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A photon generating device composed of a quantum dot and a metamaterial element

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Abstract

We propose a new single photon generating device composed of one silica-coated QD and one metamaterial element. The device was prototyped using electron beam lithography though the number of QDs was not limited to one. By the evaluation of the temperature dependence of emission characteristics, it was shown that the peak wavelength of the device hardly changed as compared with the case of QD ensemble. It suggested that the peak was originated by upward high directivity of QD emission resonated to the metamaterial element.

1. Introduction

Quantum information technology has attracted much attention in order to increase the capacity of information and the secure reliability for the development of advanced information society. Quantum dot (QD) is one of the promising materials for the technology. To improve position controllability for the fabrication of quantum circuit, we have succeeded in controlling the apparent size of QD by silica coating maintaining the emission wavelength [1]. Meanwhile, researches on metamaterials have been carried out intensively in order to realize electromagnetic characteristics not in nature. In this study, we propose a new single photon generating device combining a silica-coated QD and a metamaterial element (Fig.1). With this combination, high speed light emission, improved directivity and polarization control are expected based on Purcell effect. We fabricated the device and evaluated its basic optical characteristics.

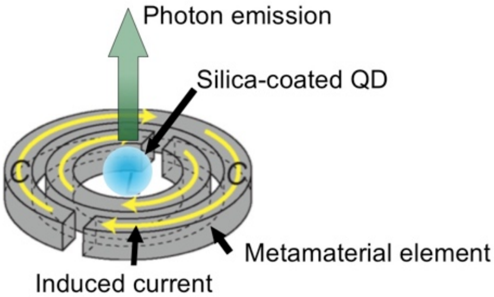

Fig. 1 Schematic of photon emission device

2. Experimental

A double split ring shape was chosen as the metamaterial element because the device size can be made larger than other shapes and it is relatively easy to trap a QD at the center. In order to arrange a QD with a diameter of about 5 nm accurately, silica was coated on QD surface to increase the apparent size. Assuming the device on a Si substrate, light emission from the QD was simulated using the finite-difference time-domain (FDTD) method to design the structure resonating with light at the wavelength of 1.3 μm.

PbS QDs were synthesized by well-known method [2], and silica shell was formed by the reverse micelle method. Figure 2 shows the scanning electron microscope (SEM) image of prepared silica-coated PbS QDs. The diameter of the particle was about 70 nm.

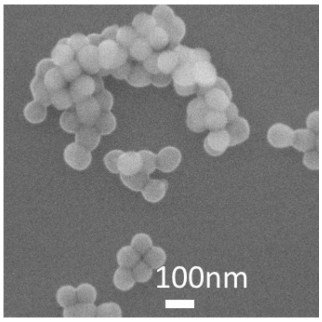

Fig. 2 SEM image of silica-coated QDs.

The silica-coated QDs were dropped onto Au metamaterial prepared by electron beam lithography, and the excess QDs were wiped off with an industrial swab [3]. The temperature dependence of the emission spectra of the device was evaluated by micro photoluminescence (PL) measurement at between liquid nitrogen temperature and room temperature. Upward emission from the device was collected through the objective lens.

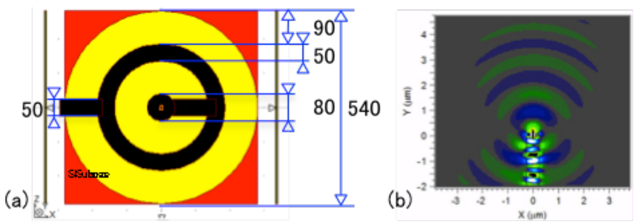

Fig. 3 (a) Plan-view layout (unit: nm) and
(b) cross-sectional optical mode diagram of the designed device
(device position: x=0, y=0)

3. Results and discussion

After the FDTD simulation, thickness of 100 nm, outer diameter of 540 nm, line width of 90 nm, split interval of 50 nm, and center diameter of 80 nm were obtained for the Au parts. With this structure, upward good directionality of emission was confirmed as shown in Fig. 3.

Figure 4 shows how QDs were arranged on a metamaterial element during the fabrication process of the device. Many QDs covered the entire surface of the metamaterial element just after dropping QD solution and the number of QDs became much less after wiping. The aim was to trap one QD at the center of the metamaterial element, however, a considerable number of QDs were finally trapped at the center position, between the two rings, and at the periphery of the element.

