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An Accurate Method for Extracting the Three Fowler-Nordheim Tunnelling Parameters Using I-V Characteristic

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Abstract In this work, we have developed an approach for determining the electrical Fowler-Nordheim parameters such as the barrier height (ϕ_0), the correction term (ΔV) relating to work-function differences between the oxide-facing surfaces of the "metal" gate and the semiconductor, and to any band-bending effects as well as the series resistance (R). In this method the barrier height has been extracted from both the classical parameters A and B in the case $\phi_{0B} = \phi_{0A}$. The correction term (ΔV) is considered as a parameter, not assumed or ignored. This method is proved to be useful and of a great interest after being tested.

Keywords MOS Device, Extraction, Parameters, Fowler-Nordheim

1. Introduction

The elementary structure used in the majority of electronic devices such as field effect transistors and EEPROM memories is the metal-oxide-semiconductor (MOS) structure[1]. A fundamental process in the description of the current–voltage (I–V) characteristic of a metal - oxide - semiconductor structure is the advent of Fowler –Nordheim (F-N) tunneling[2]. The F-N formula has been widely used to explain clearly the conduction behavior in the conventional SiO_2 films[3].Values for Fowler–Nordheim (F-N) tunnelling parameters, A and B, are important in the simulation of circuits where floating-gate transistors (FGMOS) are used, as they are related to artificial neural networks, pattern recognition circuits, offset trimming[4, 5]. The parameter B is mainly sensitive to the oxide field. Therefore, an accurate determination of the oxide field is necessary for the accurate determination of the parameters A and B. This will in turn give a correct value of barrier height. This can be done by choosing a thick oxide, and correcting the oxide voltage by the flat-band voltage[6]. The extraction of the F-N parameters is still under discussion, contributing to the extraction of theoretical and experimental parameters. Accurate knowledge of these parameters is necessary to explain the conduction in the conventional SiO_2 films. According to the F-N model[7], the current that flows through a thin dielectric layer when a field F is applied reads:

$$I = SJ_M = SAF^2 \exp\left(-\frac{B}{F}\right) \quad (1)$$

where S is the junction area, J_M is the average tunnelling current density, A and B are parameters given by[2-14]

$$A = a / \left(r_{ox}\, \phi_0\right) \quad (2)$$

$$B = b\,(r_{ox})^{1/2}\, \phi_0^{3/2} \quad (3)$$

where a[≅1.5414 μA eV V^{-2}] and b[≅6.8309 $eV^{-3/2}$ V nm^{-1}] are the Fowler-Nordheim Constants, ϕ_0 is the energy -barrier height for tunnelling from the cathode into the oxide. Equations (2) and (3) can be inverted to give

$$\phi_{0A} = a / (r_{ox} A) \quad (4)$$

$$\phi_{0B} = \left(B / b\right)^{2/3} r_{ox}^{-1/3} \quad (5)$$

In the context of MOS-type structures, the oxide field F is given by[8, 9]:

$$F = \left(V - \Delta V - RI\right) / t_{ox} \quad (6)$$

where t_{ox} is the oxide thickness, and V is the applied voltage between the conducting contacts to the "semiconductor" and to the "metal" (often really a n+ polysilicon) gate–taking the "metal" as the voltage reference zero. ΔV is a correction term relating to work-function differences between the oxide-facing surfaces of the "metal" gate and the semiconductor, and to any band-bending effects that may be

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present. R is the series resistance (in the electron path between the contacts) that is due to effects other than tunnelling.

In the literature, the "classical method" derives the barrier height, ϕ_0 from the parameter B because the parameter B is the dominant parameter determining the current flow in the gate oxide.

However, it is known that the value of B extracted from a F-N plot made in terms of the applied voltage V (rather than oxide field F) is affected by the values of the correction term (ΔV) (see Fig. 2) and by the series resistance (R)[8, 9]. Normally, the largest component in ΔV for thick oxides is the so-called "flat-band voltage" V_{FB}, which relates to the work-function differences between the oxide-facing surfaces of the "gate" and the "substrate". This flat-band voltage is determined by the band-structures of the gate and substrate, and is influenced by the presence of trapped charge. Generally, its value is extracted from capacitance voltage (C–V) measurement and depends on the manufacturing conditions of the device[15]. Accordingly, any device has its own correction term (ΔV).

