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Polarization Controlled Spontaneous Emission from a GaInAsP/InP Strained QW 2D Photonic Crystal

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We fabricated a GaInAsP/InP strained quantum-well 2-dimensional (2D) photonic crystal with low process damage by using an ECR dry etching and a wet chemical etching. From the observation of photoluminescence characteristics, we found that emission inside the 2D plane was TM polarized when the designed photonic band gap for TE polarization overlapped with emission frequency, while the emission from the as-grown wafer was TE polarized. These results are considered to be the evidence of spontaneous emission control effect by the quantum confinement for photons and electrons.

1. Introduction

The photonic crystal is of great interest owing to the possibility of spontaneous emission control, which allows the thresholdless operation in laser diodes.[1] Recently, 2-dimensional (2D) structures are attracting attention because of its ease of fabrication compared to that for 3D ones.[2-6] However, the evidence of spontaneous emission control has never been obtained, although some authors reported trial fabrication of semiconductor structure based on GaAs/AlGaAs compounds by using dry etching techniques.[4,5] One of the most serious problems is the nonradiative recombination at semiconductor surface damaged by the dry etchings.

To avoid this problem, we have employed GaInAsP /InP compounds in our experiments.[6] It has a surface recombination velocity one order of magnitude slower than that of GaAs/AlGaAs. Another advantage of the compounds is the long emission wavelength, which makes the designed structure 1.4 - 1.8 times larger than that for GaAs/AlGaAs ones, resulting in much easier fabrication.

In this report, we describe the fabrication of GaInAsP/InP compressively strained quantum-well (CS-QW) 2D photonic crystal by using an ECR dry etching and a wet chemical etching. We evaluate the etching damage from the photoluminescence (PL) measurement. In addition, we show the alternation of polarization characteristics of the luminescence from several samples, depending on their design. This result can be interpreted as the spontaneous emission control effect by the quantum confinement for photons and electrons. We discuss the correspondence between the experiment and theory.

2. Fabrication Process and Evaluation of Etching Damage

In the experiment, we prepared 1.55 μm range GaInAsP/InP CS-QW laser wafer. The active layer consists of four quaternary wells and GRIN SCH structures.

First, we formed two types of periodic circular dot patterns, as illustrated in Fig. 1(a) and (b), on the wafer by using an electron beam lithography. The corresponding first Brillouin zone in the reciprocal space is also shown in Fig. 1(c).

Then, we vertically etched the wafer to the cladding below the active layer by using ECR etching technique with $CH_4/H_2/Ar$ gaseous source. Although the gas flow was little (CH_4:H_2:Ar=0.75:0.3:0.3 sccm) and the gas pressure in the etching chamber was as low as 8×10^{-5} Torr, the stable plasma condition was maintained. In

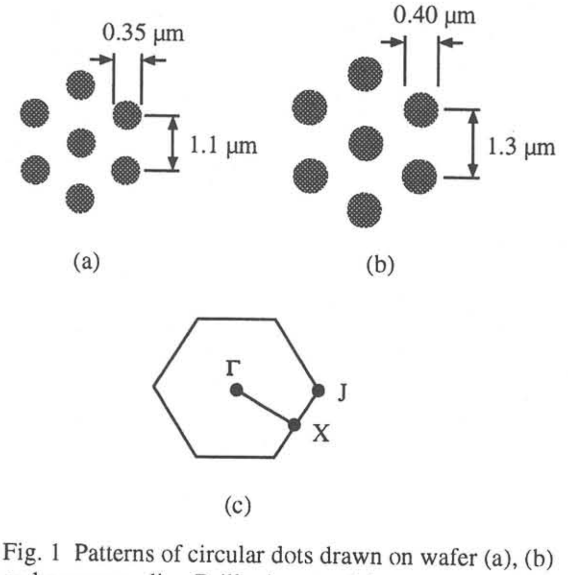

Fig. 1 Patterns of circular dots drawn on wafer (a), (b) and corresponding Brillouin zone (c).

the preliminary experiment, we found that, on this gas condition and with accelarated voltage of 200 V and microwave power of 100 W, the maximum etching rate for InP was as high as 80 nm/min. The depth of formed mesas including the active layer was nearly 0.8 μm after 15 min etching. The etched surface and side walls were smooth as a mirror.

