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Valence Band Modulation in InGaAs/InAlAs Superlattices with Tensilely Strained Wells Grown on InGaAs Quasi-Substrate on GaAs

Kouji TOMINAGA, Makoto HOSODA and Toshihide WATANABE

ATR Optical and Radio Communications Research Laboratories
2-2 Hikaridai, Seika-cho, Soraku-gun, Kyoto 619-02 JAPAN

Kenzo FUJIWARA

Department of Electrical Engineering, Kyushu Institute of Technology
Tobata-ku, Kitakyushu 804 JAPAN

We have studied optical properties of strained InGaAs/InAlAs superlattices grown on an InGaAs quasi-substrate on GaAs by photoluminescence and photocurrent spectroscopy. The measurements were performed for two sample groups: one was Wannier-Stark type superlattices (SLs) with thin barriers and the other was quantum confined Stark effect type SLs with relatively thick barriers. In each group, we obtained evidences for modulation effects on the SL's band structure by tensile strain, which is controlled by the lattice constant of the InGaAs quasi-substrate.

1. INTRODUCTION

Self-electro-optic effect devices (SEEDs) using the quantum confined Stark effect (QCSE)[1)] or the Wannier-Stark localization (WSL) effect[2)] are attractive due to their low switching power, high sensitivity and integratability for optical modulator applications. Introducing strain into the superlattice (SL) in these devices is an effective way of improving their characteristics, because this enables us to design a desirable valence band structure. For example, a polarization-independent modulator based on the QCSE was studied using a strained $In_XGa_{1-X}AsP/In_YGa_{1-Y}AsP$ multi quantum wells (MQWs) on InP substrate[3)], and a transparent QCSE-type SEED was developed using strained InGaAs/(Al)GaAs MQWs on GaAs substrate.[4)] On the GaAs substrate, however, strain had been restricted to compressive strain in the well layer, because there had been no proper materials for a tensilely strained well layer whose bandgap energy and lattice constant are smaller than those of GaAs. In particular, it had been difficult to use strain effects in WSL-type devices due to the critical layer thickness problem, because the barrier thickness is much thinner than the well in WSL-type SLs. In this paper, we report observation of the WSL effect and the QCSE in (In)GaAs/InAlAs SLs prepared on InGaAs buffer layers grown on a GaAs substrate. Modulation of the SL valence band structure by changing the In content of the InGaAs buffer layer is demonstrated.

2. EXPERIMENT

The strained SLs were grown by molecular beam epitaxy on GaAs substrates, by introducing specially designed buffer layers consisting of two sections. The first section was an In-composition-graded $In_YGa_{1-Y}As$ layer, whose In content Y changed linearly from 0 to X, and the second was a layer of strain-relaxed thick $In_XGa_{1-X}As$. This second buffer layer was expected to play the role of a quasi-substrate and control the strain in the SLs. The six samples shown in Table 1 were prepared. Half of those had WSL-type SLs with thin barriers, and the remaining half had QCSE-type SLs. In each group, three samples had the same SL structure and only the In content of the InGaAs quasi-substrate was different. A cross-hatched morphology was

Table 1 Heterostructures parameters of prepared samples. Three of them are WSL-type SLs with thin barriers and the others are QCSE-type SLs with relatively thick barriers.

sample name	In content of quasi-substrate	well / barrier	pair number	type
W1 W2 W3	0.087 0.105 0.13	$In_{0.09}Ga_{0.91}As$ (4.5 nm) $In_{0.18}Al_{0.82}As$ (1 nm)	60	WSL
Q1 Q2 Q3	0 0.1 0.2	GaAs (5 nm) $In_{0.2}Al_{0.8}As$ (5 nm)	30	QCSE

