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E-7-3 Saturation characteristics simulation of intersubband absorption for [(CdS/ZnSe/BeTe)/(ZnSe/BeTe)] coupled quantum wells

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1. Introduction

Intersubband-transition (ISBT) all-optical switches show great potential in the next-generation ultrafast (>100 Gb/s) telecommunication network at λ ~ 1.55 μm. Such ISBT switches have been realized in III-V, III-nitride, and II-VI quantum systems [1-3]. Currently, to decrease the switching energy (E_s) to an applicable level is the main task for such photonic devices. By improving waveguide structure, we have lowered E_s to 1.13 pJ/dB for our II-VI system [4]. To further such decrease, we proposed the coupled quantum wells (CQW) in Fig. 1 in order to slow down the relaxation by introducing the e2 sublevel [5]. In Ref. [5], the samples of CQW given in Fig. 1(a) were grown by dual-chamber molecular beam epitaxy system and we have studied the sublevel-coupling dependent intersubband absorption and carrier dynamics. The intersubband absorption spectra of these samples are shown in Fig. 2, in which we realized the strong sublevel coupling between e2 and e3 states, as indicated by the anticrossing between e_{12} and e_{13} and their reverse intensity evolution. Such coupling is expected to reduce $\tau_{32}<\tau_{31}$ and increase τ_{21}, and then the overall relaxation time will be increased. Thus E_s is expected to be lowered since it is inversely proportional to the relaxation time. Therefore, in this letter, we simulate the saturation characteristics of intersubband absorption to calculate E_s for CQW in order to examine its effectiveness in reducing E_s.

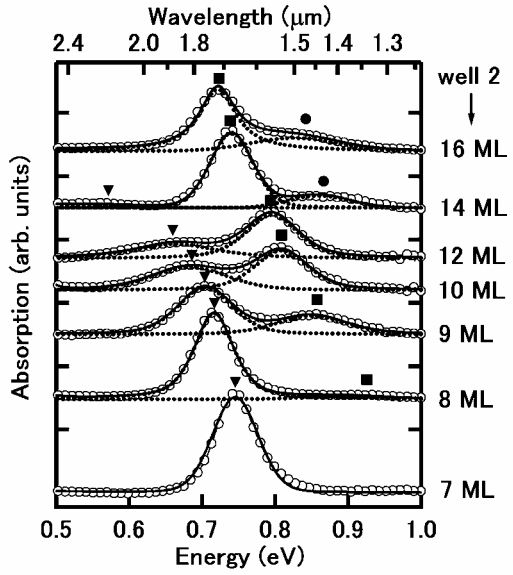

Fig. 2. Intersubband absorption spectra (circles) with different well 2 thicknesses and the corresponding fitting spectra (the solid lines denote the sum of the fitting components (dotted lines)). The markers (▼,■,●) respectively indicate the e_{12}, e_{13} and e_{14} transitions.

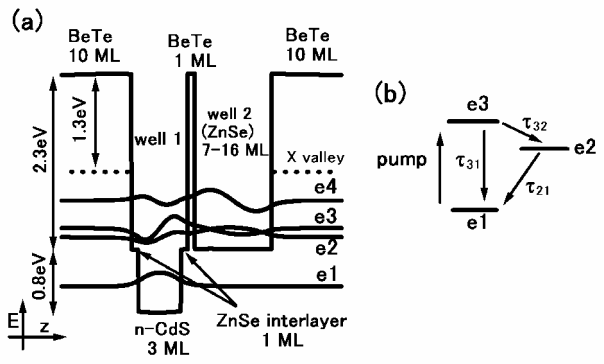

Fig. 1. (a) A representative self-consistent subband structure of II-VI-based CQW with layer parameters, and (b) its intersubband dynamic scheme. e1~e4 denotes the lowest electron states and τ_{ij} is the scattering time from *j*-th to *i*-th subband.

2. Simulation method

A common method to estimate the switching intensity (I_s) for two-level systems under the continuous wave (CW) pump is to use the eq. (1), in which *c*, ε_0, and $\hbar$ have their usual meanings, while τ and μ are the relaxation time and transition dipole, respectively. But for the quantum systems involving >3 sublevels, the eq. (1) fails to predict the real I_s,

$$I_s = c\varepsilon_0\hbar^2/(\tau|\mu|^2) \qquad (1)$$

especially for pulse pumps, since we cannot use a simple τ to describe the complex dynamics in such systems. So for I_s of the CQW in Fig. 1, we simulate the pump process by iteratively solving the motion equation of polarization and rate equations [6], where the scattering times are calculated based on LO-phonon scattering mechanism.[5] Subsequently, the temporal electron concentration (N_i) under pump at the *i*-th subband can be obtained. Fig. 3 exhibits the time dependence of carrier densities under e1-e3 resonant pump with the pulse width=0.1 ps and e1-e3 probe. Based on such temporal carrier density, the transient response of the absorption coefficient (α) can be calculated. Fig. 4(a) gives the corresponding transient α for Fig. 3 with the input pulse. A series of such temporal α will be obtained by gradually increasing the pump intensity (I). Then we can plot the minimum α in Fig. 4(a) versus the pump intensity; in other words, the saturation curve is obtained in Fig. 4(b). In each intensity dependent saturation curve, I_s can be derived by using $\alpha=\alpha_0(1-I/I_s)$ when $I\to 0$. For pulse pump, $E_s=I_s\cdot\Delta t$, where Δt is the pulse width. Finally, we obtain the pulse-width dependent E_s for each CQW.

