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Multiple-wavelength selective channel electroabsorption intensity modulators have been fabricated on a single InGaAs/InGaAsP chip using a one-step quantum well intermixing process. This technique was demonstrated for tailoring the intensity modulator operating wavelength by incorporating low-energy (360 keV) phosphorus ions implantation induced disordering process with gray-mask lithography technology. A modulation depth of −15 dB has been measured from these devices with a voltage swing of −4.5 V. © *2002 American Institute of Physics.*
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The beginning of the information age has induced an explosive growth for high speed, large bandwidth lightwave technology in carrying the vast amounts of data reliably, efficiently, and cost effectively in optical fiber communication systems.[1–3] For example, the availability of photonic integration devices such as multiple wavelength laser sources/optical modulators and low-loss passive waveguides are the main building block to meet the necessities of complex dense wavelength division multiplexing systems. In this letter, we report the fabrication and characterization of ten wavelength channel electroabsorption intensity modulators using a one-step quantum well (QW) intermixing[4] process. This technique was achieved using a combination of one-step gray mask lithography and reactive ion etching followed by low energy phosphorus ion implantation induced disordering process. The results reported are to demonstrate that this technique could be a brilliant contributor as a method because of its relative simplicity and low-cost for the production of wavelength division multiplexing components, as well as other photonic integrated circuits.[5]

Samples used in this study had an InGaAs/InGaAsP multiple quantum well structure grown by metalorganic vapor phase epitaxy. The samples were of the form of a stepped graded index heterostructure. The quantum well region was undoped and consisted of five 5.5-nm-thick $In_{0.53}Ga_{0.47}As$ wells, separated by six 12 nm InGaAsP barriers. The thicknesses of the stepped graded index layers (from the QWs barrier outward) were 50 and 80 nm. Both the upper (1.4 μm) and the lower (1 μm) cladding layers were made of InP and doped to a concentration of 5×10^{17} cm^{-3} (zinc) and 2.5×10^{18} cm^{-3} (sulphur), respectively. The contact layers consisted of 50 nm InGaAsP (Zn-doped to 2×10^{18} cm^{-3}) and 100 nm InGaAs (Zn-doped to 2×10^{19} cm^{-3}).

The sample was first coated with 900 nm thick of silicon dioxide (SiO_2) using plasma enhanced chemical deposition. As verified from the transport of ions into matters[6] simulation, this thickness was required to totally block phosphorus ions from reaching the semiconductor during implantation. Next, the standard ultraviolet photolithography step was carried out to create gray patterns of photoresist onto the samples by means of gray mask. The gray mask made use of different transparencies of masks to control the degree of the exposure of photoresist at selected regions. In this case, the gray mask was considered to have ten gray-tone levels for ten different energy band gaps, i.e., with ultraviolet light transmittance levels, ranging from 0% (channel 1) to 100% (channel 10). The relationship between optical density (OD) of mask and the ultraviolet light transmitivity level (T) during lithography process can be expressed by $\mathrm{OD}=-\log(T)$. Thus, it gave rise to ten different thicknesses or graded pattern of photoresist after lithographical development.

Reactive ion etching was then performed to transfer the graded photoresist pattern onto SiO_2 such that at selected regions, ten different thicknesses of SiO_2, ranging from 0 to 900 nm [denoted as channel 10 (0 nm) and channel 1 (900 nm)] were achieved across the sample. Channel 10 implies that the concentration of the phosphorus ions introduced is the highest whereas channel 1 is the least. The resulting graded patterns of SiO_2 were used as an implant mask to control the concentration of impurities introduced into the material at selected regions through ion implantation.

