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Optical waveguiding in proton-implanted GaAs†

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We have produced optical waveguides in n-type GaAs by implantation with 300-keV protons. The guiding is shown to be due to the elimination of charge carriers from the implanted region. Annealing of the waveguide leads to very large reductions in the 1.15-μ guided-wave absorption.

Optical guiding has been observed previously[1] in proton-implanted fused silica. Our own interest in fabricating active integrated optics components in semiconductors led us to explore the effect of proton bombardment in GaAs. We found that polished n-type GaAs crystals implanted with 300-keV protons form effective waveguides for light of 1.15-μ wavelength.

Proton bombardment in GaAs is known to produce compensation of both n- and p-type materials.[2] This compensated layer has a thickness of ~1 μ for each 100-keV proton energy.[3] The implanted region, which has a much smaller free-carrier concentration than the substrate, possesses a smaller plasma contribution to the refractive index. Thus its optical dielectric constant exceeds that of the substrate by

$$\Delta\epsilon = \frac{(N_s - N_c)e^2}{m^*\omega^2}, \qquad (1)$$

where N_s and N_c are the carrier densities in the substrate and in the compensated region, respectively. m^* and e are the effective mass and charge of the carriers and ω is the radian optical frequency. If the implanted layer is to support confined optical mode propagation, the condition

$$\frac{\Delta\epsilon}{\epsilon_0} > \left(\frac{\lambda_0}{4t}\right)^2 \qquad (2)$$

has to be satisfied, where t is the thickness of the implanted layer and λ_0 is the wavelength in vacuum. Combining this with (1) leads to a condition for guiding,

$$N_s - N_c > \frac{\pi^2 c_0^2 m^* \epsilon_0}{4e^2 t^2}, \qquad (3)$$

where c_0 is the velocity of light in vacuum. For effective compensation, $N_s \gg N_c$ and (3) becomes a condition for the minimum substrate carrier concentration necessary for guiding. We note that condition (3) is independent of the optical wavelength. This circumstance is due to the dependence $\Delta\epsilon \propto \omega^{-2}$ of the plasma effect.

In our experiment 300-keV protons were implanted with doses ≈ $10^{15}/\text{cm}^2$ into polished (100) or (111) faces of n-type GaAs. The thickness of the compensated layer was 3 μ, measured both from capacitance data and with a scanning electron microscope. The optical waveguiding profile was determined with the setup in Fig. 1. The method of coupling light into and out of the cleaved faces of the waveguide was similar to that used in Ref. 4. A vibrating mirror galvanometer was used to scan the image past the (fixed) detector slit thereby making it possible to obtain an instantaneous and continuous display of the output intensity profile on an oscilloscope. Typical light profiles are shown in Fig. 2.

Using $t = 3$ μ in condition (3) gives $N_s = 6\times 10^{17}$ cm^{-3} as the minimum substrate concentration for confined optical propagation. We observed strong guiding in samples with $N_s = 2\times 10^{18}$ cm^{-3}, weak guiding in samples with $N_s = 6\times 10^{17}$ cm^{-3}, and no guiding with $N_s = 4\times 10^{17}$ cm^{-3}. These results are consistent with the plasma model for the dielectric constant difference.

The propagating mode attenuation was determined from the dependence of the output-input ratio of the mode power on the length of the guide. This procedure also yields the input coupling efficiency. With light focusing into the front cleaved surface of the waveguide, as much

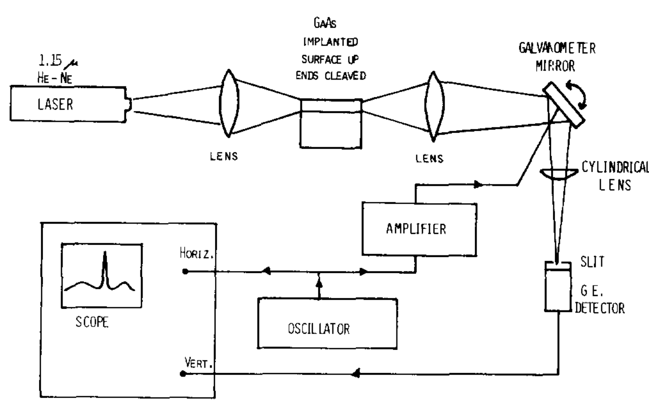

FIG. 1. Experimental apparatus.

