Modeling Fluctuations in the Threshold Voltage and ON-Current and Threshold Voltage Fluctuation due to Random Telegraph Noise

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***Abstract* - We investigate the influence of two traps in close proximity within one nanometer located at the semiconductor/oxide interface (positioned in the middle of the gate width and moved from the source end to the drain end of the channel) on the threshold voltage and the ON-current variation. We find that when one of the traps is located at the source end of the channel, the threshold voltage and the magnitude of the drain current are dominated by the potential barrier created by the negatively charged trap. When the trap is positioned at the drain-end of the channel, the barrier effect is smaller and screening (for small drain bias) and the absence of screening (at large drain bias due to the presence of the pinch-off region) determine whether current will be degraded or not.**

I. INTRODUCTION

In very small electronic devices the alternate capture and emission of carriers at an individual defect site generates discrete switching in the device conductance referred to as a random telegraph signal (RTS) or random telegraph noise (RTN) [1]. The study of RTS has provided a powerful means of investigating the capture and emission kinetics of single defect in addition to demonstrating the possible microscopic origins of low frequency 1/f noise in these devices and also providing new insight into the nature of defects at an interface. With each generation of device scaling, the total number of active dopants in the channel region decreases to the extent that, when the device gate length is scaled below sub-100 nm, the dopant distribution can be considered random where the channel is formed. Consequently, a few defects at the Si/SiO_2 interface or inside the SiO_2 dielectric are sufficient to cause severe RTS related device failure when the dopant distribution becomes fully random across the channel region. For instance, Fig. 1 illustrates the measurement data from a 90nm SRAM design [2]. The minimum supply voltage (V_{ccmin}), which is highly sensitive to device threshold voltage, exhibits a similar pattern in the time domain as that of random telegraph noise fluctuation (RTF). The impact of RTF in this case is more than 200mV, which is catastrophic to the yield and low-power design of SRAM. Therefore, accurate and physical models of RTF are essential to predict and optimize circuit performance during the design stage. The compound between RTF and other sources of variation, such as random dopant fluctuations (RDF) in active channel region and underlying depletion comprising of random bulk dopant ions, further complicates the situation especially in extremely scaled CMOS design.

In this research work the integration of random defects positioned across the channel at the Si/SiO_2 interface from source end to the drain end in the presence of different random channel and bulk dopant distributions are used to conduct Ensemble Monte-Carlo (EMC) based numerical simulation of key device performance metrics for 45 nm gate length MOSFET device.

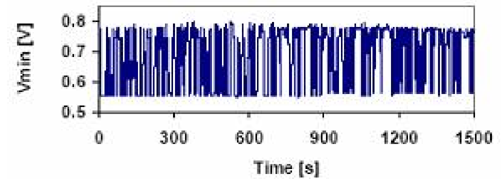

Fig. 1. The fluctuation of SRAM V_{ccmin} due to RTF.

The two main performance parameters that affect RTS based reliability measurements are percentage change in relative drain current fluctuation, particularly in the saturation region where most digital circuits operate, and percentage change in threshold voltage that affects the device transconductance and on-current drive. It has been observed via our simulations that changes in both ON-current and the threshold voltage values rapidly decrease as the defect position is gradually moved from source end to the drain end of the channel.

II. THEORETICAL MODEL

With the down-scaling of MOSFET devices, electrons in the conducting channel are in ever closer proximity to the high-density electron gases present in the source and drain regions—separated from each other by as little as tens of nanometers—and in the polycrystalline Si gate—separated from the channel by as little as 1.5 nm of SiO_2. As studied in [3], the role of these long-range Coulomb interactions is two-fold: (1) The interaction between electrons in the channel and the high-density electron gases in the source and drain regions can be pictured classically as a reshaping of the electron distribution in the channel caused by the potential-fluctuations, associated with plasma oscillations in the source and drain regions, leaking into the low-density channel. Quantum-mechanically, this corresponds to emission and absorption of plasmons by the channel electrons. While these processes do not subtract directly momentum from the electron gas, their net effect is a thermalization of the hot electrons energy distribution in the

channel, the resulting higher energy tail being affected by additional momentum-relaxation processes (phonons, ionized impurities). This causes, indirectly, a reduction of the effective electron velocity in the channel, and so, a depression of the transconductance as the channel length is reduced below about 4 nm. On the other hand, (2) the interaction between channel-electrons and electrons in the gate (Coulomb drag across the very thin insulator) results in a direct loss of momentum of the electrons in the channel. Semi-classically, this interaction—also plasmon-mediated—has been studied by a group at IBM [4] predicting a significant depression of the electron velocity for SiO_2 layers thinner than about 2–3 nm. This behavior has also been observed experimentally [5], recent results being in quantitative agreement with early theoretical estimates.

