Modeling of Fowler-Nordheim current of metal/ ultra-thin oxide/ semiconductor structures

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In this paper we present results of a modeling of the current-voltage characteristics of metal/ultra-thin oxide/semiconductor structures with negatively biased metal gate (V<0), when the oxide thickness varies from 45Å to 80Å. We analyze the theoretical influence of the temperature and Schottky effect on the Fowler-Nordheim (FN) conduction. The results obtained show that these influences depend on the electric field in the oxide and on the potential barrier at the metal/oxide interface. At the ambient temperature, the influence on this potential barrier is lower than 1.5%. However, it can reach 45% on the pre-exponential coefficient of the FN current. It is therefore necessary to consider in the FN classical conduction expression a correction term that takes account the temperature and Schottky effects. These results are validated experimentally by modeling the current-voltage characteristics of the realized structures at high field,.

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I. INTRODUCTION

The elementary structure used in the majority of electronic devices such as field effect transistors and EEPROM memories [1,2] is the metal/ oxide/ semiconductor (MOS) structure. The reduction in dimension of this structure involves an oxide thickness lower than a hundredth of Angstrom, which introduces major reliability, as well as performance, problems. The impact of these problems is clearly observed on the electronic properties of MOS structures such as: Fowler-Nordheim (FN) conduction [3,4,5], destructive breakdown [3,19] and aging [20,21]. In the case of conduction, an important difference is observed between experimental and theoretical current-voltage characteristics.

In previous studies [3,4] we have analyzed in terms of the classical model of FN conduction [6-8], the current-voltage characteristics of MOS structures where the oxide thickness varies from 40 Å to 130 Å. From this model, we have extracted the conduction parameters: the pre-exponential factor K1 and the potential-barrier (Φ_m) at the metal/oxide interface. We have found that (Φ_m) is very close to the ideal value (3eV) [9] at high field when the oxide thickness is lower than 110Å, and both at high and low fields when the thickness is higher than 110 Å. However, for each structure the experimental value of K_1 is higher than the theoretical one. This disagreement is probably due to the fact that the theoretical model ignores a corrective factor due to the temperature and the lowering of the barrier in the oxide by the Schottky effect [7,10,11]. For thicknesses lower than 110Å and at low field, the experimental values for the conduction parameters are smaller than the theoretical values. We have attributed this result to the presence of an excess current, which is due to the degradation of the conduction properties by defects localized in the oxide layer.

In order to explain the disagreement between the experimental and the theoretical values of the prefactor K1, we analyze here the theoretical influence of the temperature and of the Schottky effect on the conduction under negative gate bias (V<0) from numerical simulations of the FN conduction using general models. We determine at the ambient temperature, the correction factor value due to the temperature and the Schottky effect of the classical model. Finally, we validate these results from experimental current-voltage I(V) characteristics.

II. EXPERIMENTAL PROCEDURES

The samples are capacitors made on P-type silicon wafers, <100> oriented, with a doping level (1-3) $x10^{15}$ cm^{-3}. The substrates are prepared by a standard procedure [12] including the growth of a sacrificial oxide of 3500 Å thickness followed by an attack and cleaning in a bath (HF/Ethanol) [13]. The growth of oxide is obtained in a chlorinated atmosphere diluted in Nitrogen at 900 °C, followed by an annealing at 1050°C in nitrogen[14]. A chromium gate is then deposited, etched and annealed at 450°C in a "Forming Gas". The capacitors areas S are equal to 10^{-6} cm^2.

The tests are carried out using capacitance-voltage C(V) [15] at 1MHz and 1KHz and I(V) [16] measurements. These measurements, which are made on several devices (about a hundred), enable us to obtain the oxide layer thickness (Dox), the silicon doping and the conduction mode. In previous studies presented in reference [22] we have shown a good reproducibility of the I(V) characteristics, demonstrating that the oxide thickness is uniform over the wafers.

