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Low-Temperature Photocurrent Measurements of Asymmetric Double-Well GaAs/AlAs Superlattices with Layer Sequence Inversion

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1. Introduction

Up to now, we have investigated additional structural modulation of semiconductor superlattices (SLs) to introduce further freedom into designing SLs. Asymmetric double-well SL (ADW-SL) has been reported, whose unit structure consists of an array of two different size wells separated by thin barriers with one thickness ($Lb/Lw_1/Lb/Lw_2$) [1-3]. In this structure, the spatially indirect Stark-ladder transitions are selectively observed reflecting the well coupling enhanced by the resonance between the electron ground states in the wide and narrow wells. In addition, the introduction of barrier sequence modulation into ADW-SLs ($Lb_1/Lw_1/Lb_2/Lw_2$) has enabled to control the selectivity of the spatially indirect ladder transitions [4].

In this paper, we introduce a new structural parameter into ADW-SLs, that is, superlattice sequence inversion with respect to applied electric field direction, ($Lb_1/Lw_1/Lb_2/Lw_2$) and ($Lb_2/Lw_1/Lb_1/Lw_2$), and investigate its effect on the ADW-SL optical transitions using low-temperature photocurrent (PC) spectroscopy.

2. Experimental

Two types of ADW-SL samples in a p-i-n diode configuration were grown on n-type GaAs(100) substrates by molecular beam epitaxy. The ADW-SLs are located in the intrinsic regions and are sandwiched between n- and p-type $Al_{0.4}Ga_{0.6}As$ cladding layers. A p-type GaAs cap layer was deposited on the top to form ohmic contact. The SL sequence in the unit structures from the substrate side is AlAs-0.46 nm/GaAs-3.11 nm/AlAs-1.42 nm/GaAs-3.68 nm for Sample A, and AlAs-1.42 nm/GaAs-3.11 nm/AlAs-0.46 nm/GaAs-3.68 nm for Sample B. Figures 1(a) and 1(b) show potential energy diagrams of the two samples under the flat band condition. The ground states in the wide (narrow) wells are coupled through the whole ADW-SL structure to form the lower (upper) minibands. Note that under the flat band condition there is no difference between the two cases of miniband structures in spite of the different SL sequence.

PC spectra were measured at 17 K using a halogen lamp connected to a monochromator for excitation and a computer-controlled electrometer for dc detection.

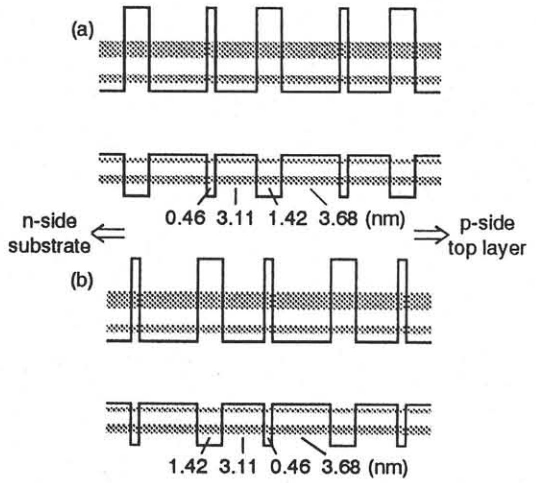

Fig. 1 Potential energy diagrams under the flat band condition of (a) AlAs-0.46 nm/GaAs-3.11 nm/AlAs-1.42 nm/GaAs-3.68 nm for Sample A, and (b) AlAs-1.42 nm/GaAs-3.11 nm/AlAs-0.46 nm/GaAs-3.68 nm for Sample B.

3. Results and discussion

Figures 2(a) and 2(b) show PC spectra of Samples A and B, respectively, as a function of applied bias voltage (V_b) between 1.2 V (forward bias) and −16 V (reverse bias). Dashed lines are guides to the eye to indicate the evolution of the PC peaks associated with the heavy-hole states. The spectra are vertically shifted for clarity. Under the applied low electric fields ($V_b > 1.0$ V, where the built-in-voltage is about 1.5 V), the shapes of the PC spectra of both samples resemble each other because the miniband structures are nearly the same. The optical transitions at 1.682 eV for Sample A and at 1.675 eV for Sample B are attributed to the superlattice excitonic transitions between the edge states of the lower electron and heavy-hole minibands. Moreover, the peaks at 1.783 eV for Sample A and at 1.781 eV for Sample B are related to the similar transitions between the upper electron and heavy-hole miniband states. Other peaks at 1.708 eV for Sample A and at 1.701 eV for Sample B are probably caused by the light-hole related SL transitions. The slight discrepancy between the peak energy positions may be due to deviations in the actual SL layer thickness from the designed values.

