A novel coupled quantum well structure and its excellent electro-optical properties

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A novel InGaAs/InAlAs coupled quantum well structure is proposed for large field-induced refractive index change with low absorption loss. In the case of low applied electric field of 15 kV/cm and low absorption loss ($\alpha \leq 100$ cm^{-1}), a large field-induced refractive index change (for transverse electric (TE) mode, $\Delta n = 0.012$; for transverse magnetic (TM) mode, $\Delta n = 0.0126$) is obtained in the structure at the operation wavelength of 1.55 μm. The value is larger by over one order of magnitude than that in a rectangular quantum well. The result is very attractive for semiconductor optical switching devices.

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Optical space switches often require polarization-independent large refractive index change at low applied electric field. Quantum-confined Stark effect (QCSE) in multiquantum-well (MQW) structures offers the unique capability of obtaining resonant enhancement of electrooptic effects as well as monolithic integration with active components. The large electrorefraction in MQW structures makes it possible to realize ultracompact optical switches that are smaller by almost an order of magnitude, thereby enabling a higher switching bandwidth by a similar magnitude due to reduced velocity mismatch requirements and microwave losses, as compared with devices that employ Franz-Keldysh effect in bulk layers. However, the large refractive index change is at or close to the absorption edge, where the absorption loss is very large (i.e., several thousand cm^{-1}); it not only leads to excess insertion loss but also makes it difficult to obtain good on/off ratio for optical switching devices[1,2].

In order to obtain a large refractive index change in the case of low absorption loss, some coupled quantum well structures have been studies for electroabsorption and electrorefraction in recent years[3−5]. In particular, five-step asymmetric coupled quantum well structure[5] utilized two combined exciton absorption peaks to obtain a large refractive index change when the operation wavelength is away from the absorption edge. However, in order to obtain two combined exciton absorption peaks, the applied electric field demanded by the five-step asymmetric coupled quantum well structures is very large ($F > 30$ kV/cm)[5]. It is well known that at increasingly applied electric field, the contrast between the on and off states for optical switches decreases due to broadening of the excitonic absorption peak. Furthermore, due to red shift of the absorption edge, the absorption loss increases.

In this letter, we propose a novel InGaAs/InAlAs coupled quantum well structure as shown in Fig. 1. The novel coupled quantum well is grown on an InP substrate, the thick $\mathrm{In_{0.52}Al_{0.48}As}$ barriers (10 nm) are lattice-matched to the substrate. To obtain polarization independence, the lattice constant of $\mathrm{In_{0.49}Ga_{0.51}As}$ quantum wells is mismatched to that of the InP substrate and has an internal strain of −1.7%.

In order to validate the novel structure, we firstly analyze its ground eigenvalues and eigenfunctions for zero applied electric field and their changes along with an applied electric field. If we adopt the effective-mass approximation presented by Bastard[6,7] and only study steady-state problems in one-dimension, Schrödinger equation can be expressed as

$$-\frac{\hbar^2}{2}\frac{\mathrm{d}}{\mathrm{d}x}\left(\frac{1}{\overset{*}{m}(x)}\frac{\mathrm{d}}{\mathrm{d}x}\right)\psi(x)+V(x)\psi(x)=E\psi(x), \quad (1)$$

where $\psi(x)$ is the eigenfunction, E is the eigenvalue, $\hbar$ is Planck's constant divided by 2π, $\overset{*}{m}(x)$ is the effective mass of electron or heavy (or light) hole and obtained by parameter interpolation principle[8], $V(x)$ is the potential energy of quantum well and written as

$$V(x) = V_0 \pm eFx, \quad (2)$$

where V_0 is the potential energy of quantum well in the case of applied electric field $F = 0$; plus sign is for electron and minus sign is for hole. In terms of parameter interpolation principle, calculations are performed for band gaps and band offsets in strained quantum well layers on InP substrate[9]. The field-induced variation of eigenfunctions of electrons and holes in the novel coupled quantum well is shown in Fig. 2.

From Fig. 2, we can find that when $F = 15$ kV/cm, the eigenfunction overlap integrals between e1 and hh2,

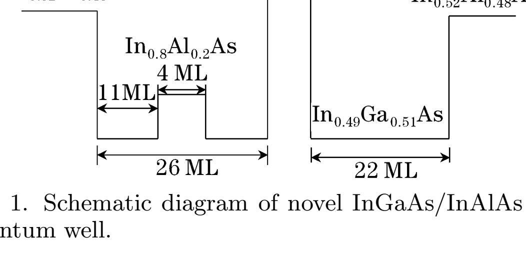

Fig. 1. Schematic diagram of novel InGaAs/InAlAs coupled quantum well.

