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MeV ION BEAM INDUCED INDEX OF REFRACTION CHANGES IN LAYERED GaAs/AlGaAs WAVEGUIDES

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ABSTRACT

Previously, we showed that localized optical modifications could be produced without subsequent post thermal annealing in selectively masked planar GaAs/$Al_{.4}Ga_{.6}As$ waveguide structures using 10 MeV oxygen ions. In our present investigation, irradiation experiments were performed on masked GaAs/$Al_{.4}Ga_{.6}As$ waveguide samples at 298 K using 10 MeV oxygen and 8 MeV carbon ions. The two ion incident energies were chosen to yield the maximum electronic stopping power near the interface separating the top cladding layer and the guiding layer. This localized modification process emphasizes the crucial role that the electronic energy transfer plays on the degree to which the refractive index of the guiding layer is altered. Propagation loss measurements on the fabricated channel waveguides were performed by end fire coupling a laser diode source at a wavelength of 1.3 µm. Observation of the extracted propagation loss values reveal that further optimization of the ion beam parameters are required before practical applications can be achieved. The relative efficiency of the various ions to induce optically altered regions which serve as lateral confinement barriers of laser light shows that this fabrication process is sensitive to the ion beam current.

INTRODUCTION

Ion beam processing offers the advantage of being a highly controllable modification technique, in addition to being a cost effective alternative to some techniques which require time consuming processing steps. The technical approach centers around the ability of energetic ions to influence the bulk optical properties of planar waveguide materials [1]. The most conventional method by which to alter the optical properties of infrared semiconductor waveguides focuses on implanting chemically suitable ion species directly into the quantum layered structures. Most optical modifications techniques of this choice rely upon the potential of low energy (keV) ions to transfer energy to the target material through a high number of nuclear collisions [2-4]. These nuclear collisions, which are dominant during the end of the ion's projected range, can lead to a cascade of lattice site displacements. If the cascade distributions sufficiently overlap one another a number of bulk material properties can be modified. In a quantum layered semiconductor waveguide a high probability of target atom displacement sites are desirable near the interface separating two dissimilar layers. After displacement the lattice atoms can migrate and optimally relax back into site defects created during the collision interaction process. In order to achieve a high defect density a large ion fluence level is needed, in some cases as high as 1×10^{16} ions/cm^2 [5]. Unfortunately, in many of these cases recoil collisions can lead to damage of the original lattice. Further device processing development is restricted by the need for a high temperature post bombardment annealing step. Furthermore, chemical effects that the incident ions have on the electronical properties have to be taken into account because of the ions' shallow penetration depth. This type of compositional disordering technique is widely used to create optical and electrical modifications in quantum layered semiconductor waveguide structures.

We at the Howard J. Foster Center for Irradiation of Materials have attempted to develop a much more valuable technique by which to modify the optical properties of planar waveguide structures in the GaAs/AlGaAs system. Progress has been accomplished from the combined efforts of our research collaborators, and our determination to achieve optimization of the channel waveguide fabrication process using high energy ion beams was evident by our most recent publication detailing our preliminary degree of success [6]. Previously, we showed that by selectively masking planar GaAs/$Al_{.4}Ga_{.6}As$ waveguides structures with gold stripes and then subjecting them to an irradiation process using 10 MeV oxygen ions at fluences of 3×10^{13} and 3×10^{14} ions/cm^2, localized optical modifications could be produced without subsequent post thermal annealing. Our current investigation includes carbon bombarded waveguide samples with beam parameters similar to those in the oxygen case.

In this report it is our intent to utilize these results as a means to better understand the dynamic mechanism responsible for inducing the optical alterations as they relate to the selected ion beam parameters. A relative comparison between the propagation losses extracted after irradiation experiments using the two different ion species gives insight as to which bombarding species and beam parameters are more effective at inducing noticeable optical changes.

EXPERIMENTAL

Prior to performing high energy irradiation experiments on the planar GaAs/$Al_{.4}Ga_{.6}As$ waveguide structures a series of gold stripes were electroplated (5-8 μm in mask width) on the surface of the samples to serve as a protective mask. The entire masking procedure used to prevent ion penetration in selective regions of the waveguide structures is described in the previous investigation [6]. Gold was selected as the masking element because it has a large stopping power which results from its large atomic mass. Utilizing the TRIM [7] code the required thickness of the gold stripes were determined from the predicted projection range values after inserting the selected ion incident energies. The sample surfaces were examined after ion bombardment using a Nikon Optiphot-2 Microscope to determine if the gold stripes were preserved.

