Modeling strong light-matter interaction in polaritonic semiconductors as open systems

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Introduction. The interaction between electrons ("matter") and electromagnetic fields ("light") within the same confined space has given rise to a new class of phenomena known as strong light-matter coupling regime : light and matter can no longer be treated as independent entities, but instead, they combine to form a hybrid physical entity known as a polariton which has already being implemented in various platforms. The goal of this work is to investigate polariton effects in semiconductor electron devices—specifically, quantum well heterostructures—at THz frequencies and room temperature (See Fig. 1(a)). We argue that this emerging phenomenon holds the potential to revolutionize electronics by naturally bridging electronics and photonics.

Although the quantum optics community has developed a robust understanding of the phenomenology of cavity quantum electrodynamics, and some experimental prototypes of operating at room temperature have been documented [1-4], the electronics community has largely overlooked these phenomena.

Model. The whole Hamiltonian of the light (q) and matter (x) (see Fig. 1(b) and 1(c)) is given by:

$$H = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V - \frac{\hbar\omega}{2}\frac{\partial^2}{\partial q^2} + \frac{\hbar\omega}{2}q^2 + \alpha q x,$$

where m is the electron mass, V is the potential profile of a quantum well, α is the coupling constant and ω the frequency of the optical cavity. A general solution of the Schrodinger equation is:

$$\Psi(x,q,t) = \sum_{n=0}^{N}\left(a_n(t)\phi_n(x)\psi_0(q) + b_n(t)\phi_n(x)\psi_1(q)\right),$$

where ϕ_n are the typical scattering states in tunneling scenarios (see Fig. 1(c)) and $\psi_{0/1}$ is the states of the light for $0/1$ photons (see Fig. 1(b)). Inside the quantum well, an electron in the ground state absorbs a photon and "jumps" to the exicted state, and then emits the photon into the cavity again (see Rabi oscillations in Fig. 2).

The typical polaritonic models found in the literature, such us Rabi and Dicke models, are developed for closed systems (i.e., the matter and the light do not escape from their cavities). However, a realistic physical system is never perfectly isolated and, in fact, intersubband polaritonic systems are based on electrons entering and leaving the quantum well. In this conferecne, we present a (semi) analytical formalism of the time evolution of such polaritonic systems in hetrostructures by seeking the energy eigenvalues and eigenestates of the whole polaritonic quantum systems.

We compute the traditional scattering states (which are energy eigenstates of the electron Hamiltonian alone, but not of the full electron-light Hamiltonian) as seen in Fig. 3. Then, we diagonalize the entire Hamiltonian to find the polaritonic energy eigenstates, which have a different spectrum from the electron-only states (see Fig. 1(d)). Once these eigenstates are known, we can analytically compute the full wavefunction evolution at any time to identify the optimal conditions for maximizing transmission (as an open system) and (Rabi) oscillations inside the well while electrons traverse the barrier region.

Conclusion. From the early days of electronics, the interplay between electrons and electromagnetic fields has played a fundamental role in technological advancements. In this conference, we demonstrate how this relationship can now be redefined through pure quantum interactions between light and matter, blending electronics and photonics for novel applications. By exploring this uncharted territory, our work aims to unlock the immense potential of polaritonic phenomena to sustain and transform semiconductor electronics.

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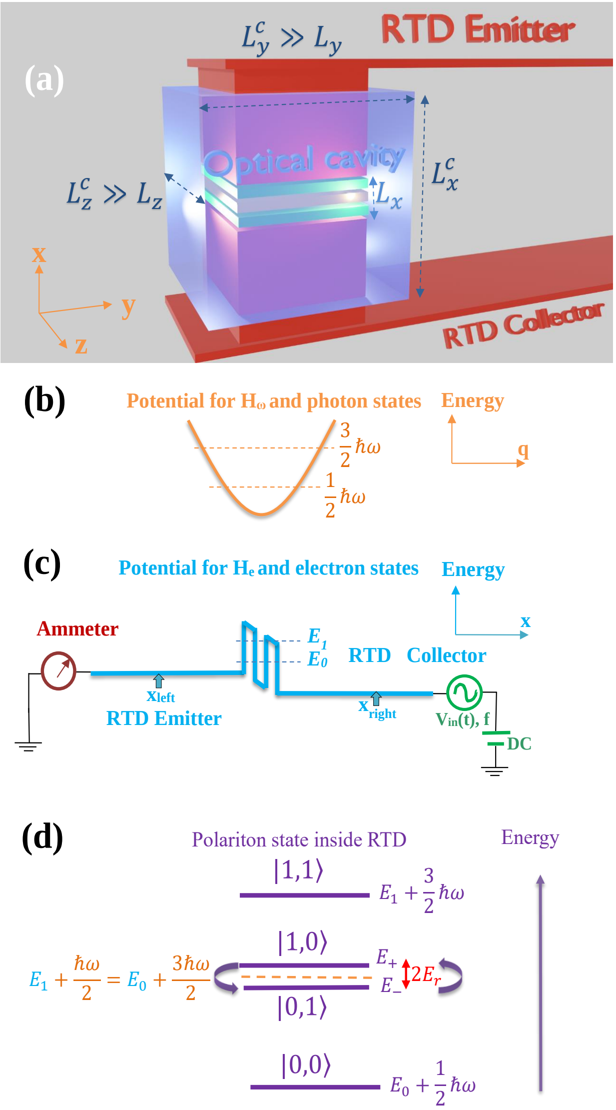

