Lithographic band gap tuning in photonic band gap crystals

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We describe the lithographic control over the spectral response of three-dimensional photonic crystals. By precise microfabrication of the geometry using a reproducible and reliable procedure consisting of electron beam lithography followed by dry etching, we have shifted the conduction band of crystals within the near-infrared. Such microfabrication has enabled us to reproducibly define photonic crystals with lattice parameters ranging from 650 to 730 nm. In GaAs semiconductor wafers, these can serve as high-reflectivity ($>95\%$) mirrors. Here, we show the procedure used to generate these photonic crystals and describe the geometry dependence of their spectral response. © *1996 American Vacuum Society.*

I. INTRODUCTION

A photonic band gap crystal is a three-dimensional (3D) periodic dielectric structure in which electromagnetic waves are forbidden irrespective of their propagation directions.[1–7] Both computer models and microwave measurements have shown that a face centered cubic (fcc) crystal of cylindrical holes in a dielectric matrix exhibits such a photonic band gap.[6] We have previously reported on the technology for microfabricating photonic crystals with combination of high resolution lithography and anisotropic ion etching in compound semiconductors.[8,9] Photonic crystals are expected to be used in defining microcavities for single-mode light emitting diodes and other devices with inhibited spontaneous emission. Thin photonic band gap mirrors can also find use as microfabricated high-reflectivity mirrors in materials systems where epitaxial growth of Bragg reflectors is limited due to low inherent refractive index contrast between lattice-matched materials.

For all of these applications, it is necessary to geometrically control the spectral response of the photonic crystals. Here we show that photonic crystals can be microfabricated to define 3D mirrors with geometrically controlled wavelengths and wide free spectral ranges. The 3D interlinked mesh structure which results from microfabricating a fcc crystal is also ideally suited for electrical pumping of optoelectronic devices and for directional coupling of light emission.

II. PROCEDURE

We use the combination of high resolution lithography and dry etching technologies[10] to fabricate 3D photonic bandgap structures in the optical wavelength range. First, electron beam lithography with a 30 kV incident beam energy is used to create a hexagonal hole pattern on the surface of the sample, which corresponds to the (111) plane of the microfabricated fcc crystal. Next, we transfer the PMMA patterns into a 60-nm-thick gold layer by argon ion milling. We then transfer the gold pattern into 150 nm of sputter-deposited silicon dioxide by reactive ion etching using 60 mTorr C_2F_6 as the reactive gas at an etch rate of 25 nm/min. The selectivity between Au and SiO_2 is not very high (6:1) but this dry process significantly improves the reproducibility. To further improve the mask durability, we use ion milling to transfer this SiO_2 pattern into a 150-nm-thick nickel etch mask because the selectivity between Ni and GaAs in the presence of chlorine is three times higher than that between SiO_2 and GaAs. Finally, we use a chemically assisted ion beam etching (CAIBE) system[11] to fabricate the optical crystals in GaAs by angled etching of the masked semiconductor with an argon ion beam assisted by Cl_2 reactive gas. During this etch, the surface of the semiconductor is tilted at 35° to the normal and the sample is rotated into the three directions which correspond to the close-packed $\langle 110 \rangle$ directions of the microfabricated fcc crystal. In this way, 3D photonic crystals with thickness of about 1.5 μm are generated.

Provided that the pattern transfer is anisotropic, the lithographic dimensions obtained during electron beam exposure, together with the etch depth, determine the optical response of the crystal. These mirror characteristics are measured by transmission experiments for which the photonic crystals are placed into 40×40 μm^2 microfabricated nickel apertures. Their transmission spectra are determined using monochromatic light produced by a white light source passing through the monochromator. The monochromatic light is then focused by a confocal mirror onto the patterns and collected by an InGaAs detector. Since transmission spectra are measured over a large wavelength range, reflective optics are used to minimize the effect of chromatic aberration on the amplitude measurement. This aberration generally results in a smooth variation of intensity throughout the spectral range, making absolute light intensity measurements very difficult. The measured optical response from photonic crystals is then normalized to the measurements of unpatterned apertures, and compared with equivalent microwave models.[8]

