CLASSICAL AND QUANTUM COMPARISON OF THE HIGH-FREQUENCY TRANSCONDUCTANCE OF NANOSCALE FIELD EFFECT TRANSISTORS

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In order to provide accurate predictions for state-of-the-art devices, the quantum mechanical (QM) theory gradually upgrades (by including concepts such as tunnelling, quantization,..) the different approaches used for modelling electron transport. Recently, CMOS has been demonstrated to be a viable technology for very-high-bit-rate broadband and wireless communication systems up to 40 Gb/s and 50 GHz [1]. Therefore, a study of the novel effects that the QM theory can introduce on the performance of phase-coherent devices driven at high frequencies, f, comparables to the inverse of the electron transit time, seems mandatory. In this work, we compare the classical and quantum small-signal admittance parameters for a nanoscale double gate MOSFET with an intrinsic channel of L=15 nm length and t=2nm width, that provides transport through a two-dimensional (2D) electron gas, (see fig. 1).

First, using a classical Monte Carlo (MC) technique [2], we analyze the transconductance (i.e. the Y_{21} small-signal admittance parameter) by Fourier-transforming the transient current after a small step gate voltage perturbation [3]. The role of the acoustic and optical phonon scattering (for 2D electron gas [4]) on the transconductance is analyzed in figs. 2 and 3. The unavoidable collisions of 2D electrons with phonons slightly reduce the current and increase the transit time (reducing the operating frequency). The final delay is proportional to the device length, L, and inversely proportional to its width, t, (due to the form factor of the 2D phonon scattering rates [4]). The expected analytical behaviour of the AC-transconductane as a function of the oscillating frequency, $Y_{21}(f) = g_o e^{-j2\pi f\tau}$, is also depicted in fig. 3 where g_o is the DC-transconductance and τ the delay time.

Second, using an approach based on the Floquet theory [5], we analyze the role of the wave-like nature of electrons on Y_{21}. For the AC conditions depicted in fig 4, the quantum transport properties are determined by the spatial and also by the temporal phase-coherence of electrons. The time dependent Schrödinger equation (TDSE) is numerically solved for wave-packets using the oscillating potentials depicted in fig. 4. The QM current under AC conditions is computed from the dynamic transmission coefficient obtained from previous wave packets within the appropriate energy range [5]. Assuming small bias conditions, the QM admittance parameter Y_{21} is computed, using the steady-state transfer function [3], as the ratio between the complex AC current and the complex sinusoidal gate voltage.

The comparison between the transconductance behaviours obtained from the classical MC and quantum TDSE approaches are depicted in fig. 3. One dimensional non-selfconsistent potential profiles are used for all simulations. The differences between the full QM treatment and the classical results (with or without scattering) can be explained as a consequence of the wave-like (i.e. non-local) nature of electrons: the QM electrons 'feel' the potential oscillations in a broader space-time region than classical ones (see fig. 5). On the other hand, for low frequencies the results are comparable because the QM and classical transit times are quite similar (as seen in fig. 6). As expected, all results depend on the electron effective mass, but are independent of the shape of the wave packets (see fig 6).

The present results (summarized in fig. 3) provide a serious restriction towards the possibility of reaching THz cut-off frequencies, even for aggressively scaled Si transistors. Present results have to be interpreted as the 'ultimate' frequency limit for nanoscale MOSFET. On the other hand, the explicit consideration of the electron-electron interactions on the classical or QM formalisms will contribute to a reduction of such 'ultimate' cut-off frequencies. Future work will follow this path through the construction of a 3D Poisson solver for nanoscale MOSFET.

References:

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[2] V.Sverdlov, X. Oriols and K.Likharev, IEEE Transaction on Nanotechnology.**2** (2003) 59.
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[4] P.J.Price, Annals of Physics, **133** (1981) 217
[5] M.Grifoni and P.Hanggi, Physics Reports, **304** (1998) 229.

Figures

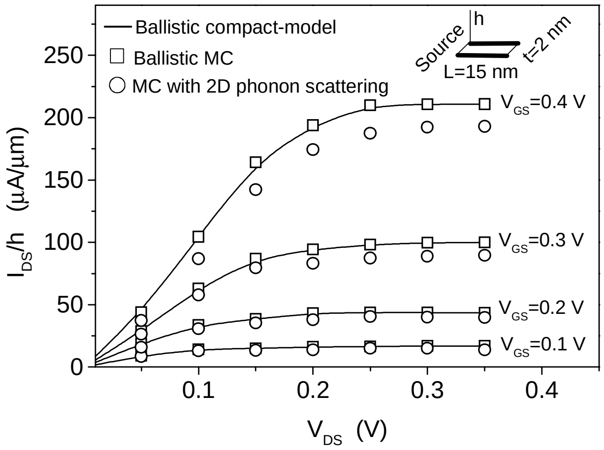

Fig 1: Current vs. voltage characteristics for the DG MOSFET. The MC results include energy quantization and 2D-degenerate injection.

