Picosecond signal recovery in type II tunneling bi-quantum well etalon

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We demonstrate picosecond signal recovery in all optical gate operation using a type II tunneling bi-quantum well (TBQ) etalon. The type II TBQ consists of a series of GaAs wells, AlGaAs barriers, and AlAs layers. In this structure, photoexcited electrons in the GaAs wells escape by tunneling through the AlGaAs barriers toward X states in the AlAs layers. Therefore, the time for recovery from excitonic absorption bleaching in GaAs wells is controlled directly by the AlGaAs barrier thickness. The type II TBQ etalon with 1.7 nm barriers showed a fast signal recovery of 17 ps by carrier tunneling.

Excitonic optical nonlinearity in multiple quantum wells (MQWs) is attracting wide interest because of its potential for optical switching and computing. In particular, Gibbs *et al.* showed the optical bistability in a GaAs etalon[1] and Migus *et al.* demonstrated a 1 ps NOR gate operation using GaAs/AlGaAs MQW etalon.[2] Upon photoexciton of the exciton peak, nonlinear absorption, and refraction changes occur in MQWs with a time constant less than 1 ps.[3] However, the slow recovery of optical properties, such as absorption, is a serious problem. The typical recovery time from excitonic absorption bleaching in a GaAs/AlGaAs MQW is 30 ns at 300 K.[4] This limits the response time of devices using excitonic optical nonlinearity.

Recovery time is reduced using tunneling,[5–9] surface recombination,[10–12] or proton bombardment.[13] Whatever method is used, it is very important not to sacrifice optical nonlinearity. To meet this condition, we previously proposed a superlattice structure using carrier tunneling which we called a tunneling bi-quantum well (TBQ) structure.[5,6] The structure (referred to as type I TBQ in the following) consists of a series of narrow GaAs wells, AlGaAs barriers, and wide GaAs wells. In this structure, photoexcited electrons in the narrow GaAs wells escape by tunneling through the AlGaAs barriers toward the wide GaAs wells. Therefore, the recovery time from excitonic absorption bleaching in the narrow GaAs wells is controlled directly by the AlGaAs barrier thickness. However, type I TBQ has additional optical absorption in wide GaAs wells.[5] This additional absorption is troublesome in developing cavity devices such as the etalon, since the absorption disturbs the sharp resonance profile of the cavity. To prevent optical absorption, we recently proposed a new type of TBQ in which the wide wells were replaced by AlAs indirect gap layers.[14] In the structure (referred to as type II TBQ), photoexcited electrons in the GaAs wells escape by tunneling through AlGaAs barriers to X states in AlAs. Since the X states of the AlAs do not contribute to optical absorption, type II TBQ is free from the additional absorption. Also, the recovery time is controlled directly by the AlGaAs barrier thickness. In this letter, we report the picosecond signal recovery, in all-optical gate operation, of an etalon using type II TBQs.

The type II TBQ etalon consists of 14 periods of 57.7-nm thick $Al_{0.25}Ga_{0.75}As$/65.4-nm thick AlAs quarter-wave Bragg reflectors as the back mirror; 102 periods of type II TBQs with 2.8-nm thick GaAs quantum wells, 7.1-nm thick AlAs wells, and 1.7-nm thick $Al_{0.51}Ga_{0.49}As$ barriers; and 9 periods of $Al_{0.25}Ga_{0.75}As$/AlAs Bragg reflectors for the front mirror. The structure was grown monolithically on a semi-insulating (100) GaAs substrate by molecular beam epitaxy. Figure 2 shows the reflection spectrum for the type II TBQ etalon. We can clearly observe a cavity resonance at 770.2 nm with a width of 3 nm (full width at half maximum) and the *e*1-*hh*1 excitonic absorption peak in GaAs wells at 745 nm. The effective mirror reflectivity is 78%, estimated from the measured finesse of 13.

We measured the change in intensity of the type II TBQ etalon's reflection beam using two-wave time-resolved pump-probe measurement. Two tunable mode-locked dye lasers, one using Pyridine 1 and the other Styryl 8, were synchronously pumped by compressed YAG laser pulses at 82 MHz. The generated pulse widths of pump and probe pulses were 1–2 ps. The pump beam intensity was 1.8 mW in front of the sample and focused on a 15-μm diam spot. At this intensity, pump energy per pulse was 120 fJ/μm^2. The pump beam was modulated at 6 MHz by

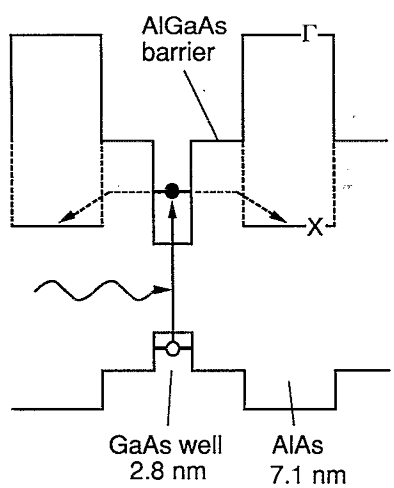

FIG. 1. Energy band diagram of type II TBQ structure. The type II TBQ structure consists of GaAs wells, AlGaAs barriers, and AlAs layers. The photoexcited electrons in GaAs wells escape through AlGaAs barriers by tunneling toward X states in AlAs layers.