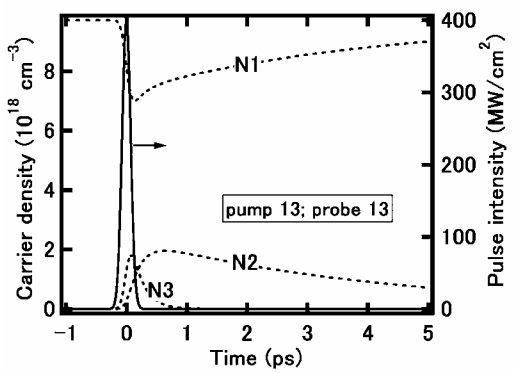

Fig. 3. Response of carrier density at each sublevel under pulse pump. (ij means from *i* to *j* subbands)

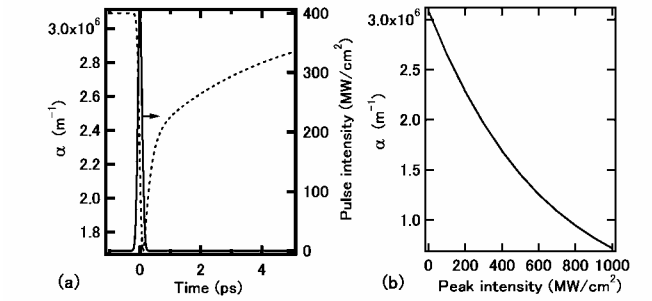

Fig. 4. (a) Temporal absorption coefficient for the pulse pump in Fig. 3. (b) Intensity dependent absorption coefficient.

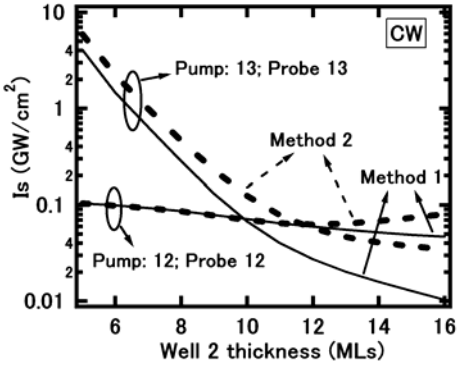

Fig. 5. Comparison on I_s between two methods for two kinds of pump-probe scheme under CW.

3. Results and Discussion

First we compare the calculated I_s by using eq. (1) (method 1) and that by above method based on saturation simulation (method 2) to examine the reliability. For two-level system simulation, τ in eq. (1) can set to be τ_{21}, but for three-level system, an effective $\tau_{eff}=\tau_{31}(2\tau_{32}+\tau_{21})/(\tau_{31}+\tau_{32})$ is necessary if we still use eq. (1). Fig. 5 shows such comparison on I_s, in which two methods match each other for e1-e2 pump in the e_{12} transition dominant region (well 2 thickness < 9.6 ML); however, they deviate from each other for e1-e3 pump in the whole well 2 thickness region due to the involved three sublevels. Therefore, not only Fig. 5 proves the reliability of method 2, but also shows the inappropriateness of eq.(1) in describing >3 level quantum systems .

Consequently, by using method 2 aforementioned, we calculated the E_s for CQW in Fig. 1(a) under different pump pulse widths, as shown in Fig. 6. It indicates that each pulse width corresponds to an optimum CQW structure. With increasing the pulse width from 0.1 to 5 ps, the lowest E_s transfers gradually from e_{12} to e_{13} transition, in other words, it shifts to larger well 2 thickness. CQW with thinner well 2 is suitable for narrow pulses by adopting e_{12} transition, while CQW with thicker well 2 is better for wider pulses by adopting e_{13} transition. Based on our previous research [5], such structural dependent E_s results from the sublevel-coupling dependent carrier dynamics. Comparing well 2 = 5 and 12 ML, E_s for the latter can be lowered ~37% for the pulse width of 5 ps, and ~45% for CW pump. As predicted, such decrease in E_s is attributed to the increase in the relaxation time.

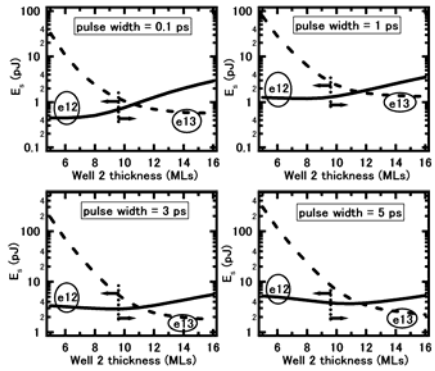

Fig. 6. Structural dependence of E_s for different pump pulse widths. A dot line with two arrows indicates the dominant intersubband transition.

4. Conclusions

The saturation characteristics of II-VI CQW were simulated by solving the motion equation of polarization and rate equations, based on which E_s for different pump pulse width was optimized with respect to the well 2 thickness. It was concluded that E_s of CQW in strong sublevel coupling region can be lowered compared with SQW when pulse widths >1 ps for both e_{12} and e_{13} transitions.

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