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Electrical Injection of a Photonic Crystal Nanocavity

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ABSTRACT

The possibility of electrical pumping of a single QD and the integration of such a device in an opto-electronic circuit would be a fundamental step towards achieving an “on demand” single photon source. In this paper we describe the fabrication process and preliminary results of a Light Emitting Diode (LED) integrated with a photonic crystal (PhC) nanocavity on a GaAs membrane. We demonstrate effective electric pumping of the QDs embedded into the membrane by contacting the doped layers (p and n) of the thin membrane, and the excitation of cavity modes of the PhC nanocavity fabricated on it at telecom wavelength.

Keywords: electrical injection, photonic crystal, microcavities, quantum dots, single photon sources.

1. INTRODUCTION

In the fields of quantum computing, quantum key distribution and also for fundamental studied on quantum electrodynamics (QED) it would be fundamental to have at disposal single photon sources at telecom wavelength. Photonic crystals (PhCs) are a very powerful instrument for handling light at $\sim\mu\text{m}$ scale and allow the fabrication of waveguides and very high Q microcavities. In recent years intense activity [1-4] has been dedicated to study the coupling between emitter and cavity in order to control the available electromagnetic modes and so the spontaneous emission rate [5] to obtain high efficiency sources. Using a modified L3 defect nanocavity (3 in-line missing holes) in a PhC on a GaAs membrane with a single layer of low density ($5 - 7 \text{ dot}/\mu\text{m}^2$) QDs in its center, we obtained quality factors Q as high as 16500 and measured, in resonance conditions, a Purcell factor of 8 at 1300 nm for the first time [6,7]. Most of these experiments are performed using optical pumping while a device for practical application should work under electrical injection[8]. We present here a LED-like device based on a PhC nanocavity able to efficiently pump the InAs QDs and the cavity electromagnetic modes.

2. FABRICATION PROCESS

The fabrication process is very challenging and it is based on e-beam lithography (EBL) and standard thin-film processes. It consists of several steps and each new layer needs to be aligned to the previous one with an accuracy $\leq 500 \text{ nm}$. The sample is grown by molecular beam epitaxy (MBE) and it is a 370 nm thick GaAs membrane on top of a 1.5 μm $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ sacrificial layer. The membrane is p-doped in the upper part and n-doped in the lower one. A single layer of low areal density InAs QDs, with emission at 1.3 μm at liquid helium temperature, is embedded in the middle of the membrane. Mesas with diameter between 8 to 10 μm are wet-etched in diluted $\text{H}_3\text{PO}_4 / \text{H}_2\text{O}_2 / \text{H}_2\text{O}$ solution to a height of about 300 nm using EBL exposed HSQ (hydrogen silsesquioxane) negative resist as a mask. To pattern the n-contact at the bottom of the mesa an alloy of Ni/Ge/Au/Ni/Au has been deposited and annealed to obtain a better electrical behavior and the p-contact on top of the mesa has been made of a Cr/Au bilayer 100 nm thick. Insulation between the two contacts has been obtained by a 200 nm thick layer of Si_3N_4 , deposited by PECVD. Electric pads have been designed to match the ground-signal-ground probe (2 external ground contacts and one center signal contact) of the cryogenic-probe system used for the electrical measurement. A 150 nm thick layer of SiO_2 is deposited by ECR-PECVD and the PhC nanocavities are transferred on it by EBL on PMMA resist on the top of the mesa. Successive etching of the SiO_2 (CHF_3/Ar based reactive ion etching-RIE) and of the GaAs membrane ($\text{SiCl}_4 / \text{O}_2 / \text{Ar}$ RIE) allows the transfer of the PhC cavity. The membrane is then released in diluted HF. The chosen cavity is an L3 type. The air filling factor was measured to be around 27%. The first holes on each side are shifted outwards by 15% and rescaled to 61% of the unperturbed holes diameters, following [2,6,9]

The modified L3 cavity is clearly visible at the center of the SEM image in figure 1. The darker area around the PhC nanocavity is the mesa: its border is apparent through the gold top contact, which also serves as a cover to block photons emitted outside the PhC region and the side of the mesa. On the top of the image, the n-contact looks darker, since it is covered by the insulating Si_3N_4 .

