Comparative Analysis of Threshold Voltage Variations in Presence of Random Channel Dopants And A Single Random Interface Trap for 45 nm n-MOSFET As Predicted By Ensemble Monte Carlo Simulation And Existing Analytical Model Expressions

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ABSTRACT

Proper analytical physically based model to predict fluctuations in the threshold voltage due to a single interface trap at a random location along the channel in a typical sub-50 nm MOSFET is of utmost significance. This research summary compares the efficacy of the existing analytical model based on dopant number fluctuation estimation in the channel of a MOSFET when compared to 3D Ensemble Monte Carlo (EMC) device simulation model in the presence of a random interface trap in the channel between the source and drain regions. The gate length of the nMOSFET device being investigated is 45 nm and the effective channel length is 32 nm. We demonstrate, for the first time, the shortcomings of the analytical models in capturing the short range Coulomb force interactions when the interface trap is located near the source end of the channel.

Keywords: random dopant fluctuations, random interface trap, threshold voltage variations, short range Coulomb interactions, 3D Monte Carlo device simulations

1 INTRODUCTION

Random telegraph noise fluctuation (RTF) manifests itself as the fluctuation in transistor threshold voltage (V_T) and drive (on) current. Accurate and physical models for RTF are essential to predict and optimize circuit performance during the design stage [1]. Currently, such models are not available for circuit simulation. The compound between RTF and other sources of variation, such as random dopant fluctuations (RDF), further complicates the situation especially in extremely scaled CMOS design. In the vicinity of a trap site, the electrostatic short range Coulomb forces between a trap, a number of carriers in flow within the trap's boundary and dopant ions just underneath the channel in the depletion region, modify the electrostatic surface potential in the channel from source to drain in spatially random and discrete manner. Accurate replication of these multiple peaks and valleys of the surface potential is critical to be accounted for by the analytical models for inversion conditions and when spatial inhomogeneity exists due to interface trap, inversion carriers and depletion region dopant ions. This aspect is not presently accounted for by most analytical device models including the models presented in Refs. [2-3] that are related to the present research.

This article first outlines the procedure for the computation of the threshold voltage (V_T) and its variations, by use of an existing analytical model given in Ref. [2] that is most cited in literature, in the presence of random interface trap in the channel region of a 45 nm MOSFET device with an effective channel length of 32 nm for a statistically different set of twenty random dopant configurations in the channel and bulk region of the MOSFET. Next the V_T estimation and its variations are calculated using 3D Ensemble Monte Carlo (EMC) based device simulation model [4-5] for the same set of random dopant configurations. Simulation results from the EMC device simulations for the cases of: (i) inclusion of short range electron-electron and electron-ion based Coulomb force interactions, and (ii) exclusion of the short range Coulomb force interactions. Extracted threshold voltages V_T are compared with the analytical model currently studied in this paper (Ref. [2]).

This analysis is followed by the presentation of results of V_T fluctuation analysis (induced by static interface trap in the presence of random channel dopant configurations) [3]. Comparisons are shown between the 3D EMC device simulation model results and the present analytical model results. These results suggest that there is a need of accurate short range Coulomb force interactions modeling to properly account for proper transport situation that exists at inversion condition at threshold when an interface trap is positioned near the source end of the channel of a MOSFET (and can alter the trapping and drift velocity of carriers injected from the source side affecting both the threshold voltage and the device transconductance). The concluding section, in addition to summarizing the above results, explains the shortcomings of the existing analytical model to explain the relative threshold voltage fluctuations induced by source-side trap positions at the interface when compared against 3D Ensemble Monte Carlo device simulation results.

2 DESCRIPTION OF ANALYTICAL MODELS

To properly account for the random number and position of the dopant ions in the depletion region of the channel, the model presented in Ref. [2] accomplishes this in the following manner. The simulation domain is divided into small boxes by discretizing the channel length and width into small square cells of dimension *l* with a volume assisted by the depth of X that extends from the channel to ideally the maximum depletion width. The random dopant ions are positioned in each of these cell volumes in random number and assortment that is based on the uniform nominal doping density. Thus, the number of dopant ions that can reside in a volume cell is dependent on the dimensions of the cell (square dimension *l* and depth dimension *X*). If this number is too small and close to unity, the calculated V_T will be too small and almost invariant from cell to cell. Therefore, the volume of the cell of dimension *l* and X for this research report are chosen in a way that when a certain random dopant configuration is used to distribute the dopant ions in the cell volume, a dopant number variation up to a maximum of 4 can be expected to reside in the cell. The required device parameters for the 45 nm physical gate length MOSFET are *L* (gate length) = 45 nm, *W* (gate width) = 50 nm, t_{ox} (oxide depth) = 0.9 nm and $N_A = 8.9\times10^{24}$ m^{-3}. We have shown earlier that V_T variation for a typical channel random dopant correlates to a few nm depth from the interface [6]. With the above information, the designed cell dimensions are computed to be l = 10 nm and X = 4.5 nm retrenched from the maximum possible depletion depth of W_{max} = 12.34 nm. The calculated threshold voltage V_T values using the expressions given in Ref. [2] are summarized in Table 1. After calculating the local cell threshold voltage from its dopant number value, all the threshold voltage values from all the cells in a 2D array have been averaged to extract the final form of threshold voltage for a particular random dopant configuration.

