Influence of mobility fluctuations on random telegraph signal amplitude
in $n$-channel metal–oxide–semiconductor field-effect transistors

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(Received 22 May 1997; accepted for publication 17 July 1997)

The amplitude of random telegraph signals (RTS) in an $n$-channel metal–oxide–semiconductor field-effect transistor has been investigated. Current fluctuations originating when a single-channel electron is trapped or detrapped in the silicon dioxide have been evaluated. A simulation has been performed where the inversion-layer quantization, the dependence of the electron mobility on the transverse and longitudinal electric fields, and the influence of the oxide charges on free-carrier density and on electron mobility have been taken into account. This procedure provides the chance of studying the influence of trap depth in the oxide on the RTS amplitude. In addition, the contributions of the mobility and carrier fluctuations on the amplitude of discrete current switching have been separated, revealing the importance of each factor. Normalized mobility fluctuation has been defined and it was found that its dependence on the gate and drain voltages helped to explain the behavior of the normalized current fluctuations. Finally, the scattering coefficient was evaluated, showing good agreement with previously published data. All these results have allowed us to gain further insight into the role played by electron mobility fluctuations on random telegraph signal amplitude. © 1997 American Institute of Physics. [S0021-8979(97)00421-0]

I. INTRODUCTION

Due to the continuous scaling down of metal–oxide–semiconductor field-effect transistors (MOSFETs), it can occur that only one oxide trap with an energy within a few $kT$ of the surface Fermi level over the entire channel exists. Under these conditions, the drain current of the device behaves discretely. These discrete drain current fluctuations are known as random telegraph signals (RTS) and are due to the capture and emission of free-channel carriers by a single interface defect near the Si/SiO$_2$ interface. Figure 1 shows a typical time domain plot of the drain current, which highlights the basic parameters characterizing RTS noise. In this case, an acceptorlike trap was considered where $I_0$ is the current level when the trap is empty for a time $\tau_c$ (capture time), and $I_q$ is the current level when the trap is negatively charged for a time $\tau_e$ (emission time). $\Delta I$ is the amplitude of the RTS, defined as the difference between the two current levels.

When a single-channel electron is captured or released from an interface trap, the number of free carriers in the inversion layer changes. Moreover, as the oxide trap changes its electrical state, individual scatterers are turned on and off and, therefore, channel mobility is also affected. Thus, the amplitude of the current fluctuations is calculated as the combined effect of carrier number and mobility fluctuations, which can be written as

$$\frac{\Delta I_{DS}}{I_{DS}} = \frac{\Delta N}{N} + \frac{\Delta \mu}{\mu} = -\frac{1}{WL} \left[ \frac{1}{\nu_{th}(C_{ox} + C_d) + N_{inv}} \pm \alpha N_T \right],$$

where $\nu_{th}$ is the thermal voltage, $C_{ox}$ and $C_d$ are the oxide and depletion capacitances, respectively, $N_{inv}$ is the inversion-charge concentration, and $\alpha$ is the scattering coefficient.

The first term on the right-hand side arises from the change in the number of channel carriers due to trapping and detrapping from a single trap and is derived from Reimbold’s theory. The second term comes from the mobility modulation caused by the oxide charge and is derived from a widely used model based on Matthiessen’s rule

$$\frac{1}{\mu} = \frac{1}{\mu_{ox}} + \frac{1}{\mu_a} = \frac{1}{\mu_a} \pm \alpha N_T,$$

where $\mu_{ox}$ is the mobility limited by oxide-charge scattering, $\mu_a$ is the mobility limited by the other mechanisms, and $N_T$ is the number of charged traps per unit area. The sign before the scattering coefficient in Eqs. (1) and (2) depends on the state of the trap when it is ionized. It should be noted, however, that until now it has been difficult to distinguish the contribution of the two noise generation mechanisms, $\Delta N$ and $\Delta \mu$, independently.

