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Influence of Type-I to Type-II Transition by an Applied Electric Field on Photoluminescence and Carrier Transport in GaAs/AlAs Type-I Short-Period Superlattices

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We have investigated the influence of type-I to type-II transition by an applied electric field on photoluminescence and carrier transport in GaAs/AlAs short-period superlattices, by time-of-flight experiments. We confirmed the type-I to type-II transition by observing degenerated photoluminescence spectra. The rise time of the time-resolved photocurrent was found to increase by the type-I to type-II transition. This result clearly shows that the tunneling time through type-II alignment is longer than that of through type-I alignment.

1. Introduction

Optical and electrical characteristics of superlattices and multi-quantum-well (MQW) structures applied in novel devices have been energetically investigated. GaAs/AlAs superlattices can be classified into two types: type-I where electrons and holes are confined to the same layer and type-II where they are confined to the adjacent layers. Although the classification depends on differences in layer thickness, a type-I to type-II transition can be achieved using the same superlattice structure by applying an electric field perpendicular to the layers. Meynadier *et al.* reported the effect of a type-II to type-I transition by applying an electric field on the photoluminescence (PL) property of a type-II MQW; they confirmed Γ-X mixing[1].

Self-electro-optic effect devices [2] based on Wannier-Stark localization (WSL) in thin-barrier superlattices [3] are expected to be useful in achieving ultra-fast opto-electric devices. In order to confirm the high-speed operation, the large amount of photo-generated carriers must be quickly swept out from the MQW, so as not to saturate the optical absorption. In the case of superlattice devices with a thin barrier thickness, such carriers mainly move by tunneling through the barriers, not by thermionic emission. It is widely accepted that the tunneling time steeply decreases with decreasing barrier thickness and with increasing applied electric field[4]. However, we have found a novel phenomenon of carrier transport in type-I short-period superlattices by time-of-flight experiments; an anomalously delayed photocurrent (Pc) component is most likely caused by the effect of X-valley states on the carrier transport[5]. It is not very clear what influence the X-valley states have on the carrier transport. Moreover, there have been no reports on the carrier transport process and PL properties of the type-I to type-II transition in short-period superlattices. In this paper, we study PL spectra and time-resolved Pc in short-period superlattices that can be switched from type-I to type-II.

2. Experimental

We used a *p-i-n* diode with a 50 μm square mesa and the intrinsic layer consisting of a (100)-oriented 100-period GaAs/AlAs (31Å/17Å) superlattice sandwiched by 500Å undoped $Al_{0.4}Ga_{0.6}As$ cladding layers. Figure 1 shows a fan-chart of Γ and X energy levels. A transfer matrix method with envelope function approximation was used. The Γ conduction band offset for GaAs/AlAs was set to between 66 and 67 % of the band gap discontinuity [6]; therefore, we assumed the bottom of the X-valley to be 175 meV from the GaAs conduction band. This superlattice was designed such that the Γ-valley ground state in the GaAs well would stay at a higher potential energy than the X-valley ground state in the adjacent AlAs barrier when the reverse bias voltage exceeded 5 V, and the sequential resonant tunneling could not occur below 22 V. The photoluminescence wavelength of Γ1-hh1 in the WSL formation was about 695 nm. The time-of-flight experiments were performed using the second harmonics of a mode-locked Ti-Sapphire laser (430 nm, 82 MHz repetition rate, 600 fs pulse duration), and a sampling oscilloscope. The laser beam was focused by a 10x objective lens on the p-cap layer of the sample and its diameter was about 20 μm. A PL signal was coupled through the same objective lens into a set comprising a monochromator and a high-sensitivity streak camera.

