High index contrast mirrors for optical microcavities

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A new technique for constructing multilayer dielectric mirrors is described that results in high reflectivities with only two or three dielectric layer pairs per mirror. These structures are obtained by selectively etching layered $Al_xGa_{1-x}As$ material grown by molecular beam epitaxy and then replacing the etched regions with acrylic resin or air. A thin optical cavity produced by this technique is demonstrated with mirror reflectivities near 96%. These techniques allow the fabrication of lasers, light-emitting diodes, or optical switches with high contrast ratio mirrors on both sides of an optically active region in order to enhance output coupling, lower laser thresholds, and increase modulation rates.

Multilayer dielectric mirrors grown by molecular beam epitaxy (MBE)[1-4] are presently used to form optical microcavities. Typically 7 to 20 layered pairs of materials with optical index ratios near 3.5/3.0 are used to obtain high reflectivities in the range from 90 to 99.8%. We describe new fabrication techniques that allow obtaining similar reflectivities with only two or three paired layers with high contrast index ratios in the range 2–4. The decreased optical dimensions of these high index ratio cavities increase the spectral bandwidth of the cavity and the associated modulation bandwidth. For example, a simulation comparing the resonant cavity bandwidth of two cavities, each with mirror reflectivities of 96.7%, one with a low index ratio 3.5/3.0 (11 layered pairs in each mirror) and the other with a high index ratio 3.0/1.5 (2 layered pairs in each mirror), results in an increase in spectral bandwidth of nearly a factor of 5 for the high index contrast case. This increased bandwidth can be important for coupling light out of luminescent structures or in wide bandwidth laser modulation. It has also been suggested that high index ratio structures can be used to significantly enhance or inhibit the total spontaneous emission rate for radiative processes,[5-8] e.g., emission from excitons in quantum well layer. This involves effectively reducing the number of optical modes accessible for radiative processes within the structure.[5] In the limit that only one field mode is allowed by the structure, a "zero threshold" laser[9] is envisioned where each emitted photon is in the laser mode, even at low excitation rates. This type of structural control of the field modes can also lead to control of the emitted photon statistics through the exciting process, e.g., high efficiency constant current (sub-Poissonian) excitation.[7]

Fabrication of high index contrast mirrors is presently achieved by deposition of nonepitaxial layers (e.g., alternate layers of ZnS and SiO_2). This technique can be used for the top mirror of an optical cavity surrounding a MBE-grown active region but the bottom mirror must either be many layers of MBE material or the supporting rear substrate must be etched away for deposition of a nonepitaxial high contrast mirror. We use a selective etching technique[9,10] in a MBE structure to obtain thin, high index contrast mirrors on *both* sides of a quantum well active region. A schematic diagram of the initial MBE-grown structure is shown in Figs. 1 (a) and 1(b). Alternate layers of $Al_{0.28}Ga_{0.72}As$ (2966 Å) and $Al_{0.6}Ga_{0.4}As$ (1448 Å) are grown by MBE at a temperature of 640 °C on the GaAs substrate. The $Al_{0.28}Ga_{0.72}As$ layer thickness is chosen to be $5\lambda/4$ (λ is the wavelength in the material) at the wavelength for the heavy hole transition for the 50 Å GaAs quantum well between the two mirrors ($\lambda_0 = 810$ nm in free space). These $5\lambda/4$ layers have a low enough Al concentration so that a HF or HCl etch does not significantly erode them. The alternate layers of $Al_{0.6}Ga_{0.4}As$ are selectively etched away leaving a space that can be filled with air or acrylic resin. For the experiment described here an acrylic resin was used to fill the etched regions. It has an optical index of 1.51 when solidified. Thus the 1448 Å thickness of the $Al_{0.6}Ga_{0.4}As$ corresponds to a $\lambda/4$ optical thickness when backfilled with acrylic resin. The $5\lambda/4$ layers could be reduced to the optically optimal $\lambda/4$ value; however, we wanted the extra thickness to ensure the mechanical integrity of this initial demonstration structure. The mirrors are spaced at approximately one wavelength and the quantum well is at a cavity antinode for measurements of luminescence and spontaneous decay times.

