

Photoinduced stress in a ZnSe/GaAs epilayer containing $90^\circ \alpha$ partial dislocations

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Photoinduced stress in a ZnSe/GaAs epilayer containing $90^\circ \alpha$ partial dislocations was observed *in situ* by means of polarized cathodoluminescence spectroscopy under light illumination in a transmission electron microscope. A dislocation glided under the illumination of a monochromatic light whose photon energy was above 2.07–2.40 eV, presumably due to a recombination-enhanced effect. The glide accompanied with a variation of the compression stress along [110] in the epilayer; the stress decreased at the temperature of 35 K, while it increased at higher temperatures. © 2005 American Institute of Physics. [DOI: 10.1063/1.2123392]

ZnSe has a revival of interest in its potential applications to light emitters, such as light-emitting diodes and laser diodes, that may offer a number of advantages over the commercial GaN-base diodes.^{1,2} A key issue that has hampered commercial applications of the emitters is their degradation under operating conditions. One origin of the degradation is substitutional N atoms on Se sites, i.e., N acceptors. The concentration of N acceptors decreased while that of point defects acting as donors increased during operation,^{3,4} and it was explained that the defects are Se vacancies formed by a transition of the substitutional N atoms to stable interstitial atoms.⁵ The defects would be preferentially accumulated into a compressed epilayer in a light emitter,⁶ via their migration during operation,⁷ since they help to decrease the elastic energy in the epilayer, and a light emitter with a diluted active epilayer was indeed alive much longer than light emitters with a compressed one.⁸ The other origin is partial dislocations (PDs) bounding stacking faults (SFs). They are formed inevitably during the epitaxial growth, and a small amount of PDs still exist in recent light emitters. The lifetime of a light emitter is drastically lengthened by reducing the density of PDs,⁹ since dislocation dipoles, whose type of Burgers vectors is $(a/2)\langle 110 \rangle$ lying in (001) (Ref. 10) or $(a/2)\langle 011 \rangle$ inclined at 45° to (001),¹¹ are nucleated from PDs during operation^{10–13} and the dipoles, as well as PDs and SFs, act as nonradiative recombination centers.¹³ It is considered that the dipoles are formed via accumulation of point defects,⁷ that are presumably Se vacancies formed by the preceding process,⁴ around PDs. However, the role of PDs in formation of dipoles has not been fully understood. In this letter, polarized-cathodoluminescence (*p*-CL) spectroscopy under light illumination, as well as transmission electron microscopy (TEM), revealed that a PD glides under illumination of a light that is similar to the lights emitted from usual ZnSe-base light emitters, and the glide introduces anisotropic stress around the PD by which vacancies would be preferentially accumulated at room temperature.

The sample was an undoped ZnSe epilayer of 80 nm thick, in which the SFs of Shockley-type bounded by 90° PDs existed, grown on a GaAs(001) wafer.¹⁴ The GaAs surface on a small chip of the sample was mechanically dimpled

until the center of the chip was sufficiently thin for TEM and *p*-CL spectroscopy. The thickness was estimated to be a few hundred nanometers, so ZnSe epilayer and GaAs substrate were simultaneously characterized. A beam of 160 keV electrons (the flux of about 50 A m^{-2}), nearly parallel to [001], was used for characterization. The probe size was about $1 \mu\text{m}$ in diameter. Both TEM images and *p*-CL spectra scarcely varied during the illumination of the beam. A visible light and an electron beam for characterization illuminated simultaneously a specimen surface with an apparatus.¹⁵ A monochromatic light with the photon energy of 3.10, 2.48, 2.07, or 1.77 eV from a light source (Bunko-keiki SM-5, the power density of about 10^3 W m^{-2}) or a laser light with 2.41 eV from an Ar-ion laser (10^4 W m^{-2}) was used. The temperature of a specimen would rise by the illumination since the inelastic scattering of the beams results in creation of multiphonons, and the rise in temperature was estimated to be 20–30 K by analyzing¹⁶ the CL spectra of GaAs under the illumination. The specimen temperature under the illumination ranged from 35 to 600 K.

The areas of some SFs varied during illumination of a laser light. TEM analyses¹⁴ revealed that only the SFs lying on (111) and $(11\bar{1})$ varied their areas; in other words, only $90^\circ \alpha$ PDs glided. At the temperature of 35 K, all the SFs expanded [Fig. 1(a)]; the area of a SF increased at a constant rate Δ with increasing illumination time [Fig. 1(c)]. On the other hand, most of the SFs contracted at higher temperatures [e.g., Fig. 1(b)]; the area of a SF decreased at a constant rate Δ [Fig. 1(d)], and a pair of $90^\circ \alpha$ PDs bounding a SF converted to an extended 60° dislocation [Fig. 1(e)], as observed in an epilayer under illumination of an electron beam.¹⁷ The rest of the SFs, of a small number, expanded at the temperatures. Δ s at various temperatures are summarized in Fig. 1(f). The areas of the SFs scarcely varied at any temperature without laser illumination [Fig. 1(f)].