The irradiation experiments were conducted at room temperature using 10 MeV oxygen (O^{5+}) and 8 MeV carbon (C^{4+}) ions at fluences ranging from 3×10^{13} to 1×10^{15} ions/cm^2. The ion beam current densities varied from 0.42 to 1.1 μA/cm^2. The irradiation experiments were performed at Oak Ridge National Laboratory, using a 1.7 MV General Ionex Tandem ion accelerator. Finally, optical propagation loss measurements were performed on each sample using an end fire coupling technique.

RESULTS & DISCUSSION

The waveguide and mask profiles are illustrated in Figure 1. This illustration depicts the ion bombardment procedure used to fabricate the channel regions within the planar $GaAs/Al_{.4}Ga_{.6}As$ waveguide structures. Recognizing that we could adjust the incident energy of the ions thereby causing the maximum electronic energy transfer to occur near a pre-determined interface was the basis of our technical approach. We exploited this fact by tailoring the incident energies of the oxygen and carbon ions so that the maximum electronic energy loss occurred near the interface separating the top cladding layer (i-AlGaAs) and the GaAs guiding layer. The incident energies of the oxygen and carbon ions were selected after reviewing the stopping power calculations obtained from the TRIM code. We hoped to have the changes in the refractive index of the guiding layer (Core) induced from the electronic energy transferred by the ions as they penetrated through the waveguide structure. This was our sole attempt to isolate the mechanism by which this modification process occurred using high ion beams.

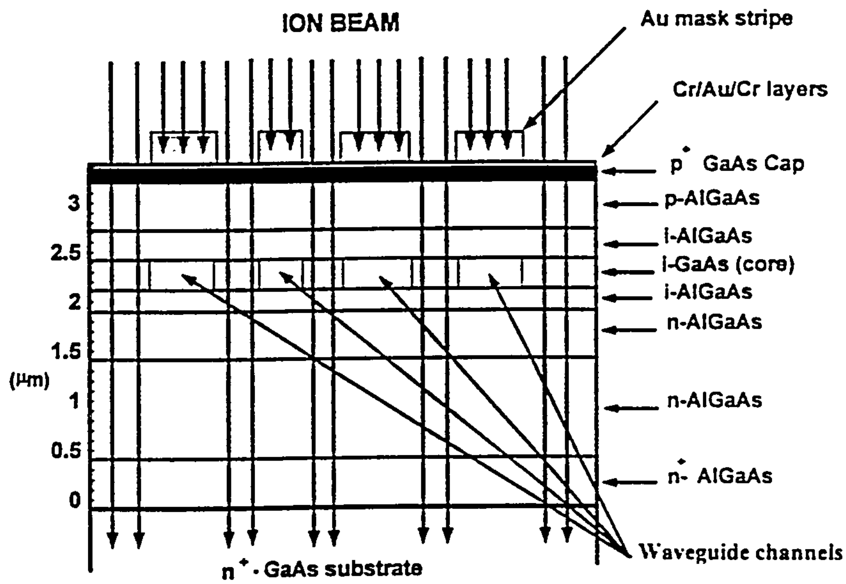

Figure 1. Schematic of the waveguide channels fabricated by high energy ion bombardment.

Evidence acquired during optical measurements indicates that the regions directly adjacent to the channel regions where ion penetration occurred were in fact behaving as lateral optical confinement barriers. This trend was shown to exist in all the waveguide samples irradiated using the oxygen and carbon ion parameters shown in Table 1. The result drawn from this observation is that the penetration of the ions had effectively altered the refractive index of the bombarded layers. The successful transmission of light at 1.3 μm through the guiding (i-GaAs) layer revealed that our initial objective had been achieved.

Table 1. Experimental Ion Beam Parameters and Corrected Propagation Loss Values.