In the past, the effect of discrete dopant random distribution in MOSFET channel has been assessed by analytical or drift-diffusion (DD) approaches. The first DD study consisted in using a stochastically fluctuating dopant distribution obeying Poisson statistics [6]. Three dimensional atomistic simulators have also been developed for studying threshold voltage fluctuations [7-8]. Even though the DD/HD (hydrodynamic) methods are very useful because of their simplicity and fast computing times, it is not at all clear whether such macroscopic simulation schemes can be exploited into the atomistic regime. In fact, it is not at all clear how such discrete electrons and impurities are modeled in macroscopic device simulations due to the long-range nature of the Coulomb potential. 3D DD/HD macroscopic models may be accurate for modeling the threshold voltage fluctuations (since the device is in the off-state) but they are definitely not accurate when examining the on-state current fluctuations.

Three-dimensional Monte Carlo (MC) simulations should provide a more realistic transport description in ultra-short MOSFETs, in particular in the on-state. The MC procedure gives an exact solution of the Boltzmann transport equation. It, thus, correctly describes the non-stationary transport conditions. Even if microscopic simulations such as the MC method are concerned, the treatment of the electrons and impurities is not straightforward due to, again, the long-range nature of the Coulomb potential. The incorporation of the long-range Coulomb potential in the MC method has been a long-standing issue [9]. This problem is, in general, avoided by assuming that the electrons and the impurities are always screened by the other carriers so that the long-range part of the Coulomb interaction is effectively suppressed. The complexity of the MC simulation increases as one takes into account more complicated screening processes by using the dynamical and wave-vector dependent dielectric function obtained from, for example, the random phase approximation. Indeed, screening is a very complicated many-body matter [10].

A novel approach has been introduced by the ASU group, in which the MC method is supplemented by a *molecular dynamics* (MD) routine [11]. In this approach, the mutual Coulomb interaction among electrons and impurities is treated in the drift part of the MC transport kernel. Indeed, the various aspects associated with the Coulomb interaction, such as dynamical screening and multiple scatterings, are automatically taken into account. Since a part of the Coulomb interaction is already taken into account by the solution of the Poisson equation, the MD treatment of the Coulomb interaction is restricted only to the limited area near the charged particles. *It is claimed that the full incorporation of the Coulomb interaction is indispensable to reproduce the correct electron mobility in highly doped silicon samples*.

III. Simulation Results

The simulator described in the previous section is presently being used in the investigation of the random trap fluctuations in 45 nm technology node MOSFET device where, in addition to the randomness of the position and the actual number of the impurity atoms in the whole simulated domain of the device, a random trap is introduced in the middle section of the channel and moved from the source-end to the drain end of the channel. An example of a discrete impurity pattern and a trap located at the source-end of the channel is shown in Fig. 2. The effective channel length of 45 nm technology node is taken to be 35 nm.

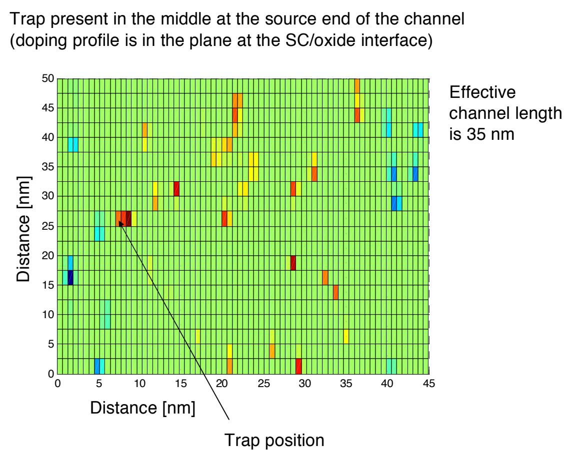

Fig. 2. Random dopant distribution and a trap located the middle of the source end of the channel.

We consider ensemble of 20 devices with different random dopant distribution. The threshold voltage of each of these devices without the presence of the trap is shown in Fig. 3.

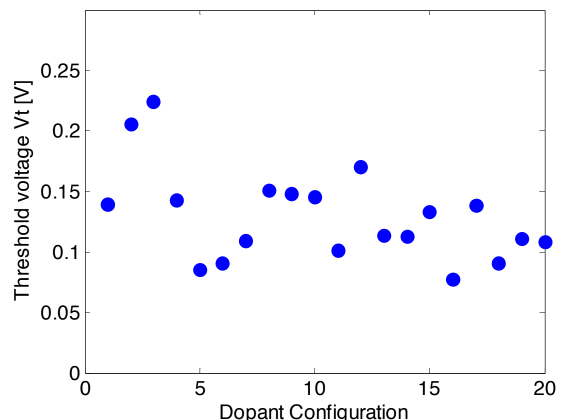

Fig. 3 Threshod voltage fluctuations due to random dopant fluctuations (without traps) for a statistical ensemble of 20 devices with different number and different distribution of the impurity atoms.

