A new remote Coulomb scattering model for ultrathin oxide MOSFETs

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***Abstract*— We studied the effect of the depletion charge in the polysilicon gate on electron mobility in ultrathin oxide MOSFETs. An improved theory for remote-charge-scattering-limited mobility in silicon inversion layers has been developed. It is shown that if the oxide is thin enough the remote Coulomb scattering due to the depletion charge in the polygate becomes an effective scattering mechanism, whose effect is comparable to those of the main scattering mechanisms that control the movement of the carriers in the MOSFET channel. The model is implemented in a Monte Carlo simulator, where the effects of the ionized impurities charge in the substrate, the interface trapped charge and the contribution of other scattering mechanisms are taken into account simultaneously. Our results show that RCS cannot be neglected for oxide thicknesses below $2nm$, but that its effects for $t_{ox} > 5nm$ are negligible. Good agreement with experimental results was obtained.**

I. INTRODUCTION

In order to scale CMOS (Complementary Metal-Oxide-Semiconductor) devices to smaller dimensions while maintaining good control of the short-channel effects, the gate oxide thickness should be reduced in close proportion to the channel length [1]. Thus, for devices with gate lengths below $0.1\mu m$, gate oxides below $2nm$ could be needed. However, oxide scaling results in several effects that impose serial limitations on MOS devices [1], including an important degree of remote Coulomb scattering due to the poly-gate charge, which strongly degrades electron mobility, [2], [3], [4], [5], [6]. In this work we show the importance of the RCS effect on electron mobility. In particular, we find that, depending on the oxide layer thickness and the poly impurity concentration, this scattering mechanism could become as important as the main scattering mechanisms that control the transport properties of carriers in the MOSFET channel. An improved theory for remote-charge-scattering limited mobility in silicon inversion layers has been developed [7]. A Monte Carlo method is used to solve the Boltzmann transport equation (BTE) taking into account the effect of RCS mechanism. A detailed description of the Monte Carlo simulator can be found elsewhere [8]. The contribution of other scattering mechanisms (phonon scattering, surface roughness scattering and Coulomb scattering due to ionized bulk doping impurities and interface charges) is simultaneously taken into account. Prior to this, the one-dimensional Schroedinger and Poisson equations are selfconsistently solved in the whole structure, and the charge in the polysilicon carefully evaluated; thus we take into account the actual distribution of the charge in the polysilicon gate, instead of using the depletion approximation to evaluate the RCS rate. Using this remote-Coulomb scattering model (detailed in Ref. [7])in a Monte Carlo simulator, we made an extensive study of the effect of the polysilicon depletion charge on electron mobility. Section II discusses the effect of the poly depletion doping concentration and the role of the oxide thickness. The effect of the substrate doping is also analyzed. A comparison with experimental results is provided. Finally the main conclusions of our work are drawn in Section III.

II. SIMULATION RESULTS AND DISCUSSIONS.

A. Coulomb Scattering Rate

We employed the new remote-coulomb scattering model to study the effect of the poly-depletion charge and oxide thickness on electron mobility. The depletion charge distribution in the poly gate was calculated by solving the Poisson equation. Thus, the actual distribution of the charge in the poly is taken into account, for each value of the gate voltage, and each value of N_{D-poly}. The particular value of the poly-depletion layer thickness depends on the poly doping concentration and on the voltage applied to the gate. We observed that for the same value of inversion charge concentration (i.e. the same value of charge in the poly depletion layer) the lower N_{D-poly}, the wider the thickness of the depletion layer, and the lower the effect of RCS, i.e., the higher the electron mobility.

