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Modification of Material Parameters for InGaAs/InAlAs Quantum Wells

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1. Introduction

Semiconductor optical modulators and switches based on phase modulation such as Mach-Zehnder (MZ) modulators are becoming more and more important in optical fiber communications. For high-performance optical modulators and switches based on phase modulation, we have developed five-layer asymmetric coupled quantum wells (FACQWs) [1-3].

In our research on the InGaAs/InAlAs FACQW for 1.55 μm wavelength, we theoretically calculated absorption coefficient spectra of InGaAs/InAlAs quantum wells (QWs) using frequently used material parameters in some references. But we found that experimental data are slightly different from the calculated. To estimate the electrorefractive index change of InGaAs/InAlAs QWs more accurately, material parameters such as energy band gap, effective masses must be modified.

In this paper, we discuss material parameters for InGaAs/InAlAs QWs comparing experimental and calculated data. Using the modified material parameters, we succeeded in obtaining the calculated absorption coefficient spectra more consistent with the experimental.

2. Modification of Material Parameters

For the calculation of absorption coefficient spectra, we used the $k{\cdot}p$ perturbation theory with a 4 x 4 Luttinger-Kohn Hamiltonian[4,5] and The effects of excitons were calculated using the non-variational approach [6] and the effect of valence band non-parabolicity was taken into account. To compare the calculated results with the experiments, we grown some InGaAs/InAlAs QWs lattice-matched to an InP substrate using metal-organic vapor phase epitaxy (MOVPE). The material parameters we investigated are the bandgap energy (E_g), the electron and hole effective masses (m_e, m_{hh}, m_{lh}). We also considered deteriorated abruptness in heterointerfaces.

2.1. Bandgap energy of $In_yAl_xGa_{1-x-y}As$

Equation (1) [7] is the expression of E_g for the $In_yAl_xGa_{1-x-y}As$ used in our calculation. It is slightly different from the experimental data which were obtained from photoluminescence (PL) of several InAlGaAs bulk crystals measured at room temperature. We modified the coefficients in Eq. (1) as summarized in Table 1.

$$E_g = a_0 + a_1 x + a_2(1-x-y) + a_3 x^2 + a_4(1-x-y)^2 + a_5 x(1-x-y) - a_6 xy(1-x-y) \quad (1)$$

2.2. Abruptness of InGaAs/InAlAs heterointerfaces

Figure 2 (a) shows a line profile of Ga luminance from the InGaAs/InAlAs FACQW with high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM). The designed structure of the FACQW is shown in Fig. 2 (b). As shown in Fig. 2(a), some deterioration of abruptness occurs in the heterointerfaces. In our calculation, we assumed that the Ga composition profile is expressed as Eq.(2) using the normal distribution function.

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{x^2}{2\sigma}\right) \quad (2)$$

2.3. Effective masses

The effective mass of a heavy hole (m_{hh}) and the effective mass of a light hole (m_{lh}) are expressed in eq. (3)

$$m_{hh} = \frac{m_0}{\gamma_1 - 2\gamma_2}, \quad m_{lh} = \frac{m_0}{\gamma_1 + 2\gamma_2} \quad (3)$$

where m_0 is the mass of a free electron and γ_1, γ_2 are the Lut-

Table 1. Coefficients of eq.(1)

	a_0	a_1	a_2	a_3	a_4	a_5	a_6
before	0.360	2.093	0.629	0.577	0.436	1.013	2
after	0.373	2.113	0.674	0.347	0.281	1.234	2

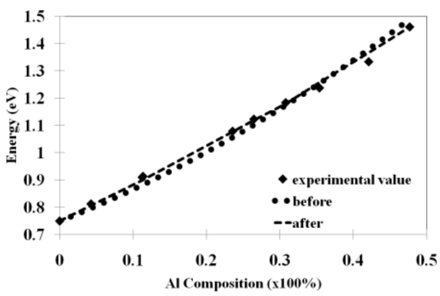
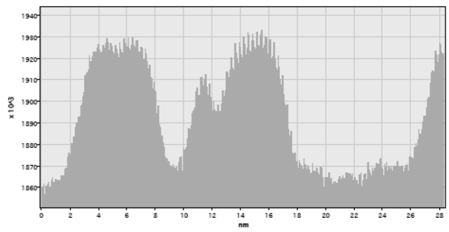
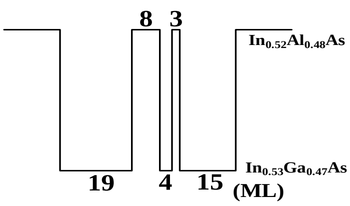


Fig.1. Experimental and calculated bandgap energy of $In_yAl_xGa_{1-x-y}As$ lattice-matched to InP.



