Impact of Scattering on Random Dopant Induced Current Fluctuations in Decanano MOSFETs

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Abstract

Intrinsic parameter fluctuations associated with random discrete dopants play an increasingly important role in next generation MOSFETs with nanometre scale dimensions. Such fluctuations already start to adversely affect the yield and the scalability of important circuit components like SRAM cells. Therefore it is crucially important to examine, by means of predictive simulations, the magnitude of such fluctuations in next generation technology nodes in order to foresee the implications for future circuit and system design. In this paper we use both Monte Carlo and Drift Diffusion simulations to separate and highlight the impact of electrostatic and transport effects on the drive current variation in decanano MOSFETs due to random discrete dopant configurations.

1 Introduction

Until now simulation studies of random dopant fluctuation effects have been predominantly performed using 3D Drift-Diffusion (DD) simulators [1,2,3]. Such simulations only capture the electrostatic effects associated with random discrete dopant distributions in providing an estimate for the variations in the threshold voltage and the drive current. However, the DD simulations cannot capture the complex effects associated with the variation in carrier transport, from device to device, associated with the different numbers and configuration of ionized dopants within the channel that act as Coulomb scattering centres in a non self-averaging manner. Therefore the published results for the variation in the drive current obtained from DD simulation most probably under estimate the real magnitude of the intrinsic parameter variations.

Although *ab initio* Coulomb scattering from ionized impurities through the real space carrier trajectories has previously been included in 3D ensemble Monte Carlo (MC) simulations [4,5,6], little statistical analysis has been performed with such simulators. Until now, no results have been published comparing the impact of the variation of numbers and position of coulomb scattering centres in the channel on the current fluctuations, with their electrostatic impact on the current percolation paths within the device. In this paper using a careful comparison between DD and MC (including *ab initio* Coulomb scattering) simulations of MOSFETs with different discrete dopant configurations, we investigate and highlight the relative importance of

the electrostatic and scattering effects when studying random dopant induced intrinsic parameter variations.

2 Methodology

In our 3D ensemble MC simulations ionized impurity scattering is removed from the conventional scattering rate tables and introduced through the real space trajectories of the electrons moving in the electrostatic potential of the individual discrete dopants. This requires a correction to be applied at short range to the mesh calculated force to account for aliasing in the mesh solution of Poisson's equation [7]. Interpolating the electric field from the mesh alone underestimates the magnitude of the Coulomb force thus diminishing the ability of the charge to act as a scattering centre and artificially increasing mobility. As illustrated in Fig.1 our *ab initio* approach of introducing impurity scattering closely reproduces the dopant concentration dependence of the mobility in Silicon.

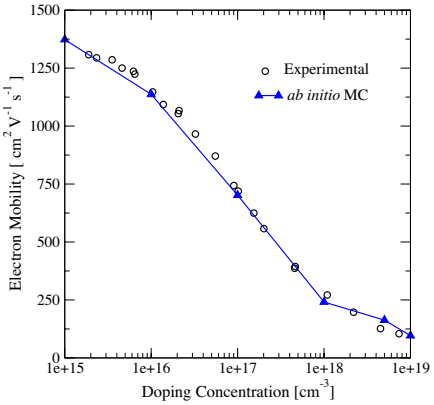

Fig.1: Concentration dependent mobility results using *ab initio* and impurity scattering rates Monte Carlo simulations compared with experimental values.

3 Results

To gain an initial understanding for the importance of scattering when calculating current variation, due to discrete dopants, we have studied the impact of a single negative charge trapped in the middle of the channel of a 30×30nm *n*-MOSFET, with otherwise continuous doping. The study was carried out at low applied drain voltage of 0.05V in a frozen field approximation. The introduction of this single trapped charge results in reduction in the drain current in both DD and MC simulations, although the reduction in the MC simulations is significantly larger. In the DD simulations at low-gate voltage the inversion layer density reduction in the vicinity of the trapped charge is large due to the absence of screening, resulting in a large reduction in the drive current. At higher gate voltage the screening from the inversion layer around the trapped charge becomes more effective and the region affected by

the trapped charge becomes more localised, reducing its impact on the current. The result is a reduction in the relative current change with the increase of the applied gate voltage to strong inversion conditions, as shown in Fig.2. While the results form the MC simulations, also presented in Fig.2, exhibit the same trend as those from the DD simulations the reduction in current is consistently larger. This is because the MC simulations capture not only the electrostatic exclusion of inversion layer charge, associated with the screened Coulomb potential of the single trapped charge, but also its impact on the current due to additional Coulomb scattering. The presence of the additional scattering centre results in a significant reduction in the average carrier velocity within the channel. As illustrated in Fig.3, the effect extends from source to drain, being most significant in the vicinity of the trapped charge. The reduction is more pronounced at lower gate voltage. This reduction in the average carrier velocity, through additional scattering, results in larger reduction in drive-current in the MC simulations as compared to DD simulations.

