宮崎大学学術情報リポジトリ
University of Miyazaki Academic Repository

Piezoelectric photothermal study of Al_x Ga_(1−x) As epitaxial layer (x=0.22, 0.28, and 0.5) grown on semi-insulating GaAs substrate

メタデータ	言語: eng 出版者: 公開日: 2020-06-21 キーワード (Ja): キーワード (En): 作成者: 福山, 敦彦, 境, 健太郎, 明石, 義人, 碇, 哲雄, Fukuhara, Hironori, Tanaka, Shin-ichi, Memon, Aftab A. メールアドレス: 所属:
URL	http://hdl.handle.net/10458/5441

Piezoelectric photothermal study of $Al_xGa_{1-x}As$ epitaxial layer ($x=0.22$, 0.28, and 0.5) grown on semi-insulating GaAs substrate

Atsuhiko Fukuyama,[a] Hironori Fukuhara,[b] Shin-ichi Tanaka,[c] Aftab A. Memon, Kentaro Sakai, Yoshito Akashi, and Tetsuo Ikari
Faculty of Engineering, Miyazaki University, 1-1 Gakuen-kibanadai nishi, Miyazaki 889-2192, Japan

(Received 5 February 2001; accepted for publication 2 August 2001)

Piezoelectric photothermal measurements of an $Al_xGa_{1-x}As$ ($x=0.22$, 0.28, and 0.5) epitaxial layer grown on a GaAs substrate were carried out in the temperature range of 297 to 80 K. In addition to the band gap signal of the GaAs substrate, the direct transition gaps of AlGaAs were clearly observed in the higher photon energy region. It was experimentally confirmed that the temperature coefficient of the direct transition gap of $Al_xGa_{1-x}As$ alloy decreases with increasing Al mole fraction. By conducting the quenching light illumination measurements at 80 K we concluded that the photoexcited electrons in the AlGaAs epitaxial layer drifted under the influence of an electric field present at the AlGaAs/GaAs interface. The drifted electrons eventually recombined with the ionized $EL2$ centers in the SI GaAs substrate. © *2001 American Institute of Physics.*
[DOI: 10.1063/1.1407309]

I. INTRODUCTION

An $Al_xGa_{1-x}As$ epitaxial layer grown on GaAs is an important alloy system for high performance heterojunction devices such as the field effect transistor (FET), the high electron mobility transistor (HEMT), and the heterobipolar transistor (HBT). In these alloy systems, liquid encapsulated Czochralski (LEC) grown semi-insulating (SI) GaAs crystal is used as a substrate. It is commonly understood that the SI property of GaAs crystal ($10^7\,\Omega\,$cm resistivity) is accomplished due to presence of a deep donor level $EL2$. Each $EL2$ donor compensates a shallow carbon acceptor. In addition to its technological importance, $EL2$ acts as a trap center and influences the device performance.[1] A number of studies have been conducted on the role of $EL2$ in the carrier transport properties of an AlGaAs/GaAs alloy system. But among all the proposed models not a single one comprehensively justifies all the observed features of the AlGaAs/GaAs alloy system.

One of the reasons for nonavailability of a comprehensive model is the lack of a suitable characterization method. The optical absorption measurement is the most common way of detecting dislocation or defect related levels in semiconductors. However, because of the low sensitivity of optical absorption measurement and low concentration of $EL2$ ($\sim10^{16}\,cm^{-3}$), a few millimeters thick sample should be prepared to detect $EL2$.

The photoluminescence (PL) technique, due to its high sensitivity and high spatial resolution features, is a powerful tool to investigate shallow donor and acceptor levels at low temperature ($T\sim4.2\,K$). But the drawback of the PL technique is that it detects only the radiative recombination processes. Whereas in the case of $EL2$, the nonradiative electron transitions are dominant over radiative transitions.

The photoacoustic (PA) spectroscopy has recently been used for investigating physical properties of semiconductors.[2] The main advantage of the PA technique is that it is a direct monitor of the nonradiative electron transitions in semiconductors. Periodic heat flow generated by the nonradiative recombinations of photoexcited carriers causes an acoustic wave in the surrounding gas and induces an expansion or a bending of the sample. By employing a microphone or a transducer these waves are detected as a PA signal. It has been reported that the PA technique was applied to investigate the energy band structures of some heterolayered semiconductors.[3–8] Unfortunately low temperature measurements in the PA technique are extremely difficult. Hence in a PA technique the accuracy of the low temperature measurements for investigating deep levels such as $EL2$ is questionable. Furthermore, electron transitions through a low density of electronic states such as defect levels cannot be detected due to the low sensitivity of the PA measurements.

To cater the deficiencies of the PA technique, we have developed a new technique; the piezoelectric photothermal (PPT) spectroscopy, employing a disk-shaped lead zircotitanate ceramics piezoelectric transducer (PZT) as a detector.[9] In this method we can easily decrease the temperature of the sample down to liquid helium temperature. Unlike the PA technique, which utilizes a microphone[3,4] or a ZnO transducer,[5–8] the sensitivity of this new technique becomes very high at low temperature. Although some authors already reported PA signal detection based on piezoelectric phenomenon,[10,11] the technique of low temperature measurements was not established. We have already reported that by using the PPT technique on a SI GaAs sample, the nonradiative electron transitions involving deep donor level $EL2$ and its metastability can easily be detected at low temperatures ($T<130\,K$).[12,13]

[a]Electronic mail: fukuyama@ssp.phys.miyazaki-u.ac.jp
[b]Present address: Kagoshima NEC Co., Ltd., Ohnohara, Demizu-city, Kagoshima 899-0216, Japan.
[c]Present address: Kyushu Matsushita Electric Co., Ltd., Hakata-ku Minoshima, Fukuoka 812-0017, Japan.

