Single mode optical waveguides and phase shifters using InGaAlAs on InP grown by molecular beam epitaxy

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We have investigated the characteristics of molecular beam epitaxial $In_{0.53}(Ga_xAl_{1-x})_{0.47}As$/InP waveguides and phase modulators in the 1.15–1.3 μm wavelength range. Loss at 1.15 μm has been measured and is ~5 dB/cm. The measured phase shift due to the electro-optic effect results in an electro-optic coefficient $r_{63} \sim 0.6 \times 10^{-12}$ m/V. Preliminary results at 1.3 μm show that the loss is reduced and is ~3.4 dB/cm.

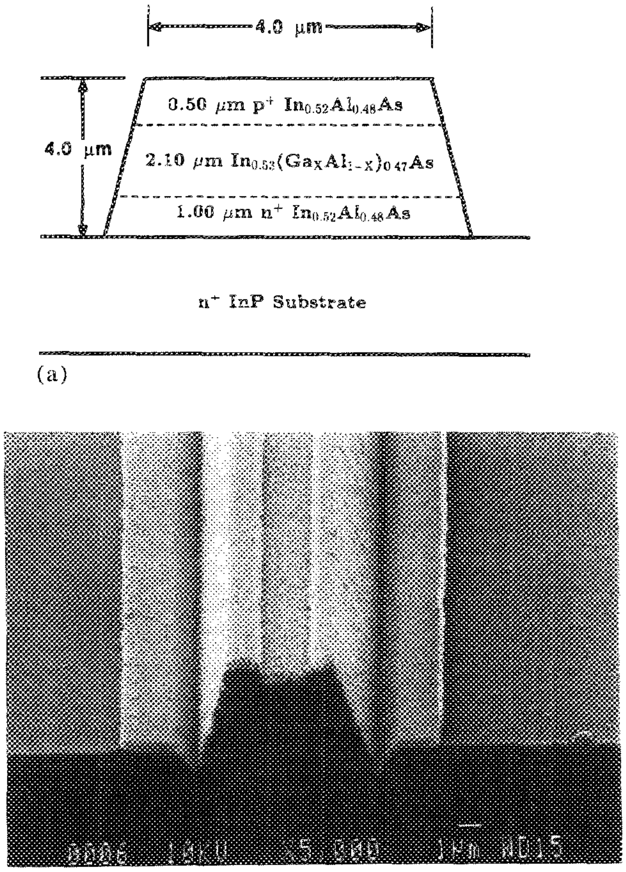
Molecular beam epitaxy (MBE) has proven to be a valuable tool for providing material for both electrical and optical applications.[1] More recent efforts have concentrated on developing devices integrating the optical and electrical functions of discrete devices onto a single chip.[2] In addition, increasing emphasis has been placed on developing devices in the 1.3–1.55 μm range where optical fibers exhibit low loss and dispersion. $In_{0.53}(Ga_xAl_{1-x})_{0.47}As$ grown on InP provides an alternative to the InGaAsP system, for this range, (i) the band edge can be tuned from that of $In_{0.53}Ga_{0.47}As$ to $In_{0.52}Al_{0.48}As$ (0.75–1.48 eV) and (ii) the InGaAlAs system can be easily grown in the conventional solid-source MBE system.

Essential to many integrated electro-optic applications are low loss, single mode waveguides and phase modulators. The guides should exhibit low attenuation, while the phase modulators should show large phase changes to limit the voltage necessary for shifting. In this letter we report on the characteristics of InGaAlAs waveguides and phase modulators. Loss and phase modulation data are provided at 1.15 μm, and initial loss data are shown at 1.3 μm. The losses are comparable to those presented by Cinguino *et al.*,[3] and for the first time phase modulation data are presented for this material.

The data presented are for a representative sample grown by MBE, shown schematically in Fig. 1(a). First a 1.0 μm Si-doped n^+-InAlAs buffer is grown on a S-doped (100) n^+-InP substrate. Then a 2.1 μm, undoped $In_{0.53}(Ga_xAl_{1-x})_{0.47}As$ ($x = 0.04$, 0.11) is grown. The quaternary layer is capped with a 0.5 μm Be-doped p^+-InAlAs layer. The growth rate and temperature were set at 0.8 μm/h and 540 °C, respectively, which resulted in the optimum quality for this material as well as for the cladding.[4] This was verified by low- and room-temperature photoluminescence measurements.

The waveguides were delineated by standard lithography and a 4-μm-wide ridge was formed by ion milling. A passivation layer of SiO_x was deposited on the sample and holes etched to define the top contact. After evaporation of the top (p^+) contact, the sample was thinned and the bottom (n^+) contact was evaporated onto the back of the sample. A scanning electron micrograph (SEM) of the completed phase shifter is shown in Fig. 1(b). For phase modulation experiments, the sample was cleaved in the $[0\bar{1}\bar{1}]$ and $[0\bar{1}1]$ crystallographic directions. The diodes have leakage currents of 30 nA and a reverse breakdown voltage of ~25 V.

The measurements were done with two optical sources: a He-Ne laser with $\lambda = 1.15\,\mu m$ and an InGaAsP diode laser with $\lambda = 1.3\,\mu m$. The guides exhibited single mode behavior at the two wavelengths. Waveguide loss was measured by the sequential cutback method. The waveguides were oriented in the $[0\bar{1}1]$ direction to allow endfire coupling into the cleavage planes through an objective lens. The output was focused onto a cooled germanium detector and detected by lock-in techniques. Figure 2(a) shows the data obtained for waveguide loss at 1.15 μm. The attenuation coefficient is



(a)

(b)

FIG. 1. (a) Schematic of waveguide/phase modulator grown by molecular beam epitaxy, and (b) SEM photomicrograph of phase modulator structure.

