

A novel coupled quantum well structure with large field-induced refractive index change and low absorption loss at 1.55 μm

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A novel coupled quantum well structure — quasi-symmetric coupled quantum well (QSCQW) is proposed. In the case of low applied electric field ($F = 25 \text{ kV/cm}$) and low absorption loss ($\alpha \approx 100 \text{ cm}^{-1}$), a large field-induced refractive index change (for TE mode, $\Delta n = 0.0106$; for TM mode, $\Delta n = 0.0115$) is obtained in QSCQW structure at operating wavelength $\lambda = 1550 \text{ nm}$. The value is larger by over one to two order of magnitude compared to that in a rectangular quantum well (RQW) and about 50% larger than that of five-step asymmetric coupled quantum well (FACQW) structure under the above work conditions.

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In future networks, very-high-speed and high-capacity direct optical switching systems will play a very important role, and an optical switching device is considered to be a key device for the construction of such high-speed optical switching systems or photonic integrated circuits^[1]. So it is imperative for optical switching device to search for a material with high-speed and large field-induced refractive index change in the case of low absorption loss. It is well known that a large electric field-induced refractive index change in rectangular quantum well (RQW) material is caused by quantum-confined Stark effect (QCSE)^[2], but the wavelength region of the large refractive index change is inside or very close to the absorption edge. Since the absorption coefficient close to the exciton resonance is very large (i.e., several thousand cm^{-1})^[3], this large Δn cannot be utilized for optical switch. To decrease transmission loss of optical signal, the operating wavelength should be 100—150 nm longer than the lowest state exciton resonance peak, where the absorption coefficient is small enough. However, the refractive index change will be severely decreased when the operating wavelength is away from the absorption edge even slightly^[4]. It is manifested in Ref. [4] that when the absorption coefficient $\alpha \approx 110 \text{ cm}^{-1}$ at operation wavelength $\lambda = 1.53 \mu\text{m}$, the refractive index change of the InGaAs/InP multiple quantum wells is about 0.0009. The value is only two to three times larger than that of bulk material^[5]. In order to solve the problem of large absorption loss in RQW material, three-step coupled quantum well structure^[6] and five-step asymmetric coupled quantum well (FACQW) structure^[7] are introduced. In particular, the FACQW structure utilizes two combined exciton absorption peaks to obtain a large refractive index change in longer operation wavelength. In this letter, a novel coupled quantum well structure — quasi-symmetric coupled quantum well (QSCQW) is proposed, where the refractive index change is larger than that in FACQW in the case of low absorption loss ($\alpha \approx 100 \text{ cm}^{-1}$) and low applied electric field ($F =$

25 kV/cm).

It is well known that the energy-level differentiations of symmetric coupled quantum well $E_{e2} - E_{e1}$, $E_{hh2} - E_{hh1}$, and $E_{lh2} - E_{lh1}$ are less than those of asymmetric coupled quantum well. Hence, in order to obtain two combined exciton absorption peaks, the electric field demanded by symmetric coupled quantum well is less than that by asymmetric coupled quantum well. It is beneficial to lower the power loss of optical switch devices. We also know that the exciton transitions closer to long wavelength are more important to the absorption coefficient change. For TE mode, the exciton transition energy from E_{hh1} to E_{e1} is the lowest. Unfortunately, in symmetric coupled quantum well, the wavefunctions corresponding to E_{hh1} and E_{e1} are symmetrically distributed into two symmetric quantum wells for zero electric field. So the wavefunction overlap integral corresponding to the transition is near to 1, namely between E_{hh1} and E_{e1} there exists a maximal absorption in the case of zero electric field. Hence, at the absorption edge, the combined exciton absorption spectrum in the presence of electric field can be cancelled by the exciton absorption spectrum in the case of zero electric field. This will result in positive and negative absorption coefficient changes, so the refractive-index change sharply decreases at the absorption edge. The similar case exists in TM mode, too. In order to overcome the shortcoming of symmetric coupled quantum well, our notion is that one of two quantum wells in symmetric coupled quantum well is changed slightly, thus it will become a so-called QSCQW.

