Polaritonic features in the THz displacement current through RTDs in microcavities

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Introduction. In electron device modelings, the interaction of electrons and electromagnetic fields is usually tackled by classical or perturbative techniques. In this work, on the contrary, we model electron devices where both degrees of freedom for electrons and electromagnetic fields are described by a unique quantum state solution of a full Hamiltonian. In the resonant strong light-matter coupling regime, our model is able to capture polaritonic signatures in the time-dependent electrical current.

Model. The minimal-coupling Hamiltonian in the Coulomb gauge, for N electrons interacting with an electromagnetic field, is considered [1]. For our qualitative goal, approximations are needed, and among them we consider a single-mode q for the electromagnetic field, in dipole approximation, and a 1D effective single-electron ballistic picture for the transport in the x-direction, in which only the conduction band plays a role, with different electrons meaning different injection times and energies, as handled by the Ramo-Shockley-Pellegrini theorem. Under all these assumptions, the quantized version of the mentioned Hamiltonian reads, for the electron degree x and the single mode degree q [2],

$$H_{xq} = -\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial x^2} + V(x) - \frac{\hbar\omega}{2}\frac{\partial^2}{\partial q^2} + \frac{\hbar\omega}{2}q^2 + \alpha q x,$$

where $\alpha = \sqrt{e^2\hbar\omega N/(\epsilon_0 L_c^3)}$ is the coupling constant, with frequency ω and cavity volume L_c^3. A general solution of the Schroedinger equation with such Hamiltonian H_{xq} in terms of is

$$\psi(x,q,t) = \sum_m^{N_\omega} \Phi_m(x,t)\phi_m^{(\omega)}(q),$$

with $\Phi_m(x,t) = \sum_n^{N_e} c_{n,m}(t)\phi_n^{(e)}(x)$. After integrating out the photon degree of freedom one obtains, with $H_{xq,e} = -\hbar^2/(2m)\partial^2/\partial x^2 + V(x)$,

$$i\hbar\frac{\partial}{\partial t}\Phi_n(x,t) = \left[H_{xq,e} + \hbar\omega(n+1/2)\right]\Phi_n(x,t) + \alpha x\left[\sqrt{n+1}\Phi_{n+1}(x,t) + \sqrt{n}\Phi_{n-1}(x,t)\right],$$

which is a set of coupled equations for the electron dynamics, each referring to a given photon number.

Results. Effects of a quantized electromagnetic field in the displacement current of a resonant tunneling diode inside a cavity (Fig. 1(a)) are analyzed. The original peaks of the bare electron transmission coefficient split into two new peaks due to the resonant electron-photon interaction (Fig. 2), leading to coherent Rabi oscillations among the polaritonic states that are developed in the system (Fig. 1(d)). This shows how a simultaneous quantum treatment of electrons (Fig. 1(c)) and electromagnetic fields (Fig. 1(b)) may open interesting paths for engineering new THz electron devices. The computational burden involved in the multi-time measurements of THz currents is tackled from a Bohmian description [3] of the light-matter interaction (Fig. 3).

Conclusion. We do believe that our modeling framework may open original unexplored paths for engineering new electron devices and new applications in the THz gap, by taking advantage of the interplay between quantum electrons and quantized electromagnetic fields.

References

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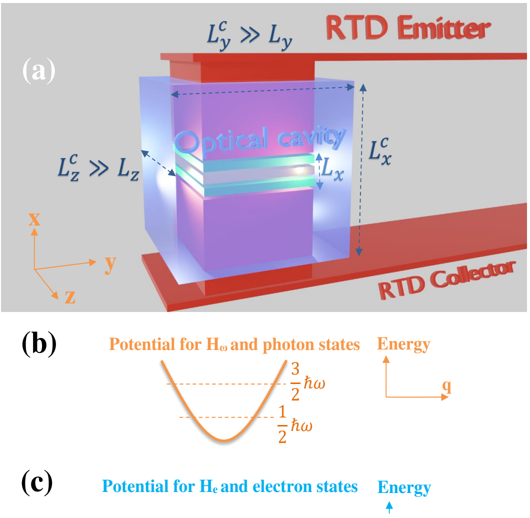

inside the RTD/cavity in the resonant strong coupling regime: state $|0,0\rangle$ almost unaffected; polaritonic states formed out of $(|0,1\rangle \pm |1,0\rangle)/\sqrt{2}$ split by $2E_r = 2\hbar\omega_r$ in comparison to the degenerate decoupled energies (dashed line); state $|1,1\rangle$ would create another polariton subspace, in a larger basis set, with state $|0,2\rangle$; $\omega_r = \alpha L_x/\hbar$ is the Rabi frequency.

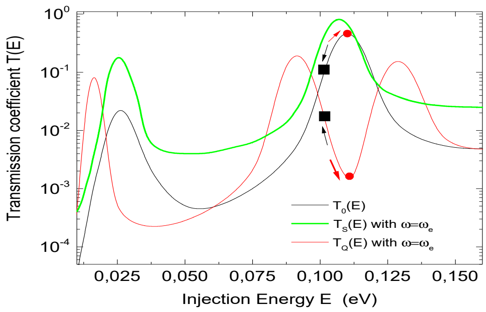

Fig. 2. Transmission coefficients $T(E)$ for: (black) no light-matter interaction $T_0(E)$; (green) resonant semiclassical interaction $T_S(E)$; (red) resonant quantum interaction $T_Q(E)$.

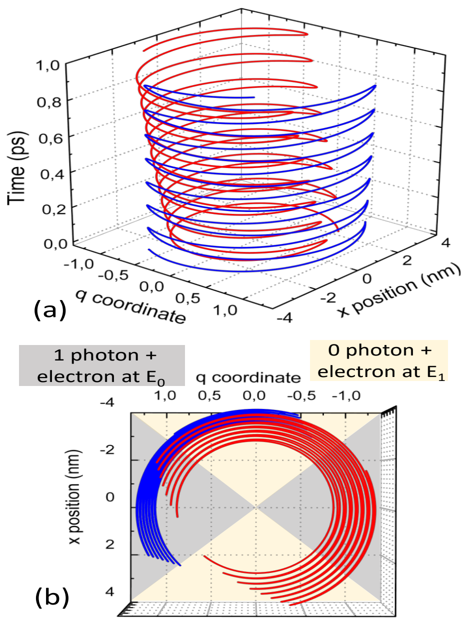

Fig. 3. (a) Example of two Bohmian trajectories in the 2D xq plane guided by the analytical evolution from the quantum scenario. (b) Schematic representation of different regions on the xq configuration space in the quantum well, with white (grey) regions corresponding to the wavefunction occupying the zero (one) photon and excited (ground) electron energy state.