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Controlled Photon Emission of Colloidal PbS Quantum Dot by Using Photonic Dot Made of Optical Polymer and Silicon

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Abstract

Microcavity device designed for on/off control of photon emission was fabricated with laminating optical polymer on silicon in combination with colloidal PbS quantum dot emitting at optical telecommunication wavelength. The resonant wavelength of the device was controlled by micromachine behavior with voltage application.

1. Introduction

Quantum dot (QD) has been investigated as a photon source for quantum information technology. To control the nature of photon emission, QD is confined in microcavity such as photonic crystal. The combination of Si microcavity with position-control technology for QD is attractive to the design of high-performance photon emitter and the device integration by silicon photonics technology. We have reported the successful position control of a single colloidal QD on Si substrate using scanning probe microscope lithography [1]. In this work, three-dimensional microcavity, namely photonic dot (PD), designed for controlled photon emission was fabricated by laminating optical polymer on Si in combination with colloidal PbS QD emitting at optical telecommunication wavelength. The cavity resonant wavelength was controlled by micromachining operation with voltage application, which suggests that the device can control on/off timing of photon emission from QD.

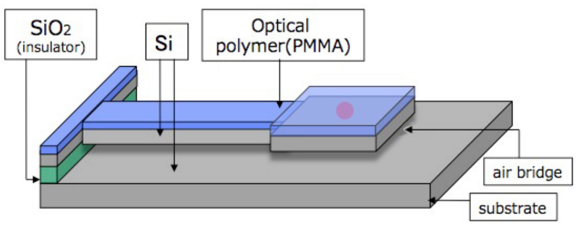
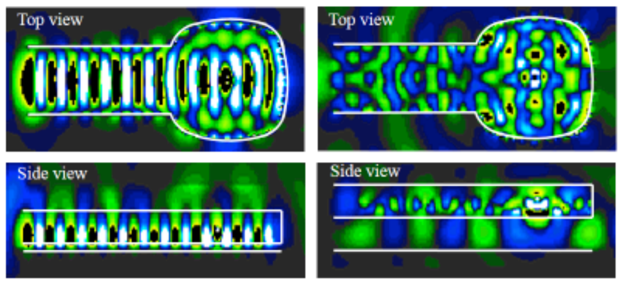


Fig. 1 Schematic of photonic dot structure in this study. PMMA/Si double layer structure configures microcavity. Metal mirror is formed on the cavity upper surface and sides and the substrate surface under the air bridge (not shown in the figure).

2. Experimental

PD structure in this study is schematically shown in Fig. 1 [2]. Microcavity is composed of Si and optical polymer with metal mirror. QD is installed inside microcavity between two layers. Optical waveguide is connected horizontally to the microcavity. PD surfaces of top and sides and Si substrate under air bridge are coated by metal mirror (not shown in the figure). The optical waveguide works concurrently as cantilever beam, i.e., it can physically change the cavity size by electrostatic force to move up and down. Resulting dephasing between cavity resonant wavelength and QD emission wavelength is used to control photon emission via the planar optical waveguide.

PD structure was designed using simulation by the FDTD (finite difference time domain) method. Designed device structure was fabricated on Si-on-insulator (SOI) substrate. Chemically-synthesized PbS QD which emits at around 1.3 μm was used. Polymethyl methacrylate (PMMA) was used as optical polymer. Electron beam lithography was used with reactive ion beam etching by SF_6 gas. After shape fabrication, Au was sputtered for mirror coating. The sputtering was done from two oblique directions to coat substrate surface under the air bridge. Optical device evaluation was done from root edge of the waveguide. For the optical coupling, tapered optical fiber was used. Halogen lamp and laser diode were used to evaluate optical reflection spectra and emission spectra, respectively.



(a) (b)

Fig. 2 Calculated light mode of 1.3-μm emission from QD located at the center of PD with air-bridge height of (a) h = 0.1 μm and (b) h = 0.9 μm.

3. Results and Discussion

PD structure was designed for the resonance at 1.3 μm. Optimized design values were 0.1 μm for air bridge height, 0.1 μm for Si layer thickness, 0.6 μm for PMMA layer thickness, 1.5 µm for waveguide width, and 2.8 µm for PD-head-side length. Figure 2 shows calculated light mode of 1.3-µm emission in the device in two cases of air bridge height. The extinction ratio of 23 dB was obtained by changing the height from 0.1 to 0.9 μm.

