RC22846 (W0307-128) July 15, 2003
Physics

IBM Research Report

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Remote Coulomb Scattering in Metal-Oxide-Semiconductor-Field-Effect Transistors: Screening by Electrons in the Gate

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(Dated: July 7, 2003)

Abstract

The effect of screening of Remote Coulomb Scattering (RCS) by free electrons in the polycrystalline silicon (polysilicon) gate of a Metal-Oxide-Semiconductor transistor has been analyzed. We have completed a previous model of RCS by adding the effects of the screening by electrons in the gate assuming a Thomas-Fermi dielectric function to take into account the response of the gate. A Monte Carlo simulator has been included in this model, in addition to phonon scattering, surface-roughness scattering and Coulomb scattering due to substrate impurities. Using this Monte Carlo simulator, we have evaluated mobility curves for different values of the oxide thickness. Although the RCS effect is certainly weakened by the screening, it is still quite important for very thin oxide layers ($T_{ox} \leq 1nm$), and therefore should be taken into account.

PACS numbers: 73.40.Qv, 72.20.Fr, 71.70.Fk, 72.10.Fk

The charged centers in the depletion region of the polycrystalline silicon (polysilicon) gate of a Metal-Oxide-Semiconductor-Field-Effect Transistor (MOSFET) provide a source of scattering which has been shown to strongly affect electron mobility when oxide layers thinner than 2nm are employed[1]. This is what has come to be called Remote Coulomb Scattering (RCS). Different studies and models have been presented in the last five years trying to shed some light on this issue[2],[3], [4], [5], [6],[7], but the actual effect of RCS is not still clear enough, either theoretically or experimentally. In fact, there is some controversy in the literature about the actual effect of RCS[7],[1]. Nevertheless, there is a common point to all the previous works published about RCS (with the possible exception of Ref. [8]); none of the previous theoretical works take into account the effect of the screening of RCS by the electrons in the gate. One of the present authors (M.V.F) has remarked on the importance of this effect[9]. Previous models [3], [5], [7] assume that the scattering centers in the depletion region of the gate are screened by the 2DEG, but not by the gate electrons. In typical cases, the gate "depletion" region is not, strictly speaking, "depleted", but simply exhibits an electron concentration lower than would be required by charge-neutrality, and should be viewed as a relatively thin region with a significant "average" density of free carriers. To quantify this charge, we have self-consistently solved the Poisson and Schroedinger equations in a MOSFET structure. In the following we shall consider a MOSFET structure consisting of degenerately doped n-type poly-Si for $-L_1 < z < 0$, an SiO_2 layer for $0 < z < L_2$ and a p-type Si substrate for $L_2 < z < L_3$. The substrate doping is taken as $N_A = 5 \times 10^{17} cm^{-3}$. Figure 1-a shows the charge concentration in a MOSFET structure for an oxide thickness of $T_{ox} = L_2 = 2nm$ and two values of the poly doping concentration: $N_{D-poly} = 1 \times 10^{20} cm^{-3}$ in solid line, and $N_{D-poly} = 1 \times 10^{19} cm^{-3}$ in dashed line. Figure 2 shows the concentration of electrons in the "depletion region" of the gate for the two values of the polysilicon doping considered. It is clear that the concentration of free carriers in the gate region near the poly/oxide interface is by no means negligible. On the contrary, a very important free carrier concentration appears near the poly/oxide interface for $N_{D-poly} = 1 \times 10^{20} cm^{-3}$. Such a high free carrier concentration could strongly screen the charged centers responsible for RCS (Figure 1) thus weakening the RCS strength. This means that the effect of the screening of poly-depletion charges by free carriers in the gate should be taken into account. Very recently, in Ref. [7] a comprehensive model for RCS scattering was developed[10] and [11]. Such a model takes into account the effects of image charges, screening by mobile carriers in the substrate, inversion layer quantization, the contribution of different subbands, oxide thickness, the actual distribution of charged centers inside the structure, the actual distribution of carriers in the inversion layer, the correlation of charged centers and the charged centers sign. We have now completed this model by adding to it the effect of the screening by mobile carriers in the gate. Following Equation 2 of Ref. [7], the Fourier transform of the potential fluctuations responsible for Coulomb scattering is given by::

