Investigation of the annealing effect on the nonradiative carrier recombination in AlGaAs/GaAs utilizing the piezoelectric photothermal technique

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The electron nonradiative recombination process of photoexcited carriers in as-grown and annealed $n=Al_{0.2}Ga_{0.8}As/GaAs$ heterostructure samples is investigated by using piezoelectric photothermal (PPT) spectroscopy. The PPT signal above the band-gap energy of GaAs substrate decreased when the sample was annealed at 815 °C. In the frequency dependent measurements, the deviations from the $1/f$ linear function are clearly observed in the AlGaAs/GaAs samples. This critical deviation frequency was found to shift to the lower frequency region by annealing. Our experimental results are explained by assuming that the sample annealing generates an unknown deep level in the AlGaAs epitaxial layer region and this level effectively traps the photoexcited carriers nonradiatively. [DOI: 10.1063/1.1515888]

Pseudo-binary compound semiconductor AlGaAs is widely used for quantum electronic devices such as the light emitting diodes (LEDs) and the heterobipolar transistor (HBT). Intrinsic deep defect levels in this material are known to cause a degradation of such devices. They trap the free carriers, and thus high frequency operation of electronic devices is seriously influenced. The annealing process followed by an ion-implantation is a most important process in the device fabrication. Since this annealing process affects a formation and a destruction of deep defect levels, it is very important to understand an annealing effect on the carrier generation and recombination properties through deep defect levels.

The recombination process of photoexcited carriers is commonly investigated by a photoluminescesnce (PL) method. However, the recombination processes of a carrier through the deep level is mainly a nonradiative recombination. A strong electron lattice interaction affects these carrier transitions. The PL method can detect only a radiative recombination process. Therefore it becomes important to establish an alternative experimental technique to investigate such transitions.

Recently, we have developed a piezoelectric photothermal (PPT) spectroscopy that has a higher sensitivity for investigating the thermal and electronic properties of semiconductors than a conventional microphone photoacoustic method.[1] This also gives us information of nonradiative transitions through deep defect levels. Extensive works for Si, GaAs, and AlGaAs/GaAs samples were carried out[1–3] and metastable natures for representative deep levels in GaAs such as *EL2* and *EL6* were clearly resolved. In the present article we propose a model to explain our experimental results for the nonradiative recombination process in the photoexcited carriers in the AlGaAs/GaAs heterostructure sample. Annealing effect on the frequency dependence of the PPT signal intensity is also explained by developing the proposed model by Todorović *et al.*[4]

The samples were the AlGaAs/GaAs heterostructure semiconductors cut to a surface dimension of 7×7 cm^2 from the AlGaAs epitaxial layer grown on a semi-insulating (SI)GaAs substrate wafer. The Si-doped, n-type $Al_{0.2}Ga_{0.8}As$ epitaxial layer (1.4 μm thickness) was grown by the metal-organic vapor phase epitaxy (MOVPE) method. The concentration of a shallow Si donor level was 3.0×10^{16} cm^{-3}. The substrate was carbon-doped, liquid encapsulated Czochralski (LEC) grown SI GaAs (600 μm thickness). The concentrations of deep donor *EL2* and shallow carbon acceptor in the substrate were 1.3 and 0.4×10^{16} cm^{-3}, respectively. Since the annealing process seems to generate a new defect level in the band gap,[5] two samples, as-grown and annealed (815 °C for 30 min in the AsH_3 atmosphere) were prepared for the experiments. The specification of the GaAs substrates was kept constant between two samples.

The experimental configuration involving the sample and the detector is shown in the inset of Fig. 1. After the

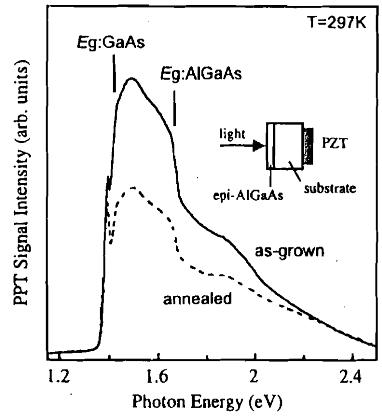

FIG. 1. PPT spectra of the AlGaAs/GaAs samples at 297 K. The solid and dashed lines denote the as-grown and the annealed samples, respectively.