Growing interest in the study of RTS noise in submicron MOSFETs is amply justified for several reasons. Due to its origin, the analysis of RTS signals provides the opportunity of studying the interaction of inversion carriers with interface states, which play a crucial role in the quality and reliability of future ultrasmall channel MOSFETs. In addition, an accurate description of the current fluctuations measured in small devices may help us to predict the noise properties of large-area MOSFETs if $1/f$ noise proceeds from superposition of RTS events as it is widely accepted, although some doubt has been raised against this idea. As can be deduced from the literature, there is considerable controversy about the $1/f$ noise origin, since two different theories have been proposed to explain the

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physical origins of flicker noise: (i) the carrier number fluctuation theory, originally proposed by McWhorter,\textsuperscript{14} and (ii) the bulk mobility fluctuation theory based on Hooge’s empirical relation.\textsuperscript{15} Nevertheless, more recent works, simultaneously incorporating both the number fluctuation and the surface mobility fluctuation induced by the fluctuating oxide charge through Coulomb scattering, have successfully described 1/f noise behavior.\textsuperscript{11,16} Thus, a study of RTS is necessary to properly model flicker noise. Finally, the continuous miniaturization of MOS technologies causes a significant increase in RTS amplitude, leading the feasibility of deep submicron devices to be questioned.\textsuperscript{17}

In this work, we have investigated the RTS amplitude of submicron $n$-channel MOSFETs in order to determine its dependence on correlated carrier number and mobility fluctuations originating in the device when trapping or detrapping from a single oxide trap occurs. We have also analyzed how this dependence is affected by trap position in the oxide and by the gate and drain-to-source voltages. In order to achieve this goal, we have used a quasi-two-dimensional short-channel MOSFET simulator including inversion-layer quantization and a one-electron Monte Carlo simulation allowing us to calculate the drain current\textsuperscript{18} both in the case of an acceptor occupied trap (negatively charged) and in the case of an empty trap (neutral). Furthermore, this procedure provides relatively simple control of all the structure parameters. These possibilities allow us to monitor the influence of factors such as the transverse and longitudinal effective fields, the position of the trap along the channel, and the depth of the trap in the oxide, and to distinguish the contribution of the carrier number and mobility fluctuations to the RTS amplitude.

In Sec. II, the procedure is outlined, focusing on the parameters employed in the drain current calculation. Different results from the device simulator, concerning normalized current fluctuations, are presented in Sec. III. The influence of the depth of the charged trap and the effect of the gate and drain bias on the amplitude of the current fluctuations is carefully analyzed. The scattering coefficient, $\alpha$, has also been evaluated and compared with values presented by other authors. Finally, the main conclusions are summarized in Sec. IV.

II. DEVICE SIMULATION

A. Drain current calculation

To study RTS noise, MOSFETs with very small channel areas ($<1 \, \mu\text{m}^2$) must be considered, since these devices can have only one oxide trap next to the surface Fermi level and next to the Si–SiO$_2$ interface over the entire channel. Therefore, the simulator must be able to simulate such devices. It is well known that when the channel dimensions in a MOSFET are reduced, two-dimensional and three-dimensional effects become important. In addition, the classical approximation to electron behavior in the inversion layer is no longer valid, making a quantum study necessary.\textsuperscript{19} Accordingly, a physically based submicron MOSFET simulator should self-consistently solve the two-dimensional Poisson, Schroedinger, and drift–diffusion equations in the entire structure. This makes the calculation very expensive in computation time and storage. Due to the above drawbacks, we have used the simpler submicron MOSFET simulator briefly described below. More details can be found elsewhere.\textsuperscript{18,20}

As the inversion layer is treated as a quasi-two-dimensional electron gas with a transverse extension given by the envelope functions, the channel can be described as a sheet layer of charge located inside the semiconductor bulk at a distance $z_f$ from the silicon–oxide interface, where $z_f$ is the mean transverse position of the electron distribution. The current in the channel is obtained by adding drift and diffusion contributions. If the voltage drop across the channel is very small, the following expression for the drain current ($I_{DS}$) is obtained\textsuperscript{20}

$$I_{DS} = \frac{q W \mu(E_f, E_z)}{L} [-N_f(\psi^*_{\text{drain}} - \psi^*_{\text{source}}) + \phi_s(N_{f,\text{drain}} - N_{f,\text{source}})],$$

(3)

where $\psi^*$ is the electrostatic potential in $z_f$, $N_f$ is the electron density in the channel extremes, $N_{f,\text{drain}}$ is the average electron density in the channel, $\phi_s$ is the thermal voltage, and $W$ and $L$ are the width and length of the channel, respectively.