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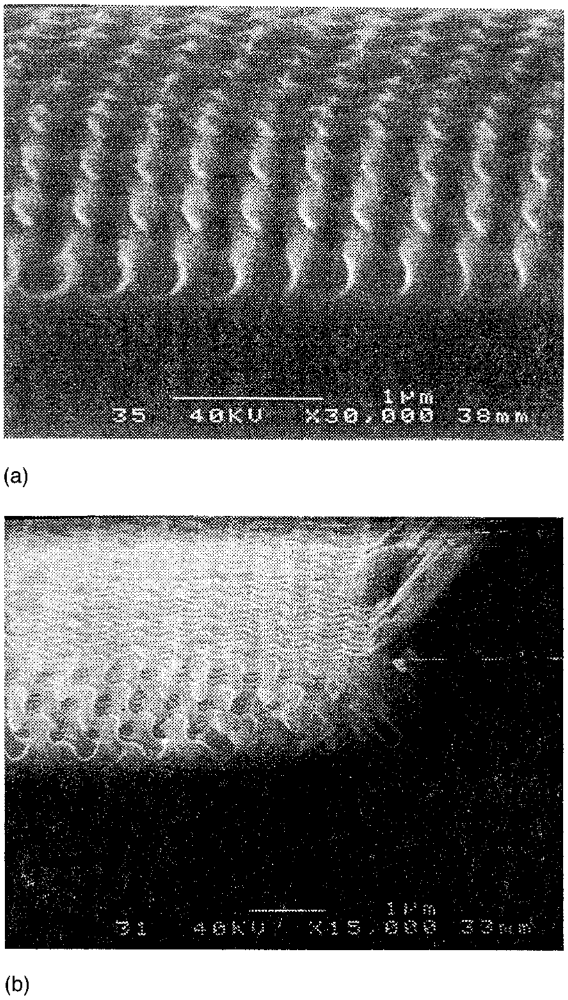

FIG. 1. (a) and (b) SEM image showing the cross section of a photonic crystal.

III. RESULTS

A. Microstructural measurements

Angle etching with a single planar mask layer requires careful selection of the mask material and the ion etching conditions in order to maximize the selectivity between the semiconductor etch rate and the mask erosion rate since the mask must be thin. Thin masks are necessary to minimize shadowing of the unmasked semiconductor surface by the etch mask during the angle etch, which results in more elliptically shaped holes with smaller sizes. Alternatively, we can build a 3D replica of the photonic crystal in a robust etch mask and then transfer this 3D mask structure into the underlying semiconductor.[12] The advantage is that this scheme minimizes the shadow effects and allows us to balance the three etch directions. The disadvantage is the increasing difficulty of masks preparation. To obtain photonic crystals with three repeating (111) planes in a 2D mask, etch rate selectivities of GaAs over the mask must be above 15:1. Furthermore, the anisotropy required for a high-quality crystal should be in excess of 10:1.

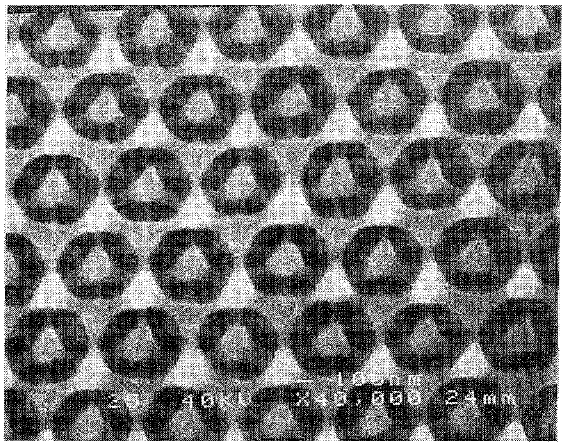

FIG. 2. SEM image of normal incident examination of a photonic crystal.