$$V\left(\overrightarrow{\mathbf{Q}}, z\right) = -2\epsilon_{Si}\sum_i S_i \int_{-L_1}^{L_3} dz_1 G_Q\left(z, z_1\right) g_i\left(z_1\right) \int_{-L_1}^{L_3} dz_2 V\left(\overrightarrow{\mathbf{Q}}, z_2\right) g_i\left(z_2\right)$$

$$+\int_{-L_1}^{L_3} dz_1 G_Q\left(z, z_1\right) \rho'_F\left(\overrightarrow{\mathbf{Q}}, z_1\right) \qquad (1)$$

ρ'_F being the total external charge responsible for Coulomb scattering:

$$\rho'_F\left(\overrightarrow{\mathbf{Q}}, z\right) = \rho_{ext}\left(\overrightarrow{\mathbf{Q}}, z\right) + \sigma_{ss1}\left(\overrightarrow{\mathbf{Q}}\right)\delta\left(z\right) + \sigma_{ss2}\left(\overrightarrow{\mathbf{Q}}\right)\delta\left(z - L_2\right) \qquad (2)$$

where $\sigma_{ssi}\left(\overrightarrow{\mathbf{Q}}\right)$ $(i = 1, 2)$ is the Fourier transform of the charge density at the polysilicon-oxide interface and the oxide-silicon interface. $g_i\left(z\right)$ is the square of the electron envelope-function in the i-th subband, $\xi_i\left(z\right)$, and S_i the screening parameter[13],[11].

In Expression 1, $G_Q\left(z, z_1\right)$ are the Green's functions for the MOS geometry given by:

$$G_Q\left(z, z_1\right) = \frac{1}{2\epsilon_{poly}Q}e^{-Q|z-z_1|} + \left[\frac{A}{2Q} - \frac{1}{2\epsilon_{poly}Q}\right]e^{-Q(|z|+|z_1|)}$$

$$+\frac{A}{2Q}\frac{\epsilon_{ox} - \epsilon_{Si}}{\epsilon_{ox} + \epsilon_{Si}}e^{-Q(|L_2-z_1|+L_2+|z|)} \quad for \quad -L_1 < z < 0 \qquad (3)$$

$$G_Q\left(z, z_1\right) = \frac{1}{2\epsilon_{ox}Q}e^{-Q|z-z_1|} + \frac{A}{4Q}\left(1 - \frac{\epsilon_{poly}}{\epsilon_{ox}}\right)e^{-Q(|z|+|z_1|)}$$

$$+\frac{B}{4Q}\left(1 - \frac{\epsilon_{Si}}{\epsilon_{ox}}\right)e^{-Q(|L_2-z|+|L_2-z_1|)} + \frac{C}{4Q}e^{-Q[(L_2-z)+L_2+|z_1|]}$$

$$+\frac{C}{4Q}e^{-Q(z+L_2+|L_2-z_1|)} \quad for \quad 0 < z < L_2 \qquad (4)$$

$$G_Q\left(z, z_1\right) = \frac{1}{2\epsilon_{Si}Q}e^{-Q|z-z_1|} + \left[\frac{B}{2Q} - \frac{1}{2\epsilon_{Si}Q}\right]e^{-Q(|z-L_2|+|z_1-L_2|)}$$

$$+\frac{B}{2Q}\frac{\epsilon_{ox}-\epsilon_{poly}}{\epsilon_{ox}+\epsilon_{Si}}e^{-Q(z+|z_1|)} \quad for \;\; L_2<z<L_3 \tag{5}$$