Electron mobility depends on both the longitudinal ($E_f$) and transverse ($E_z$) electric fields.\textsuperscript{21} The effect of the transverse electric field is obtained by calculating the electron mobility by Monte Carlo simulation.\textsuperscript{22} The effect of the longitudinal electric field is included in the simulation by the expression\textsuperscript{20}

$$\mu_0(E_f, E_z) = \frac{\mu_0(E_f)}{1 + \left(\frac{\mu_0(E_f) \times E_z}{v_{\text{sat}}}\right)^{\beta(E_f)}}^{1/\beta(E_f)},$$

(4)

where $\mu_0(E_f)$ is the low-field or Ohmic mobility, which includes the dependence of the transverse electric field, and $v_{\text{sat}}$ is the saturation electron velocity. A value of $1.1 \times 10^7 \, \text{cm/s}$ has been used for the saturation velocity, $v_{\text{sat}}$, and an empirical model has been employed for the $\beta$ parameter dependent on the longitudinal-electric field.\textsuperscript{20}
One advantage of expression (3), in addition to the use of an analytical approximation to the drift–diffusion equation, is that it requires only the one-dimensional solution of the Poisson and Schroedinger equations along two lines perpendicular to the interface, right at the channel extremes. This numerical solution is necessary in order to obtain accurate values for $N_i$ and $z_i$ in both extremes, considering the actual doping profile in the silicon bulk and the actual pseudo-Fermi-level separation as determined by the external applied voltage. Nevertheless, Eq. (3) has significant drawbacks: (a) The requirement of a very slow potential variation in the channel, which makes this procedure useless for almost all the operation conditions of short-channel MOSFETs. (b) The noninclusion of short-channel effects due to the depletion charge near the source and drain, which must be added *a posteriori*. (c) The omission of the effect of an oxide-charge distribution that is variable along the channel as in the case of one trapped electron in RTS noise.

The one-dimensional approximation is adequate as far as the Schroedinger solution is concerned, since the scale of interest in this case, the de Broglie wavelength, can actually be short for electrons in an inverted channel. In the Poisson equation, however, the Debye length can be quite long, and the longitudinal field can vary significantly. As a consequence, the two-dimensional Poisson equation solution could be required. We have adopted a quasi-two-dimensional approach, in which the two-dimensional short-channel effects due to the depletion charge near the source and drain, and the subthreshold leakage current due to junction punch-through in the subchannel region away from the interface are ignored [drawback (b)]. Notwithstanding, this approximation does not seriously limit the results of our study on RTS amplitude.

Drawbacks (a) and (c) are bypassed as shown below. We have adopted a procedure similar to the idea proposed by Tsividis\textsuperscript{22} to extend the application range of the quasistatic model, which is briefly described:

The transistor is divided into a series of *subtransistors*, each with its own imaginary source and drain points of very short length to make the voltage drop in each of them ($v_{dsi}$) so small that Eq. (3) is applicable. The gate and substrate of all these devices are common. In such a division, the following two conditions must be fulfilled: $\Sigma L_i = L_i$, $\Sigma v_{dsi} = V_{DS}$, where $L_i$ and $v_{dsi}$ are the length and the drain-to-source voltage of the $i$-th subchannel. The device is, thus, seen as a network of smaller devices connected in series. $v_{dsi}$ are fixed as very small (and are, therefore, known), while $L_i$ are initially unknown and are determined by the following iterative procedure:

(i) Starting from fixed values for the external biases, $V_{DS}$ (voltage between drain and source), $V_{GS}$ (voltage between gate and source), and $V_{SB}$ (voltage between source and substrate), $V_{DS}$ is divided among the different subchannels. To do so, we assume that $v_{dsi} = V_{DS}/N$, where $N$ is the number of subchannels considered. $N$ will be taken high enough that the number of subtransistors in the region affected by the charged trap is high enough so that the precision of the final result does not depend on it. The one-dimensional Poisson and Schroedinger equations are then self-consistently solved in the imaginary extremes of each subchannel, taking into account the actual doping profile, the oxide trapped-charge concentration, and the actual pseudo-Fermi-level separation at these points, and evaluating at each of these points the inversion and depletion charge, the electrostatic potential $\phi^*$, and the rest of the parameters in Eq. (3).