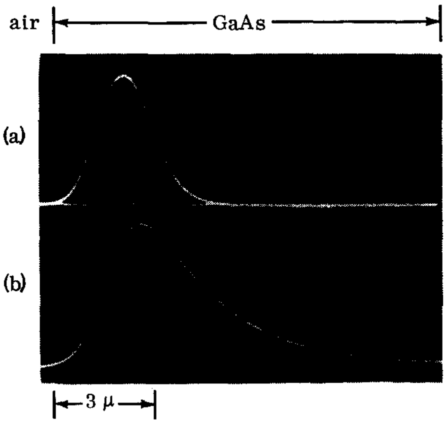

FIG. 2. Mode profiles: (a) Substrate: $6 \times 10^{18}/cm^3$; dose: $2 \times 10^{15}/cm^2$; anneal temperature: 500 °C. (b) Substrate: $2 \times 10^{18}/cm^3$; dose: $3 \times 10^{14}/cm^2$; anneal temperature: 500 °C.

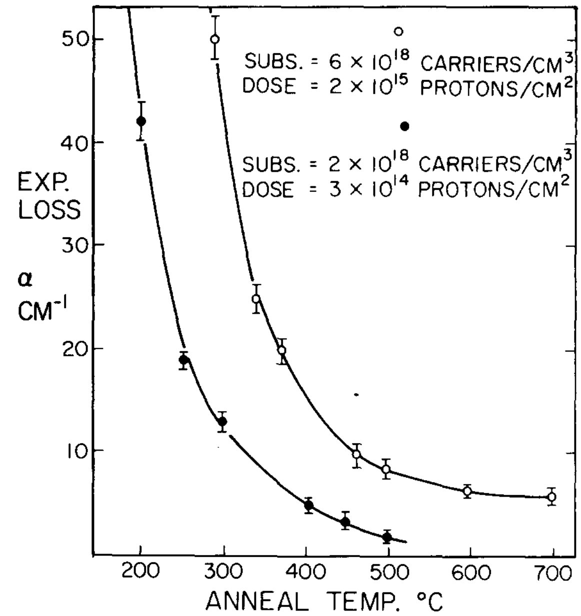

FIG. 3. Measurements of exponential power loss constant as a function of anneal temperature.

as 40% of the laser power was coupled into the guiding modes.

The proton bombardment causes a very large attenuation of the guided modes. This is possibly due to absorption involving the deep traps which are believed to be responsible for the compensation. Two have been identified at 0.4 and 0.8 eV above the valence band edge.[5] These losses can be substantially reduced by proper annealing (in flowing gas, typically for 30 min). Figure 3 shows the dependence of the mode power loss constant α on the annealing temperature. Reducing the proton dose to the minimum required for compensation should lead to a reduction of α below the value of 2 cm^{-1}, which is the lowest value to date.

Annealing above 500 °C was performed with a SiO_2 cap on the sample to prevent dissociation of GaAs. The cap was removed in HF prior to the guiding experiments. Excellent Schottky barriers were made on implanted layers which had been annealed to 700 °C, with back-bias voltages as large as 20 V and very low leakage current. Before annealing, the resistive layer allowed considerable current flow although the breakdown voltage was ~150 V. The annealed implanted waveguides should function as useful electro-optic modulators for guided light.[6]

The optical waveguiding properties of implanted layers should complement the rapidly growing body of electrical and backscattering measurements in implanted regions. If the compensated region has many fewer carriers than the substrate ($N_c \ll N_s$), the exact shape of the compensation profile does not affect the refractive-index profile. However, when the dose is decreased, or the anneal temperature is raised until $N_c \approx N_s$, measurements of waveguide properties can provide useful information.

The already demonstrated ability to obtain type conversion with ion implantation[7] and our demonstration of reasonably low-loss waveguiding in proton-implanted GaAs suggest that implantation may be a useful technique for fabricating more complex integrated optical circuits incorporating light emitting diodes (or lasers), waveguides, and detectors. Another set of interesting possibilities is suggested by the demonstration of converting GaAs into $Ga_xAl_{1-x}As$ by Al^+ implantation.[8]

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