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Stark Ladder Photoluminescence of X States in GaAs/AlAs Type-I Superlattices

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We report on the observation of the Stark ladder photoluminescence of X states in GaAs/AlAs type-I superlattices. The photoluminescence line exhibits a linear blue shift corresponding to one half the period of the superlattice with increasing bias voltage. The PL intensity then becomes maximum when X1-Γ2 mixing occurs. These results demonstrate that optical properties even in type-I superlattices are seriously affected by X states mixing with a higher Γ subband under an electric field.

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1. Introduction

Since the first proposal of semiconductor superlattices, their electrical and optical properties have been energetically investigated to research their fundamental physics and their applicability to novel devices. Carrier scattering into X states in barriers has been mainly investigated for type-II superlattices. This is because almost all electrons stay in the lowest X state in the type-II superlattice due to the indirect band configuration. Thus, it is easy to research the X electron's properties directly in type-II superlattices. Field-induced Γ-X anti-crossing[1)] and Γ-X scattering time[2)] have been observed in type-II superlattices. Conversely, there are few electrons in the X states in type-I superlattices. However, very recently, carrier transport in type-I GaAs/AlAs short-period superlattices has been found to be drastically affected by X states.[3)] An anomalously delayed photocurrent is caused by Γ-X carrier transfer. It is evident therefore that electrical conductivity even in type-I superlattices is seriously affected by the X states.

In this report, we present an observation of X1 Stark ladder photoluminescence (PL) spectra originating from X1-Γ2 mixing in type-I GaAs/AlAs superlattices under an applied electric field.

2. Experimental

The two samples studied are *p-i-n* heterostructure diodes grown on (100)-oriented n^+-GaAs substrates by molecular-beam epitaxy (MBE). Each sample consists of an n^+-GaAs (0.2 μm, 10^{18} cm^{-3} Si doping) buffer layer, an n-$Al_{0.4}Ga_{0.6}As$ (1 μm, 5×10^{17} cm^{-3} Si doping) cladding layer, an intrinsic layer, a p^+-$Al_{0.4}Ga_{0.6}As$ (0.2 μm, 10^{18} cm^{-3} Be doping) cladding layer, and a p^+-GaAs (10 nm, 5×10^{18} cm^{-3} Be doping) cap layer. The intrinsic regions of samples "A" and "B" consist of 100-period GaAs/AlAs superlattices, having 22/18 monolayers and 22/12 monolayers, respectively. The superlattice regions are sandwiched by undoped 500 Å $Al_{0.4}Ga_{0.6}As$ cladding layers. The samples are kept at 20 K in a cryostat. The built-in voltage of the samples is about 1.5 V. A He-Ne laser beam is focused by a 10× objective lens on the *p*-cap laser of the samples to excite carriers in the superlattice over an area with a diameter of about 20 μm. The samples are structured into 400 μm square mesas. Alloyed Au electrodes are prepared to apply the electric field to the intrinsic region, and the ohmic contact is confirmed by measurement of the forward biased current-voltage characteristics. The PL spectra are detected by a streak camera (Hamamatsu C4334).

3. Results and Discussion

Figure 1 shows the electron's energy level diagram of samples A and B at 20 K as a function of reverse bias voltage. The calculation contains the non-parabolicity effect on Γ electron's effective masses. The calculated Γ subbands agree well with the measured photocurrent spectra. Though electrical properties can be expected to be influenced by any energy level resonance, our research is mainly focused on the electric field that causes X1-Γ2 mixing, because delayed carrier transport in type-I superlattices is found to arise from X1-Γ2 transfer.[3)] In sample A, X1-Γ2 mixing occurs at 39 V. The X1-Γ2 mixing of sample B is found to occur at 28 V by calculation as shown in Fig. 1-b. A schematic illustration of the X1-Γ2 mixing is shown in Fig. 2.

Figures 3 and 5 show the measured PL spectra as a function of reverse bias voltage under cw He-Ne laser excitation in samples A and B, respectively.

Figure 3-b shows a PL line at around 760 nm of sample A, showing a red shift by the quantum confined Stark effect (QCSE). This can be identified as the Γ1-hh1 PL.

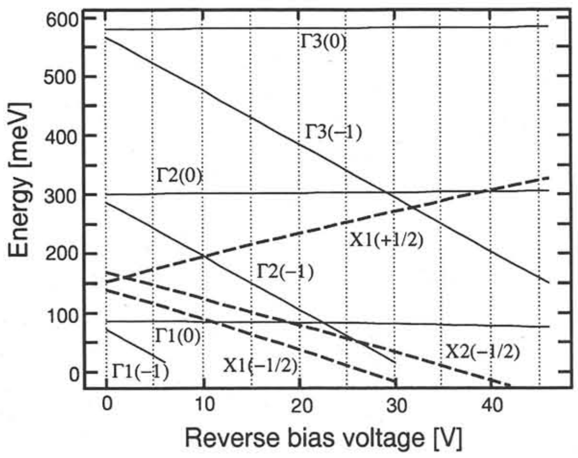

Figure 1-a: Sample A. The X1-Γ2 mixing occurs at 39 V.