 © 2001 American Institute of Physics

The aim of this article is twofold. One is to report our extensive studies on the PPT spectra of a heterostructure sample, the AlGaAs epitaxial layer grown on the SI GaAs substrate, in the temperature range of 297 to 80 K. In this respect we show that in addition to the band gap signal of GaAs, the direct transition gaps of the AlGaAs were clearly observed in the higher photon energy region. The second objective is to investigate the carrier transport properties of the AlGaAs/GaAs alloy system. In other words, the role of deep donor *EL*2 in the PPT signal generation mechanism is to be investigated. Analyzing the results of quenching light illumination at 80 K, we conclude that the photoexcited electrons in the AlGaAs epitaxial layer drift under the influence of an electric field present at the interface; these drifted electrons eventually recombine with the ionized *EL*2 centers in the SI GaAs substrate.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The samples were prepared from the AlGaAs epitaxial layers grown on a SI GaAs substrate. The nondoped $Al_xGa_{1-x}As$ epitaxial layers (1.5 μm thickness, Al mole fraction $x=0.22$, 0.28, and 0.5) were grown by the metalorganic vapor phase epitaxy (MOVPE) method. Due to the presence of residual carbon acceptors ($[C]_{epi}\sim 1\times 10^{15}\,cm^{-3}$), nondoped AlGaAs shows a *p*-type conduction. The substrate was the carbon-doped, LEC grown SI GaAs (600 μm thickness). The concentrations of deep donor *EL*2 and shallow carbon acceptor in the substrate were 1.3 and $0.4\times 10^{16}\,cm^{-3}$, respectively.

The experimental configuration involving the sample and the detector is shown in the inset of Fig. 1(a). After the samples were cut to the surface dimensions of about $1\times 1\,cm^2$, a disk-shaped PZT was attached to the surface of the GaAs substrate using a silver conducting paste. The sample and the PZT were mounted on the cold finger inside a cryostat. The setup enabled us to change the sample temperature from 297 to 80 K. The probing light to measure the PPT signal was mechanically chopped at a frequency of 100 Hz and was always focused on the surface of the epitaxial layer side. The PPT signal generated by the nonradiative electron transitions was detected by the PZT. A detailed experimental setup has already been reported.[9]

The PPT spectra in the temperature range of 297–80 K were measured as a function of photon energy of the probing light ranging from 1.1 to 2.8 eV. It was ascertained that the light intensity of the probing light was sufficiently weak ($0.17\,mW/cm^2$) to avoid any photoinduced change in the spectra,[12,13] a phenomenon to be discussed in the following section.

Figure 1(a) shows the PPT spectra of $Al_xGa_{1-x}As$ ($x=0.22$, 0.28, and 0.5) at 297 K. In the lower photon energy region around 1.4 eV, the PPT spectra of all the AlGaAs samples show a rapid increase. Since the band gap energy (E_g) of GaAs is 1.42 eV at 297 K,[14] the rapid increase is considered to be due to band-to-band electron transitions in the GaAs substrate. In the higher photon energy region above E_g of GaAs, several remarkable changes at 1.68 (*A*), 1.76 (*B*), and 2.05 eV (*C* points) are observed. The above-mentioned remarkable changes are found shifting to the higher photon energy side with increasing *x*. The phase-component spectra of above PPT measurements at 297 K are also shown in Fig. 1(b). The PPT phase drastically delay about E_g of GaAs. As in the case of amplitude-component spectra shown in Fig. 1(a), remarkable changes in phase spectra are also observed. Those phase spectral changes match the photon energy positions of signals observed in amplitude spectra.

