Orientation-dependent phase modulation in InGaAs/GaAs multiquantum well waveguides

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The electro-optic effect and phase modulation in $In_{0.2}Ga_{0.8}As$/GaAs multiple quantum wells have been experimentally studied for the first time. The experiments were done with 1.06 and 1.15 μm photoexcitation which are, respectively, 25 and 115 meV below the electron–heavy hole excitonic resonance. Strong quadratic electro-optic effect was observed near the excitonic edge in addition to the linear effect. These are characterized by $r_{63} = -1.85\times10^{-19}$ m/V and $(R_{33} - R_{13}) = 2.9\times10^{-19}$ m^2/V^2. In addition, we observe a dispersion in the value of r_{63}. The relative phase shifts are higher in the strained system at 1.06 μm than in lattice-matched GaAs/AlGaAs.

Since the theoretical prediction of a large electro-optic coefficient due to a strong electric field induced refractive index variation in multiquantum wells (MQW's),[1] there have been several experimental results[2,3] on the linear and quadratic electro-optic effects in these heterostructures. It has been shown that as the excitonic resonance is approached in the MQW, the built-in anisotropy or birefringence becomes very large and the electro-optic effect becomes strongly nonlinear. The experiments, until now, have been confined to lattice-matched GaAs/AlGaAs MQW where the built-in stress is small and principally results from the difference in the thermal coefficients of the constituent materials. InGaAs/GaAs strained-layer superlattices (SLS's) and MQW's are important materials for the design of lasers,[4] detectors,[5,6] and electroabsorption modulators[7,8] in the 1.1–1.3 μm range. In this letter we report on our studies of the phase modulation and electro-optic effects in InGaAs/GaAs MQW's grown by molecular beam epitaxy (MBE) on GaAs substrates.

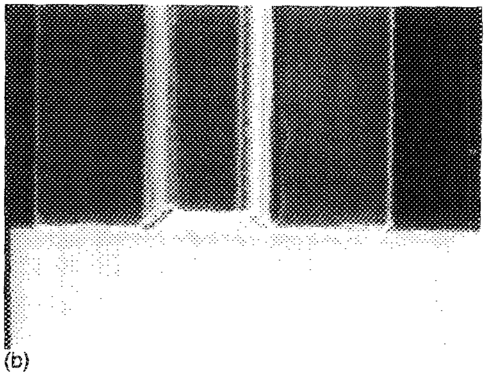
Experiments were performed with p^+-n^- (MQW)-n^+ structures shown schematically in Fig. 1(a). The carrier concentration in the unintentionally doped MQW region was found to be $n = 3\times10^{15}$ cm^{-3} as determined from capacitance-voltage measurements. It is important to note that the thickness of the intermediate composition $In_{0.1}Ga_{0.9}As$ buffer layer is ~0.9 μm and is therefore much thicker than the critical thickness for dislocation generation. Therefore, the strained MQW, whose average lattice constant is equal to that of the buffer layer, is free-standing.

Single-mode 2-μm-wide ridge waveguides with contacts on the substrate and top p^+ layers, shown in Fig. 1(b), were fabricated using photolithography and ion milling techniques. For modulation measurements 0.6–1.0 mm long waveguides were cleaved along the [110] and [1$\bar{1}$0] crystallographic directions. The diodes have leakage currents of 50 nA and reverse break-down voltages of ~30 V in the dark. Absorption data at room temperature with the incident photoexcitation polarized parallel to the layers exhibit the $e1$–hh1 excitonic transition at 1.194 eV. For polarization perpendicular to the layers a separate absorption measurement was performed on waveguiding structures. As expected the spectra in this case are dominated by a strong $e1$–lh1 transition.[9] The optical measurements were done with two optical sources: a Nd:YAG laser with $\lambda = 1.06$ μm and a He-Ne laser with $\lambda = 1.15$ μm having the excitations ~25 and ~115 meV, respectively, below the $e1$–hh1 exciton transition energy of the quantum wells. The laser light was end fired onto the cleaved edge of the waveguides through an objective lens. The near-field pattern at the output of the waveguide was focused onto a silicon detector through an analyzer and detected by lock-in techniques. For electroabsorption measurements, the output, with the analyzer adjusted for maximum, was recorded at different applied biases

0.3 μm	GaAs	Be-doped $2\times10^{18}cm^{-3}$
20 period MQW	20 Å GaAs/20 Å $In_{0.2}Ga_{0.8}As$	Be-doped $2\times10^{18}cm^{-3}$
75 period MQW	100 Å $In_{0.2}Ga_{0.8}As$/165 Å GaAs	Undoped
50 Å	GaAs	Undoped
20 period MQW	20 Å GaAs/20 Å $In_{0.2}Ga_{0.8}As$	Si-doped $2\times10^{18}cm^{-3}$
0.2 μm	$In_{0.1}Ga_{0.9}As$	Si-doped $2\times10^{18}cm^{-3}$
30 period MQW	20 Å GaAs/20 Å $In_{0.2}Ga_{0.8}As$	Si-doped $2\times10^{18}cm^{-3}$
0.5 μm	$In_{0.1}Ga_{0.9}As$	Si-doped $2\times10^{18}cm^{-3}$
0.3 μm	GaAs	Si-doped $2\times10^{18}cm^{-3}$

Si-doped GaAs Substrate

(a)



(b)

FIG. 1. (a) Schematic of phase modulation grown by molecular beam epitaxy and (b) SEM photomicrograph of waveguiding structure.