In addition, the barrier height (ϕ_{0A}) extracted from the parameter A is very discrepancy than the extracted from the parameter B. A comparison between several values of ϕ_{0A} and ϕ_{0B} previously published is presented in Table 1. From the listed values, the barrier heights (ϕ_{0A} and ϕ_{0B}) obtained for each device are significantly different.

Table 1. Comparison between several values of ϕ_{0A} and ϕ_{0B} previously published in the literature

A (μA/V^2)	B (V/nm)	r_{ox}	ϕ_{0A} (eV)	ϕ_{0B} (eV)	Ref
1.07	23.73	0.50	2.87	2.89	[12]
1.469	21.14	0.35	2.99	3.01	[5]
0.448	25.8	0.50	6.87	3.06	[11]
0.0003	6.49	0.50	10266.66	1.21	[4]
0.178	23.8	0.50	17.03	2.89	[9]

In the literature, and when using the "classical method", the correction term ΔV is often assumed or ignored during the extraction of ϕ_{0B} . Chiou[11] in his work, reported that a difference of 0.95 V in V_{FB} leads to the change of 25 % in the parameter B. So, the value of ϕ_{0B} has changed drastically. This consistency issue raises serious question on the validity of ϕ_0 extracted using the "classical method".

In conclusion, the accurate knowledge of the value ΔV and R is very important for determining the oxide field, and hence the barrier height ϕ_0 . In this study, by taking into account all the concerns mentioned above, we have proposed a simple method for extracting the Fowler-Nordheim parameters from I-V characteristic. This method uses both parameters A and B at the same time and improves the "classical method" which is based on the parameter B only. In order to show the methodology of our proposed method, we used experimental data published previously[8]. In this experimental study, MOS capacitors with oxide thickness t_{ox} = 4.9 nm and square areas (S) ranging from 10^{-5} to 10^{-3} cm^2 were used. The substrate is p-type (100) Si with a doping concentration of about 10^{15} cm^{-3}. The oxidation was carried out in a dry N_2/O_2 atmosphere at 800°C. Poly-Si gates 350 nm-thick were deposited by LPCVD and subsequently n^+ doped by $POCl_3$ diffusion at 900°C. Measurements were performed at room temperature and dark conditions. Negative voltages were applied to the gate with the substrate contact grounded (for more details see[8]). The typical I–V characteristics for different gate areas ranging from 10^{-5} to10^{-3} cm^2 are shown in Fig. 1.

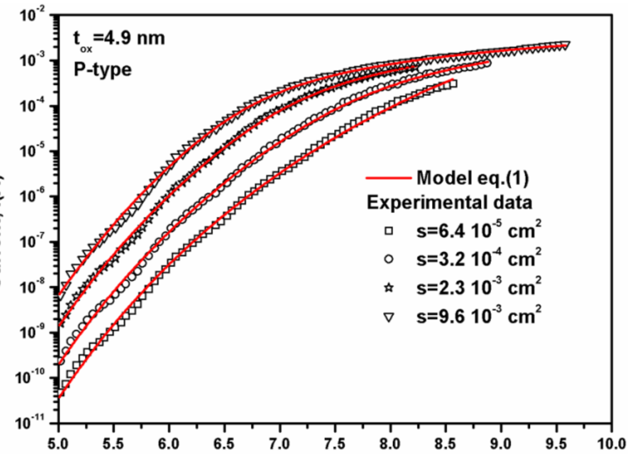

Figure 1. Current–voltage characteristics (from reference[8]) for different gate areas ranging from 10^{-5} to 10^{-3} cm^2. The symbols correspond to the experimental data whereas the solid lines correspond to the simulated I–V curves using eq.(1) with our extracted parameters reported in the table 2

Fig. 2 shows the influence of the correction term ΔV on the F-N plot, and hence on the parameters A and B. However, the linear relation in F-N plots is unaffected.