Unless otherwise stated, we considered a silicon inversion layer with the following parameters: substrate doping concentration $N_A = 5 \times 10^{17} cm^{-3}$, poly impurity concentration, $N_{D-poly} = 1 \times 10^{20} cm^{-3}$, and an interface trap concentration of $N_{it} = 5 \times 10^{10} cm^{-2}$ at the oxide/silicon and poly/oxide interfaces. Different values of the oxide thickness ranging from $t_{ox} = 1nm$ to $t_{ox} = 10nm$ are assumed. Figure 1 shows the Coulomb scattering rate for the electrons in the ground subband taking into account the poly depletion charge (solid line) and ignoring the effects of the poly depletion charge (dashed line). The contributions of the substrate doping charge ($N_A = 5 \times 10^{17} cm^{-3}$) and of the interface trapped charge ($N_{it} = 5 \times 10^{10} cm^{-2}$) are considered in evaluating the Coulomb scattering rate. In both cases, the effects of the oxide thickness and of the different dielectric constant between the oxide and the polysilicon are considered. Two values of the

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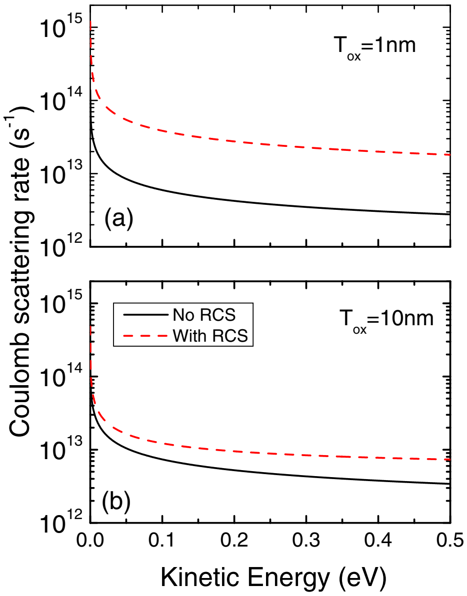

Fig. 1. Coulomb scattering rate for the electrons in the ground subband of a silicon inversion layer taking into account the poly depletion charge (solid line) and ignoring the effects of poly depletion charge (dashed line). The contribution of the substrate doping charge ($N_A = 5\times10^{17}cm^{-3}$), and the interface trapped charge ($N_{it} = 5\times10^{10}cm^{-2}$) was considered when the Coulomb scattering rate was evaluated. The poly doping concentration was assumed to be $N_{D-poly} = 1\times10^{20}cm^{-3}$. (a) $t_{ox} = 1nm$, (b) $t_{ox} = 10nm$.

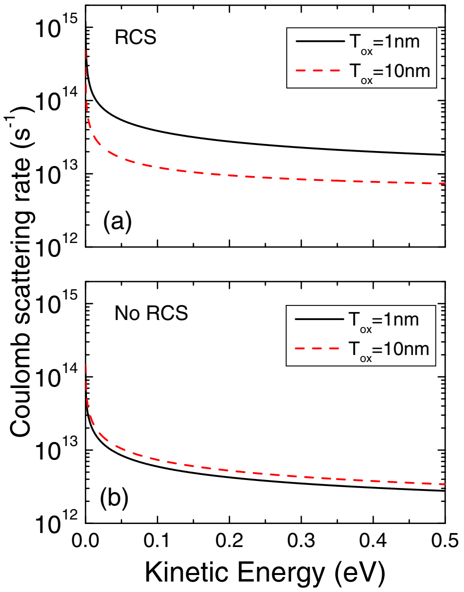

Fig. 2. Coulomb scattering rate for the electrons in the ground subband of a silicon inversion layer for two values of the oxide thickness $t_{ox} = 1nm$ (solid line) and $t_{ox} = 10nm$ (dashed line). The contribution of the substrate doping charge ($N_A = 5\times10^{17}cm^{-3}$), and the interface trapped charge ($N_{it} = 5\times10^{10}cm^{-2}$) has been considered to evaluate the Coulomb scattering rate. The poly doping concentration was assumed to be $N_{D-poly} = 1\times10^{20}cm^{-3}$.(a) The effect of RCS is considered. (b) The effect of RCS is ignored.

oxide thickness were considered, $t_{ox} = 1nm$ and $t_{ox} = 10nm$. Note that, as expected, the contribution of the poly charge coulomb scattering is more important as the oxide thickness decreases. Figure 1-a indicates that, for $t_{ox} = 1nm$, the RCS effect is more important than the Coulomb scattering rate due to substrate doping, even when, as in this case, N_A is very large.

