effective mass in SiO_2, m_h
3.26 1	4.60 3	8.985	0.424m	0.576m

Table V. Calculated band offsets, band gap of SiO_2 and carrier effective masses in SiO_2

CBO to one decimal place (eV)	VBO to one decimal place (eV)	Bandgap to one decimal place (eV)	m_e to two decimal place	m_h to two decimal place
3.2	4.6	8.9	0.42m	0.58m

Gate voltage and current data from T.P. Ma's invited IEEE paper of 1998 on Jet Vapor Deposited (JVD) nitride containing grounded Al-metal-gated MNSFET is taken and the MNS structure is characterised. The data is presented in Tables VI-VIII. Equivalent Oxide Thickness (EOT) of the Nitride film is 5.2 nm [27]. The data is contained in Fig.13 of the reference. It can be observed in the figure that hole injection in the VB starts at 3.8 V and the electron injection in the CB starts at 2.5 V, which is (3.8-0.2-1.1) V.

Table VI. Calculated slope constants from gate tunnelling electron current and substrate hole current versus oxide voltage characteristics at high oxide fields in a metal- gated n-channel MNSFET having 5.2nm equivalent oxide thickness of nitride and grounded substrate [27].

Current type	$V_1/V_{ox,1}$ (V)	I_1 (A)	$V_2/V_{ox,2}$ (V)	I_2 (A)	Slope constant, B_e and B_h, (MV/cm)
Gate tunnelling electron current	3.3/3.1	10^{-10}	4.8/4.6	7 x 10^{-8}	105.34
Substrate hole current over the anode barrier	4.4/4.6	5 x 10^{-10}	4.7/4.9	2 x 10^{-9}	182.59

Table VII. Calculated band offsets, band gap of nitride and carrier effective masses in SiN

Electron Band Offset, ϕ_e (eV)	Hole Band Offset ϕ_h (eV)	Bandgap of JVD SiN, E_g (eV)	Electron effective mass in SiN, m_e	Hole effective mass in SiN, m_h
1.753	2.339	5.213	0.44m	0.56m

The above values are obtained by utilising the BOEMDET technique with 7 trials and error. This technique has the advantage of giving band offsets and bandgap values to two decimal places instead of one decimal place by the internal photoemission technique which has a resolution of ± 0.1 eV. There could be small errors in reading the currents and voltages from a published article.

Table VIII. Calculated band offsets, band gap of nitride and carrier effective masses in SiN

CBO to one decimal place (eV)	VBO to one decimal place (eV)	Bandgap to one decimal place (eV)	m_e to two decimal place	m_h to two decimal place
1.7	2.3	5.1	0.44m	0.56m

The above data matches very closely to the data of D.J. DiMaria and P.C. Arnett's article of June 1975[28], where the band offsets were determined by Internal Photoemission instead of FN tunnelling. They obtained CBO of 1.9 eV, VBO of 2.1 eV, E_g of 5.1 eV for Si/Si_3N_4 interface having a resolution of ±0.1 eV. It can be observed in Table VII, that the FN based BOEMDET technique can provide offsets and bandgap values to two decimal places or more.

A. Trial and error utilized in BOEMDET

The three simultaneous nonlinear equations (9), (10), and (11) can be reduced to two equations by substituting the value of $E_g = \phi_e + \phi_h + 1.12$ in the other two equations (9) and (10) and substituting the obtained values of B_e and B_h. Then the two equations obtained for the Si/SiN/Al device are:

$2.38(\phi_e + \phi_h + 1.12) = (\phi_e + 0.55)\ \phi_e^3$ (16)

$7.15(\phi_e + \phi_h + 1.12) = (\phi_h + 0.57)\ \phi_h^3$ (17)

Assuming a initial value of 0.5m for the electron effective mass and using the equation for B_e, we get ϕ_e=1.68 eV. So one can start with a guess ϕ_e=1.7 eV. With this ϕ_e, using equation (16), results in a value for ϕ_h. By substituting this value of ϕ_h in equation (17), again yields a value for ϕ_e. This value for ϕ_e should match the first value of ϕ_e=1.7. If it does not match, then in equation (16), we increase the guess value for ϕ_e, until it matches ϕ_e obtained from equation (17). After 7 trials, the value of ϕ_e obtained was 1.753 eV.

If a measurement technique has an established theory like the above, the accuracy of the measurements, or the uncertainty in the measurement can be reduced to minimum by invoking statistical parameters like mean and standard deviation. The data set of current and voltage used in the above study is just one set of measurements. Many measurements can be taken to reduce the percentage of error in the calculations of interface barrier energies and bandgap of SiN. Keeping the above in view, a Si MOSFET has the advantage that it can be used with all insulators with different bandgaps as the bandgap of Si is only 1.12 eV, but it is difficult to fabricate the device. MOS devices, both n- and p- type with metal gates are easier to fabricate and can be used with 4H-SiC[4, 5], but the bandgap of 4H-SiC is large and so only the insulators with bandgap larger than that of 4H-SiC, that is, larger than 3.23 eV and having at least 1 eV offset on either side can be characterised. Silicon MOS devices with poly-silicon carbide gates fabricated by laser ablation is an alternative, and all semiconductor/insulator interfaces can be characterised by the BOEMDET technique.

IV. Conclusion

The Si/SiO_2/poly-Si and the Si/SiN/Al MIS structures have been characterised utilising FETs biased in inversion at high FN fields. The CBO and VBO of Si/SiO_2 interface are 3.2 eV and 4.6 eV, the bandgap of SiO_2 is 8.9 eV and the electron and hole effective masses in SiO_2 are 0.42m and 0.58m, where m is the free electron mass. The CBO and VBO of Si/SiN interface are determined to be 1.7 eV and 2.3 eV, the bandgap of SiN is 5.1 eV, and the electron and hole effective masses in SiN are 0.44m and 0.56m. The use of metal gates in case of Si/SiN/Al device removes the uncertainty in the oxide voltages due to the absence of polysilicon depletion. The FN based technique that the author calls BOEMDET can be an accurate technique for MIS characterisation using grounded MOSFETs having thin oxides of 5 to 10 nm, where the experimental threshold voltage V_T, the depletion charge Q_d and insulator capacitance C_i can be determined for the individual sample FET to determine the oxide correction voltage. V_{poly} varies with the substrate doping. The technique falls alongside the internal photoemission technique and can provide band offset data to two decimal places.

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IOSR Journal of Applied Physics (IOSR-JAP) is UGC approved Journal with Sl. No. 5010, Journal no. 49054.

Dr. R. K. Chanana. "Polysilicon and Metal-Gated N-Channel Grounded Si Mosfets As Devices To Characterise MIS Structures By The BOEMDET Technique." IOSR Journal of Applied Physics (IOSR-JAP) , vol. 10, no. 6, 2018, pp. 50-57