Remote charge scattering in MOSFETs with ultra-thin gate dielectrics

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Abstract

In this work, we have studied the mobility degradation of inversion charge due to remote charge scattering (RCS), referring to scattering of mobile charges in the inversion layer by charged impurities present in the gate material of a MOSFET. The results indicate a 20 - 30 % reduction in the electron mobility because of RCS, for gate oxide thicknesses lower than 15$\AA$.

Introduction

The SiO_2 thickness in a nano-scale MOSFET corresponds to a few monolayers of oxide. At these oxide dimensions gate leakage currents due to direct tunneling may limit gate oxide (T_{ox}) scaling [1]. Another concern is the mobility degradation due to the large vertical electric field [2]. Thus far, the gains in the drain current (I_{DSAT}) arising from T_{ox} reduction have far outweighed these limitations. In this article, we report another mechanism that assumes significance with further T_{ox} scaling. It is known that the poly-Si gate material in the MOS systems is depleted of free charge at the oxide interface [3], leaving ionized impurities in the depleted region. We have studied the mobility degradation of the inversion charge due to scattering caused by the remote ionized impurities present in the gate material.

Model

Following the approach in [4], we have developed the model for RCS by computing the impurity potential in the channel, which is obtained by solving the Poisson equation for the impurity, taking into account size quantization effects and 2-D screening of the carriers. We have expanded on the remote impurity scattering model developed for quantum wells [5] to the MOSFET. First, we solve the impurity Poisson equation by factoring in the presence of an insulator between the depleted poly and the inversion charges, which introduces spatially varying dielectric permittivities. Second, quantization effects in the inversion layer are captured by a self-consistent solution of the Schrödinger and the Poisson equations [6]. The following briefly details the solution of the impurity Poisson equation.

Taking advantage of the cylindrical geometry of the system, the potential of an ionized impurity is expanded in its radial and transverse components, $J_0(qr)$ and $F_q(x)$, respectively [4]. (q represents the wave vector, J_0 is the zeroth order Bessel function, r is parallel to the plane of the transport and x is perpendicular to the interface). Hence, the impurity Poisson equation is reduced to the following form:

$$F_q^{''}(x) - q^2F_q(x) - 2q_s g(x)\int_0^\infty dx\, F(x)g(x) = \frac{-Ze\delta(x-x_0)}{2\pi\epsilon(x)} \qquad (1)$$

where $F_q^{''}(x)$ is the 2^{nd} order derivative of the transverse potential with respect to x, x_0 the position of the impurity (of charge Ze) located in the gate, q_s the 2D screening parameter, $g(x)$ the inversion charge distribution, e the electronic charge, and ϵ the dielectric permittivity, which is equal to that of Si in the poly and the channel regions (ϵ_{si}), and that of the dielectric in the insulator region (ϵ_{ox}).

The integral equation (1) may be solved using Green's functions satisfying the appropriate boundary conditions at the interfaces (continuity of electric displacement) and at infinity (homogenous Dirichlet). It is possible to arrive at a solution for any arbitrary charge distribution. However, a reasonably accurate estimate for the scattering rates may be obtained using an impurity potential derived from approximating the charge distribution as a delta function in eqn. (1). We give the result for the transverse potential in the channel (averaged over the charge distribution) below:

$$\overline{F}_q(d,x_0) = \left[\frac{1-\beta^2}{\{1-\beta^2 exp(-2qt_{ox})\}q + \{1-\beta^2\}q_s}\right] \times \frac{e}{4\pi\epsilon_{si}}\, exp(-q(|d-x_0|)) \qquad (2)$$

$$\beta = \frac{\epsilon_{ox}-\epsilon_{si}}{\epsilon_{ox}+\epsilon_{si}} \qquad (3)$$

where d is the centroid of the inversion charge. The differential cross section based on the Born approximation is given by [4]:

$$\sigma(\theta) = \frac{2\pi m^* e^2}{\hbar^3 v}\,(\overline{F}_Q(d,x_0))^2 \qquad (4)$$

where θ is the scattering angle, and the scattered vector $Q = 2q\, sin(\theta/2)$. The self-consistent simulation of the Schrödinger and Poisson equations gives the charge centroid, with which the differential cross section is obtained (eqns. (2), (4)). Summing the differential cross section over all scattering angles and scattering centers [4], the momentum scattering rate and hence, the RCS mobility can be calculated. The developed model to evaluate the scattering rate due to the remote charge centers in a MOSFET is fairly accurate in strong inversion where the presence of 2D screening of the quantized inversion charge eliminates the problem of diverging cross sections at small scattering angles.

