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Analysis of Two-Dimensional Photonic Crystal Cavities with Low Refractive Index Material Cladding

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1. Introduction

Recently, we research and develop the heterogeneous integration of compound semiconductor two-dimensional photonic crystals (2D PCs) onto a silicon wafer. The compound semiconductor 2D PCs have the potential to realize highly efficient active devices such as ultracompact single-photon sources and thresholdless lasers. The heterogeneous integration of GaAs 2D PCs onto a silicon wafer has been demonstrated using divinylsiloxane-bis(benzocyclobutene) (DVS-BCB) wafer bonding [1]. 2D PCs with a low refractive index material cladding, such as organic polymers and SiO_2, are more adapted for the hybrid devices than those with air cladding from the viewpoint of mechanical strength, the passivation, and the additional integration of devices. In this paper, we have theoretically investigated 2D PC optical cavities with a low refractive index material cladding.

2. Device Structure and Calculation Model

Figure 1 shows the compound semiconductor 2D PC cavity with a low refractive index material cladding on a silicon wafer. Figure 2 shows the 2D PC L3 cavity, which is formed by filling 3 holes. The L3 cavity is a typical cavity structure in air-bridge 2D PCs. The refractive indices of compound semiconductor and a low refractive index material are assumed to be 3.4 and 1.535, which correspond to GaAs (or InP) and DVS-BCB. The slab thickness and hole radius of a 2D PC are 0.7*a* and 0.31*a*.

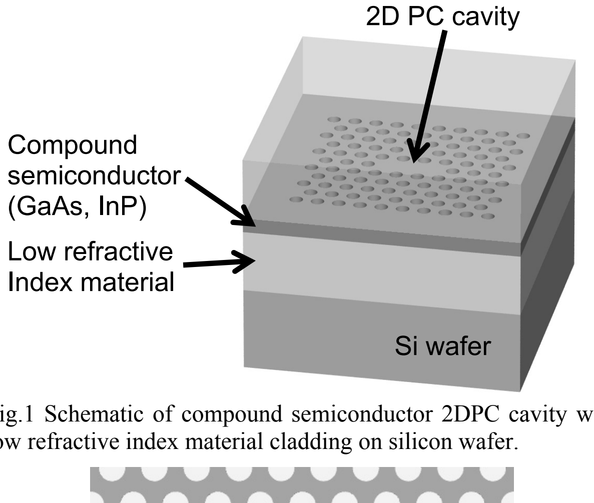

Fig.1 Schematic of compound semiconductor 2DPC cavity with low refractive index material cladding on silicon wafer.

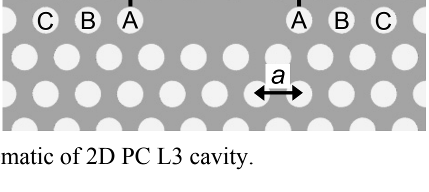

Fig.2 Schematic of 2D PC L3 cavity.

3. Results and Discussion

We have analyzed L3 cavities with a low refractive index material cladding as shown in Fig. 2 by the 3D finite-difference time-domain (FDTD) method using the group theory [2]. *Q* factor and modal volume of the normal L3 cavity are 675 and $0.70(\lambda/n)^3$, where λ and n are the wavelength of light in air and the refractive index of the compound semiconductor. The modal volume is on the same order of magnitude as that in the air-bridge 2D PC L3 cavity [3].

In the L3 cavity, two holes at position A (the most neighboring holes) were shifted outside. *Q* factor increases 3.4 times (Q = 2280). The similar results were reported in air-bridge 2D PC L3 cavities [3]. Besides, two holes at position A were shifted to the opposite side (inside), and it was confirmed that *Q* factor increases 3.2 times (Q = 2140). Figure 3 shows the dependence of *Q* factor on the shift of holes at position A. There is a peak in both outside and inside positions.

When the shift of holes at position A, r_A, is $-0.64a$, *Q* factor is local maximum. In the case of $r_A = -0.64a$, two holes at position B (the second neighboring holes) were

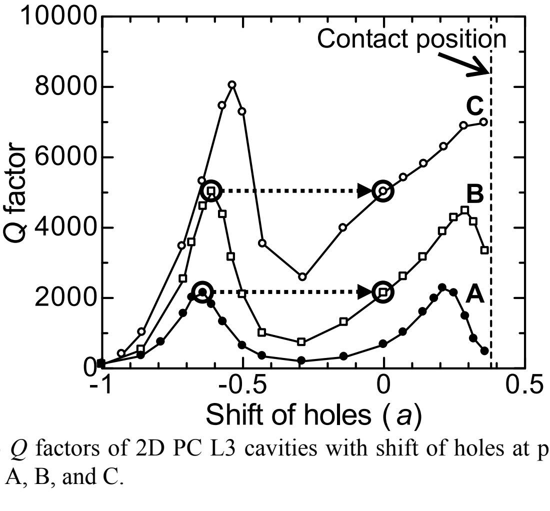

Fig.3 *Q* factors of 2D PC L3 cavities with shift of holes at positions A, B, and C.

then shifted both outside and inside. *Q* factor increases in both sides as well as the above case. *Q* factor increases 6.6 times (Q = 4470) in the outside position, and increases 7.4 times (Q = 5020) in the inside position, $r_B = -0.61a$.

