Demonstration of Quality Factor over 10,000 in Three-Dimensional Photonic Crystal Nanocavity by Cavity Size Control

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1. Introduction

Much interest has arisen in the use of photonic crystals (PhC) to localize light in sub-wavelength-dimensions due to the existence of the photonic bandgap (PBG). When a defect is introduced into a perfect crystal, localized modes within the PBG can be generated. Therefore, light that couples to these modes can be strongly confined within a point defect cavity. In order to achieve a full control of light in all directions, a complete PBG provided by three-dimensional (3D) PhC is required. However, so far there are only a few reports demonstrating 3D PhC cavities due to difficulty in fabrication. Recently, we have demonstrated a coupling of quantum dots (QDs) with high quality (Q) factor defect nanocavities located in a woodpile PhC [1,2]. By fine tuning the cavity mode frequency to the middle of the complete PBG by means of optimization of the size of the square-shaped defect cavity, Q factor of up to 8,600 was achieved [2].

In this work, we further improve Q factor of 3D PhC cavity modes by controlling size of defect cavities in the woodpile PhC fabricated using micromanipulation techniques [1]. A high Q of more than 10,000 is achieved when the defect size is fined tuned so that a cavity mode is located at the exact midgap. This Q factor is the highest value reported so far in 3D PhCs.

2. Fabrication

A schematic illustration of the fabricated woodpile structures is shown in Fig. 1. The structures are stacks of GaAs layers, each containing a line-and-space pattern with a number of in-plane rods of 11. The in-plane (x-y plane) periodicity (a) and width (r) of rods were set to 500 nm 0.26a, respectively. In the fabrication, each layer was a 200-nm-thick GaAs slab prepared in a form of suspending air-bridge structures. An active layer was processed in the same way as for the GaAs layers except that it contained a defect cavity and three-layer stacked InAs/Sb:GaAs QD layers (dot density, 2×10^{10} cm^{-2} per layer), in which the middle QD layer was at the center of the slab. The QD ground state emission peak is at 1.41 μm at room temperature. Figures 2(a)-(e) show SEM images of defects with five different sizes, labeled i to v, generated at the center of the pattern of the active layers to form nanocavities. The dimensions of the individual defects ($\Delta x \times \Delta y$) were as followed: i, 1.25a × 1.25a; ii, 2.30a × 1.15a; iii, 2.30a × 2.30a; iv, 3.15a × 3.15a; v, 4.30a × 4.30a. The GaAs and active layers were then stacked using the micromanipulation techniques [1] to construct the 3D structures. First, a stack of twelve GaAs layers was assembled. The active layer with the defect nanocavity was then placed on top of the stack followed by another twelve GaAs plates to complete the 3D structure with twenty five stacked layers in total. An SEM image of one of the fabricated structures with defect iv is shown in Fig. 2(f). The stacking errors were determined to be within 50 nm. The fabrication time required for assembling one layer was approximately 10 minutes.

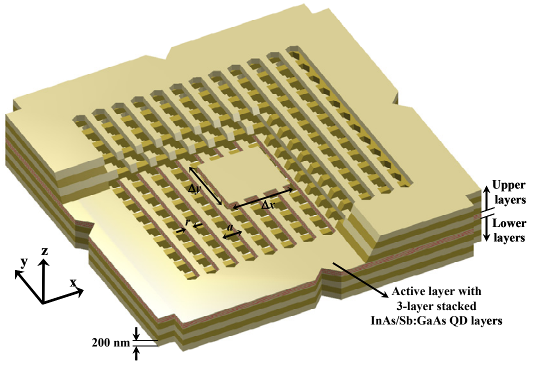

Fig. 1. Schematic illustration of fabricated structures. A portion of upper layers is removed to show a cross section of the stacked structure and to reveal the cavity.

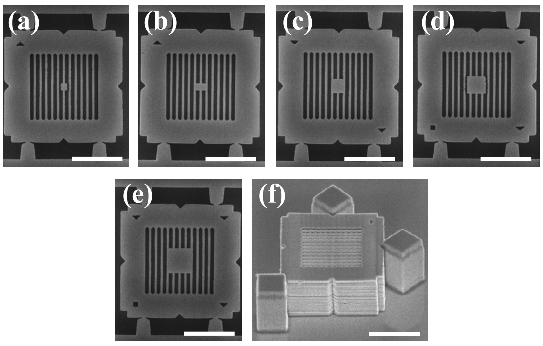

Fig. 2. (a)-(e) SEM images of introduced defects i to v, respectively. (f) SEM image of the fabricated 25-layer woodpile structure. Bars 5μm.