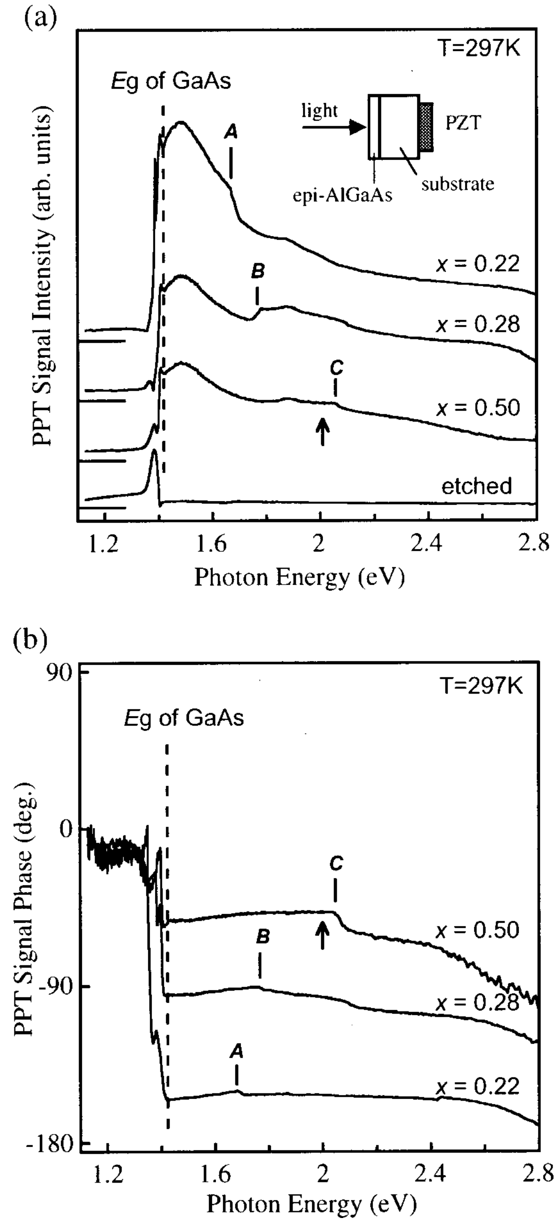

FIG. 1. The PPT (a) amplitude and (b) the phase spectra of the $Al_xGa_{1-x}As$ ($x=0.22$, 0.28, and 0.5) at 297 K. The experimental configuration involving the sample and the detector is shown in the inset of (a). In addition to the band gap signal of the GaAs substrate, several remarkable changes at 1.68 (*A*), 1.76 (*B*), and 2.05 eV (*C* points) are observed in the higher photon energy region. (a) also shows the PPT spectrum of a chemically etched sample in which the AlGaAs epitaxial layer was completely removed. A distinct peak around E_g of GaAs is observed and no other peak or change in the higher photon energy region is observed.

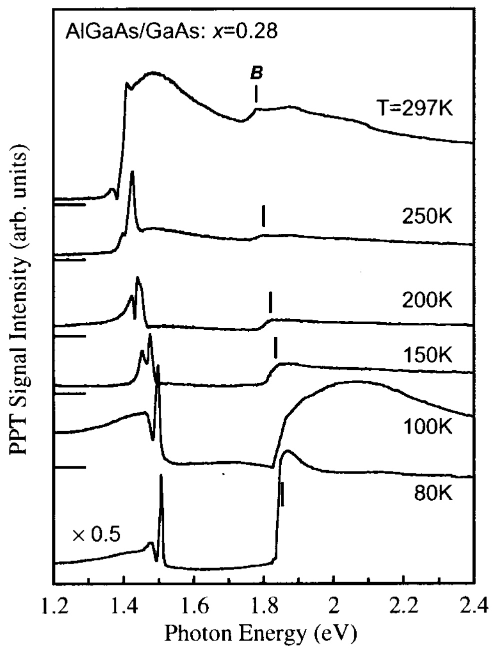

FIG. 2. Temperature variation of the PPT spectrum of $Al_{0.28}Ga_{0.72}As$ at the temperature of the sample ranging from 297 to 80 K. As the temperature of the sample decreases, the PPT signal due to E_g of GaAs and the point B shift to the higher photon energy side. In addition, the PPT signal intensities corresponding to the energy region between E_g of GaAs and point B decrease drastically.

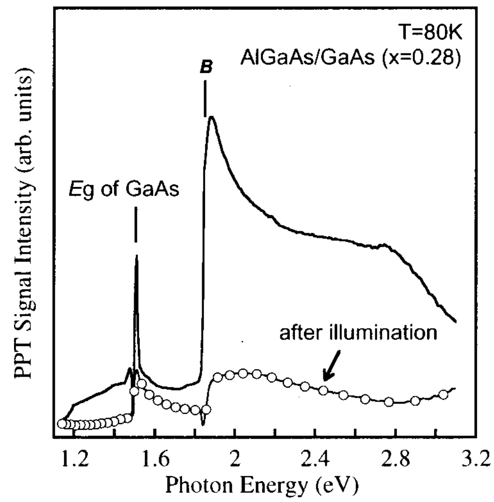

FIG. 3. The effect of the quenching light illumination at 80 K on the PPT signal. A considerable decrease in the intensities of the PPT signals is observed in the whole photon energy region. The PPT spectrum before the quenching light illumination was completely reproduced after the sample was annealed at 150 K for a few minutes and was subsequently cooled down to 80 K.

The effect on PPT spectrum of the $Al_{0.28}Ga_{0.72}As$ ($x = 0.22$) sample, due to changes in temperature from 297 to 80 K, is shown in Fig. 2. As the temperature of the sample decreases, the PPT signal due to E_g of GaAs and the signal at point B of the spectrum shift to the higher photon energy side. In addition, the PPT signal intensities corresponding to the energy region between E_g of GaAs and the point B decrease drastically.

Since the AlGaAs epitaxial layer is grown on the SI GaAs substrate, the contributions of both the epitaxial layer and the substrate should be considered simultaneously. To separate the two contributions, the sample was chemically etched and the PPT spectrum of the etched sample was measured. The epitaxial layer was removed and a mirror-like surface was obtained by immersing the sample for 2 min in a H_2SO_4 (5): H_2O_2 (1): H_2O (1) solution at 40 °C. For comparison the PPT spectrum of the etched sample is shown together with the spectra of AlGaAs samples in Fig. 1(a). A distinctive peak around E_g of GaAs is observed and no other peak or spectral change in the higher photon energy region is observed. Since the overall features of the PPT spectrum of the chemically etched sample are very similar to those of the LEC grown SI GaAs sample reported earlier,[15] the AlGaAs epitaxial layer of 1.5 μm thickness was completely removed.

