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Plate-Insertion Stacking Method for Three-Dimensional Photonic Crystal Fabrication

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Abstract

We propose a fabrication method for layer-by-layer three-dimensional (3D) photonic crystal (PC) structures. In this method, which we name the plate-insertion stacking method, each elemental layer is stacked and aligned along a trench using micromanipulation. The uniform trench structure allows for the fabrication of 3D PCs which are larger in the stacking direction than those that could be made by previously reported stacking methods. Using this new method we have successfully fabricated 3D PC nanocavities and observed cavity mode emissions.

1. Introduction

Three-dimensional (3D) photonic crystals (PCs) possessing complete photonic band gaps (cPBGs) provide high controllability of light, and 3D optical circuits which integrate optical waveguides and nanocavity-based devices such as lasers and filters are one of key applications of 3D PCs. So far, 3D PCs have been demonstrated using various materials such as metals [1], organics [2] or semiconductor materials [3-7]. In particular, semiconductor materials are important, since their high refractive indices can open wide photonic bandgaps. Moreover, efficient light emitters like quantum dots can be easily incorporated in semiconductor materials.

One promising technique for the fabrication of semiconductor 3D PCs is a micro-manipulation technique where thin plates with 2D patterns are stacked to form an target 3D structure. Since the demonstration of 3D PCs with cPBGs in the infrared wavelength region [5], the micro-manipulation technique has been technically improved. In particular, we have developed a plate alignment technique [6] using standing guide posts, and achieved highly accurate stacking with an accuracy of better than 50 nm. Using this stacking technique, both the highest quality factor, *Q*, among 3D PC nanocavities and also a 3D PC nanocavity laser have been realized in the near infrared wavelength region [6, 7].

The current challenge for micro-manipulation fabrication of 3D optical circuits is to enlarge the volume of the 3D PCs whilst still maintaining the high accuracy. The limited number of stackable layers (limited by the height of the guide posts) is one obstacle in particular. Although the number of stacked layers can be increased by lengthening the posts, deep and vertical dry etching for such high and uniform posts is practically difficult. Therefore, a stacking method without standing posts is desirable.

In this study, we propose a plate-insertion stacking method where plates are stacked laterally along a trench, and use the method to fabricate 3D PCs. Taking advantage of the uniformity of the guide trench, the proposed method has accuracy as high as the currently used post-based stacking method, which is clarified by scanning electron microscope (SEM) analysis. We also observe cavity modes in the spectra of the 3D PC nanocavities using micro-photoluminescence (μ-PL) spectroscopy. Since the guide trench can be elongated to an arbitrary length, it should in principle be easy to increase the number of layers, making this method advantageous.

2. Plate insertion stacking method

The proposed stacking method is schematically shown in Fig. 1(a) together with the currently used stacking method in Fig. 1(b). In the proposed method, we insert plates one by one into a trench and set them on their edge. The plates are stacked in the lateral direction along the edge of the trench. In this method, the stacking accuracy strongly depends on the uniformity of the edge of the trench, while is determined by the verticality of the posts in the post-based method. Since the trench can be made with an arbitrary length by EB lithography, a large number of layers can be stacked. On the other hand, the posts with an arbitrary height are difficult to fabricate with straight edges because they are fabricated by deep and vertical etching. Therefore, with respect to enlarging the volume of 3D PCs in the

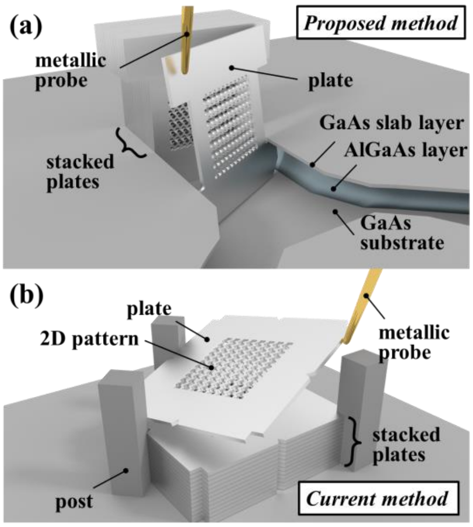

Fig. 1 Schematics of (a) the plate insertion stacking method and (b) the post-based stacking method in the micromanipulation technique.

stacking direction, the proposed method (Fig. 1(a)) has the advantage compared to the post-based stacking method (Fig. 1(b)).

In order to experimentally demonstrate the proposed stacking technique, we adopted a <110>-layered diamond structure [8] possessing a cPBG at 1200 nm wavelength and fabricated 3D PCs using plate-insertion. For the fabrication of the trench structure, we firstly prepared a GaAs substrate on which a 3 μm-thick AlGaAs sacrificial layer and 225 nm-thick GaAs slab layer were sequentially grown. After the trench pattern was drawn by EB lithography, the pattern was transferred into the GaAs slab layer by dry etching, and the AlGaAs layer was then removed by wet etching. Since the wet etching occurs isotopically, parts of GaAs slab layer become suspended, forming guides for accurate alignment of plates (see Fig. 1 (a)). 2D plates used for the construction of the 3D PCs were fabricated as in previous reports [6, 7], albeit with a modified shape to fit the trench structure.