Figure2 compares the Coulomb scattering rate for the two values of the oxide thickness considered taking into account the RCS effect (Figure 2-a) and ignoring its effect (Figure 2-b). Figure 2-a shows that the RCS effect is quite important as the silicon thickness is reduced, and thus the Coulomb scattering rate is higher for $t_{ox} = 1nm$ than for $t_{ox} = 10nm$. However, if we ignore the effect of RCS, and although the same substrate doping concentration and the same interface-trap density are used, the Coulomb scattering rate curves for the two oxide thicknesses do not coincide; surprisingly the rate curve corresponding to the thinnest oxide is lower than that corresponding to the thickest one. This fact is due to the effect of the finite size of the oxide (which is accounted for in the model developed. See Ref. [7]) and the different dielectric constant between the polysilicon and the oxide, which is responsible for an image effect at the interface between the polysilicon and the oxide.

B. Electron Mobility

1) Oxide Thickness: Using a one-electron Monte Carlo simulator, we studied the effect of RCS on electron mobility, for different values of the oxide thickness and different values of the poly doping concentration. The influence of other scattering mechanisms (phonon and surface roughness) and substrate doping impurities and interface trapped charges is also analyzed. The first factor to consider is whether, when the RCS contribution is ignored, mobility curves depend on the oxide thickness. For this purpose, Figure 3 shows electron mobility curves versus the transverse effective field for different values of the oxide thickness. Only phonon scattering and surface roughness scattering are taken into account in the curves with open symbols. Surface roughness parameters were assumed to be $L = 1.5nm$ and $\Delta = 0.185nm$. Coulomb scattering due only to substrate ionized impurities and to the interface traps (considered to be present at a concentration of $N_{it} = 5\times10^{10}cm^{-2}$) has been added in the curves with closed symbols. In this figure we see that when Coulomb scattering is fully ignored (i.e. only phonon scattering and surface roughness scatterings are taken into account) no dependence of the mobility on the oxide thickness is observed. However, and as previously discussed, when the effect of the Coulomb scattering due to substrate doping concentration is considered ($N_A = 5\times10^{17}cm^{-3}$), a very slight increase in electron mobility at low transverse electric

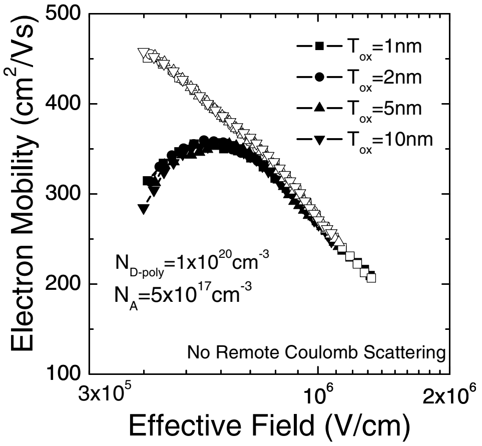

Fig. 3. Electron mobility curves versus the transverse effective field for different values of oxide thickness, ignoring the effects of RCS. Open symbols: only phonon and surface roughness scatterings are considered. Closed symbols: Coulomb scattering due to an interface trap concentration of $N_{it} = 5 \times 10^{10} cm^{-2}$ at the oxide/silicon interface and silicon bulk impurities ($N_A = 5 \times 10^{17} cm^{-3}$) are also considered.

