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Formation Process of High-Field Domain in Superlattices Observed by Photoluminescence Spectra Branch

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1. Introduction

In weakly coupled superlattices (SLs), resonant tunneling in the conduction band between different Gamma subbands frequently shows high-field domain formation [1, 2]. For small carrier densities, the electric field distribution across the superlattice is homogeneous. However, for intermediate and large carrier densities, the formation of stable and oscillating electric-field domains has been reported in recent years [2-5]. The application of this oscillating behavior is expected as a microwave oscillator. The static domain shows no oscillation, and their current-voltage characteristics contain a number of current branches and discontinuities. Therefore, experimental investigation on the formation process of the high-field domain with varying the carrier density has been requested and studied from the viewpoint of both physics and applications [6, 7].

This paper studies formation process of the high-field domain by analyzing photoluminescence (PL) spectra. Changes in splitting feature of the PL spectra are observed with varying excitation carrier density at near the resonance voltages between the Γ states. This result clarifies how the inner electric field in superlattices varies with increasing the carrier density.

2. Experiments

The sample is a p-i-n heterostructure diode grown on (100)-oriented n^+-GaAs substrates by molecular beam epitaxy. The sample consists of an n^+-GaAs buffer layer, an n-$Al_{0.4}Ga_{0.6}As$ cladding layer, an intrinsic layer, a p-$Al_{0.4}Ga_{0.6}As$ cladding layer and a p^+-GaAs cap layer. The intrinsic region consists of a 50-period type-I GaAs/AlAs SL sandwiched by undoped 50 nm $Al_{0.4}Ga_{0.6}As$ cladding layers. The GaAs quantum well (QW) and AlAs barrier width is 9.7 nm and 3.7 nm, respectively. The focused laser beam (a cw He-Ne laser) was irradiated on the p-cap layer of the sample in a cryostat through a microscope objective lens. The beam diameter was about 20 μm. We measured photocurrents and PL spectra from the recombination between the first Γ state (Γ_1) and the first heavy hole state (hh_1) in QW under various excitation intensities and the bias voltages. All of the experiments were carried out at 20 K.

3. Results and Discussion

Figures 1 and 2 show the photocurrent (Pc) and the PL spectra as a function of the reverse bias voltage at 20 K. In Fig. 2, the brightness corresponds to the PL intensity. The calculated resonance voltages between the Γ_i states in the superlattice are about 7 V and 16 V for Γ_1-Γ_2 and Γ_1-Γ_3, respectively. As shown in Figs. 1 and 2a, there is a peak in the Pc and a dip in the PL intensity at 7 V, which correspond to almost the resonance voltages of Γ_1-Γ_2. Similar results, i.e., increase in the Pc and decrease in the PL intensity (quenching due to the improvement of the carrier sweep-out), are obtained near the resonance voltages of Γ_1-Γ_3. As represented by Fig. 2a, Γ_1-PL peak wavelength shows a red shift due to quantum confined Stark effect (QCSE). From the wavelength shift, inner electric field that is felt by the QWs in the superlattice is evaluated.

As indicated in Fig. 1, Pc under low and medium photo-excitation intensity (5μW and 0.1mW) shows a peak at 7 V, which supports increase in the electron drift velocity due to the Γ_1-Γ_2 resonance. Under high excitation density (5mW), Pc-V characteristics show a saw-tooth like feature, which indicates high-field domain formation. On the other hand, as shown in Figs. 2b-2d, the PL spectra for the same carrier densities as those in Fig. 1 show peculiar behaviors at around the Γ_1-Γ_2 resonance voltage. Under low carrier density in Fig. 2b, two PL branches A and B belong different QCSE branches between lower and higher voltages of Γ_1-Γ_2 resonance point (7 V). Under a medium excitation carrier density shown in Fig. 2c, the QCSE shift has a continuity. Under further high carrier density in Fig. 2d, two PL branches A and C coexist at around the resonance voltage. This coexistence indicates that two domains, i.e., low and high electric field domains exist in the superlattice, and supports that high-field domain formation occurs as shown in Fig. 1.

The anomaly in PL spectra is clearly interpreted by considering the capacity of current flow characteristics versus the inner electric field, as schematically illustrated in Fig. 3. Under low carrier density, i.e. low current flow **j1**, stacked carriers by low drift velocity below the Γ_1-Γ_2 resonance point F1 weakly modify the inner electric field and tend to move the electric field towards point A. At higher bias voltage after the resonance peak, this moving force tends to decrease the electric field towards point B, because the higher electric field, e.g. area D, suppresses the current flow and causes space charges. Therefore, two branches arise before and after the resonance peak, which supports the phenomenon in Fig. 2b. Under medium carrier density of the **j2** current flow, the cross section between current flow and the flow capacity is single point. This condition arises a continuous electric field variation as shown in Fig. 2c. Under high carrier density **j3**, excited carrier density exceeds over the capacity of current flow, and carriers are remained as a number of space charges. These space charges can sufficiently modify the inner electric field, and draw the resonance peak F2 positioned at higher electric field.

Thus, the two electric field domains coexist, as shown in Fig. 2d.

In addition to the Γ_1 PL observation, we have measured PL from higher subbands. PL from Γ_2 and Γ_3 was clearly observed at each Γ_1-Γ_2 and Γ_1-Γ_3 resonance voltages, which supports the background of the analysis in this report.