4. Results and discussion

Figure 2(a) shows an SEM image of a 3D PC fabricated by this method. In this example, 24 layers were successfully stacked in the trench (of which the suspended slab region is visible due to a slightly lighter color). Figure 2(b) shows a magnified image around the edge of a 3D PC structure composed of 29 stacked layers. The stacking error, which is defined as the maximum in-plane displacement of stacked plates, is Δx ~ 40 nm, which is comparable to the 3D PCs fabricated by the post-based stacking method [5]. This demonstrates the suitability of the proposed method for the fabrication of 3D PC structures with high accuracy. Moreover, as discussed before, in the proposed method, it is possible to stack much larger number of plates, which has not been achieved in the post-based method.

We also fabricated 3D PC nanocavities using the plate insertion method for optical characterization. We performed μ-PL measurements at cryogenic temperature. The observed PL spectra from a 3D PC nanocavity with 17 layers are shown in Fig. 3. At the middle of the structure (i.e. as the 9^{th} layer), an active cavity layer embedding InAs/GaAs quantum dots was stacked. A cuboid defect located at the center of the plate works as a nanocavity. The inset in Fig. 3 shows the bare PL emission spectrum where

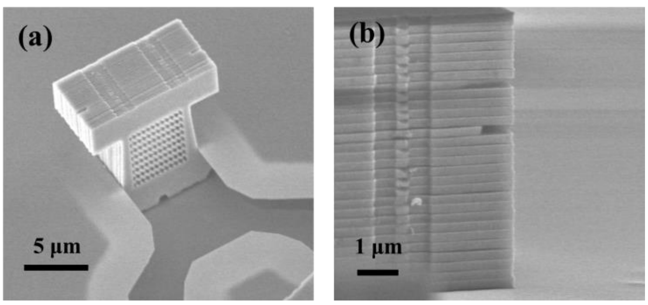

Fig. 2 SEM images of 3D PC nanocavities fabricated by the plate-insertion stacking method. (a) 24-layer 3D PC. (b) Magnified image of the edge of a PC with 29 layers.

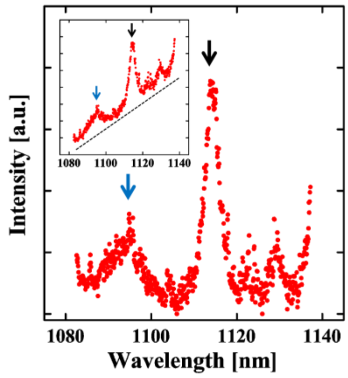

Fig. 3 μ-PL spectrum observed from a 3D PC nanocavity with 17 layers. Arrows indicate the peaks originate from the cavity modes. The background shown by a dashed line in the inset is subtracted in the main figure.

a dashed line shows the background emission spectrum from ensemble QDs (subtracted in the main figure). The peaks at 1095 nm and 1114 nm (see the arrows in Fig. 3) originate from cavity modes. Cavity *Q*s of these modes are estimated as 440 for the peak at 1095 nm and 310 for the peak at 1114 nm, respectively (estimations were made by fitting each peak with a Lorentzian lineshape function). The reason for the small *Q*s in this example is most likely the small number of the stacked layers. In principle the value could be increased by stacking a number of layers, which is a key feature of the proposed method.

5. Conclusions

We have proposed a plate-insertion stacking method for the fabrication of 3D photonic crystals, whereby plates that form the final structure are stacked laterally along a trench. 3D PCs fabricated by the proposed method are successfully demonstrated. Taking advantage of the uniformity of the guide trench, the proposed method has accuracy as high as the currently used post-based stacking method, which is clarified by SEM analysis of the fabricated 3D PCs. Since the length of the trench can be easily elongated, the number of stacked plates is expected to be dramatically increased. This advantage will enable the fabrication of large 3D PC structures by micro-manipulation, leading to the development of optical circuits containing nanocavities, waveguides, and various optical devices.

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References

[1] M. Deubel, *el at*,. Nature Mater, **3,** 444 (2004).
[2] J. G. Fleming. *et al.*, Nature, **417**, 2 (2002).
[3] S. Noda, *et al.*, science, **289**, 604 (2000).
[4] M. Qi, *et al*., Nature. 429, 538 (2004).
[5] K. Aoki *et al*., Nature Mater. **2**, 117 (2003).
[6] K. Aoki, et al., Nature Photon, **2**, 688 (2008).
[7] A. Tandaechanurat, *et al*., Nature photon. **5**, 91 (2011).
[8] T. Tajiri, *et al*., Jpn. J. Appl. Phys. **53**, 04EG08 (2014).