Experimental and Theoretical Analysis of Polarization Insensitive Integrated-Waveguides Fabricated using Ion Implantation-Induced Disordering

H.S. Djie*, S.L. Ng, O. Gunawan, P. Dowd
[1]Photonics Research Group, School of Electrical and Electronic Engineering,
Nanyang Technological University, Singapore 639798
*hery@pmail.ntu.edu.sg

V. Aimez, J. Beauvais and J. Beerens
Centre de recherche sur les propriétés électroniques des matériaux avancés,
Département de Génie Électrique et Génie Informatique, Université de Sherbrooke, Sherbrooke,
Québec, Canada J1K 2R1

A theoretical model of the quantum well waveguide interdiffusion process has been developed to understand the polarization insensitive behavior through the strain build up at 1.55 µm-wavelength operation using the low energy ion implantation-induced disordering.

Keywords: waveguide, polarization, quantum well intermixing, ion implantation.

Introduction

Quantum well (QW) waveguide on lattice-matched InGaAs/InP laser structures have exhibited an inherent drawback: a strong polarization dependence on the incident light (transverse electric (TE) and transverse magnetic (TM)). This is due to the separation between the electron-light-hole (E-LH) and the electron-heavy-hole (E-HH) transition energies in an unstrained QW, resulting in a large discrepancy between TE and TM gain at any operating wavelength. As a result, this leads to polarization sensitive performance, which is disadvantageous, as the light polarization would not be preserved after travelling through a given distance. In recent years, Quantum well intermixing (QWI) based on the ion implantation–induced disordering (IID) technique has been used as a successful photonic integration technique [1]. The interdiffusion of QW and barrier material has been shown to modify the strain at the QW, and hence the HH and LH band splitting [1,2,3]. This indicates the possibility of using the IID technique to produce polarization-insensitive QW waveguide structures, which could interconnect the multiple photonic devices for photonic integration purposes, such as laser, modulator, amplifier etc in a single chip.

In this work, we report on the polarization insensitive performance of intermixed QW waveguides using a lattice-matched InGaAs/InGaAsP QW structure, and operating at a wavelength of about 1.55 µm. The fabrication method is based on the combination of using gray-mask lithography and a low-energy As and P ion-implantation process at 360 keV [4]. To understand the polarization-dependent behavior of the fabricated QW waveguide, a theoretical model based on interdiffusion of group III and V atoms through the strain build-up and the refractive index change has been developed.

Theoretical Model

In the $In_xGa_{1-x}As_yP_{1-y}$ QWs structure, In and Ga represent the group-III sublattices while As and P represent the two group-V sublattices. The extent of the interdiffusion can be characterized by the diffusion length parameter, $L_d = \sqrt{Dt}$, where D is the diffusion coefficient and t is the diffusion time normally associated with annealing time. The diffusion length ratio of group-V to group-III can be defined as interdiffusion ratio $k = L_{dV}/L_{dIII}$, which L_{dIII} and L_{dV} denote the diffusion length of group-III and -V respectively. Given additional knowledge of k, and the strain contribution is known, the more accurate band edge profile can be calculated. Assuming Fick's law and concentration independent diffusion coefficients, the concentration profile of the QW can be derived in term of superposition of error functions. The group-III concentration in the active layer profile can be expressed as a superposition of the active layers:

$$x(z, L_{dIII}) = x_B + \sum_{n=1}^{N} \Delta x_n \left[1 - \frac{1}{2} erf\left(\frac{z + \frac{1}{2} L_{Zn}}{2L_{dIII}} \right) + \frac{1}{2} erf\left(\frac{z - \frac{1}{2} L_{Zn}}{2L_{dIII}} \right) \right] \tag{1}$$

where $x(z,L_{dIII})$ is the group-III concentration and x_B is the concentration at the outer barrier, Δx_n is the difference in the concentration of the subsequent layers, z is the direction along growth, L_{Zn} is the nth layer's width and n is the QW layer number. The group-V concentration can be formulated using the analogy of Eq (1). After interdiffusion process, the QW confinement profiles (V_r) calculation of C, HH, and LH is expressed as:

$$V_r(z) = Q_r \lfloor E_g(z) - E_{go} - S_{r\,biaxial}(x, y) \rfloor \pm S_{r\,uniaxial}(x, y) + zq_e E_{Field} \tag{2}$$

Q_r is the band offset splitting ratio, E_g is the energy bandgap, $S_{r\ biaxial}$ is the change in the bulk band gap due to the biaxial component of strain and the $S_{r\ uniaxial}$ is the potential corresponding to the HH and LH band edge splitting induced by the uniaxial component of strain. The positive sign represents the confined HH profile, the negative sign represents the confined LH profile, and for the confined electron profile, $S_{C\ uniaxial}$, is equal to zero. The presence of an applied external field is denoted as E_{Field}. All the parameters above are assumed to obey Vegard's law, so that they depend directly on the compositional profile across the QW. The sub-band states in the QW were calculated [5] by solving the Ben Daniel Duke's equation, through transformation of the differential equation into an eigen-value matrix equation, called the Finite Difference Eigen Value (FDEV) method.