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for input polarizations both parallel (TE-like) and perpendicular (TM-like) to the layers. The analyzer adjusted for minimum and maximum signals for both TE-like and TM-like input excitations shows ~2–5% mode conversion. As expected from absorption measurements, electroabsorption sets in at smaller voltages with TE-like excitation than with TM-like excitation. For phase modulation measurements the waveguide was excited with a polarization oriented at 45° to the direction of the applied electric field. Both TE-like and TM-like modes were launched in the waveguide. Due to the built-in birefringence and the built-in potential of the *p-n* junction, the observed output polarization was elliptic in nature at zero applied bias. With the application of an external bias the eccentricity as well as the orientation of the ellipse was changed. Output signals for the maxima and the minima were recorded at their respective orientations and the phase difference was calculated from the data.

The measured electroabsorptions of 1.06 and 1.15 μm guided light, for polarizations parallel and perpendicular to the layers, are shown in Figs. 2(a) and 2(b). It is seen that at $\lambda = 1.06\,\mu$m there is negligible electroabsorption of the TM-like mode up to ~8 V. On the contrary, there is considerable absorption of the TE-like mode even at zero bias. At $\lambda = 1.15\,\mu$m there is no noticeable electroabsorption of the TM-like mode. The absorption profile of the TE-like mode first increases with bias and then decreases for $V \geqslant 4$ V. The decrease at higher biases is as expected. The initial apparent increase is thought to be due to better optical confinement in the guide. Theoretical calculations of the refractive index change with applied electric field in quantum wells by Yamamoto *et al.*[1] show a similar profile of $\Delta n/n$ with TE-like photoexcitation near the band gap.

Results of the measured phase change with the application of bias to the quantum wells are shown in Figs. 3(a) and 3(b). The corresponding junction electric field is in the range $(1–8)\times 10^4$ V/cm. The values of the phase shift quoted in the ordinate scale, ϕ_m, are really a component of the total phase difference $2n\pi \pm \phi_m$. As discussed earlier, since the phase was measured from the rotation of the ellipse with respect to that at zero bias, rather than a true compensation, the $2n\pi$ component could not be estimated. It is evident, however, that much larger phase shifts are obtained for the $[1\bar{1}0]$ direction at $\lambda = 1.06\,\mu$m than for the $[110]$ direction. For similar detuning from the excitonic peak a high loss coefficient of 30 cm^{-1} is also associated.[10] As expected, the measured phase changes are much smaller at $\lambda = 1.15\,\mu$m. It should be noted that this interferometric technique measures the TE-TM difference. The electro-optic coefficients

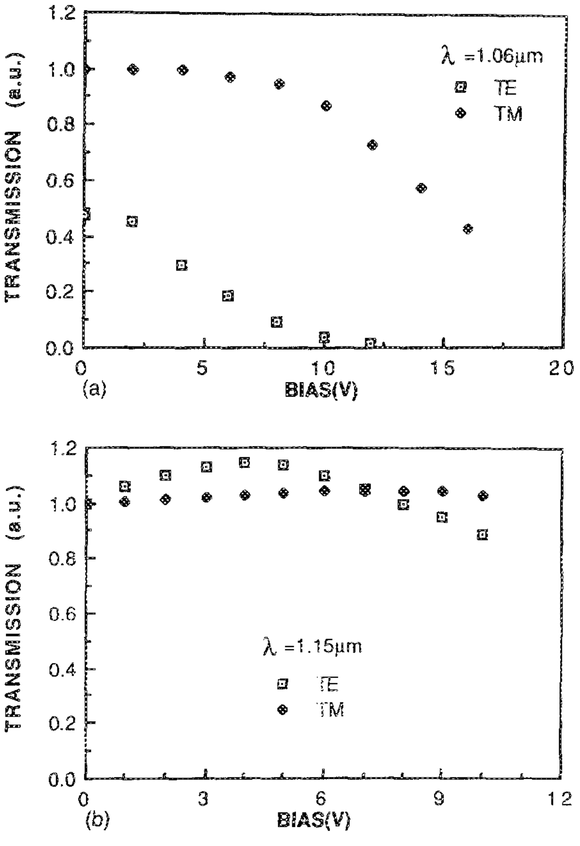

FIG. 2. Relative transmission of $In_{0.2}Ga_{0.8}As$/GaAs MQW as a function of applied bias at (a) $\lambda = 1.06\,\mu$m and (b) $\lambda = 1.15\,\mu$m.

