# Low-loss optical waveguides made with molecular beam epitaxial $In_{0.012}Ga_{0.988}As$ and $In_{0.2}Ga_{0.8}As$-GaAs superlattices

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We demonstrate for the first time low-loss optical guiding in In-doped GaAs. Ridge waveguides are made with single $In_{0.012}Ga_{0.988}As$ ternary layers and $In_{0.2}Ga_{0.8}As$-GaAs superlattices. Attenuation constants of ~ 1.3 dB/cm are measured and the principal loss mechanism is identified to be scattering at the ridge walls. It is expected that improved fabrication techniques will lead to guides with attenuation ⩽0.5 dB/cm.

With the development of optical fiber transmission systems, there has been considerable advances in optoelectronic devices made with GaAs-AlGaAs for wavelengths ~0.8–0.9 $\mu$m and with InGaAsP-InP for wavelength ⩽1.6 $\mu$m. In fiber communication devices and optical integrated circuits, optical elements such as waveguides, couplers, and modulators are essential components. In particular, low-loss optical guides are vital as optical links and they form integral parts of lasers and light modulators. It is known that the refractive index of GaAs is increased by the incorporation of small amounts of In in the lattice. We have recently calculated the extent of this increase,[1] which can be ideally used for light confinement. Practical guides using this scheme can either be homogeneous single epitaxial layers, in which case the In content needs to be small to avoid lattice mismatch effects, or strained-layer superlattices (SLS's) in which the $In_xGa_{1-x}As$ well regions can have $x$ as high as 0.5. Growth by molecular beam epitaxy (MBE) allows such layers and superlattices to be grown fairly easily. The use of SLS's allows additional tailoring of the effective band gap by proper choice of the superlattice parameters. Optoelectronic devices with InGaAs-GaAs SLS's have been demonstrated[2–5] and photoluminescence measurements made on the material indicate good structural integrity.[6] In this letter we present the characteristics of ridge guides made with single layer $In_xGa_{1-x}As$ and $In_xGa_{1-x}As$-GaAs SLS's. Such guides can be integrated with devices made with similar materials. It is seen that the propagation losses of such guides are amongst the smallest that have been measured with III-V semiconductors. It is to be noted that the present devices are different from elasto-optic guides demonstrated earlier,[7,8] where the strain was applied by a superimposed dielectric or metal stripe.

$In_{0.2}Ga_{0.8}As$-GaAs SLS was grown by MBE on Si-doped (001) GaAs substrates at 540 °C. A 0.3-$\mu$m GaAs layer ($n = 2\times10^{18}$ cm$^{-3}$) was first grown, followed by a 1-$\mu$m $In_{0.1}Ga_{0.9}As$ layer ($n = 2\times10^{18}$ cm$^{-3}$) and a 2-$\mu$m n SLS. To enable the fabrication of junction diodes a $p^+$ $In_{0.1}Ga_{0.9}As$ followed by $p^+$GaAs was grown on top. For the structure investigated here the SLS consists of 25 Å GaAs barrier and 94 Å $In_{0.2}Ga_{0.8}As$ well regions. 2-$\mu$m-thick undoped $In_{0.012}Ga_{0.988}As$ layers were grown on similar GaAs substrates at 510 °C followed by a 0.2-$\mu$m $p^+$ GaAs. The composition and thickness of the layers of the SLS were confirmed by analysis of x-ray diffraction data.[9] Low-temperature photoluminescence measurements were also performed to determine the quality of the grown materials. The photoluminescence in the SLS was dominated by a single bound exciton peak at a spectral energy of 1.26 eV. The spectrum of the undoped $In_{0.012}Ga_{0.988}As$ was similar to that of high-purity GaAs, with a significant difference. The familiar defect related bound exciton lines in the edge luminescence of MBE GaAs[10] were very weak or mostly absent. From capacitance-voltage measurements the free-carrier concentrations were found to be ~ (3–5) × $10^{15}$ cm$^{-3}$ in the single-layer and SLS guiding regions.