It is well known that AlAs selectively etches relative to GaAs by a very large ratio ($>10^6$:1).[11] We found that $A_xGa_{1-x}As$ with $x = 0.6$ yielded high optical quality surfaces (especially important for high index ratios) and good etch selectivity. A key component to this combination of properties is the deposition of this alloy in layered fashion. We used alternate 6 Å layers of AlAs and 4 Å layers of GaAs to build up the total 2966 Å thickness. Etch rates in a uniformly deposited alloy were at least a factor of 10 slower and the selectivity was significantly degraded. At higher growth temperatures pure AlAs forms good quality optical surfaces and has higher etch selectivity than the alloy. We are presently varying material composition and other parameters in order to optimize the process. The $Al_{0.28}Ga_{0.72}As$ composition is chosen to minimize the Al concentration (optimize the etch selectivity) while main-

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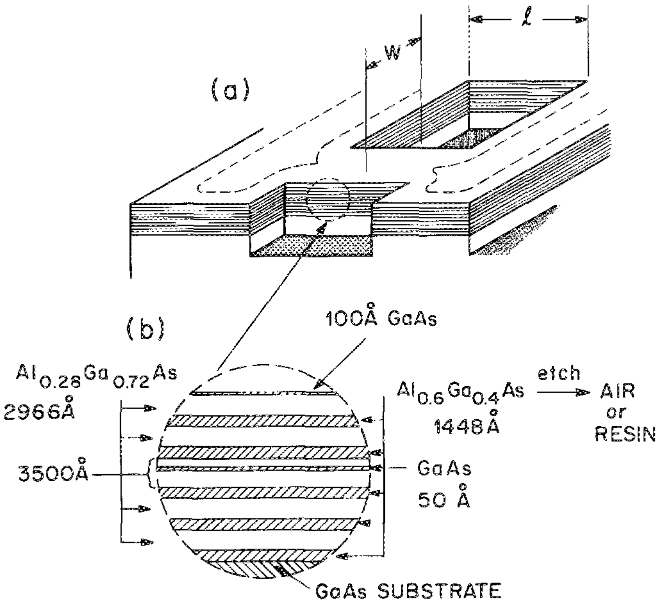

FIG. 1. Schematic drawing of the structure and layer compositions used for producing high index ratio optical microcavities. Layers of $Al_xGaAs_{1-x}As$ are grown by molecular beam epitaxy on a GaAs substrate and patterned by SiO_2 mask and nonselective etch as shown in (a). The depth of the etched regions is typically 1 μm below the MBE-grown layers. In (b) a detail of the layered structure is shown including the composition and thicknesses of the layers. The $Al_{0.6}Ga_{0.4}As$ was grown as alternate 6 Å AlAs and 4 Å GaAs layers in order to enhance optical smoothness and etch selectivity. Selective etching erodes the $Al_{0.6}Ga_{0.4}As$ regions into the "bridges" and support "pillars" for a distance of the order of half the bridge width w so that the bridge regions are cleared of the selectively etched material. The remaining support pillars are outlines by the dashed lines.

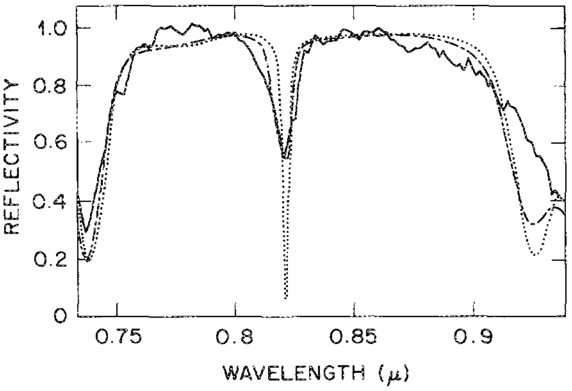

FIG. 2. Reflectivity spectra are shown for an optical microcavity illustrated in Fig. 1 with acrylic resin replacing the selectively etched layers. The measured reflectivity, using a full angle of 53° to illuminate a 5-μ-diam area near the center of a 30×30 μm^2 bridge, is shown as the solid line. A computer simulation of the reflection spectra for normal incidence illumination is shown as the dotted curved. An angularly averaged reflectivity simulation corresponding to the experimental parameters is shown as the dashed curve.

taining a sufficiently high barrier for the GaAs active layer. A protective 100 Å GaAs layer over the entire structure prevents interaction of the $Al_{0.28}Ga_{0.72}As$ with the etches and the atmosphere. This type of thin GaAs cladding layer can also be added between mirror layers to enhance the etch selectivity.