The capacitance versus voltage C(V) was measured using an impedance analyzer HP4192A (Hewlett-Packard). The current-voltage I(V) measurements were taken using an HP4145A semiconductor parameter analyzer in the medium sampling mode.

III. RESULTS & DISCUSSIONS

A. THEORETICAL ANALYSIS

1. Classical model of Fowler-Nordheim conduction

For tunneling in the x-direction (figure1), the transmission coefficient T(Ex), a function of the x-component of energy E_x incident on the barrier at the metal/oxide interface, is given by the following expression[17]:

$$T(E_x) = \exp\left\{-2\int_{Xti}^{Xtx}\left(\frac{2\,m_{ox}}{\eta^2}\right)^{1/2}\left[(q\,\Psi(x)-E_x)^{1/2}\right]dx\right\} \quad (1)$$

where: m_{ox} is the effective mass of an electron in the oxide, h(η) is the (reduced) Planck constant, qΨ(x) is the potential barrier in the oxide layer at x abscissa, q is the electron charge, and X_{tx}-X_{ti} is the tunnel distance in the oxide layer (fig.1)[4]. In the absence of Schottky effect: X_{ti}= 0Å.
By summing up over all possible energy, the FN current density J_{FN} can be expressed in the following form[17] :

$$J_{FN} = \frac{4\,\pi\,q\,m_o}{\eta^3}\int_{E_x} T(E_x)\,dE_x \int_{E_x}^{+\infty} f(E_x,T)\,dE \qquad -2-$$

where m_o: free electron mass, T: temperature, f (E_x,T): Fermi Dirac function [11].

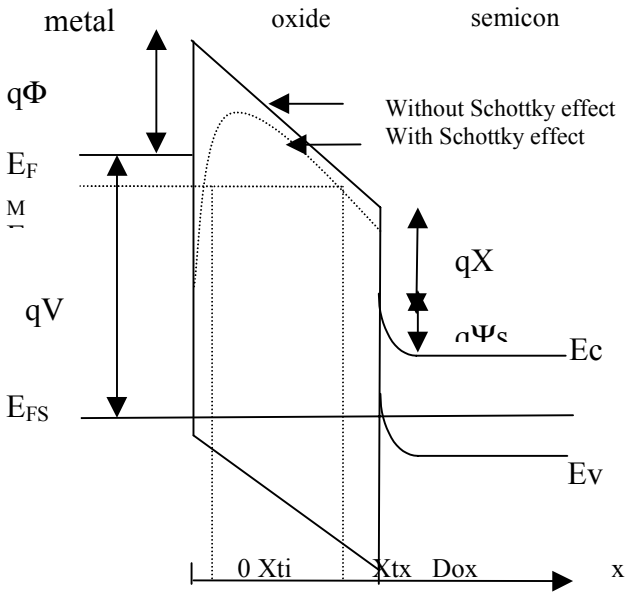

FIG. 1: Energy band diagram for metal/ oxide/ semiconductor with negatively biased metal gate (V), and without charge in the oxide layer.
where:
E_C: Energy level at the conduction band bottom,
E_v : Energy level at the valence band top,
E_{FS} : Semiconductor Fermi level,
E_{FM} : Metal Fermi level,
$q\Phi_m$: Potential barrier at the metal/oxide interface,
Ψs :Potential at the oxide/semiconductor interface in the semiconductor,
qX: Potential barrier at the oxide/semiconductor interface.

By using the Wentzel-Kramers-Brillouin (WKB) approximation, which ignores the temperature influence and the lowering of the barrier by the Schottky effect, the FN current density (expression 2) can be written as [6-8]:

$$J_{FN}^{o} = K_1^{o}\,Ei^2\exp\left(-\frac{K_2^{o}}{Ei}\right) \quad (3)$$

with: $$K_1^{o} = 1.5413\;\;10^{-6}\,\frac{m_o}{m_{ox}}\,\frac{1}{\Phi_m} \quad (4)$$

and $$K_2^{o} = 6.828\;\;10^{7}\,\sqrt{\frac{m_{ox}}{m_o}}\,\Phi_m^{3/2} \quad (5)$$

Where Ei is the electric field in the oxide layer[18] and Φ_m: potential barrier at the metal/oxide interface.