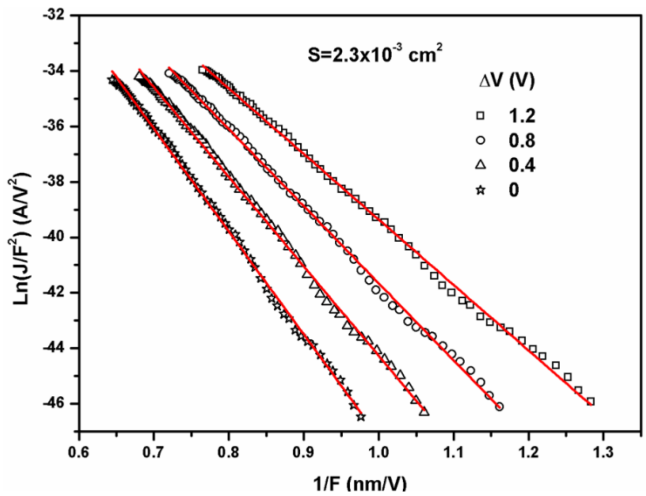

Figure 2. The effect of uncertainty of the correction term ΔV for the gate area S=2.3x10^{-3} cm^2 with R=883 Ohm

2. Intersection Point Method (IPM)

This method is based on the Fowler-Nordheim plot. The idea of this approach is very simple. For each given resistance (R) we follow these two steps:

1- First, we vary the flat band voltage, then we extract the two barrier heights ϕ_{0B} and ϕ_{0A} from the parameters B and A respectively by using a linear least-squares fitting procedure of the transformed data $\left(1/F, Ln(I/SF^2)\right)$. The convergence of the first step of the program occurs when the two barrier heights are equal ($\phi_{0A} = \phi_{0B}$). The simple least squares regression model determines the straight line that minimizes the sum of the square of the absolute errors. It can be shown that this occurs when the slope B of the line and A the y-axis intercept are given by[16]

$$B = \sum_{j=1}^{N}\left(x_j - \bar{x}\right)\left(y_j - \bar{y}\right) / \sum_{j=1}^{N}\left(x_j - \bar{x}\right)^2 \qquad (7)$$

$$A = \bar{y} - B\bar{x} \qquad (8)$$

where $\bar{x}, \bar{y}$ are the mean of the measured x and y data and N is the number of data pairs (x_j, y_j). In our case Ln(I/SF^2) represents y axis and 1/F represents x axis.

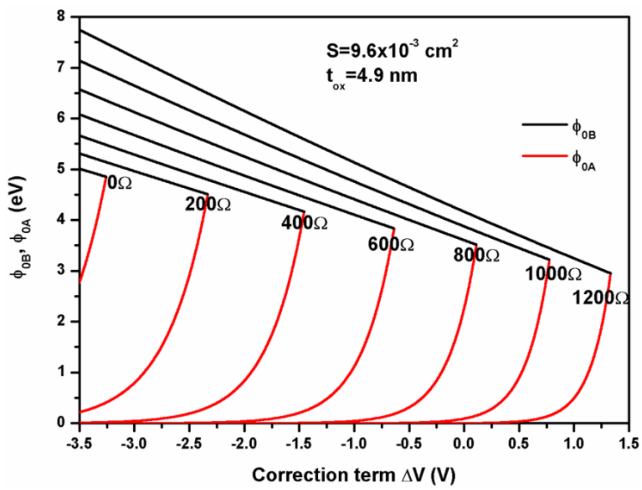

Figure 3. Intersection of the two curves of ϕ_{0A}, ϕ_{0B} against the correction term (ΔV) at various resistances for the MOS structure area S=9.6x10^{-3} cm^2

Fig.3 shows the curves of ϕ_{0A} and ϕ_{0B} against the correction term (ΔV) at various resistances. The point of intersection of the two curves gives the two initial parameters ϕ_0 and ΔV in addition to the third initial (input) parameter R.

