Extended Abstracts of the 1996 International Conference on Solid State Devices and Materials, Yokohama, 1996, pp. 217-219 **C-1-3**

New Realization Method for Three-Dimensional Photonic Crystal in Optical Wavelength Region -Experimental Consideration-

Noritsugu Yamamoto, Susumu Noda, and Akio Sasaki*

Department of Electronic Science and Engineering, Kyoto University
Yoshidahonmachi, Sakyo-ku, Kyoto City, Kyoto 606, Japan
(**Present address: Department of Electronic Engineering, Osaka Eloectro-Commun. University*
Hatumachi 18-8, Neyagawa, Osaka 572, Japan)

We investigate experimentally the possibility of the realization method for the photonic crystal in optical wavelength region, which we proposed previously. The micromachining techniques such as dry-etching, wafer-bonding, and laser beam diffraction pattern observation techniques are combined. Each process is experimentally investigated using the AlGaAs/GaAs semiconductor system, and the possibility is successfully demonstrated.

1. Introduction.

Photonic crystal is a new type of material in which a refractive index is periodically changed[1]. A band structure is formed in the crystal on the analogy of the solid-state physics. The excited atom could not emit photons with the energy corresponding to the forbidden band when it is incorporated in the photonic crystal. In addition, the introduction of the phase shift into the periodic structure produces an allowed level in the photonic bandgap.[1] Therefore, a new optoelectronic device such as a single wavelength light-emitting diode will be expected. In spite of such scientific and engineering interests, a three-dimensional photonic crystal has not been realized yet in the optical wavelength region. This is because the refractive index inside the photonic crystal should be changed with the same order of the wavelength of the light considered, and the process to make such a small three-dimensional structure is considered very difficult. Thus, a new realization method for the three-dimensional photonic crystal is strongly required.

Recently, we have proposed a new realization method for the three-dimensional photonic crystal[2),3)], where micromachining techniques such as dry-etching, wafer-bonding and laser beam diffraction pattern observation techniques are utilized. In the following, we demonstrate experimentally the feasibility of the proposed method.

2. New realization method for photonic crystal.

Figure 1 shows an example of the proposed method using GaAs/AlGaAs/GaAs system. (i)AlGaAs and GaAs layers are grown on a GaAs substrate. The GaAs layer (hatched in the figure) is the layer to form photonic crystal. The AlGaAs layer is an etching stop layer for the selective etching process at the step (iv). (ii)A stripe pattern is formed on the GaAs layer by dry-etching technique. (iii)The wafers with stripe patterns are stacked with a desired configuration and are wafer-bonded by heating in the H_2 atmosphere. (iv)One side of substrate and AlGaAs layer is etched selectively and sequentially. (v)The wafer obtained by step (iv) is cleaved into two pieces, and the steps (iii) and (iv) are repeated to form the face-centered cubic structure finally.