where the coefficients A, B and C are given by:

$$A=\frac{2\left(\epsilon_{ox}+\epsilon_{Si}\right)}{\left(\epsilon_{ox}+\epsilon_{poly}\right)\left(\epsilon_{ox}+\epsilon_{Si}\right)-e^{-2QL_2}\left(\epsilon_{ox}-\epsilon_{poly}\right)\left(\epsilon_{ox}-\epsilon_{Si}\right)} \tag{6}$$

$$B=\frac{2\left(\epsilon_{ox}+\epsilon_{poly}\right)}{\left(\epsilon_{ox}+\epsilon_{poly}\right)\left(\epsilon_{ox}+\epsilon_{Si}\right)-e^{-2QL_2}\left(\epsilon_{ox}-\epsilon_{poly}\right)\left(\epsilon_{ox}-\epsilon_{Si}\right)} \tag{7}$$

$$C=\frac{2\left(\epsilon_{ox}-\epsilon_{poly}\right)\left(\epsilon_{ox}-\epsilon_{Si}\right)}{\epsilon_{ox}\left[\left(\epsilon_{ox}+\epsilon_{poly}\right)\left(\epsilon_{ox}+\epsilon_{Si}\right)-e^{-2QL_2}\left(\epsilon_{ox}-\epsilon_{poly}\right)\left(\epsilon_{ox}-\epsilon_{Si}\right)\right]} \tag{8}$$

Note that in the case $\epsilon_{ox}=\epsilon_{poly}$, and setting the origin at the oxide-silicon interface, the Green's functions (Equations 3-5) are reduced to Expression 11 of Ref.[11], corresponding to the previous scattering model with very thick oxide layers ($t_{ox}\rightarrow\infty$). It is easy to add the effect of screening by free carriers in the gate following this scheme. To add the effect of screening by free carriers in the gate we need only replace in expressions 6,7 and 8 ϵ_{poly} by $\epsilon_{poly}\left(\sqrt{2}Q,\omega\rightarrow 0\right)$, following Appendix B in Ref.[12].We have considered a Thomas-Fermi type dielectric function for $\epsilon_{poly}\left(\sqrt{2}Q,\omega\rightarrow 0\right)$[14]:

$$\epsilon_{poly}\left(\sqrt{2}Q,z\right)=\epsilon_{poly}\left(1+\frac{e^2 n_{poly}}{\epsilon_{poly}k_BT\left(\sqrt{2}Q\right)^2}\right) \tag{9}$$

k_B being the Boltzmann constant, e the electron charge, T the temperature and n_{poly} the average density of free electrons in the "depleted" region of the poly gate. Note that according to Expressions 3 to 8 electrons in the gate not only screen the charged centers due to the poly depletion, but also screen the impurities in the silicon substrate.

Figure 2 shows that the distribution of free electrons in the gate, $n_{3D}\left(z\right)$, is not uniform across the polysilicon depletion region. Since the treatment of the dielectric response of an inhomogeneous electron gas is a formidable problem still largely unsolved, different choices could be made to evaluate n_{poly}:

i) n_{poly} could be set equal to the electron concentration at the poly/oxide interface, i.e.,

$$n_{poly} = n_{3D}\left(z = 0\right); \tag{10}$$

as shown below, using the surface concentration will severely underestimate the mobility (as it will underestimate screening for most of the impurities).

ii) A second choice for n_{poly} could be the average of $n_{3D}\left(z\right)$ over the depletion region:

$$n_{poly} = \frac{\int_{-W_{depl}}^{0} n_{3D}\left(z\right)dz}{W_{depl}} \tag{11}$$

