3P1-7
Proceedings of Symposium on Ultrasonic Electronics, Vol. 37 (2016)
16-18 November, 2016

Piezoelectric photothermal detection of the mini-band edge energies of strain-balanced InGaAs/GaAsP superlattice structures

光熱変換法による InGaAs/GaAsP 超格子に形成されるミニバンド端エネルギーの測定

Tetsuo Ikari[1†], Atsuhiko Fukuyama[1], Tsubasa Nakamura[1], Masakazu Sugiyama[2], and Yoshiaki Nakano[3] ([1]Fac. Eng., Univ. Miyazaki, [2] Grad. School Eng., Univ. Tokyo, [3]RCAST, Univ. Tokyo)
碇哲雄 [1†], 福山敦彦 [1], 中村翼 [1], 杉山正和 [2], 中野義昭 [3]（[1] 宮崎大工, [2] 東京大工, [3] 東京大 RCAST）

1. Introduction

Two possible structures are promising in progress for realizing a solar cell with ultrahigh conversion efficiency, greater than the Shockley–Queisser limit[1)]. The key is that how the absorbing wavelength region covers the whole solar spectrum. One is a multi-junction solar cell structures. Although the InGaP/InGaAs/Ge is the commonly used for triple-junction solar cells, a large difference in the band gap energies between InGaAs and Ge cells induces a serious current mismatch problem. Another candidate is an embedding of a multiple quantum-well (MQW) structure into the absorbing intrinsic layer of the solar cells[2)]. Although the MQWs can extend the sunlight absorption region towards the longer-wavelength region and enhance the short-circuit current, interfaces of the MQWs themselves act as carrier recombination centers for photogenerated carriers. This degrades both the open-circuit voltage and fill factor, thus lowering the conversion efficiency.

Recently, an MQW with a very thin barrier structure, hereafter called a superlattice (SL) structure, has been proposed to enhance the efficiency of the quantum-structure-embedded solar cells[3)]. In the SL structure, it is known that the coupling of the wave functions between adjacent quantum wells causes a formation of miniband along the growth direction. For solar cell application, it is expected that the photogenerated carriers can move across the absorbing i-region through these minibands without recombination. However, the currently used current–voltage and quantum efficiency measurements only reveal the macroscopic properties of the solar cells. The detection and estimation of the miniband becomes important to optimize a configurations of the MQW and SL structures for improving the photovoltaic performance. Photoreflactance (PR) and photoluminescence (PL) are the useful technique for investigating the miniband formation. However, these techniques only estimate the critical energies of the band edges. In this study, we carry out a piezoelectric photothermal (PPT) technique to observe the energy dispersion of the miniband (density of states) and discuss the effect of miniband formation on the exciton formation as well as the performance of the carrier recombination properties.

2. Experimental

We prepared two sets of samples. The strain-balanced InGaAs/GaAsP MQW were embedded in the intrinsic region of the p-i-n GaAs solar cell structures. The compositions and the thicknesses were summarized in **Table 1**. Another strain-balanced InGaAs/GaAsP super lattice (SL) samples were also prepared. Since the barrier width of 1.9 nm is very thin, the wavefunctions in the neighboring QW are sufficiently overlapped. The PPT measurements were carried out by using PZT transducer attached directly to the sample[4)]. The heat and elastic waves generated by the nonradiative recombination of the photoexcited electrons were measured. The incident light was modulated at a frequency of 100 Hz. Conventional PR measurements were also carried out by using Ar ion laser and halogen lamp as light sources. Since the signal was weak and multiple critical energies were included in the narrow wavelength region, the observed optical reflectance signal was transformed into the modulus PR signal by a Kramers-Kronig relation. All the measurements were carried out at room temperature.

	well	Barrier
MQW	$In_{0.23}GaAs_{0.77}$	$GaAs_{0.61}P_{0.39}$
	7.4 nm	10.8 nm
SL	$In_{0.21}GaAs_{0.79}$	$GaAs_{0.59}P_{0.41}$
	5.0 nm	1.9 nm

Table 1. Sample compositions and thicknesses of the quantum wells (QW). The barrier width is about 5 times smaller for the SL sample.

3. Results an discussion

The PPT and the modulus PR spectra of MQW sample were shown in **Fig. 1**. Strong signals observed above 1.4 eV were due to the band edge signals from GaAs. The band gap energy of GaAs is 1.42 eV at room temperature. The peaks at 1.238 and 1.246 eV were observed for PPT and modulus PR spectra, respectively. Since the PPT signal is proportional to the absorption coefficient (absorbance) in this photon energy region below the energy gap of GaAs, the observed peak of 1.238 eV is arisen from the MQW structure. This peak and following step function like signal were decomposed into the exciton and the transition between the quantized e1 (the lowest quantized level of electrons in the conduction band) and hh1 (the lowest quantized level of the heavy hole valence band) energy levels. This decomposition procedure and corresponding discussion were already established for GaInNAs single quantum well[5]. The peak of the modulus PR spectrum was considered to be a band edge energy of the quantized level, e1 to hh1 transition, the energy difference between the peaks at 1.238 (PPT) and 1.246 eV (PL) is considered to be an exciton binding energy.