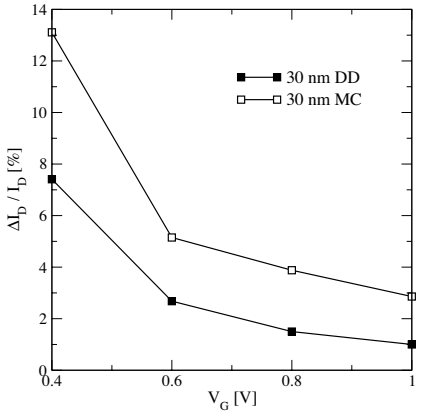

Fig.2: Percentage reduction in drive-current upon introducing a trapped charge in the centre of the channel. Results for Drift-Diffusion (DD) and Monte Carlo (MC) are shown for a 30nm channel length *n*-MOSFET at V_D= 0.05V

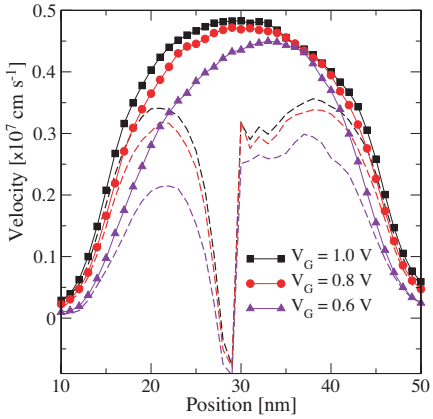

Fig.3: Velocity profile though position of trapped charge, placed at 30 nm, with and without the charge present for different gate voltages.

Further to this we have studied the relative change in the current calculated using DD and MC for three 30×30nm MOSFETs with different atomistic dopant configurations in the channel. These devices are chosen from an ensemble of 200 microscopically different devices to have the highest, lowest and average threshold voltage in the ensemble. The average carrier velocity distribution in the channel of the transistors is shown in Fig.4.

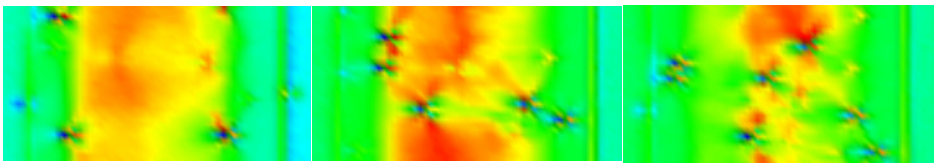

Fig.4: Channel velocity for 3 atomistic MOSFETs with: (left) low, (middle) average and (right) high threshold voltage (blue=low velocity; red=high velocity).

We have calculated at low drain voltage (V_D=0.05V) the percentage change in drive current due to the atomistic doping using both DD and MC. From the results summarized in Table 1, it is clear that the *ab initio* inclusion of impurity scattering due to discrete dopants in the MC simulations results in a significant increase in the current variation.

	$\Delta I_D/I_D$ (Low V_T)	$\Delta I_D/I_D$ (Average V_T)	$\Delta I_D/I_D$ (High V_T)
Drift-Diffusion	7.65%	2.91%	-8.60%
Monte Carlo	24.5%	13.2%	-12.9%

Table 1: $\Delta I_D / I_D$ $[(I_{D\ atomistic} - I_{D\ continuous})/I_{D\ continuous}]$ for the 3 atomistic MOSFETs shown in figure 4, comparing DD to MC. (V_D=0.05V, V_G=1V)

4 Conclusions

We have performed both MC and DD simulations to study the variation in drive current due to discrete dopants in decanano MOSFETs. By carefully comparing the results from DD and MC we have been able to separate the influence of both electrostatic and carrier transport effects due to the presence of random discrete dopants in the simulations. We have studied both the case of a single trapped charge in the centre of a 30nm MOSFET, as well as a fully atomistic channel MOSFET. In both cases the variation in the current obtain from MC is greater than that obtained from DD (by a factor of two or more in some cases. It is clear that both the electrostatic and carrier transport effects due to discrete random dopants are important in determining the variation in the device characteristics, each playing a dominant role in particular operation conditions.

References

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