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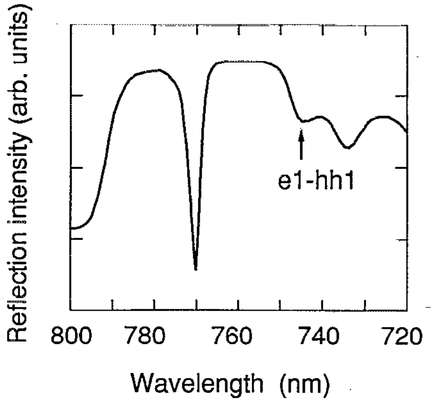

FIG. 2. Reflection spectrum for the type II TBQ etalon at room temperature. A cavity resonance is at 770.2 nm and the peak at 745 nm is the *e*1-*hh*1 excitonic absorption peak in GaAs wells.

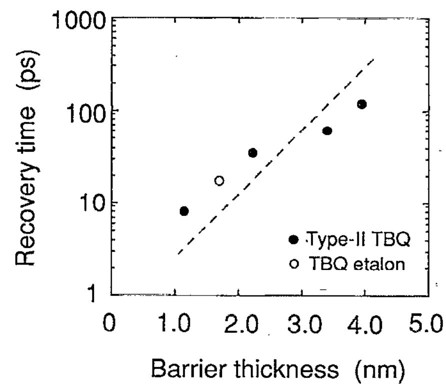

FIG. 4. Semilogarithmic plot of the experimental recovery time of type II TBQ systems as a function of barrier thickness.

an EO-modulator for lock-in amplification. Optical delay was moved by a stepping motor. The time resolution was about 7 ps due to jitter of two dye lasers. The pump beam wavelength was 700 nm which is outside the high-reflectivity wavelength region of the Bragg reflectors.

Figure 3 shows the change in intensity of light reflected from the type II TBQ etalon at 768.7 and 771.8 nm. All-optical gate operation is indicated by the shift of the resonance peak toward shorter wavelength. Note that a fast signal recovery is realized by carrier tunneling. The recovery time is 17 ps in single exponential fitting. There is also a slow recovery tail following the fast relaxation. The tail has a magnitude of about 50% of the initial signal change with a time constant slower than 1 ns. This is very similar to the time evolution of *e*1-*hh*1 excitonic absorption changes of type II TBQs.[14] In type II TBQs, only electrons can escape from GaAs wells. Since we tuned the wavelength to the half maximum of the resonance peak, where the reflection intensity shows almost linear dependence on the wavelength, the intensity change is almost proportional to the refraction change. We attribute the slow recovery

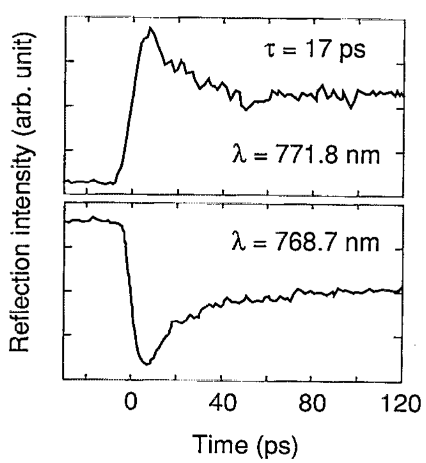

FIG. 3. Intensity change in the reflection light from the type II TBQ etalon at 768.7 and 771.8 nm. Gate operation by the shift of the resonant peak toward shorter wavelength and a fast signal recovery of 17 ps are observed.

tails to refractive effect by holes left in the GaAs wells. As for the peak to tail magnitude ratio, it will be improved by tuning the initial wavelength to the high-energy side of the resonance peak, where the reflection intensity shows a nonlinear dependence on the wavelength.

Figure 4 shows the semilogarithmic plot of experimental recovery time for type II TBQ systems as a function of barrier thickness. We also show the recovery time from *e*1-*hh*1 excitonic absorption bleaching in type II TBQs.[14] The type II TBQ samples consist of 50 periods of 2.8-nm thick GaAs quantum wells, 7.1-nm thick AlAs wells, and $Al_{0.51}Ga_{0.49}As$ barriers. By thinning barriers to 1.1 nm, the absorption recovery time of type II TBQ is reduced to 8 ps. Since the cavity response time, $2nL/c(1\text{-}R) \simeq 230$ fs (where n, refractive index; L, cavity length; c, velocity of light in free space, and R, reflectivity), of the present etalon is much shorter than the observed signal recovery time of 17 ps, 17 ps is regarded as the recovery time from excitonic absorption bleaching of the type II TBQ with 1.7 nm barriers. The nearly linear dependence of the experimental recovery times of type II TBQ and the type II TBQ etalon, on the semilogarithmic plot, indicates that their recovery time is controlled by a tunneling process. This also indicates that signal recovery time can be reduced further by thinner barriers.