Ridge waveguides along the ⟨110⟩ direction were formed by photolithographic patterning followed by wet chemical etching in 1:1:8::$H_3PO_4$:$H_2O_2$:$H_2O$ at 30 °C. The micrograph of a typical superlattice waveguide is shown in Fig. 1. Typical etch depths were ~4 $\mu$m in the SLS guides to include the guiding and top $p^+$ regions. For the single layer guides, the etch depth was ~2 $\mu$m. For the measurement of propagation loss in the waveguides, the conventional cut-back method was used. It should be mentioned that in using

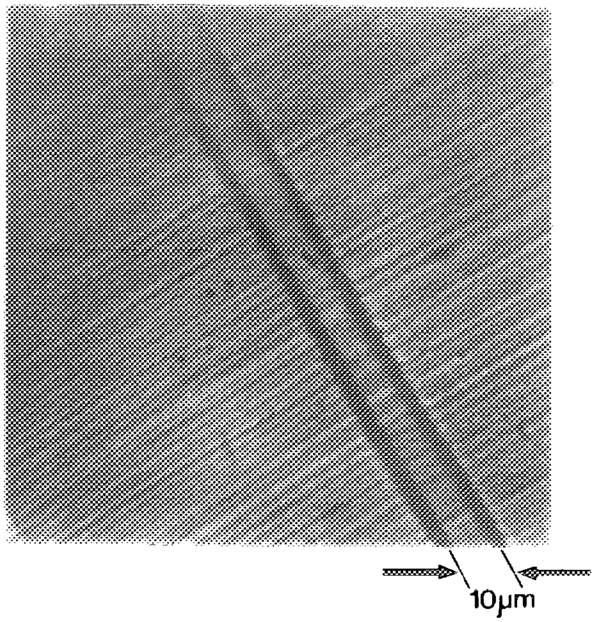

FIG. 1. Photomicrograph of a 10-$\mu$m-wide ridge waveguide formed with a 2-$\mu$m-thick $In_{0.2}Ga_{0.8}As$-GaAs SLS.

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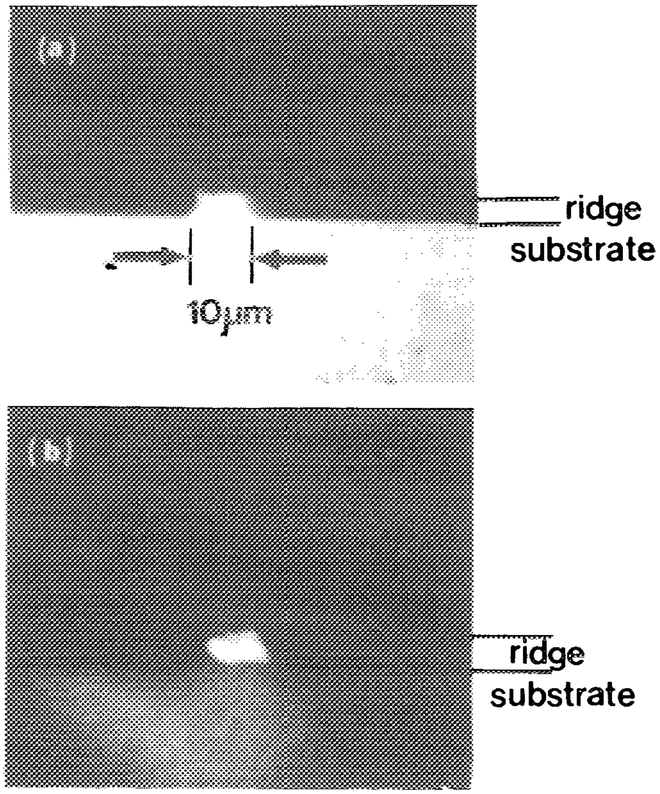

FIG. 2. (a) Cleaved cross section of ridge; (b) near-field image of guided light at output end. The substrate is back illuminated with lamp to reveal waveguide cross section.

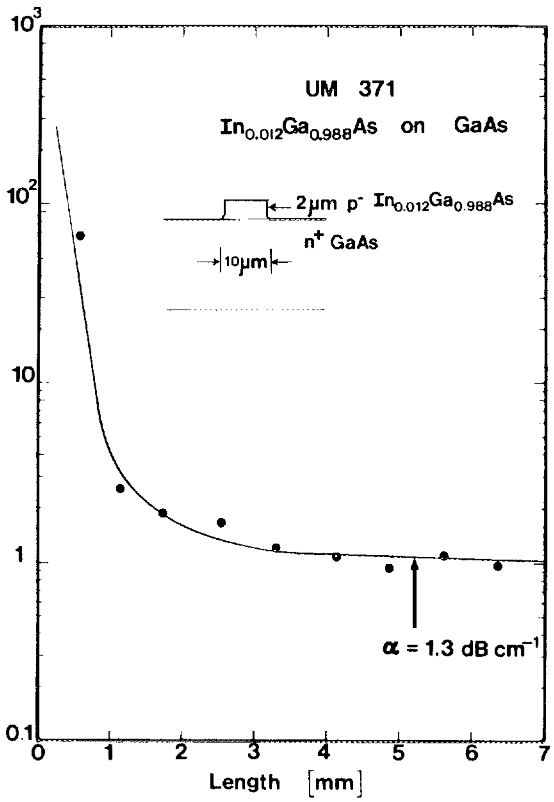

FIG. 3. Output power as a function of $\mathrm{In_{0.012}Ga_{0.988}As}$ waveguide length.