In the literature, relations 3-5 are generally used for characterizing the quality of the insulator layer from the FN plot of the experimental current-density Jexp. From these curves we have deduced by a fitting method [3,4], the conduction parameters K_1^{exp} (the intercept of the linear curve with the log(Jexp/Ei^2) axis and K_2^{exp} or the barrier Φ_m^{exp} (by the slope of Log(Jexp/Ei^2) as a function of 1/Ei)).
In figure 2 (curve a) we have presented, at the ambient temperature (300°K), the FN plot of the current density J_{FN}^{o} by taking a barrier height $q\Phi_m$ of 3eV [9] and an effective electron mass m_{ox}=0.5m_o [9].

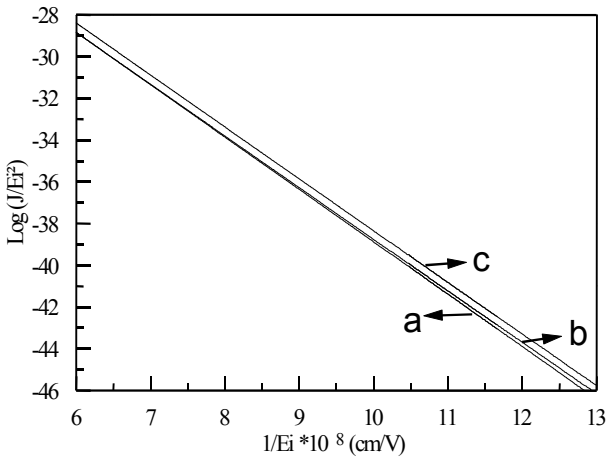

FIG. 2 : Theoretical Fowler-Nordheim plots of the current density J :
expression 3, (b) expression 2, (c) expression (1, 2 and 10).

2. Temperature Influence

The current density expression (relation 2) shows that the FN conduction depends on the temperature via the Fermi-Dirac distribution. On figure 2 (curve b) we have simulated at the ambient temperature, this relation using the same previous parameters. The curve obtained, compared to that plotted from the classical model (relation 3), shows an increase of the current density particularly at low fields, and straight line both at high ($1/Ei*10^8$ varies from 6.5 to 9 cm/V) and low fields ($1/Ei*10^8$ varies from 10 to 12.5 cm/V). By taking into account the temperature effect, the J_{FN}^{T} current-density can be written as a function of the field Ei and the barrier Φ_m^T :

$$J_{FN}^{T} = K_1^T\left(Ei,\Phi_m^T\right) Ei^2 \exp\left(-\frac{K_2^T\left(Ei,\Phi_m^T\right)}{Ei}\right) \qquad (6)$$

The extraction of the conduction parameters ($K_1^T\left(Ei,\Phi_m^T\right), \Phi_m^T$) at low and high fields shows on comparison with the previous results obtained without taking account of the temperature influence, that the effective barrier Φ_m^T decreases by 1.38% (0.97%) at low (high) field and that the pre-exponential factor K_1^T decreases by 32 % (20%) at low (high) field. These values show that the temperature influence on the conduction is more important at low field, particularly on K_1^T. However, the influence on the barrier at the metal/oxide interface is lower.

Using the classical model (relation 3) the correct expression of J_{FN}^{T} current can be written as :

$$J_{FN}^{T} = A^T\left(Ei,\Phi_m^T\right)K_1^o\left(\Phi_m^T\right)Ei^2 \exp\left(-\frac{K_2^T\left(Ei,\Phi_m^T\right)}{Ei}\right) \qquad (7)$$

where : $A^T\left(Ei,\Phi_m^T\right)$ is the corrective factor due to the temperature. It is given by:

$$A^T\left(Ei,\Phi_m^T\right) = \frac{K_1^T\left(Ei,\Phi_m^T\right)}{K_1^o\left(\Phi_m^T\right)} \qquad (8)$$