We know that applied electric field can change the space distribution states of electron and hole wavefunctions; moreover the essence of putting electric field on quantum well is altering the potential distribution states of quantum well. So we can also alter the potential distribute states of quantum well by changing the structure of quantum well, consequently the aim of regulating the space distribution states of electron and hole wavefunctions is achieved similarly. Firstly, the left-side

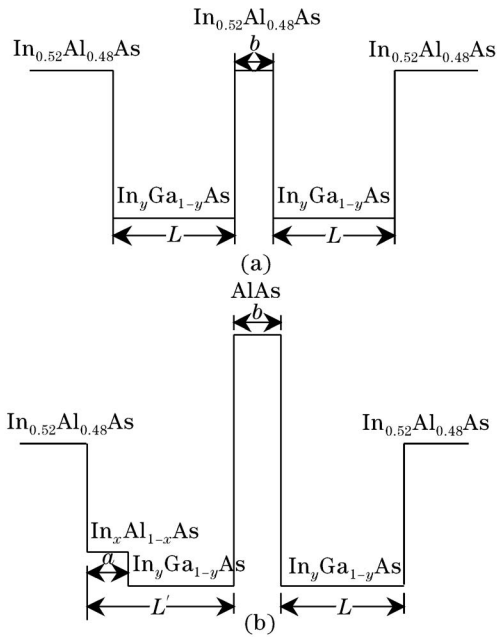


Fig. 1. Symmetric coupled quantum well (a) and quasi-symmetric coupled quantum well (b).

quantum well's width L in Fig. 1(a) is added to L' , and $L' - L < 0.1L$. Secondly, in order to decrease the ground eigenenergies difference increased by the asymmetric configuration of quantum well, we will take the following remedial measures. We substitute AlAs for $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ in order to decrease the coupling between the left-side well and the right-side well. We append a small potential barrier $\text{In}_x\text{Al}_{1-x}\text{As}$ in the left-side quantum well in order to step up the bottom of the left-side quantum well. Finally, we obtain the so-called QSCQW shown in Fig. 1(b). From the above discussion, we can draw the following conclusions: from the point of view of energy-level properties, QSCQW is similar to symmetric coupled quantum well. However, from the point of view of wavefunction distribution, QSCQW is similar to asymmetric coupled quantum well. Hence, by reconstructing symmetric coupled quantum well, we not only obtain a relatively small eigenenergy difference, but also achieve the objective of decreasing the wavefunction overlap integrals between E_{hh1} and E_{e1} , E_{lh1} and E_{e1} in the case of zero electric field.

In Fig. 1, we suppose: $a = b = 4 \text{ ML}$, $L' = 23 \text{ ML}$, $L = 22 \text{ ML}$ ($1 \text{ ML} = 0.283 \text{ nm}$). The QSCQW is grown on InP substrate; the $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ barriers are lattice-matched to the substrate. In terms of parameter interpolation principle^[8], calculations are performed for band gaps and band offsets in strained quantum well layers on InP substrate^[9]. Using the finite-element method^[10], we can deduce the wavefunctions corresponding to the ground eigenenergies and their changes with applied electric field. Based on the demands of optical switch for quantum well materials, we find that when $x = 0.8$, $y = 0.51$, the configuration of the QSCQW is optimal. In order to validate our optimal result, the refractive index change Δn of the optimized QSCQW is plotted in Fig. 2 (TE mode is denoted by solid lines, TM mode is denoted by dashed lines). The exciton absorption coefficient is deduced by the Lorentzian line shape function^[11] and

half width at half maximum (HWHM) semi-empirical formula^[12], and the refractive index change is calculated by Kramers-Kronig relations^[13].