We use scanning electron microscopy to confirm the quality and thickness of the resulting microfabricated photonic crystals. This was done both by normal incidence examination as well as by side view imaging of cleaved cross-sections. Figures 1(a) and 1(b) show such cross sections of a typical photonic band gap crystal from two separate directions. From these micrographs, we can measure the total depth of the photonic crystal to be approximately 1.5 μm or three repeating (111) planes deep. In Fig. 1(b), the edge of the 40×40 μm^2 microfabricated aperture can be observed which blocks the ion beam during the angle etching process, thereby disrupting the periodicity of the microfabricated crystal lattice. This figure reveals the anisotropy of the individual holes formed during the angle etch. Normal-incidence SEM examination also reveals the overall uniformity of the microstructures, and is useful to confirm the precise lattice parameter and porosity (Fig. 2).

B. Tuning by microfabrication

We have fabricated and characterized an array of photonic crystals with varying spacings and hole sizes on a double-polished GaAs wafer [Figs. 3(a)–3(i)]. The lithographic dimensions of these crystals were chosen from model predictions to yield photonic band gaps in the near-infrared wavelength range.

The spacing (d) between the holes in the lithographic pattern which defines the (111) plane of the fcc crystal is proportional to the lattice parameter and center wavelength of the band gap in a photonic crystal. Thus, it is possible to tune the center wavelength of a structure during the electron beam writing step by systematically changing the distances between holes. Similarly, the sizes of the holes with a given spacing also influences the spectral response since the hole size changes the porosity of the crystal, and thereby alters the average refractive index of the resulting photonic structure. The hole diameter can also be changed lithographically, and can be conveniently adjusted by altering the exposure dose during the beam writing process.

