Strong Light-Matter Coupling for Polaritonic Semiconductor Devices

Abdelilah Benali[1,*], *Juan José* Seoane[1], *Xavier* Cartoixà[1], and *Xavier* Oriols[1]

[1]Department of Electronic Engineering Universitat Autònoma de Barcelona, Barcelona, Spain

Abstract. Electronics have traditionally involved the interplay between electrons and electromagnetic fields, in both classical and quantum forms. A new milestone in this successful coexistence is the regime of strong light-matter coupling, where the boundaries between light and matter fade, giving rise to hybrid quasiparticles known as polaritons. In this work, we present our research focused on the strong and ultrastrong coupling regime, particularly involving intersubband polaritons in semiconductor quantum wells, embedded into an optical cavity, to explore how electronic technologies can benefit from this emerging physics. In particular, realistic scenarios are investigated considering the quantum well as an open system, where electrons enter and exit the quantum well while interacting with light. The implications of polaritons on semiconductor devices, particularly those operating at terahertz frequencies, will also be discussed. Integrating cavity quantum electrodynamics with semiconductor electronics could lead to revolutionary advancements in new electronic-based platforms for quantum information technologies and photonic-electronic systems.

1 Introduction

The interaction between electrons ("matter") and electromagnetic fields ("light") within a confined space has given rise to a new class of quantum phenomena known as cavity quantum electrodynamics (CQED), which occurs, for example, when electrons are confined within a quantum well, while terahertz (THz) radiation is trapped within an optical resonant cavity.

In CQED, when a regime known in the optics community as strong light-matter coupling occurs, the distinction between light and matter fades [1]. Instead of behaving as separate entities, they merge into a hybrid quasiparticle known as a polariton. In recent years, this field has attracted significant attention in the quantum optical community and is already being implemented in various technological platforms. A notable example is Google's work in quantum computing, where superconducting electrons are driven by GHz-frequency signals. In this work, we study the polaritonic interaction between quantum electrons and quantum light, beyond what is currently considered in the literature for electronic devices. We focus on electrons as the matter component and THz radiation as the light component, and its application for new electronic-based platforms for quantum information technologies and photonic-electronic systems.

*e-mail: abdelilah.benali@uab.cat

1.1 Strong Light-Matter Coupling Regime in Electronics

For decades, scientists and engineers have harnessed the interaction between electrons and electromagnetic fields to create groundbreaking electronic devices. However, every commercial device built so far operates under the premise that electrons and electromagnetic fields are distinct, independent entities Fig. 1(c). Traditional approaches, such as self-consistent solutions to the Poisson-Schrödinger equations, reinforce this notion by treating light purely as a classical phenomenon. Even in optoelectronic devices like LEDs and lasers, electrons and photons are modeled as separate actors: light is seen merely as an external disturbance affecting electrons—akin to a novel type of collision—while electrons modify light only indirectly by shifting the refractive index.

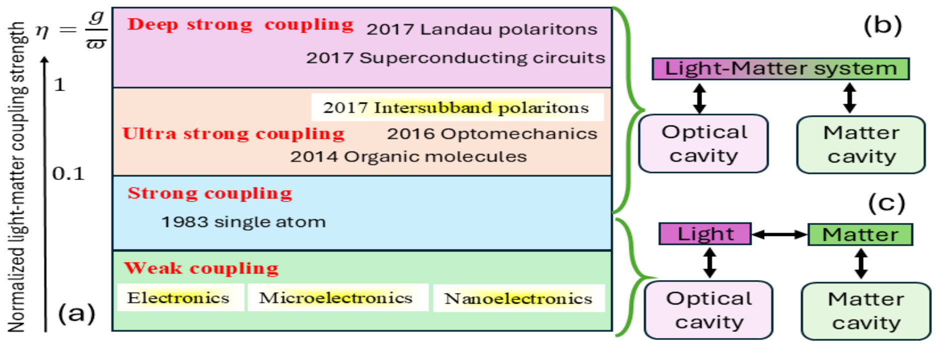

Figure 1. (a) Different light-matter coupling regimes as a function of the parameter η defined in the text. (b) A hybridized state of light and matter inside and optical and matter cavities. (c) Light and matter as interacting, but independent physical entities. All electronic devices belong to this weak regime.