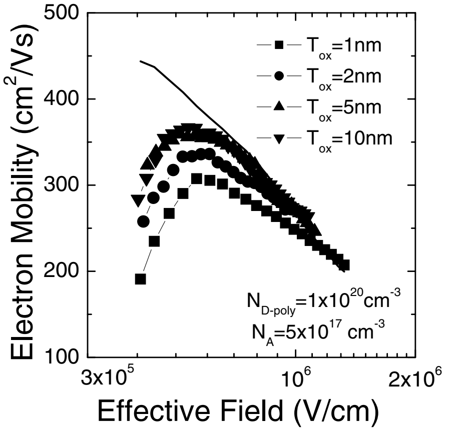

Fig. 4. Electron mobility curves versus the transverse effective field for different values of oxide thickness taking into account the effects of RCS ($N_{D-poly} = 1 \times 10^{20} cm^{-2}$). Phonon, surface roughness and Coulomb scattering are taken into account. An interface trap concentration of $N_{it} = 5 \times 10^{10} cm^{-2}$ at the oxide/silicon interface and silicon bulk impurities ($N_A = 5 \times 10^{17} cm^{-3}$) are also considered. For the sake of comparison, a universal mobility curve (only phonon and surface-roughness scattering) is added in solid line (no symbols)

fields is observed. Figure 4 shows the same mobility curves as in Figure 3, but taking into account the RCS effect. For the sake of comparison, a universal mobility curve (only phonon and surface-roughness scattering) is added in solid line (no symbols). The first fact to note is that, as expected, the mobility curve for $t_{ox} = 10nm$ (downward-pointing triangles) coincides with mobility curves when no RCS effect is taken into account (closed-symbol curves in Figure 3). However, as the oxide thickness is reduced the effect of RCS becomes more and more important (reaching 30% for $t_{ox} = 1nm$), mainly, as expected, at low transverse effective fields even for high concentrations of silicon bulk impurities. Mobility curves taking into account only the contribution of the poly depletion charge to the Coulomb scattering rate are shown in Figure 5 as a function of the oxide thickness. For the sake of comparison, a universal mobility curve (only phonon and surface-roughness scattering) is added in solid line (no symbols). As can be observed, the effect of the RCS for oxide thicknesses greater than $10nm$ is very weak (mobility curves almost coincide with the universal mobility curve in the whole electric field range.

2) Polysilicon doping concentration.: We also studied the effect of the concentration of impurities in the polysilicon. Figure 6 shows mobility curves versus the transverse effective field for different values of the poly doping concentration: closed squares: $N_{D-poly} = 1 \times 10^{19} cm^{-3}$, closed circles: $N_{D-poly} = 1 \times 10^{20} cm^{-3}$, and closed triangles: $N_{D-poly} = 1 \times 10^{21} cm^{-3}$. Two values of the oxide thickness were assumed (a) $t_{ox} = 1nm$ and (b) $t_{ox} = 10nm$.As seen, for the thicker oxide value no influence of the polysilicon doping concentration is observed, even for the higher poly doping concentration sample.However, in the case of the thinnest oxide ($t_{ox} = 1nm$), an important effect on the poly doping concentration is observed: the higher N_{D-poly} the lower the electron mobility. Figure 6-(a) shows a mobility curve ignoring the effects of RCS (open symbols). The comparison shows that even for the less doped polysilicon sample, the RCS effect is important when very thin oxides are used, and in consequence its effect should be taken into account.

3) Comparison with experimental results.: We compared our results with those available in the literature. Figure 7 shows the dependence of RCS-limited mobility on gate oxide thickness. RCS-limited mobility was obtained by calculating mobility curves but ignoring the effects of RCS (the polysilicon doping concentration is assumed to be $N_{D-poly} = 5 \times 10^{19} cm^{-3}$ in this figure) , and taking into account the RCS. The model developed here provides a better agreement with experimental results than do previous models.