Additionally, we slightly etched the surface and side walls by using chemical solution $HCl:H_2O$= 4:1 to remove the ECR etching damage. Etched depth was estimated to be 0.1 - 0.2 μm by the etching for 6 s at 2 ℃. Fig. 2 shows the SEM photograph of fabricated structure. It is seen that mushroom shape was formed by the undercut of cladding layer at the chemical etching.

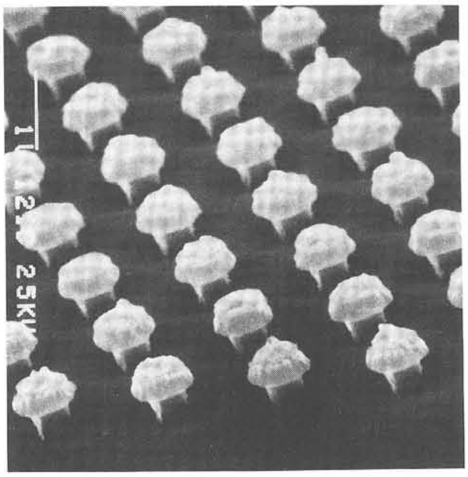

Fig. 2 SEM view of fabricated 2D photonic crystal.

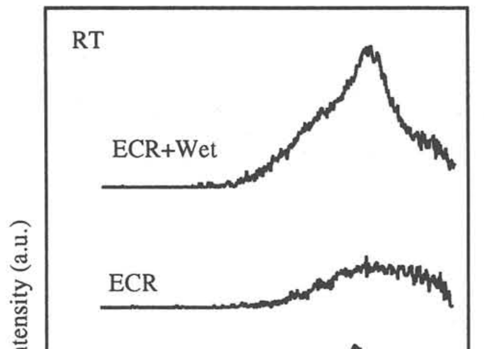

Fig. 3 Measured photoluminescence spectra before and after etchings.

Fig. 3 shows PL spectra measured before and after the etchings. Here, the luminescence was catched by a multimode optical fiber from the direction normal to the substrate surface and analyzed by the optical spectrum analyzer. We can see that, although the PL intensity is degraded after the ECR etching, it recovers by the chemical etching to almost the same level as that before etchings. From another preliminary experiment on the ECR etching, we confirmed that the damage depth is no deeper than 0.2 μm against the etching condition described above. This value is small enough to form 0.5 - 0.6 μm pitch periodic structure of photonic crystal, which is designed for the wavelength range of 1.3 - 1.55 μm.

3. Polarization Control by Photonic Crystal

Next, we measured the PL characteristics of emission radiated to the horizontal direction (in this experiment, X direction in Fig. 1(c)), since the spontaneous emission control in 2D photonic crystals is considered to be the most effective inside the substrate plane.[6)] The emission was collimated and focused into the multimode fiber by a couple of lenses having numerical aperture of 0.24. The polarization of emission was analyzed by a polarizer inserted between the lenses. The emission spectra were observed by the optical spectrum analyzer with low wavelength resolution of 5 nm.

The peak intensity was recorded with the polarizer angle, as shown in Fig. 4. We observed the TE polarized emission from the as-grown wafer 3 times stronger than TM one. This seems to be due to the electron quantum confinement in CS-QW.[7)] On the other hand, TE polarized emission from fabricated structure type (a) (see Fig. 1) was effectively suppressed, while TM one enhanced. The absolute intensity of the polarized emission was difficult to evaluate accurately, since it was very sensitive to the optical alignment. However, all the fabricated samples of type (a) exhibited the TM emission slightly stronger than TM emission from the as-grown wafer. By taking into account the reduced volume of active region in the fabricated structure, we can evaluate that TM emission from the fabricated structure was enhanced to several times stronger than from the as-grown wafer. Thus we consider that this alternation of polarization is not caused by a simple wavelength filtering in the periodic structure but by the alternation of spontaneous emission lifetime in the photonic crystal. We have also observed that such alternation of polarization characteristic became ambiguous for structure type (b), as shown in Fig. 4.