Results and Discussion

The nature of boundary conditions for solving the impurity Poisson equation renders the scattering cross section of an ionized impurity vary exponentially with the separation of the inversion charge centroid from the impurity position. Thus the RCS mobility also shows an approximate exponential relationship with the dielectric thicknesses. The three main factors that determine the RCS mobility are the transport mass, inversion charge screening, and the position of the charge centroid. The RCS electron and hole mobilities as a function of T_{ox} at various remote charge densities, and a fixed inversion charge density of $2.8 \times 10^{12}/cm^2$, are shown in Figs. 1 and 2, respectively.

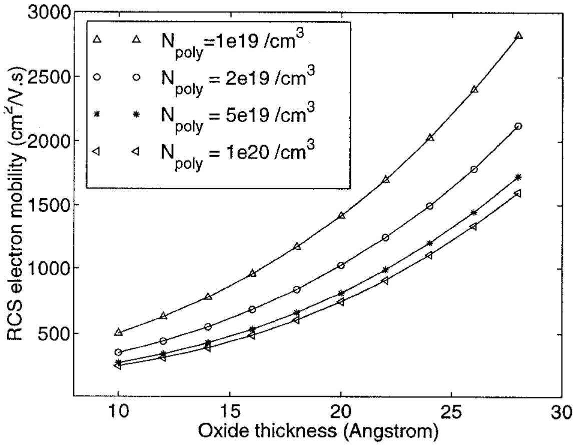

Figure 1. The electron RCS mobility dependence on the gate oxide thickness for a fixed inversion charge density in a MOSFET.

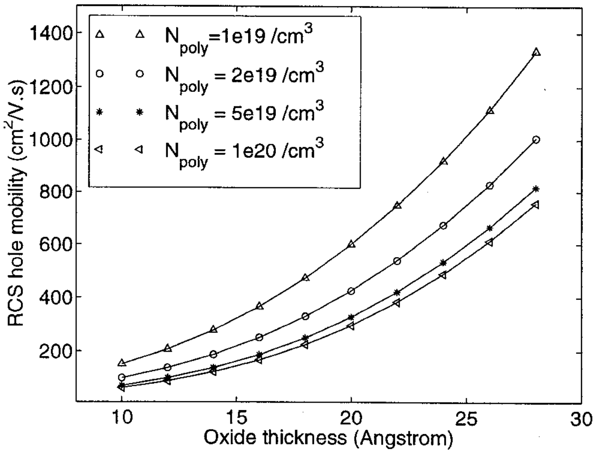

Figure 2. The hole RCS mobility dependence on the gate oxide thickness for a fixed inversion charge density in a MOSFET.

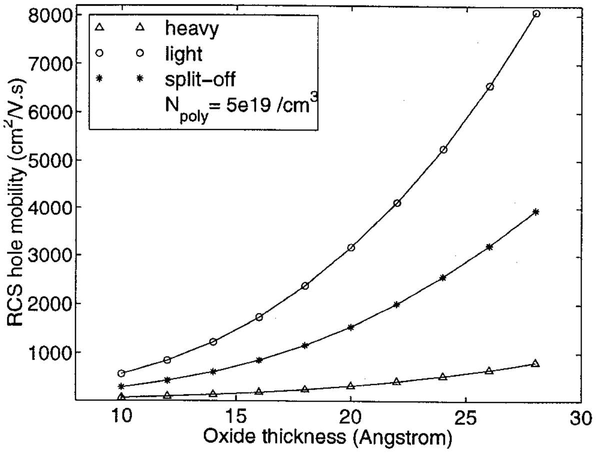

Figure 3. The dependence of RCS mobility for different hole bands on the gate oxide thickness in a MOSFET.

For a T_{ox} of 10 Å, and a poly doping level of $5 \times 10^{19}/cm^3$, the electron RCS mobility is $270 cm^2/V.s$. The classical effective electron mobility [7] (due to phonon, background impurity, surface roughness) is therefore, reduced by 31 % because of RCS. At room temperature, the majority of holes are heavy holes, and their properties determine the overall transport behavior. As the effective density of states is higher for holes compared to that of electrons, the holes exhibit greater 2D screening. Also, the charge centroid of the holes is further away from the Si/SiO_2 interface relative to that of electrons. This is because, perpendicular to the interface, the effective mass of holes is lower than that of the electrons for the lowest sub-band, thereby extending the hole wave function further into the Si substrate relative to that of electrons. The increase in hole RCS mobility because of the last two mentioned effects is countered by a reduction in mobility due to the large heavy hole transport mass. The net result is that the RCS mobility for holes is smaller than, but comparable to that of electrons as shown in Fig. 2. Therefore, the total mobility, including both the classical mobility and the RCS mobility remains practically unaffected in holes. The RCS mobilities for the different hole bands are shown in Fig. 3, which again is a result of the three factors described above.