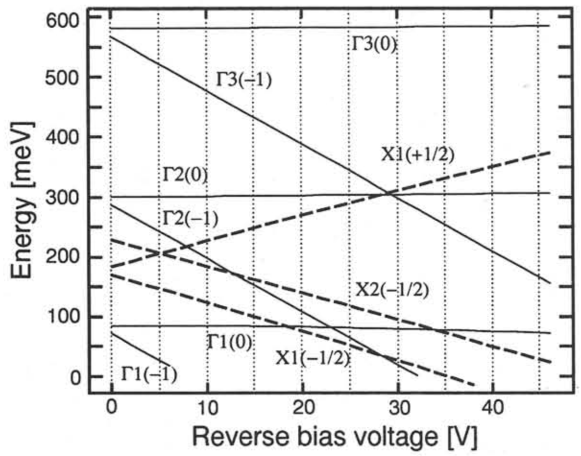

Figure 1-b: Sample B. The X1-Γ2 mixing occurs at 28 V.

Figure 1: Calculated electron's subband diagrams of sample A and B as a function of reverse bias voltage. The solid lines represent Γ subbands, while the broken lines represent X subbands, respectively.

On the other hand, the PL line of a higher subband at 675 nm (in Fig. 3-a) is observed at around 39 V. The energy 1.836 eV corresponding to the PL wavelength at 39 V agrees well with the Γ2-hh1 optical transition energy. This higher subband PL also shows a blue shift with increasing electric field. The blue shift agrees well with the calculated X1(+1/2) Stark ladder transition, as shown in Fig. 1-a. The blue-shifted PL intensity increases with increasing electric field and becomes maximum at 39 V as shown in Fig. 4. This indicates that the blue-shifted PL intensity depends on the energy difference between X1 and Γ2 and becomes maximum at around 39 V due to the X1-Γ2 mixing. This voltage causing the X1-Γ2 mixing also agrees well with the calculation. Therefore, the blue-shifted higher subband PL can be identified as an X1(+1/2) Stark ladder.

The emission of X1-hh1 PL clearly indicates that a certain amount of electrons are trapped in X1 states. However, the X1-hh1 PL does not occur until the X1-Γ2 mixing occurs. For type-II superlattices, the oscillator

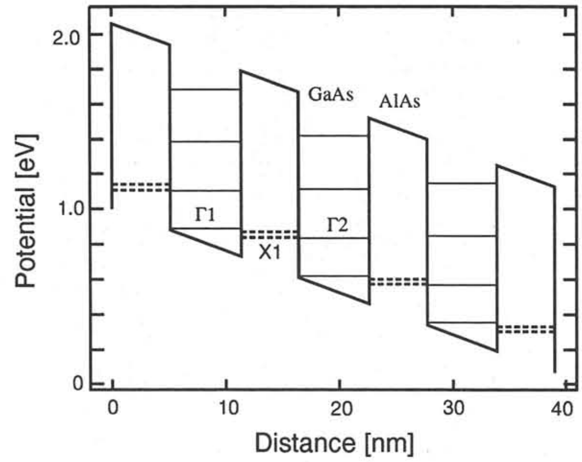

Figure 2: A schematic illustration of X1-Γ2 mixing of sample A in an applied bias voltage. Solid lines in GaAs wells represent Γ states, while broken lines in AlAs barriers represent X states.

strength for radiative transition between X1 electrons and heavy holes depends on the energy difference between X1 and Γ1.[4)] Conversely, for the studied samples, since the closest Γ state to X1 is Γ2 because of the type-I band configuration, the X1-hh1 PL intensity is determined by the X1 and Γ2 energy difference. Figure 4 clearly suggests that the X1 PL intensity depends on the X1-Γ2 mixing and becomes maximum when the X1 and Γ2 energy difference is minimum due to the X1-Γ2 mixing. The PL intensity decreases with a further increase in the bias voltage while maintaining its wavelength rather constantly. This constant wavelength corresponds to the Γ2-hh1 transition energy.

A similar phenomenon is also observed in sample B. Figure 5 shows a Γ2-hh1 PL at 25 V at 675 nm originating from Γ1-Γ2 resonance and a blue-shifted PL line originating from an X1-hh1 radiative transition. The intensity of the blue-shifted X1-hh1 PL becomes maximum at 28 V due to X1-Γ2 mixing. The energy shift corresponding to the field-induced blue shift agrees well with the X1(+1/2) Stark ladder.

