MONTE CARLO MODELLING OF ELECTRON TRANSPORT IN SI QUANTUM-WIRE DOUBLE-GATE MOSFETs IN PRESENCE OF ATOMISTIC IMPURITIES

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Silicon nanowire multiple-gate MOSFETs are now-a-days accepted as one of the most promising candidates to achieve with success the next future CMOS technology requirements. In one hand, the addition of multiple-gate structures to the near vicinity of the extremely thin nanowire channels offers an exceptional electrostatic robustness that prevents from the jeopardizing short-channel effects. On the other hand, multiple-gate MOSFETs do not require channel doping to operate, and in this sense, such structures are inherently more resistant to random dopant fluctuation effects than conventional single-gate MOSFETs [1]. Nevertheless, with regard to this second point, even "undoped" channels can contain doping atoms arising from contamination or from Source/Drain implantation processes. Due to the random nature of such processes, the number and position of doping atoms are subject to stochastic variations, and consequently, differences between particular members of a same technology appear [2].

The origin of random doping fluctuations effects is fundamentally electrostatic. In this sense, the importance of properly treating the short-range Coulomb forces is particularly relevant when the channel of nanoscale MOSFETs is reduced to a few nanometres. Although the electron-impurity interaction has been treated more or less accurately in previous works devoted to investigate this topic, electron-electron interactions are usually approximated or simply ignored [3,4]. In the present work we take up again this topic describing the electrostatics by means of a classical many-particle electron transport formalism (Monte Carlo like) that goes beyond the standard "mean field" approximation [5]. In particular, we compute the electron dynamics by solving a different 3D Poisson equation for each particular i-electron (with a particular charge density and boundary conditions for each electron) that avoids the consideration of its own charge and considers, without any approximation, not only the electron-impurity interaction, but also the electro-electron correlations.

Here we evaluate the relevance of the random doping fluctuation effects within the main characteristics of a double-gate quantum-wire MOSFET (see fig. 1) by placing single ionized impurities, positive or negative, in three different places along its channel (centred in lateral directions). Fig. 2 shows the mean current through the active region of the nanowire as a function of the applied gate voltage, V_{Gate}, in the saturation region (V_{Drain}=0.5V). Caused by the potential barrier associated to a negative dopant within the channel and the potential well associated to a positive one, negative impurities present higher threshold voltages than positive ones. It can be also observed that negative ions are more effective in blockading current when they are closer to the source contact (and vice versa for positive impurities). Fig. 3 shows the current density distribution in a particular slice located at the position of the positive/negative impurity (which is situated at the source-channel interface). Notice that while the positive impurity does not cause any relevant deformation on the current density distribution (fig. 3.a), the negative one produces not only a reduction on the maximum value of the current density, but also an important deformation of its spatial distribution, pushing carrier dynamics away its location (fig. 3.b). It is important to remark that, due to lateral confinement, the injection of carriers obeys a sinusoidal spatial distribution centred on "y" and "z" dimensions that causes volume inversion along the channel. Finally, the probability of an electron injected from the source contact to achieve the drain contact (i.e. transmission) is presented in figure 4 as a function of its injection energy (i.e. the kinetic energy of the electron when it is situated at the source-channel interface) for V_{Gate}=0 and V_{Drain}=0.5V. In particular, the transmission is computed in presence of a negative impurity at different positions along the channel. Although the transmission is increased as the dopant is moved from source to drain at low energies, this order is lost for higher energies. This interesting effect is a particular characteristic of the many-particle systems, which allow energy interchange between particles as they move along the channel. As the ionized impurity is moved from source to drain, the time elapsed between the injection of an electron at the source and the achievement of the impurity position is increased. Therefore, such an electron will interact more and more with the rest of carriers as the ionized atom is moved toward the drain contact.

References:

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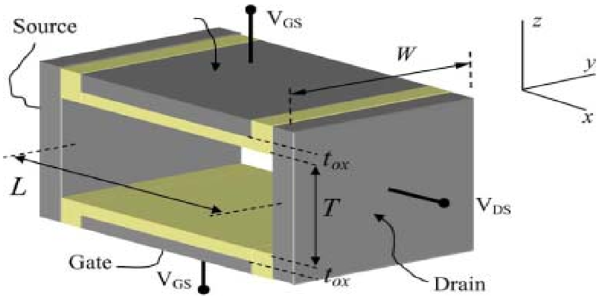

Fig. 1. Schematic representation of the quantum wire double gate FET. Electron transport in the "x" direction (from source to drain) takes place along a Silicon (100) orientation channel, at room temperature. The channel (nanowire) of the FET has lateral dimensions, W=5nm and T=2nm, that determine the electron confinement. The minimum energy of the first sub-band for one of the six equivalent ellipsoidal constant energy valleys is $E_{1D}^{q} = 0.182eV$. Due to the lateral electron confinement, the velocities in the "y" and "z" directions are zero.

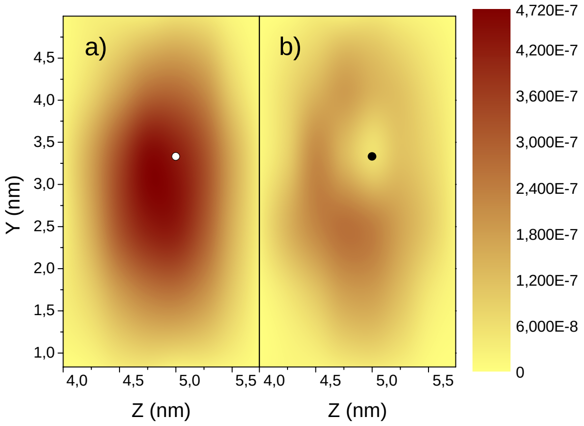

Fig. 3. Current density distribution for a particular slice of the quantum wire situated at the position of a positive, a), or negative, b), impurity situated at the source-channel interface.

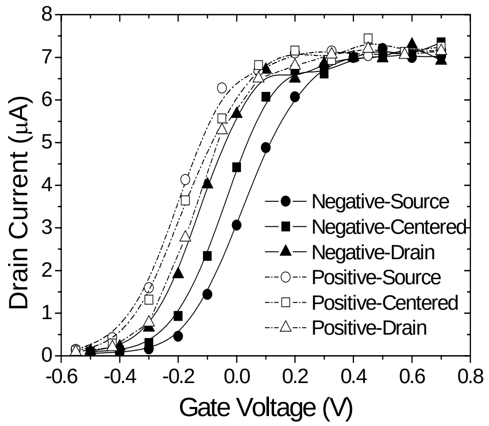

Fig. 2. Average drain current at V_{Drain}=1V as a function of the gate voltage for positive/negative impurities located at different places along the channel.

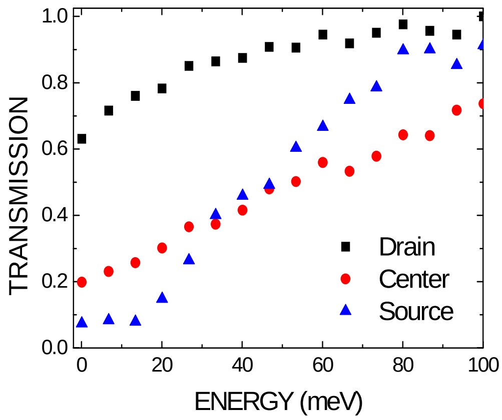

Fig. 4. Transmission as a function of the injection energy for a negative dopant located at different places along the nanowire.