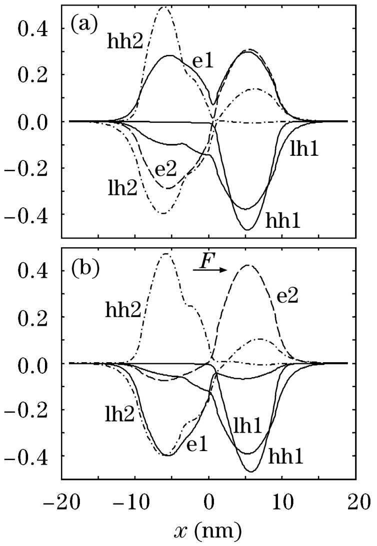

Fig. 2. Field-induced variation of eigenfunctions of electrons and holes in the novel coupled quantum well. (a) $F = 0$ kV/cm; (b) $F = 15$ kV/cm.

and between e2 and hh1 for transverse electric (TE) mode attain a maximal value, close to 1. The eigenfunction overlap integrals between e1 and lh2, and between e2 and lh1 for transverse magnetic (TM) mode attain a maximal value, too. This manifests that in order to obtain two combined exciton absorption peaks, the applied electric field demanded by the novel coupled quantum well structures is lower than that of five-step asymmetric coupled quantum well structures. The calculation method of absorption spectra is the same as that of Ref. [10]. The Lorentzian lineshape functions with a semi-empirical formula for half-width at half-maximum (HWHM)[11] are employed in the calculation and expressed as

$$\Gamma_{\mathrm{ex}}(L_{\mathrm{w}},F) = 20.7 - 0.24L_{\mathrm{w}} + 1.3\times10^{-3}L_{\mathrm{w}}^{2} + F(0.102 + 2.2\times10^{-9}L_{\mathrm{w}}^{2}), \tag{3}$$

where Γ_{ex} unit is meV, well width L_{w} unit is Å, and applied electric field F unit is V/μm. The relationship between change in absorption $\Delta\alpha$ and change in refractive index Δn is given by the Kramers-Kronig relation[12]

$$\Delta n = \frac{\lambda^2}{2\pi^2}P\int\frac{\Delta\alpha\,(\lambda')}{\lambda^2-\lambda'^2}\mathrm{d}\lambda', \tag{4}$$

where λ is the wavelength of incident light and P denotes the principle value of the integral. The absorption coefficient α and refractive index change Δn of the novel InGaAs/InAlAs coupled quantum well are plotted in Figs. 3 and 4 (TE mode is denoted by real lines, TM mode is denoted by dotted lines) respectively.

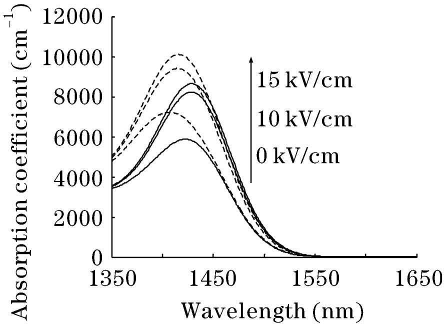

Fig. 3. Absorption coefficient versus applied electric field.

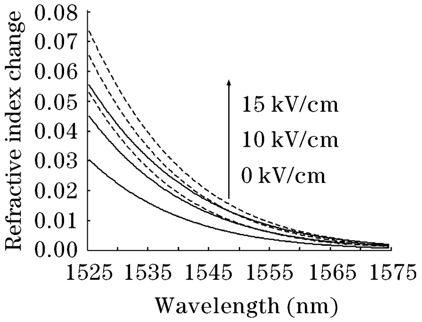

Fig. 4. Refractive index change versus applied electric field.

From Figs. 3 and 4, we can come to the following conclusions. Firstly, the absorption edges of TE mode is very close to that of TM mode in the novel InGaAs/InAlAs coupled quantum well. Secondly, a very large refractive index change for TE mode and TM mode is obtained in the novel coupled quantum well. Furthermore, in the case of low absorption loss ($\alpha < 100$ cm^{-1}) and low applied electric field ($F = 15$ kV/cm), the strained quasi-symmetric asymmetric coupled quantum well still has a large refractive index change (for TE mode, $\Delta n = 0.012$; for TM mode, $\Delta n = 0.0126$) at operating wavelength of 1550 nm. The refractive index change is very attractive for the polarization-independent semiconductor optical switch. The novel coupled quantum well structure is a promising quantum well structure applied to optical switch and traveling wave modulator.

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References

1. J. E. Zucker, L. B. Joseph, G. Sucha, U. Koren, B. C. Miller, and D. S. Chemla, Electron. Lett. **24,** 458 (1988).
2. J. E. Zucker and T. L. Hendrickson, Appl. Phys. Lett. **52,** 945 (1988).
3. N. Susa, IEEE J. Quantum Electron. **31,** 92 (1995).
4. M. N. Islam, R. L. Hillman, D. A. B. Miller, and D. S. Chemia, Appl. Phys. Lett. **50,** 1098 (1987).
5. H. Feng, J. P. Pang, M. Sugiyama, K. Tada, and Y. Nakano, IEEE J. Quantum Electron. **34,** 1197 (1998).
6. G. Bastard, Phys. Rev. B **24,** 5693 (1981).
7. G. Bastard and J. A. Brum, IEEE J. Quantum Electron. **22,** 1625 (1986).
8. S. Adachi, J. Appl. Phys. **53,** 8775 (1982).
9. T. Ishikama and J. E. Bowers, IEEE J. Quantum Electron. **30,** 562 (1994).
10. Y. Kan, H. Nagai, M. Yamanishi, and I. Suemune, IEEE J. Quantum Electron. **23,** 2167 (1987).
11. A. N. Cheng, H. H. Wider, and W. S. C. Chang, IEEE Photon. Technol. Lett. **7,** 1159 (1995).
12. F. Stern, Phys. Rev. A **133,** 1653 (1964).