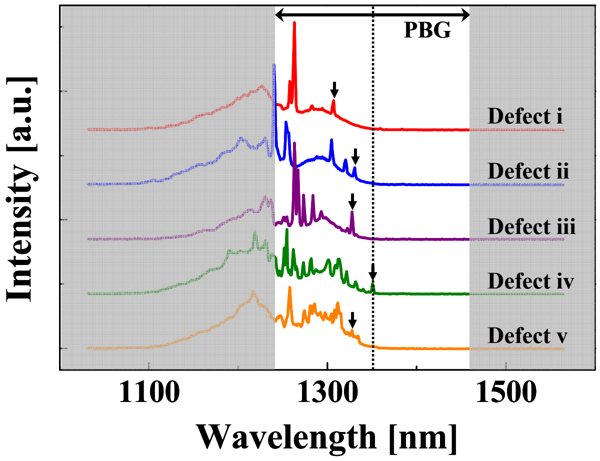

Fig. 3. PL spectra from defects i to v. The gray shadings indicate the calculated dielectric and air bands of the PhC with the complete PBG shown in unshaded area. Dotted line represents the midgap frequency of the PBG..

3. Experimental Results and Discussions

Photoluminescence (PL) measurements were performed at 9 K. The samples were optically pumped by a continuous-wave Ti:sapphire laser operating at 895 nm. Figure 3 shows the PL spectra for the fabricated structures with defects i to v exhibiting a number of sharp peaks in the QD emission spectra. These peaks are fallen within a complete PBG between 1240 and 1460 nm calculated by using a plane-wave expansion (PWE) method. We also confirmed that these peaks were polarized and spatially localized at the defect regions (data not shown), indicating that they originated from the cavity resonances. The number of cavity modes increases as the defect size increases, and becomes so large that individual modes can barely be distinguished for defect v. The *Q* factors of cavity modes of each defect, indicated by arrows, were then determined and plotted in Fig. 4(a). It is seen that the *Q* factor rises up as the defect size increases, and reaches the highest value for defect iv. Figure 4(b) shows the high-resolution PL spectrum for the cavity mode of defect iv fitted with a Lorentzian function. The linewidth of 0.134 nm corresponds to the estimated *Q* factor of more than 10,000.

The origin of the increase of *Q* as the defect size increases is unlike 2D PhC cavities, in which a larger size of defect results in smaller loss into the vertical direction determined by total internal reflection. In 3D system, light confinement mechanism in all directions of the cavity modes locating within the complete PBG is due to the PBG effect. Therefore in finite-size 3D structures, the strong localization of the cavity mode can be expected when the mode is tuned to the midgap frequency of the complete PBG, where the mode localization is strongest [2]. Therefore, in the same defect structure, the mode that is closer to the midgap has higher *Q*. From Fig. 3 it is seen that as the defect size increases the cavity modes of interest are tuned to the midgap, and the mode is at the exact midgap for defect iv resulting in the highest *Q*. For defect v, in addition to the detuning of the mode from the midgap, the large size of the defect gives rise to power loss into the in-plane direction because the number of PhC periods surrounding the defect cavity becomes smaller, and this loss also limits the *Q*.

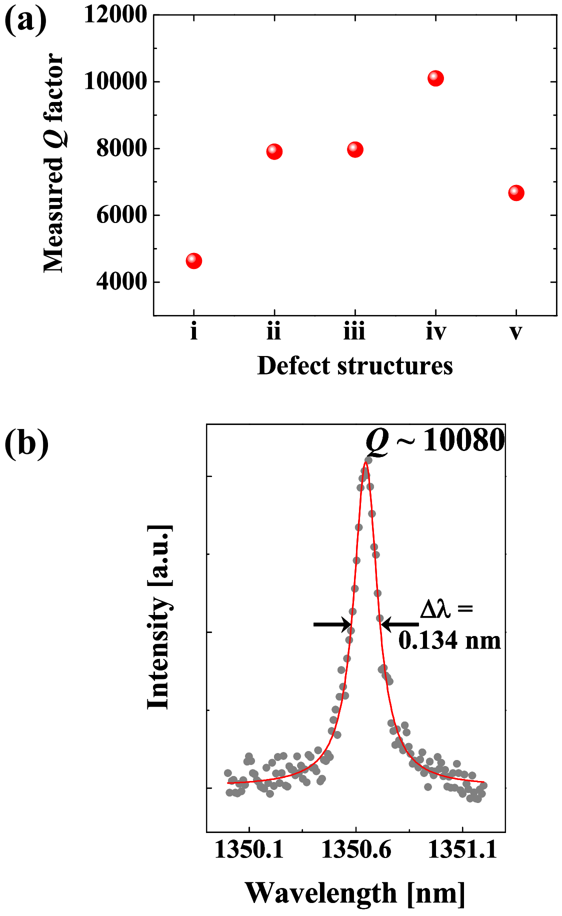

Fig. 4. (a) Dependence of *Q* factors of cavity modes of defect i to v on the defect structure. (b) High-resolution PL spectrum for the cavity mode of defect iv fitted with a Lorentzian function.

4. Conclusions

In conclusion, we have fabricated 3D PhC nanocavities coupled with InAs/Sb:GaAs QDs and demonstrated a high *Q* factor over 10,000 by controlling size of defect cavity. This obtained *Q* is the highest value reported in 3D PhCs. The high *Q* cavity was achieved when the cavity mode was tuned to the middle of the complete photonic bandgap. These results are important steps toward the realization of ultralow threshold lasers in 3D PhC.

Acknowledgements

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References

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