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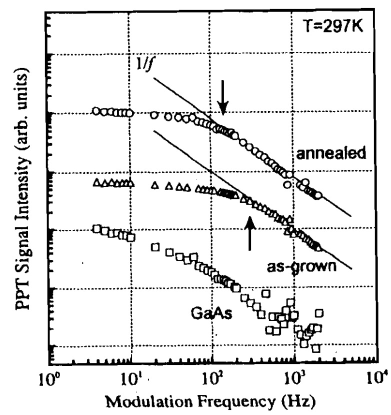

FIG. 2. Frequency dependence of the PPT signal of the as-grown, annealed, and the GaAs substrate samples at 297 K.

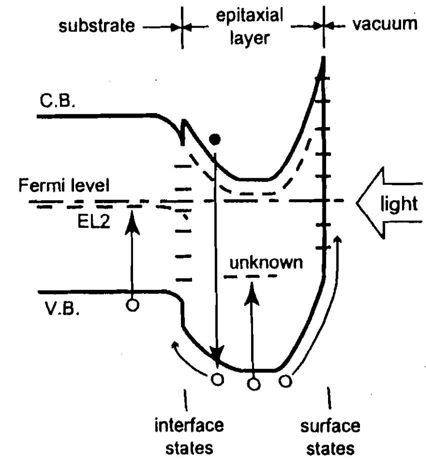

FIG. 3. Schematic band diagram near the epitaxial layer and the substrate interface. A depletion region bearing an electric field and band offsets are created.

sample was cut from the wafer, a disk-shaped piezoelectric transducer (PZT) was attached to the surface of the GaAs substrate using a silver conducting paste. The probing light to measure the PPT signal was modulated and way 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.[1]

Figure 1 shows the PPT spectra of AlGaAs/GaAs at 297 K. The PPT signal intensity was recorded as a function of incident photon energy of the probing light ranging from 1.1 to 2.8 eV). The modulation frequency of the probing light was set at 200 Hz. Since the same GaAs substrates were used for two samples, the PPT signal amplitudes were normalized below the band gap (E_g) of GaAs. As shown in the figure, the PPT signal above E_g of GaAs decreased when the sample was annealed.

In the frequency dependent measurements, the PPT signal intensity at 297 K was, then, measured as a function of the modulation frequency f between 4 and 2000 Hz. The wavelength of the probing light was set at 770 nm ($h\nu = 1.65$ eV). Results are shown in Fig. 2. In this figure, frequency dependence of the PPT signal intensity of the LEC-grown SI GaAs substrate sample is also shown. This exhibits almost linear dependence. On the other hand, the deviations from $1/f$ liner function are clearly observed in the AlGaAs/GaAs samples. This critical deviation frequency was found to shift to the lower frequency region by annealing.

The PPT signals originated from the AlGaAs epitaxial layer are considerably large compared with that from the substrate. In our previous article,[3] we concluded that electrons photoexcited within the nondoped p-AlGaAs epitaxial layer drifted under the influence of an electric field present at the interface. These drifted electrons eventually recombined with the ionized $EL2$ in the GaAs substrate. In the present case, a similar argument is possible. As shown in Fig. 3, an electric field and band offsets are created at the interface between the n-AlGaAs epitaxial layer and the SI GaAs substrate. Holes photoexcited within the epitaxial layer drifted and eventually recombined with the neutral $EL2$ in the GaAs substrate. Since this transition is known to have a strong nonradiative component,[2] the generated heat by this transition causes the PPT signal.

