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Characterization of Residual Stress in Semi-Insulating GaAs:Cr by Photoluminescence Method

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We have measured systematically the Cr-related zero-phonon line at 0.839 eV in a series of plastically-bent semi-insulating GaAs:Cr with some compressive or tensile stresses along various bending axes. As a result, we have found that the residual stress in semi-insulating GaAs:Cr wafers can be characterized from a splitting and shift of the 0.839 eV Cr-related luminescence line by the low-temperature photoluminescence method.

1. Introduction

The recent development of GaAs devices has led to them to a promising position in both high-speed and optoelectronic devices. However, there is plenty of room for improvement in device yield and reliability, compared with silicon devices. Much efforts have been made to establish some key techniques to grow reproducibly GaAs crystal of good quality and to characterize the material with confidence. It is important to obtain information about the residual stress in GaAs wafers, since the residual stress greatly affects the performance and reliability of LSI devices. The residual stress induced during mechanical or thermal treatments causes occasionally the redistribution of the residual impurities and the compensators, and this leads to the thermal-conversion in conductivity type of GaAs crystal.[1] On the other hand, the residual stress induced by lattice mismatch in heteroepitaxial structures such as room-temperature operating semiconductor heterojunction laser has been found to play a major role in determining the recombination velocity of minority carriers at the heteroepitaxial interfaces.[2] From these points of view, a new powerful characterization technique for residual stresses in GaAs crystal is strongly desired.

Cr-doped semi-insulating GaAs crystals have been technologically important as the substrate materials for high-speed GaAs integrated circuits and considerable efforts have been made to understand some basic electronic behaviors of this transition metal in GaAs.[3,4] The low-temperature photoluminescence (PL) associated with Cr in GaAs has been intensively studied so far,[5-9] the spectrum being dominated by a sharp zero-phonon line at 0.839 eV together with a broad band in its lower energy side. Recent Zeeman spectroscopic data[8] on this 0.839 eV line have revealed that the luminescent center has <111> C_{3v} axial symmetry rather than T_d symmetry of an isolated Cr ion at the Ga site in GaAs crystal. This suggests a complex involving a Cr and another unidentified impurity or defect, which has been recently demonstrated to be an arsenic-vacancy by us,[6] in the neighborhood of the Cr ion as the Cr-related luminescent center. Effects of uniaxial stress on the Cr-related 0.839 eV line have been also studied in details to get further knowledge about the origin of this luminescent center and it has been illustrated that the results are well interpreted by the hypothesis of a substitutional Cr^{2+} ion on a Ga site subjected to a perturbation of C_{3v} symmetry.[9]

In this paper, we report results of systematic measurements on the Cr-related zero-phonon line at 0.839 eV in a series of plastically bent semi-insulating GaAs:Cr wafers along the three principal crystallographic [001],

[110] and [111] axes. We have considered the use of these PL results for characterizing the residual stress in GaAs:Cr wafers and demonstrated that the type and magnitude of the residual stress in GaAs:Cr wafers can be estimates by this PL method.

2. Experiments

Mirror-polished specimens used in this work with the [110],[111] or [001] bending axis were cut from Cr-doped GaAs wafers with (100) or (110) crystal orientation, which were grown by a gradient freeze (GF) technique. In order to produce homogeneous deformation, one surface of the specimen was abraded with #3000 silicon-carbide powder before the deformation. The specimen was bent at 350 °C or 400 °C by a four-point bending apparatus previously described[10] with a bending rate of 100 μm/min, or 500 μm/min. The deformation was stopped at some crosshead displacement and the specimens were rapidly dropped into water to quench dislocation distributions during bending. The specimens obtained in this way involve some residual stresses along the axis.

PL measurements were carried out with the specimens directly immersed in liquid He at 4.2 K. The photoexcitation source was a cw mode Ar^+ laser operating at 5145 A with a beam diameter of 1 mm and an incident power of 400mW was mainly used. The luminescence was analyzed by a SPEX 1704 grating monochromator with a 600 grooves/mm grating blazed at 1.25 μm, and detected by a North-Coast Ge pin photodiode cooled by liquid N_2. the detector output was amplified by a lock-in amplifier PAR EG&G 124A and processed with a computer-controlled signal averaging system.