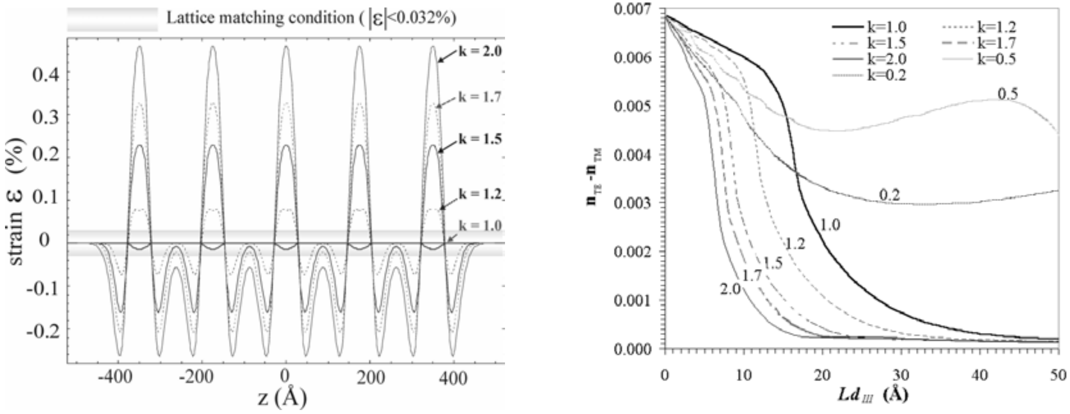
Based on the interdiffused composition profile of the QW layers, the refractive index profiles in the transparency region, where the transition occurs in the centre of Brillouin zone, can be calculated using Interband Transition Model [6]. Since the operating wavelength is apart from the bandgap of devices, the effective index of QWs structure in the transparency region is then approximated by the root mean square (RMS) extended model [7].

Experimental Works

The QW waveguide laser structure was designed for wavelength operation at around 1.55 µm, grown by metal-organic vapour phase epitaxy (MOVPE) on a (100)-orientated n+-type S-doped InP-substrates [5]. It consists of an undoped lattice-matched InGaAs/InGaAsP/InP QW material with five 5.5 nm wide $In_{0.53}Ga_{0.47}As$ wells, separated by six 12 nm InGaAsP barriers and utilised GRIN optical confinement layers. The as-grown sample gave a photoluminescence (PL) peak at 1.55 µm at room temperature. The waveguide sample was first coated with 450 nm and 900 nm thick SiO_2 layer, to minimize the damage due to 360 keV As and P ions. Next, a photolithography step was carried out to transfer the gray patterns on to the samples. A single step reactive ion etching (RIE) was then performed to transfer the graded photo-resist pattern into SiO_2 such that 10 different thickness of SiO_2, ranging from 0 nm to 450 nm (As) and 900 nm (P) were achieved across the wafer to perform different degrees of intermixing. The sample was then implanted at 200 ºC with As dose of $1x10^{14}cm^{-2}$, accelerated at 360keV with the ion angle tilted by 7º. The created point defects are subsequently diffused through the QW by a rapid thermal processor (RTP) at 590 ºC for 2 min. As-grown samples (without implantation) were included into each run to act as control samples. As a result, 10 degrees of intermixing can be obtained laterally across the wafer by introducing different concentration of impurities into materials. Each individual waveguide has dimensions of 400x500 µm^2 with a 50 µm wide active window, 500 µm cavity length and 20 µm wide isolation trenches. To conduct the photocurrent absorption measurement for observation of the polarization behaviour between TE and TM modes, the electrodes are defined on the top and bottom of waveguides after thinning down the sample to 180 µm.

Results and Discussion

It has been reported that the group-V interdiffusion ratio is faster than group-III (k>1) for InGaAs/InP QW amplifiers with high-energy P ion implantation [8] and electro-absorption (EA) modulators with low-energy As ion implantation [3].



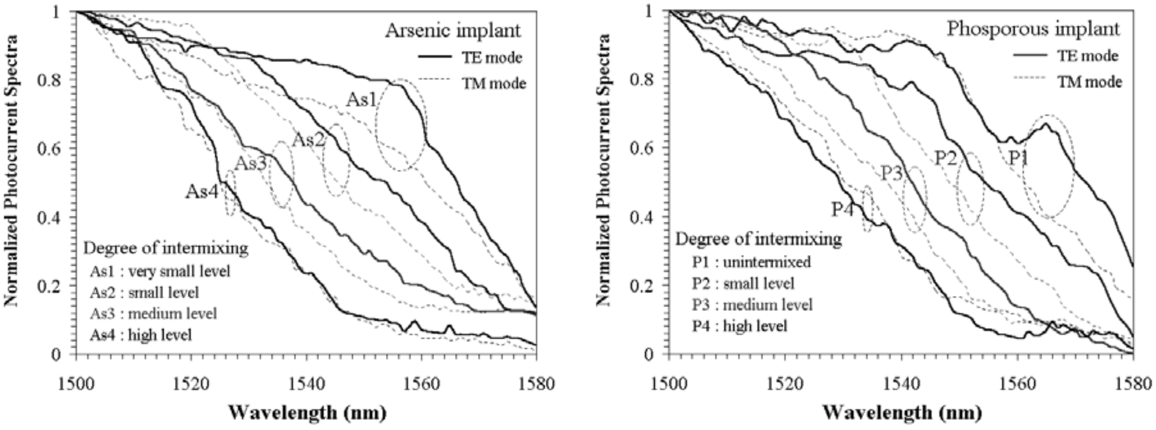
(a) (b)