(ii) An arbitrary current level $I_{DS}$ in the MOSFET channel is assumed. This current level is also the channel current in all the subchannels, and the length of each channel, $L_i$, is obtained by applying the modified charge-sheet model given in expression (3). The results obtained by self-consistently solving the Poisson and Schroedinger equations in the extremes of each subtransistor in the previous step are taken into account.

(iii) The total channel length, $L$, is compared with the sum of channel lengths, $L_i$, of each subtransistor into which the MOSFET is divided. If the two magnitudes do not coincide, the current level is modified, and steps (ii) and (iii) are repeated until $L = \Sigma L_i$, within a convergence criterium. This procedure allows us to obtain, in addition to the drain current, an approximation to the potential distribution along the channel, $\phi_0(x,y)$.

**B. Low-field electron mobility calculation**

The use of an accurate expression for the low-field mobility and its dependencies on the transverse-electric field, the longitudinal-electric field, and the temperature, is crucial to evaluate the drain current in our study of RTS amplitude. The local electron mobility in every channel point, $\mu_0(E_x,E_z)$, must be calculated using expression (4), and to do so, the low-field mobility has to be previously known. Furthermore, since the transverse-electric-field profile varies along the channel due to the presence of oxide traps, this variation must be taken into account when considering the mobility in each subchannel.

To simulate local mobility in the transistor, we started by calculating the low longitudinal-field mobility, $\mu_0(E_z)$, obtained from a Monte Carlo calculation applied to a long-channel transistor. Phonon and surface-roughness scattering\textsuperscript{24,25} and the Coulomb scattering from both the doping impurities and the oxide and interface charges\textsuperscript{22,26} were taken into account. In this Monte Carlo procedure, we have allowed the electron to travel in six subbands and to move among them.\textsuperscript{22} For low temperatures, Coulomb scattering determines the carrier mobility, so we have employed a comprehensive Coulomb-scattering model in semiconductor inversion layers (see Refs. 22 and 26) that allows the actual profile of the oxide-charge distribution and the screening by mobile carriers to be considered.

The presence of a trapped electron at the interface or in the oxide will induce a change in the local surface potential and the local carrier mobility over a distance $L_i$.\textsuperscript{27} This effect has been taken into account in our simulator by considering a two-dimensional uniform charge concentration of
length $L_t$, located around the trap, with a concentration of $N_{int} = (L/W)^{-1}$, as shown in Fig. 2. An acceptor oxide trap that can be charged or neutral has been assumed. In the charged state, we used an estimation of $L_t = 0.625 \times t_{ox} = 3.125$ nm for the length of the potential, carrier, and mobility perturbation. This is in agreement with the model provided by Mueller and Schulz for local perturbations in a uniform channel. Thus, the influence of surface potential fluctuations on the local electron mobility and free carrier concentration are considered in our approach, since this oxide-charge concentration is taken into account when the Poisson and Schroedinger equations are solved in the channel points located below the $L_t$ length. The reduced low-field electron mobility, $\mu_0(E||)$, due to the increase in Coulomb scattering will be used when expression (4) is evaluated in the transistors below $L_t$. Therefore, the local longitudinal low-field mobility in the assumed device will be calculated considering two different cases: (i) channel carriers not under the influence of the charged trap, and (ii) under the effect of the charged trap.

In this paper, low drain-to-source voltage values were considered so that the devices always operate in the linear region. Under these conditions, the inversion and depletion charges are nearly uniform from source to drain. Therefore, when different positions of the oxide trap in the channel were considered (near the drain, the source, or in the middle of the channel) we always obtained the same results, indicating no dependence of RTS amplitude on trap position along the channel.