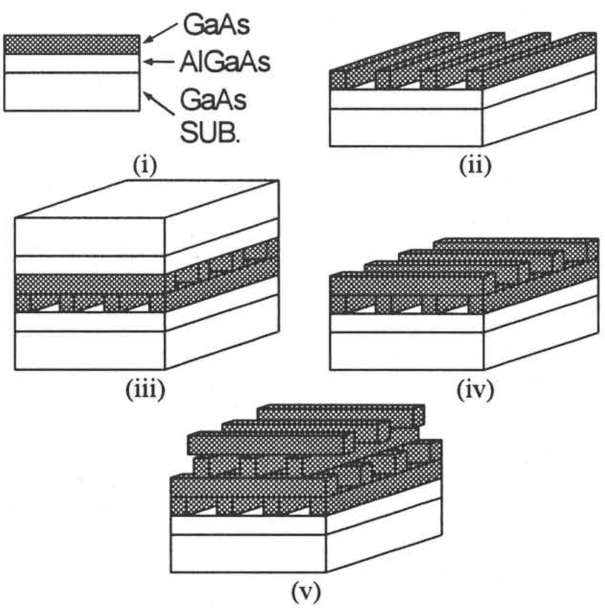

Fig. 1 The process to realize the photonic crystal in optical wavelength region. (i)The photonic crystal layer and etching stop layer are grown. (ii)Stripe pattern is formed on the photonic crystal layer. (iii)A pair of striped photonic crystal layers are stacked and wafer-bonded by heating in the H_2 atmosphere. (iv)One side of substrate and etching stop layer are removed by selective etching sequentially. (v)The steps (iii) and (iv) are repeated to form the face-centered cubic structure after cleaving the wafer of (iv) into two pieces.

The merits of this method are as follows. (1)Many kinds of structures can be formed by changing the two-dimensional basic structure and the stacking pattern. (2)By disturbing the stacking pattern, the phase shift can be introduced. (3)By stacking a quantum well layer, the radiation layer can be installed. (4)As will be stated later, the fine alignment for the stacking will be made by using a laser beam diffraction pattern observation technique. (5)Due to the utilization of the wafer-bonding technique, the interfaces between individual layers are electronically active. These merits are considered very important for the application to the optoelectronic devices.

3. Experiment.

To demonstrate the feasibility of this method, we have investigated the above processes step by step.

At step (i), a GaAs buffer layer, an $Al_{0.65}Ga_{0.35}As$ layer (1.0μm thickness), and a GaAs layer (1.5μm) were grown on a GaAs substrate by MBE at 560°C. The stripe pattern with 12.5μm width and 15.5μm period was formed at step (ii) by using photo-lithography and reactive ion etching (RIE) with CH_4+H_2 mixed gas. At this step, the RIE for the GaAs layer was stopped at 1.2μm depth for the total thickness of 1.5μm. The reason for this is to prevent the another side of the AlGaAs layer from being etched in the successive selective etching process at step (iv). At step (iii), the striped wafers were stacked with crossed configuration after the pretreatment by buffered HF solution and heated in H_2 atmosphere at 650°C for 30 minutes for wafer-bonding. Figure 2 shows the transmission infrared-micrograph of the bonded interface. In the figure, the bright and dark areas correspond to the bonded and etched regions, respectively. It is seen that the wafers were uniform bonded. The bonded wafers were not separated even if the force of a few tens of Newton was applied. At step (iv), one side of GaAs substrate and AlGaAs layer was removed. To remove the GaAs substrate, the substrate was thinned down to about 50μm thickness mechanically, and then it was etched selectively with $NH_4OH+H_2O_2$ solution. The AlGaAs etching stop layer was removed with HF solution. As the stripe pattern was etched to only 1.2μm depth by RIE at step (iii), 0.3μm thickness GaAs flat layer remained. Thus, to remove the flat layer, we made RIE again using CH_4+H_2 mixed gas. The micrograph of the wafer obtained by these processes is shown in Fig. 3. It is seen that the uniform stacking of the stripes has been successfully achieved.

For the step (v) in Fig. 1, it is necessary that the upper and lower stripes with same direction should be shifted by half a period of the stripes to form a face-centered cubic structure. Therefore, the precise alignment is required. As described in references 2) and 3), we have proposed to use a laser beam diffraction pattern observation technique for the alignment. To examine the feasibility of the alignment by this method, a laser beam with a wavelength of 0.9μm was incident to a pair of striped (15.5μm period) wafers which was stacked with same direction normally, and we observed the change of the intensities of the diffraction spots versus the relative position of the stripes. Figure 4 shows the results for the ±1st, 0th order diffraction spots. In the figure, the intensity of 0th order spot was hardly changed. On the other hand, the intensities of the ±1st order spots became weaker when the relative position r was increased from 0 to r=7.5μm, where the zero point of the relative position r was determined such that the intensities of the all diffraction spots became maximum. Then, the intensities of the ±1st order spots became brighter again when r was increased from r=7.5 to r=15μm.