this method, the measurements were made as accurately as possible to minimize differences in coupling loss. Light from a 1.15-μm He-Ne laser was focused to a 2-μm spot at the input cleaved end of the guide. The polarization of the input light was parallel to the layers. The near-field pattern at the output was observed with a microscope IR camera combination and displayed on a monitor. A typical image of the light output of a SLS guide is shown in Fig. 2. Similar strong light confinement in the vertical direction was observed for the single layer alloy guides also, which is not usually observed in undoped GaAs. The guides tested here were usually multi mode, but single mode propagation throughout the entire guide length can be achieved by the reduction of the guide width. The output power was simultaneously measured with a pinhole-Ge detector (cooled) assembly. Care was taken to ascertain that the cleaved end faces were of high optical quality and that the cleaved end towards the input was the same throughout the experiment. The output power was maximized by proper positioning of the sample and optimum light coupling at the input. The output power was monitored for various guide lengths and such data are shown in Figs. 3 and 4 for $\mathrm{In_{0.012}Ga_{0.988}As}$ and $\mathrm{In_{0.2}Ga_{0.8}As}$-GaAs SLS's, respectively. A very high attenuation of the input light observed for smaller lengths of the guides for both materials can be attributed to the extinction of higher order modes.

It is interesting to note here that higher order modes decay over larger lengths in the $\mathrm{In_{0.2}Ga_{0.8}As}$-GaAs SLS guide than in the $\mathrm{In_{0.012}Ga_{0.988}As}$ guide. This is possibly due to the higher refractive index of the former. It is estimated that the refractive index in the single layer and the SLS are

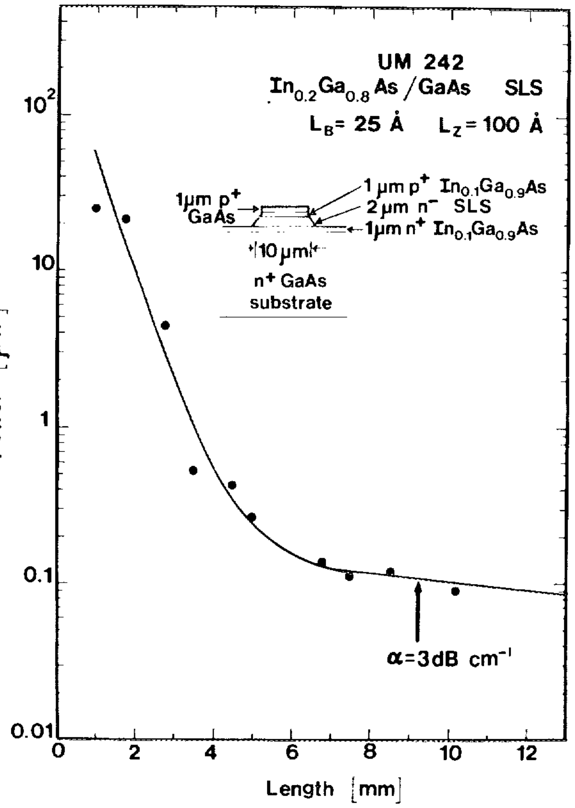

FIG. 4. Output power as a function of $\mathrm{In_{0.2}Ga_{0.8}As}$-GaAs SLS guide length.

3.41 and 3.52, respectively. Loss coefficients of 1.3 dB/cm for the $In_{0.012}Ga_{0.988}As$ layer and 3 dB/cm for the $In_{0.2}Ga_{0.8}As$-GaAs SLS are measured. We have analyzed the waveguide losses in both cases by considering free-carrier loss and losses due to scattering at the surfaces. It is evident that the dominant loss mechanism in the guides is scattering at the side walls of the etched ridges. The unevenness of the side walls is larger in the case of the SLS, as can be seen from Fig. 1. This accounts for the larger measured attenuation constant, compared to the $In_{0.012}Ga_{0.988}As$ waveguides. It is, however, important to note that the measured attenuation constants, particularly in the single layer guides, are comparable to the lowest values reported from GaAs devices.[11,12]

In conclusion, we have demonstrated that addition of small amounts of In to GaAs gives material with increased refractive index. Such material can be used as single layers or strained-layer superlattices to form low-loss optical waveguides. The measured attenuation constants of 1–3 dB/cm can be further reduced to below 1 dB/cm by improved photolithography and dry etching techniques. These experiments are in progress. This first demonstration of efficient guiding in In-doped GaAs can have important applications in the fabrication of lasers and other optically integrated structures.

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