To truly capture the quantum essence of strong light-matter interactions, one must turn to quantum electrodynamics (pioneered by Dirac over a century ago), also known as quantum optics [1]. Within this framework, light and matter are not separate concepts but interconnected degrees of freedom governed by the same quantum wave function—much like the spatial coordinates x, y, and z, which define an electron's position within a single 3D wave function. As a result, when light and matter enter a regime of strong coupling, they no longer behave as independent entities but instead form a unified quantum state Fig. 1(b). This hybridized state, known as a polariton, represents a fundamental departure from conventional treatment of electrons and electromagnetic fields, where the collective behavior of the system defies the properties of its individual components [2], [3].

As depicted in Fig. 1, different strengths of the coupling are possible. This work is mainly focused on the so-called strong or ultrastrong regimes where the energies of the light-matter system are neither the electron nor photon ones as seen in Fig. 2 (d) [4]. The ultrastrong coupling regime for this type of structure depicted in Fig. 2 is referred to in the literature as intersubband polaritons [3, 5]. These intersubband polaritons were experimentally demonstrated for the first time in 2009 [6] with η=0.11. The parameter η has been progressively increased in several experiments [7] , reaching the value η=0.45. Initially, these intersubband polaritons were observed in multi-quantum wells at very low temperature, but in last 5 years this phenomenon has been observed at room temperature [8–10], even for double quantum wells [11] and single quantum wells [12].

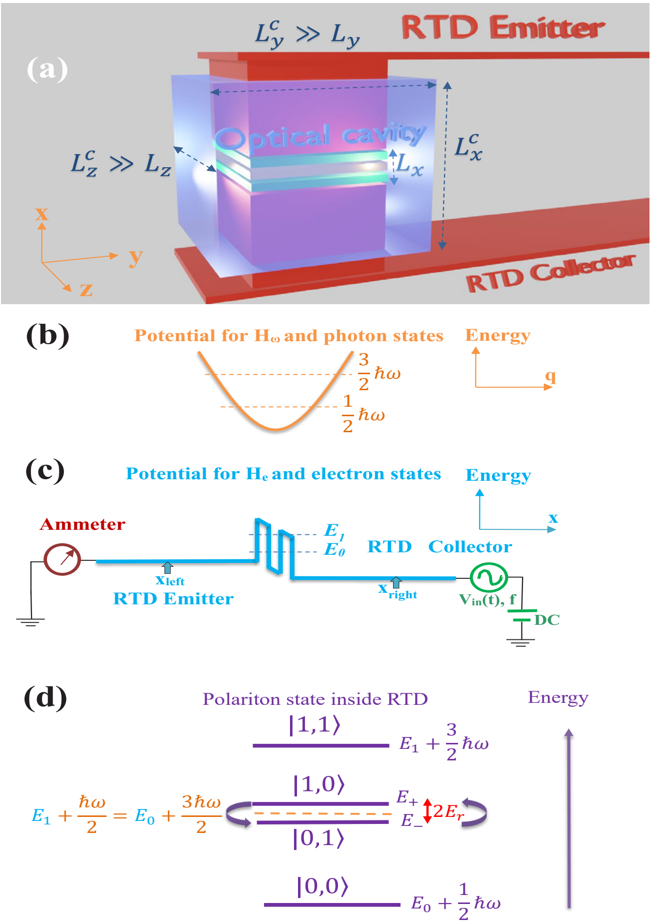

Figure 2. (a) 3D spatial representation of the transport through a RTD whose active region is inside a cavity, and whose transport direction size is much smaller than the lateral sizes, $L_y, L_z \gg L_x$. (b) zero-photon $|0\rangle$ and single-photon $|1\rangle$ states for the quantized single mode 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.