III. RESULTS AND DISCUSSION

Let us now examine the effect that trapping and de-trapping of an electron by an acceptor trap has on the performance of an actual device. The $n$-channel MOSFET simulated in this study has a gate oxide thickness of 5 nm, and a channel length and width of 0.1 and 2 $\mu$m, respectively. An ionic implantation with boron was considered for the substrate with a peak concentration of $3 \times 10^{17}$ cm$^{-3}$ at 0.1 $\mu$m from the Si–SiO$_2$ interface to control threshold voltage and avoid punch-through, while maintaining high electron mobility in the channel. The mobility curves simulated for this device are shown for $T = 88$ K in Fig. 3. The different curves represent the local longitudinal low-field mobility, $\mu_0(E||)$, obtained from a Monte Carlo calculation, that one electron has when: (1) the trap is empty; (2) the electron is under the influence of a negatively charged trap located inside the oxide at 15 Å from the interface; and (3) if the charged trap is placed right at the Si/SiO$_2$ interface. These curves are widely separated for the low effective-field regime because Coulomb scattering becomes dominant. When the effective field increases, the free carrier density rises, screening the charged trap and leading to higher Coulomb mobility. However, for high enough effective-field, phonon and surface-roughness scattering become dominant, reducing the electron mobility. Both contrary tendencies produce the peak observed in Fig. 3. It should also be noted how the depth of the charged trap in the oxide influences the mobility, as demonstrated by the difference between curves (2) and (3) in Fig. 3.

In our simulations, we have always supposed that the trap spends the same time in the charged and neutral state, namely, that the capture and emission times shown in Fig. 1 are equal. These conditions will be maintained throughout the paper since we shall not deal with time constants. Therefore, the average current and amplitude of the fluctuations can be defined as

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

where $I_0$ is the drain-to-source current when no charge is trapped, and $I_q$ is the current when the acceptor trap is occupied. $\Delta I$ is the difference between the two levels and $I$ is the average current, which drives along the device supposing the same time in each state.
\[ \Delta I \] can be thought of as the combined effect of carrier number fluctuation and mobility fluctuation. This fact may be expressed as

\[ \frac{\Delta I}{I} = \Phi_{\Delta n} + \Phi_{\Delta \mu} . \]  

(6)

The first term on the right-hand side of Eq. (6) indicates the relative current fluctuation evaluated when the mobility used corresponds with that calculated when the trap is empty, although the effect of the charged trap is included in the calculation of the inversion and depletion charges. On the other hand, the second term on the right-hand side of Eq. (6) indicates the relative current fluctuation calculated when the mobility used takes into account the effect of the negatively charged trap, although it is not considered in the calculation of the inversion and depletion charges. Expression (6) has the advantage of allowing us to obtain the relative contribution of the mobility and free-carrier fluctuations to the total discrete current switching. The different terms in Eq. (6) were evaluated at \( T = 88 \) K and \( V_{DS} = 1 \) mV and are shown in Fig. 4. Curve (1) corresponds to the total current fluctuation where mobility and carrier number fluctuations were simultaneously included. Curve (2) (dashed line) corresponds to the first term on the right-hand side Eq. (6) and curve (3) with the second term on the right-hand side of Eq. (6). Therefore, it is clear from Fig. 4 that mobility fluctuations play the main role in determining the behavior of RTS amplitude. This result is not surprising since it has been previously reported that the charged-trap-induced mobility fluctuation effect dominates \( 1/f \) noise performance of \( n \)-channel MOSFETs at low gate biases.29

In a previous work,\textsuperscript{30} it was shown that at room-temperature current fluctuation decreases when the inversion charge surpasses the depletion one. Nevertheless, for \( T = 88 \) K, the RTS amplitude decreases before the inversion charge overcomes the depletion one. Therefore, it can be concluded that a strong inversion operation is not necessary to reduce the amplitude of the normalized current fluctuations. These facts forced us to deliberate over the screening effect of the free carriers located in the channel on the charged trap. The influence of the screening on the carrier number fluctuation and mobility fluctuation has also been discussed, demonstrating the necessity of taking into account Coulomb-scattering screening to explain the behavior of the current fluctuations.