SFs of Shockley type are usually formed under a shear stress, and so the stress in a specimen was estimated by means of a CL technique.¹⁸ The photon energy of the CL light emitted from a GaAs substrate, via the band-to-band transition, was measured at any temperature, and the energy was lower than that from bulk GaAs crystals due to the tensile stress arising from the misfit between ZnSe and GaAs [e.g., Fig. 2(b)]. The stress along [110] was larger than that

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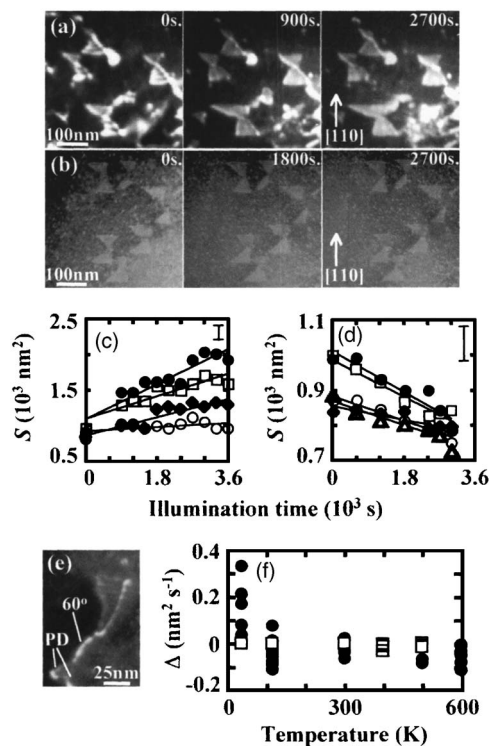


FIG. 1. (a) Photoinduced expansion of SFs at 35 K and (b) photoinduced contract of SFs at 600 K. The SFs of Shockley-type lying on (111) and $(11\bar{1})$ are observed by a weak-beam TEM technique. Variation of the areas of different SFs as a function of illumination time; (c) at 35 and (d) 600 K. The area of each SF, S varies at a constant rate Δ [solid lines in (c) and (d)]. (e) A 60° dislocation converted from a pair of PDs. (f) Δ s at various temperatures. S varies under laser illumination (circles), while it scarcely varies without laser illumination (squares).

along $[1\bar{1}0]$, since analyses of p -CL spectra,¹⁹ e.g., Fig. 2(b), showed that the intensity of the CL light polarized along $[1\bar{1}0]$ and that along $[110]$, $I_{[1\bar{1}0]}$ and $I_{[110]}$, are maximal and minimal, respectively. The degree of linear polarization (DLP),²⁰ defined by $DLP = (I_{[1\bar{1}0]} - I_{[110]}) / (I_{[1\bar{1}0]} + I_{[110]})$, was estimated to be about 20%. The absolute value of the tensile stress in the thin substrate (of the order of a few kilobars)²¹ should be almost the same as that of the compression stress in the ZnSe epilayer on the substrate. The compression stress varied anisotropically during illumination of a laser light, since DLP decreased at 35 K [e.g., Fig. 2(c)] while it increased at higher temperatures. Moreover, the photon energy increased at 35 K [e.g., Fig. 2(e)], while it decreased at higher temperatures [e.g., Fig. 2(d)]. These results indicate that the compression stress along $[110]$ decreased at 35 K and it increased at higher temperatures. This is consistent with the TEM data in Fig. 1, since the compression stress along $[110]$ would decrease with increasing the areas of the SFs lying on (111) and $(11\bar{1})$.¹⁴

It is considered that a PD in a light emitter under operating conditions creates local thermal stress by consumption of photons at the dangling bonds on the PD,¹¹ and the emitter would be degraded since vacancies are accumulated around the PD, via their migration during operation,⁵ so as to reduce the thermal stress, as well as the built-in stress.^{11,12} This letter shows that an additional compression stress would be introduced around a $90^\circ \alpha$ PD via the photoinduced glide of the PD at temperatures above 35 K. It is known that dislocation dipoles in a degraded emitter elongate anisotropically