The effect of the quenching light illumination on the PPT spectra were also measured. The sample was first cooled down to 80 K in the dark. The quenching light of 1.12 eV ($4.5\,mW/cm^2$) was illuminated on the sample surface for 30 min while keeping the temperature of the sample 80 K. After the quenching light was cut off, the PPT spectrum was measured again. The PPT spectra before and after the quenching light illumination were then compared. A typical result is shown in Fig. 3. A considerable decrease in the intensities of PPT signals after illumination is observed in the whole photon energy region. The PPT spectrum before the quenching light illumination was completely reproduced after the sample was annealed at 150 K for a few minutes and was subsequently cooled down to 80 K. The above results were observed for all the samples measured in the present study.

Figure 4 shows the decrease rate of the intensity of the

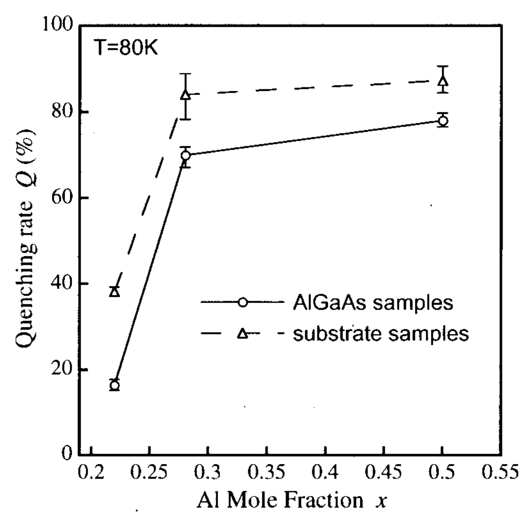

FIG. 4. The quenching rate Q as a function of x. Q of three corresponding substrate samples obtained by chemical etching are also plotted to compare with that of AlGaAs samples. The photon energies of the probing light were selected to be 2.2 and 1.12 eV for the AlGaAs and the substrate samples, respectively. The x dependence of Q of the AlGaAs sample coincides well with that of $EL2$ in the SI GaAs substrate.

PPT signal due to the quenching light illumination (quenching rate Q) as a function of x. The Q is defined as[12]

$$Q = 100(I_N - I_Q)/I_N(\%), \tag{1}$$

where I_N and I_Q are the PPT signal intensities at 2.2 eV before and after the quenching light illumination, respectively. As shown in Fig. 4, Q of the $Al_{0.22}Ga_{0.78}As$ ($x = 0.22$) sample is considerably smaller than those of other mole fractions. In order to explore the influence of SI GaAs substrate on the quenching light illumination measurements, the quenching light illumination measurements were carried out for chemically etched samples in which the AlGaAs epitaxial layer was completely removed and resulted in only the LEC grown SI GaAs substrate. The Qs of these three substrate samples obtained by chemical etching are also shown in Fig. 4. In this case, the photon energies of both I_N and I_Q were selected to be 1.12 eV because the optical absorption coefficient at this photon energy is reportedly proportional to the total $EL2$ concentration.[16] The x dependence of Q of the AlGaAs sample well coincides with that of $EL2$ in the SI GaAs substrate.

III. DISCUSSION

First of all, we have to discuss extraction of the AlGaAs signal from the PPT spectra of the AlGaAs/GaAs alloy system. Figure 1(a) shows the PPT spectrum of a chemically etched sample in which the AlGaAs epitaxial layer was completely removed. A distinct peak around E_g of GaAs is observed and no other peak or change in the higher photon energy region is observed. The observed spectrum is exactly similar to the spectrum of the LEC grown SI GaAs sample reported earlier.[15] Therefore it is reasonably considered that the PPT signals above E_g of GaAs including signals at points A, B, and C in the spectra contain the optical information of the AlGaAs epitaxial layer.

Saxena[17] has reported an Al mole fraction dependence of the band gaps (Γ direct, X indirect, and L indirect transition gaps) at room temperature in the $Al_xGa_{1-x}As$ alloy. The three band gaps (in eV) are given as

$$E_g(\Gamma) = 1.420 + 1.087x + 0.438x^2, \tag{2}$$

$$E_g(X) = 1.905 + 0.10x + 0.16x^2, \tag{3}$$

and

$$E_g(L) = 1.705 + 0.695x, \tag{4}$$

respectively. For $x < 0.45$, the electron transitions through the band gap of the AlGaAs are direct transitions,[17] therefore the band gaps for $x = 0.22$ and 0.28 of $Al_xGa_{1-x}As$ at 297 K calculated from Eq. (2) are 1.68 and 1.76 eV, respectively. It is found that the observed points A (1.68) and B (1.76 eV) in the PPT spectra well coincide with E_gs of $Al_{0.22}Ga_{0.78}As$ and $Al_{0.28}Ga_{0.72}As$, respectively. The optical absorption length $1/\beta$, where β is an absorption coefficient at the photon energy above E_g of AlGaAs, is estimated to be about 1 μm for $\beta \sim 10^4\ \mathrm{cm}^{-1}$. Since the thickness of the epitaxial layer is 1.5 μm, the probing light is completely absorbed within the AlGaAs epitaxial layer. Therefore it is considered that electrons are photogenerated within the AlGaAs epitaxial layer and their nonradiative transitions are detected as points A and B in the PPT spectra.