3. Results and Discussion

Figure 2 shows PL spectra measured by the streak camera at 20 K. When the reverse bias voltage (V_b) was 4 V, the peak of the PL intensity occurred at about 703 nm. This wavelength is a little longer than the $\Gamma 1$-hh1 optical transition. We consider that the WSL cannot be resolved under 4 V; as a result, the optical transition from the bottom of the $\Gamma 1$ miniband makes the PL wavelength slightly long. The PL spectra at 4 and 4.5 V showed a shoulder at the left side of the peak. We consider that it was created by the $X1$-hh1 optical transition, and it gradually increased with increasing electric field, because $X1$ was located closer to $\Gamma 1$. When V_b was 5 V, the PL spectrum was split and had two peaks by Γ-X mixing. We consider this profile to give evidence that the large amount of carriers remained in the X-valley energy level. The wavelength difference was about 8 nm, corresponding to 20 meV. When V_b was 6V, the direct optical transition wavelength appeared at 695 nm; this agrees well with a simple envelope function calculation. The PL spectra at 5.5 and 6 V showed a shoulder at the right side of the peak. It was probably created by the $X1$-hh1 optical transition, and it gradually decreased with increasing electric field and finally vanished.

A time-resolved Pc excited by an optical pulse at 20 K is shown in Fig. 3. The Pc decay curves did not show any delayed component as reported in Ref. 5. When V_b was varied from 0 to 3 V, the Pc response time became faster, because the tunneling time decreased with increasing electric field. However, when V_b was above 5 V and the band configuration was changed to type-II, the Pc response time became slow. In particular, the rise time of Pc became longer. This results indicate that the tunneling time becomes longer in type-II than in type-I. Above 5 V, the carriers in the Γ levels could relax into adjacent X levels and subsequently relax into adjacent Γ levels by the emission of a phonon, because the X level was located between Γ and the next Γ as shown in Fig. 4. Therefore, carriers can move not only by sequential tunneling from Γ to the next Γ directly but also by Γ-X-Γ transfer. We consider that the delayed rise time of the Pc was mainly caused by Γ-X-Γ transfer, because the Γ-Γ sequential tunneling time is known to gradually decrease with increasing electric field if the sequential resonant tunneling does not occur[4),7)]. At 14 V, the rise time of the Pc became the longest, and the energy difference between Γ and its adjacent X level became closer to the GaAs LO-phonon energy (36 meV). This results says that the maximum number of carriers in the Γ levels can transfer to the adjacent X levels at around 14 V because the phonon-assisted Γ-X transfer rate becomes maximum. We consider that if the number of carriers in the X levels increases, the Pc response time becomes longer, because the subsequent X-Γ transfer must take a much longer time than the Γ-Γ sequential tunneling [8)].

4. Conclusion

We have investigated, for the first time, the influence of type-I to type-II transition by an applied electric field on PL and time-resolved Pc in GaAs/AlAs type-I short-period superlattices. We confirmed the type-I to type-II transition by observing degenerated PL spectra. Furthermore, we found that the Pc response time becomes slow when the band configuration is changed to type-II. This result clearly indicates that the carrier transport process is seriously affected by the type-I to type-II transition.

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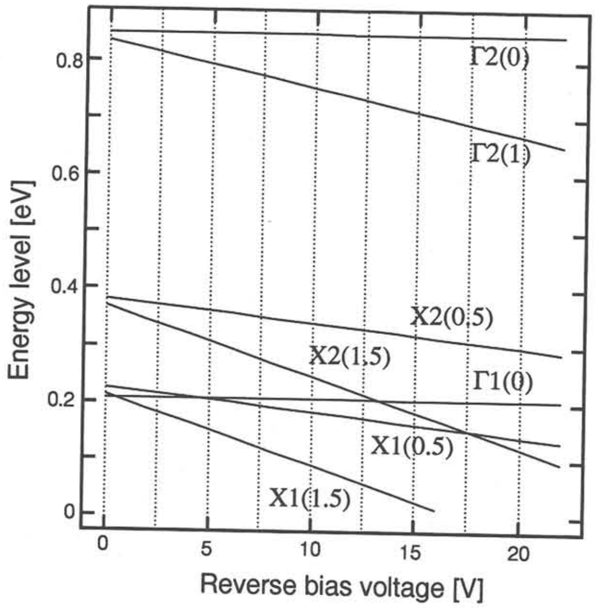