A. Influence on RTS amplitude of trap depth in the oxide

Channel carriers can be captured by traps located at different depths from the Si–SiO\textsubscript{2} interface, which also affects the RTS amplitude. To study this phenomenon, an acceptor trap was situated at two distances from the interface, at 15 Å and right at the interface. It is well known that electron scattering by charged centers quickly decreases when the charge is kept away from the interface and it has been proved that for charges placed at 100 Å or more from the interface, Coulomb scattering is negligible.\textsuperscript{31} This behavior was reproduced in our mobility calculations, as can be observed in Fig. 3, where curve (2) corresponds to a charged trap at 15 Å from the interface and curve (3) corresponds to a charged trap right at the interface. Figure 5 shows the relative amplitude of the current fluctuations evaluated for both situations. The solid line corresponds to the charged trap located right at the interface while the dashed line represents the charged trap inside the oxide. As may be seen from Fig. 5, the amplitude increases when the charge is nearer the channel, but this difference is reduced when the inversion-channel charge increases due to the fact that the growth in the number of

![FIG. 4. Normalized RTS amplitude vs drain current for a charged trap 15 Å from the interface. In curve (1), carrier number fluctuations and mobility fluctuations are simultaneously considered. In curve (2) (dashed line), the mobility used involves the effect of the negatively charged trap although it is not considered in the calculation of the inversion and depletion charges. In curve (3), the mobility always corresponds to the empty trap, and the influence of the charged trap is included in the calculation of the inversion and depletion charges (\( T = 88 \) K, \( V_{DS} = 1 \) mV).](image1)

![FIG. 5. RTS amplitude for a charged trap at different depths in the oxide. The solid line was obtained with the charge situated right at the Si–SiO\textsubscript{2} interface and the dashed line with the charge at 15 Å from the interface.](image2)
carriers in the channel screens the effect of the charged trap, and the curves tend to coincide. On the other hand, it seems clear from these results that different trap depths in the oxide can cause dispersion of the experimental values since the depth of the active traps in the oxide can be considered as a random variable. Nevertheless, there are other factors, such as the Si–SiO₂ interface imperfections, which simultaneously give rise to fluctuations in the RTS amplitude.

B. Influence of the gate and drain bias on RTS amplitude

In order to study the combined effect of the gate and drain voltages on RTS amplitude, we fixed the gate voltage at 0.5 V while the drain–source voltage was varied from 1 to 50 mV. Under these conditions, \( N_{\text{inv}} \) does not change too much and, thus, with a variable drain voltage, the normalized current fluctuations should be proportional to \( \rho \mu \), according to Eq. (1). In support of this argument, in Fig. 6 the normalized current fluctuations (solid line) were represented next to the average mobility (dashed line), defined as the electron mobility \( \mu \) calculated for each drain–source voltage divided by the low-field mobility \( \mu_{0} \). At low drain–source voltage, \( \mu \) is approximately the same as \( \mu_{0} \), but at higher values of \( V_{\text{DS}} \), the degradation of the mobility caused by the lateral field reduces its value with respect to the low-field mobility. It can be noted in Fig. 6 that both magnitudes have a similar dependence on drain-to-source voltage and, therefore, a strong correlation.

To check this assumption, the gate voltage was also varied. Three different gate voltages, 0.45, 0.5, and 0.55 V, were used and the corresponding normalized current fluctuations calculated as indicated in Fig. 7. As can be observed, the increase in gate voltage, and therefore, of the effective field, reduces the value of the normalized amplitude. To explain this behavior, two magnitudes have been defined:

\[ \Delta \mu = \mu_{0} - \mu, \quad \mu = \frac{\mu_{0} + \mu_{q}}{2}, \]

