The role of the displacement current in quantifying the speed of ballistic nano devices: beyond the quasi-static approximation

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The development of faster electron devices is a constant demand from electronic industry and the ITRS roadmap envisions next future nano devices working at THz frequencies. For such devices, which are in the frontier between electronics and electromagnetism, the correct prediction of their performance enforces us to revisit the usual modelling of electron transport which only considers particle current (with drift and diffusion components) in semiconductors, and displacement current in dielectrics. In nano ballistic devices, since the dielectric relaxation time τ_{Die} (the time needed for other electrons to screen the non- neutral electrical fields) is comparable to the electron transit time, an electron travelling through such active region generates a time-dependent electric field, which is detected as displacement current at the contacts when dealing with frequencies higher than $1/\tau_{Die}$□die.Therefore, for predictions of the ballistic nano device involving THz frequencies, the displacement current needs to be explicitly considered.

In particular, predictions on the speed of THz electron devices, either for analog or digital applications, are usually quantified in terms of the cut-off frequency, fT , defined as the frequency where the current gain equals to one (0 dB). In this conference, we will show that the usual computation of fT under the quasi-static approximation (which directly neglects the displacement current on the drain contact) is no longer valid for ballistic devices at THz frequencies. The value of fT, for dual-gate 2D channel transistors plotted in Fig. 1(a), is estimated by a Fourier transform (*Y*-parameters) of the time-dependent currents computed from the BITLLES simulator [1-3]. From Figs. 3 and 6, we show that the displacement current is comparable to the particle (drift and diffusion) current. The quasi-static prediction of the device speed can be one order of magnitude faster than what these devices can really offer. Even in some design (not shown here), one can get $T \rightarrow \infty$ when the drain phasor current is greater than the gate phasor current at all frequencies.

We propose to predict the speed of such nano devices working in the THz regime, from time-dependent simulations of the total (particle plus displacement) currents, i.e., from the intrinsic delay time τ_d illustrated in Figs. 3 and 6 [4].

In conclusion, for ballistic nano devices, the electric field generated by electrons cannot be screened inside the device active region at frequencies higher than $1/\tau_{die}$. Then, the displacement current becomes as relevant as particle current and it has to be properly included in electron modelling. This conclusion is particularly critical for the speed predictions of nano devices which usually require quantum modelling. The proper quantum formulation of the displacement current faces important practical and conceptual issues. For example, the explicit simulations of the time-dependent displacement current requires a self-consistent simulation of the electric field along the device, which demand huge amount of computational resources to deal with the many- body problem. In this conference, the solutions proposed by the group of Dr. Oriols in terms of quantum trajectories, including electron-electron interaction beyond mean field for the direct computation of the particle and displacement currents, will also be presented [1-3]. These difficulties explain why most of the speed predictions for quantum devices are based on the quasi-static approximation that, as we have shown above, can provide quite exaggerated predictions.

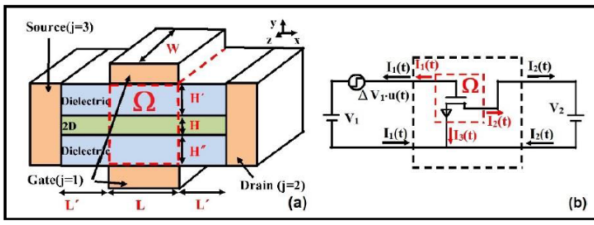

Fig. 1 (a) The cross-section of the active region Ω=L×(H'+H+H")×W for a dual-gate FET used in our simulations. L is the gate length. (b) A two-port network of the intrinsic device.

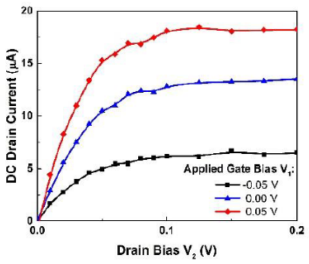

Fig. 2 The output characteristic of **Device A** for different V_1. Ω_A=100×(45+1+45)× 1125 nm^3 with gate length L=100 nm.

Device A

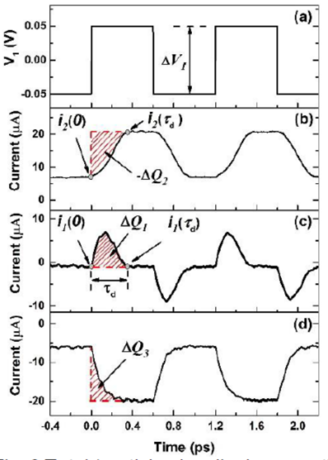

Fig. 3 Total (particle plus displacement) transient currents on the drain (b), gate (c) and source (d) of **device A** when a voltage (a) is applied on the gate in BITLLES simulator.

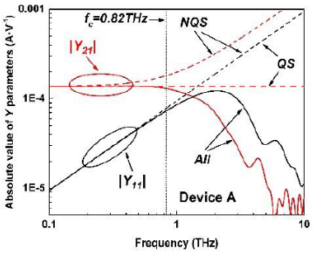

Fig. 4 The *Y* parameters computed in **device A** with: (*All*) the exact time-dependent simulation of the total currents, (*NQS*) a zero-order Taylor expansion and (*QS*) a quasi-static approximation.

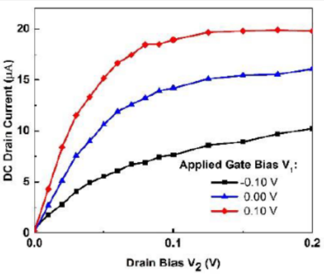

Fig. 5 The output characteristic of **Device B** for different V_1. Ω_B=20×(45+1+45)× 700 nm^3 with gate length L=20 nm.

Device B

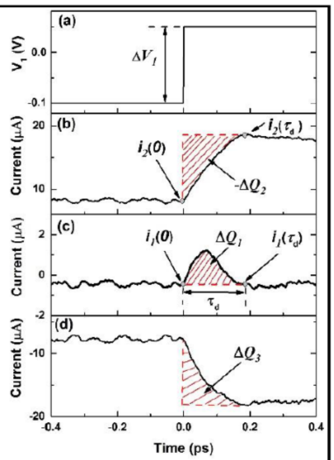

Fig. 6 Total (particle plus displacement) transient currents on the drain (b), gate (c) and source (d) of **device B** when a voltage (a) is applied on the gate in BITLLES simulator.

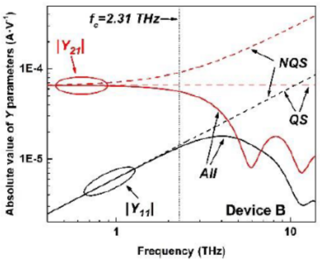

Fig. 7 The *Y* parameters computed from the time-dependent simulation of the total currents in **device B** (as that of device A in Fig. 4).

[1] X. Oriols, PRL, 98 (2007) 066803.
[2] D. Marian, N. Zanghì and X. Oriols, PRL, 116 (2016) 110404.
[3] http://europe.uab.es/bitlles.
[4] Z. Zhan, E. Colomés and X. Oriols, Submitted (2017).