Direct observation of intersubband relaxation dynamics and application to subpicosecond all-optical modulation

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Introduction: Intersubband transitions (ISB-Ts) in quantum well (QW) structures[1] have been drawing much attention due to an ultrafast energy relaxation by means of longitudinal optical (LO) phonon scattering (~ ps). We have previously proposed an ultrafast all-optical modulation scheme based on ISB-T in n-doped QWs aimed for the application to ultrafast optical communication systems. [2] In the scheme (Fig. 1-(a)), the electron occupation probability in CB1 is decreased by ISB-resonant (CB1-CB2) control light, and the consequent increase in the optical interband transition (IB-T) probability modulates the intensity of IB-resonant (HH1-CB1) signal light that passes thorough the QWs.

The modulation scheme has been experimentally demonstrated in GaAs/AlGaAs QWs by using two-color pump-probe method. [3] Although the FWHM of the modulation profile was as short as 1 ps with a weak pump condition (~ 4fJ/μm^2), it also had a slowly tailing component (τ = 3~5 ps). The results mean that the relaxation process cannot be explained only by a simple LO phonon scattering model. The slow component strongly restricts the repetition time of the modulation that is very important for applications. **In this report**, we investigate the ISB relaxation process by a novel pump-probe method that can precisely monitor the dynamics of electron distribution during the relaxation. A new modulation scheme that can avoid the slow component is proposed and demonstrated by using the obtained results.

Experimental: The sample prepared was multiple QWs that consist of 150 periods of GaAs (59Å) / $Al_{0.35}Ga_{0.65}As$ (150Å), which was grown by molecular beam epitaxy on a GaAs substrate. The barriers were doped in the center 140 Å with Si at a concentration of 1.5×10^{18} cm^{-3}, and the wells were un-doped. At first, the energy separations between the subbands were determined by ordinary optical absorption measurements (the inset in Fig. 2-(b)). Next, the sample was pumped by a femtosecond (~ 150 fs) ISB-resonant light pulse ($\hbar\omega$ = 0.17 eV) and was probed by a white light continuum ranges from 1.4 to 2.0 eV, which can simultaneously monitor HH1-CB1 and HH2-CB2 transitions. Relatively intense pump condition (~ 100 fJ/μm^2) was used to obtain enough S/N ratio.

Investigation of the Relaxation Process: Figure 3 shows an example of the measured pump-probe profiles (T/T_0). The profile in a photon energy range of 1.50 ~ 1.7 eV shows the removal of the electrons from CB1 and the subsequent population recovery. The profile in a photon energy range of 1.7 ~ 1.9 eV shows the electron injection into CB2 and the subsequent population reduction. The electron dynamics in each subband was successfully obtained, and we have noticed the following two surprising features in the figure:

(A) The population reduction time in CB2 is much shorter than the population recovery time in CB1. The 1/e relaxation time of the profile at 1.75 eV (CB2) is about 0.2ps, and that at 1.55 eV (CB1) is about ~ 4 ps (which is almost dominated by the slow component due to the intense pump condition).
(B) The number of electrons injected to CB2 is distinctly smaller than that removed from CB1. Estimation by using exact theoretical model shows that $|\Delta N2| / |\Delta N1|$ is only 30% at delay time 0, where $\Delta N1$ ($\Delta N2$) is the variation in the total electron population in CB1 (CB2).

Further detailed analysis of the pump-probe profile gave a model that can explain the above features, where the electron relaxation is composed from the following two parallel paths (Fig. 3) :

(1) Direct path (~ 30%): The scattering from CB2 to CB1 (τ ~ 0.8 ps), which is the electron–LO phonon scattering process.
(2) Indirect path (~ 70%): The scattering from CB2 to unknown trapping state(s) (τ ~ 0.3 ps) followed by the scattering from the trapping state(s) to CB1 (τ ~ 4 ps).

Although the trapping state is not still identified, the most likely candidate for the trapping states is considered to be a subband confined in the barrier layer, which is formed due to the band bending in a modulation doped structure (Fig. 3). [4]

New Modulation Scheme and Demonstration: The above investigation indicates that the slow component of the previous modulation scheme results from the existence of the indirect path. However, the electron escape time from CB2 cannot become longer by the existence of parallel relaxation paths. Therefore, we have proposed a new modulation scheme that utilizes CB2, where the wavelength of the signal light is tuned to HH2-CB2 resonance (Fig. 1-(b)). As already shown in Fig. 2, the response time of the modulation is shorter than 0.3 ps, and no tailing components have been observed.

Conclusion: The ultrafast all-optical modulation of the order of subpicosecond has been proposed and successfully demonstrated as a result of precise investigation on intersubband relaxation dynamics.

