TIME-DEPENDENT ELECTRON DRIVEN TUNNELING PHENOMENA FOR MULTIPURPOSE TERAHERTZ APPLICATIONS: SELF-CONSISTENT COMPUTATION OF CONDUCTION AND DISPLACEMENT CURRENT IN MESOSCOPIC SYSTEMS

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Nowadays, systems for reaching the Terahertz (THz) electromagnetic gap are based on down-conversion of optical frequencies [1]. As alternative to these dominant strategies we propose a transistor-like tunneling electron device, that we named driven tunneling device (DTD), working at frequencies comparable to the inverse of the electron transit time (see Fig. 1). Our (single-device and room temperature) proposal provides future THz systems with reduced costs, sizes, and complexities. In this conference, we present several applications of the DTD for generating/manipulating signals at the THz gap (see Figs. 2, 3 and 4). For an accurate computation of tunneling transport through these DTDs at THz frequencies, a novel algorithm for the self-consistent computation of the time-dependent total (conduction plus displacement) current, $I(t)$, is presented.

The time-dependent evolution of a quantum system of N (coulomb and exchange) interacting electrons can be described by a many-particle Schrödinger equation [2]:

$$i\hbar \frac{\partial \Phi(\vec{r}_1,...,\vec{r}_N,t)}{\partial t} = \left\{ \sum_{a=1}^{N} -\frac{\hbar^2}{2 \cdot m} \nabla_a^2 + U(\vec{r}_1,...,\vec{r}_N,t) \right\} \Phi(\vec{r}_1,...,\vec{r}_N,t) \tag{1}$$

However, from a computational point of view, the direct solution of equation (1) is inaccessible because (for a real space with N_L points) it implies manipulating matrixes of N_L^{3N} elements. We have recently shown [2] that many-particle Bohm trajectories associated to (1) can be computed from a (coupled) system of single-particle time-dependent Schrödinger equations whose numerical complexity is just $N \cdot N_L^3$:

$$i\hbar \frac{\partial \Psi_a(\vec{r}_a,t)}{\partial t} = \left\{ -\frac{\hbar^2}{2 \cdot m} \nabla_a^2 + U(\vec{r}_1[t],.,\vec{r}_a,.,\vec{r}_N[t],t) + G_a(\vec{r}_a,t) + i \cdot J_a(\vec{r}_a,t) \right\} \Psi_a(\vec{r}_a,t) \tag{2}$$

The self-consistent coupling between the electron dynamics obtained from equation (2) and the electrostatic potential (obtained from the 3D Poisson solver) is achieved by using Bohm trajectories [2]. From a numerical point of view, we compute the total current, $I(t)$, using a quantum version of Ramo-Shockley theorem [3], without numerical approximations, through a volume Ω limited by a surface S (See Fig. 1):

$$I(t) = -\int_{\Omega} \vec{F}(\vec{r}) \cdot \vec{J}_p(\vec{r},t) \cdot d^3\vec{r} + \int_{S} \vec{F}(\vec{r}) \cdot \varepsilon(\vec{r}) \cdot \frac{\partial}{\partial t} A_o(\vec{r},t) \cdot d\vec{s} \tag{3}$$

In order to show the numerical viability of our approach and the great interest of the DTD at the THz gap, we develop three different THz applications: a rectifier, a harmonic generator, and an amplitude modulator [4]. In Fig. 2, we show a THz rectifier for a primary set of DTD parameters (i.e. the geometries of the barriers, quantum well, dielectric and contact shown in Fig. 1) with a input gate voltage $V_G(t)$ [see dashed line in Fig. 2]. The output voltage rectifies the signal [see solid line in Fig. 2] because negative gate voltages produce a very opaque barrier. In Fig. 3(a), we show a THz harmonic generator for a second set of DTD parameters and an input gate voltage $V_G(t)$ [see dashed line in Fig. 3(a)]. In this case, we accommodate three resonant energies inside the quantum well. The output voltage [solid line in Fig. 3(a)] oscillates several times during a period of the input signal. The frequency multiplication is due to the fact that the DTD current acquires a maximum each time that a resonant energy of the quantum well crosses the Fermi energy. The power spectral density for output voltage is plotted in the solid line of Fig. 3(b) to show the harmonic generation. In Fig. 4(a), we show an amplitude modulator for THz frequencies for a third set of DTD parameters with a input gate voltage $V_G(t)$ and the input voltage $V_{in}(t)$ [see dashed and dotted lines, respectively, in Fig. 4(a)]. The output voltage [solid line in Fig. 4(a)] and its power spectral density [Fig. 4(b)] clearly show an amplitude modulator.