The sample was then implanted at 200 °C with a phosphorus ion dose of 1×10^{14} cm^{-2}, accelerated at 360 keV (using doubly charged ions and an acceleration voltage of 180 kV) with the ion angle tilted by 7° to limit the ion

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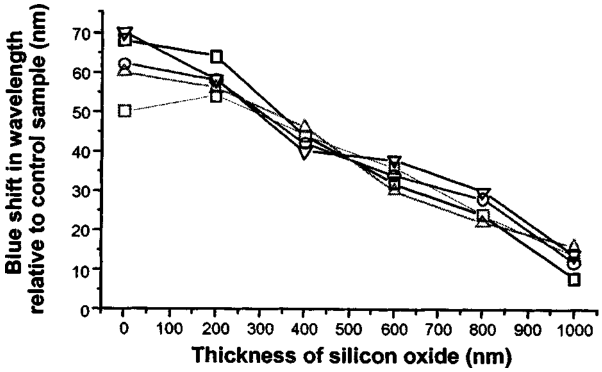

FIG. 1. Wavelength blueshift relative to control sample as a function of silicon dixoide thickness for the introduction of different impurity concentrations into the material. The experiments were repeated five times.

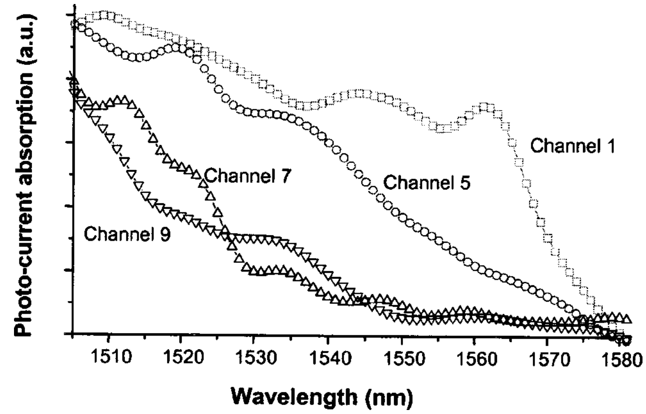

FIG. 2. Photocurrent absorption for modulators, which have undergone intermixing that resulted in blue wavelength shifting of 0 nm (channel 1), 26 nm (channel 5), 48 nm (channel 7), and channel 9.

channeling effect.[7] The intermixing step was then carried out using a rapid thermal processor at 590 °C for 120 s. As-grown samples (without implant) were included into each run to act as the control sample. The samples were faced down on a piece of GaAs substrate to provide arsenic overpressure to the surface and hence to minimize the outdiffusion of arsenic during annealing. Hence, a one-step impurity induced disordering process to achieve selective area intermixing could be obtained laterally across the sample by introducing different concentrations of impurities into the material.

This phenomenon was verified by photoluminescence measurement at low-temperature (77 K) by using 1064 nm line of Nd: yttritium–aluminum–garnet laser. Figure 1 shows the blueshift in wavelength, relative to the control sample, as a function of thickness of SiO_2. From Fig. 1, it is obvious from the test samples that different degrees of intermixing can be obtained for each thickness of SiO_2 implant mask.

After the intermixing process, ten-channels monolithic multiple wavelength electroabsorption modulators were fabricated. The samples were first coated with a 200 nm SiO_2 dielectric cap. The 50 μm stripe channel width were defined using a photolithography process, and both dry and wet etching was used to open the channel. To minimize any damages, the dry etching was first carried out, followed by the wet-etching using the diluted HF to remove the remaining SiO_2. After this, front contact metallization (*p*-type: Ti/Au) was done using an electron beam evaporator. Samples were then thinned to a thickness of around 180 μm. Another metallization for back contact (*n*-type: Au/Ge/Au/Ni/Au) was evaporated, and finally the samples were annealed at 360 °C for 60 s to complete the entire fabrication. The processed samples were then scribed into individual modulators for measurements. Each individual modulator has a dimension of $400 \times 500\ \mu m^2$ and 50 μm channel width, 500 μm cavity length, and 20 μm width of isolation trench. All modulators were functioned as multiple mode devices at room temperature with an internal loss of about 30 cm^{-1} (for the most intermixed devices).

