Photocurrent spectra and Wannier-Stark localization of $In_{0.53}Ga_{0.47}As/InP$ superlattices with different barrier thicknesses

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Abstract

Wannier-Stark localization in a pair of high quality lattice-matched InGaAs/InP superlattices (SL) p-i-n diodes with wide (60 meV) and narrow (14 meV) electron miniband widths has been investigated by room temperature photocurrent (PC) response measurements. PC spectra as well as PC versus reverse bias voltage characteristics of the SL samples exhibit a clear excitonic absorption edge redshifted due to the miniband formation and show distinct Stark ladder transitions, which evolve with the applied electric field. The transition energy fan diagrams are analyzed for the SL model potential structures using transfer matrix calculations. It is found that observed blueshifts of the absorption edge by decreasing the miniband width and by increasing the field exactly coincide with half of the transition miniband width, thus providing the electroabsorption modulation with InGaAs/InP SL's. Good agreement of the transition energies is obtained between theory and experiment, using band offset and effective mass parameters proposed by Gershoni et al., Phys. Rev. B38, 7870 (1988).

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1. Introduction

Wannier-Stark localization (WSL) in superlattices (SL's) [1,2] have been given a great deal of recent attention for potential applications to optical bistable devices and/or optical modulators. This is because the WSL phenomena show unique electric-field-induced changes of the optical absorption spectra due to, so-called Stark-ladder transitions, accompanying with a blue shift of the optical absorption edge. Therefore, a big change of the absorption oscillator strength with the field is in principle possible with reduced transmission losses. Previously, the WSL phenomena have been studied mainly in GaAs/AlGaAs SL systems because of the high-quality of the epitaxial materials, which exhibit optical responses to illumination of around 0.8 μm wavelengths [3-6]. For applications to optical communications which are based on the low-loss and low-dispersion characteristics of the optical fibers at longer wavelengths of 1.3 μm or 1.5 μm, the optical modulators operative at the longer wavelength region are very interesting. However, to the best of our knowledge, there are only few reports, which discuss the WSL phenomena and the suitable material properties at the longer wavelengths [7-10].

In this paper, we have investigated room temperature photocurrent responses to monochromatic light illumination in a pair of high quality $In_{0.53}Ga_{0.47}As$/InP SL samples, prepared by gas-source molecular beam epitaxy. In the two SL samples the width of the ternary wells is the same, but only the InP barrier thickness is different. So that, the miniband width is different between the two samples, but they should have the same Stark localized state under the high applied field. In the SL system with the ternary InGaAs well layer lattice-matched to the InP barrier layer, the optical absorption edge can be adjusted to the wavelength region around 1.5 μm, for example by tuning the well width. Therefore, using the SL diodes, we expect to obtain distinct electroabsorption properties due to the WSL mechanism, which is applicable to the optical modulators operating at the longer wavelengths. In fact, a large blue shift of the optical absorption edge and clear Stark-ladder transitions are observed in the thinner barrier SL sample, in comparison to the thicker barrier SL. Furthermore, the Stark ladder transition energies are calculated based on the transfer matrix theory and good agreement is obtained between theory and experiment.

2. Experimental

Two $In_{0.53}Ga_{0.47}As$/InP SL samples (#1 and #2) were grown on n-type InP (001) substrates by gas-source molecular beam epitaxy, using solid source Ga and In as group III elements and AsH_3 and PH_3 as group V elements. The nominally undoped SL layer embedded in 50 nm each undoped InP outer barriers was sandwiched between 0.2 μm n-type InP and 0.1 μm p-type InP cladding layers to form a p-i-n diode structure. These epitaxial layers were terminated by a 10-20 nm p^+-$In_{0.53}Ga_{0.47}As$ layer for ohmic contact formation. The SL sample #1 consists of 100 periods of $L_Z = 5.0$ nm $In_{0.53}Ga_{0.47}As$ wells and $L_B = 5.0$ nm InP barriers. In the sample #2 the well width is the same as the sample #1 but the barrier thickness is different and is reduced to a half value of $L_B = 2.5$ nm. These SL layer thicknesses were determined by X-ray diffraction measurements. To fabricate p-i-n diode chips, a 100-μm circular mesa with a 30-μm circular Au electrode was etched down through the epitaxial layers by conventional wet chemical etching. The sample structure is schematically shown in Fig. 1.