The phase component of the PPT signal is strongly affected by a local position of the signal generation and its propagation characteristics.[2] If the photon energy of the probing light is less than E_g of GaAs, the incident light propagates through the sample and transmits out from the backside of the sample. Under this situation, the whole sample acts like a signal source. When the photon energy becomes larger than E_g of GaAs but less than E_g of AlGaAs, almost all the probing light is absorbed within the illuminated thin surface region of the GaAs substrate. This results in a drastic delay of the phase. The delay is due to a shift of the mean position of the signal source from the whole sample to the restricted thin surface region. In this photon energy region the AlGaAs epitaxial layer grown on the substrate acts as a transparent layer because the photon energy is less than E_g of AlGaAs. In the higher photon energy region above E_g of AlGaAs, as discussed above, the probing light is almost absorbed in the AlGaAs epitaxial layer. Therefore a shift of the mean position of the signal source occurs and the PPT signal phase shows an additional delay at point A or B corresponding to E_g of AlGaAs.

When x is larger than 0.45, the band structure of AlGaAs changes from a direct to an indirect transition gap.[17] It is expected that the PPT signal of $Al_{0.5}Ga_{0.5}As$ also shows a remarkable change at E_g of 1.99 eV [arrows in Figs. 1(a) and 1(b)] as calculated from Eq. (3). However, the point C (2.05 eV) is very close to 2.07 eV calculated for the Γ direct transition gap by using Eq. (2). In this sample, the X indirect (1.99) and Γ direct (2.07 eV) transition gaps are very close to each other. The absorption coefficient of the X indirect transition gap gradually increases with the photon energy from 1.99 eV. On the other hand, in the case for the Γ direct transition gap, the absorption coefficient suddenly increases from 2.07 eV up to $10^4\ \mathrm{cm}^{-1}$. The signal contribution from the X indirect transition gap may be smeared out by the Γ direct transition gap. These results lead to the conclusion that the points A, B, and C observed in the PPT spectra were due to the Γ direct transition gaps of the AlGaAs epitaxial layers.

We have already established that the PPT technique can detect the AlGaAs epitaxial layer grown on the SI GaAs substrate. Now we discuss the temperature coefficients of the Γ transition gaps of AlGaAs. In most of the semiconductors the temperature dependence of E_g is known to be linear for temperatures higher than 150 K.[14,18] The temperature coefficients of the Γ direct transition gap [$dE_g(\Gamma)/dT$] of GaAs (Ref. 19) and AlAs (Ref. 20) had been measured to be -3.95 and -5.1×10^{-4} eV/K, respectively. By using the interpolation scheme between values of GaAs and AlAs, the $dE_g(\Gamma)/dT$ of $Al_xGa_{1-x}As$ alloy was reported as[18]

$$dE_g(\Gamma)/dT = -3.95 - 1.15x \quad (10^{-4}\ \mathrm{eV/K}). \tag{5}$$

It is obvious from Eq. (5) that the $dE_g(\Gamma)/dT$ of AlGaAs is expected to decrease linearly with increasing x.

Figure 5 shows the temperature dependence of the photon energy positions of points A, B, and C. The relevant positions of the three points are easily distinguishable in the

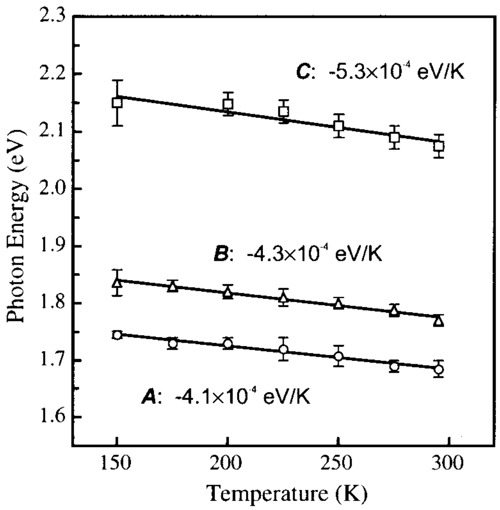

FIG. 5. The temperature dependence of the photon energy positions of the points A, B, and C. The temperature coefficients of three points were about -4.1, -4.3, and -5.3×10^{-4} eV/K, respectively. The temperature coefficient of the Γ direct transition gap of the $Al_xGa_{1-x}As$ alloy decreased with increasing the Al mole fraction.

phase spectra of PPT signal. Therefore all the data of Fig. 5 were extracted from the temperature dependent phase spectra of the PPT signal, such spectra are shown in Fig. 1(b). In the PPT amplitude spectra, such as shown in Fig. 1(a), it was difficult to locate the exact positions of points A, B, and C. The $dE_g(\Gamma)/dT$s of points A, B, and C were about -4.1, -4.3, and -5.3×10^{-4} eV/K, respectively. On the other hand for the same Al mole fractions ($x=0.22$, 0.28, and 0.5) in $Al_xGa_{1-x}As$ samples, the expected values of $dE_g(\Gamma)/dT$ calculated from Eq. (5) are given as -4.2, -4.3, and -4.5×10^{-4} eV/K, respectively. Although the $dE_g(\Gamma)/dT$s of points A, B, and C are slightly different from the expected values, it is experimentally confirmed that the temperature coefficient of the Γ direct transition gap of the $Al_xGa_{1-x}As$ alloy decreases with increasing the Al mole fraction.