Based on the designed structure, we estimated the micromachining operation by voltage application. Figure 3 shows the relationship between displacement of cantilever beam and applied voltage calculated using

$$V^2 = \frac{2wET^3d^3}{27L^3\varepsilon S} \qquad (1)$$

where V is voltage, w is beam width, E is Young's modulus, T is beam thickness, d is displacement, L is beam length, ε is the permittivity, and S is the stress parameter [3]. Voltage of 15.8 V is required with the waveguide length of 10 μm for the displacement of 0.8 μm.

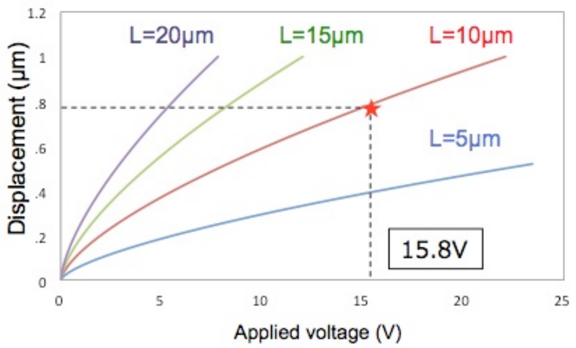


Fig. 3 Relationship between applied voltage and displacement of cantilever beam in several cases of cantilever beam length (L). 0.8 μm displacement occurs at 15.8 V with L = 10 μm.

Fig. 4 shows plan-view image of fabricated PD structure. Size difference from design values was less than 8%. QDs were mixed in PMMA and position control of single QD was not implemented in this study.

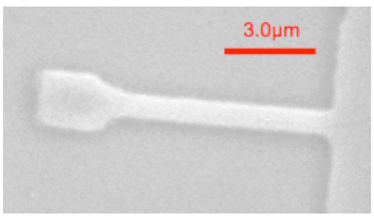


Fig. 4 Plan-view SEM images of fabricated PD device.

Results of optical evaluation are presented in Fig. 5. Insufficient optical coupling between device and tapered fiber caused noisy spectra. Reflection spectrum had a peak at near 1.17 μm that corresponds to cavity resonant wavelength. Deviation from design value of 1.3 μm was attributed to size error. On the other hand, in emission spectrum at applied voltage of 0 V, we can see that emission peak is located at approximately 1.2 μm. Without cavity, QDs' emission spectrum had a peak at 1.27 μm and was extended to higher energy side. PD emission peak can be attributed to the results of the convolution of PD resonance spectrum and QD emission spectrum.

PD emission peak was successfully controlled by voltage application. As shown in Fig. 5(a), emission peak showed 70.3-meV blue shift by 15.8-V application. The extinction ratio at 1.2 μm was 4.8 dB, which agree well with the value of 6.5 dB estimated based on the actual device structure. The result suggests that QD's photon emission timing will be controlled by the voltage application if the device holds a single QD emitting at the cavity-resonant wavelength.

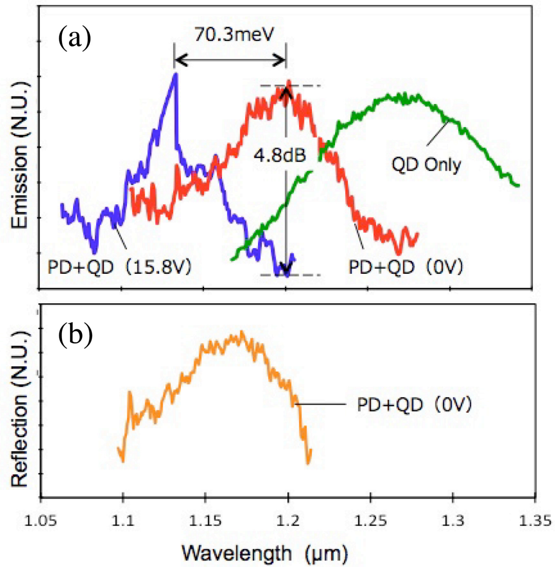


Fig. 5 (a) Emission spectra of fabricated device with and without voltage application. Spectrum of QDs without cavity is also shown. (b) Reflection spectrum of fabricated device.

4. Conclusions

Microcavity device composed of stacked optical polymer on Si layers with PbS QD was proposed as a on/off-controllable photon emitter. Electrostatic micromachining operation enabled control of cavity resonant wavelength and resulting emission wavelength of QDs at optical telecommunication wavelength.

Acknowledgements

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References

[1] K. Mukai, A. Hirota, and S. Nakashima, Jpn. J. Appl. Phys. **54** (2015) 04DJ02.
[2] K. Mukai, Y. Yamamoto, J. Cryst. Growth **301** (2007) 984.
[3] P.M. Osterberg, S.D. Senturia, J. MEMS **6** (1997) 107.