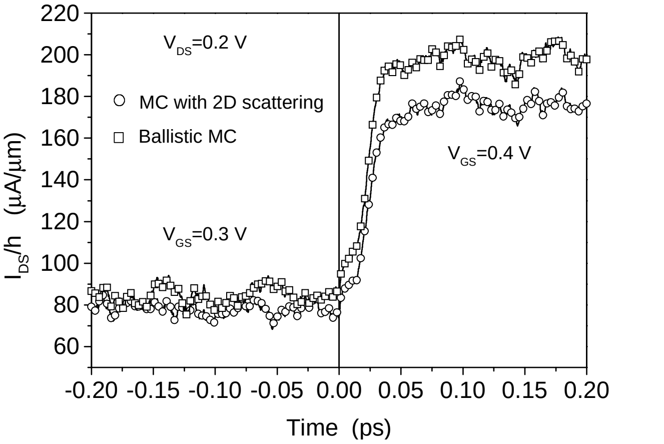

Fig 2: The MC (non-self consistent) results of the current transient response to a gate step voltage, 0.1V, while the V_{DS} is fixed.

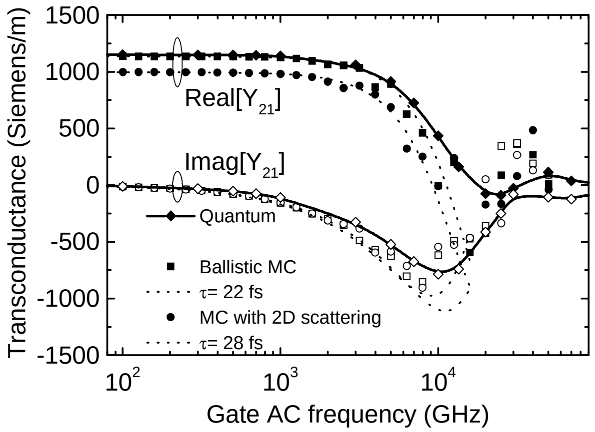

Fig 3: Transconductance frequency response. Symbols O/□, MC with/without scattering. Solid line and ◊, Quantum TDSE. Dotted lines correspond to the expected analytical response for different τ .

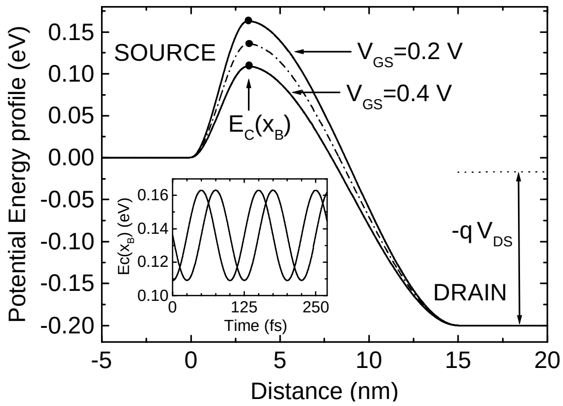

Fig 4: Oscillating (non-self consistent) energy potential profile Inset: Maximum of Ex(x,t) for a cos/sinusoidal oscillating gate voltage.

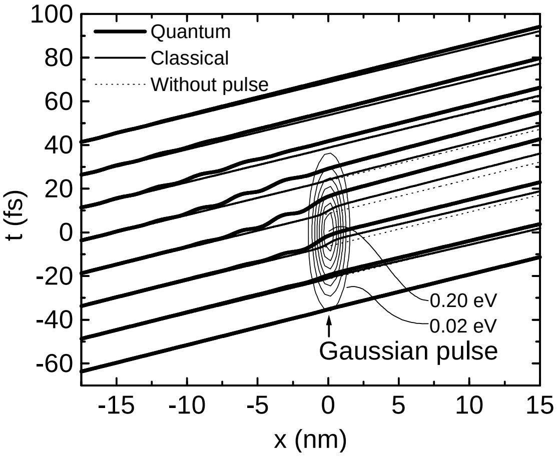

Fig: 5: Classical (thin solid line) and QM trajectories (thick solid line) for a E=0.22 eV electron interacting with a Gaussian pulse. The QM non-local dynamics are computed using Bohm trajectories.

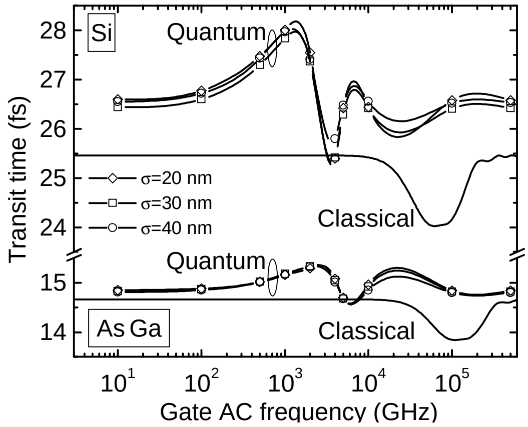

Fig 6: Classical and QM transit time as a function of the gate frequency. The shapes are different, but both values are quite similar and independent of the wave-packet dispersion σ, for a fixed (Si or AsGa) effective mass.