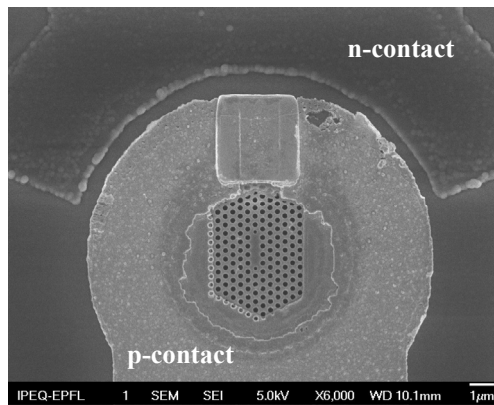


Figure 1. Scanning Electron Microscopy (SEM) image of a modified L3 photonic crystal cavity on membrane.

3. RESULTS

The electro-optical characterization of the LED has been performed in a cryogenic electro-probe station coupled with a microelectroluminescence (μ EL) setup. The sample is mounted on a cold-finger cooled by an holder dipped in liquid He (about 5 K). The optical emission from the top of devices can escape from the cryogenic set up through a window and is collected by a microscope objective (numerical aperture 0.4). A mirror reflects the Infra-Red (IR) radiation (which is sent to an IR camera or focused into a single mode optical-fiber and sent to the spectrometer) and transmits the visible radiation (that allows to observe the samples surface by a CCD camera). The electroluminescence (EL) is dispersed into a 1m focal length monochromator equipped with a cooled InGaAs photodiode array detector; the spectral resolution of the setup is better than $30 \mu\text{eV}$ ($\approx 0.04 \text{ nm}$). The sample was measured both at liquid helium (LHe) and liquid nitrogen (LN_2) temperature. IV-curves were recorded, showing clear diode behavior and a relatively low threshold voltage of 2 V, which proves the high quality of the process and very good electrical contacts.

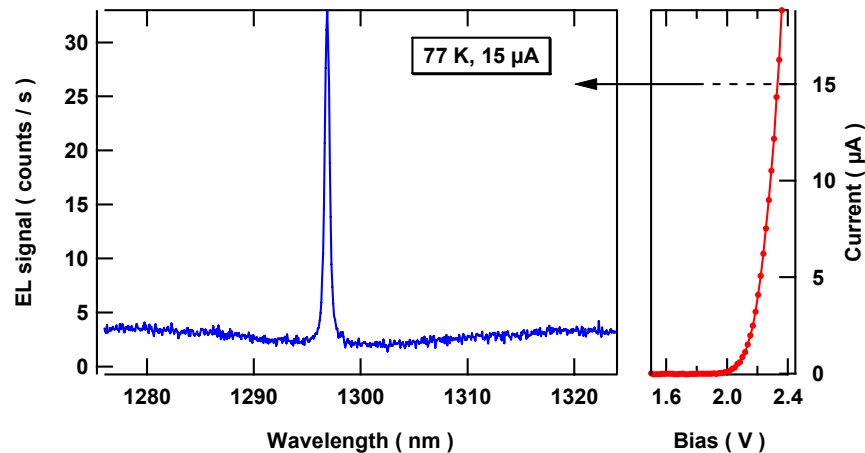


Figure 2. a) Electroluminescence spectrum under $15 \mu\text{A}$ excitation and b) IV-curve of a modified L3 photonic at 77 K.

The electroluminescence spectrum presented in figure 2 was performed at 77 K on a device with PhC lattice parameter $a = 231 \text{ nm}$ under $15 \mu\text{A}$ continuous current. A cavity mode is clearly observed, with a measured quality factor (Q) above 2600. This shows that this process approach lead to PhC cavities with low optical losses, despite the presence of doped layers and metal contacts. Work is now in progress to demonstrate Purcell-enhanced emission under electrical injection [9].

4. CONCLUSIONS

In this paper we presented a device that demonstrate successful electrical pumping of InAs QD's in PhC membrane modified L3 nanocavity under continuous bias at LN_2 and LHe temperature. This results represents a fundamental achievement in the integration of PhC nanocavities in electrical circuits. Time resolved experiments are in progress to demonstrate Purcell effect on these devices.

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