PhD or Post-Doctoral opening

“Optoelectronic devices enabled by vacuum-field photons”

We have an opening for a three-year PhD position (or for a two-year post-doctoral appointment) at University Paris Saclay (France) and CNRS, within the Centre for Nanosciences and Nanotechnologies (C2N).

The goal of the project is to explore the electronic response of semiconductor devices embedded in optical microcavities operating in the ultra-strong light matter coupling regime. In this regime, the light-matter interaction is so strong that it alters even fundamental properties of the device, such as its conductance in the dark (that is, in absence of any photonic excitation).

Optoelectronic devices, from light-emitting diodes and solar cells to lasers and detectors, are an integral part of our daily life and are expected to play an increasingly important role in the future. As the basic operating principles of optoelectronic devices are known, their improvement – while important – is often incremental. Finding radically new avenues to implement novel functionalities is a key challenge: cavity quantum electrodynamics promises new approaches to innovate such devices by exploiting the concept of strong (SC) light-matter coupling regimes in microcavities [1]. In this regime, the coupling of photons to electronic/molecular excitations exceeds the decay processes, inducing the formation of new hybridized states known as polaritons.

When the light-matter interaction becomes comparable to the unperturbed electronic transition energy, one reaches the so called ultra-strong (USC) coupling regime. In this regime, a device electronic behavior *in the dark* can be modified [2]: the sole presence of the cavity affects the quantum level positions, and the electronic transport is modified too, even without external driving fields. This concept, preliminarily observed in organic conductors [3] or 2D electron gas [4], can lead to **the development of a novel class of optoelectronic devices, opening up important opportunities in science and applications**.

In this context, the vision and goal of this research project, that can be developed as a PhD cursus or a post-doc fellowship depending on the candidate, **is to demonstrate and elucidate the direct influence of the electro-magnetic vacuum on the electronic energy levels and the electronic transport properties in semiconductor optoelectronic quantum devices.** The advance with respect to current systems is that, contrary to molecules, the energy levels in semiconductor quantum heterostructures can be precisely engineered [5].

The research will focus on optoelectronic devices relying on so-called *intersubband* transitions between quantum-confined electronic states in semiconductor quantum wells (QWs). Such transitions are the building blocks of mid-infrared/THz quantum devices (quantum cascade lasers, infrared QW detector). Furthermore, their flexibility recently led to the first demonstration of the ultra-strong light-matter coupling regime in solid-state physics [6] [7]. **These devices perfectly suit the exploration of new phenomena where cavity electrodynamics and electronic transport both play a fundamental role. Two main research axis will be pursued in synergy.**

The first axis focuses on the photo-transport properties of polaritonic states. The aim is to investigate in depth the resonant extraction of electrons from polaritonic states under optical pumping. The key bottleneck here is the presence of dark electronic states that are not coupled to the cavity field, but do affect the polaritonic transport. By selectively exciting the polaritonic states, one can access their resonant *extraction* into an electric current, as we recently demonstrated [8] [9] (although not in the *ultra*-strong coupling regime). **The long term goal** is to understand the long-standing problem of resonant *injection* of electrons into a polariton state, paving the way to exotic and more efficient mid-IR light sources.

The second research axis is more fundamental: it will explore the effect of the ultra-strong light-matter coupling regime on electron tunneling between adjacent quantum wells, in the absence of photons. By placing the quantum wells in judiciously designed microcavities and tuning the light-matter interaction strength, the relevant design parameters will be isolated and optimized to demonstrate a device whose conductivity depends on the cavity, i.e. on the light matter coupling, in the absence of photons. In this scenario, *the sole presence* of the cavity affects the quantum vacuum and – as a consequence – the electronic transport.

This latter concept is intuitively explained in Figure 1. In a generic photo-conductor detector (panel b) when a photon is absorbed electrons are promoted to an excited transport channel and generate photocurrent. In the dark (panel a), at low temperatures, the conductance is very different as only the fundamental transport channel is available. In the ultra-strong coupling regime, virtual photons make the excited transport channel accessible and the conductance is modified in the dark (panel c). This is the regime where we want the devices to operate.