For designing an optimum device such as an etalon, it should be noted that controlling absorption recovery time is very important. Generally, to develop high speed devices, faster recovery is required for the nonlinear medium. However, for low power operation, the recovery which is too fast is not appropriate. In switching devices with a cavity such as the etalon, the maximum signal change is obtained at the time when both the absorption bleaching and the cavity buildup (or decay) of photons are completed. To ensure the maximum carrier density in quantum wells for complete absorption bleaching, the recovery time must be longer than the pump pulse width. Also, the recovery time should be slower than the cavity response (buildup or decay) time. In the etalon, since the refraction change by photoexcitation occurs as fast as absorption bleaching, the switching time is determined by the cavity response time. If the cavity response time is slower than the recovery time of the nonlinear medium, absorption bleaching recovery occurs before completion of the cavity buildup (or decay). The dependence in Fig. 4 indicates a wide-range controllability of recovery time in type II TBQ by changing barrier thickness. This shows the advantage of type II TBQs for cavity device design to obtain the most efficient and the fastest response for given cavity characteristics and pulse width. The type II TBQ is appropriate for constructing cavity devices which require a picosecond response.

In summary, we demonstrated the optical gate operation of a Fabry–Perot etalon using a type II tunneling bi-quantum well (TBQ) etalon structure. In type II TBQs, photoexcited electrons in the GaAs wells escape by tunneling through the AlGaAs barriers toward X states in the AlAs layers. Therefore, the recovery time from excitonic absorption bleaching in GaAs wells is controlled directly by the AlGaAs barrier thickness. The type II TBQ etalon with 1.7 nm barriers showed a signal recovery of 17 ps by carrier tunneling. This result proves the high potential of type II TBQ for cavity device applications which require a high-speed response and response time controllability.

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[1] H. M. Gibbs, S. S. Tarng, J. L. Jewell, D. A. Weinberger, K. Tai, A. C. Gossard, S. L. McCall, A. Passner, and W. Wiegmann, Appl. Phys. Lett. **41**, 221 (1982).
[2] A. Migus, A. Antonetti, D. Hulin, A. Mysyrowicz, H. M. Gibbs, N. Peyghambarian, and J. L. Jewell, Appl. Phys. Lett. **46**, 70 (1985).
[3] W. H. Knox, R. L. Fork, M. C. Downer, D. A. B. Miller, D. S. Chemla, C. V. Shank, A. C. Gossard, and W. Wiegmann, Phys. Rev. Lett. **54**, 1306 (1985).
[4] D. S. Chemla, D. A. B. Miller, P. W. Smith, A. C. Gossard, and W. Wiegmann, IEEE J. Quantum Electron. **QE-20**, 265 (1984).
[5] A. Tackeuchi, S. Muto, T. Inata, and T. Fujii, Jpn. J. Appl. Phys. **28** L1098 (1989).
[6] A. Tackeuchi, S. Muto, T. Inata, and T. Fujii, Appl. Phys. Lett. **58**, 1670 (1991).
[7] S. Muto, T. Inata, A. Tackeuchi, Y. Sugiyama, and T. Fujii, Appl. Phys. Lett. **58**, 2393 (1991).
[8] Y. Sugiyama, A. Tackeuchi, T. Inata, and S. Muto, Jpn. J. Appl. Phys. **30**, L1454 (1991).
[9] A. Tackeuchi, S. Muto, T. Inata, and T. Fujii, Jpn. J. Appl. Phys. **30**, 2730 (1991).
[10] J. L. Jewell, M. C. Rushford, and H. M. Gibbs, Appl. Phys. Lett. **44**, 172 (1984).
[11] J. L. Jewell, A. Scherer, S. L. McCall, A. C. Gossard, and J. H. English, Appl. Phys. Lett. **51**, 94 (1987).
[12] A. Tackeuchi, H. Kitada, H. Arimoto, Y. Sugiyama, A. Endoh, Y. Nakata, T. Inata, and S. Muto, Appl. Phys. Lett. **59**, 1114 (1991).
[13] Y. Silberberg, P. W. Smith, D. A. B. Miller, B. Tell, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. **46**, 701 (1985).
[14] A. Tackeuchi, T. Inata, Y. Sugiyama, Y. Nakata, S. Nakamura, and S. Muto, Jpn. J. Appl. Phys. **31**, L669 (1992).