PC spectra were measured for the two SL samples at room temperature under various applied bias voltages using a lock-in amplifier system for AC detection. A monochromator combined with a halogen lamp is used as the excitation source. The intensity of the PC signals as a function of wavelength was normalized by the lamp intensity measured under the same experimental configuration. For analyzing the data, numerical calculations of the transition energies for the SL samples as a function of electric field were carried out based on the transfer-matrix method within the effective mass approximation [11]. As for the effective-mass parameters of $In_{0.53}Ga_{0.47}As$ (InP) electrons and heavy-holes, we have used values of m_e = 0.041 (0.079) and m_h = 0.377 (0.606), respectively [12]. We have also used a value of 0.750 eV (1.351 eV) for the room temperature energy band gap of $In_{0.53}Ga_{0.47}As$ (InP), assuming the conduction band offset ratio of 0.395 [12]. These calculations have been done for a model potential structure consisting of 7-period SL's. The inclined potential profiles under the applied electric field were approximated by five piecewise constant potential steps both for the wells and barriers.

3. Results and discussion

Figure 2 shows PC spectra of SL samples #1 (upper two solid curves) and #2 (lower two solid curves) at a zero bias voltage (V_B = 0.0 V) and a large reverse bias voltage (V_B = -5.0 V). Horizontal bars labeled by HH and LH indicate the transition energy miniband widths for the electron to heavy-hole (HH) and to light-hole (LH) transitions, respectively, which are calculated for the Kronig-Penney model. Theoretical miniband widths for the electron states of samples #1 and #2 are 14 meV and 60 meV, respectively, while the heavy-hole miniband width is negligible small (less than 0.2 meV) for the both cases.

In the PC spectrum of sample #1 at the zero bias voltage, a leading peak is observed around 1440 nm as shown in Fig. 2. We note that the wavelength position of the PC peak exactly coincides with the expected one by the calculations. When the large reverse bias of -5.0 V is applied, the leading PC peak becomes sharper and a distinct shoulder appears at the longer wavelength side. These results indicate that even at the zero bias, a built-in electric field is present due to the build-in potential, which we estimate to be about 0.6 V. Therefore, in this sample having the small miniband width, the electron envelope wave function is already localized in each quantum well at the zero bias, giving the sharp excitonic absorption peak in the PC spectrum. With increasing the applied reverse bias voltage, the main PC peak becomes narrower by the excitonic enhancement effect due to the strong localization of the wave function under the high field.

In the PC spectrum of sample #2 at V_B = 0.0 V, on the other hand, a much broader absorption edge is observed around 1490 nm, which is significantly redshifted from the corresponding edge of sample #1. A broad peak observed around 1400 nm may be related with the saddle point exciton peak associated with the HH states [13]. Under the large reverse bias voltage, however, the localized excitonic peak reappears at 1440 nm, which we attribute to the field induced localization of the miniband states. Thus, a pronounced blue shift of the optical absorption edge is obtained according to the WSL mechanism. Here we note that, although the two samples show different PC spectra under the low electric field condition (V_B = 0.0 V), the wavelength position of the localized excitonic PC peak of the two samples is located exactly at the same position under the large electric field (V_B = -5.0

V). This is because both samples have the same well width ($L_Z = 5.0$ nm). That is, their eigenstates associated with the same isolated quantum well are recovered, since the applied strong field forces to break down the tunneling induced couplings between the wells through the thin barriers by the Stark effect. Details of this field induced variation of the optical absorption properties are shown in Figs. 3 and 4 as discussed below.

