Compact Mach-Zehnder space switch combining bandfilling and the Quantum Confined Stark Effect

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Abstract: Integrated optical crossconnects and add-drop multiplexers require low-loss polarization independent MZI space switches. We have developed a quantum well material in which the electrorefraction due to the Quantum Confined Stark Effect and bandfilling are added. The operating wavelength in an undoped InGaAs/InAsP quantum well was first determined by limiting the excess waveguide loss to 0.2 dB/cm and the electroabsorption loss to 0.1 dB/mm. Without doping, a polarization independent Δn *of* $7.8.10^{-4}$ *was obtained at 100 kV/cm. Bandfilling increases* Δn *to* 2.10^{-3} *at 100 kV/cm, resulting in a phase shifter length of 0.46 mm in push pull configuration.*

Introduction

Integrated optical crossconnects [1] and add-drop multiplexers require low-loss polarization independent space switches. Recently, the crosstalk performance of dilated Mach-Zehnder Interferometric (MZI) switches have been reduced down to –40 dB [2]. Now that the size of a phased array demultiplexer can be reduced down to 0.8x0.75 mm, the length of the phase shifter in a MZI space switch of typically 2 mm is becoming the main bottleneck for further reducing the size of integrated crossconnects. In Ref. 2, a bulk quaternary layer, which has been doped up to $6.10^{17}/cm^2$, has been employed in which bandfilling and the Pockels effect add together. We have recently reported a polarization independent MZI space swith based on the Quantum Confined Stark Effect (QCSE) using coupled quantum wells in which the phase shifter length could be reduced down to 0.64 mm using a push-pull configuration [3,4], at the expense of a 11V switching voltage. In this paper, we will investigate doped InGaAs/InAsP quantum well material in which bandfilling effects and electrorefraction due to the QCSE add up. We will show that the combination of electrorefraction and bandfilling effects in quantum wells is very useful for reducing the switching voltage while simultaneously maintaining low waveguide loss.

Bandfilling of a quantum well at zero applied field introduces a blockade of the absorption near the bandgap. Carrier depletion at an applied field removes this blockade, resulting in an effective red shift of the absorption spectrum. This effective red shift of the absorption spectrum adds up to the QCSE, which yields a red shift of the bandgap with increasing external field. When we want to limit the excess waveguide absorption loss due to interband and free carrier absorption to 0.5 dB/cm, the doping of quantum well material within the waveguide core should be limited to $2.10^{11}/cm^2$, assuming 50 quantum wells within the waveguide core. For this carrier density, the index of refraction variation due to bandfilling is comparable to the index of refraction variation due to the QCSE. For optimising the index of refraction variations in doped quantum wells, we should thus independently optimise both the QCSE and the bandfilling effects. For this purpose, we investigated “indirect in real space (IRS)” InGaAs/InP/InAsP quantum wells [5] which can be grown between InP barriers. In these quantum wells, the lowest electron level is confined in the InAsP layer with a conduction band offset of 70%, while the highest hole state is confined inside the InGaAs layer with a valence band offset of 60%. As a consequence, this quantum well in indirect in real space, resulting in linear Stark shift proportional to the product of the external applied field and the average electron-hole separation.

For calculating the electrorefraction, we first solved [3,4] for the quantum well energy levels and the envelope functions in InGaAs/InAsP coupled quantum wells in the presence of an electric field. The valence band dispersion relations were subsequently calculated by solving the 4x4 Luttinger-Kohn Hamiltonian to provide us with the correct polarization dependence, which is strongly determined by heavy hole–light hole interactions. We subsequently calculated the optical susceptibility χ using the density matrix formalism [6]

$$\chi(\omega) = \sum_n \sum_J \int_{E_g + E_{cn} + E_{vn}^J} dE\,\overline{C}(E)\,\rho_r^J M_J^2 [f_{cn}^J(E) - f_{vn}^J(E)] \left(\frac{i}{\pi}\right) \frac{\hbar/\tau_{in} - i(E_{ph} - E)}{(E_{ph} - E)^2 + \left(\hbar/\tau\right)^2}$$

with E_{ph} the photon energy, E the transition energy, τ_{in} the interband relaxation time, ρ_r^J is the joint density of states and M_J the momentum matrix element as detemined in the framework of the 4x4 Luttinger Kohn theory. f_{cn}^J and f_{vn}^J are the Fermi Dirac distributions for electrons and holes. The absorption and the refractive index change relative to the bulk refractive index n_r is

$$\Delta\alpha = -(k/n_r)\,\mathrm{Im}(\chi); \; \Delta n = (1/2n_r)\,\mathrm{Re}(\chi)$$

Our calculation of bandgap renormalization is based on the model of Ahn *et.al.* [7]. The band gap renormalization due to many body effect is proportional to $(n_{2D})^{1/3}$ at higher carrier concentration and $(n_{2D})^{1/2}$ at lower carrier densities. The free carrier contribution to the refractive index [8] is found to be negligible.