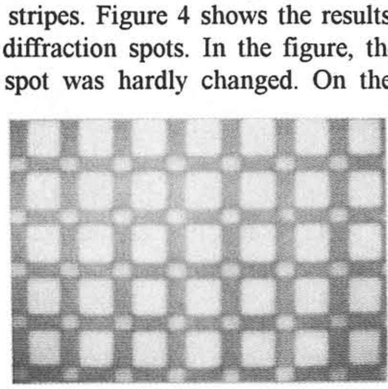

Fig. 2 Transmission infrared micrograph of the wafer-bonded striped structures. The bright and dark areas correspond to the bonded and the etched areas, respectively.

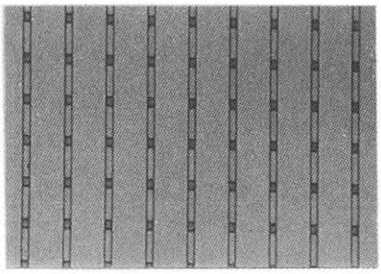

Fig. 3 The top view micrograph of a pair of stacked stripes which corresponds to Fig. 1(iv). It is seen that the uniform stacking has been successfully achieved.

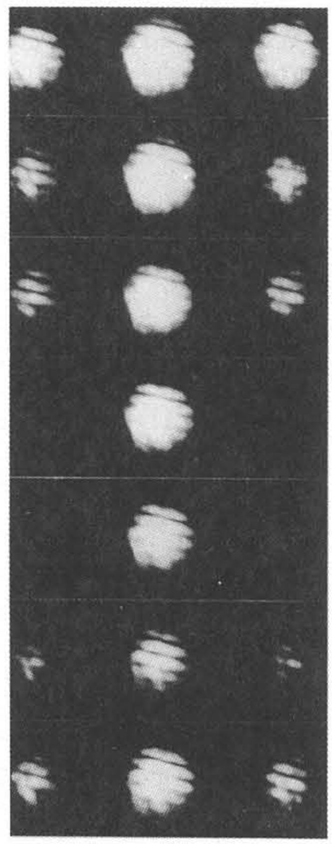

Fig. 4 Laser beam diffraction patterns as a function of the relative position r. The zero point r=0 was determined such that the intensities of ±1st order spots became maximum.

Another important point for the alignment is to adjust the angle(θ) between stripes. When the angle between stripes deviates from parallel(θ≠0), the moiré pattern appeared. Figure 5 shows the ±1st and 0th order spots when the angle between stripes was about 0.6°. In the figure, a dark line is observed in the ±1st order diffraction spots. Thus, we can precisely adjust θ=0 by checking the dark line in the spots.

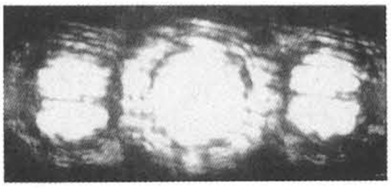

Fig. 5 The photograph of ±1st and 0th order diffraction spots for θ=0.6°. The dark line is observed in the ±1st order spots.

4. Discussion.

We discuss at first about the laser beam diffraction pattern observation technique. In the experiment, the intensities of the ±1st order spots changed with one cycle for the relative position change of one period of each stripe, where the zero point of the relative position *r* was determined such that the intensities of all spots became maximum. To connect the relative position with the actual position of stripes, we made a simple theoretical calculation. Figure 6 shows the model of the calculation, where d, T, ΔT mean the vertical distance between stripes, the period of stripes, and the horizontal deviation of individual stripes. Figure 7 shows the calculated intensities of -4th to +4th order spots for various ΔT from 0 to 16μm with a step of 1μm for the other parameters: d=1.2μm, T=15.5μm, the wavelength of laser beam λ=0.9μm. In the figure, the intensities of the ±nth spots change by n cycle for the ΔT change of one cycle. Especially the calculated result on the in the intensities of the ±1st order diffraction spots agrees well with the experimental result. Thus, we may say that when the intensities of ±1st order diffraction spots become maximum, the individual stripes coincide with each other, and when they become minimum the individual stripes are shifted with half a period to each other.