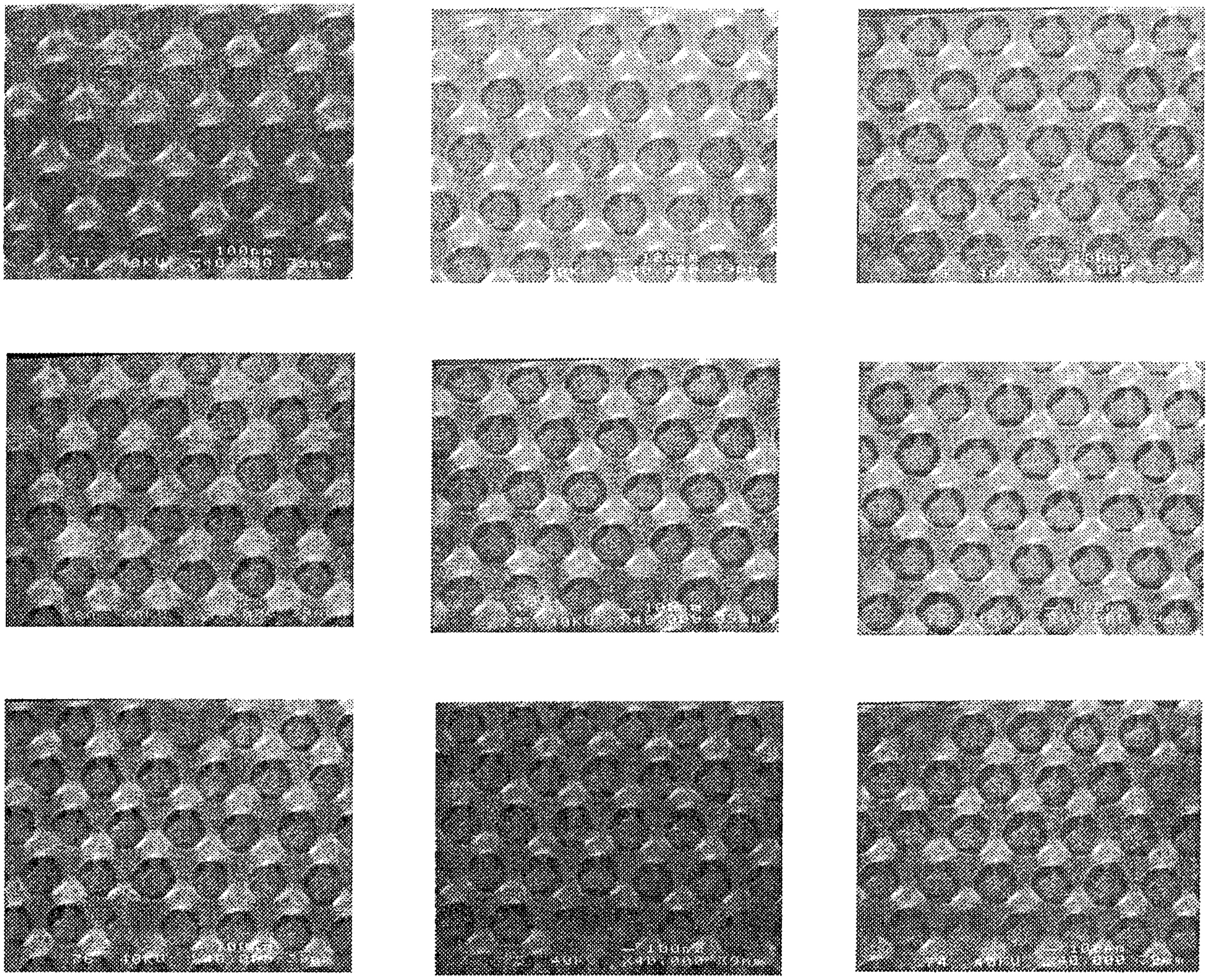

FIG. 3. (a)–(i) SEM images of an array of photonic crystals. The spacings becomes smaller from top to bottom and the hole sizes become larger from left to right.

C. Optical measurements

Optical measurements were undertaken on a series of microfabricated photonic band gap crystals shown in Fig. 3. Here, we show transmission as a function of wavelength. As would be expected when the lattice parameter becomes larger, we observe a shift of the spectral features to higher wavelengths. Figure 4(a) shows the spectra of three of the crystals characterized by Figs. 3(a), 3(b), and 3(c). For comparison, we also include another spectrum from a 850 nm lattice spacing crystal which was measured on a separately fabricated GaAs chip. The similar spectral shifts shown in Figs. 4(a) and 4(b) are also observed all over the whole array.

If only the sizes of the holes are changed in a series of microfabricated crystals with fixed lattice parameters, we again observe a shift in the spectra. This can be observed in Fig. 4(b), where we note that crystals with higher porosities shift their spectral features to lower wavelengths. This shift can be qualitatively explained by the lower average refractive index of the more porous crystals. We have so far reproduced these measurements on other microfabricated samples, and believe that it is possible to predict the spectral features of photonic crystals by careful control over the microfabrication mask.

As the depth increases, the amount of attenuation should increase as predicted from microwave measurements.[15] Three periods of a perfect 3D photonic crystals should yield a reflectivity in excess of 95%. The structural depth of our crystals can be observed nondestructively by scanning electron microscopy (SEM) observation along the direction of one of the etched holes, and by counting the number of repetitions of (111) planes. Figure 5 shows how this method can be used to characterize a GaAs photonic crystal which was etched four (111) planes deep. Such inspection also allows the measurement of the depth-dependent variations of hole sizes and porosities.

Microwave measurements for three repeating periods of a photonic crystal have been taken and scaled down to optical wavelength range to compare to our optical results. The scaling number was carefully chosen by the ratio of spacings,