The PPT signal above E_g of the GaAs substrate decreased when the sample was annealed at 815 °C for 30 min. We, then, assume that the present annealing treatment generates an unknown deep level in the band gap within the AlGaAs epitaxial layer as suggested by other authors.[5] Supposing that this deep level can act as a faster recombination center for holes, the photoexcited holes cannot drift to the GaAs substrate side. It is well understood that this results in a decrease of the PPT signal intensities in the photon-energy region above E_g of GaAs by annealing. If the deep level acts as a nonradiative center, the capturing of the photoexcited hole by an unknown deep level generates a heat and this contributes to increase the PPT signal intensity. This is not the case for the present experimental results. In general, however, nonradiative transition is dominant in the electron transition through such a deep level. Therefore we have to think about other influences in order to explain the present experimental results.

Here, we pay attention to the results of the frequency dependent measurements. As shown in Fig. 2, the critical deviation frequency was found to shift to the lower frequency region by the sample annealing. To explain this shift of the critical deviation frequency, we develop the theory for the photoacoustic signal generation mechanism proposed first by Todorović *et al.*, hereafter referred to as the Todorović model.[4] Note that they have considered that the photoacoustic signal is detected by using a microphone, which is away from the sample surface by the air gap. However, our PZT detector is directly attached to the rear sample surface. Such a difference should be kept in mind for further discussions. Anyway, we first assume here that the generated PPT signal at the sample surface is completely detected by PZT whichever signal is caused by a pyroelectric or a piezoelectric effects.[1]

In the Todorović model, the photoacoustic signal is caused by the following three components: (a) TD (thermal-diffusion), (b) TE (thermoelastic), and (c) ED (electronic deformation) components. The TD component is a consequence of the thermal (heat) diffusion processes in the sample, i.e., it depends on the periodic temperature variation on the rear sample surface. The TE component is the consequence of the sample surface displacement, that is, the thermoelastic expansion and bending. This is an important effect in the photoacoustic signal generation mechanism, especially at higher frequencies. Furthermore, the photoexcited free carriers, electron and hole pairs, produce a periodic elastic deformation in the sample directly, so-called an elastic deformation (ED), which in turn generates the photoacoustic signal. The theoretical calculation to check the contribution of each component to the frequency dependence of the PPT signal intensity was carried out. The TD component exhibits almost $1/f$ linear dependence. On the other hand, the TE and ED components show the deviation from $1/f$ linear function below each critical frequency.

In the present experimental frequency region ($f = 4-2000$ Hz), the ED component can be neglected because the intensity is very low compared with other components. Therefore, two contributions, TD and TE, may explain the present experimental results. If the TE component becomes more dominant than TD, a critical deviation frequency of the sum of two components (PPT signal) is expected to shift to the lower frequency region. This is the case of our present experimental results. In other words, a bending of the rear sample surface becomes larger for the annealed sample than that for the as-grown sample. The photon energy of the probing light is near the E_g of AlGaAs, and the excess free carriers are generated in the AlGaAs epitaxial layer side. If the unknown deep level fabricated by the sample annealing acts as the nonradiative center and traps the photoexcited hole, the heat generates mainly within the AlGaAs epitaxial layer. This results in the bending term in the TE component increasing. This is a reason for the shift of the critical deviation frequency by the sample annealing.

To conclude, by using the PPT method, we have investigated the nonradiative carrier recombination processes, in an n-AlGaAs/GaAs heterostructure sample. The PPT signal above E_g of GaAs decreased by the sample annealing. By developing the Todorović theory for the signal generation mechanism, we have explained the experimental results of the frequency dependence. Two contributions, namely thermal diffusion (TD) and thermoelastic (TE) components, are considered. Discussion on the contribution of these two components on PPT signal implied that the deep level fabricated within the AlGaAs epitaxial layer side by sample annealing acts as a nonradiative center.

Since the PPT method does not necessitate the fabrication of electrodes, the usefulness of this method for studying the electron nonradiative recombination process nondestructively is pointed out. However, a more detailed quantitative consideration is necessary for the next step.

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