The total variation of the threshold voltage as a function of the trap position in the middle portion of the channel, when double-trap is moved from the source end to the drain end of the channel, is shown in Fig. 4. We see that the threshold voltage increases from its average value when the double-trap is located at the source end of the channel. This is due to the fact that carriers see additional large potential barrier due to the presence of the charged trap and are reflected back in the source contact. The threshold voltage reduces when the double-trap is moved away from the source injection barrier because when the electrons are injected in the channel, even though the electric field is small (due to small drain bias applied when measuring threshold voltage) they slowly drift towards the drain contact.

In Fig. 5 we depict the threshold voltage fluctuation taken as a percentage relative to the values in Fig. 3 as a function of the

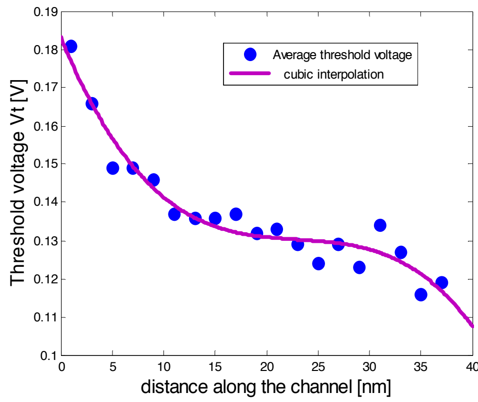

Fig. 4. Threshold voltage variation with trap position variation. (These results are averages over the ensemble of 20 devices).

trap position when trap is being moved from the middle of the source end of the channel to the middle of the drain end of the channel. An explanation of the results given in Fig. 5 is schematically shown in Fig. 6.

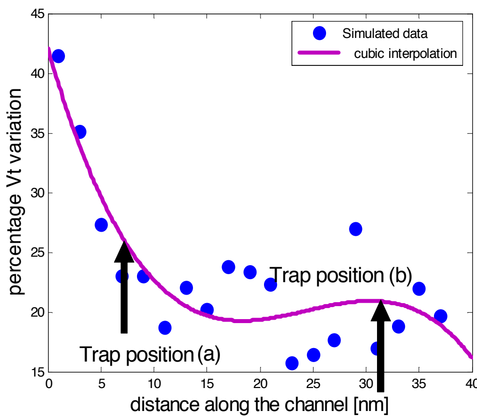

Fig. 5. Percentage threshold voltage due to trap located at the semiconductor/oxide interface and different positions along the middle section of the channel. 20 devices with different random dopant distributions have been averaged out..

At threshold voltage, the sheet electron density in the channel is small, therefore screening is not important. Traps near the source end of the channel have the largest influence since they are major obstacles to the electrons because of the large input barrier depicted in case (a) shown on the left panel of Fig. 6. Traps near the drain end of the channel have smaller influence since electrons are accelerated by the small electric field – case (b) shown on the right panel of Fig. 6.

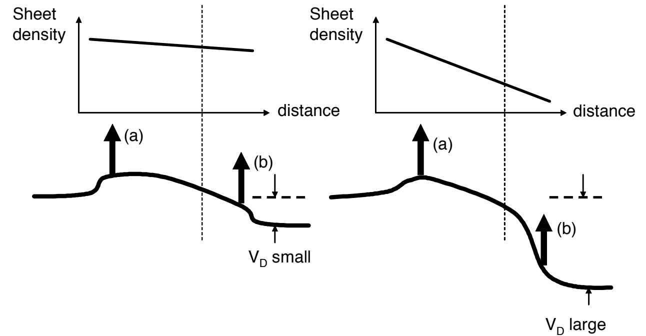

Fig. 6. Schematic explanations of the results presented in Fig. 5.

Fig. 7 shows the ON-current degradation as a function of the double-trap position. As depicted on the figure, near the source end of the channel the current degradation due to the presence of a negatively charged trap is large because the trap introduces additional barrier for the current flow. When the trap is in the middle section of the channel the current degradation is smaller. Traps near the drain contact, where the electron density is pinched off for the bias conditions used, are not effectively screened and a notable increase of the current degradation is observed. At the drain contact, the degradation drops practically to zero because there traps are effectively screened by the electrons. The expected current trends under small and large drain voltages are explained in Fig. 8.