3. Results and Discussion

Figure 1 shows the Cr-related luminescence spectra in the 0.839 eV region for the mirror-polished compression side of plastically-deformed semi-insulating GaAs:Cr specimens with various bending axes, together with that of the as-received wafer. It is clearly seen that the Cr lines observed in the as-received wafer shift accompanying the appearance of new lines in the bent specimens. This observation is well explained by the splitting of the degenerate Cr levels in GaAs under residual stresses. Furthermore, in accordance with the direction of the bending axis, the observed Cr-related luminescence spectra are quite different between each other, which reflects the symmetry of the luminescent center. We have also measured these luminescence spectra for mirror-polished specimens with some tensile stresses along various bending axes. As a result, we have found that the intensity of the main Cr-related luminescence line also decreases in the specimen with tensile stresses and new lines appear, and also that a specific Cr-related luminescence is observed in accordance with the tensile stress direction, which is different from that observed with compressive stresses even if the bending is carried out along the same axis.

Figure 2 shows the Cr-related luminescence spectra for plastically bent specimens with the compressive stress along the [110] bending axis as a parameter of load-point deflection (the crosshead displacement), together with that of the as-received wafer. The specimens were

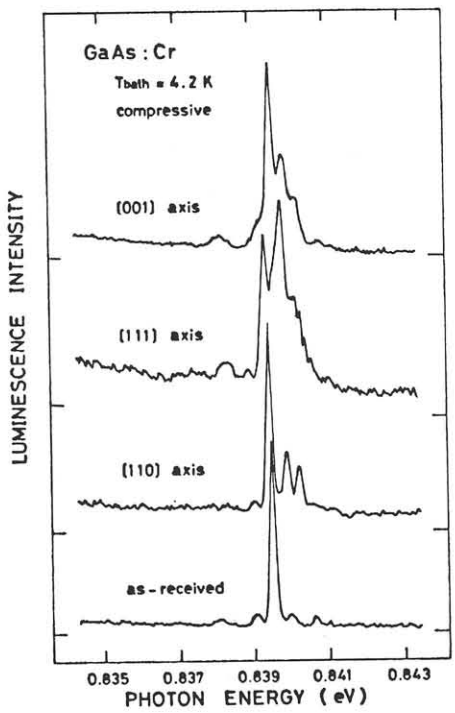

Fig. 1 Cr-related luminescence spectra of as-received and plastically-deformed GaAs:Cr wafers with compressive stresses along various bending axes.

deformed at 400 °C with a bending rate of 100 μm/min. In the specimens with the compressive stress along the [110] bending axis the intensity of the main Cr-related PL line decreases and a pair of new lines appears in the higher-energy side, as indicated by arrows in Fig. 2. The peak positions of these stress-induced lines shift toward the higher-energy side with increasing the load-point deflection, though the peak position of the main luminescence line is unchanged. When the load-point deflection increases up to 600 μm, a pair of stress-induced lines disappear and the main luminescence line becomes broad with the peak position unchanged. this broadening of the main luminescence line is interpreted by the existence of the stress distribution over the excited area on the specimen surface due to the introduction of dislocations from the rear side abraded with silicon-carbide powder, which is confirmed by the observation of such dislocation distribution on the cleaved plane by the etch pit method using AB etchant.[11]

Based on uniaxial-stress data of the 0.839 eV of Cr-related luminescence line, we can estimate the magnitude of the residual compressive stress in the bent specimen from the Cr-related luminescence line shift. In Fig. 3, the solid lines represent the [110] uniaxial stress dependence of the 0.839 eV Cr-related line in GaAs by Barrau et al.[9] The peak positions of the main line and a pair of stress-induced lines observed in the specimens with compressive stresses along the [110] bending axis are plotted in this figure to fit them to the solid lines. Here the closed circles correspond to data shown in Fig. 2. Therefore, for example, the magnitude of the residual stress for the specimens of Fig. 2 can be easily estimated to be 28.5 MPa at the load-point deflection of 257 μm and 54.0 MPa at 372 μm, respectively.

The Cr-related luminescence spectra in plastically deformed specimens with tensile stress along the [110] bending axis indicate stress-induced lines on both sides of the main luminescence line, as shown in Fig. 4. This figure shows a comparison between Cr-related luminescence spectrum for the specimen with tensile stress along the [110] bending axis, which is plastically deformed st 350 °C with a bending rate of 100 μm/min, and that for the as-received wafer. With particular emphasis on the stress-induced line in the higher-energy side

