**CThJ2** **11:00 am**

## New realization method of three-dimensional photonic crystal in optical wavelength region

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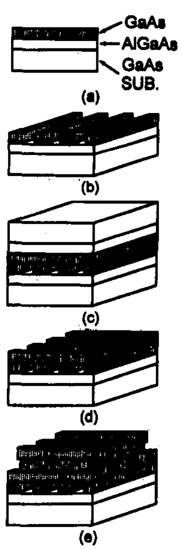
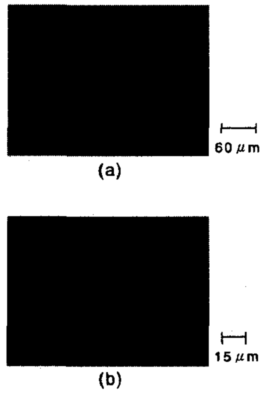
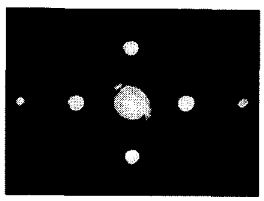
Photonic crystal is a new class of material in which a refractive index is periodically changed.[1] A photonic band gap is formed in the crystal, and the propagation of electromagnetic waves is forbidden for all wave vectors, which gives potential scientific applications such as zero-threshold semiconductor lasers, the absence of spontaneous emission, and single-mode light-emitting diode. In spite of such promising applications, the three-dimensional (3-D) photonic crystal has not been realized yet in optical wavelength region. This is because the shorter the wavelength becomes, the more the process becomes difficult. Thus, the 3-D photonic crystal has been limited to micro- to millimeter-wave regions. In the case of optical wavelength region, a two-dimensional structure has been mainly studied, however, the complete confinement of a light is impossible because a light leaks out to the residual one direction. Therefore, an important issue for the photonic crystal is how to realize the 3-D photonic crystal in optical wavelength region. In this paper, we propose a new method by utilizing a wafer-bonding technique combined with a microfabrication technique.




**CThJ2 Fig. 1** Proposed method of realizing 3-D photonic crystal: (a) growth of AlGaAs and GaAs layers, (b) stripe formation on the GaAs layer, (c) stacking of the striped wafers and wafer-bonding, (d) selective etching of substrate and AlGaAs layers, (e) cleaving wafers and repeating processes of [(c) and (d)]. The resulting structure corresponds to asymmetric face-centered cubic structure. Not only the stripe pattern but also any other patterns such as cross pattern can be utilized as the unit structure. For the wafer alignment, the observation of a deflected laser beam pattern (see Fig. 3) can be utilized.




**CThJ2 Fig. 2** (a) Transmitted infrared image of the wafer-bonded wafers, where white square region is the wafer-bonded region and the black mesh region corresponds to the etched region, (b) photograph of the stacked GaAs stripes. It is seen that uniform stacking of the striped GaAs layers have been achieved.



**CThJ2 Fig. 3** Deflected pattern of a laser beam, which was incident normally to the wafer-bonded GaAs stripes. The observation of the deflected pattern can be utilized also for the precise wafer alignment.

Figure 1 shows an example of the proposed method where we use the AlGaAs/GaAs semiconductor system: (a) AlGaAs and GaAs layers are grown on a GaAs substrate. The hatched GaAs layer is utilized to form the photonic crystal, and the thickness is determined by a required wavelength. The AlGaAs layer is utilized for the etching stop layer for the successive selective etching process. (b) The stripe patterns are formed on the GaAs layer by using an electron beam lithography and dry-etching techniques. (c) A pair of wafers with the stripe patterns are stacked as shown in the figure with the crossed configuration and are bonded in the $H_2$ atmosphere at high temperature. (d) One side of the substrate and the AlGaAs layer are selectively and sequentially etched. (e) Then the wafer is cleaved into two pieces, and the above processes [(c) and (d)] are repeated. This structure constructs a photonic crystal with an asymmetric face-centered cubic structure. In the microwave region, the similar structure was constructed by building an $Al_2O_3$ rod with 0.3-cm diameter mechanically and it was shown that it forms a band gap for all microwave vectors.[2] Thus, the above structure is considered to form a complete photonic crystal and, moreover, because the size can be made very small by the microfabrication technique using an electron beam lithography and the wafer bonding technique, the band gap can be formed in the optical wavelength region. For the 0.8–10-μm wavelength region, the stripe width and thickness are 0.1–1.0 μm and considered within the present available process technique.