Fig. 1. (a) 3D spatial representation of the transport through a resonant tunneling diode (RTD) whose active region is inside a cavity, and whose transport direction size is much smaller than the lateral sizes, $L_y, L_z \gg L_x$. (b) zero-photon $|0\rangle$ and single-photon $|1\rangle$ states for the quantized single mode cavity field with energies $\hbar\omega/2$ and $3\hbar\omega/2$. (c) 1D-view of the RTD device showing ground $|0\rangle$ and first excited $|1\rangle$ electron states with energies E_0 and E_1; the light-matter interaction is effective only inside the active region, while a much larger simulation box is used to deal with open boundary conditions, with $X_{left,\,right}$ indicating the positions where wavepackets are initialized. (d) $|$electron,photon$\rangle$ states 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.

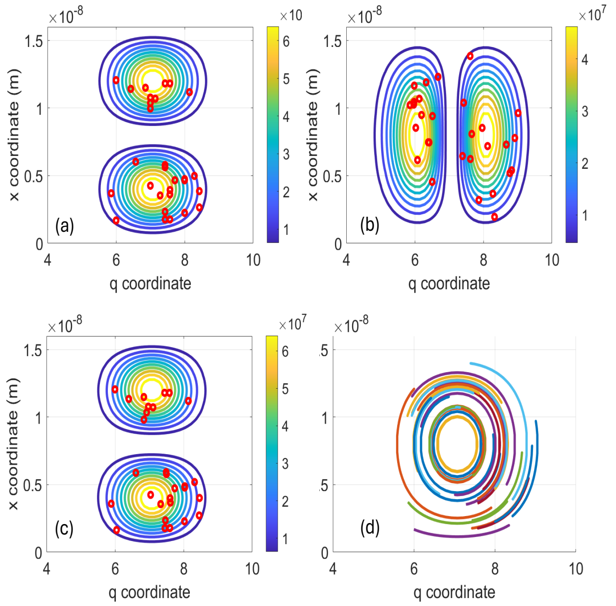

Fig. 2. Probability density of the wavefunction $\psi(x,q,t)$ in the $x-q$ configuration space at $t = 0fs$ (a), $t = 40fs$ (b), and $t = 80fs$ (c). Red circles indicate the positions of $M = 30$ Bohmian trajectories $x^j(t)$ and q^j (t) selected with random initial positions according to $|\psi(x,q,0)|^2$. In (d), the continuous path of these trajectories is plotted, showing their (Rabi) oscillations.

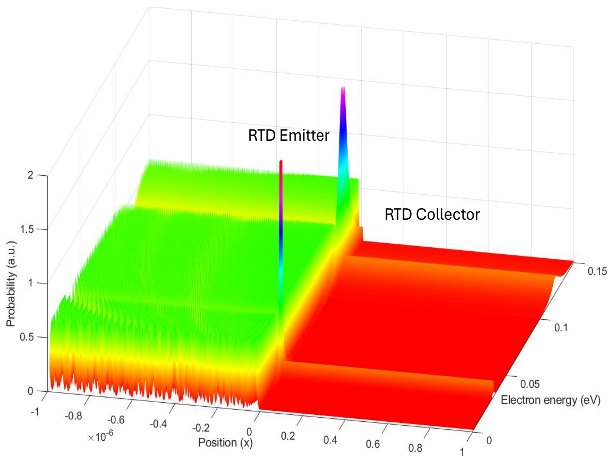

Fig. 3. Scattering states in the emitter, barrier and collector regions showing the openness of the RTD. These states are no longer energy eigenstates of the whole light matter system depicted in Fig. 1(d).