Bias polarity dependence of carrier injection into high-energy states in asymmetric GaAs/AlAs multiple-quantum wells embedded in an n-i-n diode

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Abstract. We investigated the electric field dependence of photoluminescence (PL) spectra from a GaAs/AlAs asymmetric multiple-quantum well (AMQW) embedded in an n-i-n diode. The bias polarity dependence of the PL spectra caused by the difference of the subband resonances was observed. In the forward bias voltage regime, PL from the narrower QW was observed due to carrier injection by an X state in the thick AlAs barrier. The PL intensity strictly depends on the carrier injection caused by the $\Gamma$-X-$\Gamma$ and the LO-phonon-assisted transfers.

1. Introduction

Recently, mid-infrared light sources have been attracting much interest due to their applications in the fields of environmental sensing and optical wireless communication. The subband states in semiconductor multiple-quantum-well (MQW) structures are frequently used in applications of new photonic devices, such as quantum cascade lasers (QCLs) [1] and quantum well infrared photodetectors (QWIPs) [2]. In QCLs, asymmetric MQW (AMQW) structures are used to easily cause population inversion. However, the experimental results and the interpretations of these systems are very complex. Moreover, reports are scarce on resonances between higher energy subband states and related carrier transport. Very recently, however, complicated carrier transport paths and photoluminescence (PL) spectra in biased AMQWs originating from $\Gamma$-X resonances between excited states have been observed [3, 4]. In this paper, we report the observation of the bias polarity dependence of PL spectra in GaAs/AlAs AMQWs caused by the difference of subband resonances.

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2. Experimental and sample structure
The sample was grown on a (001)-oriented n'-GaAs substrate by molecular beam epitaxy (MBE). The growth sequence is an n'-GaAs buffer layer, an n-GaAs layer, an n'-GaAs layer, an undoped 20-period AMQW structure, an n'-GaAs layer, an n-GaAs layer, and finally an n'-GaAs cap. One period of the AMQW structure consists of an AlAs/GaAs/AlAs/GaAs/AlAs/GaAs/AlAs/GaAs heterostructure of 15/11/2/2/2/2/2/15 monolayer (ML) thickness from the n-substrate to the n-cap (Figure 1). Note that the first and last barrier layers are delta-doped. The diode was fabricated into 400-μm square mesas with alloyed Au electrodes as contacts. In this paper, forward bias is defined as applying a positive voltage to the n-cap, while reverse bias is defined as applying a positive voltage to the substrate. A He-Ne laser is irradiated on the n'-GaAs cap layer through a 10x objective lens to excite the carriers in the intrinsic region. PL signals are detected using a cooled CCD. All PL measurements were performed at 20 K.

3. Results and discussion
Figures 2(a) and (b) show PL spectra as a function of forward and reverse bias voltages. The observed PL properties strictly depend on the direction of the bias voltage.

Fig. 1. Schematic illustration of subband energies of conduction and valence bands in AMQWs under flatband condition. Thick arrows denote recombination transition. Left direction is n-cap side of n-i-n diode.

Fig. 2. Electric field dependence of PL spectra as functions of: (a) forward bias voltage and (b) reverse bias voltage for a laser intensity of 0.05 mW. Brightness is proportional to PL intensity. Broken lines are eye guides for electric field dependence of recombination energies.
In the forward bias voltage regime, two kinds of PL signals are observed around 685 and 730 nm. The PL intensity around 730 nm becomes strong at around 3.5 V. In addition, the PL signal around 685 nm becomes strong at 7.5 V. Moreover, with further increase of the forward bias voltage, two PL signals are red-shifted. To assign the origin of these PL signals, we performed transfer matrix calculation on the Γ, X, heavy hole, and light hole subbands in the context of effective mass approximation.

Based on the calculations, the PL signal around 730 nm can be attributed to the recombination energy between the electron ground state (Γ1) and the hole ground state (hh1) in the 15 ML QW (WQW), while the PL signal around 685 nm can be attributed to the recombination energy in the 11 ML QW (NQW). The broken lines in Figs. 2(a) and (b) are eye guides for the electric field dependence of the recombination energies including exciton binding energies. The red-shift of the two PL signals above 8 V is most likely caused by thermal effect due to an increase of photocurrent.

Figure 1 shows the alignments of the subband energies under a flatband condition. The Γ1 state in NQW (Γ1n) is type-II aligned under the flatband condition, because the adjacent X1 state in the thick AlAs layer is lower than the Γ1n state. Therefore, PL signal from NQW is not observed at 0 V.

![Schematic illustrations of subband energies in biased conduction band profiles at forward bias voltages of (a) 3.3 V, (b) 4.8 V, and (c) 7.5 V. Thick arrows denote carrier transport paths.](image)

To assign the origin of anomalous PL property when applying bias voltage, the carrier transport paths caused by subband resonance must be analyzed. Figs. 3(a), (b), and (c) show the alignments of the subband energies at 3.3, 4.8, and 7.5 V in the forward bias voltage, respectively. As shown in Fig. 3(a), the electrons in the Γ1 state in WQW (Γ1w) can tunnel to the next period by the X1 state in the thick AlAs barrier, because the Γ1w state is in resonance with the adjacent X1 state at 3.3 V. However, the ground state in NQW, which is the Γ1n state, is located above the adjacent X1 state. This means that electrons tunneling from the AlAs barrier cannot stay in NQW. Thus, electrons must subsequently tunnel through the three thin barriers and stay in the WQW. This carrier transport path results in strengthened 730 nm PL intensity around 3.5 V.

As shown in Fig. 3(b), however, electrons can stay in the Γ1n state above 4.8 V, because Γ1n and Γ1w are in resonance by the X1 state around 4.8 V. This Γ1w-X1-Γ1n carrier transport path leads to a radiative transition in NQW as well as observation of 685-nm PL above 4.8 V. The 730-nm PL intensity becomes weak above 4.8 V inversely because the Γ1w-X1-Γ1n carrier transfer decreases the population of electrons in the Γ1w state.
The 685-nm PL shows maximum intensity around 7.5 V. This is most likely caused by LO-phonon-assisted carrier injection into the \( \Gamma' \) state. The difference between the \( \Gamma' \) and X states is 36 meV at 7.5 V, as shown in Fig. 3(c), which corresponds to the GaAs LO-phonon energy. This indicates that the LO-phonon-assisted carrier injection into the \( \Gamma' \) state maximizes the population of electrons in the \( \Gamma' \) state.

On the contrary, a PL signal around 685 nm was not observed in the reverse bias voltage regime. Figure 4 shows the alignments of the subband energies at 5.6 V in the reverse bias voltage. Populations of holes concentrate in the WQW in the reverse bias voltage regime. In addition, electrons in the \( \Gamma' \) state relax into the adjacent X state in the thick AlAs barrier, because the X state is lower than the \( \Gamma' \) state. This leads to considerable decrease of the population of the electrons and holes in NQW.

Consequently, the anomalous PL property observed can be attributed to novel carrier transport paths that strictly depend on the resonant voltages of subband states.

4. Conclusion

We measured the electric field dependence of PL spectra from a GaAs/AlAs AMQW embedded in an n-i-n diode. The observed PL property strictly depends on the direction of the bias voltage. In the forward bias voltage regime, PL from a narrower QW was observed. The anomalous PL property strictly depends on the resonance of the \( \Gamma \) and X states. To analyze the electric field dependence of PL properties, novel carrier transport paths caused by the resonance of subband states must be found.

References

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