III. CONCLUSIONS

In summary, we have shown that the combination of an ultrathin oxide and a very highly doped polysilicon gate causes an important degradation of the electron mobility in the channel, which should be taken into account. We have developed a RCS model which considers the effects of image charges, screening, 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. The model is implemented in a Monte Carlo simulator, where the effects of the ionized impurities charge, the interface trapped charge and the contribution of other scattering mechanisms are taken into account simultaneously. Our results show that RCS cannot be neglected for oxide thicknesses below $2nm$, even when

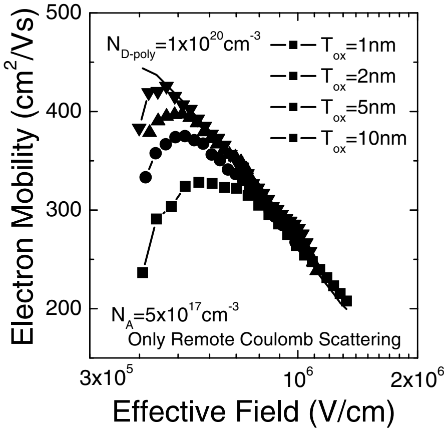

Fig. 5. Electron mobility curves versus the transverse effective field for different values of oxide thickness. Only the effects of RCS ($N_{D-poly} = 1 \times 10^{20} cm^{-2}$) are considered as Coulomb scattering source (i.e. substrate doping impurities and interface trapped charges are not taken into account in the evaluation of the Coulomb scattering rate). Phonon, surface roughness and Coulomb scattering are taken into account. ($N_A = 5 \times 10^{17} cm^{-3}$). For the sake of comparison, a universal mobility curve (only phonon and surface-roughness scattering) is added in solid line (no symbols).

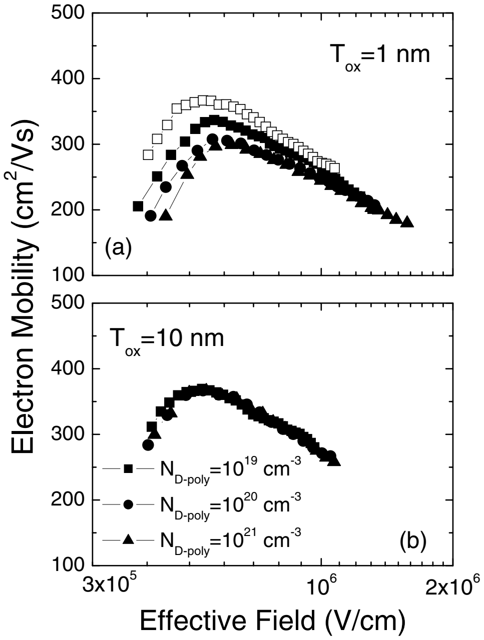

Fig. 6. Mobility curves versus the transverse effective field for different values of the poly doping concentration. Two values of the oxide thickness were assumed (a) $t_{ox} = 1nm$ and (b) $t_{ox} = 10nm$. Phonon, surface roughness, and total Coulomb scattering are assumed.

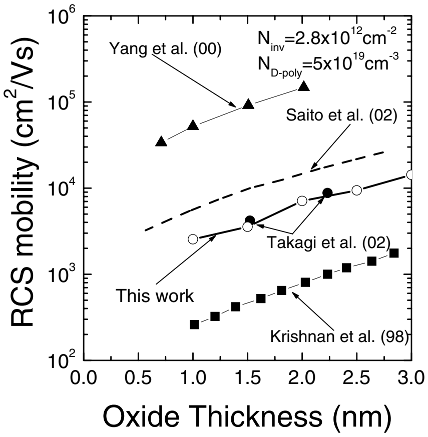

Fig. 7. Dependence of RCS-limited mobility on oxide thickness. $N_{D-poly} = 5 \times 10^{19} cm^{-2}$.

very high substrate doping concentrations or relatively low poly doping concentrations are used. However, we have seen that RCS effects for $t_{ox} > 5nm$ are negligible. Finally, we compared simulated results with experimental ones and found that the results obtained with the RCS model developed here compare much better with experimental results than do previous models.

IV. ACKNOWLEDGMENTS

This work has been carried out within the framework of Research Project No. TIC2001-3243 supported by the Spanish Government.

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