Enhancement of the quantum dot photoluminescence using transfer-printed porous silicon microcavities

I S Kryukova¹, D S Dovzhenko¹, Yu P Rakovich¹,²,³, I R Nabiev¹,⁴
¹National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409 Moscow, Russian Federation
²Centro de Fisica de Materiales, 20018 San Sebastian, Spain
³IKERBASQUE, Basque Foundation for Science, 48013 Bilbao, Spain
⁴Laboratoire de Recherche en Nanosciences, LRRN-EA4682, Université de Reims Champagne-Ardenne, Reims 51100, France

Abstract. Enhancement of the photoluminescence signal intensity from organic and inorganic fluorophores increases the sensitivity of operation of optical sensors, detectors, and photonic diagnostic assays. Here, we have engineered and compared optical and fluorescence-enhancing properties of two types of one-dimensional porous silicon photonic crystals: a transfer-printed microcavity based on the freestanding photonic crystal and a conventional “one-piece” microcavity created on a monocrystalline silicon substrate. Comparative analysis of the eigenmodes and the photonic bandgaps of both types of microcavities demonstrated a high quality of transfer-printed microcavities and good correlation of their reflection spectra with the spectra of “one-piece” microcavities. Moreover, embedding of a highly concentrated solution of quantum dots (QDs) in the eigenmode localization region of transfer-printed microcavity was followed by three-fold reduction of the full-width-at-half-maximum of their luminescence spectrum at the microcavity eigenmode wavelength, thus confirming a weak coupling regime of QD exciton and microcavity eigenmode interaction and significant enhancement of QD luminescence within the microcavity.

1. Introduction

Today, the photonic systems based on porous matrices attract much interest for fundamental research of their optical properties and prospective sensing and optoelectronic applications. Porous silicon (PS) is one of the most versatile materials for their fabrication. Due to the possibility to accurately control its porosity by variation of parameters of the electrochemical silicon etching process [1], a wide range of high-quality microcavities based on PS can be designed [2]. Embedding organic or inorganic luminophores (e.g., semiconductor quantum dots (QDs), dyes or polymer molecules) into these structures allows light emission manipulation, demanded in many applications, such as lasers [3] and displays [4], or for fundamental investigations of the effects related to light–matter interaction [5]. In this last case, the efficiency of light–matter interaction is directly proportional to the intensity of the electric field component near the luminophore [5]. At the same time, the electromagnetic field in the microcavity is mainly located in the eigenmode localization region. In this regard, the technology for designing microcavities with emitting particles placed exactly in the eigenmode localization region...
should be developed if the new breakthrough effects related to the light-matter interactions need to be observed.

2. Materials and methods
The technology of manufacturing transfer-printed PS microcavities used in this study is based on the electrochemical etching of monocrystalline silicon and detaching PS structures from the monocrystalline substrate by electropolishing in a water–alcohol solution of hydrofluoric acid. For detaching the porous layers from the substrate, we used a high etching current and a fluoride-depleted electrolyte solution, which provide layer-by-layer removal of silicon atoms at the interface between the porous silicon and the monocrystalline substrate [6]. The bottom Bragg mirror was fabricated together with a cavity on a monocrystalline silicon substrate; the top Bragg mirror was fabricated separately, detached from its substrate and placed on the top of the bottom Bragg mirror. Since we have had an access to the cavity region during the system fabrication, a highly concentrated solution of CdSe/CdS/ZnS QDs was used to embed the QDs into the cavity prior to covering it with the top Bragg mirror.

We have also engineered a microcavity with similar parameters using the standard electrochemical etching process of the entire microcavity structure on a single monocrystalline substrate in order to compare the optical properties of conventional “one-piece” and transfer-printed microcavities.

3. Results and discussion
Analysis of the reflection spectra demonstrates that the full-width-at-half-maximum of the eigenmode and the photonic band gap for both microcavities are about 5 nm and 155 nm, respectively (Figure 1). The Q-factor was found to be about 130, which is typical of porous silicon microcavities in the visible region of the optical spectrum [6,7]. Good correlation of the optical characteristics of microcavities of both types means that the proposed method of transfer-printed microcavity fabrication does not affect their optical properties, i.e., reflectance (over 99%), and a relatively high Q-factor.

![Figure 1. Reflectance of a transfer-printed PS microcavity.](image)

It is known that the Purcell effect is an enhancement of spontaneous emission rate and luminescence intensity of a luminophore placed in a resonant cavity at its eigenmode wavelength [8]. In the transfer-printed PS microcavities prepared in this work, the full-width-at-half-maximum of the QD luminescence spectra narrows from 35 nm for the QD solution to 9 nm for the QDs embedded in the eigenmode localization region of the microcavity (Figure 2), thus demonstrating the appearance of the Purcell effect. Indeed, the narrowing of the QD luminescence spectrum is observed due to suppression of their luminescence at the other wavelengths in the photonic bandgap. The Purcell effect is also known to be a straightforward indication of the presence of the weak coupling regime of interaction between the exciton in the QD and the microcavity eigenmode [9]. In this regime, the rate of coherent energy exchange (i.e., coupling strength) is lower than the average of the inverse lifetimes of exciton and cavity
photon [10]. We assume that further increase in electromagnetic field localization together with controlling spatial distribution of the emitters in the cavity region will allow us to make the coupling strength large enough to overcome the losses in a hybrid system and achieve a strong coupling regime.

![Figure 2](image_url)

**Figure 2.** Luminescence spectrum of QDs in solution (dashed line) and in the eigenmode localization region of a transfer-printed PS microcavity (solid line).

4. Conclusion
In this study, we have engineered, and compared the optical and fluorescence-enhancing properties of, hybrid structures based on luminophores located in the region of spatial localization of the PS-based photonic crystal eigenmodes of (1) transfer-printed microcavities based on a freestanding photonic crystal and (2) conventional “one-piece” microcavities created on a monocrystalline silicon substrate. The data show a three-fold decrease in the full-width-at-half maximum of the luminescence spectrum of QDs embedded in the eigenmode localization region of transfer-printed microcavities, which indicates its luminescence enhancement due to the Purcell effect and realization of the weak coupling regime between the QD exciton and the microcavity eigenmode. The developed technology for designing microcavities with emitting particles placed exactly in the eigenmode localization region paves the way to investigation of new breakthrough effects related to the light-matter interactions and opens new opportunities for researching light emission manipulation and related applications.

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