Propagation Loss Analysis of Ion Implantation Induced Quantum Well Intermixed GaAs/AlGaAs Waveguides

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Propagation losses for semiconductor waveguides formed using a GaAs/AlGaAs superlattice material system have been analyzed. Single-mode 3 μm wide ridge waveguides, with an etch depth of 1 μm, have been fabricated using the as-grown and ion implantation induced quantum well intermixed material, which has been exposed to various doses of As$^{2+}$ ions. The Fabry-Perot technique has been used to study the effect of quantum well intermixing on propagation losses, for which the blue-shift achieved using various doses is used to determine the attenuation. It has been observed in the measured data that the dominant loss mechanism is impurity scattering which is introduced by ion implantation.

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I. INTRODUCTION

Quantum well intermixing (QWI) has proven to be a very effective low loss integration technique for the development of optoelectronic integrated circuits [1]. In this technique the energy band-gap of the material is widened in selected areas such that the light absorption is suppressed. This enables the development of active and passive elements which are monolithically integrated on a single semiconductor chip [2]. Various processes have been developed in order to achieve the required level of spatial resolution for the intermixing. This includes diffusion related processes such as: impurity induced intermixing [1], impurity free intermixing [3, 4], and the sputtered SiO$_2$ intermixing process [5, 6]. These diffusion related processes have been able to achieve a large shift in the absorption peak and have been successfully employed in the realization of various monolithically integrated devices. However, their large spatial resolution has limited their application in modern micro- and nano-fabrication [1, 7], whereas ion implantation induced intermixing has proven to achieve a superb spatial resolution in the realization of buried micron scale features [7].

The main objective of any intermixing process is to achieve lower losses in the passive sections of an integrated device. These losses include absorption and attenuation. Although the absorption can be suppressed by increasing the amount of intermixing, it increases the attenuation in the case of impurity induced intermixing and compromises the spatial resolution in the case of impurity free intermixing. Since impurity free intermixing processes
rely on the diffusion of point defects created on the surface of the material under high temperatures, therefore increasing the temperature also increases the lateral diffusion of intermixing, whereas the impurity induced intermixing processes achieve a large shift in the absorption peak by increasing the concentration of impurities in the material, which results in scattering and thus increases the attenuation. Therefore, in this paper we present the propagation loss analysis of ion implantation induced quantum well intermixed waveguides created in a GaAs/AlGaAs material system.

II. ION IMPLANTATION INDUCED INTERMIXING

In ion implantation induced intermixing, heavy ions are bombarded on the surface of the material, e.g., $\text{As}^{2+}$ in the case of the GaAs/AlGaAs material system. Due to the high energy of these ions, lattice dislocations are created. These dislocations cause further dislocations of atoms such that a disordering cluster is formed in the material. Once the implantation has been performed, the material is annealed up to a very high temperature in order to restore its lattice structure. During this annealing, the inter-diffusion at group III sites in III-V material systems causes the heterojunctions to smooth out. This increases the band-gap energy of the quantum wells, as shown in Fig. 1, and blue-shifts the absorption peak.

![Schematic representation of quantum well intermixing. The inter-diffusion of group III atoms in III-V material systems increases the band-gap energy.](image)

Ion implantation has an advantage of superior spatial resolution over other intermixing techniques when achieving deep QWI [7]. However, due to the introduction of heavy ions as an impurity, the propagation losses increase. Thus it is challenging to achieve the desired level of intermixing while keeping the propagation losses to a minimum possible
value. Hence in this paper we present an extensive study of the propagation losses caused by the ion implantation of a varying dose.

III. MATERIAL STRUCTURE AND DEVICE DESIGN

The material structure used in our study is a GaAs/AlGaAs superlattice core heterostructure, which has been reported on previously in [7]. The superlattice core of 600 nm thickness is composed of 14:14 monolayer GaAs/Al_{0.85}Ga_{0.15}As, which is bounded by core cladding layers of 300 nm thick Al_{0.56}Ga_{0.44}As on either side. The outer cladding layers of 800 nm thick Al_{0.60}Ga_{0.40}As are present on either side of the structure. A base layer of 1000 nm thick Al_{0.85}Ga_{0.15}As is used for the isolation of the guided modes. The complete structure is grown using molecular beam epitaxy on a GaAs substrate. The room temperature photoluminescence of this material was measured to be 775 nm.

