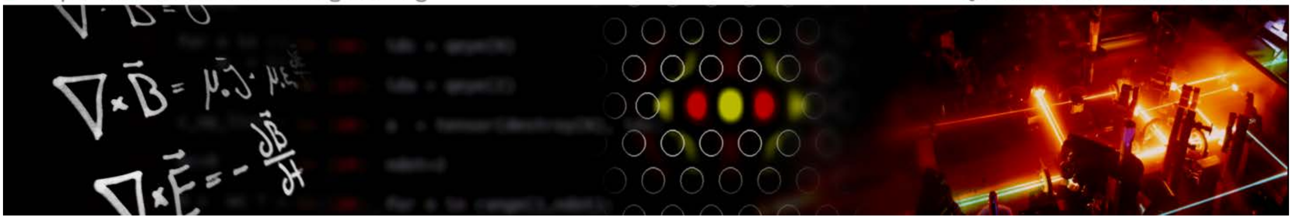

B.Sc./M.Sc. Project

Theory of single-photon sources

The single-photon source (SPS) is a key device within quantum information processing, where it is used to generate quantum bits encoded on photons for optical quantum computing and for secure communication based on quantum cryptography. One of the most promising platforms for constructing SPSs is based on the semiconductor quantum dot (QD), which is a two-level system capable of deterministically emitting single-photons on demand.

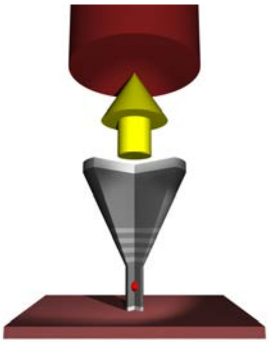

Fig. 1: Sketch of nanowire SPS with inverted tapering

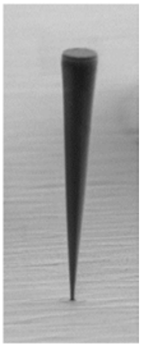

Fig. 2: SEM image of the inverted nanowire (CEA Grenoble)

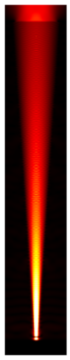

Fig. 3: Optical field profile.

Due to the symmetry, light from a QD in a bulk material is emitted in all directions, and the efficiency, defined as the number of photons detected by the collection optics per trigger, is low. However, by placing the QD inside a structured environment such as a photonic crystal membrane, a micropillar or a nanowire, light can be efficiently directed towards the collection optics. The photonic nanowire (Fig. 1) with typical diameter of ~ 200 nm is a particularly simple geometry [1], which allows for control of the light emission. DTU Fotonik is collaborating with the Commissariat à l'Energie Atomique (CEA) in Grenoble, France, which fabricates (Fig. 2) and characterizes the nanowire SPS based on designs provided by Fotonik.

However, for quantum information processing applications, not only are high efficiency sources required but also the emitted photons must be quantum mechanically indistinguishable. In other words, the photons should be completely identical with respect to wavelength, polarization, optical mode profile etc. However,

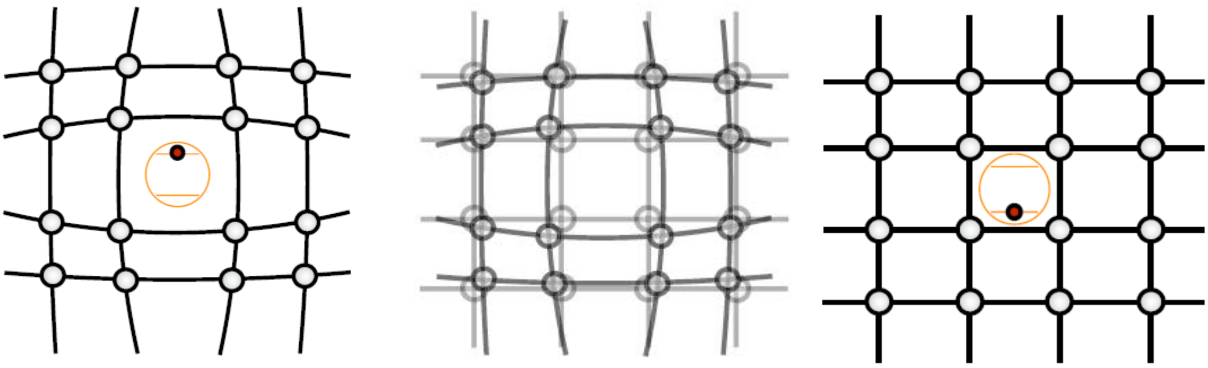

Fig. 4: Interaction of the QD with lattice vibrations (phonons) in the solid-state environment.

decoherence effects due to the interaction between a QD and its solid-state environment, as illustrated in

Fig. 4, limits the indistinguishability of the emitted photons. In particular, non-Markovian dynamics induced through strong coupling with quantized lattice vibrations – phonons – leads to a trade-off [2] between the maximum efficiency and indistinguishability simultaneously obtainable. Currently, how to obtain efficient light emission (Fig. 3) in combination with high indistinguishability is not well understood.

The overall aim of this project is to establish a theoretical understanding of the physical mechanisms governing light emission in semiconductor QDs, and ultimately develop improved SPS. This may be tackled through two avenues with significant overlap: through optical simulations novel photonic structures will be proposed to maximise the efficiency of SPS; by developing microscopic theories of QD emission in photonic structures, new approaches for enhancing photon indistinguishability will be investigated. A possible strategy is to combine optical modelling with a microscopic theory for phonon interactions to propose novel principles for photonic engineering that control not only the light emission, but also the interaction with phonons through the tailoring of the local density of states.

While the exact nature of the project will depend upon the student's interests, possible activities are to:

- Develop an optical modelling tool to simulate Maxwell's equations and predict the efficiency.
- Using an open systems approach, develop a model to describe the emission properties of QDs in photonic structures, capturing non-Markovian phonon processes.
- Analyse the local density of states of a nanowire SPS design.
- Implement weak cavity effects such as distributed Bragg reflector.
- Propose an SPS design with Purcell enhanced emission of single photons for emission of indistinguishable photons.

For a student interested in the optical modelling aspect of this project, knowledge of electromagnetics (Maxwell's equations), waveguide theory, and Matlab programming is recommended. Describing the microscopic behaviour of QDs would suit a student interested in applications of quantum theory; it is recommended that the student has a solid grounding in the fundamentals of quantum mechanics or quantum optics, with basic knowledge of coding (Matlab, Python, or Mathematica).

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References:

[1]: J. Claudon, J. Bleuse, N. S. Malik, M. Bazin, P. Jaffrennou, N. Gregersen, C. Sauvan, P. Lalanne, and J.-M. Gérard, "A highly efficient single-photon source based on a quantum dot in a photonic nanowire," Nat. Photonics **4**, 174–177 (2010).

[2]: J. Iles-Smith, D. P. S. McCutcheon, A. Nazir, and J. Mørk, "Phonon scattering inhibits simultaneous near-unity efficiency and indistinguishability in semiconductor single-photon sources," Nat. Photonics **11**, 521–526 (2017).