A Novel Coupled Quantum Well Structure with Low-Driving Voltage, Low Absorption Loss and Large Field-Induced Refractive Index Change *

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Based on a two-energy-level system, we analyse the changing ground eigenenergies of symmetric GaAs/Al_xGa_{1-x}As coupled quantum wells in the presence of an applied electric field. From the theoretical analysis for symmetric coupled quantum well, we find the advantages and disadvantages when it is applied to travelling wave modulator. Hence the conception of quasi-symmetric coupled quantum wells is put forward. Based on the demands of travelling wave modulator for quantum well materials, the configuration of quasi-symmetric coupled quantum well is further optimized. Consequently, in the case of low applied electric field ($F = 20\,kV/cm$) and low absorption loss ($\alpha \leq 100\,cm^{-1}$), a large field-induced refractive change Δn (for TE mode, $\Delta n = 0.021$; for TM mode, $\Delta n = 0.0121$) is attained in the optimized coupled quantum well.

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Large refractive index change under low absorption loss and low-drive voltage is often expected in integrated photonic circuits, such as travelling wave modulator and compact optical switch. Therefore, researchers introduced three-step coupled quantum well structures[1,2] and five-step asymmetric coupled quantum well structures.[3] In particular, the five-step asymmetric coupled quantum well structure[3] utilized two combined exciton absorption peaks to obtain a large refractive index change in longer operation wavelength. However, the authors of Ref. [3] did not illustrate the relations between $e1$ and $e2$, $hh1$ and $hh2$, $lh1$ and $lh2$ for zero electric field, and also did not illustrate the change of $e1$ and $e2$, $hh1$ and $hh2$, $lh1$ and $lh2$ along with applied electric field. All these are very important to design and optimize the configuration of coupled quantum well for travelling wave modulator or optical switch.

In this Letter, starting from two-energy-level system, we derive the energy shifts of the ground eigenstates of symmetric GaAs/$Al_{0.32}Ga_{0.68}$As coupled quantum well with applied electric field F along the direction of the well (oz). The experimentally determined value of $\Delta E_c : \Delta E_v = 0.57 : 0.43$ is used for AlAs/GaAs to determine the AlAs position.[4] Then we put forward the conception of quasi-symmetric coupled quantum wells, and the configuration of quasi-symmetric coupled quantum wells is optimized. Consequently, the optimized coupled quantum wells have larger refractive index change and lower power loss than the five-step asymmetric coupled quantum well structure under an identical absorption coefficient.[3]

In Fig. 1(a), we schematically depict the ground eigenstates of the symmetric coupled quantum well for zero applied electric field along with the transitions related to the following discussions between the ground electron and hole eigenstates. There is coupling between two quantum wells; the degenerate states (dotted line) are split into symmetric and antisymmetric combinations of eigenstates with the symmetric state having the lower energy. The ground eigenenergies corresponding to electron, heavy-hole and light-hole symmetric states are denoted by E_{e1}, E_{hh1}, and E_{lh1}; the ground eigenenergies corresponding to electron, heavy-hole and light-hole antisymmetric states are denoted by E_{e2}, E_{hh2}, and E_{lh2}, respectively.

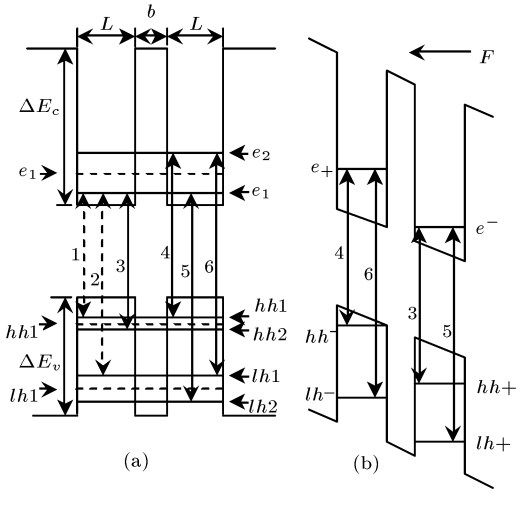


Fig. 1. (a) Ground eigenstates of the symmetric coupled quantum well for zero applied electric field. (b) Change of the coupled symmetric and antisymmetric eigenstates with applied electric field.