Sample Number	Ion Specie	Beam Fluence (ions/cm^2)	Beam Current Density (μA/cm^2)	Sample Length (mm)	TE Mode (dB/mm)	TM Mode (dB/mm)
1	C	$1x10^{15}$	0.42	1	8.1	12.6
2	C	$1x10^{14}$	1.1	1.2	5.8	10.3
3	O	$1x10^{15}$	0.77	1.2	10.7	15.2
4	O	$3x10^{13}$	0.99	0.8	11.2	9.8
5	O	$3x10^{14}$	0.99	1.2	-------	6.5

It is interesting to note that optical transmission of the laser light through the GaAs substrate layer displayed the relative depth to which the ions had penetrated the waveguide samples. The calculated depths of the ions were in good agreement with the projected range predicted by the TRIM code. These increased absorption regions which extended about 2 μm past the top of the GaAs substrate coincide with the locations where the ions were allowed to penetrate around the gold stripes. These results point out numerous advantages to using high energy MeV ions as opposed to low energy keV ions. First the majority of damage which results from nuclear interactions is mainly confined within the GaAs substrate layer. Secondly, this fabrication technique could serve to drastically reduce undesired doping effects because the ions possess longer projected ranges. Also, these ions can be used to create high resistivity regions for device isolation purposes. Finally, the gold stripes which were shown using a Nikon Optiphot-2 Microscope to have been excellently preserved after ion beam exposure can function as high speed electrodes during future experiments.

Although we have demonstrated that this fabrication process does produce optically altered regions within the planar waveguide structures it was necessary to perform optical propagation loss measurements to test their suitability as actual channel waveguides. To facilitate these optical measurements we used a laser diode source operating at a wavelength of 1.3 μm. This collimated light source was coupled into the channel waveguides by directly focusing the beam onto a cleaved face of the waveguide sample. The basic experimental setup used to determine the optical mode profiles and the loss values is described below. The laser source was coupled to the channel waveguide sample by focusing the beam onto a cleaved face of the waveguide sample using a microscope objective lens. A polarizing beam splitter was used to quickly change between TE and TM modes during analysis. The same reference channel underwent evaluation on each waveguide sample. A second microscope lens was used to image the output onto an IR camera for visual observation or onto a rotating plane mirror for quantitative measurements. This rotating mirror scanned the mode image across an IR detector. The signal from the detector was amplified and monitored on an oscilloscope. The captured image could be scanned to produce a real time display yielding both width and depth mode profiles. The alignment of the waveguide samples and the focusing lens was accomplished by using three micropositioner mounts capable of x-y-z linear motion.

The propagation loss values were determined by coupling laser light to the channel waveguides and measuring the optical output. The propagation loss is calculated according to the relationship given by

$$\alpha = \frac{\log(P_i/P_o) - CouplingLoss}{L} \qquad (1)$$

where P_i and P_o are the inserted and emitted optical powers from each waveguide of length L. Using equation (1) corrected propagation loss values were calculated after measuring the insertion loss and then subtracting the estimated coupling loss due to mode mismatch and Fresnel Reflection. Both the TE and TM modes for each waveguide used in this study are shown in Table 1.

The variation of the sample TE loss values can be directly linked to the variation of the ion beam parameters. Unfortunately, no TE data was recorded on sample 5 which displayed the best optical characteristics. It is unclear what caused variation of the TM loss values. These relatively high losses may have resulted in part from weak waveguiding. The TE loss values can be associated with the relative strength of the ions to produce lateral modification of the refractive index in the guiding layer. The results obtained for samples 2 and 4 appear to be approaching those supplied from sample 5. We originally hoped that the beam fluence would have more of an impact on the extracted loss values. Instead, the selected beam current density provides insight as to which direction we must proceed. Comparatively, the oxygen ions appear to function as a better choice than the carbon ions under similar beam conditions. The samples which display the best propagation loss values were irradiated with a beam current density of at least 0.99 $\mu A/cm^2$. This suggests that a thermal effect may be taking place. We speculated that the energy transferred by the ions could be sufficient enough to cause a noticeable temperature rise. The variation of the TM loss values, which we really didn't expect to see because of the protective mask, may result from an atomic diffusion process. Until constructive and destructive analytical techniques are performed, the exact mechanism by which the ions induce the optical alterations remains unclear. It is apparent that further optimization of the beam parameters is necessary before practical applications can be achieved.

CONCLUSIONS

We have been able to selectively create localized optical alterations in planar $GaAs/Al_{.4}Ga_{.6}As$ waveguide structures using both oxygen and carbon ions with energies of 10 MeV and 8 MeV respectively. The extracted optical loss measurements indicate that several ion beam parameters have to be optimized before we can improve the fabrication process. In the current density range investigated, the optimum current density appears to be about 1.0 $\mu m/cm^2$. Using current densities greater than 1.0 $\mu m/cm^2$ should represent a significant improvement to this fabraction technique. We hope that after employment of a few well known analytical techniques better knowledge of the mechanism responsible for optically modifying the $GaAs/Al_{.4}Ga_{.6}As$ waveguide samples will be revealed.

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