GaAs/Al_{0.85}Ga_{0.15}As superlattices have been an attractive choice for nonlinear optical frequency conversion applications. They have been used to demonstrate various second order nonlinear optical frequency conversion processes [8, 9] by employing QWI to achieve quasi-phase matching and spatial modulation in $\chi^{(2)}$.

In order to study the propagation losses caused by ion implantation induced QWI, single-mode waveguides have been designed. These waveguides are 3 $\mu$m wide and have an etch depth of $\sim 1 \mu$m. The effective refractive index $n_{\text{eff}}$ for the TE and TM fundamental modes has been calculated using a commercial mode solver in which a 1500 nm excitation wavelength has been used, whereas the refractive index for each epitaxial layer has been obtained using the Gehrsitz model [10]. In the case of the refractive index of the superlattice core, the periodic heterostructure has been considered as a single Al$_x$Ga$_{1-x}$As layer whose Al mole fraction has been obtained using Equation (1), given in [11]:

$$E_T^g(x) = 1.425 + 1.155x + 0.37x^2.$$  \hspace{1cm} (1)

Figure 2 shows the variation in $n_{\text{eff}}$ of the waveguide when the Al mole fraction is increased. This increase in the mole fraction is caused by increasing the dose of ion implantation. In our earlier work we have reported that the blue-shift increases by increasing the implantation dose of As$^{2+}$ ions in GaAs/AlGaAs superlattice material [7]. This increase in blue-shift, and the corresponding mole fraction of Al in the resulting intermixed material, has been given in Fig. 3(a), and (b), respectively. It should be noted that the blue-shift increases when the post-implantation annealing temperature is increased, however, in this case we have kept the annealing temperature constant at 775 $^\circ$C for 60 s.

IV. PROPAGATION LOSS ANALYSIS

The propagation loss incorporates the attenuation of light which is generally measured using the Fabry-Perot technique for waveguides [12]. An optical waveguide whose edges are parallel to each other and are cleaved perpendicular to the length of the waveguide
acts as a Fabry-Perot resonator. If the light from a coherent source whose wavelength is far away from the absorption peak is launched into the waveguide the cavity modes are formed. The transmitted power $P_T$ and the launched power $P_e$ in this case are related using Equation (2) [12], given that the waveguide facets are of high quality and they cause minimum scattering.

$$\frac{P_T}{P_e} = \eta \frac{(1 - R_1)(1 - R_2)e^{-\alpha L}}{1 - 2\sqrt{R_1 R_2} e^{-\alpha L}\cos(2\beta L) + R_1 R_2 e^{-2\alpha L}},$$

where $R_1$ and $R_2$ are the Fresnel reflectivity of the waveguide facets (Equation (3)), $\eta$ is the coupling coefficient for the fundamental mode, $\alpha$ is the attenuation coefficient, $L$ is the waveguide length, and $\beta = 2\pi n_{\text{eff}}/\lambda$ is the propagation constant of the fundamental mode.

$$R = \left(\frac{n_0 - n_{\text{eff}}}{n_0 + n_{\text{eff}}}\right)^2.$$ 

The reflectivity calculated for the TE and TM polarized fundamental modes is given in Fig. 4 for our waveguide. Increasing the Al mole fraction in the equivalent $\text{Al}_x\text{Ga}_{1-x}\text{As}$ core layer decreases the reflectivity. The TM mode has the lower reflectivity due to its lower $n_{\text{eff}}$. 
FIG. 3: (a) The low temperature (77 K) blue-shift measured in the GaAs/AlGaAs superlattice material system. The implantation has been performed using As$^{2+}$ ions of varying dose (10$^{13}$ ions/cm$^2$). (b) The calculated Al mole fraction of the equivalent Al$_x$Ga$_{1-x}$As layer used to replace the superlattice core. The solid lines are a smoothed fit to the data.

The transmitted power $P_T$ will vary periodically in this optical waveguide such that the resonant cavity modes at $\Phi = 2\beta L = 4\pi L n_{\text{eff}}/\lambda$ will have the maximum transmittance. Now if the waveguide parameters, such as $L$, $n_{\text{eff}}$, or the free-space wavelength $\lambda$ of the launched light is varied, then the attenuation $\alpha L$ can be determined independently of the coupling parameter using Equation (4) [12].

$$\alpha L = \ln \left( R \frac{1 + \sqrt{P_{\min}/P_{\max}}}{1 - \sqrt{P_{\min}/P_{\max}}} \right),$$

where $P_{\min}$ and $P_{\max}$ are the minimum and maximum transmitted powers when one of the parameters: $L$, $n_{\text{eff}}$, or $\lambda$ is varied. For varying the waveguide parameters $L$ and $n_{\text{eff}}$, the optical waveguide can be heated, and for varying $\lambda$, a very narrow line-width tunable source is required.