It is clear from this figure that the values of ϕ_0 and ΔV depend on the value of the resistance R. The barrier height, ϕ_{0B} varies slightly and linearly with ΔV whereas the barrier height ϕ_{0A} varies rapidly. This result confirms that the parameter B is predominant but is not sufficient to determine the barrier height ϕ_0. For this purpose, we need the parameter A to determine the correct value of barrier height ϕ_0. This occurs when the value of ϕ_{0A} equals ϕ_{0B}.

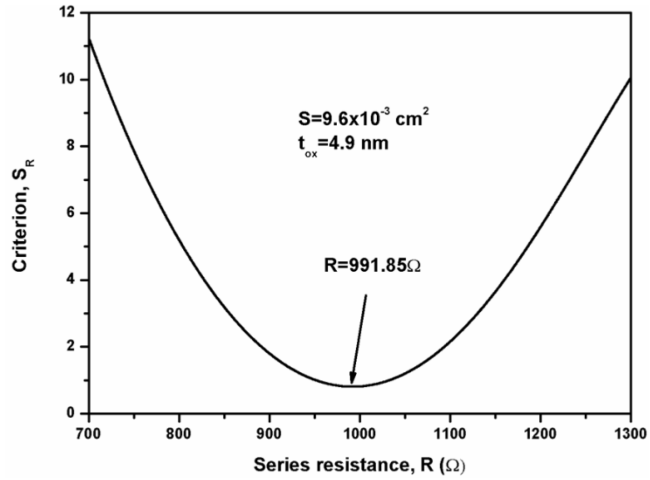

Figure 4. The sum of the quadratic relative errors against series resistance for the MOS structure area S=9. 6x10^{-3} cm^2. The effective mass of the electrons in the oxide has been assumed, m*= 0.5m

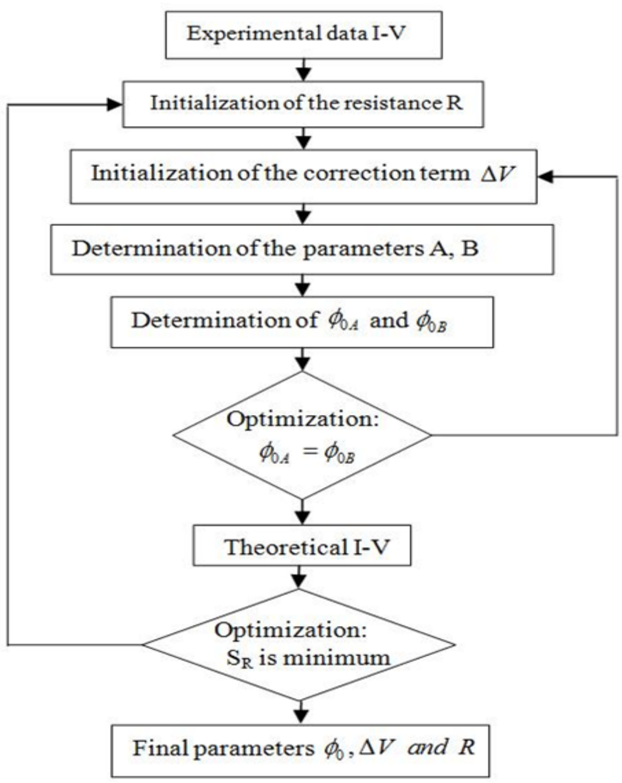

Figure 5. Algorithm for the determination of F-N parameters by the intersection point method

2-Secondly, in order to determine the best parameters (ϕ_0, ΔV and R) which verify the best fit of the experimental variables (I,V), we use the criterion (S_R) that presents the quadratic relative errors and should be minimum (Fig. 4).

This criterion was proposed for the first time by Osvald[17] for extracting the Schottky diode parameters from forward I-V characteristic.

$$S_R = \sum_{j=1}^{N}\left(\left(I_j^{th} - I_j^{\exp}\right)/I_j^{th}\right)^2 \qquad (9)$$

where $I_i^{\exp}$ is the ith experimental value, I_i^{Th} is the fitting value of the current, i.e. given by solving the equation (1) by using Newton's iteration method with the extracted initial values (ϕ_0 , ΔV and R) selected in the step 1. This second step is not necessary for thick oxides because the term "RI" in equation (6) can be ignored, as it is negligible compared to $(V - \Delta V)$. Fig .5 summarizes the methodology of F-N parameters extraction by the intersection point method.