Since the magnitude of the Stark shift in IRS QW's is proportional to the average separation of the electron and hole wavefunctions, we first investigated the Stark shift and the electrorefraction in an undoped $In_{0.38}Ga_{0.62}As$(4 nm)/InP/$InAs_{0.65}P_{0.35}$(2.5 nm) quantum well as a function of the InP intermediate barrier.

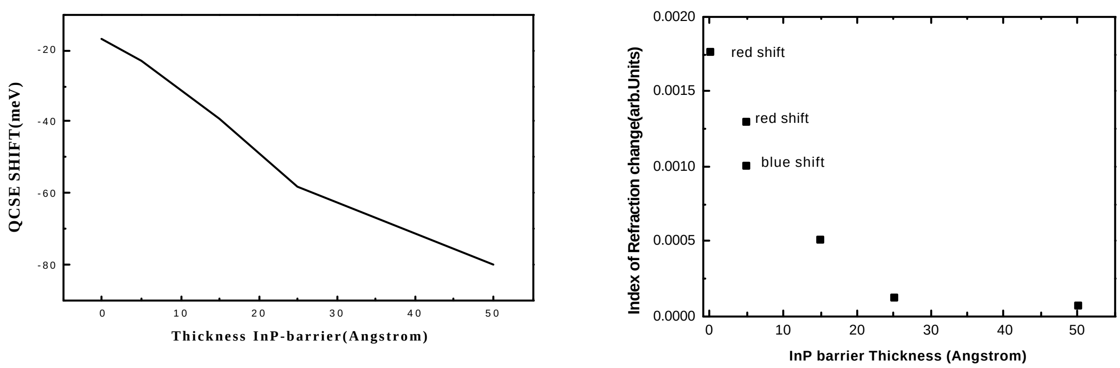

Figure 1: (a) QCSE red shift and (b) electrorefraction in a $In_{0.38}Ga_{0.62}As$(4 nm)/InP/ $InAs_{0.65}P_{0.35}$(3.7 nm) quantum well versus the InP intermediate barrier width at 100 kV/cm.

Fig. 1 shows that the QCSE red shift increases for increasing InP barrier thickness since the effective electron-hole separation also increases. The electrorefraction however decreases due to the strongly decreasing oscillator strength, as determined by the overlap of the electron and hole envelope wavefunctions. For the remainder of this paper, we will investigate a 2.5/2 nm $In_{0.38}Ga_{0.62}As/InAs_{0.65}P_{0.35}$ quantum well with a zero InP barrier, which yields the largest electrorefraction. The electrorefraction for this quantum well is shown in Figure 2. Since the hole levels are primarily confined inside the InGaAs layer, the polarization dependence of the electrorefraction is determined by the heavy to light hole splitting inside the InGaAs well. A polarization independent behavior can thus be realized by applying a tensile strain to the InGaAs, which can be compensated by a compressive strain in the InAsP. We find that an $In_{0.38}Ga_{0.62}As$ layer yields an almost polarization independent electrorefraction at 827 meV (1500 nm) for an applied bias of 100 kV/cm. The operating wavelength of this structure has been determined by allowing an absorption loss of 0.2 dB/cm in the unbiased waveguides and an electroabsorption loss 0.1 dB/mm in the phase section of the Mach-Zehnder, assuming a confinement factor of 0.25. These losses can be read from the Urbach tail of the quantum well bandgap, which extends to lower energy as shown in the inset in Fig. 2. It should be emphasized that the excess waveguide loss and the electroabsorption loss play an entirely different role in the performance of an MZI space switch. The excess waveguide loss, which comes on top of the usual processing induced scattering losses due to sidewall roughness, should be kept low to limit the excess loss in the input and output waveguides of the MZI. The electroabsorption loss will however introduce an imbalance within the MZI, which results into crosstalk. We recently showed [4] that 1 dB electroabsorption results in –25dB excess crosstalk, while 0.5 dB electroabsorption results in –31 dB excess crosstalk due to imbalance in the MZI.