Figure 1: Fan chart of calculated Γ and X states in a GaAs/AlAs (31Å/17Å) superlattice embedded in a *p-i-n* structure. The built-in voltage was about 1.5 V. An envelope function approximation was used for numerical calculations. $\Gamma n(0)$ and $\Gamma n(1)$ denote the n-th Γ states in a GaAs well and in the next well, respectively. $Xm(0.5)$ denotes the m- th X states in the adjacent AlAs barrier. $\Gamma 1(0)$-$X1(0.5)$ mixing occurs at about 5 V.

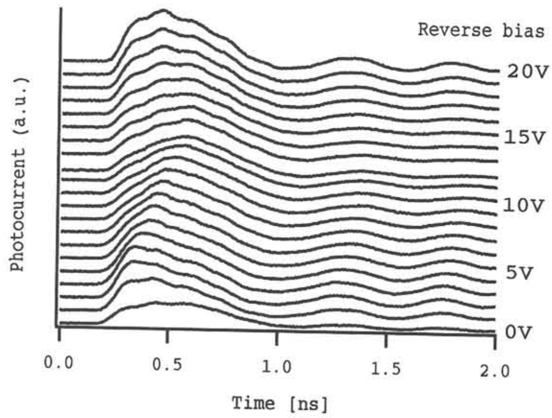

Figure 3: Time-resolved photocurrent taken at intervals of 1 V from 0 to 20 V at 20 K. The excitation intensity was 150 W/cm^2.

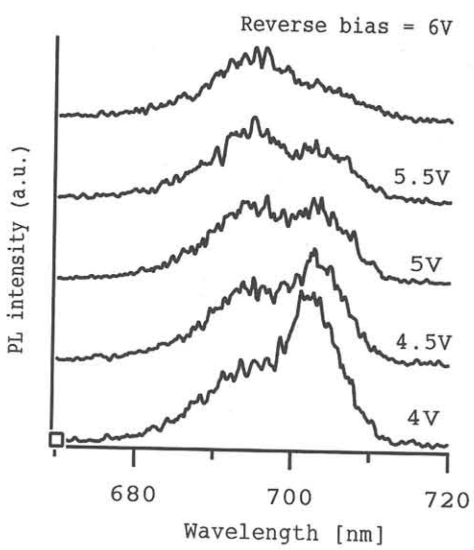

Figure 2: Photoluminescence spectra of a superlattice taken at around 5 V, under irradiation with an 82 MHz repetition rate, 430 nm wavelength, and 600 fs light pulse from a mode-locked Ti-Sapphire laser with a 20 μm beam diameter. The excitation intensity was 15 W/cm^2

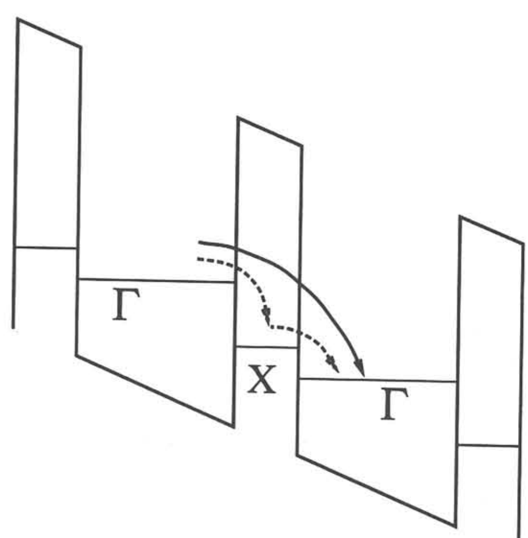

Figure 4: Schematic illustration of carrier transport. The solid arrow shows Γ-Γ sequential tunneling. The dashed arrow shows Γ-X-Γ transfer.