In conclusions, we have observed the Stark ladder PL in type-I GaAs/AlAs superlattices for the first time, to our knowledge. The PL intensity depends on the X1 and Γ2 energy difference and becomes maximum at the X1-Γ2 mixing voltage. The X1-hh1 PL line exhibits a linear blue shift corresponding to one half the period of the SL with increasing bias voltage. These results clearly suggest that the radiative recombination process even in type-I superlattices is seriously influenced by X states under an electric field.

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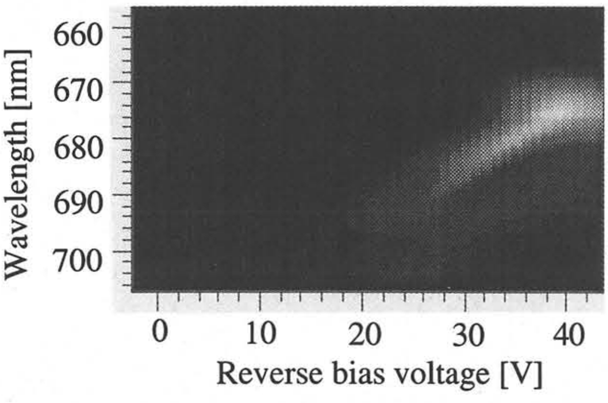

Figure 3-a: X1-hh1 PL spectra.

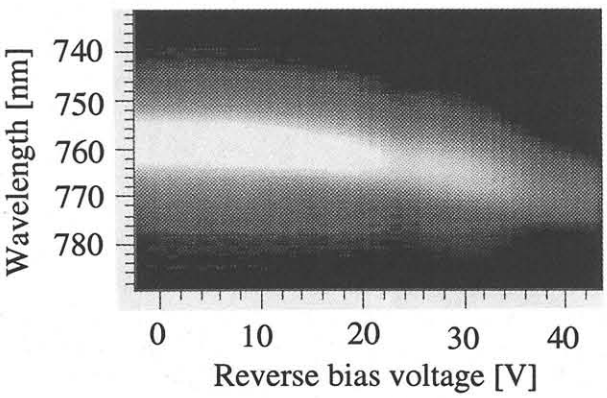

Figure 3-b: Γ1-hh1 PL spectra.

Figure 3: PL spectra of sample A versus reverse bias voltage. The brightness is proportional to logarithmic PL intensity. The excitation intensity was about 3.5 mW using a cw He-Ne laser. The intensity range is different in the two figures. Fig. 3-a shows an approximate 10^{-4} compared to that of Fig. 3-b for displaying a weak PL.

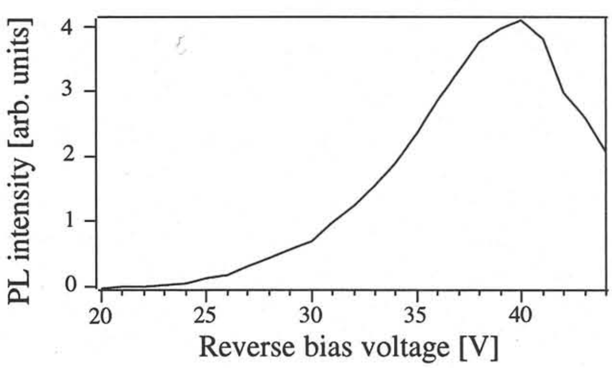

Figure 4: X1 PL intensity vs reverse bias voltage of sample A, plotting the data shown in Fig. 3-a.

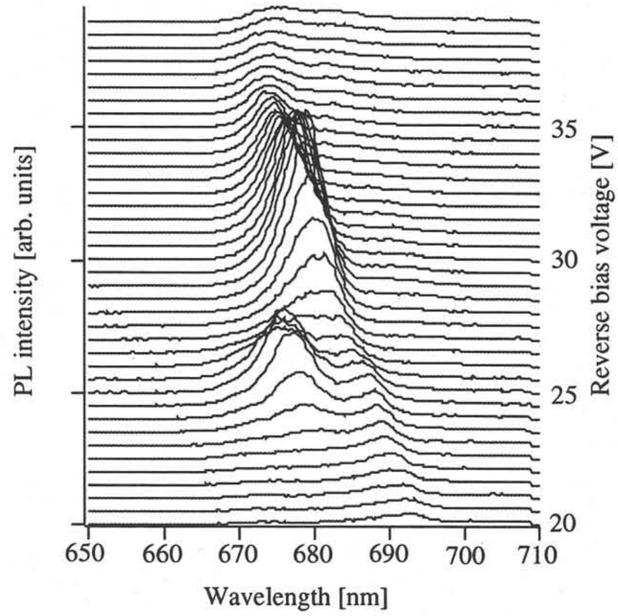

Figure 5: PL spectra of sample B versus reverse bias voltage. PL spectra are taken at intervals of 0.5 V from 20 V to 39 V. The excitation intensity is about 3.5 mW using a cw He-Ne laser.

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