The photocurrent measurements at 0 V bias were performed by end-fire coupling a laser into the quantum-well active region. A tunable laser, with the wavelength ranging from 1500 to 1580 nm was used in this experiment. Figure 2 shows the photocurrent absorption for the electroabsorption modulators with wavelength, which have undergone selective area intermixing that resulted in blue wavelength shifting of 0 nm (channel 1), 26 nm (channel 5), and 48 nm (channel 7), respectively. Note that the band edge of channel 9 could not be determined due to the limitation of the tunable laser source. It is observed from this figure that the photocurrent absorption curves have been blueshifted as a function of SiO_2 thickness. This implies that the different degrees of the quantum well disordering could be achieved and tailored by the one-step process, in accordance with the SiO_2 thickness. Furthermore, the absorption spectrum from Fig. 2 also shows that the heavy-hole and light-hole are relatively well resolved. This suggests that the optical quality of the material is still high after intermixing up to channel 7.

Figure 3 shows the band edge of the quantum well corresponding to each channel, i.e., each thickness of SiO_2. The band edge was obtained for channel 1–8, due to the limit of the tunable range of the laser. The band edges of the quantum wells are 1561, 1550, 1545, 1541, 1535, 1523, 1513, and 1506 nm for first 8 channels, respectively. From this figure, it indicates that the thickness of the SiO_2 is not linearly related to the band edge of the quantum well or the degree of quantum well intermixing. However, the results suggest that a linear relationship could be achieved by controlling the thickness or deposition process of the SiO_2.

The intermixed electroabsorption modulator with chan-

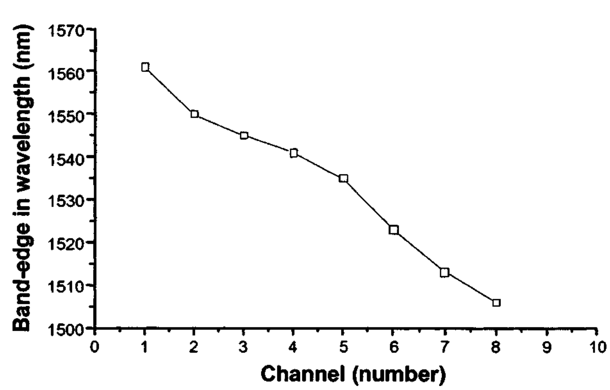

FIG. 3. Absorption band edge of the quantum well corresponds to each channel, i.e., each thickness of SiO_2. The band edge was obtained for channels 1–7. The band edge for both channels 9 and 10 cannot be deduced due to the tunability of laser source.

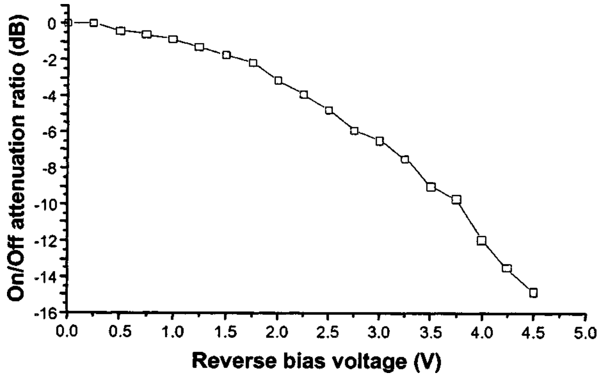

FIG. 4. Plot of on/off attenuation against applied reverse voltage for modulator which have undergone intermixing that resulted in blue wavelength shifting of 26 nm (channel 5). The wavelength of the input polarized laser was set at 1555 nm.

nel 5 (i.e., band edge of 1535 nm) was then biased with reverse voltage across the *p*-type and the *n*-type contacts to assess the modulation depth versus voltage swing. The wavelength of the laser was set at 1555 nm, which was just below the absorption edge. Figure 4 shows the plot of the on/off attenuation against the applied reverse voltage. The figure shows that a modulation depth of −15 dB could be achieved with a voltage swing of −4.5 V.

We have demonstrated the fabrication of ten-channels monolithic multiple wavelength electroabsorption modulators using the one-step phosphorus ion implantation induced disordering process. There is no clear penalty imposed by the quantum well intermixing process on the material quality even for large blueshifts. An average modulation rate of 3.3 dB/V was obtained for these devices.

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