Our second objective is to discuss the role of deep donor level $EL2$ in the substrate on the PPT signal generation mechanisms. The SI GaAs substrate sample used for the present study contained a deep donor $EL2$ concentration of about $1.3\times10^{16}\,cm^{-3}$. The best way to examine the influence of $EL2$ is to use the photoquenching effect.[12,13] In this phenomenon all the optical and electrical properties of $EL2$ are extinguished when the LEC grown SI GaAs sample was exposed to about 1.1 eV light illumination at low temperatures ($T<130\,K$). This photoquenched state is metastable because all the extinguished properties of $EL2$ can be recovered when the sample is annealed around 150 K for a few minutes and is subsequently cooled down to 80 K.

As shown in Fig. 3, after the quenching light illumination at 80 K, considerable decreases in the PPT signal intensities were observed. Moreover, the PPT spectrum before quenching light illumination was completely reproduced after the sample was annealed at 150 K for a few minutes and was subsequently cooled down to 80 K. It is obvious that the photoquenching and the thermal recovery effects are due to deep donor level $EL2$.[12,13] The question now arises: where does $EL2$ exist and how does it contribute to photoquenching and thermal recovery effects? It is reported that $EL2$ also exists in the AlGaAs epitaxial layer and is responsible for the photoquenching effect,[21] one might think that $EL2$ in the AlGaAs epitaxial layer of AlGaAs/GaAs alloy system contributes to these effects. However, this is not the case here. We support our claim with the following justifications. First, consider Fig. 4, the x dependence of Q at 2.2 eV for the AlGaAs epitaxial layer sample well coincides with that of $EL2$ in the SI GaAs substrate. Second, since the thickness of the substrate is 400 times more than that of the epitaxial layer, the quenching light illumination should affect $EL2$ in the GaAs substrate. Therefore it is justifiable to consider that the decrease in PPT signals of the AlGaAs samples by the quenching light illumination is due to the photoquenching of $EL2$ in the substrate. It means $EL2$ in the SI GaAs substrate plays an important role in generating the PPT signal in the AlGaAs/GaAs heterostructure sample.

Before discussing further the role of $EL2$ in the SI GaAs substrate on the PPT signal generation mechanism, it is worth mentioning an effect caused by the quenching light illumination. It is known as the persistent photoconductivity effect that is attributed to the DX center in the AlGaAs epitaxial layer.[22,23] In this phenomenon, the photoconduction effect remains for a long time ($\tau\sim$ hours) when the sample was exposed to about 1.1 eV light illumination at low temperature ($T<150\,K$). Increase of carrier lifetime may cause the decrease of the PPT signals. However, this effect has been only observed in the n-type AlGaAs sample that is intentionally doped with a donor impurity such as Te or Si.[23] In our present study we use the nondoped, p-type AlGaAs. Accordingly, a considerable decrease of the PPT signals cannot be explained in terms of the DX center nor can it be explained in terms of the persistent photoconductivity effect in the AlGaAs epitaxial layer.

To explain the effect of the photoquenching of $EL2$ we propose a model. According to this model the electrons photoexcited within the AlGaAs epitaxial layer drift towards the SI GaAs substrate and nonradiatively recombine with the ionized $EL2$ ($EL2^+$) in the substrate. When the photoquenching of $EL2$ occurs, drifted electrons cannot recombine with $EL2^+$ and result in a drastic decrease of the PPT signal intensity. Since the model satisfies our experimental results it is important to discuss it in detail.

A schematic band diagram of the AlGaAs sample is proposed and is shown in Fig. 6. The Fermi level in the SI GaAs substrate is calculated to be 0.745 eV below the conduction band. The following parameters are considered for the above calculation. The E_g of GaAs is taken as 1.42 eV. The concentration ($[EL2]_{sub}$) and the activation energy of deep donor level $EL2$ are $1.3\times10^{16}\,cm^{-3}$ and 0.75 eV below the conduction band, respectively. For the shallow carbon acceptor, the concentration ($[C]_{sub}$) and the activation energy are $0.4\times10^{16}\,cm^{-3}$ and 0.026 eV above the valence band, respectively. The Fermi level is found to be located slightly above the $EL2$ level. On the other hand, the Fermi level in the AlGaAs epitaxial layer is located near the valence band because of the existence of a residual carbon acceptor ($[C]_{epi}\sim1\times10^{15}\,cm^{-3}$). Using a value of $9.87\times10^{18}\,cm^{-3}$