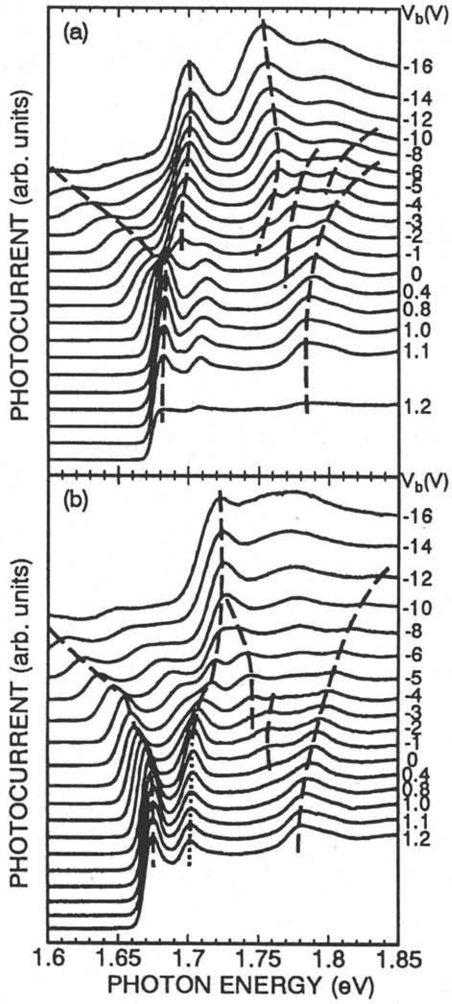

Fig. 2 Low-temperature (17 K) photocurrent spectra of Samples A (a) and B (b). Dashed lines indicate the evolution of the PC peaks associated with the heavy-hole states. The spectra are vertically shifted for clarity.

In the middle of the field range, some spatially indirect ladder transitions appear in the PC spectra. Their complex behaviors with the field increase can be interpreted by theoretical calculations using the transfer matrix method (TMM) within the effective mass approximation. In Sample B, it seems that the light-hole related transition which evolves from 1.701 eV at V_b = 1.2 V merges into a heavy-hole related transition. The border between them is not clear, so that the dotted line is used to indicate the unclearness.

At the highest applied field (V_b = –16 V), the observed peaks at 1.700 eV and 1.752 eV of Sample A are assigned to the heavy-hole related spatially direct Stark-ladder transitions in the wide and narrow wells, respectively, which are confirmed by TMM. On the other hand, the spatially direct transitions in the wide and narrow wells of Sample B are overlapped each other and are located at 1.723 eV.

The blue-shift values of the transitions in the wide wells induced by the applied field are, hence, 18 meV for Sample A and 48 meV for Sample B. This enhanced value of Sample B is interpreted as follows. Under the nearly flat band condition, the lower minibands repulse the upper ones because of the thin barriers in both samples, so that the center of the lower minibands shift to the lower energy side than the electron ground state in the spatially isolated wide well. This shift values of the two ADW-SLs are the same reflecting the sameness of their miniband structures. On the other hand, it is important to discuss the high field condition where the electron ground states in the wide and narrow wells of the ADW-SLs resonate to each other. The double well structures to make such resonance are GaAs-3.11 nm/AlAs-1.42 nm/GaAs-3.68 nm for Sample A and GaAs-3.11 nm/AlAs-0.46 nm/GaAs-3.68 nm for Sample B, which are counted from the lower potential side. Because the thinner barrier is inserted between the narrow well and the wide well located at the higher potential side in Sample B, the resonance is much stronger than that of Sample A. Consequently, the electron states in the wide wells of Sample B are pushed up with a larger degree than those of Sample A under the applied high filed after the resonance. The blue-shift value of Sample B is hence enhanced with the help of the stronger resonance.

4. Conclusions

In summary, we have investigated the effect of the SL sequence anisotropy on the Stark-ladder transitions of the ADW-SLs by low-temperature photocurrent spectroscopy. It found that the introduction of the SL sequence anisotropy results in drastic changes in the PC spectra under the high electric field application although the miniband structures under the flat band condition are the same.

References

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