W_{depl} being the thickness of the polygate depletion region. This latter choice will overestimate the mobility (as it will overestimate screening of the impurities closer to the channel). These two approaches will "bracket" the actual effect of the screening. This is why we propose the following:

iii) A third choice for n_{poly} has been considered, in which the electron distribution is weighted with the net charge in the gate, $Q_{gate}(z)$:

$$n_{poly} = \frac{\int_{-L_1}^{0} n_{3D}\left(z\right)Q_{gate}\left(z\right)dz}{\int_{-L_1}^{0} Q_{gate}\left(z\right)dz} \tag{12}$$

Using a Monte Carlo simulator (detailed elsewhere) we have evaluated electron mobility taking into account the effect of RCS and the screening by the electrons in the gate. The different choices of n_{poly} have been considered. Phonon scattering, surface roughness scattering ($L_{sr} = 1.3nm$,and $\Delta_{sr} = 0.3nm$), and Coulomb scattering due to the impurities in the substrate have been considered ($N_A = 5x10^{17}cm^{-3}$). Figure 3 shows mobility curves versus the transverse effective field for two values of the silicon thickness, $T_{ox} = 1nm$, (upper graph)a and $T_{ox} = 5nm$ (lower graph). Dashed lines correspond to mobility curves when RCS is ignored, and solid squares correspond to mobility curves when screening by gate electrons is ignored. Curves with open symbols correspond to mobility curves taking into account RCS, and the different choices of screening by electrons in the gate. An immediate observation is that for $T_{ox} = 5nm$, the effect of RCS is negligible (as reported in Ref.[7]), and therefore screening hardly modifies the mobility curves. However, for $T_{ox} = 1nm$, the RCS effect is important, and therefore screening by electrons in the gate becomes noticeable. As mentioned above, when the first option is considered for n_{poly} (open triangles), the screening is underestimated and the electron mobility curve almost coincides with the mobility curve when screening is ignored. In contrast, when the second option is selected (open circles) the screening is overestimated, the scattering is strongly weakened, and the mobility curve in this case almost coincides with the mobility curve when the RCS effect is ignored. It can be seen that the mobility curve strongly depends on the choice of n_{poly} to evaluate the screening by electrons in the gate. It is expected that mobility curves obtained using the third choice would be nearer the actual result, since the electron distribution is weighted by the net charge in the depleted region, which is ultimately responsible for RCS. Finally, Figure 4 shows mobility curves taking into account the effect of RCS and the screening of the electrons in the gate using the third choice for n_{poly}, for different values of the oxide thickness. As can be seen, the separation between the mobility curves is now much less than when the screening by electrons in the gate is ignored. This curve gives us an idea of the actual dependence of the mobility on the oxide thickness. In summary, the effect of screening of RCS by free electrons in the polysilicon gate of a MOSFET has been analyzed. We have included the effect of screening by electrons in the gate on Remote Coulomb scattering due to the charges in the polysilicon depletion layer. Using a Monte Carlo simulator we have studied the effect of the screening by electrons in the gate, and we have seen that although the RCS effect is certainly weakened, it is still important for very thin oxide layers ($T_{ox} < 2nm$), and therefore should be taken into account.

This work has been carried out within the framework of Research Project No. TIC-2001-3243 supported by the Spanish Government.

