Random telegraph signal amplitude in submicron n-channel metal oxide semiconductor field effect transistors

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Random telegraph signal (RTS) amplitude has been studied in a submicron n-channel metal oxide semiconductor field effect transistor as a function of gate voltage. To do so, we have employed a complete simulator of metal oxide semiconductor devices where the effect of a single acceptor trap placed in the silicon oxide was taken into account. The dominant role played by the screening of the charged trap due to free channel carriers has been demonstrated. Furthermore, the effect of the mobility and carrier number fluctuations on the normalized drain current fluctuations were separated, revealing the importance of mobility variations on the RTS amplitude. © 1997 American Institute of Physics. [S0003-6951(97)02916-1]

The continuous shrinking in the characteristic dimensions of metal oxide semiconductor field effect transistors (MOSFET) brings into prominence single electron effects, one of the most important of which are Random telegraph signals (RTS). These signals are generally considered as carrier trapping–detrapping from traps situated in the silicon oxide. Studies on noise from individual oxide traps in small structures supply new information of device operation as well as degradation phenomena. When the channel area of the devices is small enough, it is possible that only one trap may be close to the surface Fermi level over the entire channel. Thus, individual traps can be observed in their neutral or charged state and, as a consequence, the current fluctuates between two discrete levels. For an acceptor trap, the high level corresponds to the negatively charged state. There-icerca number is modified. As may be seen, the main goal of this letter is to study the contribution of carrier number fluctuations and mobility fluctuations on the discrete switching current events for different gate biases in a submicron MOSFET.

To accomplish this, we have used a quasi-two-dimensional short-channel MOSFET simulator that includes inversion-layer quantization, a nonparabolic band model, and the electron mobility data obtained by a one-electron Monte Carlo simulation. All this allows us to calculate the drain current whether the trap is negatively charged or neutral. This simulator self-consistently solves the Poisson, Schroedinger, and drift-diffusion equations in the entire structure. The inversion layer is treated as a quasi-two-dimensional electron gas contained in electric subbands with a transverse extension given by the envelope functions. The effect of the transverse electric field on the mobility is obtained by calculating the electron mobility by Monte Carlo simulation taking into account phonon, surface roughness, and Coulomb scattering from both the doping impurities and the oxide and interface-trapped charges. We have employed a comprehensive Coulomb-scattering model in semiconductor layers that allows the actual profile of the oxide-charge distribution and the screening by mobile carriers to be taken into account.

In our study, we have considered an n-channel MOSFET with a gate oxide thickness (t_{ox}) of 5 nm, channel length and width of 0.1 and 2 μm, respectively, and an implanted profile with a Boron peak doping density of $3 \times 10^{17}$ cm$^{-3}$. We have also considered an acceptor trap that can be either charged or neutral. An electrical length $L_t$ was introduced, where the effect of a charged trap is present. In this work, $L_t$ has been taken as 0.65×t_{ox}, which is in good agreement with the values calculated by Mueller. The local longitudinal low-field mobility, $\mu_0(E_\perp)$, obtained from a Monte Carlo calculation, is shown in Fig. 1; that is to
say, the mobility that one electron would have in a given position inside the channel, and that can vary depending on whether this position is or is not under the influence of a charged trap. In this model, we have assumed that if the electron is not under the influence of the charged trap, it will have the mobility of curve 1, but if it is under the influence of the charged trap then it will have mobility of curve 2. In curves 2 and 3, we considered one negative charge inside the oxide, situated at 15 Å from the interface and right at the interface, respectively. For low transverse fields, the curves are widely separated due to the effect of Coulomb scattering. As the transverse effective field increases, Coulomb scattering is reduced due to the screening effect, leading to higher Coulomb mobility. In contrast, surface roughness and phonon scattering increase as the transverse effective field increases. For high enough transverse fields, the surface-roughness mechanism becomes dominant and the local-mobility curves tend to coincide and no differences can be appreciated between them. Attention should be drawn to the influence of the depth of the trap in the oxide on the low field mobility curves, as is shown in Fig. 1. The effect of the longitudinal electric field is included in the simulation as usual.14

