Campagne 2020 Contrats Doctoraux Instituts/Initiatives

Proposition de Projet de Recherche Doctoral (PRD)

Appel à projet CIQ - Centre d'information quantique 2020

Intitulé du Projet de Recherche Doctoral : Semiconductor quantum dots for integrated quantum technologies

Directeur de Thèse porteur du projet (titulaire d'une HDR) :

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Unité de Recherche :
Intitulé : Institut des NanoSciences de Paris
Code *(ex. UMR xxxx)* : UMR7588

Ecole Doctorale de rattachement de l'équipe & d'inscription du doctorant : **ED564-Physique en IdF**

Doctorants actuellement encadrés par le directeur de thèse (préciser le nombre de doctorants, leur année de 1ere inscription et la quotité d'encadrement) : 0

Co-encadrant :

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Cotutelle internationale : ☒ Non ☐ Oui, précisez Pays et Université :

Description du projet de recherche doctoral ***(en français ou en anglais)***
3 pages maximum – interligne simple – Ce texte sera diffusé en ligne

Détailler le contexte, l'objectif scientifique, la justification de l'approche scientifique ainsi que l'adéquation à l'initiative/l'Institut.
Le cas échéant, préciser le rôle de chaque encadrant ainsi que les compétences scientifiques apportées. Indiquer les publications/productions des encadrants en lien avec le projet.
Préciser le profil d'étudiant(e) recherché.

I. General context of the project

Quantum information technologies rely on coherent manipulations of individual quantum systems, or quantum bits (qubits), with single qubit and two-qubit quantum gates necessary to perform quantum computations. For quantum logical operations, solid-state systems are very attractive, because they pave the way towards integrated devices using advanced nano-fabrication techniques. In particular, semiconductor Quantum Dots (QDs) with their discrete level structure and their direct incorporation into device architectures are appealing candidates for quantum communication, processing and storage.

The long term project that we propose here, aims to integrate site-controlled semiconductor quantum dot molecules (QDM), i.e. two InAs QDs vertically stacked and separated by an GaAs barrier, into specific designed photonic nanostructures to perform all-optical and on-chip manipulations of single qubits. In particular, the spin-state of a single hole trapped in such QDM will implement the qubit, all-optically controlled by embedding the QDM in photonic crystal waveguides or cavities. This approach will allow highly efficient qubit preparation, manipulation and readout. Thus, our proposal lays the groundwork towards entanglement between holes trapped in distant QDM, using single photons, and towards exploration of quantum non-linear optics with few photons [Lukin14]. This approach is based on theoretical predictions that have only been partially addressed in the literature [Economou12, Jennings19]. Our project has been funded by the French ANR program Technologies Quantiques in 2018, started in 2019 and involves three French laboratories (INSP, C2N and LP2N in Bordeaux). At INSP two teams are involved: the optics group (Richard Hostein, Benoit Eble, Valia Voliotis and François Dubin) and the growth group (Paola Atkinson); C2N will be leading the nanofabrication (Isabelle Sagnes , Rémy Braive) and the LP2n group(Philippe Lalanne) will lead the simulations and design of nanophotonic structures.

II. Scientific project

In QDMs, tunneling between the dots leads to hybridization of the electronic levels and delocalized electronic wave functions. A large number of states is then available that can be used to built three-level (Lambda) systems. The spin states of a single hole confined in the QDM will constitute the ground states (G1 and G2) and the third level (E) is an optically excited higher energy state (the so-called trion state) [Economou12]. This is motivated by important advantages:

- Hole spins are less sensitive than electron spins to decoherence mechanisms such as hyperfine interactions with nuclei. Coherence times up to μs are actually expected for holes [Fras12].
- The hole-spin mixing factor may be modified by changing growth conditions to vary the QD aspect ratio or the lateral offset between the vertically stacked dots in the molecule. The aim is to obtain well-separated spin-mixed trion states and avoid unwanted transitions during the rotation of the qubit as necessary to perform quantum logic gates with highest fidelities.
- The hole ground and excited states can realize a three-level (Lambda) system involving an indirect transition (inter-dot transition) which has a large electric dipole and can therefore be tuned electrically to match a target energy, e.g. a cavity mode frequency. The hole will be initially localized in the top QD of a molecule embedded in a n-i-p diode structure. Thus, the QDM energy levels will be tuned electrically and set such that a single hole is trapped deterministically. To initialize its spin state we will rely on resonant optical pumping on the G1-E transition. After spontaneous emission the hole-spin is projected in the lowest-lying level (G2). Direct readout can be made on another cycling transition. In this example of state preparation, we make use of the valence band mixing between holes states, which is more pronounced in the case of QDM. Indeed, the coupling between heavy and light-hole leads to singlet-triplet mixing

allowing optical excitation of excited levels with mixed hole-spin states. To perform the all-optical coherent control of the hole-spin with highest fidelity, QDMs will be embedded in photonic devices. At a first stage and for simplicity we will use 1D waveguides obtained by etching directly the InAs/GaAs heterostructure hosting a dilute ensemble of QDMs. We have proposed and successfully demonstrated this technique at INSP, e.g. to perform Rabi oscillation with single and neutral QD [Moniello13] [Reigue17]. In a second and more advanced step, QDMs will be studied in photonic crystal (PhC) waveguides and cavities. This will allow us to reduce the size of the electromagnetic mode interacting with a single hole by orders of magnitude, and then boost the QDM-photon coupling strength, which scales as the inverse of the electromagnetic mode volume. We consider waveguide and cavity geometries, which can actually become equivalent when the electronic transition of a QDM is set at the band-edge of a PhC waveguide and thus act as a dielectric defect localizing a single photon [Kimble15].