Number of atoms in the cell	Threshold Voltage (V)
0	0.0000
1	0.0218
2	0.1178
3	0.1919
4	0.2546

Table 1: The calculated threshold voltage values for dopant number distributions as arranged in the cell.

Once the reference V_T values for different random dopant type and distributions as arranged in the cells of the discretized channel region are extracted using the procedure described in Ref. [2], we have used the results from Ref. [3] to calculate the threshold voltage V_T fluctuation percentage for an interface trap positioned along the channel from source to drain of an effective 32 nm channel length nMOSFET. Since single interface traps are taken to be at locations that are 2 nm apart, the length *l* of the cell is now reduced to 2 nm while the width l' (different from square cell) is kept at 10 nm. This places a maximum of 2 atoms per cell for a particular trap to interact with. Since the random interface trap is located at the middle of the gate width, the cell left edge in the width direction is 20 nm and the right edge is at 30 nm (where an interface trap can be found) to accommodate the required 25 nm gate width point with a margin of ± 5 nm. A typical pictorial arrangement for random dopant ions as distributed and assorted in cellular array with a random interface trap is shown in Figure 1 where, for simplicity, the rather long arrangement of cells in the length direction for 2 nm case has been supplanted by previous 10 nm cell dimension in the channel length direction.

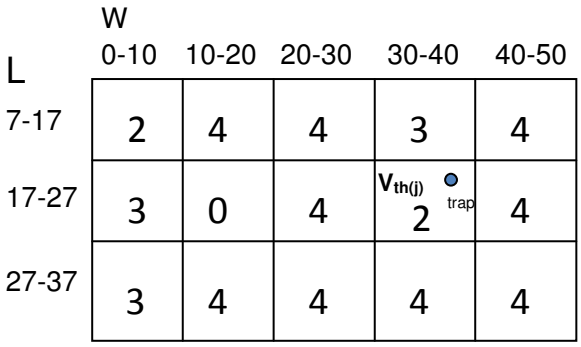

Figure 1: Cellular arrangement of random dopant ions (designated by integer numbers) and an interface trap located at a particular gate width (horizontal) and channel (vertical) direction positioned cell.

In the original cellular arrangement in the channel direction where the trap is spaced 2 nm along the channel from one position to the next, first the trap's position in the j^{th} location of the cell is determined from its channel direction position and gate width direction (which is always 20-30 nm cell in the *W* direction). Since the actual random dopant number present inside the j^{th} cell can vary from 0-2, based on this fact, the corresponding V_T (j) is computed as per equations given in the analytical model from Ref. [3]. Then for a particular trap, as described for a designated random dopant type using the equations detailed in the Ref. [3], calculation of threshold voltage difference ΔV_T from reference V_T and threshold voltage when trap is positioned at a particular channel site $V_T(j)$ for a particular random dopant distribution of the channel and bulk is extracted. Similar values are computed for all trap positions within the

32 nm channel length and for the set of 20 random dopant distributions. From ΔV_T values the fluctuation percentage relative to reference V_T value (Ref. [2]), for a particular random dopant type in presence of a particular interface trap position, is generated. Next, average over fluctuation percentage values is made over all random channel and bulk dopant distributions for a particular interface trap position along the channel from source to drain.

3 3D EMC DEVICE SIMULATION MODEL

For accurate representation of trap's random trapping and detrapping of channel carriers in a temporal way, EMC device simulation is not the method of choice. This is due to the fact that in real time, capture and emission processes are of a few milliseconds to a second range. On the other hand, the EMC device simulation time for steady state convergence cannot be reduced below a few nanoseconds and time dependent capture and, therefore, capture and emission process cannot be properly modeled by the EMC simulation scheme. Therefore, in the EMC simulation study presently conducted, the trap is modeled as a static negative charge. The short range Coulomb interaction in the development of this 3D EMC simulation model is accounted for by using a *molecular dynamics* (MD) routine [4-5]. Within this approach, the mutual Coulomb interaction amongst 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. For the case of EMC simulation run excluding the short range e-e and e-ion-trap Coulomb interactions, the MD treatment is omitted and direct solution of Poisson's equation on a finite difference mesh is computed.