In conclusion, in this conference, we present a novel approach for the self-consistent simulation of the time-dependent total (conduction plus displacement) current in mesoscopic tunneling devices at THz frequencies [2]. This numerical approach is applied for the computation of tunneling currents in three different DTD configurations for developing (single-device and room temperature) THz applications [4].

References:

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Figures

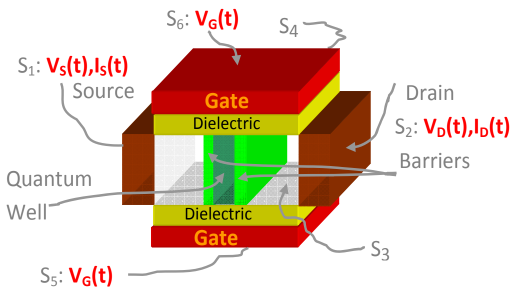

Fig. 1. 3D representation of the active region of the D. It consists in a double barrier structure inside a double-gate transistor-like tunneling electron device.

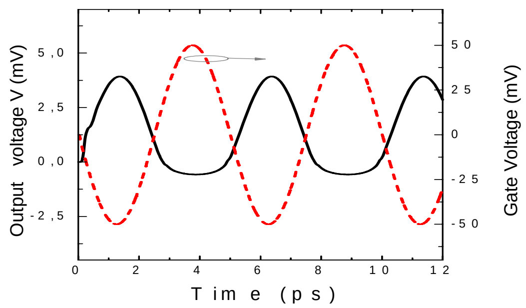

Fig. 2. (Solid line) Calculated output current for a THz rectifier. (Dashed line) input gate voltage $V_G(t)$.

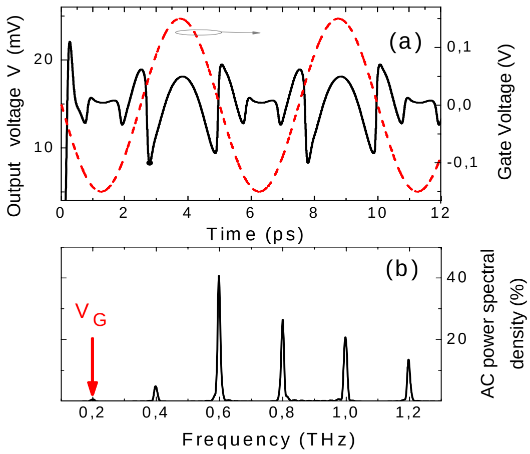

Fig. 3. *(a)* (Solid line) Calculated output current for a THz harmonic generation. *(b)* Calculated power spectral density.

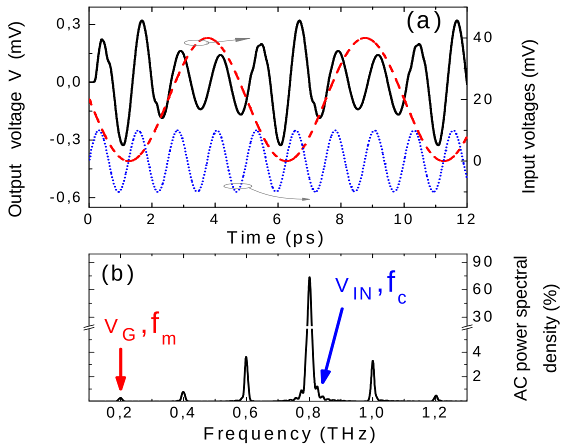

Fig. 4. *(a)* Amplitude modulated current (solid line), carrier input voltage (dotted line), and modulating gate voltage (dashed line) as a function of time. *(b)* Calculated power spectral density.