III. Implementation.

In this PhD proposal and for a three years period, we plan to complete the following tasks:
-1. Growth of QDM (INSP, P. Atkinson, 0-24 months). The first objective of the project is to establish a growth strategy for strained QDMs with unprecedented precision over the dots' position, energy and tunnel coupling rate. This strategy is based on the use of ex-situ nanohole-patterned substrates to exert control over the migration of adatoms on the growing surface, leading to controllable nanoscale variations in thickness and composition during growth. The effect both of growth conditions, and the design of patterned substrates to control the adatom migration during growth and subsequently improve the uniformity and optical quality of the QDMs constitutes a fundamental aspect of this work package. The INSP is equipped with a RIBER Compact 21 MBE system and a carbon sublimation source for p-type doping will be added to allow controlled hole injection into QDM.
- 2. Fabrication of photonic devices (INSP, R. Hostein, F. Dubin; C2N, R. Braive 0-24 months). Photonic nanostructures will be optimized for site-controlled QDMs charged with a single hole. We envision a segmented architecture, including optical input and output ports directly coupled to the region where a QDM is coupled to the mode of a PhC waveguide or cavity. To design such devices we will rely on the expertise of our collaborator at LP2N. Nanostructures will then be realized on the samples grown at INSP using the cleanroom at C2N. Sample processing will also include the contacting of the field-effect structures (metal deposition, microbonding).
- 3. Optical experiments (INSP, R. Hostein, B. Eble, V. Voliotis, 0- 36months).
a) Mapping and study of molecular states in QDM: When QDMs are embedded in a n-i-p diode structure, an applied electric field tunes the energy levels one relative to another and relative to the Fermi level of the highly doped contacts. Mapping all the optical transitions will be fundamental and will provide information for the growth team in order to adjust the diode parameters (barrier thickness between the QDs, relative sizes of the QDs, thickness of the intrinsic layer in the diode and spacing between the p-doping layer and the QDM) to reach an operating regime where one hole is always present in the top QD. These initial experiments will be performed with a magnetic field applied in Faraday geometry to ensure a sufficient Zeeman splitting of the spin states so that they can be individually addressed. For that, we will upgrade our closed-cycle cryostat by adding a superconducting magnet directly inside the chamber (up to 2T in split pair configuration).
b) Coherent control of a hole-spin in a QDM: As mentioned previously, the initialization of the hole-spin will be realized using σ – polarized laser light resonant with the optical transition between the G1 state and one molecular branch of the mixed state (E). Thus, the hole-spin will be optically pumped in the ground state G2, and its coherence time will be measured by Ramsey interferences. For that purpose, the hole-spin state will be controlled using two off-resonant and phase-locked lasers achieving a stimulated

Raman transition between the G1 and G2 ground states. Moreover, we will introduce a controlled phase difference between these two ground states using an additional laser, detuned from resonance, implementing a phase gate through the optical Stark effect. Finally, we will use cycling transitions resonant between G2 and another excited state at different energy for non-destructive readout.

Preliminary results : GaAs/AlGaAs QDM with random position have been grown recently at INSP. Preliminary μPL experiments have been performed. QDM are embedded in 1-D waveguide fabricated at C2N. The upper and lower dots are deliberately well separated in energy in order to address unambiguously each state. We performed resonant Rabi oscillations of the charged exciton in the lower and upper dot and verify that the emitters are almost perfect single photon sources with low backscattered light. This demonstrates the ability to manipulate a QDM transition with a ps laser as it is proposed in the above project.

IV. Impact/ Impact

The integration of epitaxial QDs into opto-electronic devices gives an opportunity for a fully integrated quantum technology. Mastering the combination of: i) site-controlled dot growth, ii) PhC cavity design and fabrication and iii) spin-spin entanglement in a QD-PhC system, will be a major breakthrough in demonstrating the viability of an optically driven semiconductor-QD-based nanophotonic platform. This would have a great impact for quantum communication networks based on an ordered array of stationary qubits (single hole-spin), with single guided photons (flying qubits) distributing entanglement between the distant qubits. This task still remains a major challenge. The proposed project meets the criteria of the CIQ initiative concerning quantum communications and the success of the project will give high international visibility to the SU community.

References
[Atkinson12] J. Appl. Phys. 112, 5, 054303 (2012);[Economou12] PRB 86, 085319 (2012); [Fras12] PRB 86 161303 (2012); [Jennings19] Adv. Quantum Technol. 1900085 (2019); [Kimble15] Nat. Phot. 9, 326 (2015);[Lukin14] Nat. Phot. 8, 685 (2014)

Reférences des encadrants en lien avec le projet: [Moniello13] PRL 111, 026403 (2013); [Moniello14] Phys. Rev. B 90, 041303(R) (2014); [Reigue17] PRL 118, 233602 (2017); [Reigue18] Appl. Phys. Lett. 112, 073103 (2018)

Profil de l'étudiant recherché: Le candidat devra être titulaire d'un Master de physique et avoir les bases en propriétés électroniques et optiques des solides et en physique des semiconducteurs.