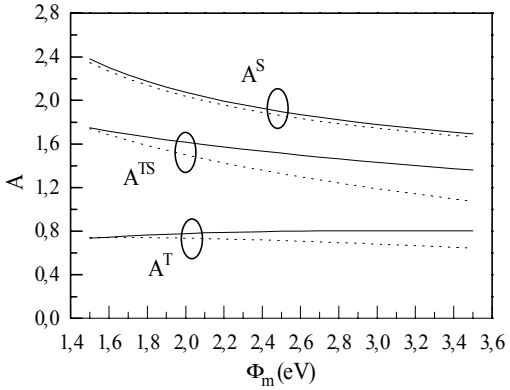

FIG. 3 : Influence of the potential barrier at the metal/oxide interface on the prefactors $A^T(Ei, \Phi_m^T)$, $A^{TS}(Ei, \Phi_m^{TS})$ et $A^S(Ei, \Phi_m^{TS})$. (------) low fields, (——) high fields.

Expression 7 can be given by :

$$J_{FN}^{T} = A^T\left(Ei,\Phi_m^T\right)J_{FN}^{o}\left(Ei,\Phi_m^T\right) \qquad (9)$$

This relation shows that the temperature influence on the FN current can be expressed by a correction of the classical current relation. As shown in figure 3 at the ambient temperature the corrective factor $A^T\left(Ei,\Phi_m^T\right)$ depends little on the barrier at the metal/oxide interface. In the case of a barrier of 3 eV, it is of the order of 0.681 (0.804) at low (high) field. The temperature effect requires one to introduce a correction term lower than 1. The increase of the FN current density is explained by a decrease of the effective barrier at the metal/oxide interface.

3. Schottky effect

In the oxide layer, the Schottky effect decreases the potential-barrier $\Psi(x)$ (see figure1) [11]. By introducing this effect, the potential barrier is given by [11] :

$$q\Psi(x) = q\Phi_m - \frac{q^2}{16\pi\varepsilon i\, x} - q\,Ei\,x \qquad (10)$$

where : εi is the oxide permittivity.

The current density J_{FN}^{TS}, including both the temperature and the Schottky effect, can be determined from relations (1,2,10). In figure 2 (curve c) we have presented the Fowler-Nordheim plot of J_{FN}^{TS} current density. It gives a linear behavior showing that J_{FN}^{TS}, including the temperature and Schottky effect, can be expressed in terms of the field Ei and the potential barrier Φ_m^{TS} at the metal/oxide interface as:

$$J_{FN}^{TS} = K_1^{TS}\left(Ei,\Phi_m^{TS}\right)Ei^2 \exp\left(-\frac{K_2^{TS}\left(Ei,\Phi_m^{TS}\right)}{Ei}\right) \qquad (11)$$

The extraction of the conduction parameters ($K_1^{TS}\left(Ei,\Phi_m^{TS}\right), \Phi_m^{TS}$) shows that the effective barrier Φ_m^{TS} decreases by 1.17% (0.71%) at low (high) fields, and the factor K_1^{TS} increases by 19 % (43%) at low (high) fields. Therefore, the Schottky effect is important, particularly on the pre-exponential factor K_1 at high fields. However, the influence on the barrier at the metal/oxide interface is lower. From the previous results the J_{FN}^{TS} current density can be written as :

$$J_{FN}^{TS} = A^S\left(Ei,\Phi_m^{TS}\right)A^T\left(Ei,\Phi_m^{TS}\right)K_1^o\left(\Phi_m^{TS}\right) \times Ei^2 \exp\left(-\frac{K_2^{TS}\left(Ei,\Phi_m^{TS}\right)}{Ei}\right) \qquad (12)$$

Where: $A^{T}\left(Ei,\Phi_{m}^{TS}\right)$ is a temperature and field dependence coefficient. It is given by:

$$A^{T}\left(Ei,\Phi_{m}^{TS}\right)=\frac{K_{1}^{T}\left(Ei,\Phi_{m}^{TS}\right)}{K_{1}^{o}\left(\Phi_{m}^{TS}\right)}, \qquad (13)$$