2 Modeling Approach

2.1 Closed vs. Open Systems

Traditional Rabi and Dicke models, like most polaritonic models in the literature, are typically developed for closed systems where neither matter nor light escapes their respective cavities [13]. This simplifiers the computational burden since electron and light eigenstates can be easily known analytically. However, in realistic systems, perfect isolation is impossible. Indeed, in intersubband polaritonic implemented in electronic devices, electrons continuously enter and leave the quantum well.

2.2 Time-Dependent and Analytical Modeling for Open Systems

We have already developed a finite-difference time-dependent model to explore the openness of the "matter cavity", while still considering light in a closed cavity, using our BITLLES simulator [1]. Building upon this, we have developed a formalism to compute the energy eigenvalues of the polaritonic (electron+light) quantum system in a realistic resonant tunneling diode, build by a two-barriers potential energy.

The whole Hamiltonian of the light (q) and matter (x) Figs. 2 (b) and (c) is given by [4, 14]:

$$H = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V - \frac{\hbar\omega}{2}\frac{\partial^2}{\partial q^2} + \frac{\hbar\omega}{2}q^2 + \alpha q x, \tag{1}$$

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:

$$\Psi(x, q, t) = \sum_{n=0}^{N} \left(a_n(t)\phi_n(x)\psi_0(q) + b_n(t)\phi_n(x)\psi_1(q)\right), \tag{2}$$

where ϕ_n are the typical scattering states in tunneling scenarios Fig. 2(c) and $\psi_{0/1}$ is the states of the light for $0/1$ photons Fig. 2(b).

The main steps of the formalism are as follows:

- Numerical electron calculation ϕ_n: The traditional scattering states of the Landauer model for open systems, which represent energy eigenstates of the electron Hamiltonian alone (the first two terms of the right hand side of Eq. (1)) excluding light-Hamiltonian and light-matter interactions are computed. See Fig. 3.

- Analytical Photons state $\psi_{0/1}$: The analytical photons states, solution of the parabolic well depicted on the third and fourth terms in the potentials in the right hand side of Eq. (1), are considered.

- Hamiltonian Diagonalization: We diagonalize the entire Hamiltonian in Eq. (1), incorporating both electron and light interactions, to determine the polaritonic energy eigenstates. These exhibit a distinct spectrum compared to electron-only and light-only states. These different spectrum is the manifestation of the strong (or ultrastrong) polaritonic regime exhibited by this systems.

[1] BITLLES simulator : https://europe.uab.es/bitlles/

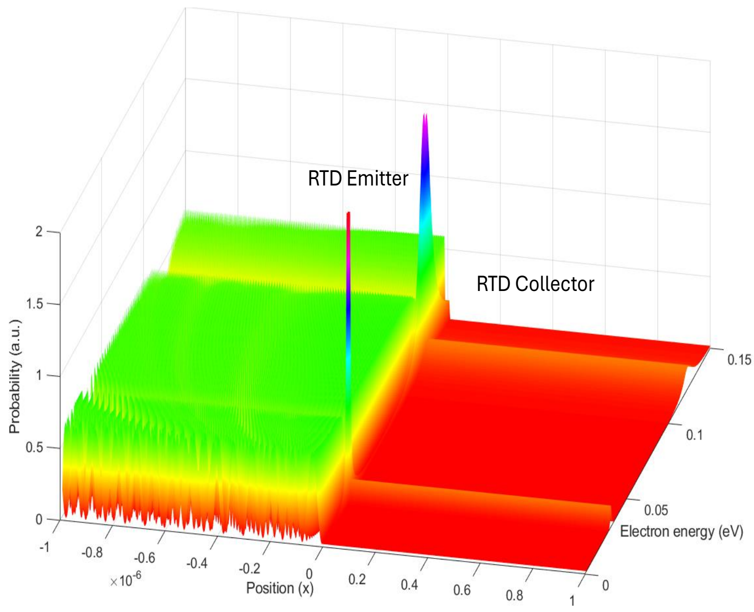

Figure 3. Spatial distribution of the probability presence of scattering states as a function of energy, when impinging from left (emitter) to right(collector) upon a the double barrier in a resonant tunneling diode (RTD).