The criterion S_R exhibits a minimum as a function of R, as clearly shown in Fig. 4. In the particular case under investigation (S=9.6x10^{-3} cm^2), the minimum of S_R corresponds to the extracted parameters: ϕ_0 = 3.228 eV, ΔV = 0.750 V and R = 991.85 Ω .

The extracted parameters for all gate areas are presented in Table 2 and plotted as a function of the gate area as shown in Fig.6 and Fig.7.

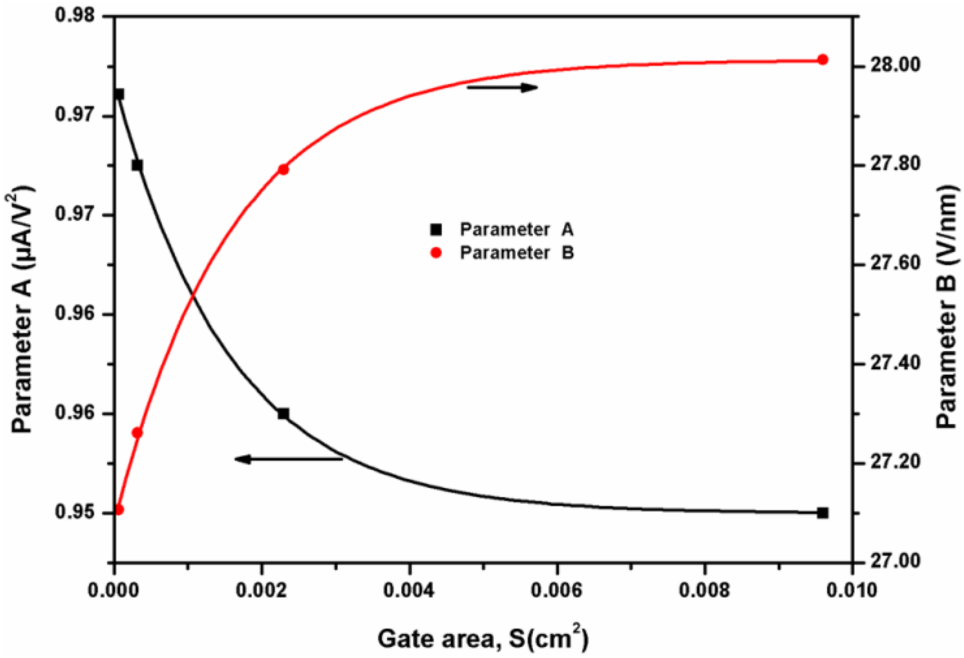

Figure 6. Extracted parameters, A and B as a function of the gate area

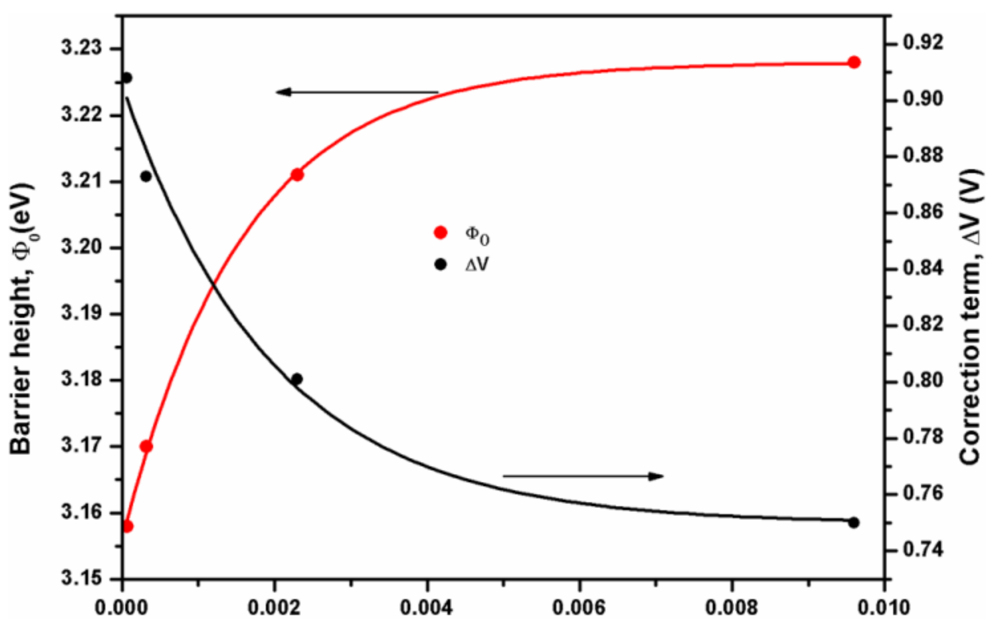

Figure 7. Extracted parameters ϕ_0 and ΔV as a function of the gate area

Table 2. Comparison between the parameters extracted by using our method and the classical method for the experimental I-V data scanned from reference[8]

	Intersection Point Method				Classical Method
Area(cm^2)	$6.4x10^{-5}$	$3.2x10^{-4}$	$2.3x10^{-3}$	$9.6x10^{-3}$	$9.6x10^{-3}$
A(μA/V2)	0.976	0.972	0.960	0.955	0.178
B (V/nm)	27.17	27.26	27.79	28.01	23.80
ϕ_0 (eV)	**3.158**	3.170	3.211	3.228	2.895
ΔV (V)	0.908	0.873	0.801	0.750	1.200
R (Ω)	150.83	691.82	883.20	991.85	952.30

The values of barrier heights extracted by using our method are close to the theoretical value 3.15 eV[10] and are different from the extracted barrier height using the classical method (2.89 eV). On the other hand, the values of correction term ΔV are different from the assumed value (1.2 V). If we accept that the intersection point method gives the exact parameters, the uncertainties of 10%, 60% and 4% in the barrier height, the correction term (ΔV) and the series resistance, respectively are estimated by the classical method for the MOS structure area S=$9.6x10^{-3}$ cm^2.