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Due to different effective masses between electron, heavy-hole, and light-hole,[4] the relations between the symmetric eigenenergies and the antisymmetric eigenenergies for zero applied electric field can be written as

$$E_{hh2} - E_{hh1} < E_{lh2} - E_{lh1} < E_{e2} - E_{e1}. \quad (1)$$

In the following, we consider the energy shifts of the ground eigenstates of the symmetric coupled quantum well with applied electric field. Firstly, we discuss the conduction-band case. If the coupling is weak, $E_{e2} - E_{e1}$ is very small, and they are apart from the other eigenstates. The effect of the other eigenstates can be omitted, the system consisted of E_{e1} and E_{e2} can be regarded as the two-energy-level system. In the presence of applied electric field, the Hamiltonian of the system is $H = H_0 + eFz = H + H'$, where H_0 is the zero-electric-field Hamiltonian and has two nondegenerate eigenenergies E_{e1} and E_{e2},

$$H_0|e1\rangle = E_{e1}|e1\rangle, \quad H_0|e2\rangle = E_{e2}|e2\rangle. \quad (2)$$

In the representation of H_0, H is written as

$$H = \begin{pmatrix} E_{e1} & H'_{e1e2} \\ H'^{*}_{e1e2} & E_{e2} \end{pmatrix}, \quad (3)$$

where $H'_{e1e2} = \langle e1|H'|e2\rangle = H'^{*}_{e1e2}$. Based on the second-order perturbation approximation, the eigenenergies of H can be written as

$$E_{e-} = E_{e1} - \frac{|H'_{e1e2}|^2}{E_{e2} - E_{e1}}, \quad (4a)$$

$$E_{e+} = E_{e2} + \frac{|H'_{e1e2}|^2}{E_{e2} - E_{e1}}, \quad (4b)$$

and the change of the electron ground eigenenergies E_{e1} and E_{e2} with applied electric field is described by

$$(E_{e+} - E_{e-}) - (E_{e2} - E_{e1}) = \frac{2|H'_{e1e2}|^2}{E_{e2} - E_{e1}}. \quad (4c)$$

The eigenstates of H can be written as

$$|e-\rangle = -|e1\rangle + \frac{|H'_{e1e2}|}{E_{e2} - E_{e1}}|e2\rangle, \quad (5a)$$

$$|e+\rangle = |e2\rangle + \frac{|H'_{e1e2}|}{E_{e2} - E_{e1}}|e1\rangle. \quad (5b)$$

Accordingly, the changes of the heavy-hole ground eigenenergies E_{hh1} and E_{hh2}, the light-hole ground eigenenergies E_{lh1} and E_{lh2} with applied electric field can be written as

$$(E_{hh+} - E_{hh-}) - (E_{hh2} - E_{hh1}) = \frac{2|H'_{hh1hh2}|^2}{E_{hh2} - E_{hh1}}, \quad (6a)$$

$$(E_{lh+} - E_{lh-}) - (E_{lh2} - E_{lh1}) = \frac{2|H'_{lh1lh2}|^2}{E_{lh2} - E_{lh1}}, \quad (6b)$$

where $H'_{hh1hh2} = \langle hh1|H'|hh2\rangle = H'^{*}_{hh1hh2}$, $H'_{lh1lh2} = \langle lh1|H'|lh2\rangle = H'^{*}_{lh1lh2}$. The change of the coupled symmetric and antisymmetric eigenstates with applied electric field is illustrated in Fig. 1(b). Combining Eqs. (1), (4c), (6a), (6b) with Refs. [4–5], we can obtain the following relations:

$$\begin{aligned} &(E_{e+} - E_{e-}) - (E_{e2} - E_{e1}) \\ &< (E_{lh+} - E_{lh-}) - (E_{lh2} - E_{lh1}), \end{aligned} \quad (7a)$$

$$\begin{aligned} &(E_{e+} - E_{e-}) - (E_{e2} - E_{e1}) \\ &< (E_{hh+} - E_{hh-}) - (E_{hh2} - E_{hh1}). \end{aligned} \quad (7b)$$

From the above discussions, we can draw the following conclusions. For TE mode, we mainly consider the transitions from the heavy-hole band to the conduction band. Transition 3 is closer to transition 4 with increasing applied electric field. For TM modes, we mainly consider the transitions from the light-hole band to the conduction band. Transition 5 is also closer to transition 6 with increasing applied electric field. Considering 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 the 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 of the asymmetric coupled quantum well. This is beneficial to lower the power loss of travelling wave modulator.