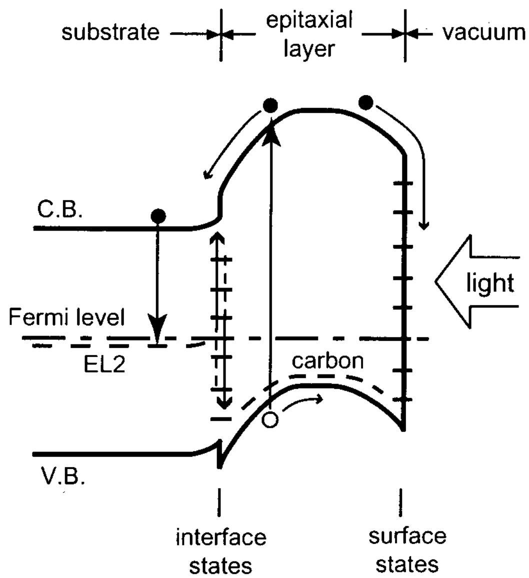

FIG. 6. Schematic band diagram near the epitaxial layer and the substrate interface. The Fermi levels in the SI GaAs substrate and the nondoped *p*-type AlGaAs epitaxial layer are calculated to be 0.745 eV below the conduction band and 0.236 eV above the valence band, respectively. A depletion region bearing an electric field and some band offsets are created at the interface between the epitaxial layer and the substrate.

for the effective density of states in the valence band of the $Al_{0.28}Ga_{0.72}As$ at 297 K,[18] the Fermi level is calculated to be about 0.236 eV above the valence band. In this argument we assume that there is no donor that compensates the carbon acceptor. Therefore when a heterojunction is fabricated, a depletion region bearing an electric field and some band offsets are created at the interface between the epitaxial layer and the substrate. In our sample the depletion region width calculated using Poisson's equation comes out to be 0.84 μm. The carrier concentrations in the *p*-type epitaxial layer and in the SI substrate were $[C]_{epi}=1\times10^{15}\,cm^{-3}$ and $[EL2]_{sub}-[C]_{sub}=0.9\times10^{16}\,cm^{-3}$, respectively. Since the carrier concentration in the substrate is nine times larger than that in the epitaxial layer, the depletion region is mainly extended into the epitaxial layer side. Using the band offsets chart measured by Kroemer,[24] band offsets are determined to be 0.19 and 0.14 eV for the conduction and the valence bands, respectively. We also took into account the surface state between the AlGaAs epitaxial layer and vacuum. Since the lattice constant of $Al_{0.28}Ga_{0.72}As$ is 5.66 Å,[18] a free dangling bond density in a (100) plane is estimated to be about $1.25\times10^{15}\,cm^{-2}$, which can be considered as the surface state density. This is within the region where the Fermi level at the surface is fixed to a point located at one-third of E_g, the so-called Bardeen limit.

When the probing light with the photon energy above E_g of AlGaAs is illuminated on the sample, electron–hole pairs are produced within the epitaxial layer. The electrons and holes will be separated by the electric field at the interface. Electrons in the conduction band will drift to the SI GaAs substrate side, whereas holes in the valence band will drift to the AlGaAs epitaxial layer side. Drifted electrons in the substrate eventually recombine with $EL2^+$ and generate the PPT signals. If all $EL2$ become optically and electrically inactive due to the photoquenching effect at low temperature ($T<130\,K$), the incoming electrons to the substrate cannot recombine with $EL2^+$. This results in a drastic decrease of the PPT signal as is evident in Fig. 3. The proposed model well satisfies the obtained experimental results.

When the electron–hole pairs are generated due to the probing light, as we discussed above, the electrons and holes may also be separated by the sample surface electric field. In this case, electrons will drift to the surface side and will recombine with the surface state. If the PPT signal is generated by this mechanism, the PPT spectrum should not be influenced by the photoquenching effect of $EL2$. Accordingly, it seems reasonable to suppose that the PPT signals generated after the complete photoquenching of $EL2$ are due to the electron nonradiative transitions through the surface states.

It is necessary to comment here on the origin of the PPT signals in the region between E_gs of GaAs and AlGaAs. The PPT signals in this region also decrease by the quenching light illumination, as shown in Fig. 3. The $EL2$ in the SI GaAs substrate should play an important role in the PPT signal generation mechanism as happened in the case of the region above E_g of AlGaAs. However, the decrease of the signal in this region is relatively small. We hereafter refer to this photon energy region as the *D* region. Consider first that the *D* region may be due to a residual carbon acceptor in the AlGaAs epitaxial layer. The photoexcited electrons from ionized carbon acceptors are assumed to drift to the substrate side and eventually recombine with $EL2^+$.

It must be noted that the *D* region drastically decreases with decreasing the temperature of the sample, as shown in Fig. 2. This leads to a conclusion that the decrease of the PPT signal intensity may be due to a reduction of the ionized carbon acceptor concentration. In other words, the decrease in the *D* region may be caused by the neutralization of the ionized carbon acceptor due to a movement of the Fermi level towards the carbon acceptor level that is attributed to a decrease of the sample temperature. However, an amount of the neutralization due to the decrease of the temperature from 297 to 80 K is estimated to be less than 2% of the carbon concentration. This contribution is too small to justify the present experimental results. Moreover, if the single acceptor level such as carbon acceptor generates the *D* region, the PPT spectrum should show a distinct peak around 0.026 eV below E_g of AlGaAs. But this is not the case, as is evident from Figs. 1(a) and 2. No other peak or change is observed in the *D* region. Therefore it is unlikely that the *D* region is due to the residual carbon acceptors in the AlGaAs epitaxial layer.