To demonstrate the possibility of the proposed method, we have investigated the above processes step by step. First of all, a GaAs buffer, an AlGaAs etching stop layer (1.0 μm), and a GaAs layer (1.2 μm) were grown on GaAs substrate by MBE. The stripe patterns (3 μm/12 μm) were formed by reactive ion etching using $H_2$ + $CH_4$ mixed gas. A pair of striped wafers, which were pretreated with a buffered HF solution, were stacked and heated in $H_2$ atmosphere at 650°C for 30 min. Figure 2(a) shows the transmitted infrared photograph of the wafers bonded thus, and it is seen that the wafers were uniformly bonded. It was also confirmed that the bonded wafers were not removed even if the force of a few tens of newtons was applied. Then one side of the GaAs substrate was mechanically thinned and followed by selective-etching by $NH_4OH$ + $H_2O_2$ solution, and the residual AlGaAs etch stop layer was removed by HF solution. Figure 2(b) shows a photograph of the wafer thus fabricated. It is seen that the uniform stacking of the striped GaAs layers was successfully achieved. Figure 3 shows a deflected pattern of a laser beam, which was incident normally to the sample surface thus fabricated. The symmetrically deflected pattern indicates the uniformness of these structures. The observation of the deflected patterns can be utilized also for a fine alignment of the wafers. These results indicate the possibility of the proposed method, and we can realize the complete photonic crystal by repeating these processes at most twice. The details including optical characterization are reported at the conference.

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**CThJ3** **11:15 am**

## Two-dimensional photonic band-gap mirrors at 850 and 980 nm

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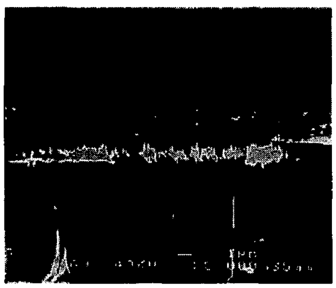
Photonic band-gap (PBG) crystals can be fabricated in semiconductor devices through the etching of patterns of holes

CThJ3 **Fig. 1** Top view of the hexagonal air hole pattern in the GaAs device.



CThJ3 **Fig. 2** Cross-section of the GaAs SQW, GRINSCH structure and the 2-D mirror.

in the device, resulting in a periodic dielectric structure. One of the more practical uses of photonic crystals in optoelectronic devices is for thin, high-reflectivity mirrors. The use of hexagonal arrays of etched circular holes results in a 2-D photonic band-gap mirror that can be tuned to a specific wavelength by varying the hole radius and the lattice spacing. 2-D mirror characterization is performed by evaluating the light emission from an active waveguide.

The 2-D PBG mirrors are etched into molecular beam epitaxially (MBE) grown single quantum well (SQW) graded-index separate-confinement heterostructures (GRINSCH). We have fabricated PBG mirrors in GaAs and InGaAs SQW GRINSCH structures that emit at 850 and 980 nm respectively. Both structures are grown on a GaAs substrate with graded AlGaAs cladding layers. The MBE grown structures are similar to those in previously published studies.[1,2] Contact to the p-side is made through 10-μm-wide AuZn/Au metal stripes.