Figure 3(a) shows detailed PC spectra of SL sample #2 with thinner barriers as a function of applied bias voltage. With increasing the applied reverse bias voltage, multiple peaks and shoulders appear, which we attribute to the higher order (n-th) Stark-ladder transitions, as indicated and assigned by Stark ladder indices (n). In Fig. 3, solid curves labeled by the indices (n) are only guides to the eye. However, we see clear Stark ladder transitions in the room temperature PC spectra which evolve with the field like a fan under the high field conditions, as expected by theory [2]. Concerning a broad peak around 1360 nm (labeled by asterisk) in Fig. 3, we tentatively assign it as originating from the light-hole related transition. Since the second ($n = -2$) order Stark ladder transition shows only a weak shoulder in the PC spectra, we have additionally measured the PC intensity as a function of bias voltage at a fixed illumination wavelength with increments of 1 nm, called photocurrent-voltage (PC-V) characteristics, which covers the wavelength range from 1440 nm to 1489 nm expected for the higher order Stark-ladder transitions with negative indices. The results are shown in Fig. 3(b). We note that the PC intensities due to the Strak ladder resonances are more clearly enhanced and resolved as $n = -1$ and $n = -2$ peaks. Under the short wavelength illumination around 1450 nm, a single negative differential conductance (NDC) region is observed which is applicable to the bistable operation of self-electro-optic effect devices

(SEED)[14]. Under the illumination of longer wavelengths than 1460 nm, we obtain two NDC regions useful for the multistable optical switching operation [4-6].

For SL sample #1 with thicker barriers, the results of PC-V measurements are shown in Fig. 4 covering a wavelength range from 1430 nm to 1470 nm, where the n = -1 Stark-ladder transition is expected to appear. In fact, the n = -1 transition which was not so well resolved in the PC spectra is now more clearly observed as a sharp resonance peak in Fig. 4. A broad structure seen in the high reverse bias region in Fig. 4 is due to the quantum confined Stark effect [15].

In order to analyze the observed transition energies in more details we have calculated the Stark ladder eigenenergies as a function of electric field, based on the transfer matrix method within the effective mass approximation, neglecting the excitonic effects. The results are plotted in Fig. 5(a) and (b) by solid dots, together with the experimental values by crosses for samples #1 and #2, respectively. For the calculations we have used the band offset parameters as well as the effective masses proposed by Gershoni et al [12]. Excellent agreement is obtained between theory and experiment without any adjusting procedures for the both cases. Although not shown here, similar agreement is also obtained for the LH related transition. These results indicate high material qualities of these SL samples, and the SL heterostructures can be fabricated as designed with respect to the well and barrier thicknesses. These results also suggest potentiality of ultrathin $In_{0.53}Ga_{0.47}As/InP$ SL material systems for fabricating optical modulators and switches with large modulation depth, which are suitable for the optical fiber communication networks.

4. Conclusion

We have investigated Wannier-Stark localization (WSL) phenomena of a pair of InGaAs/InP superlattice (SL) p-i-n diodes with wide (60 meV) and narrow (14 meV) electron miniband widths by photocurrent (PC) response measurements. PC spectra as well as PC versus reverse bias voltage characteristics of the SL samples exhibit clear excitonic absorption edges redshifted due to the miniband formation and show distinct Stark ladder transitions, which evolve with the applied electric field. The transition energies are analyzed for SL model potential structures using transfer matrix calculations. It is found that the observed blueshifts of the absorption edge by decreasing the miniband width and by increasing the field exactly coincide with half of the transition miniband width, thus providing the electroabsorption modulation with InGaAs/InP SL's. Excellent agreement is obtained between theoretical transition energies and experimental ones. These results indicate high qualities of the $In_{0.53}Ga_{0.47}As$/InP SL material systems which are useful for the optical fiber communication networks.

Footnote

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References

[1] E. E. Mendez, F. Agullo-Rueda, J. M. Hong, Phys. Rev. Lett. **60** (23) (1988) 2426-2429.