The other possible candidate for the signal generation mechanism of the *D* region is a nonradiative transition through the interface states between the epitaxial layer and the substrate. Since several levels with different activation energies are expected to exist in the interface, the PPT spectrum may show a broadband such as the *D* region. However, in the lattice matched heterostructure of AlGaAs and GaAs, the concentration of the interface states are expected to be at most in the order of $10^{12}\,cm^{-2}$. These are too few to explain the signal intensity of the D region. A detailed explanation is not yet conclusive.

IV. CONCLUSION

The PPT measurements of AlGaAs epitaxial layers grown on the SI GaAs substrate were carried out in the temperature range of 297 to 80 K. In addition to the band gap signal of the GaAs substrate, the Γ direct transition gaps of the $Al_xGa_{1-x}As$ ($x=0.22$, 0.28, and 0.5) were clearly observed in the higher photon energy region. The temperature coefficients of these direct transition gaps were estimated to be about -4.1, -4.3, and -5.3×10^{-4} eV/K, respectively. It was experimentally confirmed that the temperature coefficient of the Γ direct transition gap of the $Al_xGa_{1-x}As$ alloy decreased with increasing Al mole fraction x. By conducting the quenching light illumination measurements at 80 K we concluded that the electrons photoexcited within the AlGaAs epitaxial layer drifted under the influence of an electric field present at the interface. These drifted electrons eventually recombined with the ionized $EL2$ centers in the SI GaAs substrate. In spite of its low density of about $10^{12}\,cm^{-2}$, significant PPT signals were observed so that the interface states were considered as a source. The usefulness of the PPT technique for investigating the semiconductor heterostructure samples was successfully demonstrated.

ACKNOWLEDGMENT

The authors wish to thank Dr. Yohei Otoki of Hitachi Cable Co., Ltd. for supplying high quality heterostructure samples.

[1] G. M. Martin, Electron. Lett. **13**, 191 (1977).
[2] *Progress in Photothermal and Photoacoustic Science and Technology, Volume IV: Semiconductors and Electronic Materials*, edited by A. Mandelis and P. Hess (SPIE, Washington, 2000).
[3] R. Cingolani, L. Baldassarre, M. Ferrara, M. Lugarâ, and K. Ploog, Phys. Rev. B **40**, 6101 (1989).
[4] J. H. Chu, Y. H. Bak, J. H. Kim, H. L. Park, S. H. Park, U. Kim, J. G. Choi, and J. G. Kim, Appl. Phys. Lett. **64**, 745 (1994).
[5] Y. Ohba, M. Mizuta, and H. Kukimoto, Jpn. J. Appl. Phys., Part 2 **22**, L61 (1983).
[6] K. Kubota, H. Murai, and H. Nakatsu, J. Appl. Phys. **55**, 1520 (1984).
[7] T. Hata, S. Adachi, and S. Horita, Jpn. J. Appl. Phys., Suppl. **28**, 243 (1988).
[8] Y. Kanemitsu and H. Nabeta, Appl. Phys. Lett. **59**, 715 (1991).
[9] T. Ikari, H. Yokoyama, S. Shigetomi, and K. Futagami, Jpn. J. Appl. Phys., Part 1 **29**, 887 (1990).
[10] M. M. Farrow, R. K. Burnham, M. Auzanneau, S. L. Olsen, N. Purdie, and E. M. Eyring, Appl. Opt. **17**, 1093 (1978).
[11] W. Jackson and N. M. Amer, J. Appl. Phys. **51**, 3343 (1980).
[12] A. Fukuyama, Y. Morooka, Y. Akashi, K. Yoshino, K. Maeda, and T. Ikari, J. Appl. Phys. **81**, 7567 (1997).
[13] A. Fukuyama, Y. Akashi, K. Yoshino, K. Maeda, and T. Ikari, Phys. Rev. B **58**, 12868 (1998).
[14] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981).
[15] T. Ikari, K. Miyazaki, A. Fukuyama, H. Yokoyama, K. Maeda, and K. Futagami, J. Appl. Phys. **71**, 2408 (1992).
[16] G. M. Martin, Appl. Phys. Lett. **39**, 747 (1981).
[17] A. K. Saxena, Phys. Status Solidi B **105**, 777 (1981).
[18] S. Adachi, J. Appl. Phys. **58**, R1 (1985).
[19] M. Zavara, Phys. Status Solidi **27**, K157 (1968).
[20] B. Monemar, Phys. Rev. B **8**, 5711 (1973).
[21] Y. F. Zhang, Q. Zhuo, M. H. Zhang, Q. Huang, and J. M. Zhou, Appl. Phys. Lett. **77**, 702 (2000).
[22] P. M. Mooney, J. Appl. Phys. **67**, R1 (1990).
[23] M. Mizuta, M. Tachikawa, H. Kukimoto, and S. Minomura, Jpn. J. Appl. Phys., Part 2 **24**, L143 (1985).
[24] H. Kroemer, Surf. Sci. **174**, 299 (1986).

Journal of Applied Physics is copyrighted by the American Institute of Physics (AIP). Redistribution of journal material is subject to the AIP online journal license and/or AIP copyright. For more information, see http://ojps.aip.org/japo/japcr/jsp