The photonic band-gap design we used is a periodic hexagonal array that has a band gap for TE waves.[3] The 2-D hexagonal array was tuned for TE midgap wavelengths of 850 and 980 nm for the GaAs and InGaAs structures respectively. For the GaAs SQW structure we used a center-to-center hole spacing of 212.5 nm, and a hole radius of 70 nm. The lattice spacing and hole radius used in the 980-nm InGaAs SQW devices are just scaled by the wavelength. The mirrors consist of a pattern 25-μm wide by 4-μm long of the hexagonal lattice. The holes are etched 1.8-μm deep so as to penetrate slightly into the bottom n-doped AlGaAs cladding layer. A top view of the mirror and a cross-section of the mirror are given in Figs. 1 and 2.

The 2-D photonic crystal is processed through a succession of pattern transfers and etch steps.[4–6] The lithographic mask consists of a hard-baked photoresist layer followed by a layer of PMMA. The hexagonal pattern is first transferred into PMMA with electron beam writing. Then the hexagonal pattern is transferred vertically into the photoresist mask and into the Au stripe contact with an $Ar^+$ ion beam etch. The SQW GRINSCH structure is then etched with a $Cl_2$ chemically assisted ion beam to a depth of approximately 1.8 μm.

The 2-D mirror is characterized by electrically pumping the SQW GRINSCH material and measuring the emission spectrum. Cavities formed by two 2-D PBG mirrors and cavities formed by one 2-D PBG mirror and one cleaved facet are characterized.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**CThJ4** **11:30 am**

## 1-D photonic-band-gap structure along photonic wire


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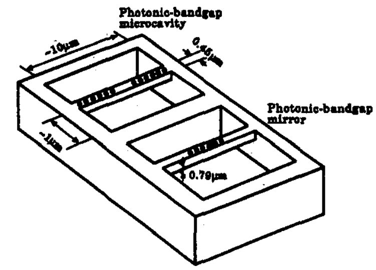
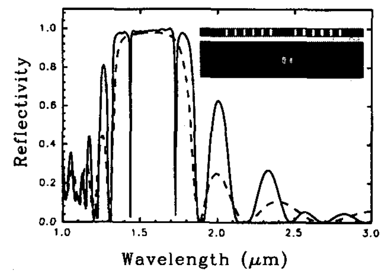
There has been much interest in the modification of spontaneous emission in artificial photonic structures, including photonic band-gap structures, microcavities, and low-dimensional photonic structures. Recently, low-dimensional photonic structures, such as microdisks[1] and photonic wires,[2] have been used to realize novel lasers with dimensions and characteristics much different from lasers with conventional structures. Photonic-wire structures are strongly guided one-dimensional waveguides with tightly-confined mode area. It was shown that in a strongly guided waveguide, the photonic density of states can be modified, leading to a significant modification of spontaneous emission in the waveguide.[3]




CThJ4 **Fig. 1** Schematic diagram of the suspended photonic-wire mirror and micro-cavity. Holes were etched in the photonic wire to form a one-dimensional photonic-band-gap structure.




CThJ4 **Fig. 2** Calculated reflection spectrum of a 0.3-μm photonic-wire mirror with six rectangle holes (dash line) and reflection spectrum of the photonic-wire microcavity (solid line). The insets shows the geometry and field distribution in a 0.3-μm photonic-wire microcavity. The cavity length is 0.775 μm, and six (0.225 × 0.1 $\mu m^2$) holes are on either side to form a Fabry-Perot cavity.

CThJ4 **Fig. 3** SEM image of a 0.45-μm suspended photonic-wire microcavity.

Ho *et al.* and Meade *et al.* suggested that 1-D photonic band-gap reflectors can be fabricated along a strongly guided waveguide (i.e. a photonic wire) to form a novel microcavity laser structure.[4,5] The novel microcavity laser can be seen as a linear cavity version of the photonic-wire laser and will expect it to also have a high spontaneous emission coupling efficiency. In this paper, we report our fabrication of the proposed 1-D photonic band-gap structure along the photonic