$A^{S}\left(Ei,\Phi_{m}^{TS}\right)$ is a Schottky effect and field dependence coefficient given by:

$$A^{S}\left(Ei,\Phi_{m}^{TS}\right)=\frac{K_{1}^{TS}\left(Ei,\Phi_{m}^{TS}\right)}{K_{1}^{T}\left(Ei,\Phi_{m}^{TS}\right)} \qquad (14)$$

Taking these coefficients into account, the current density J_{FN}^{TS} can be written as follows:

$$J_{FN}^{TS}=A^{TS}\left(Ei,\Phi_{m}^{TS}\right)J_{FN}^{o}\left(Ei,\Phi_{m}^{TS}\right) \qquad (15)$$

where :

$$A^{TS}\left(Ei,\Phi_{m}^{TS}\right)=A^{S}\left(Ei,\Phi_{m}^{TS}\right)A^{T}\left(Ei,\Phi_{m}^{TS}\right) \qquad (16)$$

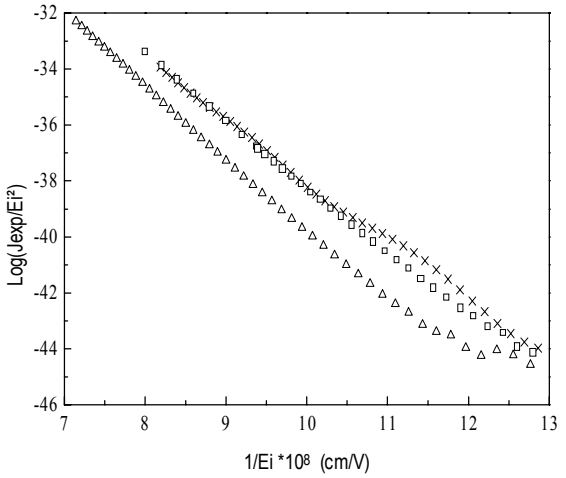

FIG. 4 : Fowler-Nordheim plot of the experimental current density (Jexp) according to the oxide thickness.
Dox (Å) : (x) 45, (□) 65, (Δ) 74
S (cm^2) : 1 10^{-6}

Relation 12 allows one to dissociate the temperature influence from the Schottky effect. The influence of the barrier at the metal/ oxide interface on these different factors ($A^{TS}\left(Ei,\Phi_{m}^{TS}\right)$, $A^{S}\left(Ei,\Phi_{m}^{TS}\right)$) (figure 3), shows that they increase with decreasing barrier. Since the factor ($A^{T}\left(Ei,\Phi_{m}^{TS}\right)$) depends little on the barrier, we could conclude that the factor ($A^{S}\left(Ei,\Phi_{m}^{TS}\right)$) due to the Schottky effect is important, particularly for the lower barriers.
At the ambient temperature, the correction term ($A^{S}\left(Ei,\Phi_{m}^{S}\right)$), corresponding to the Schottky effect, is of the order of (1.746) at low field and (1.779) at high fields. These values show that the Schottky effect is more important than the temperature effect (approximately double).
The term $A^{TS}\left(Ei,\Phi_{m}^{TS}\right)$ resulting from the temperature and the Schottky effect is of the order of (1.191) at low fields and (1.431) at high field. This indicates that the correction term of the classical FN current density cannot be neglected, in particular at high fields (Ei > 10 MV/cm).

B. EXPERIMENTAL RESULTS, VALIDATION OF THE THEORETICAL RESULTS

The typical FN plot of experimental current-voltage characteristics is presented in figure 4. It shows a linear behavior showing that the conduction is of FN type at low and high fields. The conduction parameter mean values (pre-exponential K_{1}^{exp}, barrier at the metal/ oxide interface Φ_{m}^{exp}) at low and high fields, are presented in table1. The error margin is about 0.8% for the barrier values and 14% for the K_{1}^{exp} values. For each structure, we have calculated the theoretical value of K_{1}^{0} from relation 4 by taking the experimental mean value of the barrier Φ_{m}^{exp} (see table 1).