Unetched regions of the structure shown by the dashed lines in Fig. 1(a) serve as "pillars" to support the thin etched mirror layers that are formed as "bridges" of width w and length l. A SiO_2 mask and a nonselective etch (H_2SO_4:H_2O_2:H_2O at 2:10:40 volume ratio) form the bridge/pillar structure. After this patterning and removal of the SiO_2 mask a selective etch of 10% HF in H_2O at 0 °C is used to etch away the $\lambda/4$ layers into the structure at a rate of ~ 10 μ/h until the layers in the bridge regions are cleared. After etching and dilution with H_2O the suspended mirrors are stable and the uniformity of the etch can be checked by a Nomarski contrast microscope.

The next key to the process is replacement of H_2O in the etched regions with air or acrylic resin without collapsing the structure. If the water is simply allowed to evaporate, the surface tension between the layers invariably collapses the structure. We have used two processes to replace the water. The first procedure is critical point drying commonly for histological studies.[12] Acetone is used to replace the water with a dilution of ~ 1000:1. Then the sample is placed in a pressure chamber where liquid CO_2 replaces the acetone, again with a large dilution ratio. Finally the pressurized CO_2 temperature is increased above the critical point ($T_c = 31.5$ °C, $p = 1100$ psi) and then the cell pressure is reduced to atmospheric pressure while maintaining $T > T_c$. In this way there is never a liquid/gas boundary in the structure to cause collapse. The resulting air spaced mirrors are stable, although we have not studied the effects of strong illumination that might cause stresses due to charging effects.

The second water replacement process has been used more extensively and results in quite stable structures. This process also begins by replacement of water with acetone. The next step is replacement of the acetone with a low viscosity acrylic resin commonly used for encapsulating biological samples for microscopic studies.[13] Considering the large aspect ratio of the layered structure (~ 300:1), it is amazing that this replacement process is effective in a period of less than an hour. The resin can be solidified by several techniques including heating to temperatures between 60 and 120 °C for periods of less than 1 h, illumination with ultraviolet light and the use of a fixing agent. We have had good results with the heating technique using a flat coverglass over the top of the sample that results in a relatively flat layer of acrylic resin over the structure a few microns thick. Cavities made by this technique have been stable over a periods of months, even after cycling to liquid-nitrogen temperature and laser illumination.

A reflection spectrum is shown in Fig. 2 for the microcavity sketched in Fig. 1 using the acrylic resin replacement technique. A simulation of the normal mirror reflectivities predicts a reflectivity of 97.4% for the bottom mirror and 95.4% for the top mirror resulting in maximum cavity reflectivity of 97.5% in stopband region of the spectrum between 0.85 and 0.9 μm. The simulation and experimental reflectivity spectrum were done with the quantum well absorption shifted off the cavity resonance but include a small absorption of 2% from the 100 Å GaAs overlayer. The microscope objective used to illuminate the cavity for this measurement had a full angular width of 53° that caused a broadening of the resonant reflectivity dip. Good agreement between the angularly averaged reflectivity simulation and measured reflectivity is obtained over a major portion of the resonant region and the stop band region between 0.75 and 0.92 μ. This agreement indicates that high mirror reflectivities near 96% can be obtained for only two layered semiconductor/acrylic pairs. A quantum well laser cavity may require three layered pairs to achieve a mirror reflectivity of 99%.

In conclusion, we have demonstrated a new technique to produce high index contrast mirrors and microcavities that uses molecular beam epitaxy, selective etching, and relatively simple, stable air or acrylic resins as replacements for the selectively etched regions. These structures offer enhanced spectral bandwidth and modulation rates for surface-emitting light sources or optical switches. We are also designing structures based on this technology that promise to significantly restrict the number of optical modes allowed for radiation from quantum well structures within the optical cavity region. These mode restrictions should allow significant modification of the total spontaneous emission rates from within the structures and lead to surface-emitting lasers with lower thresholds and control over the emitted photon statistics.[5–9]

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