

# Analysis of Vertically Stacked Structures of 2D PC Cavity and Amorphous-Silicon-Wire Waveguide with Low-Refractive-Index Material Cladding

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## 1. Introduction

Compound semiconductor two-dimensional photonic crystal (2D PC) cavities have the potential to realize highly efficient light emitters such as ultracompact single-photon sources and thresholdless lasers. However, the highly efficient light extraction is difficult. Recently 2D PC cavities with low-refractive-index (low- $n$ ) material cladding have been researched [1-3], and they have the important advantage of the vertical stacking of additional devices. In this work, we propose a useful light extraction means using an amorphous-silicon (a-Si:H)-wire waveguide, and theoretically investigate the vertically stacked structures of a 2D PC cavity and an a-Si:H-wire waveguide with low- $n$  material cladding.

## 2. Device Structure and Calculation Model

Figure 1 shows the vertically stacked structure of a compound semiconductor 2D PC cavity and an a-Si:H-wire waveguide on a silicon wafer. They can be fabricated using wafer bonding technique. Figure 2 shows the 2D PC optimized L7 cavity, which is formed by filling 7 holes and adjusting positions of eight holes (A-D). The refrac-

tive indices of compound semiconductor and low- $n$  material are assumed to be 3.4 and 1.445, which correspond to GaAs (or InP) and SiO<sub>2</sub>, respectively. The slab thickness and holes radius of a 2D PC are  $0.7a$  and  $0.31a$ , where  $a$  is the lattice constant. The core size and refractive index of the a-Si:H-wire waveguide are  $400 \times 200$  nm<sup>2</sup> and 3.5, where  $a$  is 392 nm.

## 3. Results and Discussion

First, we optimized the 2D PC L7 cavity by adjusting positions of eight holes (A-D) to realize a high  $Q$  factor. The  $Q$  factor and modal volume of the optimized L7 cavity shown in Fig. 2 are  $1.48 \times 10^5$  and  $1.52(\lambda/n)^3$ , where  $\lambda$  and  $n$  are the wavelength of light in air and the refractive index of compound semiconductor. The  $Q$  factor is 6.2 times higher than that of the L7 cavity without adjustment. When  $a$  is 392 nm, the resonant wavelength is 1.55 μm.

We then investigated the light extraction from the optimized L7 cavity to the a-Si:H-wire waveguide by the 3D finite-difference time-domain method. In this work, we have used two kinds of a-Si:H-wire waveguides. Figure 3(a) and 3(c) show cross-section views of the vertically stacked structures, where the center-to-center distance between the optimized L7 cavity and a-Si:H-wire waveguide is  $1.225a$ . The light is extracted from the cavity to two output ports in Fig. 3(a) and to one output port in Fig. 3(b).

Figure 3(b) shows a distribution of the electric field,  $E_y$ , in the structure shown in Fig. 3(a). The light of the resonant

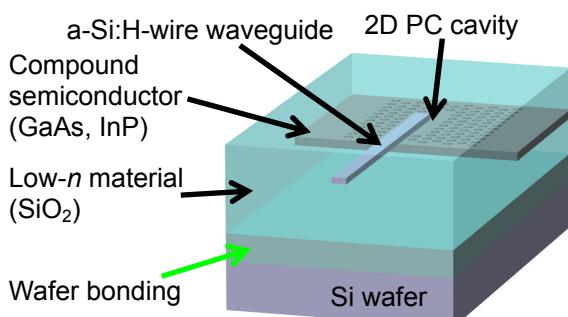


Fig.1 Schematic of vertically stacked structure of compound semiconductor 2DPC cavity and a-Si:H-wire waveguide with low- $n$  material cladding on silicon wafer.

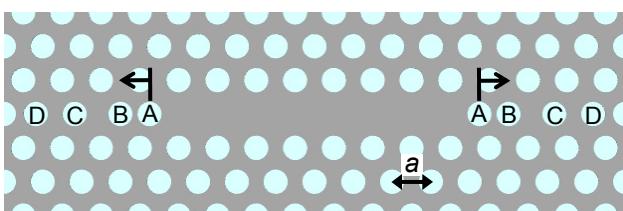


Fig.2 Schematic of 2D PC optimized L7 cavity.