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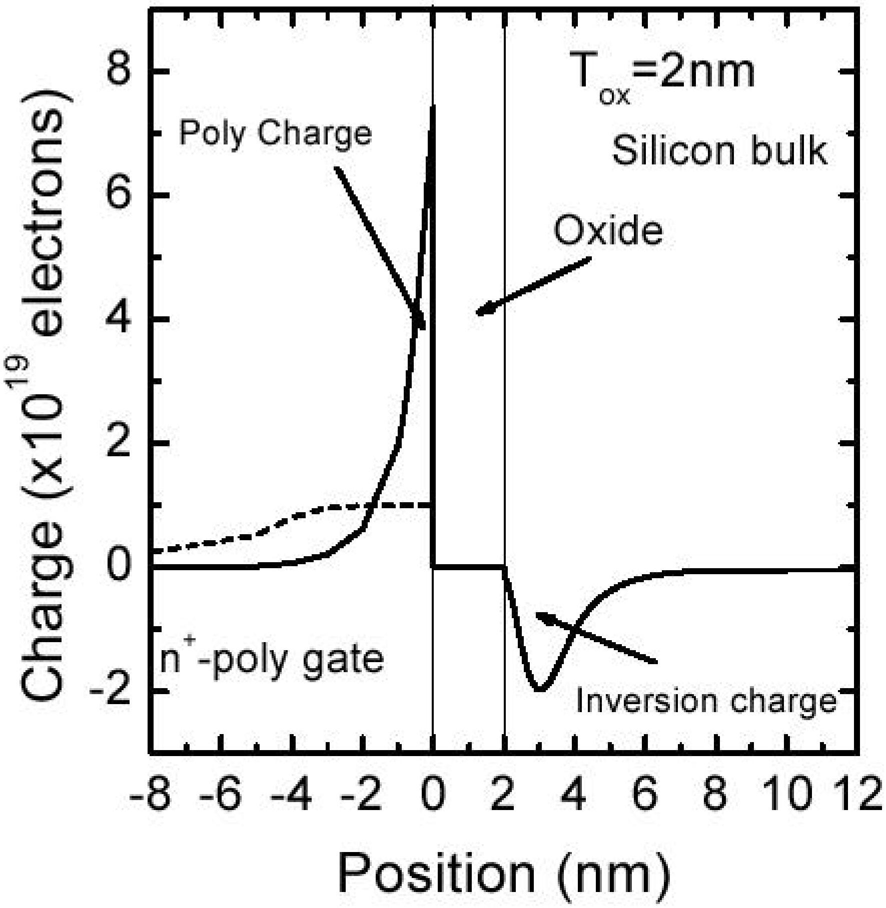

FIG.1.- Net charge distribution along a MOS structure for two values of the polysilicon doping concentration (dashed line: $N_{D-poly} = 1 \times 10^{19} cm^{-3}$; $N_{D-poly} = 1 \times 10^{20} cm^{-3}$). Inversion charge concentration set to $N_{inv} = 3.5 \times 10^{12} cm^{-2}$. (Substrate doping concentration: $N_A = 5 \times 10^{17} cm^{-3}$).