(a)

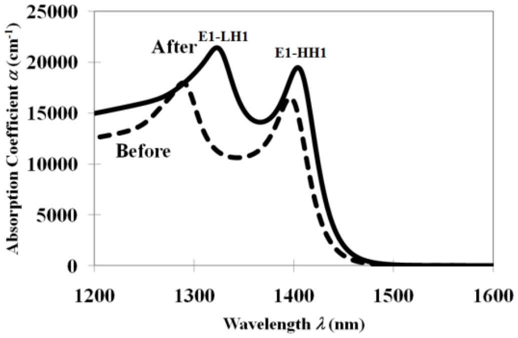


(b)

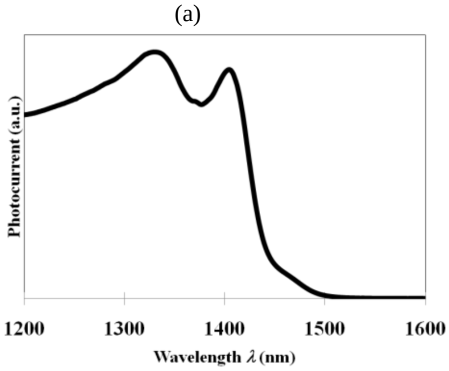
Fig.2. (a) Line profile of Ga luminance of InGaAs/InAlAs FACQW measured using HAADF-STEM and (b) a potential profile of InGaAs/InAlAs FACQW.

Table 2. Parameters used for the calculations. The parameters before modification are referred from Ref. [7].

	before	after
E_g($In_{0.53}Ga_{0.47}As$) (eV)	0.75	0.75
E_g($In_{0.52}Al_{0.48}As$) (eV)	1.49	1.45
m_e/m_0($In_{0.53}Ga_{0.47}As$)	0.044	0.052
m_e/m_0($In_{0.52}Al_{0.48}As$)	0.084	0.101
m_{hh}/m_0($In_{0.53}Ga_{0.47}As$)	0.307	0.307
m_{hh}/m_0($In_{0.52}Al_{0.48}As$)	0.336	0.336
m_{lh}/m_0($In_{0.53}Ga_{0.47}As$)	0.040	0.048
m_{lh}/m_0($In_{0.52}Al_{0.48}As$)	0.046	0.055



(a)



(b)

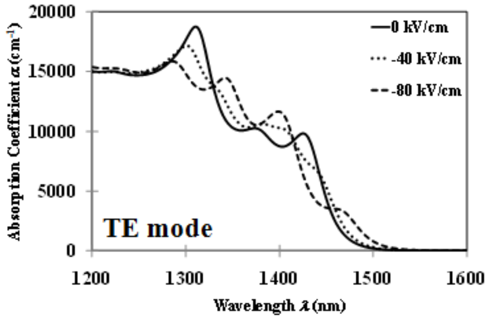
Fig.3. (a) Calculated absorption coefficient spectra and (b) the photocurrent spectra of InGaAs/InAlAs rectangular quantum well (well width 5 nm).

tinger parameter. Using γ_1 and γ_2 as fitting parameters, we modified m_{hh} and m_{lh}. The modified parameters are summarized in Table 2.

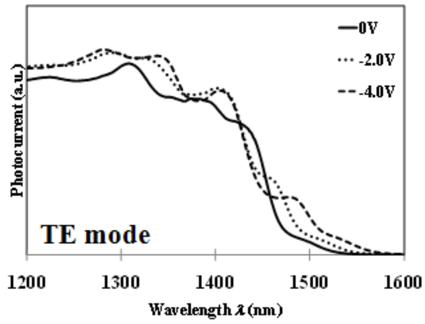
3. Modified Absorption Coefficient Spectra

Figure 3(a) shows the calculated absorption coefficient spectra using the parameters in Ref.[7] and the modified ones. A photocurrent spectrum of an InGaAs/InAlAs rectangular QW (well width 5 nm) measured at room temperature is shown in Fig .3 (b). The spectrum calculated using the modified parameters agrees well with the experimental result. In the case of the 10-nm thick InGaAs QW, we also obtained the spectrum agreed well with the experiments.

Figure 4 (a) shows the absorption coefficient spectra of



(a)



(b)

Fig.4. (a) Calculated absorption coefficient spectra and (b) the photocurrent spectra of InGaAs/InAlAs rectangular quantum well (well width 5 nm).

a symmetric coupled QW under the applied voltages, and it shows the typical quantum confined Stark effect (QCSE). The QW is composed of 4.4-nm InGaAs well layers and a 0.88-nm InAlAs barrier layer. The absorption coefficient spectra calculated using the modified parameters in Fig.4 (b) agrees well with Fig. 4 (a).

4. Conclusions

We discussed the material parameters of InGaAs/InAlAs QWs. Comparing the experimental and the calculated data, we successfully obtained more appropriate material parameters for predicting photocurrent spectra of InGaAs/InAlAs QWs. The modified parameters are quite useful for InGaAs/InAlAs QW optical devices such as optical modulators and switches.

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