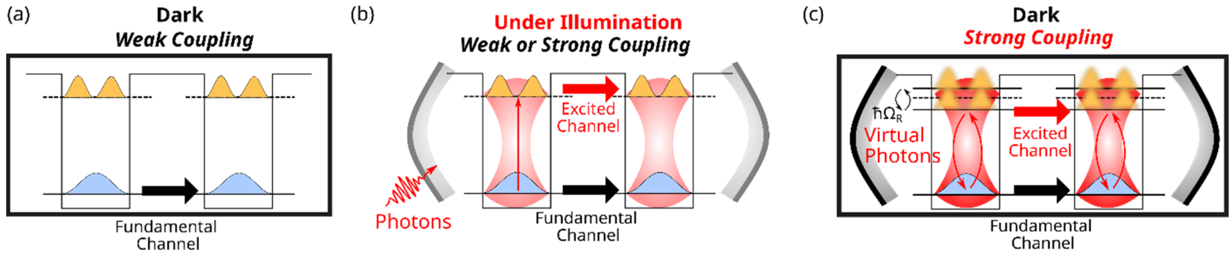

Figure 1: (a) At low temperature in the dark, usual devices operating in the weak coupling regime only possess a single, fundamental transport channel relying on quantum tunneling. (b) Upon illumination, excited transport channels are accessible both in the weak and in the strong light-matter coupling regime. (c) In the ultra-strong coupling regime, transitions mediated by virtual photons are possible, activating a parallel transport channel.

The final objective is to demonstrate a new class of devices whose properties are governed by vacuum fields. One practical realization will consist in the fabrication of a proximity sensor that can detect a metallic surface and measure its distance solely based on the perturbation induced on the light-matter coupling, without emission and detection of photons. **This perspective device can be seen as a *Casimir transistor***: the current in the device is controlled not electrically by a gate, but mechanically by the proximity of a metallic surface.

Acquired know-how: quantum devices physics and technology; electromagnetic modeling; device cleanroom fabrication; optoelectronic characterization techniques; quantum design; python programming and instrument control. Numerical simulation capabilities, characterization tools, fabrication facilities are available at the host institution. The project benefits from collaborations with Univ. Paris 7 (FR), ETH/Zurich (CH) and TU/Wien (AT).

Applicant Profile: The project is experimental with an important part of quantum/electromagnetic simulations. **For a PhD application**, the successful applicant will be an energetic individual with interest in semiconductor physics. She/he will have completed an undergraduate program in Physics, Optics or Engineering. PhD salary fixed at national level, ~25 kE/year gross salary.
For a post-doc application, the successful applicant will have completed an experimental PhD program in Physics, Optics or Engineering. The salary level will be negotiated depending on the CV.

Details: The position is available with a starting date between October and December 2022. Applications, including cover letter and a CV, should be sent to R. Colombelli (raffaele.colombelli@c2n.upsaclay.fr) and M. Jeannin (mathieu.jeannin@c2n.upsaclay.fr).

Relevant References:

[1] A. Frisk Kockum, A. Miranowicz, S. De Liberato, S. Savasta, and F. Nori, Nat. Rev. Phys. **1**, 19 (2019).
[2] F. J. Garcia-Vidal, C. Ciuti, and T. W. Ebbesen, Science **373**, 178 (2021).
[3] E. Orgiu, J. George, J. A. Hutchison, E. Devaux, J. F. Dayen, B. Doudin, F. Stellacci, C. Genet, J. Schachenmayer, C. Genes, G. Pupillo, P. Samorì, and T. W. Ebbesen, Nat. Mater. **14**, 1123 (2015).
[4] F. Appugliese, J. Enkner, G. L. Paravicini-Bagliani, M. Beck, C. Reichl, W. Wegscheider, G. Scalari, C. Ciuti, and J. Faist, Science **375**, 1030 (2022).
[5] F. Capasso, Science **235**, 172 (1987).
[6] C. Ciuti, G. Bastard, and I. Carusotto, Phys. Rev. B **72**, 115303 (2005).
[7] Y. Todorov, A. M. Andrews, R. Colombelli, S. De Liberato, C. Ciuti, P. Klang, G. Strasser, and C. Sirtori, Phys. Rev. Lett. **105**, 196402 (2010).
[8] P.-B. Vigneron, S. Pirotta, I. Carusotto, N.-L. Tran, G. Biasiol, J.-M. Manceau, A. Bousseksou, and R. Colombelli, Appl. Phys. Lett. **114**, 131104 (2019).
[9] M. Lagrée, M. Jeannin, G. Quinchard, O. Ouznali, A. Evirgen, V. Trinité, R. Colombelli, and A. Delga, Phys. Rev. Appl. **17**, 44021 (2021).

Web: https://odin.c2n.universite-paris-saclay.fr/en/activities/mir-thz-devices/
Publications : http://www.mir-thz-devices.u-psud.fr/Publications/publications.htm