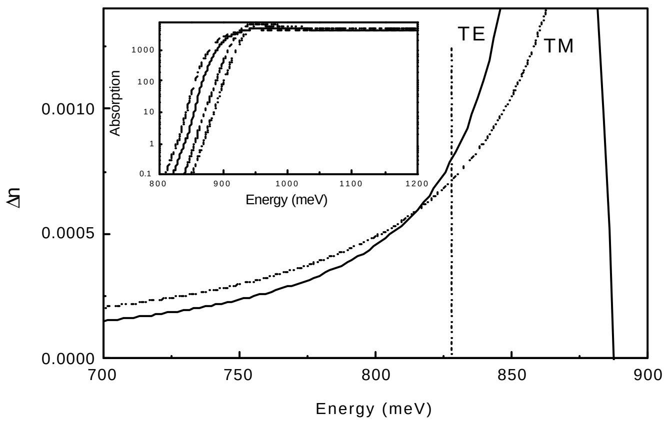

Figure 2: Electrorefraction as a function of energy (wavelength) for an undoped 2.5/2 nm InGaAs/InAsP QW. At 827 meV, the absorption loss is 0.2 dB/cm as deduced from the Urbach tail of the absorption spectrum. We find a TE electrorefraction of $7.8.10^{-4}$ and a TM electrorefraction of $7.1.10^{-4}$ at 827 meV. The inset shows the Urbach tails. From left to right, the curves are 100 kV/cm TE, zero field TE, 100 kV/cm TM, zero field TM

In order to estimate the length of the phase shifting section of the MZI, we assume 10 nm InP barriers in between the QW's, resulting in a confinement factor of 0.31. We also take into account the Pockels effect with an estimated r_{41} of $-1.5.10^{-12}$ m/V, resulting in an index of refraction change of $2.5.10^{-5}$/Volt over the entire waveguide core. All effects together result in a phase shifter length of 1.7 mm.

In order to further reduce the length of the phase shifting section, we investigate $2.10^{11}/cm^2$ doped InGaAs/InAsP quantum wells which can be fully depleted at 100 kV/cm applied bias. This doping level results in an additional free carrier loss of 0.4 dB, yielding a total electroabsorption loss of 0.5 dB, which results in an excess crosstalk [4] of –31 dB due to the electroabsorption-induced imbalance within the MZI.

We finally calculated the electrorefraction in doped $In_{0.38}Ga_{0.62}As$(2.5 nm)/$InAs_{0.65}P_{0.35}$(2 nm) quantum wells. We observe that the TE electrorefraction increases from $0.76.10^{-3}$ for an undoped QW to $2.02.10^{-3}$ and $3.19.10^{-3}$ for doping levels of $2.10^{11}/cm^2$ and $4.10^{11}/cm^2$ respectively. We thus observe a 2.6 times increase in the TE electrorefraction by doping the InGaAs/InAsP quantum well with a carrier concentration of $2.10^{11}/cm^2$. This again shows that both the QCSE and the bandfilling effect are essential to reach large total electrorefraction. A further increase of the doping level inside the quantum wells not only

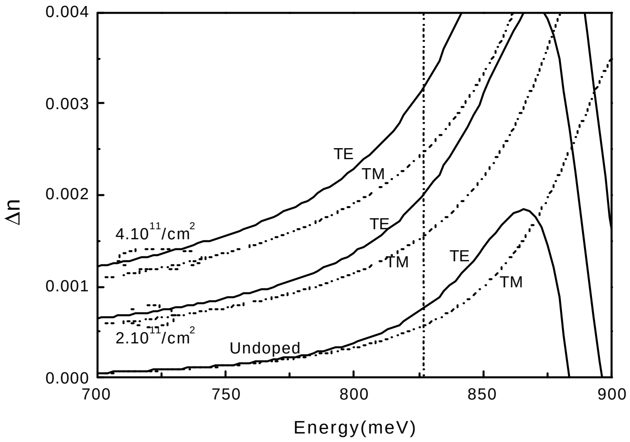

Figure 4: Electrorefraction for doped and undoped $In_{0.38}Ga_{0.62}As$(2.5nm)/$InAs_{0.65}P_{0.35}$(2 nm) quantum wells at 100 kV/cm. At the operating wavelength of 827 meV (1500 nm), the TE electrorefraction changes from $0.76.10^{-3}$ for an undoped QW to $2.02.10^{-3}$ and $3.19.10^{-3}$ for doping levels of $2.10^{11}/cm^2$ and $4.10^{11}/cm^2$ respectively.

detoriates the waveguide loss and electroabsorption-induced crosstalk, but also increases the electrorefraction in a sublinear way only, as can be seen from the curve at $4.10^{11}/cm^2$. We finally calculated the length of the phase shifting section for a $2.10^{11}/cm^2$ doped quantum well. Again taking also the Pockels effect into account, we find a phase shifter length of 0.92 mm for this quantum well. In the push-pull configuration [4], the length of the phase shifter can be further decreased to 0.46 mm.

Conclusions

In conclusion, have investigated the electrorefraction in doped InGaAs/InAsP quantum well within InP. The QCSE yields a nearly polarization independent electrorefraction $\Delta n=7.8.10^{-4}$ for TE polarization at 100 kV/cm, combined with a waveguide loss of 0.2 dB/cm and an electroabsorption of only 0.1 dB/mm due to interband absorption. Bandfilling effects further increase the electrorefraction up to 2.10^{-3}, resulting in a phase shifter length in an MZI of 0.85 mm for a π phase shift or 0.43 mm in push pull operation.

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