[2] H. T. Grahn (Ed), Semiconductor Superlattices: Growth and Electronic Properties, World Scientific, Singapore, 1995.

[3] I. Bar-Joseph, K. W. Goossen, J. M. Kuo, R. F. Kopf, D. A. B. Miller, D. S. Chemla, Appl. Phys. Lett. **55** (4) (1989) 340-342.

[4] H. Schneider, K. Fujiwara, H. T. Grahn, K. v. Klitzing, K. Ploog, Appl. Phys. Lett. **56** (7) (1990) 605-607.

[5] K. Kawashima, K. Fujiwara, T. Yamamoto, K. Kobayashi, Jpn. J. Appl. Phys. **31** (9A) (1992) 2682-2686.

[6] K. Kawashima, M. Hosoda, K. Fujiwara, Appl. Phys. Lett. **62** (2) (1993) 184-186.

[7] J. Couturier, P. Voisan, J. C. Harmand, Appl. Phys. Lett. **64** (6) (1994) 742-744.

[8] H. C. Neitzert, C. Cacciatore, D. Campi, C. Rigo, C. Coriasso, A. Stano, IEEE Photon. Thechnol. Lett., **7** (8) (1995) 875-877.

[9] Michel Allovon, Sylvie Fouchet, Jean-Christophe Harmand, Abdallsh Ougazzaden, Benoit Rose, Andre Gloukhian, Fabrice Devaux, IEEE Photon. Thechnol. Lett., **7** (2) (1995) 185-187.

[10] Osamu Tadanaga, Toshiaki Kagawa, Yutaka Matsuoka, Appl. Phys. Lett. **71** (8) (1997) 1014-1016.

[11] B. Jonsson, S. T. Eng, IEEE J.Quantum Electron. **QE-26** (11) (1990) 2025-2035.

[12] D. Gershoni, H. Temkin, M. B. Panish, Phys. Rev. B **38** (11) (1988) 7870-7873.

[13] K. Fujiwara, K. Kawashima, T. Yamamoto, N. Sano, R. Cingolani, H. T. Grahn, K. Ploog, Phys. Rev. B **49** (3) (1994) 1809-1812.

[14] D. A. B. Miller, Optical, and Quantum Electronics **22** (1990) S61-S98.

[15] D. A .B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegmann, T. H. Wood, C. A. Burrus, Phys. Rev. B **32** (2) (1985) 1043-1060.

Figure Captions

Figure 1

Schematic diagram of the p-i-n diode sample containing a 100-period of $In_{0.53}Ga_{0.47}As/InP$ SL.

Figure 2

Room temperature PC spectra of the SL samples #1 (upper curves) and #2 (lower curves) at a low bias voltage of $V_B = 0.0$ V and a high reverse bias voltage of $V_B = -5.0$ V. Calculated transition miniband widths corresponding to the heavy-hole (HH) and light-hole (LH) ones under flat-band are indicated by the horizontal bars.

Figure 3

(a) PC spectra (PCS) between 0.0 V and -5.0 V with increments of -0.2 V of sample #2 ($L_Z/L_B = 5.0$ nm/2.5 nm) as a function of applied bias voltage. (b) PC-V characteristics of sample #2 measured under the fixed illumination wavelength ranging from 1440 nm to 1489 nm with increments of 1 nm. Solid curves are guides to the eye to show shifts of the Stark-ladder resonance.

Figure 4

PC-V characteristics of sample #1 ($L_Z/L_B = 5.0$ nm/5.0 nm) measured under the fixed illumination wavelengths ranging from 1430 nm to 1470 nm with increments of 1 nm. A solid curve is guides to the eye to show shifts of the Stark-ladder resonance.

Figure 5

Calculated transition energies between the electron Stark-ladder states and the localized heavy-hole state are shown by solid dots for sample #1 (a) and #2 (b). Field-induced energy evolution of the spectroscopic features observed in the PC spectra as well as PC-V curves are indicated by crosses. Calculated transition energies in the upper energy region are due to the second subband states.