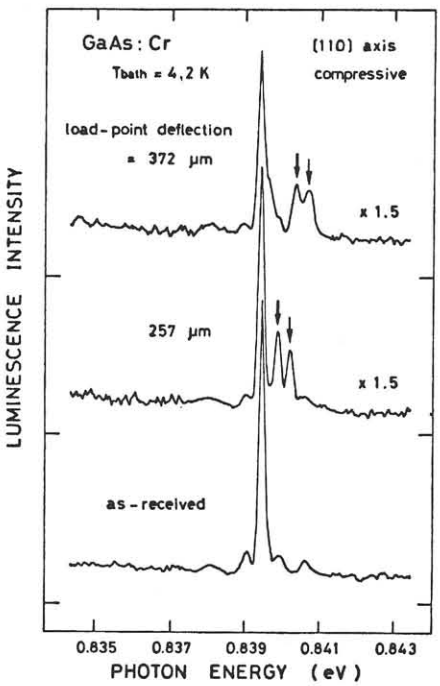

Fig. 2 Cr-related luminescence spectra of as-received and plastically-deformed GaAs:Cr wafers with compressive stresses along the [110] bending axis.

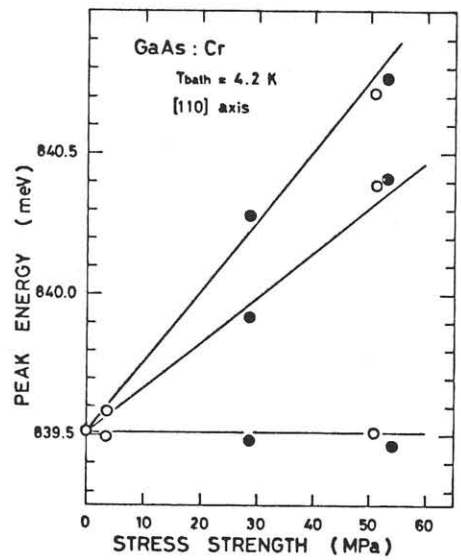

Fig. 3 Relation between the peak positions of the Cr-related luminescence lines observed in the specimens with the [110] uniaxial atress and the strength of stress.

of the main luminescence line, we have systematically investigated its behavior as a parameter of load-point deflection in specimens plastically deformed at 400 °C with a bending rate of 100 μm/min. As a result, it has been found that the peak position of the main line is unchanged and the peak position of the stress-induced line shifts toward the higher-energy side with the increase of the load-point deflection reaching the maximum value at the load-point deflection of 350 μm. Thereafter, it goes backward and the stress-induced line disappears at the load-point deflection of 600 μm into the tail of the main line which becomes broad by the similar reason previously described. Considering that the shift of the stress-induced line from the main luminescence line is proportional, even for the case of tensile stress, to the strength of residual stress involved in plastically deformed specimen, this result indicates that the maximum residual stress remains in the specimen deformed at the load-point deflection of 350 μm.

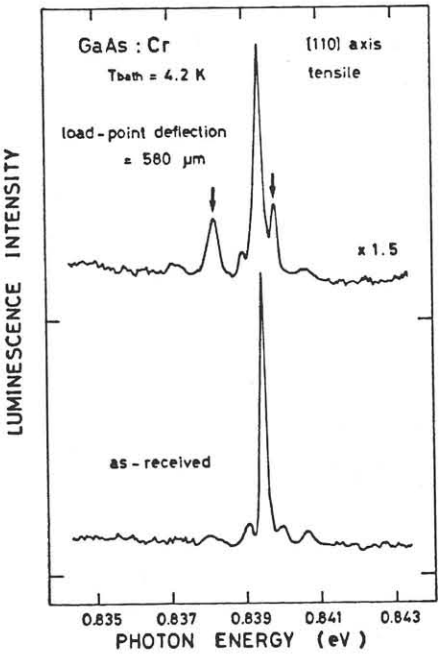

Fig. 4 Cr-related luminescence spectra of as-received and plastically-deformed GaAs:Cr wafers with tensile stresses along the [110] bending axis.

4. Conclusions

We have systematically investigated the Cr-related luminescence lines in the 0.839 eV region in a series of plastically-bent semi-insulating GaAs:Cr with compressive or tensile stresses along various bending axis. As a result, we have found that the residual stresses in semi-insulating GaAs:Cr wafers can be characterized by the low-temperature photoluminescence methods, since the specific Cr-related luminescence lines in the bent specimen are observed in a different way depending upon the type of stress, compressive or tensile, and also the direction and magnitude of the stresses. Though the residual stress in the specimens we studied is restricted at present to uniaxial-stresses, this photoluminescence method measuring the Cr-related deep acceptor luminescence can be applied to characterize two-dimensional stresses, for example, the residual stresses involved in GaAs thin films epitaxial grown on GaAs:Cr substrate by MBE or MOCVD methods.

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