4. Conclusions

We have studied PL spectra relating to the high-field domain formation. We have found anomalous split of the QCSE branch in the PL spectra. This result was explained with simple analysis of an electric-field dependent current-flow capacity model, and clarified the formation process of high-field domain. It was especially shown that there was a modification of the inner electric field even under a low carrier density.

References

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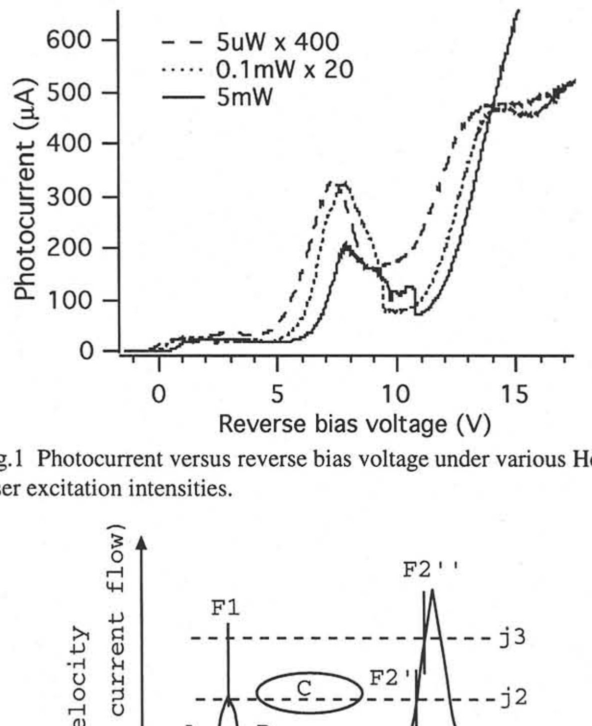

Fig.1 Photocurrent versus reverse bias voltage under various HeNe laser excitation intensities.

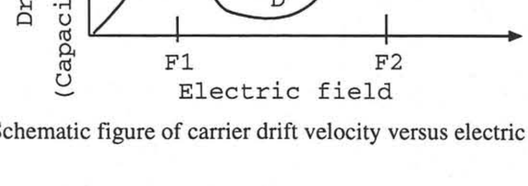

Fig.3 Schematic figure of carrier drift velocity versus electric field.

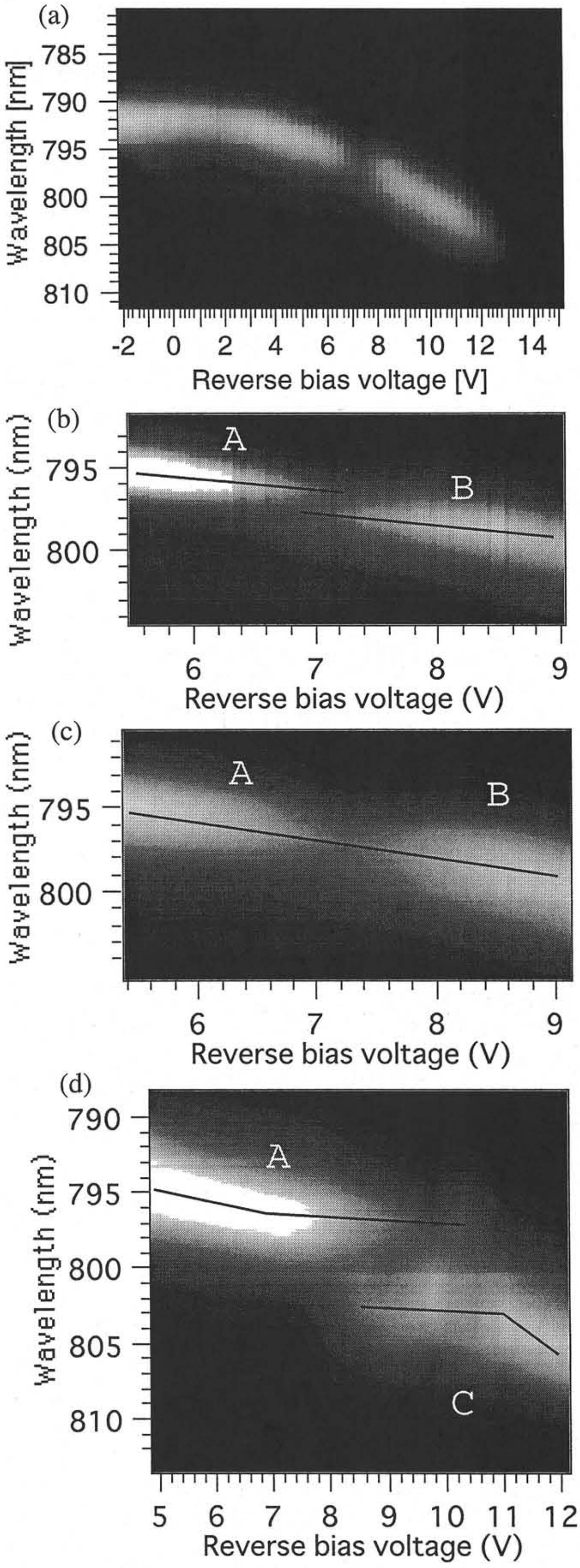

Fig.2 PL spectra as a function of the reverse bias voltage. HeNe laser intensity: (a) 0.1mW, (b) 50μW, (c) 0.1mW, (d) 5mW. The brightness corresponds to the PL intensity.