In this paper, we utilized the stripe pattern with 12.5μm width, 15.5μm period, and 1.2μm depth as the two-dimensional basic structure. This structure, however, do not generate complete photonic bandgap because the filling factor and the period are too large to generate photonic bandgap in the optical wavelength region. When we want to have the bandgap wavelength near 10μm, the width, period, and thickness should be 1μm, 4μm, and 1.2μm, respectively. When the wavelength of 1.55μm is required, the width, period, and thickness should be 0.155μm, 0.62μm, and 0.186μm, respectively. Very recently we have performed the above processes by using the stripe pattern with 1μm width, 4μm period, and 1.2μm thickness. In spite of such a smaller structure, the wafer-bonding and selective etching (up to step (iv) in Fig. 1) have been successfully achieved. We have also achieved the stacking of four layers, although the alignment was not made precisely. The four layers-stacked structure corresponds to one cycle of the face-centered cubic structure. The result encourages us very much to realize the photonic crystal in optical wavelength region.

5. Conclusion.

We have experimentally considered the possibility of the realization method for the photonic crystal in optical wavelength region, which we proposed previously. The

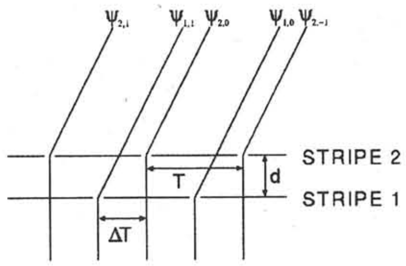

Fig. 6 The model for theoretical calculation on the intensities of diffraction spots. It is assumed that the beams diffracted by stripe1($\psi_{1,n}$) and stripe2($\psi_{2,n}$) are interfered.

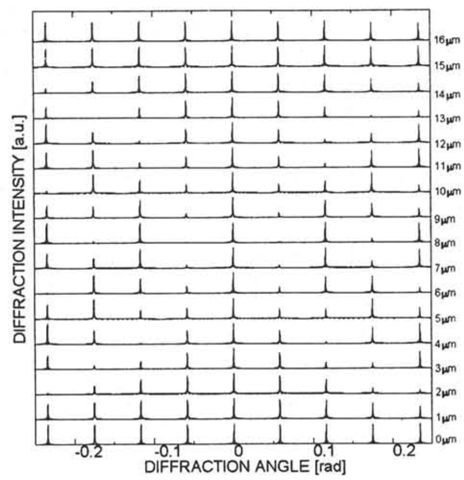

Fig. 7 Calculated results of -4th to 4th order diffraction spots as a function of ΔT.

micromachining techniques such as dry-etching, wafer-bonding, and laser beam diffraction pattern observation techniques are combined. Each process has been experimentally investigated using the AlGaAs/GaAs semiconductor system, and uniform stacking of a pair of stripes with 12.5μm width, 15.5μm period, and 1.2μm thickness has been successfully demonstrated. It has been also shown that the laser beam diffraction pattern observation technique can be effectively utilized for the alignment of the striped wafers. Based on the above results, we have very recently succeeded in the stacking of the four-striped layers with much smaller size of 1μm width, 4μm period, and 1.2μm thickness, which is expected to have the bandgap wavelength of 10μm region.

6. Acknowledgment.

The authors would like to thank Dr. A. Wakahara and Mr. N. Kiyota for valuable discussions. This work was partly supported by Venture Business Laboratory of Kyoto University.

7. Reference.

1) E. Yablonovitch: Phys. Rev. Lett. **58**(1987) 2059.
2) S. Noda, N. Yamamoto, and A. Sasaki: CLEO'96, Anaheim, USA, (1996), paper CThJ2.
3) S. Noda, N. Yamamoto, and A. Sasaki: Jpn. J. Appl. Phys. Lett. (July 15, 1996) (to be published).