Electron Injection Model for the Particle-Simulation of 3D, 2D and 1D Nanoscale FETs

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ABSTRACT

In nanoscale systems, electron transport becomes ballistic and the current and its fluctuations are mainly determined by the injection process. We present an electron injection model suitable for the semi-classical (or the quantum) Monte Carlo simulation of nanoscale field effect transistors (FET) with or without electron confinement. As an application, we show that the signal-to-noise ratio and the bit-error are drastically degraded because of electron confinement.

INJECTION MODEL

For ballistic devices, the average current, $\bar{I}$, and the power spectral density at zero frequency of the current fluctuations, $S(0)$, are determined from the Binomial probability $P(N,\tau)$ that N electrons (e$^-$) are injected during a time interval τ [1, 2]:

$$P(N,\tau)=\frac{M_\tau!}{N!\cdot(M_\tau-N)!}f(E)^N\left(1-f(E)\right)^{N-1} \qquad (1)$$

where $M_\tau=\tau/t_0$ is the number of attempts of injecting an e$^-$ during τ and $f(E)$ is the contact Fermi distribution function. The time t_0 between two successive injection attempts is [1, 3]:

$$t_0(y,z,k_x,k_y,k_z)\big|_{3D}=\left(\frac{\hbar k_x\Delta y\,\Delta z\,\Delta k_x\,\Delta k_y\,\Delta k_z}{4\pi^3 m}\right)^{-1}$$

$$t_0(y,k_x,k_y)\big|_{2D}=\left(\frac{\hbar k_x\Delta y\,\Delta k_x\,\Delta k_y}{2\pi^2 m}\right)^{-1} \qquad (2)$$

$$t_0(k_x)\big|_{1D}=\left(\frac{\hbar k_x\Delta k_x}{\pi m}\right)^{-1}$$

in 3D, 2D and 1D system, respectively. A mesh in the phase-space is defined (see Fig. 1). We assume that the electrons at the contact are only correlated with those electrons in the same contact due to the Pauli exclusión principle. As a test, we show that the one-channel Landauer current [4] and the general Büttiker noise expression [4] are exactly recovered with our particle-injection model.

EFFECT OF ELECTRON CONFINEMENT ON THE CURRENT AND NOISE PROPERTIES OF ANALOG AND DIGITAL APPLICATIONS

The injection model, defined in (1) and (2), can be used to directly determine the current and noise of ballistic FETs with different dimensionality. The Fano factor F ($S(0)=F\cdot 2\cdot e\cdot\bar{I}$) is the standard parameter to classify shot noise [1, 7]. In fig. 2, we compute the Fano factors for three FET geometries as a function of the contact Fermi level In Fig. 3, we show that e$^-$ confinement can cause the output signal-to-noise ratio, $P_S/P_N=\bar{I}^2/(S(0)\cdot\Delta f)$, to decrease because of the reduction in the number of states available for electron transport. The P_S/P_N of 3D (Bulk-) and 1D (quantum wire-) FETs can differ by 40 dB with $\Delta f\equiv 1$ MHz. Smaller devices are noisier.

In Fig. 4, the noise performance of a CMOS inverter is quantified by the bit error probability (BER). For any input logic level, one of the transistors is on opened-channel conditions with zero averaged current but with thermal noise. The BER of 3D (Bulk-) and 1D (quantum wire-) FETs can differ by more than 25 dB (see fig. 4). These results, which only consider the unavoidable thermal and shot-noise that are present in expression (1) and (2), predict important drawbacks for noise properties of 2D (quantum well-) or 1D (quantum wire-) FETs.

CONCLUSION

A general electron injection model for the device simulation of the transport properties of FETs with and without electron confinement has been presented. Our injection model generalizes previous works of Gonzalez *et al.* [5] and Oriols *et al.* [6, 7]. The model exactly reproduces the (Landauer) average current and the (Büttiker) shot-noise. We have shown that for ballistic nanoscale FETs the signal-to-noise ratio and the bit-error can be drastically affected by electron confinement, which indicates drawbacks for aggressively scaled FETs.

