Coupling of Nanocrystals and Photonic Crystals for Non-Linear Applications

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***Abstract-* Modelling results are described that deal with the coupling of excitons in colloidal nanocrystals to silicon-based photonic crystal microcavities, and to the design of structures that couple the microcavities to ridge waveguides and input/output gratings that are realized on 200 mm diameter silicon-on-insulator wafers.**

SUMMARY

Motivation and Background

Microcavities of various designs, realized in high-index-contrast semiconductor hosts such as GaAs, InP, and Si, offer high quality factors, Q, small mode volumes, V, and therefore attractive Q/V figures of merit for cavity quantum electrodynamic (CQED) research and applications. In epitaxial III-V materials, both micropillar (1D Bragg cavities etched into sub-micron diameter pillars), and planar photonic crystal type cavities containing InAs quantum dots have been used to demonstrate strong coupling of excitons and cavity photons [1,2], single-photon sources [3], and resonant fluorescence [4,5].

The majority of this impressive work in chip-based CQED has so far been restricted to individual cavities. One of the potential advantages of the chip-based approach is the inherent ability it affords to couple many such cavities to one another in optical "circuits". From an optical circuit perspective, the silicon, or more precisely the silicon-on-insulator (SOI) material platform is attractive due to the relative ease of processing large wafers using industrial scale stepper technology, and therefore the ability to monolithically integrate photonic circuits [6] with CMOS electronic control circuitry.

The challenge dealing with silicon in the CQED context lies in finding the equivalent to the InAs quantum dots that are so readily obtained in III-V materials using epitaxial growth. Colloidal nanocrystals formed from PbSe or PbS are candidate sources of three dimensionally confined excitons that can be resonant with silicon based microcavity modes at wavelengths ~ 1.5 μm. Their precise transition frequency is determined by quantum confinement effects, and can be tuned to this wavelength range by stopping their growth when the diameter of the nanocrystals is ~ 5 nm. While there are both technical challenges (developing processes for maintaining the excellent solution-based, room temperature photoluminescent (PL) yield when placed on silicon, in vacuum), and fundamental challenges (understanding the complex electronic structure and mechanisms that contribute to exciton dynamics), with this approach, one significant advantage of colloidal versus epitaxial quantum dots is their more robust behaviour at elevated temperatures, owing to the higher confining potential.

Together with our collaborators who synthesize high-quality colloidal nanocrystals, we have recently made significant progress in understanding the temperature dependent PL properties of solid films of PbSe nanocrystals emitting near 1.5 μm [7], and demonstrated temperature-independent PL yield of PbSe/CdSe core-shell variants up to ~ 240K [8].

Using an atomic force microscope (AFM) lithography technique, these PbSe nanocrystals have also been site-selectively placed at the antinode of microcavities formed in 2D photonic crystal silicon membranes. Room temperature PL spectra from these samples clearly demonstrate coupling of the exciton emission to the microcavities [9].

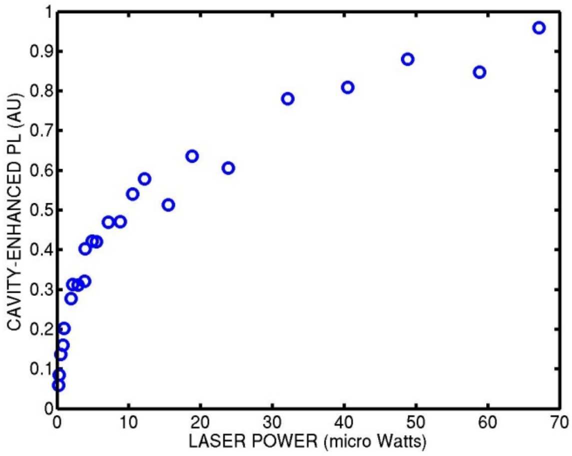

Fig. 1. Intensity of the cavity-enhanced PbSe excitonic PL measured at room temperature on an L3 microcavity as a function of the CW power of a HeNe excitation laser focussed to a 2 micron diameter.

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Modelling Colloidal Nanocrystals Coupled to Silicon Photonic Circuits

Like most III-V CQED research, the PbSe-silicon microcavity coupling referred to above was demonstrated using isolated cavities. This talk will describe modelling related aspects of two extensions to this previously reported work: i) the saturation behaviour of the cavity-coupled PL from the PbSe nanocrystals, and ii) the design and characterization of SOI structures that contain L3 microcavities [10] coupled to silicon ridge input and output waveguides, each terminated by 2D photonic crystal grating couplers.

Attempts to quantitatively explain the excitation power dependence of the cavity-coupled PL signal (see Fig. 1), revealed several subtle distinctions between this situation of spherical-shaped nanocrystals resting on the surface of the microcavity, versus the overgrown InAs quantum dots that are typically buried in the centre of the cavity. The fact that the cavity mode field strength is slightly smaller on the surface than in the centre of the silicon slab is relatively insignificant in comparison to the influence of the surface location on the background local density of photonic states felt by the exciton, and the need to accurately account for depolarization, or local field effects. Finite difference time domain (FDTD) simulations of these effects will be described.

As a first step beyond isolated cavity studies, structures like that shown in Fig. 2 were designed and fabricated on a 200 mm SOI wafer at a silicon photonics foundry in the frame of ePIXfab set-up by IMEC vzw and CEA-LETI. They contain L3 photonic crystal cavities that are coupled on either side to 1D photonic crystal waveguides which are in turn coupled to silicon ridge waveguides, and eventually to tapered waveguides connected to 2D rectangular photonic crystal grating couplers. The entire structure is fabricated using a single layer/single etch process before the cavity region is undercut using an HF acid backend etch. As will be shown, this design allows facile free space input and output coupling to the microcavities with the sample inside a cryostat. Of particular note are the grating couplers that allow efficient coupling over the typical 100 nm tuning range of commercial laser diodes in this region of the spectrum, to either or both TE and TM polarized waveguide modes.

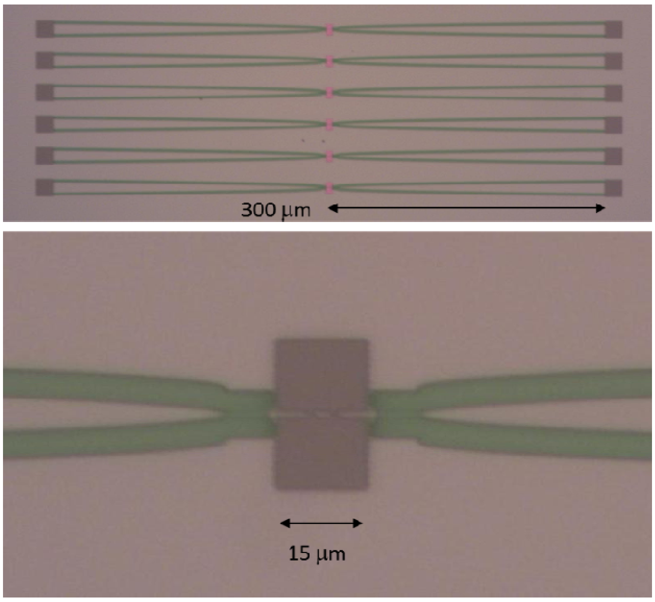

Fig. 2. Optical micrographs of six sets of the full coupled cavity structures (top), and blowup of the central cavity region showing the input and output waveguides (bottom).

ACKNOWLEDGEMENT

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