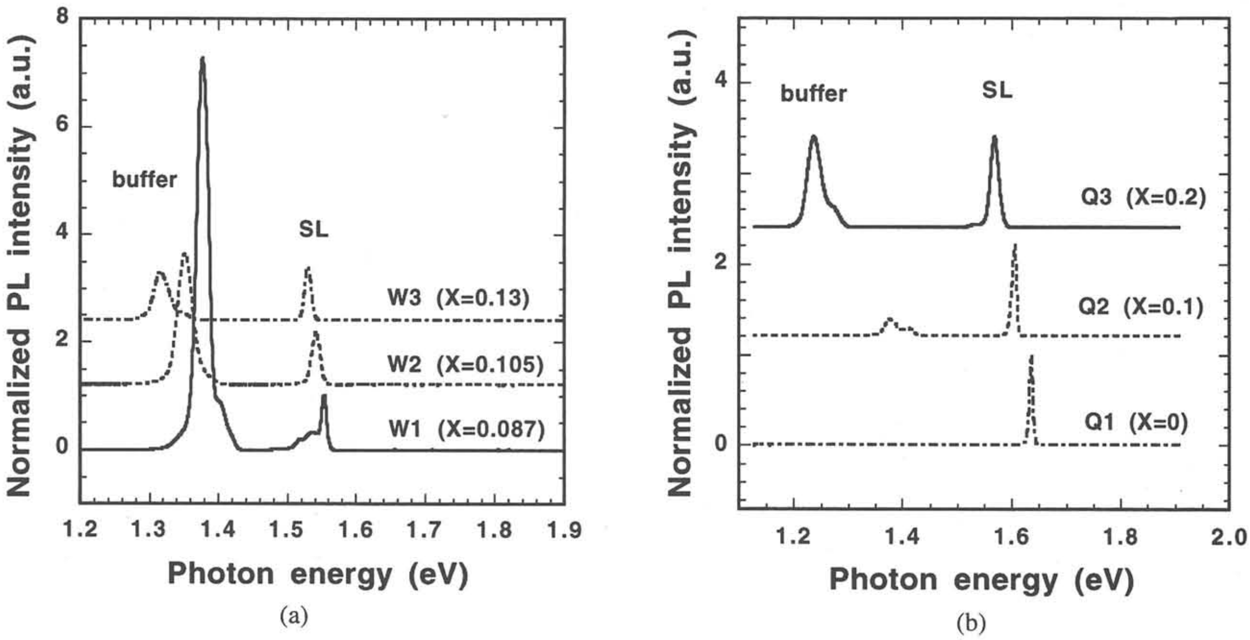


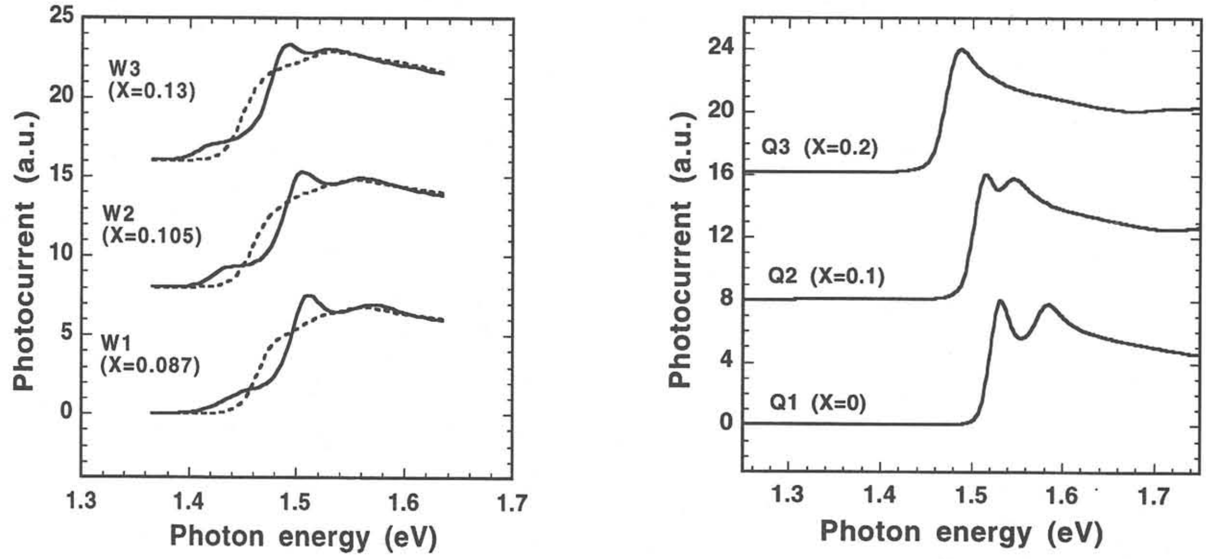
Figure 1 PL spectra at 10 K for the WSL-type samples (a) and the QCSE-type samples (b). The spectra were taken for as-grown wafers. The excitation wavelength and power are 488 nm and 8 mW, respectively. Each spectrum is normalized by the PL intensity of the SL. Note that the peak energy of the SL changes with the In content of the quasi-substrate in both types.

observed on the surface, but the formation of a periodic structure was confirmed by small-angle X-ray scattering measurements. After the growth, a 400 μm mesa was etched to fabricate pin diodes. For these SL diodes, optical properties were studied by low temperature photoluminescence (PL) and room temperature photocurrent (PC) measurements.