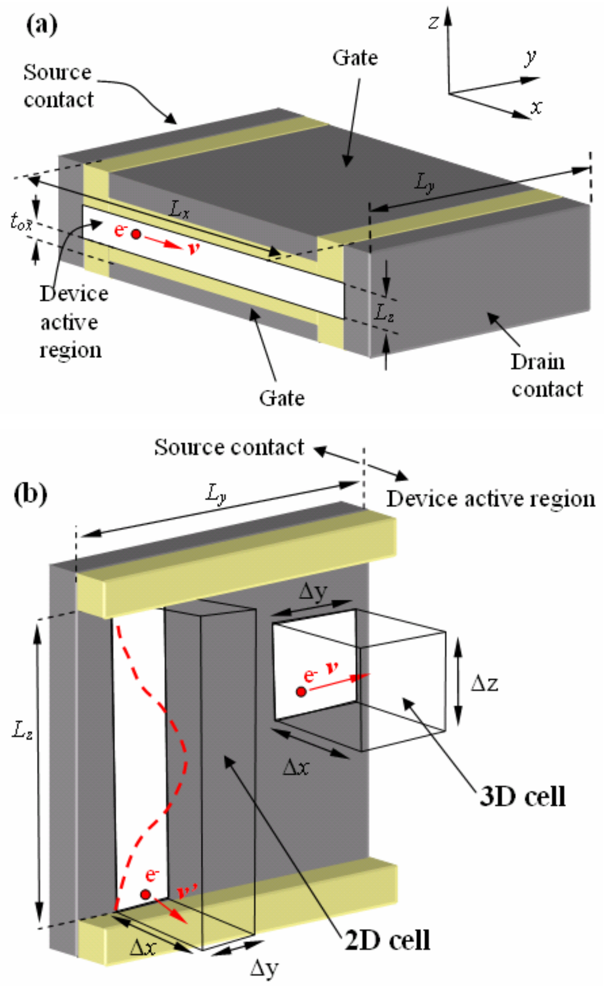

Fig. 1. (a) Schematic representation of a nanoscale double gate FET. The transversal dimensions L_y and L_z of the active region determine electron confinement. (b) Schematic representation of the 3D cell and the 2D cell used in the text (equation 2) to describe the injection of electrons through the $L_y \cdot L_z$ surface. In dashed line, for a 2D cell, schematic representation of the distribution of electrons in the direction z due to confinement

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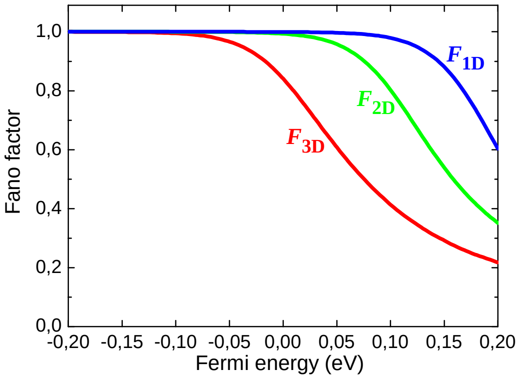

Fig. 2. Fano factors, F , for the 3D, 2D and 1D nanoscale FETs considered in this work. The transistor volumes are 15 nm x 10 nm x·8 nm, 15 nm x 10 nm x 2 nm and 15 nm x 5 nm x 2 nm for the 3D (Bulk-), 2D (quantum well-) and 1D (quantum wire-) device active regions, respectively

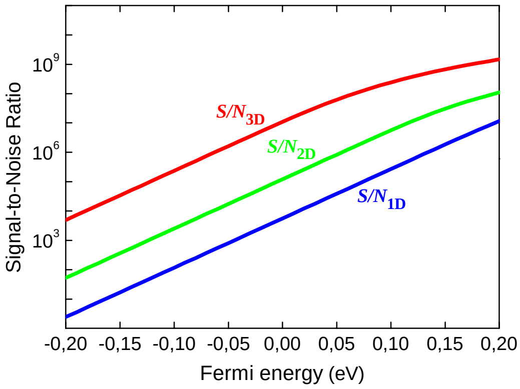

Fig. 3. Signal-to-noise ratios, P_S / P_N , for the 3D, 2D and 1D nanoscale transitors of Fig. 2.

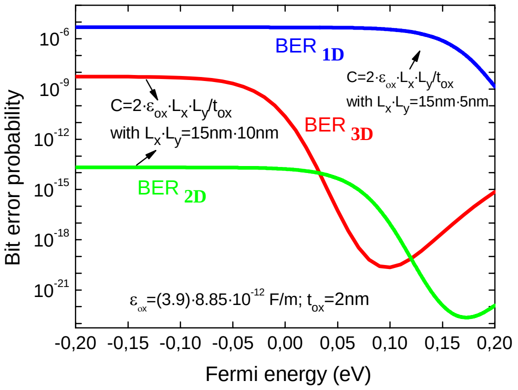

Fig. 4. Bit-error probabilities, BER, for the 3D, 2D and 1D nanoscale FETs mentioned in figure 2**.**