The calculated attenuation $\alpha L$ for various values of reflectivity is given in Fig. 5. It is observed that the ratio of the transmitted powers $P_{\min}/P_{\max}$ is lower for the high reflecting waveguide facets, which means that the Fabry-Perot cavity formed for these waveguides have a higher finesse. In our case, where QWI results in an increased Al mole fraction of the equivalent Al$_x$Ga$_{1-x}$As core layer, the variation in the reflectivity for the TE and TM modes is small, Fig. 4. For example, in case of the TE mode the reflectivity for the
waveguide formed using as-grown material is calculated to be 0.27, and the reflectivity is calculated to be 0.26 for the waveguide formed using the material which is intermixed with the maximum dose of $5 \times 10^{13}$ ions/cm$^2$. This shows that the band-gap tuning which results due to QWI causes a very small change in the reflectivity, and subsequently a low variation in $\alpha$, if only the cavity reflections are considered. The major contribution however in the propagation loss is caused by the scattering of light inside the waveguide cavity, which is explained next.

In order to measure the propagation loss caused by ion implantation induced inter-mixing, 3 $\mu$m wide ridge waveguides were fabricated using the material which was implanted with various doses of As$^{2+}$ ions and annealed at 775 °C for 60 s. The etch depth of these waveguides was 1 $\mu$m, and they were cleaved to the length of 2 mm. The Fabry-Perot technique has been employed to measure the propagation losses in these waveguides. The propagation losses, measured using TE polarized light, are given in Fig. 6. It has been observed that the propagation losses are higher in the waveguides which have been fabricated using the material exposed to higher doses of implantation. The average propagation loss for the waveguides fabricated using the as-grown material is 0.5 cm$^{-1}$.

As we know, the higher doses of ion implantation result in an increased blue-shift, Fig. 3(a). However, the variation in $n_{\text{eff}}$ caused by this blue-shift, and consequently the variation in $\alpha$, will be low. Therefore, from the propagation loss measurements we conclude that the dominant mechanism which causes attenuation in intermixed waveguides is scattering, and increasing the implantation dose will increase this attenuation.

Figure 7 shows the propagation losses measured using TM polarized light for the same
waveguides. Again, the impurity scattering which results due to ion implantation induced intermixing is the dominant loss mechanism in waveguides. It has been observed that the losses in case of TM polarization are higher as compared to their corresponding values of TE polarization for various implantation doses. This is caused by the waveguide scattering due to side-wall imperfections — the TM polarized mode interacts more with the waveguide side-walls as compared to the TE mode. In order to verify this, a 3 \( \mu \)m wide and 1 \( \mu \)m deep etched waveguide has been simulated using a commercial software - BeamPROP\textsuperscript{TM}. The calculated 1/e height of the optical field for the TE and TM modes is shown in Fig. 8(a) and (b), respectively. It is observed that the TM mode has a larger height as compared to the TE mode, this means that the TM mode will interact more with the top layers of the waveguide, and subsequently with the waveguide side-walls. In addition to this, the optical power in the top cladding layer is calculated to be larger for the TM mode as compared to the TE mode, which reiterates the TM mode’s larger interaction with the waveguide side-walls.

V. CONCLUSIONS

The propagation losses in ion implantation induced quantum well intermixed waveguides formed using GaAs/AlGaAs material system have been studied and measured. The material implanted with various doses of As\textsuperscript{2+} ions is characterized by the quantum well
intermixing achieved. The resulting blue-shifts are used to determine the Al mole fraction in the equivalent Al$_x$Ga$_{1-x}$As core layer. This mole fraction has been used to determine the variation in $n_{\text{eff}}$, and to study the attenuation $\alpha$ by employing the Fabry-Perot technique. It is concluded from the measured values of the propagation losses in waveguides, fabricated using as-grown and intermixed material, that the dominant loss mechanism in intermixed waveguides is impurity scattering.

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References

FIG. 7: The propagation losses measured using TM polarized light for the ridge waveguides fabricated using as-grown and intermixed material. The dotted lines are a linear fit to the measured data.

FIG. 8: The calculated 1/e height of the optical field in the waveguide for (a) the TE mode, and (b) the TM mode. The simulated waveguide is 3 μm wide and 1 μm deep etched — these dimensions are similar to that of the waveguides fabricated for loss measurements.