At this point, we can calculate the current fluctuation from

$$\Delta I = I_0 - I_q, \quad I = \frac{I_0 + I_q}{2},$$  

(3)

where $I_0$ is the drain current when the trap is neutral and $I_q$ the current when the trap is charged. In the simulations, the trap is considered to spend the same amount of time in each state since the time constants are not of concern in this letter. For this device, the current fluctuations have been calculated assuming $V_{DS} = 1 \text{mV}$ and for $T = 300$ and $T = 88 \text{K}$ (Fig. 2) as a function of gate voltage. To study the different contributions to the current fluctuation, the inversion and depletion charges are also given. It is shown in Fig. 2(a) ($T = 300 \text{K}$) that when the depletion charge is higher than the inversion one, the normalized current fluctuation remains constant. However, when the inversion charge surpasses the depletion one, the current fluctuation decreases. Figure 2(b) ($T = 88 \text{K}$) reveals a different behavior: the RTS amplitude starts decreasing from its plateau value before the inversion charge surpasses the depletion one. It seems clear from Fig. 2(b) that a strong inversion regime is not necessary to induce the decay of current fluctuation and, therefore, not only the number fluctuation contribution but also the mobility fluctuation should be taken into account to explain the behavior of the current fluctuation at different gate biases. In fact, the current fluctuation trend can be explained with Fig. 1 according to the mobility fluctuation. As mentioned before, at low transverse electric fields, Coulomb scattering dominates the mobility behavior separating the mobility curves (Fig. 1). As the gate voltage rises, the screening increases and the current fluctuation decreases since the contribution of Coulomb scattering is reduced, as pointed out in Fig. 1. Moreover, at low temperatures, the screening is more effective than at higher ones, because the fraction of electrons which populate the ground subband is higher in the first case. Therefore, the confinement of the electron gas, for the same effective field, is higher and the decay of the current fluctuation becomes
3. In case current fluctuations in three cases, as can be observed in Fig. 3, originated by the charged trap were simultaneously considered. In curve (2) (dashed line), we consider the effect of the charged trap on the mobility used but not on the number of carriers calculated. The mobility employed in curve (3) corresponds to the noncharged-trap case for the whole channel, while the effect of the charged-trap region is only taken into account to calculate carrier density.

Thus, we have maintained that mobil-

The effect of the screening of Coulomb scattering is essential at lower gate biases than at high temperatures. So, the amplitude of the current fluctuations.

Let us consider now the contribution of each term of Eq. (1). When a single charge carrier is trapped at the interface, a considerable fraction of the image charge is located on the gate electrode and in the substrate, especially in weak inversion, \( \Delta N \) will be small. Even in strong inversion, where \( \Delta N \) tends to unity (its maximum value), the channel carrier density \( N \) is high enough and therefore, \( \Delta N/N \) can be considered negligible. Thus, we have maintained that mobility fluctuations should be taken into account, and they are expected to have an important effect. To check this assumption, we have returned to expression (2) and calculated the current fluctuations in three cases, as can be observed in Fig. 3. In case (1), both mobility and carrier number fluctuations caused by the charged trap were simultaneously considered. For curve (2), we took into account the effect of charged traps on the mobility but not on the number of free carriers. For curve (3), we considered that the mobility corresponds to the noncharged-trap case for the whole channel while the charged-trap region is included to calculate the depletion and inversion charges. With this procedure, the contribution of each term on the total current fluctuation has been separated.

This fact has allowed us to conclude that the mobility fluctuation dominates the behavior of the drain current fluctuations.

To sum up, a complete numerical procedure to calculate the RTS amplitude has been presented. This procedure has been used to analyze the gate voltage dependence of the normalized drain current fluctuation, separating the contributions of number and mobility fluctuations. According to our calculations, the current fluctuation calculated taking into account mobility fluctuations successfully reproduces the current fluctuations. The screening decisively influences the effect of the charged trap, reducing Coulomb scattering and, therefore, the amplitude of the current fluctuations.

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\[ \Delta N/N \]

FIG. 3. Normalized drain current fluctuations vs drain current \( (T=88 \text{ K}, \ V_{DS}=1 \text{ mV}) \). In curve (1), both mobility and carrier number fluctuations originated by the charged trap are simultaneously included. In curve (2) (dashed line), we consider the effect of the charged trap on the mobility used but not on the number of carriers calculated. The mobility employed in curve (3) corresponds to the noncharged-trap case for the whole channel, while the effect of the charged-trap region is only taken into account to calculate carrier density.

\[ \Delta \text{I}_{DS}/\Delta \text{I}_{DS} \]

\[ \text{Drain Current (A)} \]

\[ \text{Normalized drain current fluctuations vs drain current (T=88 K, V_{DS}=1 mV)} \]