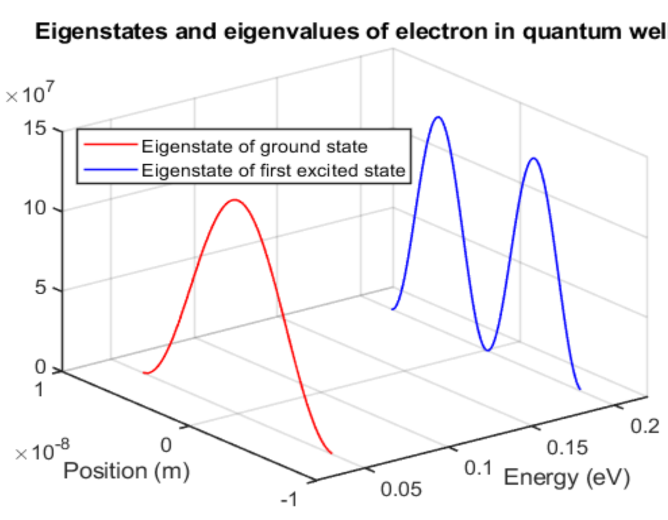

Figure 4. Eigenstates and eigenvalues of an electron in a quantum well for the ground and first excited states.

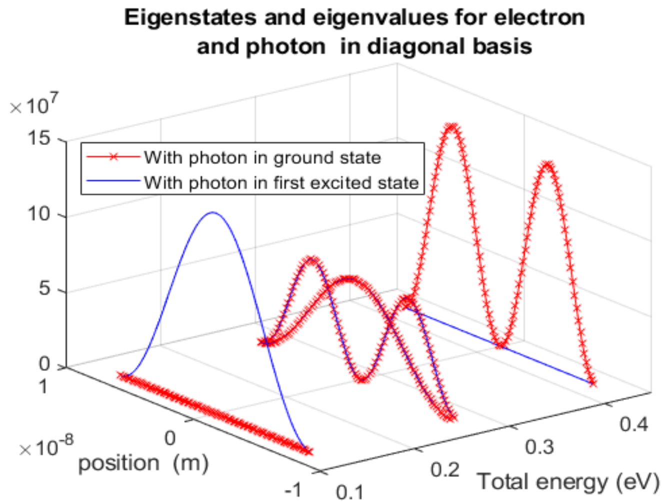

Figure 5. The eigenstates and eigenvalues for the system electron with photon in ground and in first excited states are presented.

2.3 Polaritonic Effects in Semiconductor Devices

This work aims to uncover the impact of polaritons in semiconductor electron devices, particularly quantum well heterostructures, operating at THz frequencies and room temperature. While both theoretical and experimental studies on polaritons exist, their full potential remains largely untapped in practical electronics. Despite significant advancements in the quantum optics community, the electronics community has yet to fully embrace this phenomenon. To our knowledge, this research is among the first to examine CQED explicitly from an electron-device perspective. This emerging field could revolutionize electronics by naturally integrating electronic and photonic technologies in a full quantum formalism.

3 Results

In this work, we have computed the traditional scattering states, which are energy eigenstates of the electron Hamiltonian alone, and the eigenvalues as seen in Fig. 4. The eigenstates and eigenvalues for whole Hamiltonian electron and light, taking into account the interaction term αqx in Eq. (1), are computed and presented in Fig. 5 .

As mentioned before, we diagonalize the entire Hamiltonian to find the polaritonic energy eigenstates, which have a different spectrum from the electron-only states Fig. 2(d). Once these eigenstates are known, we can 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. 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. 6.