Figure 1 (a) The in-plane strain build-up of interdiffused QW waveguide with different interdiffusion ratios at L_{DIII}=10 Å (b) Refractive index change between TE and TM at 1.55 μm operation at different interdiffusion ratios and diffusion lengths

The in-plane strain profile in Figure 1 (a) shows interesting feature of the strain buildup with different diffusion length ratio, varied from $1.0<k<2.0$. Ld_{III} is taken 10Å for correspond the large strain build-up difference within the wells. The QWs structure is no longer lattice-matched (ε>0.032%) after interdiffusion at $k>1.0$ and shows the presence of both compressive and tensile strains across the structure due atoms contents change, dominated by group V atoms. Both the compressive and tensile strain exhibit the tendency to increase as the interdiffusion ratio *k* increase and the tensile strain value at the center of well is higher than the compressive strain in the barrier close to interface for the same interdiffusion ratio. This presence of internal strain build-up not only shifts the band edge energies but also modifies the refractive index for different polarization mode.

Figure 1 (b) shows the refractive index difference of TE and TM modes at $0.2<k<2.0$ on the different interdiffusion levels. At Ld_{III}=0, the uninterdiffused refractive index difference between TE and TM modes is 0.0069 or 0.2 %. The refractive index changes of TE and TM modes are strongly dependent on the interdiffusion ratio *k* and diffusion length. At $k<1.0$, the interdiffusion ratio assumes that group-III is faster than group-V and it shows the polarization degeneracy at higher interdiffusion degree but it then saturates at refractive index change greater than 0.003. While at $k>1.0$, the refractive index difference between TE and TM tends to zero at the sufficiently high interdiffusion level. This model implies polarization independent behavior of the waveguide can be achieved for a certain diffusion length of group III atoms. As *k* increases, it requires a shorter group III diffusion length to produce polarization insensitive behavior, due to higher strain build-up across the structure. Thus choosing the appropriate implantation level, and hence interdiffusion level, can lead to a merging of the TE and TM refractive index profiles, resulting in polarization-independent performance of the interdiffused QW waveguide.

Fabricated QW waveguides using ion implantation- induced disordering have been characterized at room temperature (RT) through photocurrent measurements, using the end-fire-coupling technique to couple the light from a tunable laser diode, operating between 1500 nm and 1580 nm. The polarization-resolved photocurrent absorption spectra for selected waveguides, which have undergone different degree of intermixing, are shown in Figure 2. The energy blue shifts, resulted from levels are 11 nm, 29 nm, 46 nm, 65 nm for As ions and 0 nm, 18 nm, 53 nm, 71 nm for P ions. It can be observed that there is a quenching of the excitonic peak at higher diffusion lengths due to the more disordered QW structure, making the excitonic bond weaker. The photocurrent absorption curves have been blue-shifted as a function of SiO_2 thickness, and hence the degree of the quantum well intermixing. As the SiO_2 thickness decreases, the diffusion coefficients increases thus allowing higher point-defects created by ion implantation. For the waveguides formed using both As and P ion implantation, it can be seen that the measured bandgap energy with TE (solid lines) measurement is smaller than that of TM (dashed lines) measurement for each device. The separation of the TE and TM photocurrent absorption curves for a given waveguide decreases significantly as the degree of intermixing increases. Thus, the photocurrent curves at the highest levels of intermixing are virtually identical between TE and TM then lead to polarization independent behaviour of fabricated waveguides using low-energy ion-implantation process at 360 keV.



(a) (b)

Figure 2. Polarization-resolved TE-TM photocurrent absorption curves of intermixed QW waveguides with different degrees of intermixing for (a) As ions and (b) P ions

Conclusions

An interdiffusion model that includes strain build-up effect at different interdiffusion ratios of group-III and -V atoms has been developed to understand the polarization dependent behaviour of of InGaAs/InGaAsP/InP QW waveguide structures that have undergone different degrees of intermixing. Polarization insensitive waveguide operation has been demonstrated by proper choice of implantation mask thickness, linked to the amount of blueshift obtained and interdiffusion level. The blue shift amount of 65 nm and 71 nm for As and P ion respectively is sufficient to fabricate a transparent waveguide in polarization insensitive fashion.

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