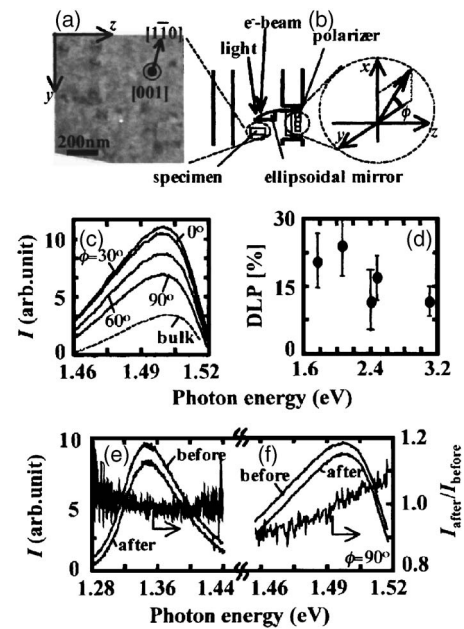


FIG. 2. (a) An experimental setup for p -CL spectroscopy. A CL light emitted from a specimen is reflected on an ellipsoidal mirror and the reflected light is transmitted in a linear polarizer. The transmission direction of the polarizer is determined by the rotation angle ϕ . Then, the transmitted light is collected into a charge coupled device detector through a monochromator. (b) p -CL spectra of a GaAs substrate obtained at 35 K without light illumination (solid lines), and a CL spectrum of a bulk GaAs crystal, which emits nonpolarized CL light, obtained at the same condition (the broken line). (c) DLP of a specimen illuminated with a monochromatic light for 600 s, at the temperature of 35 K. A p -CL spectrum varies after the laser illumination for 1800 s; (d) at 500 or (e) 35 K.

around PDs.^{10,12} Migrating vacancies, formed under operating conditions,⁵ may be preferentially accumulated around a $90^\circ \alpha$ PD so as to reduce the photoinduced compression stress along $[110]$, as well as the other stress, around the PD.

This letter briefly speculates the mechanism of the photoinduced glide of $90^\circ \alpha$ PDs. Since a SF can not expand and contract simultaneously under a single compression stress in one direction, the glide must be assisted with an extra amount of energy provided by a light, as well as with the compression stress arising from the misfit. DLP, estimated at 35 K, decreased distinctly after the illumination of a monochromatic light with the photon energy of 2.41, 2.48, or 3.10 eV, owing to the glide, while it scarcely varied after the illumination of a light with 2.07 or 1.77 eV [Fig. 2(c)]. Thus, the minimum energy needed for the glide was in the range 2.07–2.41 eV. The estimated energy is much larger than the activation energy for thermal movement of dislocations in ZnSe (about 1 eV).²² Even though dislocation glide is a thermally activated process, in the present case, it is very likely that most of the energy for dislocation motion comes from an electron-hole recombination²³ and the thermal component of glide is relatively minor. Since the estimated energy is smaller than the band gap energy (about 2.8 eV at 35 K), electrons and holes would be recombined at a localized energy level in the band gap, which may be associated with $90^\circ \alpha$ PDs (Ref. 24) or defects on the PDs such as soliton defects²⁵ and kinks. The rate Δ for each SF at a temperature, that would be related to the velocity of $90^\circ \alpha$ PDs bounding the SF (of the order of 10^{-3} nm/s),²⁶ was different [Fig. 1(f)]. This may be explained that the stress around each PD is different, even though the PDs may glide

even in a stress-free epilayer so as to reduce the electronic energy of the epilayer,^{27,28} similar to dislocations in SiC.²⁹ Photoinduced dislocation glide would take place in usual ZnSe-base light emitters under operating conditions, since they emit lights whose photon energies are large enough for the glide. Further study to determine the origin of the localized energy level may help to eliminate photoinduced stress and to fabricate light emitters with long lifetimes.

It is known that PDs of any type can move in an epilayer under illumination of an electron beam,¹⁷ presumably due to a recombination effect similar to the present study. The result suggests that, only $90^\circ \alpha$ PDs glide under illumination of a light since the efficiency of the recombination associated with the glide is rather high, or the energy needed for the glide is rather small, in comparison with the other types of PDs.

In conclusion, photoinduced stress in a ZnSe/GaAs epilayer due to photoinduced glide of $90^\circ \alpha$ PDs was investigated by means of *p*-CL spectroscopy under light illumination in a transmission electron microscope and TEM. The method will be applied to explore, at an atomistic level, the dynamic nature of defects in nonequilibrium states, i.e., under illumination of light and/or electrons.

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²¹This means that the epilayer was applied a strain of about 10^{-3} . The estimated strain was smaller than the strain reported in Ref. 20. Since the specimen was thin, stress might be free to relax near the surfaces.

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²⁶The velocity of a PD, v can be roughly estimated with a function, $v = \Delta/2h$, in which h is the epilayer thickness.

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