where \( \mu_{0} \) is the local mobility when no charges are present in the oxide and \( \mu_{q} \) is the local mobility when one electron has been captured by the acceptor trap. \( \Delta \mu \) is the difference between the local mobilities when the trap is charged or empty and \( \mu \) is the average mobility since the trap spends the same time in each state. Figure 8(a) plots the average electron mobility, \( \mu \), calculated for \( V_{\text{GS}} = 0.55 \) V, solid line, and for \( V_{\text{GS}} = 0.45 \) V, dashed line. It should be noted that, for the higher gate voltage, the mobility is greater due to the Coulomb scattering being reduced for higher transverse electric fields. Therefore, the dependence of the mobility versus gate voltage is opposite to the RTS amplitude shown in Fig. 7. In Fig. 8(b) the normalized mobility fluctuations, \( \Delta \mu/\mu \), have been represented for the two gate voltages, \( V_{\text{GS}} = 0.45 \) V, dashed line, and \( V_{\text{GS}} = 0.55 \) V, solid line, versus the drain–source voltage. As can be observed from Fig. 8, \( \Delta \mu/\mu \) reproduces the same behavior previously shown by the normalized current fluctuation where the curve for \( V_{\text{GS}} = 0.45 \) V is placed above the \( V_{\text{GS}} = 0.55 \) V curve. It has to be remembered that we are interested in the difference between the values obtained when no charge is present in the oxide and when the oxide trap is charged, not in its average value. Moreover, it can be appreciated from Figs. 7 and 8 that when the drain voltage increases, the degradation originated by the lateral field unifies all the curves and the differences between them disappear. So, we can conclude that the similarities in the behavior of the normalized current and mobility fluctuations demonstrate the importance of this noise generation mechanism.

To conclude, the procedure has been tested by calculating the scattering coefficient, \( \alpha \), defined in Eq. (2), which is an essential parameter to determine low-frequency noise characteristics. To do so, we started from Figs. 7 and 8. Under these conditions, with constant gate–source voltage and variable drain–source voltage, it is a plausible assumption to consider that the first term on the right-
hand side of Eq. (1) is approximately constant. Therefore, the difference between $\alpha I_{DS}/I_{DS}$ evaluated at two different values of $V_{DS}$ but for the same $V_{GS}$ are proportional to $\alpha \mu$. So, we do not need to know the electron density or oxide and depletion capacitance. Simply taking the values of $\alpha I_{DS}/I_{DS}$ from Fig. 7 and the mobility calculated for Fig. 8(a), the scattering coefficient can be easily obtained. For $V_{GS} = 0.45 \, \text{V}$ we obtained $\alpha = 5.5 \times 10^{-15} \, \text{V s}$ and for $V_{GS} = 0.55 \, \text{V}$, $\alpha$ was $3.5 \times 10^{-15} \, \text{V s}$. To check these values, we calculated the electron density in both cases in order to evaluate $\alpha$ with the empirical formulation proposed by Hung et al.$^{2,11}$ These results, above $10^{-15} \, \text{V s}$, were found to be in very good agreement with ours. Furthermore, it should be pointed out that Sun and Plummer$^8$ used a value of $\alpha = 2.36 \times 10^{-15} \, \text{V s}$ for modeling the oxide-charge scattering effect.

**IV. CONCLUSIONS**

We have carried out a complete study of RTS amplitude in submicron n-channel MOSFETs. To accomplish this purpose, a complete numerical simulator of these devices was developed. The contribution of the carrier number fluctuations and mobility fluctuations were separated in order to analyze their influence on the amplitude of the normalized current fluctuations. It has been shown that charged traps located right at the Si–SiO$_2$ interface produce higher RTS amplitude than deeper oxide charges. The role played by the screening of Coulomb scattering due to free-channel carriers has been studied, showing its importance to explain the behavior of current fluctuations. Moreover, a normalized mobility fluctuation was defined and evaluated and its dependence on the gate and drain voltages was taken into consideration. All these results highlight the importance of the electron mobility fluctuations on the total RTS amplitude. Finally, the scattering coefficient was calculated, and was found to show good agreement with data from other authors.

**ACKNOWLEDGMENT**

This work has been carried out within the framework of research Project No. TIC95-0511, supported by the Spanish Government (CICYT).

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