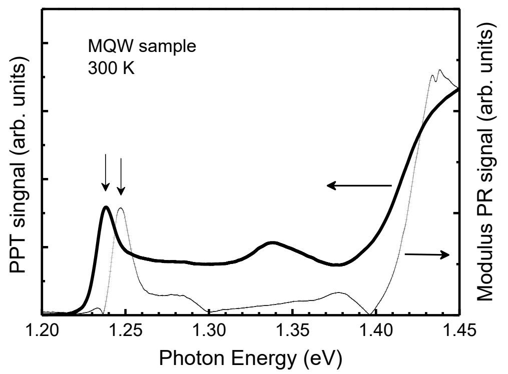

Fig. 1 PPT (solid) and modulus PR (dotted) spectra of multiquantum well (MQW) sample.

Figure 2 shows the PPT and the modulus PR spectra of SL sample. The PPT spectrum shows two broad peak at 1.284 and 1.322 eV. The modulus PR spectra also show two peaks at 1.274 and 1.284 eV. Since the barrier width is thin (1.9 nm) in this SL sample, the wavefunctions in the neighboring QWs overlapped and forms the miniband. The miniband width is determined by the effective mass of the carriers in the corresponded band, and it is larger for e1 than hh1 level. Considering that the PR peaks show the critical band energies, the observed two energies correspond to the edges of the miniband. Therefore, the 1.274 and 1.284 eV peaks are corresponding to the transitions, including "Γ" and "π" points in the mini-Brilloiun zone, respectively. The energy difference between these two peaks is a miniband width. Unlike the case for MQW sample, the energy of the observed peaks in PPT spectra are located around 10 meV larger than those of the modulus PR spectra. If the observed PPT peaks are due to the exciton transition, the energies should be smaller than the band edge energy. This is not the case here. It is, then, difficult to consider that the observed PPT peaks are due to the exciton. Even if the exciton is formed in one of the QWs, it may be relaxed because the continuous electronic states exist in the neighboring QWs at the same energy. The electric field between the QW expand the energy overlapping. Exciton lifetime may become smaller and the exciton peak cannot be observed in the SL structure. PPT spectra only bring the two dimensional step function like density of states between the quantized levels. The discussion for the barrier width dependence of the PPT spectral shape is now carrying out for further understanding of the exciton formation in the miniband.

A part of this study was supported by NEDO under the Ministry of Economy, Trade and Industry Japan and Grants-and-Aid for Scientific Research (B) and (C) under the Ministry of Education, Culture, Sports, Science and Technology.

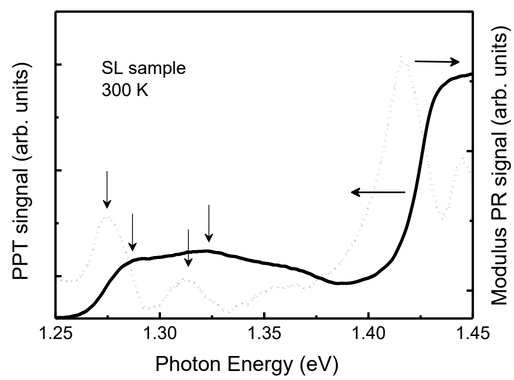

Fig. 2 PPT (solid) and modulus PR (dotted) spectra of super lattice (SL) sample.

References

1. K. W. Barnham and G. Duggan: J. Appl. Phys., **67** (1990) 3490.
2. Y. Wang, R. Onitsuka, M. Deura, M. Sugiyama and Y. Nakano, J. Cryst.Growth, **12** (2010) 71.
3. T. Aihara, A. Fukuyama, Y. Yokoyama, M. Kojima, H. Suzuki, M. Sugiyama, Y. Nakano and T. Ikari: J. Appl. Phys., **116** (2014) 044509.
4. T. Aihara, A. Fukuyama, H. Suzuki, H. Fujii, M. Sugiyama, Y. Nakano and T. Ikari: **117** (2015) 084307.
5. T. Ikari, S. Fukushima, Y. Ohta, A. Fukuyama, S. D. Wu, F. Ishikawa and M. Kondow: Phys. Rev. B**77** (2008) 125311.