At high field, the barrier values obtained Φ_{m} (≅ 3 eV) agree very well with those determined in the literature by neglecting the temperature and Schottky effects [9]. These values show, at the ambient temperature, that the influence of temperature and Schottky effect is low on the metal/oxide barrier, and confirm those obtained theoretically in paragraph III-1. However, in each case the pre-exponential K_{1}^{exp} values are higher than the theoretical values for K_{1}^{o}. This disagreement is due to neglecting the temperature and Schottky influences in expression 3. Thus, the experimental current Iexp is modeled by a relation including these two effects:

$$Iexp=S\,A_{exp}\left(Ei,\Phi_{m}^{exp}\right)K_{1}^{o}\left(\Phi_{m}^{exp}\right)\,Ei^{2}\exp\left(-\frac{K_{2}^{exp}\left(Ei,\Phi_{m}^{exp}\right)}{Ei}\right) \qquad (17)$$

Where: $A_{exp}\left(Ei,\Phi_{m}^{exp}\right)$ is a temperature and Schottky effect dependence factor. It is given by :

$$A_{exp}=\frac{K_{1}^{exp}\left(\Phi_{m}^{exp}\right)}{K_{1}^{o}\left(\Phi_{m}^{exp}\right)} \qquad (18)$$

By comparing the experimental (Table 1) and theoretical (section III-1-c) results, we conclude that at high fields, the mean experimental values A_{exp} are very close to the theoretical $A^{TS}\left(Ei,\Phi_{m}^{TS}\right)$. The error margin for A_{exp} is about 14%. This result shows on one hand the validity of the theoretical simulation, and

on the other hand that the model of the conduction by FN effect must take into account a corrective factor due to the temperature and Schottky effect.
At low field, the experimental parameter values are very low with respect to those calculated theoretically. The corrective terms due to the temperature and Schottky effects cannot explain the disagreement between the experiment and the theory. The FN current is degraded by the presence of defects localized in the oxide layer [3]: the defects decrease the potential barrier and particularly the prefactor K_1. Their characteristics such as potential barrier and effective area will be analyzed in the coming paper by modeling the excess current resulting from such defects.

	Dox (Å)	Φ_m^{exp} (eV)	K_1^{exp} x10^6 (A/V²)	K_1^0 x 10^6 (A/V^2)	A_{exp}
High fields	74	3.090	1.40	0.997	1.404
	65	2.955	1.40	1.040	1.346
	45	3.015	1.40	1.020	1.372
Low fields	74	2.885	0.075	1.060	0.070
	65	2.750	0.060	1.120	0.053
	45	2.800	0.085	1.100	0.077

Table 1 : Conduction parameters (K_1^{exp} , Φ_m^{exp}, A_{exp}) extracted from the experimental characteristics of figure 4.

IV. CONCLUSION

We have shown that the experimental Fowler-Nordheim conduction can be successfully modeled using an analysis that introduces correction factors due to the temperature influence and Schottky effect in the classical model. These two factors are field dependent. At the ambient temperature: for low fields the factor due to the temperature (Schottky) influence is of the order of 0.681 (1.746), and at high fields these parameters are of the order of 0.804 (1.779). The factor resulting from both the temperature and Schottky effect is approximately 1.191 (1.431) at low (high) fields. The variation of the effective barrier at the metal/oxide interface is less than 1.5%.

The modeling of the experimental current-voltage characteristics shows an agreement between the theoretical and the experimental correction factor values at high fields. At low fields, the experimental values are lower than those obtained theoretically, and cannot be modeled by the temperature and Schottky effect. This is attributed to the presence of excess current due to conduction degradation by the presence of defects in the oxide layer. The results concerning the excess current analysis will be published in other work.

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