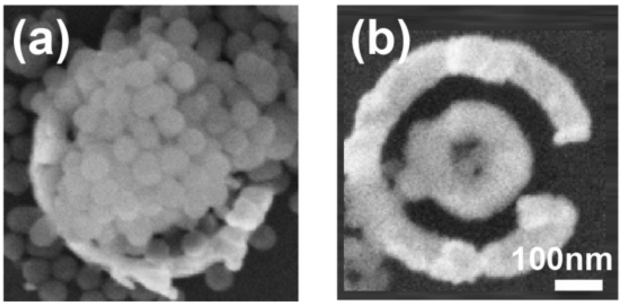

Fig. 4 SEM images of (a) metamaterial element just after deposition of silica-coated QDs and (b) metamaterial element after wiping the QDs.

Figure 5 shows the temperature dependence of peak wavelength and emission intensity of fabricated device. The measurement results of QD ensemble are also shown for comparison. Generally, the emission peak wavelength of QDs shifts reflecting the temperature dependence of the band gap. However, it was found in Fig. 5(a) that the wavelength of the device hardly changed compared with the case of QD ensemble. The resonant wavelength of metamaterial is not affected by the temperature change, and therefore, we attributed the emission peak to the QD emission resonating with the metamaterial.

Figure 5(b) shows the emission intensity as a function of temperature. With or without metamaterial, the emission intensity monotonically increased as the temperature was lowered. In the presence of a large amount of QDs on the metamaterial film, it was reported that the emission intensity nonlinearly increased at the temperature at which QD ensemble's peak wavelength matched metamaterial's resonant wavelength [4]. In this device, the temperature to be matched was around 230°C in Fig. 5(a). However, no such enhancement of emission intensity was observed in this device. This is due to the small number of QDs in the device. At any temperature, emission peak resonated with the metamaterial, and QDs contributing to the emission peak changed according to the temperature change. As long as the number of contributing QDs does not change extremely, nonlinear increase of emission intensity will not occur. We can also see in the figure that the temperature change of emission intensity of the device was smaller than that of QD ensemble. However, in some cases of other prototype device, the temperature dependence of intensity was higher than in the case of QD ensemble. The results of QD ensemble in Fig. 5(b) show the average characteristics of many QDs. The importance of choosing a QD with good optical properties was obvious in the photon generating device.

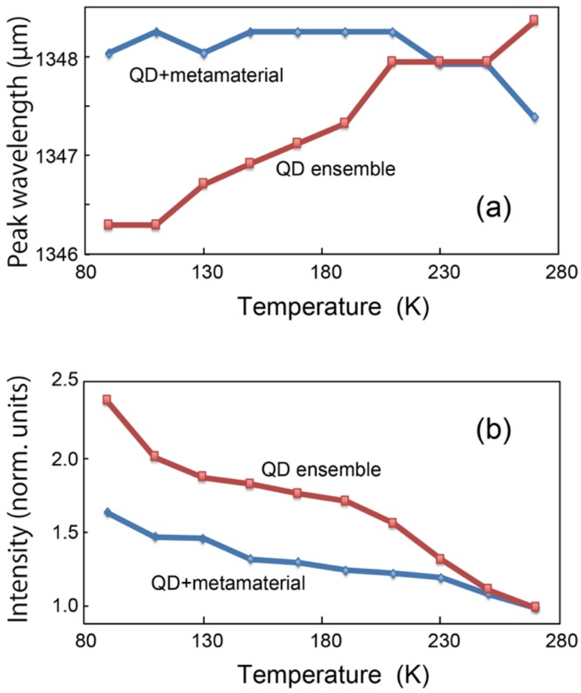

Fig. 5 Temperature dependence of PL characteristics: (a) emission peak wavelength and (b) emission intensity. The intensity was normalized with the value at 270K.

4. Conclusions

A structure composed of a silica-coated QD and a metamaterial element was proposed as a new single photon generating device. We designed a double split ring metamaterial to resonate at the wavelength of 1.3 μm. Silica-coated PbS QDs with a diameter of 70 nm were synthesized and combined with an Au metamaterial element produced by electron beam lithography. Temperature dependence of the emission characteristics was evaluated. The emission peak wavelength of the device hardly changed compared to that of QD ensemble, and no enhancement of the emission intensity at the resonance temperature was observed. These results were explained by the fact that a small number of QDs were included in the device, i.e., QDs resonating to the metamaterial element changed depending on the temperature and the peak was the resonant emission at any temperature.

Acknowledgements

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References

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