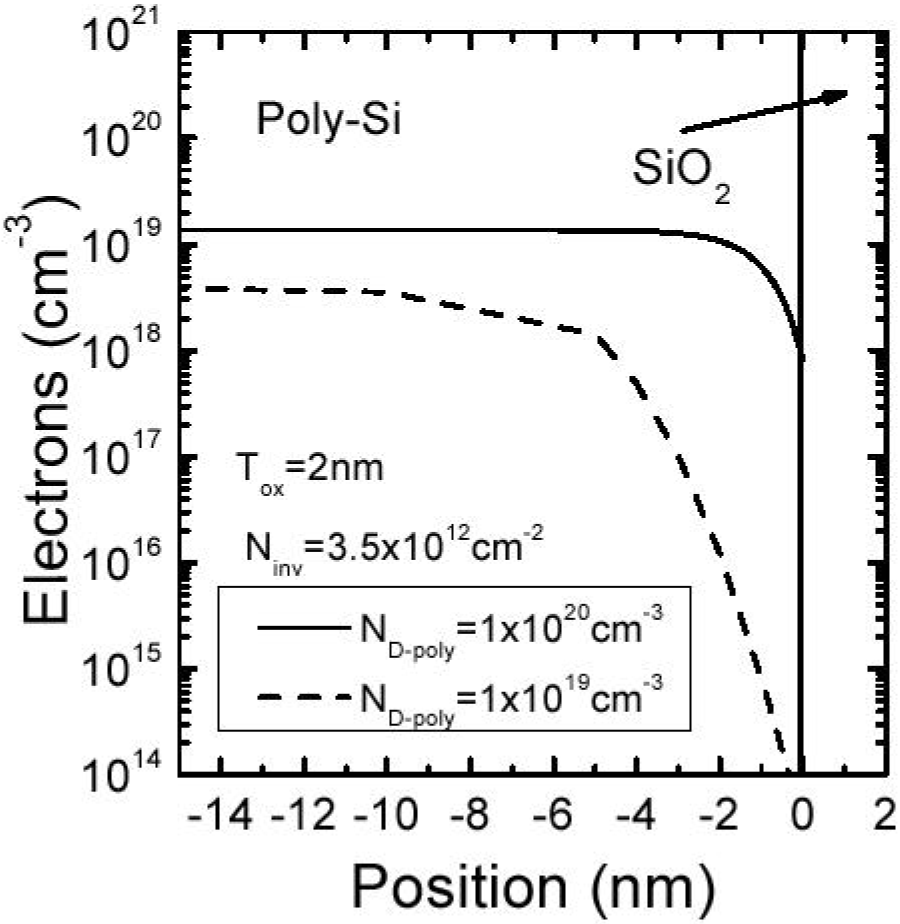

FIG.2.- Free electron concentration in the gate of a MOS structure (dashed line: $N_{D-poly} = 1 \times 10^{19} cm^{-3}$; $N_{D-poly} = 1 \times 10^{20} cm^{-3}$). Inversion charge concentration set to $N_{inv} = 3.5 \times 10^{12} cm^{-2}$. (Substrate doping concentration: $N_A = 5 \times 10^{17} cm^{-3}$).

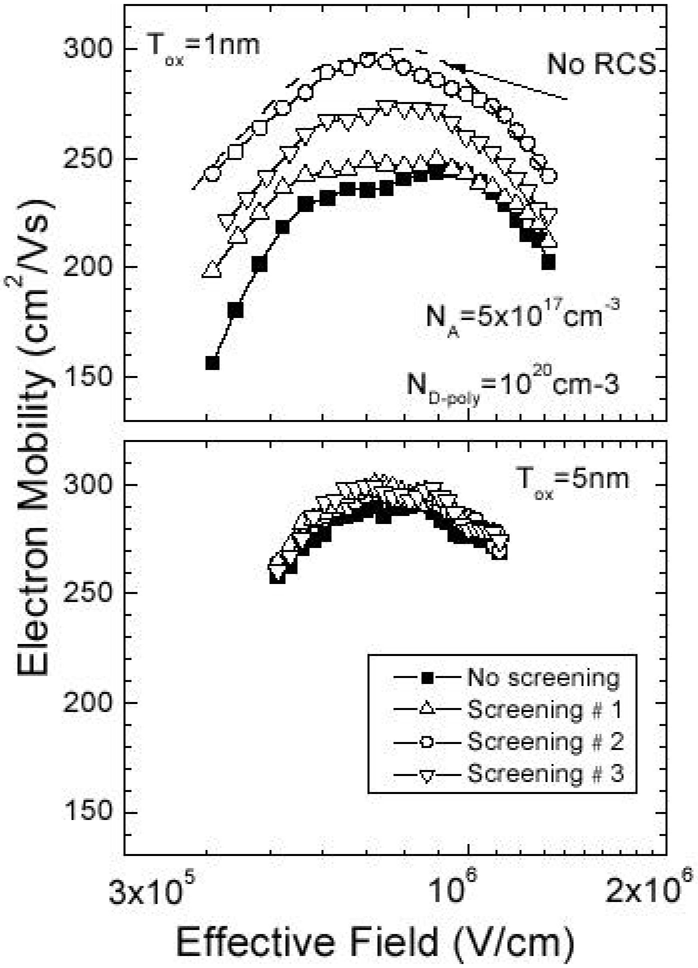

FIG.3. Electron mobility versus the transverse effective field for two values of the oxide thickness ($T_{ox} = 1nm$, upper graph, and $T_{ox} = 5nm$ lower graph). Phonon scattering, surface roughness scattering, and Coulomb scattering due to the ionized impurities in the silicon bulk and the RCS taking into account the screening due to the electrons in the gate, n_{poly}, for the different choices of n_{poly} (open symbols) are taken into account. For the sake of comparison a mobility curve is shown ignoring the effects of RCS (dashed line) and taking into account the effects of RCS but ignoring the screening by gate electrons (solid symbols). Polysilicon doping concentration was considered to be $N_{D-poly} = 1 \times 10^{20} cm^{-3}$.