4 Conclusion

This work explores the interaction between quantum electrons and electromagnetic fields in the regime of strong light-matter coupling, with a focus on ultrastrong coupling in semicon-

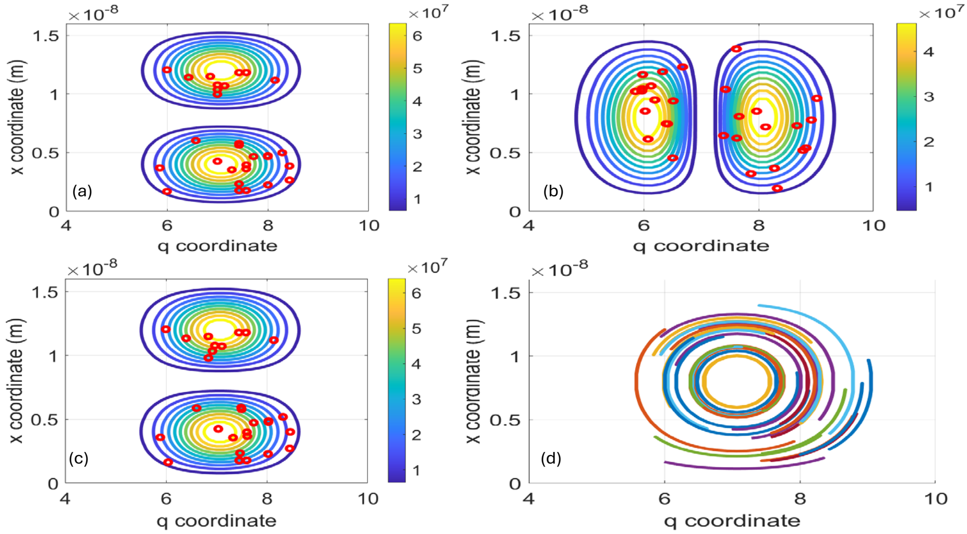

Figure 6. Probability density of the wavefunction $\psi(x, q, t)$ in the $x - q$ configuration space at $t = 0fs$ (a), $t = 40fs$ (b), and $t = 80fs$ (c). Red circles indicate the positions of $M = 30$ Bohmian trajectories $x^j(t)$ and q^j (t) selected with random initial positions according to $\psi(x, q, 0)|^2$. In (d), the continuous path of these trajectories is plotted, showing their (Rabi) oscillations.

ductor quantum wells. The study reveals the formation of polaritons, hybrid quasiparticles that merge the properties of light and matter, providing new insights into light-matter interactions. By combining numerical simulations with analytical modeling, we demonstrate how polaritons affect the behavior of semiconductor devices, particularly in quantum well heterostructures at terahertz frequencies and room temperature. The findings highlight the potential for integrating cavity quantum electrodynamics into semiconductor electronics, opening avenues for breakthroughs in quantum computing and photonics. This research offers a fresh perspective on CQED from the viewpoint of electronic devices, showing that strong light-matter coupling can lead to enhanced performance and new functionalities. The work lays the groundwork for future advancements in the rapidly evolving field of quantum electronics.

Acknowledgment

We acknowledge support from the Spain's Ministerio de Ciencia, Innovacion y Universidades under Grants PID2021-127840NB-I00 (MICINN/AEI/FEDER, UE) and PDC2023-145807-I00 (MICINN/AEI/FEDER, UE).