3. RESULTS AND DISCUSSION

Figures 1 (a) and (b) show PL spectra measured at 10 K of the three WSL-type samples and the three QCSE-type samples, respectively. In each spectrum, peaks observed at the higher energy side correspond to luminescence signals of the SL, and those at the lower energies to the relaxed $In_XGa_{1-X}As$ quasi-substrate. Each spectrum was normalized by the PL intensity of the SL. In both SL types in Fig. 1, the PL peaks observed in the SLs shifted to the lower energy sides as the In content of the quasi-substrate was increased, in spite of the same SL structure in each type. This proves that the band structures in the SLs having the same compositional structure are actually modulated by the strain, which depends on the lattice constant of the quasi-substrate.

PC measurements were made at room temperature using a monochromatic light from a halogen lamp. Figure 2 (a) shows the PC characteristics of the WSL-type samples at reverse bias voltages of 0 V (dashed lines) and 4 V (solid lines). A clear WSL effect was observed for all samples. The absorption edge was miniband-like for a weak electric field, then the leading edge shifted toward higher energy and localized exciton peaks became clear as the reverse bias was increased. Furthermore, an absorption feature due to the -1st order Stark-ladder transition[2] was clearly observed at the lower energy side of the leading exciton peak. This is the first observation of the WSL effect in strained SLs on a quasi-substrate, whose lattice constant differs from the substrate. In addition, the localized exciton absorption peak of the e1-hh1 and e1-lh1 transitions shifted toward the lower energy side as the In content X was increased. These results are consistent with the PL measurements shown in Fig. 1 (a). The energy shifts observed for the e1-hh1 and e1-lh1 exciton transitions from W1 to W3 were 19 meV and 39 meV, respectively. Thus, the peak energy separation between the e1-hh1 and e1-lh1 exciton transitions decreased by 20 meV from W1 to W3. These energy shifts in the PL and PC spectra can be explained by bandgap shrinkage effects due to the tensilely strained well layer. The same tendency could be seen in the PC characteristics for the QCSE-type samples as demonstrated in Fig. 2 (b). The energy shifts observed for the e1-hh1 and e1-lh1 transitions from Q1 to Q3 were 44 meV and 97 meV, respectively. The peak energy separation between the e1-hh1 and e1-lh1



(a) (b)

Figure 2 PC characteristics at room temperature for the WSL-type samples (a) and QCSE-type samples (b). In (a), dashed and solid lines show PC spectra at 0 V (field 43 kV/cm) and 4 V (field 157 kV/cm), respectively. In (b), PC spectra at 4 V (field 175 kV/cm) are shown. The electric field is calculated by assuming a built-in potential (1.5 V). The spectra are offset for clarity.

transitions decreased by 53 meV from Q1 to Q3. For the sample Q3, in which the In content of the quasi-substrate was 0.2, the e1-hh1 and e1-lh1 transitions merged into a single peak (the energy separation was nearly zero).

Under biaxial tension, the difference in the confinement effects on the hh1 and lh1 subbands and the strain effects on the splitting are of opposite signs, so that increasing the tensile strain in the well results in a decrease of the energy difference between the hh1 and lh1 subbands. In our samples, the lattice constant of the well is smaller than that of the barrier, and the lattice constant of the quasi-substrate, controlling the strain in an SL, is larger than the well layer. Therefore, the tensile strain in the well layer becomes larger as the In content of the quasi-substrate increases. The experimental trends of our results agreed well with the theoretical estimation, which was calculated by using the Kronig-Penny model within the effective mass approximation and taking the strain effects into account. From these results, it is expected that mixing and inversion of the heavy hole and light hole subband states in SEEDs are possible on GaAs substrate by using SLs with tensilely strained wells grown on a quasi-substrate.

4. CONCLUSION

We have clearly observed the WSL effect and the QCSE in strained InGaAs/InAlAs SLs on InGaAs buffer layers grown on GaAs substrate. In these structures, the InGaAs buffer plays a role of quasi-substrate and determines the strain in the SLs. Modulation of the valence band in the SLs due to the tensile strain controlled by the In content of the quasi-substrate was confirmed by PL and PC measurements. These results might be used for applications to optical modulators with strained SLs and MQWs grown on GaAs substrate.

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