The barrier height (ϕ_0) and the parameter B are slightly increased with increasing the injection area, while the parameter A and the correction term (ΔV) are decreased with increasing the injection area. Croci[12] in his work concluded that the gate geometry, the substrate (p or n) doping type, the nature of the tunnel oxide and the gate structure affect the F-N tunneling parameters (A, B, ϕ_0), while this is not the case for the gate area.

By analyzing of the curves in the Fig.6 and Fig.7 we have found that all the parameters (A, B, ϕ_0 and ΔV) are varied exponentially with MOS structure area according to the following equation

$$y = y_1 \exp\left(-S / \alpha\right) + y_0 \quad (10)$$

The exponential coefficient α in the eq.(10) is the dominant parameter determining the evolution of the all parameters (A, B, ϕ_0 and ΔV). For the parameters A, B and ϕ_0 the coefficient α equals $1.57x10^{-3}$ cm^2 while for the parameter ΔV equals $1.96x10^{-3}$ cm^2. The parameter ΔV dependence on the gate area (decreases with increasing the gate area) can be probably explained by the trapped charge density that decreases with increasing the gate area. In turn, this trapped charge can be the origin of the increasing of the barrier height (ϕ_0) because the exponential coefficients α for both parameters ΔV and ϕ_0 are approximated.

3. Conclusions

In conclusion, a simple method for extracting the three Fowler–Nordheim tunneling parameters using I-V characteristic parameters MOS device: the barrier height (ϕ_0), the correction term (ΔV) and the series resistance (R) has been presented. Our method called Intersection Point Method (IPM) is based on the Fowler–Nordheim plot with the condition $\phi_{0B} = \phi_{0A}$. This method allows us to extract the correction term (ΔV) due to the flatband voltage and potential drops at the electrodes by using current–voltage (I–V) characteristics and not assumed or ignored. Determining the correction term and the series resistance leads to know with accurate the oxide electrical field value.

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