Fabrication and Characterization of SiN_x/Au Nanopatch Cavities with Colloidal Nanocrystals

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Abstract: We report on the fabrication/characterization of nanoscale cavities in which a monolayer of CdSe/CdS quantum dots is embedded in a SiN_x/Au structure. The physics of the emission rate enhancement (1.2 - 3.4) is discussed.
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1. Introduction

When they were first proposed in 2008 [1], nanopatch cavities were found to provide strong mode confinement and high quality factor in the near-IR wavelength range (1-1.6 µm), which is convenient to fabricated low-threshold lasers. Lasing at 1.3µm was successfully demonstrated in 500nm-sized nanopatch cavities in which a 200-nm bulk InGaAsP layer was sandwiched between two 100-nm Au mirrors [2]. Due to their sub-wavelength dimensions, nanopatch cavities are also of interest for the fabrication of directive single-photon sources with short radiative lifetime. In [3], the control of the spontaneous emission rate and the radiation pattern of colloidal quantum dots (QDs) was demonstrated by sandwiching single (randomly distributed) QDs between a bottom Au layer and a top Au micron-sized patch. Although, the structure was not etched through to form a cavity and was bigger (1-1.2µm), an average Purcell enhancement between 5 and 15 was observed experimentally.

Here, we report the fabrication and characterization of subwavelength nanopatch cavities with colloidal QDs. These cavities (see Fig.1) consist of QDs embedded in a SiN_x matrix sandwiched between two Au surfaces. They allow the confinement of optical resonant modes in subwavelength volumes of the order of 10^{-3}-10^{-4} λ^3. Because the emission line of QDs is broad at room temperature (typically 30 nm), a low Q-factor of about 10 is required. From FDTD simulations, Purcell factors of 5-8 are nevertheless expected for a single QD in the center of the cavity, due to the small mode volume.

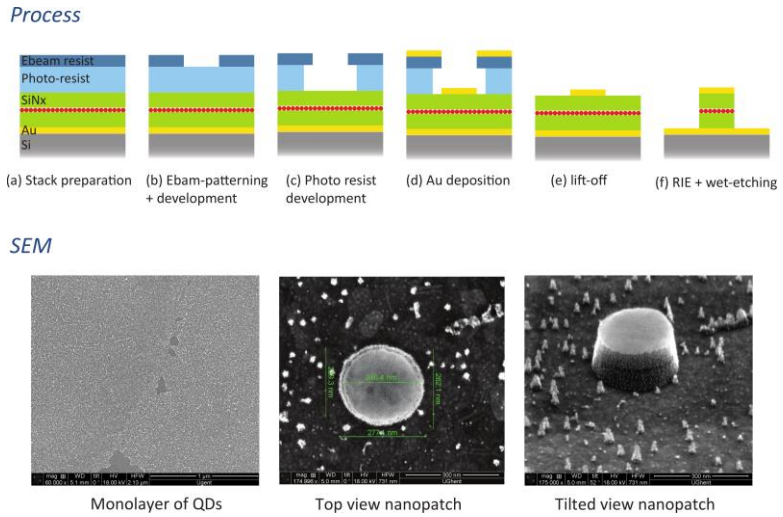

Fig. 1. Fabrication process and SEM structure characterization

2. Fabrication

The different fabrication steps are schematically represented in Fig. 1. We start from the stack shown in the top part of Fig. 1, which is made by subsequent deposition of Au (by evaporation), SiN_x (by PECVD), a monolayer of QDs (by the Langmuir-Blodgett technique), SiN_x and finally a resist double-layer. First the ebeam resist is exposed and

developed to create circular holes. Next the photoresist, which was flood-exposed on beforehand, is developed to create an undercut. With this undercut we avoid contact between deposited metal and resist layer, securing a nice Au lift-off in the next step. Finally the Au disks are used as a hard mask during the etching of SiN_x and QDs by a combination of RIE (CF4/H2) and wet etching (H3PO4). A SEM picture of a final patch is also shown in the bottom of Fig 1. By varying the dot-dose of the ebeam exposure during ebeam patterning, different sizes (diameter of 350-600 nm) are achieved. A good cavity roundness and overall fabrication quality is achieved within that size range. The roundness is limited by the resolution of the ebeam. We used CdSe/CdS colloidal QDs emitting around 620 nm. They were synthesized using the so-called "flash" method described in [4]. This synthesis method is fast and produces QDs with high radiative quantum yield (>40%). The nanopatch cavities were designed and using FDTD methods such that the wavelength of the TM_{111} mode matches 620 nm.

3. Purcell enhancement of the spontaneous emission rate

We fabricated a lattice of nanopatch cavities of different sizes (diameter of 350-600 nm) on the same chip. The luminescence from these cavities is seen on Fig. 2a. The luminescence decay from the nanopatch cavities was investigated. We compared these decays to two reference situations shown in Fig. 2b. In situation REF1, the QDs are embedded in a SiN_x matrix. The decay lifetime is then 29.2 ns (black curve in Fig. 2b). In the situation REF2, the QDs in SiN_x are sandwiched between two layers of Au : we observe that the lifetime reduces to 25.5 ns. (gray curve in Fig. 2b). The luminescence decay from QDs in cavities shows a lifetime reduction by a factor 1.2 and 3.45 (1.77 is a typical value for large cavities, see red curve in Fig. 2b.). In small cavities, the luminescence lifetime was seen to decrease by a factor of 3.45 compared to the REF1 (blue curve in Fig. 2b). Comparison with the situation REF2 shows that the observed speed-up of the spontaneous decay is mainly due to the cavity etching and not to the plasmonic coupling to Au (which only provides a moderate enhancement).

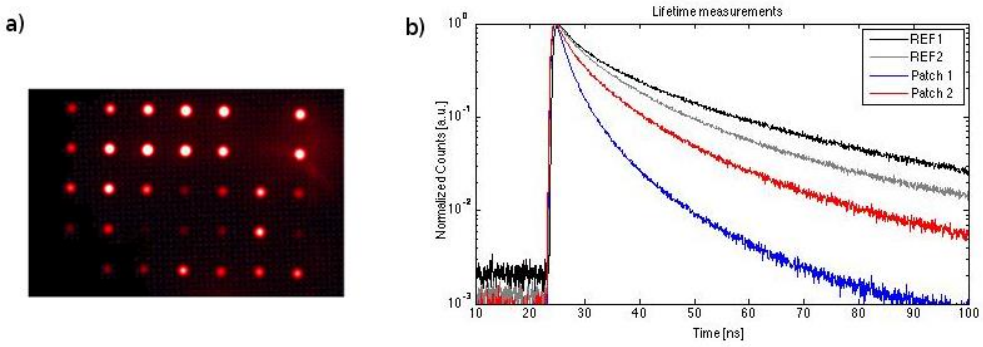

Fig. 2. a) Fluorescence image from a lattice of nanopatch cavities. b) Photoluminescence lifetimes

4. Conclusion

Although the speed-up of the spontaneous emission is modest in our experiment, it is important to keep in mind that a full monolayer of QDs is embedded in our cavities, which increases the losses. As demonstrated in [5], deterministic positioning of single colloidal QDs at predefined sites is possible with high success rate, starting from a monolayer. By combining this patterning technique with the nanopatch fabrication demonstrated here, it should be possible to demonstrate directive single-photon emission with a Purcell factor of 5-8 as expected from our simulations.

5. References

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