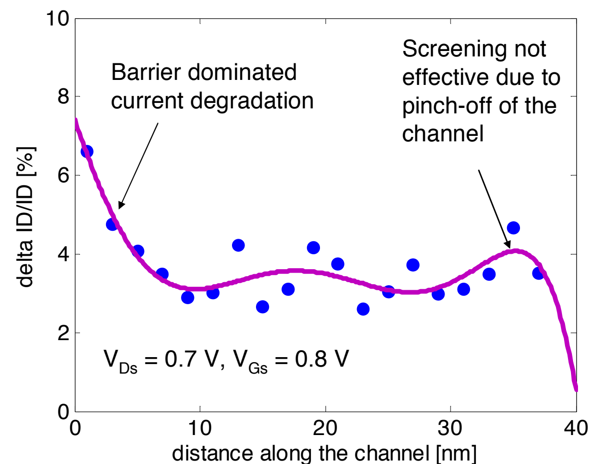

Fig. 7. ON current degradation as a function of trap position. The statistical ensemble used here consists of first seven random dopant distributions in both number and positions within the active region of the channel.

The threshold voltage standard deviation, averaged out for all 20 different random dopants analyzed as a function of trap position is shown in Fig. 9. The simulation result confirms that when a significant number of dopant distributions are used as a parameter in the EMC simulation, the standard deviation fluctuation is well controlled and strongly coherent over different trap positions which has a beneficial impact on device performance from reliability standpoint.

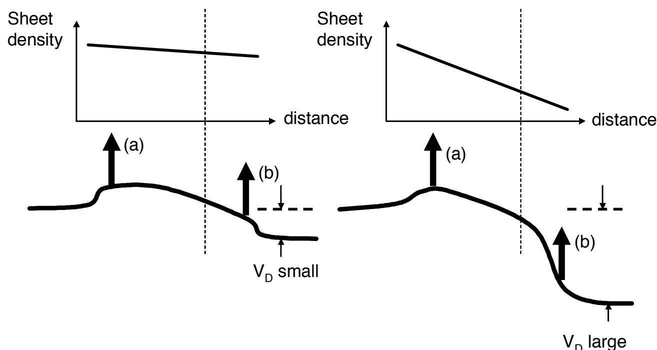

Fig. 8. Under small gate and drain bias, we have the situation depicted in Fig. 6. For large gate bias: (a) the sheet density increases which means that screening increases; (b) traps near the drain are surrounded with large number of electrons for small V_D, therefore screening of the Coulomb potential is large and there is smaller degradation of the current; (c) for large V_D traps near the drain are surrounded with smaller number of electrons, therefore screening is smaller and we have larger ID degradation.

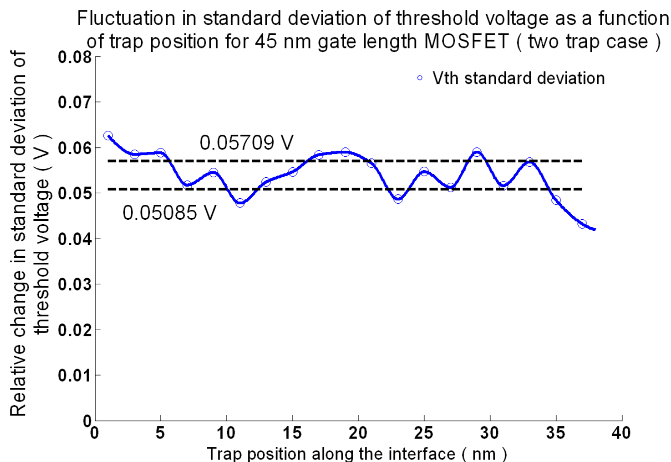

Fig. 9. Threshold voltage standard deviation as a function of trap position showing well behaved spatial correlation when sufficient number of random dopants are considered.

IV. CONCLUSIONS

Unlike most of the analytical revelation of published articles, where it has been reported that fluctuation in drain current amplitude variation and threshold voltage variation tend to diminish at strong inversion and saturation bias conditions imposing higher gate and drain bias owing to the screened out potential due to high inversion charge density at the surface with associated improvement of Coulombic-scattering related mobility, our simulations conducted at saturation bias conditions on a 45 nm MOSFET reveal that for different random dopant distributions in the channel and bulk, the fluctuation pattern exhibited by the drain current amplitude variation and the threshold voltage variation are truly statistical and random in nature, i.e., for some specific random dopant distributions, the fluctuation nature is well controlled whereas for some other random dopants, the fluctuation pattern shows significant transitions between local peak and valleys. From our EMC simulation, it has been demonstrated the fluctuations in drain current amplitude and threshold voltage have been dependent on particular random dopant distribution type, i.e, its number within the channel area and its position, in addition having strong correlation on strategically positioned interface traps along the channel from source to drain. In order to truly represent the amplitude variation to show more dependence on spatial positioning of trap than specific random dopant type, the expectation value of the statistic (drain current or threshold voltage amplitude change) or the average term needs to be studied out of a significant number of possible random channel dopant distributions.

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