The threshold voltages for all the different random dopant distributions for EMC simulation model as detailed above, were calculated from a reference current value which was computed from the drain current-gate voltage data statistics in the vicinity of low to moderate gate voltages at a low fixed drain bias voltage. The gate voltage (distinctive for a particular random dopant configuration) at this fixed reference current value has been attributed to be the threshold voltage for that random dopant configuration.

4 SIMULATION RESULTS

Figure 2 shows the computed threshold voltage values for the cases of analytical model and EMC simulation where (1) the actual short range interactions between the electron-electron and electron-ion are included, and (2) the short range force corrections are omitted. From the standard deviation of the threshold voltage values calculated for the above three cases, we find σV_{th} (analytical) of 0.0218 V, in excellent agreement with σV_{th} value of 0.0205 V extracted by EMC simulation result when short range Coulomb force corrections are omitted. This is the expected outcome when the short range spatial Coulomb interaction is excluded for a trap's interactions with neighboring channel carriers and dopant ions surrounding it as the long range part of the Coulomb interactions is obtained from the solution of the Poisson equation, identically with what has been done with the dopant number fluctuation model. Figure 3 illustrates the threshold voltage fluctuation extracted from analytical model, adjusted for trap's interactions with channel electrons inverted at threshold conditions, and also for EMC device simulation where usual short range interactions between trap-electron-electron and trap-electron-ion are accounted for. From the results presented in Figure 3 we conclude that the analytical model results deviates from the EMC simulation model data mostly at the source side trap positions, where short range Coulomb force can largely impact electron flow towards the drain. As the trap is moved from channel center gradually towards the drain side, electrons gather sufficient kinetic energy to surpass the trap's Coulombic barrier and, threfore, V_{th} fluctuations at these positions vary within a reasonable small tolerance limit.

5 CONCLUSIONS

In this paper it is shown that the existing analytical models, that are extensively used it the literature to extract V_T values and its fluctuations in presence of random interface trap and random channel dopant distributions, are semiaccurate only for the case when the trap is far away from the source injection barrier. We find that significant mobility degradation effects result from the short range Coulomb force interaction based surface potential fluctuations induced by a random interface trap near the source end of the channel. We have estimated these mobility fluctuations from trap's presence and derived a model that improves both the model given in Ref. [2] and the model given in Ref. [3]. The detailed description of this newly derived analytical model will be presented elsewhere.

ACKNOWLEDGEMENTS

The authors would like to thank Professor Gilson Wirth from UFRGS, Porto Alegre, Brazil, and Dr. Srinivasan Purushothaman from Texas Instruments, Dalas, TX. Their valuable comments have significantly improved the content of this manuscript.

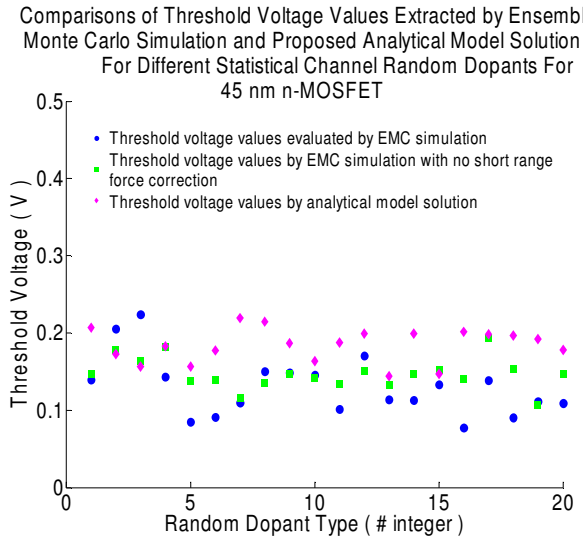

Figure 2: Threshold voltage variations computed with the proposed analytical model and EMC simulation with and without short range force corrections.

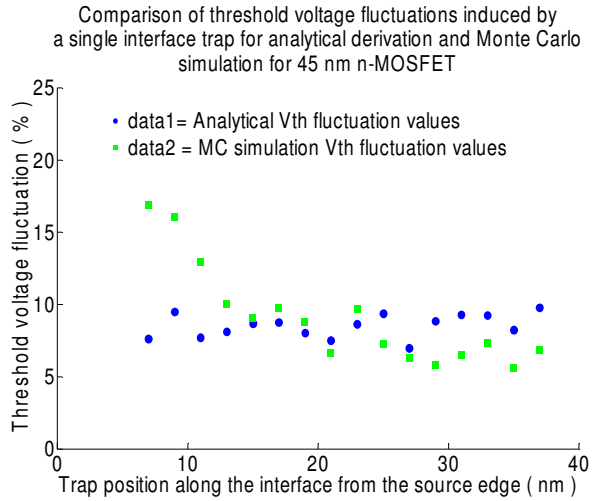

Figure 3: Threshold voltage fluctuations computed by the additional analytical model adjusted for random interface trap's interactions with channel electrons and EMC simulation method.

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