References

1. L. C. West and S. J. Eglash, *Appl. Phys. Lett.* **46** (1985) 1156 .

2. S. Noda, T. Uemura, T. Yamashita, and A. Sasaki, *J. Appl. Phys.* **68** (1990) 6529 .

3. T. Asano, S. Noda, and K. Tomoda: *Appl. Phys. Lett.* **74** (1999) 1418.

4. J. Bayer, I. M. Bayanov, U. Prodereder, A. Seilmeier: *Superlatt. Microstruct.* **19** (1996) 9.

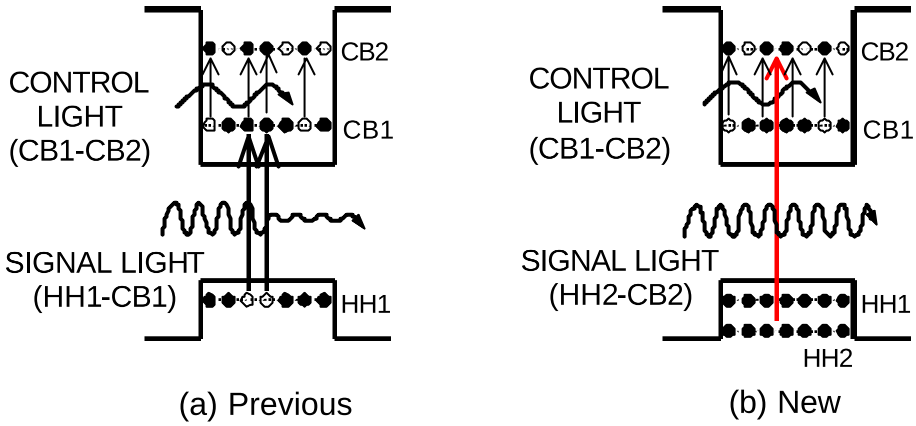
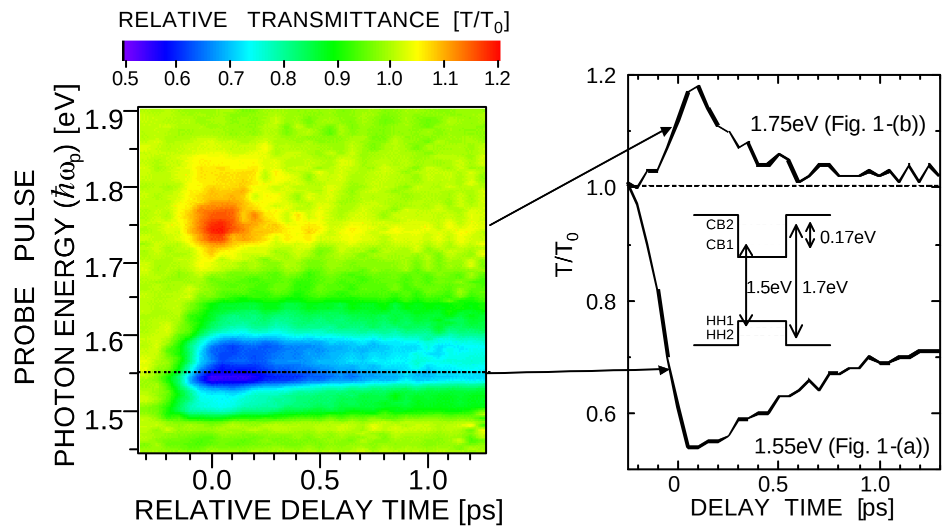


Fig. 1: Schematic diagrams of all optical modulation using intersubband transition in n-doped quantum wells. (a) Previously proposed scheme: Interband absorption for signal light (HH1-CB1) is temporally increased by exciting the electrons from CB1 to CB2 using control light. (b) Newly proposed scheme: Interband absorption (HH2-CB2) is temporally decreased by exciting the electrons from CB1 to CB2 using control light.



(a) (b)

Fig. 2 An example of intersubband-pump and interband-white-light-probe experiment. **(a)** Three-dimensional view. **(b)** Cross-section at 1.55 eV (lower line), which corresponds to the previous modulation scheme (Fig1-(a)), and cross section at 1.75eV (upper line), which corresponds to the new modulation scheme (Fig. 1-(b)). **Inset:** the energy separations between subbands measured by ordinary absorption measurements.

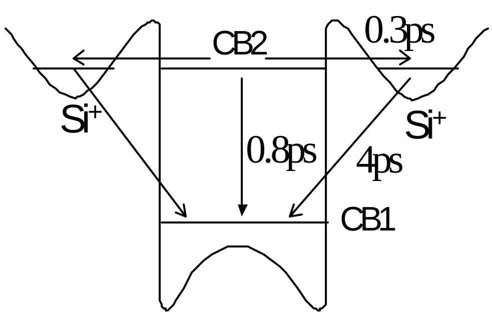


Fig. 3: A schematic diagram showing two parallel intersubband relaxation paths. The direct path: Scattering from CB2 to CB1 (~ 0.8ps). Indirect path: Scattering from CB2 to trapping states in the barrier (~ 0.3 ps) followed by the scattering from the trapping states to CB1 (~ 4 ps).