Submicron three-dimensional infrared GaAs/AlₓOᵧ-based photonic crystal using single-step epitaxial growth

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A relatively simple technique is demonstrated to fabricate three-dimensional face-centered-cubic infrared photonic crystals with submicron feature sizes using GaAs-based technology, single-step epitaxial growth, and lateral wet oxidation. The photonic crystals were fabricated with feature sizes (a) of 1.5 and 0.5 μm. Transmission measurements reveal a stopband centered at 1.0 μm with a maximum attenuation of 10 dB for the submicron (a = 0.5 μm) photonic crystal. This technique is scalable to small photonic crystal periodicity and hence to shorter wavelengths. © 2001 American Institute of Physics. [DOI: 10.1063/1.1372198]
The Al$_{0.98}$Ga$_{0.02}$As layers are preferentially oxidized to form Ga adatoms is lost within a couple of periods. The migration of the adatoms, preferential growth occurs at the edges of the feature sizes become comparable to the migration length of kinetics of the adatoms on the patterned substrate. When the success of the technique crucially depends on the growth layer, the migration length can be decreased considerably, to 450 °C and by adding a small amount of Al to the GaAs adatoms is much less. By decreasing the growth temperature, therefore stable Al$_x$Ga$_{1-x}$As layers are preferentially oxidized to form a continuous path in both a more conformal growth of the layers is obtained, thus providing a good protection to the Al$_{0.98}$Ga$_{0.02}$As layer during the interruption.

A scanning electron microscope (SEM) image of the cross sections of the PBG crystal after growth and wet oxidation is shown in the inset of Fig. 2. There are several aspects of this simple process that need to be highlighted and discussed. First, the realization of an ideal fcc structure requires MBE growth of the right thickness to occur in the grooves and mesa tops. However, such growth will cause discontinuities in the layer structures wherein the Al$_{0.98}$Ga$_{0.02}$As layer cannot be wet oxidized. We found that by etching (111) facets on the corners of the patterned mesas, a more conformal growth of the layers is obtained, thus providing a continuous path in both (001) directions. This allows the lateral wet oxidation of the Al$_{0.98}$Ga$_{0.02}$As layers to occur. The result is a modified fcc structure. Second, the success of the technique crucially depends on the growth kinetics of the adatoms on the patterned substrate. When the feature sizes become comparable to the migration length of the adatoms, preferential growth occurs at the edges of the mesas and grooves, which act as kink sites for adatom incorporation. This leads to a nonplanar surface and the initial pattern is lost within a couple of periods. The migration of Ga adatoms is ~1 μm at 560 °C. The migration of Al adatoms is much less. By decreasing the growth temperature to 450 °C and by adding a small amount of Al to the GaAs layer, the migration length can be decreased considerably, allowing conformal growth of the layers for feature sizes <1 μm. However, it is not desirable to increase the Al content in the high index layer by too much because the wet oxidation rate of this layer has to be maintained as almost negligible to provide oxidation selectivity. The wet oxidation rate of Al$_x$Ga$_{1-x}$As as a function of composition x is shown in Fig. 2. We found the ideal situation is to use Al$_{0.30}$Ga$_{0.70}$As instead of GaAs as the high index material. The growth rate is ~2 Å/s. The Al$_{0.98}$Ga$_{0.02}$As layers were grown at 580 °C. Therefore a growth interruption was necessary after the growth of this layer to reduce the substrate temperature to 450 °C. It was found that the insertion of a 30 Å GaAs layer provided good protection to the Al$_{0.98}$Ga$_{0.02}$As layer during the interruption.

The transmission spectrum of the submicron photonic crystal was measured at room temperature using a white light source, a monochromator, liquid nitrogen-cooled photomultiplier tube (PMT), and a Ge detector in the wavelength range of 900–1700 nm. The measurement results for light incident from 900 to 1200 and 1200 to 1700 nm are taken with a PMT and a Ge detector, respectively. The dotted line represents the control structure transmission spectrum, and the solid line represents the measured transmission spectrum for different angles (0°–40°) from the surface normal.
made at angles $\theta (0 \leq \theta \leq 40^\circ)$ to the normal as shown in Fig. 3(b). This corresponds to a change in incident beam direction from $\Gamma'X'$ towards $\Gamma'K'$ of the tetragonal face-centered-cubic PBG crystal. We observe that the transmission gap decreases in width as the sample is rotated. Theoretical calculations, using the plane-wave expansion technique,\textsuperscript{19} were also done for a tetragonal fcc structure with feature size of $a = 0.5 \mu m$ and $t = 0.2 \mu m$ thick layers in the $z$ direction. The calculated band structure is shown in Fig. 4. We can see that it shows a gap for $k$ around the $X'$ direction (surface normal) between 0.9 and 1.24 $\mu m$ (corresponding to a normalized frequency of 1.1–0.8) which agrees very well with the measured transmission results. One interesting feature that we consistently observe in the transmission spectra of the PBG structures of all periodicities is the existence of a double dip in the measured stopbands. The transmission data on GaAs-based photonic crystals from other research groups\textsuperscript{9,12} show similar characteristics. It could be due to the fringe effects introduced by the multilayer Al$_{0.98}$Ga$_{0.02}$As/Al$_{0.30}$Ga$_{0.70}$As structure or a feature of the photonic crystal band structure. This work was supported by the Defense Advanced Research Projects Agency under Grant No. MDA 972-00-1-0020.

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