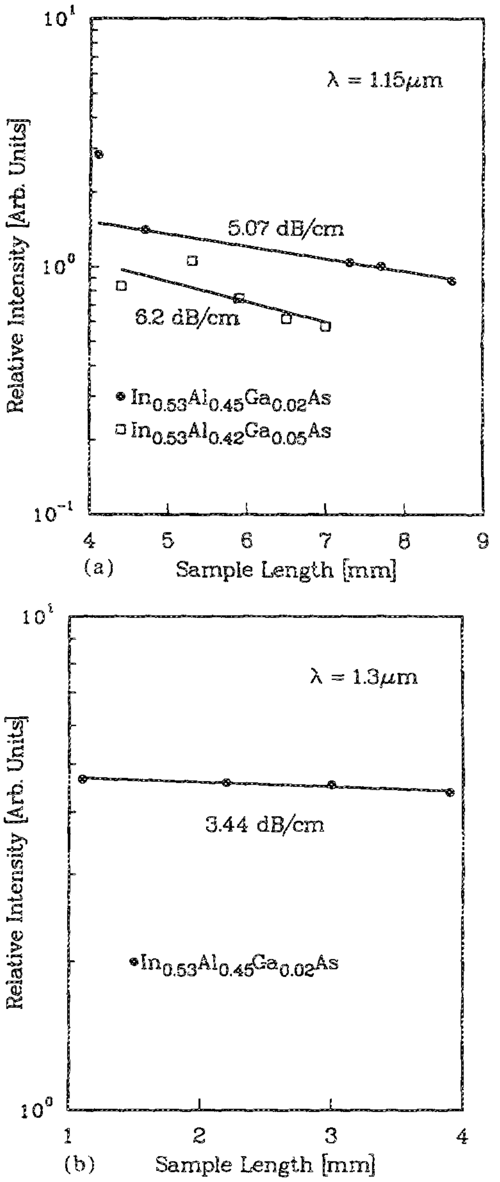


FIG. 2. Transmission vs length for single mode InGaAlAs waveguides measured at (a) 1.15 μm and (b) 1.3 μm wavelengths.

1.18 and 1.45 cm^{-1} at $x = 0.04$ and $x = 0.11$, respectively. This leads to a loss of 5.07 and 6.2 dB/cm, respectively. Figure 2(b) shows the data obtained for loss at 1.3 μm. At this wavelength the attenuation coefficient is 0.80 cm^{-1} resulting in a loss of 3.44 dB/cm ($x = 0.04$).

The phase modulation experiment was done using the He-Ne laser (1.15 μm). Electroabsorption measurements showed little modulation with an applied bias up to 10 V. The analyzer adjusted for minimum and maximum TE- and TM-like input excitations shows a ~3.3 % mode conversion. For phase modulation measurements, the waveguide was excited with a polarization oriented 45° to the direction of the applied electric field to equally excite the TE and TM modes of the guide. The near-field pattern at the output of the waveguide was focused onto a cooled germanium detector through an analyzer and was detected by lock-in techniques.

Results of the measured phase change with the application of bias are shown in Fig. 3. The corresponding average junction electric field is $\sim 4.4 \times 10^4$ V/cm. The electro-optic coefficient r_{63} was obtained by fitting the measured phase changes according to

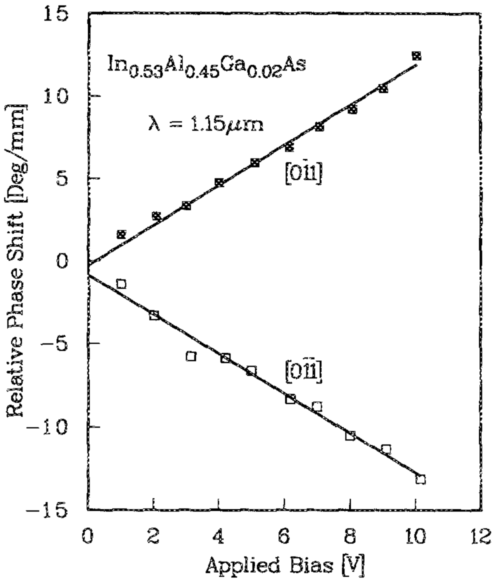


FIG. 3. Phase difference between TE- and TM-like modes for the orthogonal $[0\bar{1}\bar{1}]$ and $[0\bar{1}1]$ propagation directions.

$$\Delta\phi_{\mathrm{Eo}} = \pm \pi\Gamma n_0^3 r_{63}\bar{E}l/\lambda, \qquad (1)$$

where n_0 is the zero-field refractive index of the quaternary layer, $\bar{E}$ is the average junction electric field, Γ is the overlap of the optical field with the electric field, and l is the length of the waveguide. The refractive index of the guide layer is 3.35. We estimate the overlap of the junction electric field and the optical field distribution to be 0.76 in our samples. The variation of Γ, with applied bias, is expected to be small.

The value of the linear electro-optic coefficient at 1.15 μm estimated from a fitting to Eq. (1) is 0.639×10^{-12} m/V. This value seems somewhat low in comparison with that obtainable from InGaAsP,[5] but somewhat expected since the optical source is ~400 meV away from the band edge. Greater phase changes can be expected when operating closer to the band edge and by designing multiple quantum wells so that the quadratic electro-optic effect can be exploited.[6,7] It is evident from the preliminary data that the InGaAlAs system, as an alternative to InGaAsP, can be used for electro-optic devices. Further work must be done to investigate the properties of the quaternary near band edge and to refine the material quality to reduce the propagation loss.

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