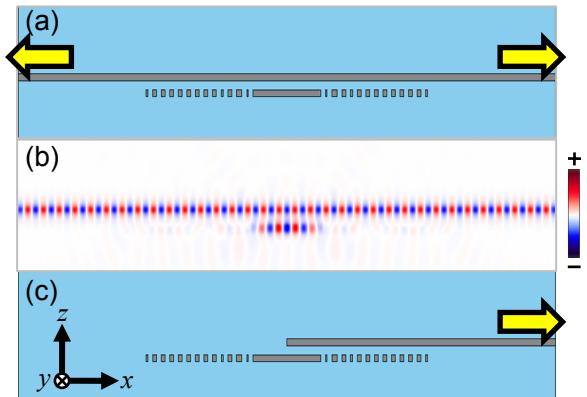


Fig.3 Schematics of the vertically stacked structures with (a) two output ports and (c) one output port. (b) Distribution of electric field,  $E_y$ , in the structure with two output ports shown in Fig.3(a).

mode in the cavity is successfully extracted to the a-Si:H-wire waveguide. The light extraction efficiency,  $\eta$ , is defined as the ratio of “the energy flow that passes all output ports” and “the whole energy flow around the cavity”. In Fig. 3(b), the  $\eta$  is 96% and the  $Q$  factor is  $5.8 \times 10^3$ .

Figure 4 shows the dependence of  $\eta$  on the center-to-center distance between the cavity and waveguide. Figure 4(a) shows  $\eta$  of the structure with two output ports. The high  $\eta$  is achieved and it is over 90% when the distance is around  $1.5a$ . When the distance is  $1.40a$ , the  $\eta$  has the maximum of 97% and the  $Q$  factor is  $2.2 \times 10^3$ . When the distance is smaller than  $1.0a$ , the  $\eta$  decreases greatly. The light propagation in the a-Si:H-wire waveguide is disturbed by the 2D PC slab. Figure 4(b) shows  $\eta$  of the structure with one output port. In the structure with one output port, the maximum  $\eta$  is 73% when the distance is  $0.98a$ . In this case, the  $Q$  factor is  $2.0 \times 10^2$ . The maximum  $\eta$  in the structure with one output port is smaller than that in the structure with two output ports because the light is scattered at the edge of the a-Si:H-wire waveguide.

To achieve a high  $\eta$  for one output port, we locate a reflection mirror at the one side of the structure with two output ports as shown in Fig. 5(a). A distribution Bragg reflector (DBR) is located and its cross-section view is shown in Fig. 5(b). The DBR consists of the waveguide and the additional a-Si:H-wire grating. The a-Si:H-wire grating has  $168 \times 110 \text{ nm}^2$  core size and periodic interval of 336 nm. When the center-to-center distance between the waveguide and the grating is 165 nm, the 1D photonic band gap of TE-like modes is generated as shown in Fig. 5(c). Figure 5(d) shows the distribution of the electric field,  $E_y$ , when the number of the DBR grating is 16. The light is successfully reflected and extracted from the cavity to the right output port. The high  $\eta$  of 92% is obtained, where the  $Q$  factor is  $3.1 \times 10^3$ .

Figure 6 shows the dependence on the position of DBR. The  $\eta$  periodically changes by about  $0.9a$  of the shift of DBR. This periodicity corresponds to half wavelength of the propagation mode is the a-Si:H-wire waveguide.

#### 4. Conclusions

We proposed the useful light extraction means from 2D PC cavities with low- $n$  material cladding. First, we optimized the 2D PC L7 cavity and a high  $Q$  factor ( $Q > 10^5$ ) can be obtained. We then analyzed the vertically stacked structure of the optimized L7 cavity and the a-Si:H-wire waveguide. Two kinds of the structures with two output ports and one output port were investigated. The light of the resonant mode in the cavity is successfully extracted to the a-Si:H-wire waveguide in the structure with two output ports. The high  $\eta$  (= 97%) can be achieved.