These results can be explained by the photonic band calculation. Type (a) and (b) have the same ratio of the dot diameter to the dot pitch. We can draw one photonic band diagram for these structures by normalizing the optical frequency ω by the dot pitch a, as shown in Fig. 5. Here, the mushroom shape was treated as multiple steps of equivalent refractive index inside the 2D plane, as shown in the inset. In Fig. 5, the shadow regions correspond to the normalized emission frequency. In the shadow region for structure type (a), we can see no band curves for TE polarization, which means the photonic gap for TE polarization. In other words, TE polarization is suppressed by the photonic gap obtained by structure type (a). In contrast to this, the shadow region for type (b) overlaps with both TE and TM curves. Thus we consider that both polarizations were allowed in type (b) and the ambiguous polarization characteristic was observed.

4. Summary

We demonstrated the polarization control of spontaneous emission in the 2D photonic crystal, which was predicted from the photonic band calculation. Further reduction of the diameter and the dot pitch will allow the overlap of emission frequency with wider photonic gaps and provide clearer effects. In this report, we deduced the alternation of spontaneous emission lifetime in fabricated photonic crystal from the observed alternation of emission intensity. We are now planning to directly measure the spontaneous emission lifetime to estimate the effect more quantitatively. The results will be reported elsewhere.

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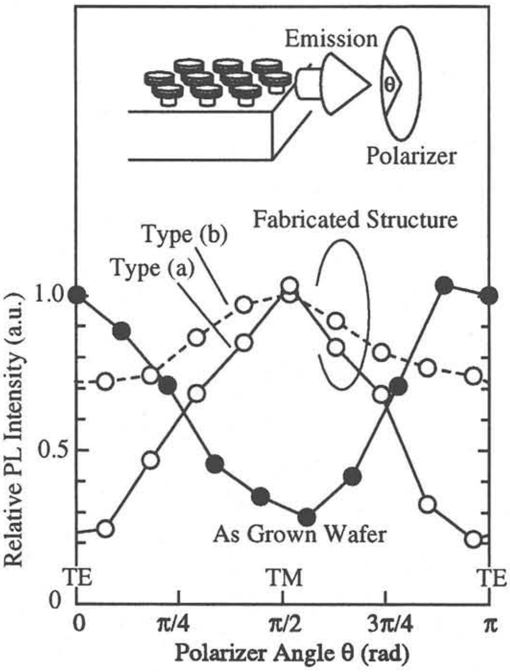

Fig. 4 Measured photoluminescence intensity before and after processing. Absolute intensity could not be evaluated accurately since it changed sensitively to condition of optical alignment.

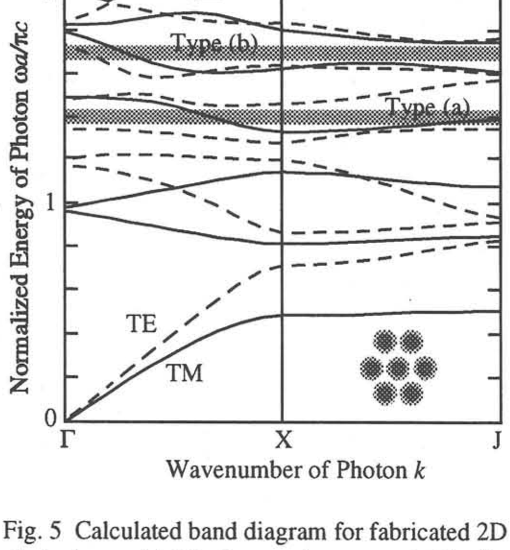

Fig. 5 Calculated band diagram for fabricated 2D photonic crystal. Mushroom shape seen in Fig. 2 was taken into account by converting it into equivalent refractive indexes inside 2D plane.