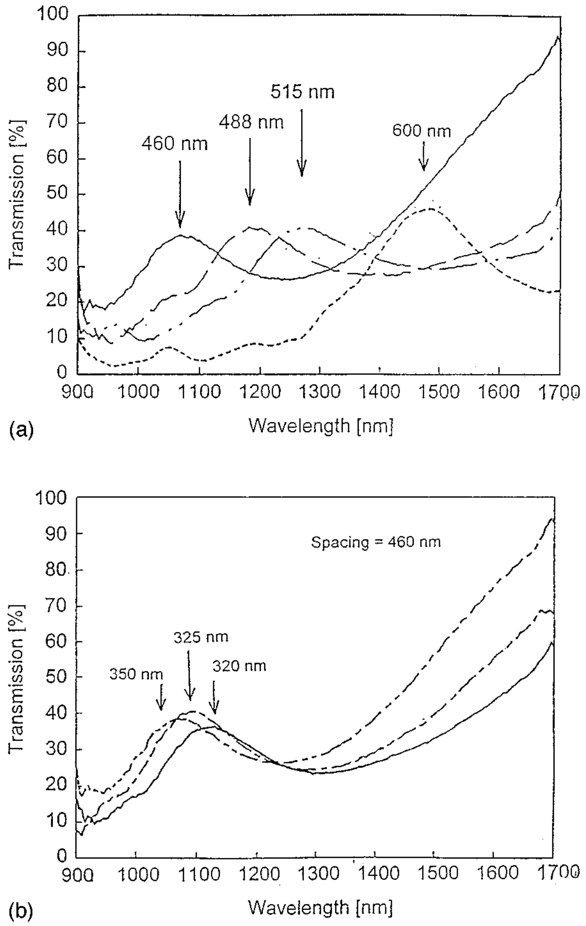

FIG. 4. (a) Transmission spectra for different spacings of photonic crystals; including the spectrum of the largest photonic crystal. (b) Transmission spectra for the same spacing (460 nm) but different hole sizes of photonic crystals.

difference of dielectric constant, porosity change, and so on. Figure 6 shows that the conduction band of microwave models is matched to optical crystals, but the attenuation in the microwave models is much stronger than in our photonic crystals. We believe that the reason for the lower attenuation is the variation of hole sizes and tapered etching which results from mask erosion during the angle etching process. Both theoretical calculation and microwave measurements of nonperfect structures are presently being performed to confirm this.

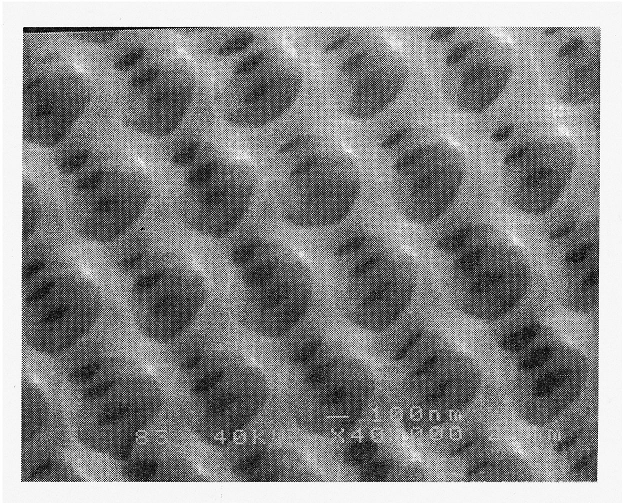

FIG. 5. SEM micrograph taken at 25° tilting shows four repeating (111) plane of a photonic crystal.

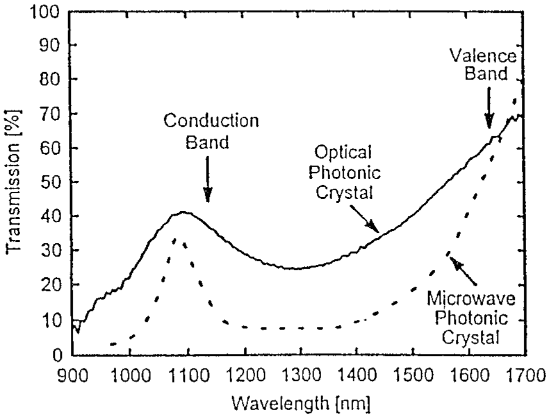

FIG. 6. A transmission spectrum is compared with microwave measurement.

IV. DISCUSSION AND CONCLUSIONS

We demonstrate the methodology required to control the transmission spectra of microfabricated mirrors based on photonic crystals in GaAs. So far, we have fabricated and characterized three to four (111) plane period deep photonic crystals with center wavelengths in the visible and near-infrared wavelength range. Lithographically, the diameters of the holes range from 280 to 500 nm, and the distances between holes range from 350 to 600 nm. This translates into photonic crystals with lattice parameters ranging from 495 to 850 nm. As high reflectivity is required for optical application, both uniformity and depth need to be further improved.[13–15] The limitation of Ni mask is the selectivity which limits the depth and the nonuniform transferring by ion milling. Therefore, new etch masks or 3D etch masks will have to be developed.[9] We have shown that the frequency of the photonic band gap mirror can be successfully adjusted by lithography during the mask definition process. Once the etch masks are optimized, many optical applications of photonic crystals in active optoelectronic devices will be possible.

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