In addition, we introduced the reflection mirror to achieve a high  $\eta$  for one output port. By introducing the DBR, the high  $\eta$  (= 92%) can be achieved.

We believe that the vertical stacking structures of compound semiconductor 2D PC cavities and a-Si:H-wire waveguides with low- $n$  material cladding on a silicon wafer

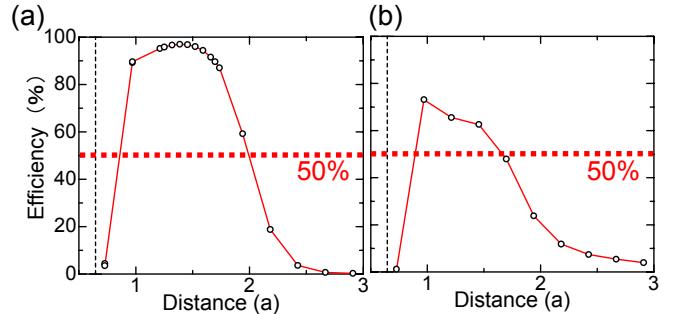


Fig.4 Dependence of  $\eta$  on the center-to-center distance between 2D PC cavity and waveguide. (a) The structure with two output ports and (b) the structure with one output port.

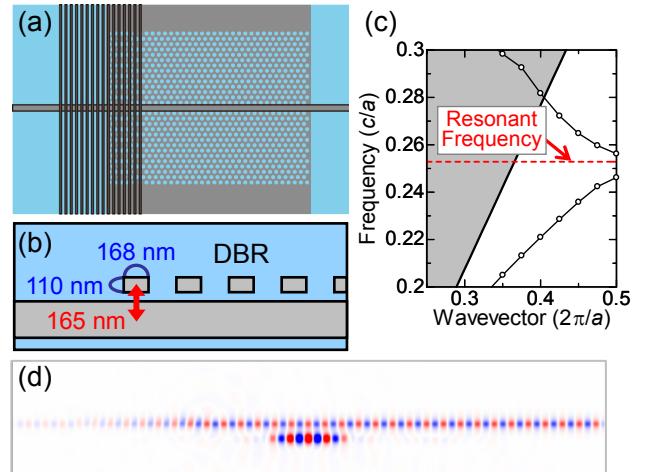


Fig.5 Schematic of (a) top view of the coupling structure with DBR and (b) cross-section view of DBR. (c) 1D photonic band structure of TE-like modes. (d) Distribution of electric field,  $E_y$ , in the structure with DBR shown in Fig.5 (a).

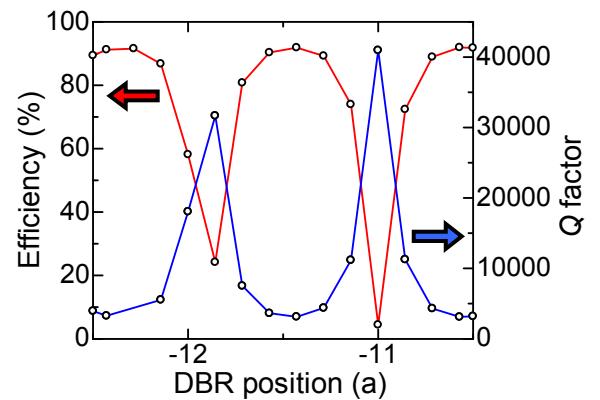


Fig.6 Dependence of  $\eta$  and  $Q$  factor on DBR position.

will play a significant role in opto-electronic integrated circuits.

#### Acknowledgements

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#### References

- [1] M. Okano et al, Jpn. J. Appl. Phys. **47** (2008) 7453.
- [2] T. Yamada et al, SSDM 2009 (2009) I-1-8.
- [3] M. Okano et al, J. Opt. **12**, (2010) 015108.