From Fig. 2, we can come to the following conclusions. Firstly, the absorption edges of TE mode is very close to that of TM mode in the optimized QSCQW. Secondly, a very large refractive index changes for both TE mode and TM mode are obtained in the optimized coupled quantum well. The sketch of the optimized FACQW is plotted in Fig. 3. The refractive index changes of the optimized QSCQW and FACQW in the case of low absorption loss ($\alpha \approx 100 \text{ cm}^{-1}$) and long operating wavelength ($\lambda = 1550 \text{ nm}$) are shown in Fig. 4 (TE mode is denoted by solid lines, TM mode is denoted by dashed lines). From Fig. 4, we can also draw the following conclusions: 1) the refractive index change

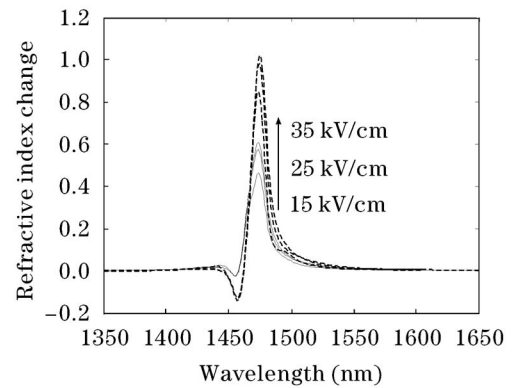


Fig. 2. Refractive index change under different applied electric fields. Solid lines: TE mode; dashed lines: TM mode.

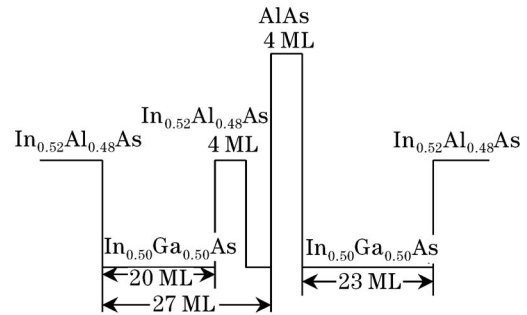


Fig. 3. Diagram of optimized FACQW.

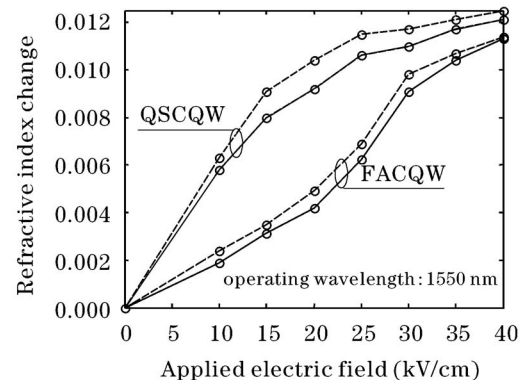


Fig. 4. Refractive index change versus applied electric field in the case of low absorption coefficient ($\alpha \approx 100 \text{ cm}^{-1}$). Solid lines: TE mode; dashed lines: TM mode.

of the optimized QSCQW is larger than that of the optimized FACQW; 2) the difference of the refractive index change between the QSCQW and the FACQW decreases with increasing applied electric field. These conclusions can be explained as follows. In the case of zero electric field, the difference of the ground eigenenergies in the QSCQW is less than that of the FACQW. Hence, to obtain two combined exciton absorption peak, the electric field intensity F demanded by the QSCQW is less than that of the FACQW.

By analyzing the ground eigenenergies in symmetric coupled quantum well, we find its advantages and disadvantages when it is applied to optical switching device, and put forward a novel coupled quantum well structure — QSCQW structure. The QSCQW can obtain a larger refractive index change Δn (for TE mode, $\Delta n = 0.0106$; for TM mode, $\Delta n = 0.0115$) in the case of lower operation voltage ($F = 25$ kV/cm) than five-step asymmetric coupled quantum well at operating wavelength $\lambda = 1550$ nm. The refractive index change is very attractive for the polarization-independent semiconductor optical switch. This manifests that QSCQW structure is a promising quantum well structure applied to optical switch and travelling wave modulator.

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