It is well known that the exciton transitions closer to long wavelength are more important to the absorption coefficient change. For TE modes, 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. Therefore, the wavefunction overlap integral corresponding to the transition is close to 1, namely a maximal absorption exists between E_{hh1} and E_{e1} in the case of zero electric field. Hence, at the absorption edge, the combined exciton absorption spectrum caused by $E_{hh-} \to E_{e+}$ and $E_{hh+} \to E_{e-}$ in the presence of electric field can be cancelled by the exciton absorption spectrum caused by $E_{hh1} \to E_{e1}$ in the case of zero electric field. This will result in positive and negative absorption coefficient change, so the refractive-index change sharply diminishes at the absorption edge. The similar case also exists in the TM mode. In order to overcome the shortcoming of the symmetric coupled quantum well, our notion is that one of the two quantum wells in the symmetric coupled quantum well is changed slightly, thus it will become the so-called quasi-symmetric coupled quantum well.

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 wells can change the potential distribution states of quantum wells. Hence we can also change the potential distribute states of quantum wells by changing the structure of quantum wells, consequently the aim of regulating the space distribute states of electron and hole wavefunctions is achieved similarly. Firstly, the left-side quantum well's width L in Fig. 1(a) is added to L', and $L' - L \leq 0.25L$. Secondly, in order to decrease the ground eigenenergies difference increased by the asymmetric configuration of the quantum well, we take the following remedial measures. (1) We substitute AlAs for $Al_{0.32}Ga_{0.68}As$ to decrease the coupling between the left-side well and the right-side well. (2) We append a small potential barrier Al_xGa_{1-x} As in the left-side quantum well to step up the bottom of the left-side quantum well. Finally, we obtain the so-called quasi-symmetric coupled quantum well, as shown in Fig. 2.

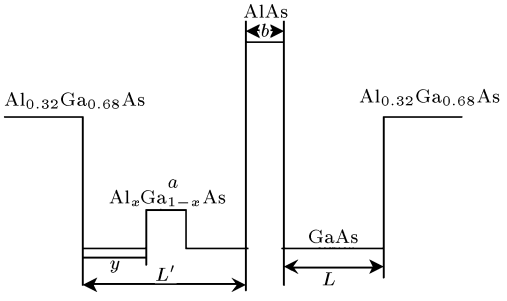


Fig. 2. Diagram of the quasi-symmetric coupled quantum well.

From the above discussion, we can draw the following conclusions: In view of energy-level properties, the quasi-symmetric coupled quantum well is similar to the symmetric coupled quantum well. However, in view of the wavefunction distribution, the quasi-symmetric coupled quantum well is similar to the asymmetric coupled quantum well. Hence, by reconstructing the 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.

The demands of travelling wave modulators for quantum well materials mainly consist of the following aspects. (1) The field-induced refractive index change of the quantum well material is as large as possible. (2) The absorption loss of the material is as low as possible. Basing on the above demands, we can bring forward the detailed optimization principles. We take an example for the TE mode. Firstly, in the case of zero electric field, the wavefunction overlap integral corresponding to E_{hh1} and E_{e1} must be as small as possible. However, based on the sum rules,[6] this will increase the wavefunction overlap integrals corresponding to E_{hh2} and E_{e1}, E_{hh1} and E_{e2}, so this is an eclectic selection. Secondly, the changes of the wavefunction overlap integrals, corresponding to E_{hh+} and E_{e-}, E_{hh-} and E_{e+}, must be as large as possible in the case of lower applied electric field. In Fig. 2, we suppose $a = b = 4ML$, $L' = 22ML$, $L = 18ML$ ($1ML = 0.283\,\text{nm}$). Using the finite-element method,[7] we can deduce the wavefunctions corresponding to the ground eigenenergies and their changes with applied electric field. By a series of numerical calculations, we find that when $y = 9ML$, $x = 0.12$, the configuration of the quasi-symmetric coupled quantum well is optimal.