Fig. 4 shows the variation of electron and hole RCS mobility with the remote charge density. Interestingly, the RCS mobility is insensitive to large bulk remote charge densities. For the same inversion and bulk depletion charge densities, increasing the remote charge density decreases the poly depletion widths. This shifts the centroids of the remote and the inversion charges closer to the poly-oxide and the oxide-substrate interfaces, respectively. As a result, the RCS mobility decreases non-linearly. However, beyond a large remote charge density ($6 \times 10^{19}/cm^3$ as seen in Fig. 4), the remote charges are distributed very close to the interface and the mobility is affected only by the areal density of the remote centers, which being constant, renders the RCS mobility insensitive to the remote charge density.

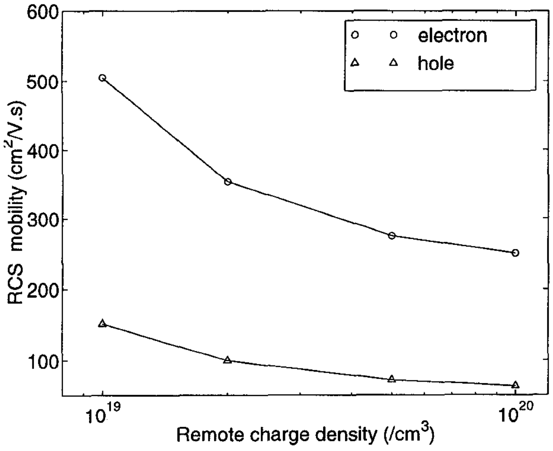

Figure 4. The variation of RCS mobility with different poly-Si doping densities in a MOSFET.

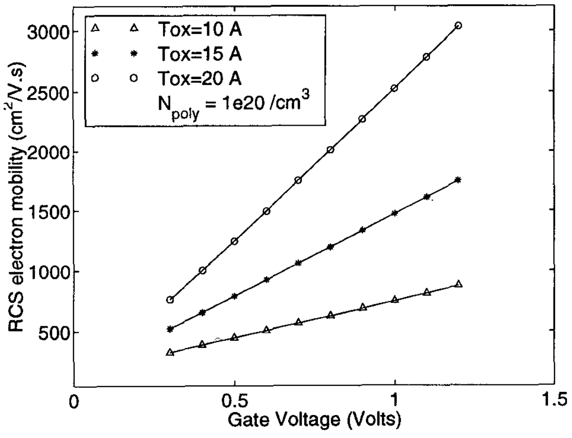

Figure 5. The effect of varying the gate bias on the RCS electron mobility for $V_T = 0.25\,V$.

The effect of gate voltage (vertical electric field) on the RCS electron mobility is plotted in Fig. 5.

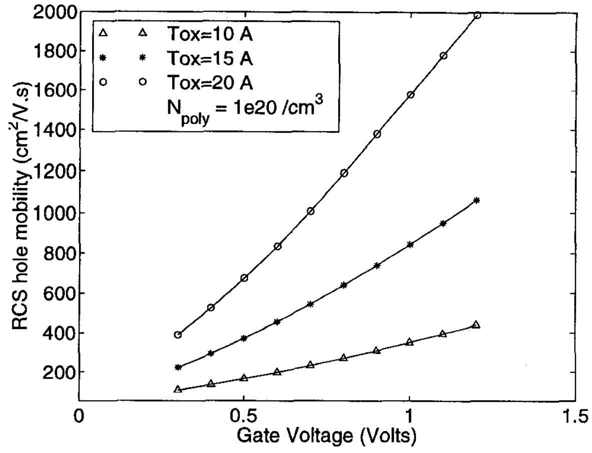

Figure 6. The effect of varying the gate bias on the RCS hole mobility $V_T = 0.25\,V$.

Increasing the gate bias increases the sheet charge density which enhances screening, thereby tending to increase the mobility. However, increasing the vertical field also shifts the inversion charge centroid closer to the Si/SiO_2 interface which tends to lower the RCS mobility. As seen in eqn. (2), screening is the dominant factor as a result of which the effect of RCS at high vertical fields diminishes. The same trend is seen for holes as shown in Fig. 6. Fig. 7 shows the universal mobility curves for electrons and holes for a T_{ox} of 10 Å. The RCS effect on holes is small for reasons described before. The relative importance of RCS on electrons may be determined from the operating voltage of a given technology. As shown in Fig. 8, operating NMOSFETs with 10 Å T_{ox} at 1 Volt decreases the electron mobility by 22 % due to RCS, and those with 20 Å T_{ox}, by 9 %. Its effect is well pronounced for NMOSFETs with ultra-thin gate oxides (T_{ox} less than 15 Å).