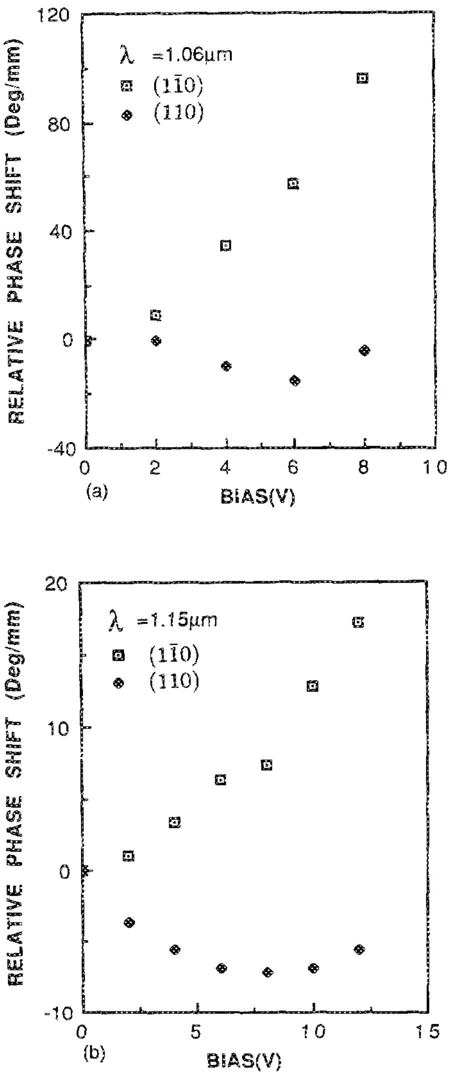

FIG. 3. Phase difference between TE-like and TM-like modes for two orthogonal light propagation directions at (a) $\lambda = 1.06\,\mu$m and (b) $\lambda = 1.15\,\mu$m.

r_{63} and $(R_{33} - R_{13})$ were obtained by comparing the measured phase changes (Fig. 3) with the calculated values according to[2]

$$\Delta\Phi_{\substack{[110]\\ [1\bar{1}0]}} = \frac{\pi n_{\|}{}^{3} L}{\lambda} \left[\pm \Gamma_1 r_{63} \overline{E}_j + \Gamma_2 (R_{33} - R_{13}) \overline{E}_j^{2} \right] + \Delta\Phi_0, \tag{1}$$

where $n_{\|}$ is the average refractive index in the multilayer for polarization parallel to the layer, E_j is the average junction electric field, Γ_1 and Γ_2 are the overlap factors for the first-order optical mode field with the junction electric field and the square of the junction electric field, respectively. The built-in birefringence in the MQW, $\Delta\Phi_0$, can be expressed as

$$\Delta\Phi_0 = (\beta_{\mathrm{TE}} - \beta_{\mathrm{TM}}) L = \Delta n L (2\pi/\lambda), \tag{2}$$

where

$$\Delta n = n_{\|} - n_{\perp}, \tag{3}$$

and $n_{\perp}$ is the refractive index for polarization perpendicular to the layers. L is the length of the waveguides. Values of Γ_1 and Γ_2 obtained in our samples are 0.98 and 1.29, respectively. Variations of Γ_1 and Γ_2 with wavelength are assumed to be small here.

The values of the linear and quadratic electro-optic coefficients at 1.06 and 1.15 μm, estimated from the fitting, are given in Table I. Recent data for GaAs/AlGaAs MQW are also included in this table for comparison. It is apparent that there is considerable variation in the values of the coefficients, even for similar GaAs/AlGaAs MQW structures. The value of r_{63} in the InGaAs/GaAs MQW is approximately a factor of 3 lower than r_{41} in pure GaAs, or that measured in GaAs/AlGaAs MQW by Glick *et al.*[2] Another important point to be noted in our samples is the fairly large dispersion in r_{63} between 1.06 and 1.15 μm. A large dispersion close to the band gap has been predicted theoretically by Adachi and Oe,[11] but was not observed in GaAs/AlGaAs MQW.[2] Finally, it is clear from our data that at $\lambda = 1.06\,\mu$m the change in phase shift with applied field is larger in the strained MQW than that observed in GaAs/AlGaAs MQW.[2] In the strained MQW, the refractive index is higher than that in the GaAs/AlGaAs system. Thus a higher relative phase change is expected. It is clear that there is a need to theoretically investigate the effects of strain on the electro-optic effect and the associated linear and quadratic coefficients. The strain-related built-in birefringence will probably be small since the strain is equally distributed between wells and barriers. However, the effect on the electro-optic coefficients is unknown.

TABLE I. Measured linear and quadratic electro-optic coefficients in InGaAs/GaAs strained MQW as compared with those in GaAs/AlGaAs systems.

λ (μm)	MQW system	ΔE^{a} (meV)	r_{63} (10^{-12} m/V)	$R_{33} - R_{13}$ (10^{-20} m^2/V)
0.8324	GaAs/AlGaAs	69	7.32	187[b]
0.888	GaAs/AlGaAs	30	1.7	19[c]
0.877	GaAs/AlGaAs	50	1.6	6[c]
1.06	InGaAs/GaAs	27	1.82	37.4[d]
1.15	InGaAs/GaAs	116	0.26	2.45[d]

[a] Energy below excitonic peak.
[b] Reference 3.
[c] Reference 2.
[d] This work.

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