References

[1] C. Cohen-Tannoudji, J. Dupont-Roc, and G. Grynberg, *Photons and Atom, Introduction to Quantum Electrodynamics* (Wiley, New York, 2004), 280-297.
https://doi.org/10.1002/9783527618422

[2] P. Forn-Díaz, L. Lamata, E. Rico, J. Kono, E. Solano, Ultrastrong coupling regimes of light-matter interaction. Rev. Mod. Phys. **91**, 025005, (2019).
https://doi.org/10.1103/RevModPhys.91.025005

[3] A. F. Kockum, A. Miranowicz, S. De Liberato, S. Savasta, and F. Nori, Ultrastrong coupling between light and matter. Nat. Rev. Phys. , **1**, 19–40, (2019).
https://doi.org/10.1038/s42254-018-0006-2

[4] C. F. Destefani, M. Villani, X. Cartoixa, M. Feiginov, X. Oriols, Resonant tunneling diodes in semiconductor microcavities: modeling polaritonic features in the THz displacement current. Phys. Rev. B **106**, 205306, (2022).
https://doi.org/10.1103/PhysRevB.106.205306

[5] N. Márquez Peraca, A. Baydin, S. Liu, and J. Kono, *Ultrastrong Light–Matter Coupling in Semiconductors*,Semiconductors and Semimetals, Vol. 105 (Academic Press, 2020), 89–124.
https://doi.org/10.1016/bs.semsem.2020.10.002

[6] A. A. Anappara, S. De Liberato, A. Tredicucci, C. Ciuti , G. Biasiol , L. Sorba, and F. Beltram, Signatures of the ultrastrong light-matter coupling regime. Phys. Rev. B, **79**(20), 201303, (2009).
https://doi.org/10.1103/PhysRevB.79.201303

[7] B. Askenazi, A. Vasanelli, Y. Todorov, E. Sakat, J.-J. Greffet, G. Beaudoin, I. Sagnes, C. R. Sirtori, Midinfrared ultrastrong light–matter coupling for THz thermal emission. ACS Photonics, **4**(10), 2550–2555, (2017).
https://doi.org/10.1021/acsphotonics.7b00838

[8] M. Jeannin, G. Mariotti Nesurini, S. Suffit, D. Gacemi, A. Vasanelli, L. Li, A. G. Davies, E. Linfield, C. Sirtori, and Y. Todorov, Ultrastrong light–matter coupling in deeply subwavelength THz LC resonators. ACS Photonics, **6**(5), 1207–1215, (2019).
https://doi.org/10.1021/acsphotonics.8b01778

[9] M. Geiser, C. Walther, G. Scalari, M. Beck, and J. Faist, Strong light-matter coupling at terahertz frequencies at room temperature in electronic LC resonators. Appl. Phys. Lett.,**97**(19), 191107, (2010).
https://doi.org/10.1063/1.3511446

[10] T. Laurent, J.-M. Manceau, E. Monroy, C. B. Lim, S. Rennesson, F. Semond, F. H. Julien, and R. Colombelli, Short-wave infrared $\lambda = 3\,\mu$m intersubband polaritons in the GaN/AlN system. Appl. Phys. Lett., **110**(13), 131102, (2017).
https://doi.org/10.1063/1.4979084

[11] B. Limbacher, M. A. Kainz, S. Schoenhuber, M. Wenclawiak, C. Derntl, A. M. Andrews, H. Detz, G. Strasser, A. Schwaighofer, B. Lendl, J. Darmo, and K. Unterrainer, Resonant tunneling diodes strongly coupled to the cavity field. Appl. Phys. Lett., **116**(22), 221101, (2020).
https://doi.org/10.1063/5.0007118

[12] P. Paul, S. J. Addamane, and P. Q. Liu, *Strong Light-Matter Interactions for Intersubband Transition in a Flexible Single Quantum Well Structure*. CLEO 2023, Technical Digest Series (Optica Publishing Group, 2023), paper FF3D.3.
https://doi.org/10.1364/CLEO_FS.2023.FF3D.3

[13] R. H. Dicke, Coherence in Spontaneous Radiation Processes. Phys. Rev. **93**, 99–110, (1954).
https://doi.org/10.1103/PhysRev.93.99

[14] J. J. Seoane, A. Benali and X. Oriols, A Simple Understanding of Quantum Electrodynamics Using Bohmian Trajectories: Detecting Non-Ontic Photons. Entropy , **28**(4), 474, (2026).
https://doi.org/10.3390/e28040474