The effect of replacing SiO_2 with higher permittivity dielectrics can be seen in Figs. 9 and 10. Though not obvious, the use of high ϵ materials reduces the effect of RCS. The following may clarify the subtlety. If an impurity charge were to be present in a homogenous dielectric medium, the bare impurity potential remains unchanged when measured as a function of an equivalent dielectric thickness. However, since eqn. (2) relates the remote impurity potential exponentially with T_{ox}, and inversely with ϵ_{si}, the remote impurity potential does not scale in a similar fashion as a bare potential, rendering it a strong function of the equivalent SiO_2 thicknesses. Conversely, RCS may not be important in MOSFETs with higher dielectric permittivities such as Ta_2O_5. Fig. 10 shows the universal mobility curves including RCS mobility for different dielectrics. Clearly, Ta_2O_5 shows an ideal universal mobility behavior.

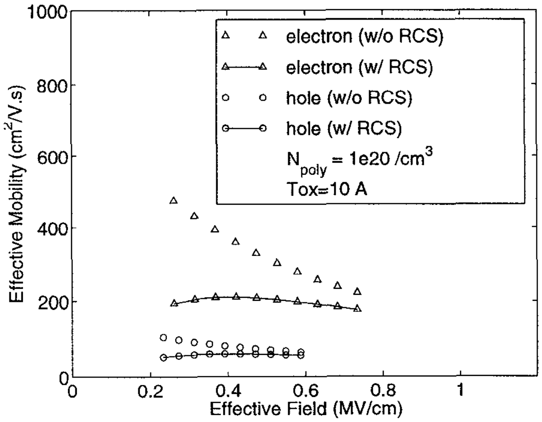

Figure 7. The universal mobility curves for electrons and holes for T_{ox}=10 A. Note that the typical field of operation is 0.5-0.6 MV/cm for this T_{ox}.

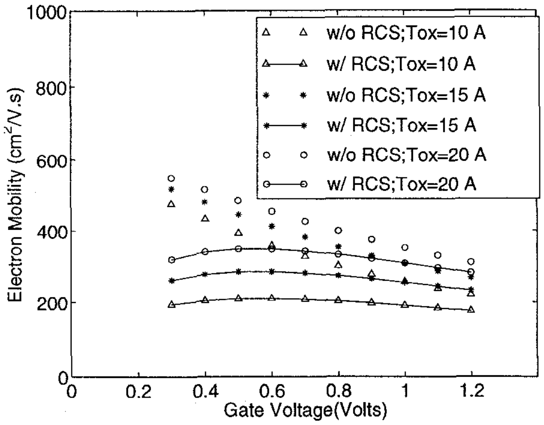

Figure 8. The effective mobility of inversion layer electrons including RCS mobility as a function of V_G.

Conclusion

We report the mobility degradation of inversion charge due to the presence of ionized charges in the depleted poly gate in MOSFETs, an effect that has not been studied before. The results indicate that remote charge scattering mechanism significantly reduces the effective mobility of inversion layer electrons, in MOSFETs with SiO_2 T_{ox} less than 15 $\AA$. Its effect on holes is comparably smaller. The use of high dielectric materials like Ta_2O_5 may mitigate the effects of RCS.

Acknowledgment

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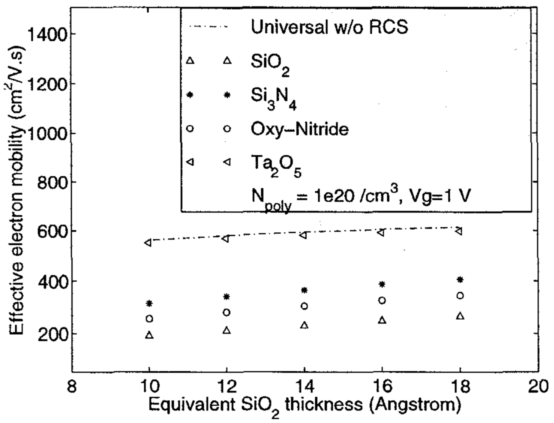

Figure 9. Effective mobility of electrons as a function of equivalent SiO_2 thickness at $V_g = 1.0V$.

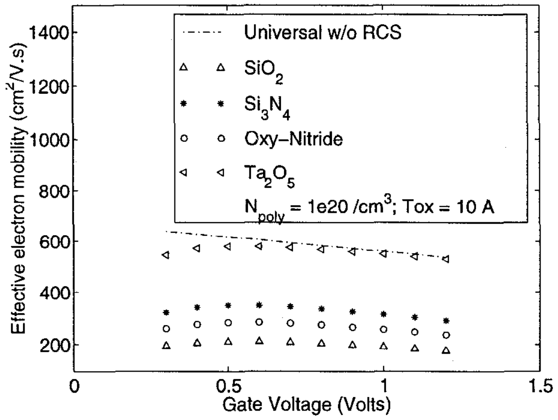

Figure 10. Effective mobility of electrons as a function of gate bias in a MOSFET; Equivalent SiO_2 thickness = $10\AA$.

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