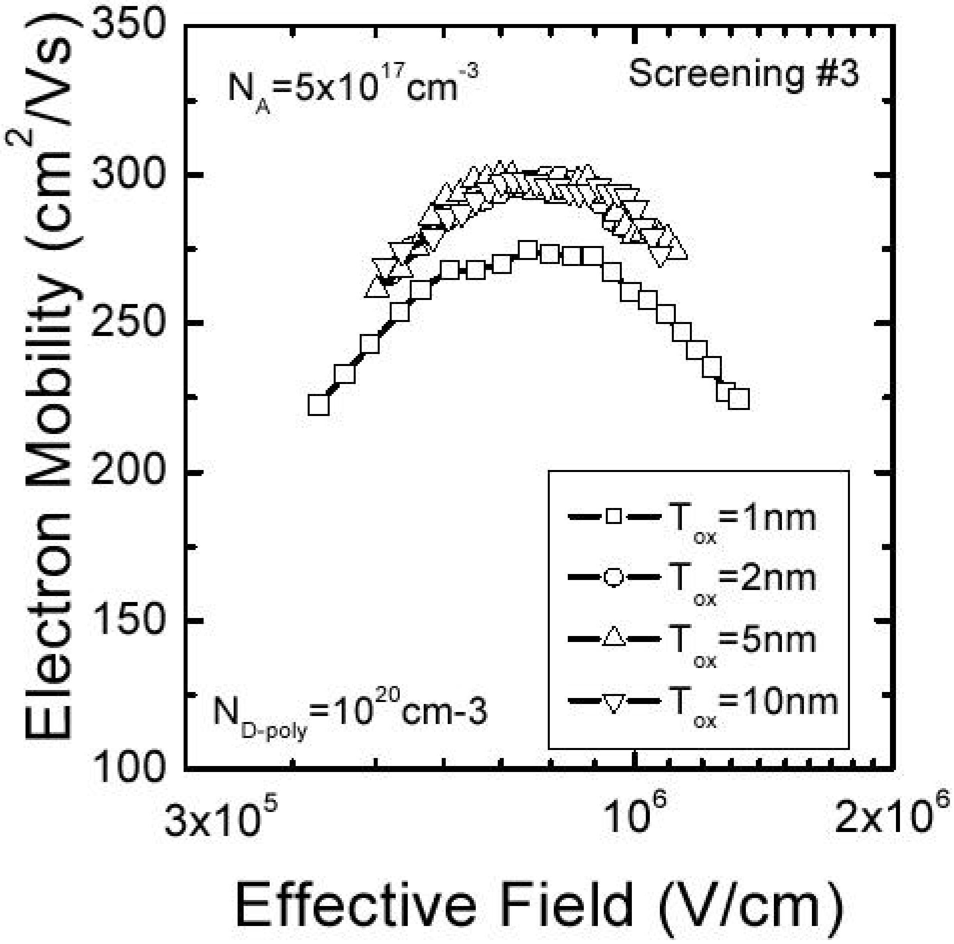

FIG.4. Electron mobility versus the transverse effective field for different values of the oxide thickness, taking into account the effect of RCS and the screening by the electrons in the gate using the third choice for n_{poly}.$(N_{D-poly} = 1 \times 10^{20} cm^{-3}, N_A = 5 \times 10^{17} cm^{-3})$