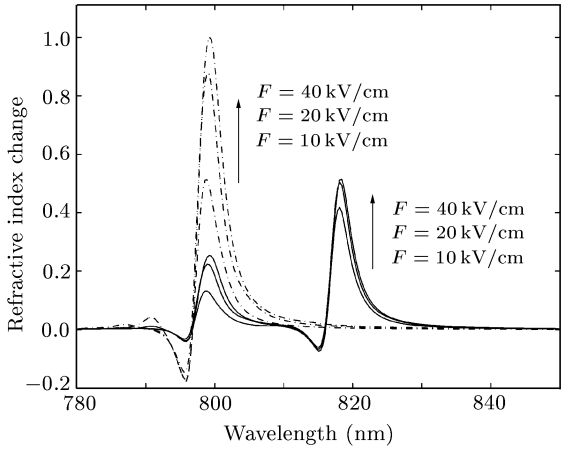


Fig. 3. Refractive index change versus applied electric field.

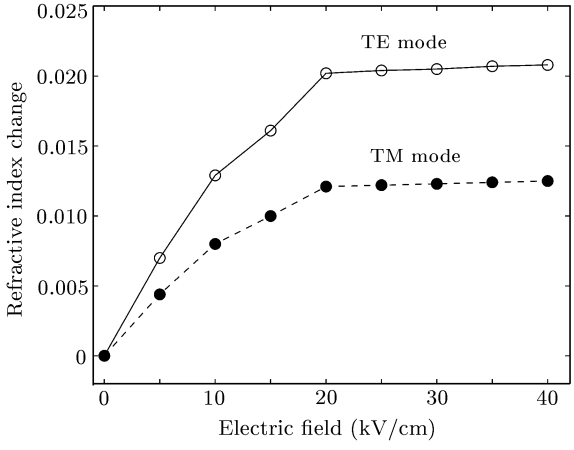


Fig. 4. Refractive index change versus applied electric field in the case of low absorption coefficient ($< 100\,\text{cm}^{-1}$).

In order to validate our optimal result, the refractive index change n with applied electric field is plotted in Fig. 3 (the TE mode is denoted by the solid

lines, the TM mode is denoted by the dot-dashed lines). The exciton absorption coefficient is deduced by the Lorentzian line shape function[8,9] and HWHM semi-empirical formula,[10] and the refractive index change is calculated by the K-K relations.[11]

Figure 3 shows that the optimized coupled quantum well has a very large field-induced refractive index change for TE and TM modes synchronously. Furthermore, when the operation wavelength is away from the absorption edge ($\alpha < 100\,\mathrm{cm}^{-1}$), the optimized coupled quantum well still has a considerable refractive index change, as shown in Fig. 4.

It is noted that for the TE mode, the operation wavelength $\lambda = 828\,\mathrm{nm}$, and for the TM mode, the operation wavelength $\lambda = 816.4$. From Fig. 4, we can come to the following conclusions: Firstly, the refractive index change of the optimized coupled quantum well is ten times larger than that of the rectangular quantum well in the same absorption loss. Secondly, when the applied electric field increases from $20\,\mathrm{kV/cm}$ to $40\,\mathrm{kV/cm}$, the refractive index change n along with the electric field is almost invariable.

In conclusion, by analysing the evolvement rule of the ground eigenenergies in a symmetric coupled quantum well, we put forward a novel coupled quantum well structure, i.e. the quasi-symmetric coupled quantum well. In the case of lower operation voltage, the optimized coupled quantum well can obtain a refractive index change larger than that of the five-step asymmetric coupled quantum well. This manifests that the quasi-symmetric coupled quantum well is a promising quantum well structure applied to travelling wave modulators and optical switches.

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