In the case of $r_A = -0.64a$ and $r_B = -0.61a$, two holes at position C (the third neighboring holes) were shifted in the same way. *Q* factor increases 10 times (Q = 6980) in the outside position, and increases up to 12 times (Q = 8030) in the inside position, $r_C = -0.54a$. These results are shown in Fig. 3. The modal volume of the optimized L3 cavity with highest *Q* is $0.89(\lambda/n)^3$.

Figure 4 shows electromagnetic field distributions, E_y, along the centerline of normal and optimized L3 cavities. In the high-*Q* cavity, the envelope of electromagnetic field distribution is similar to the Gaussian function. In the 2D PC cavity with a low refractive index material cladding, the envelope of Gaussian function increases *Q* factor effectively.

Figure 5(a) shows the radiation pattern in the normal L3 cavity. The radiation pattern has three peaks. For the light extraction in the vertical direction, the single-peaked pattern is desired. The improvement of the radiation pattern can be ovserved by shifting holes at position A inside. The improved radiation pattern, in the case of $r_A = -0.79a$, is shown in Fig. 5(b). *Q* factor and modal volume are 740 and $0.59(\lambda/n)^3$. The radiation pattern can be dramatically improved without decreasing *Q* factor and enlarging modal volume.

We then investigated the fundamental resonant modes in L0-L16 cavities. Figure 6 shows *Q* factor and modal volume, where the L0 cavity is formed by shifting two holes ±3/14*a* [4]. The modal volume is on the same order of magnitude as that in the air-bridge 2D PC cavities, and *Q* factor is lower. However, *Q* factor can be improved by simply increasing the size of the cavity. Although the refractive index of the cladding increases from 1 to 1.535, *Q* factor over 10^5 can be achieved. The L16 cavity has a high *Q* factor of 193000, and small modal volume of $3.1(\lambda/n)^3$.

2D PC cavities with a low refractive index material cladding can achieve enough high *Q* factor and small modal volume for practical applications. Cavities with moderately low *Q* factor (e.g. 10^2-10^4) and ultra-small modal volume can achieve highly efficient spontaneous emission, and are suitable for single-photon sources and thresholdless lasers [4]. Cavities with high *Q* factor (e.g. > 10^4) and ultra-small modal volume can achieve strong light confinement, and are suitable for nonlinear optical devices and strong coupling cavity quantum electrodynamics systems.

4. Conclusions

We have theoretically investigated 2D PC cavities with a low refractive index material cladding. First, we analyzed the L3 cavities. *Q* factor can be improved by shifting the neighboring holes inside as well as outside. *Q* factor increases up to 8030 by properly shifting the neighboring three pairs of holes inside. In addition, the radiation pattern becomes a single-peaked pattern by shifting the neighboring holes inside.

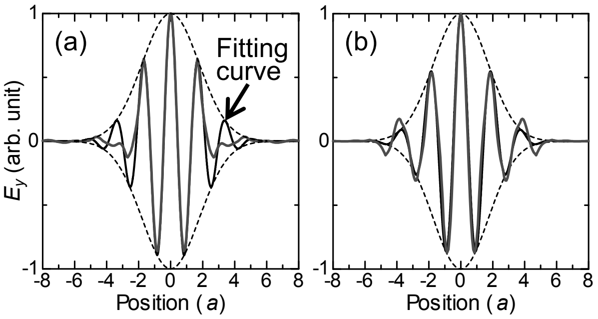

Fig.4 Electromagnetic field distribution, E_y, in (a) normal L3 cavity (Q = 675) and (b) optimized L3 cavity (Q = 8030).

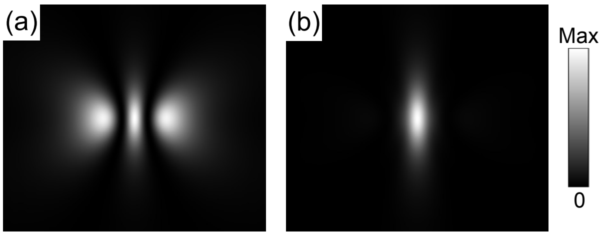

Fig.5 Radiation patterns in (a) normal L3 cavity and (b) L3 cavity of $r_A = -0.79a$. The plane of observation is 6.4*a* above the middle of 2D PC slab.

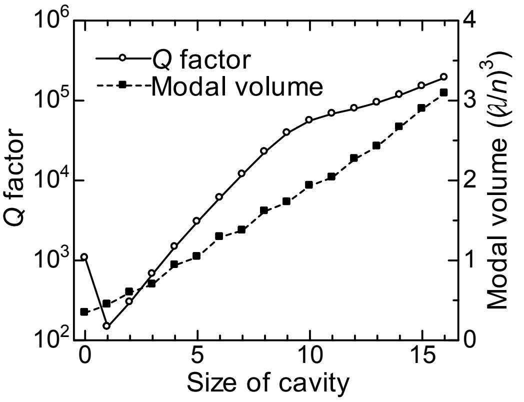

Fig.6 *Q* factor and modal volume of 2D PC L0-L16 cavities.

We then analyzed the L0-L16 cavities. Although the refractive index of the cladding increases from 1 to 1.535, *Q* factor over 10^5 can be achieved by simply increasing the cavity size. The L16 cavity has a high *Q* factor of 193000.

We believe that compound semiconductor 2D PC cavities with a low refractive index material cladding on a silicon wafer will play a significant role in the hybrid devices based on silicon photonics.

Acknowledgements

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