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# Observation of ⟨100⟩ Dark Line Defects in Optically Degraded $ZnS_xSe_{1-x}$-Based LEDs by Transmission Electron Microscopy

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## Abstract

We have used transmission electron microscopy to study the ⟨100⟩ dark line defects (DLDs) produced after photodegradation of a ZnSSe-based/GaAs heterostructure. Our results show that the DLDs are networks of elongated dislocation loops or half loops that originate in the quantum well region during device operation. Our results also show that after photodegradation the Frank-type stacking faults become tangles of dislocations while the Shockley-type stacking faults remain unchanged. We propose a mechanism for the degradation process .

## Introduction

ZnSSe-based/GaAs heterostructures have become very important for the fabrication of blue-green light emitting diodes (LEDs) and lasers. At first, the devices would only last a few seconds, or minutes.[1, 2] At present typical devices last approximately 100 hrs (LEDs) and 90 minutes (laser diode).[3] The failure of the device takes place by the generation of defects in the active region during operation. Two types of defects are commonly observed; the, so-called, dark line defects (DLDs) and the dark patches. The DLDs are dark lines along the [100] and [010] directions. The dark patches are triangular networks of dislocation loops. Both defects form from pre-existing defects and start as small dark dots that grow and widen during device operation until the whole surface of the emitting region is dark and the device fails.[4, 5, 6] The dark patches have been identified to be dislocation networks developed at the QW region and originating from V-shaped stacking faults.[6, 7] The DLDs form along traces left by mobile defects emitted from pre-existing defects.[4] In this work, we report a transmission electron microscopy (TEM) study of the DLDs produced during photodegradation of a $ZnS_xSe_{1-x}/Cd_yZn_{1-y}Se$ quantum well (QW)/$ZnS_xSe_{1-x}$/ZnSe/GaAs heterostructure. We also propose a mechanism for the generation of DLDs in these materials.

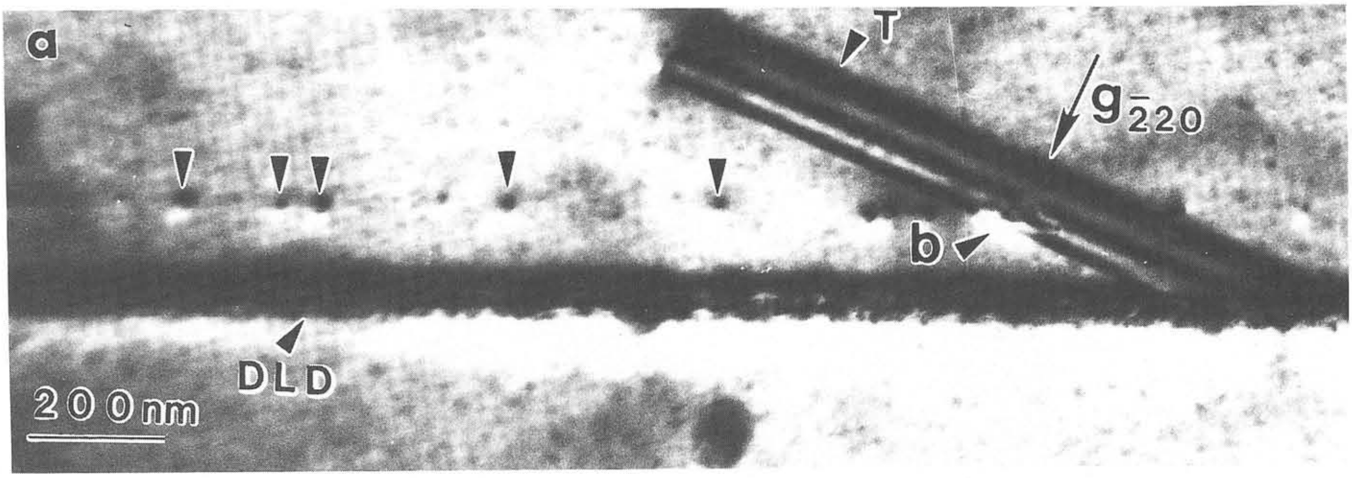
## Experimental

The samples used in this study were grown by molecular beam epitaxy (MBE) at 280° C and consisted of 0.16 $\mu$m $ZnS_{0.055}Se_{0.945}$/∼5 nm $Cd_{0.2}Zn_{0.8}Se$ QW/0.84 $\mu$m $ZnS_{0.055}Se_{0.945}$/ZnSe/GaAs buffer layer/GaAs heterostructures. The films were doped with Cl and had a net carrier concentration of $N_d$-$N_a$ $\sim$ $1\times10^{18}/cm^3$. The photodegradation was carried out by illuminating regions of the samples of $\sim 50\mu m$ in diameter along a straight line using the 351.1 and 363.8 nm lines of an Argon ion cw laser.[4] The laser was focused on the film to produce the luminescence by photopumping the $ZnS_{0.055}Se_{0.945}$ cladding layers and the $Cd_{0.2}Zn_{0.8}Se$ QW above their band gap energies. For TEM studies plan-view specimens were prepared from the photodegraded and non-degraded areas of the samples for comparison. The specimens were prepared using mechanical grinding and ion milling from the substrate side to obtain perforation. A JEOL 2000FX-II TEM was used to identify the defects induced by photodegradation.

## Results and Discussion

Figure 1 shows examples of TEM images taken from the degraded samples. These figures show networks of dislocation tangles along the ⟨100⟩ directions that we believe correspond to the DLDs. Since the images were taken from different samples and at different times we do not know if the directions of the DLDs were [100] or [010]. Therefore, we simply refer to them as ⟨100⟩. The DLDs consist of extended dislocation loops. These loops are, in some cases, broad (see Fig. 1b). This result is in agreement with the observation that during photodegradation, the DLDs broaden.[4] The dislocation networks extended over very large distances in the TEM sample. In many cases, their length exceeded the thin areas of the TEM sample ($\sim$ 5 $\mu$m). However, occasionally we were able to see the end of the DLDs. In these regions we observed a series of small dislocation loops ($\leq$ 20 nm) (marked by arrows in Fig. 1a) along the ⟨100⟩ direction and extending from the DLDs. Close to the DLDs the dislocation loops increased in size and overlapped each other. We also observed contrast or traces characteristic of lattice distortion along the line connecting the dislocation loops (see Fig. 1a). The traces can act as nucleation sites for the generation of small dislocation loops during photodegradation. The series of loops in Fig. 1a) is also connected to a small faulted defect labelled b that lies over a large faulted defect labelled T. The faulted defect T originates at the $Cd_yZn_{1-y}Se/ZnS_xSe_{1-x}$ interface. Defect b has irregular-shape and is identified as a prismatic-type defect. It is a complex faulted defect consisting of a Frank dislocation loop containing steps in the stacking fault.

The image of a broadened DLD is shown in Fig. 1b). In this figure many elongated dislocation half-loops (marked by arrowheads) are observed. Segments of the elongated dislocation half-loops appear to have glided and cross slipped along the ⟨110⟩ direction during the photodegradation process and become "hair pin"-like dislocation half-loops when they reached the film surface. The loops are identified as glissile dislocation loops with Burgers vector $\mathbf{b} = 1/2\langle\bar{1}01\rangle$-type lying on the {111}-type planes. Since only the screw segments of the dislocation loops are allowed to cross slip, elongated dislocation loops or half-loops are produced when the DLDs broaden.



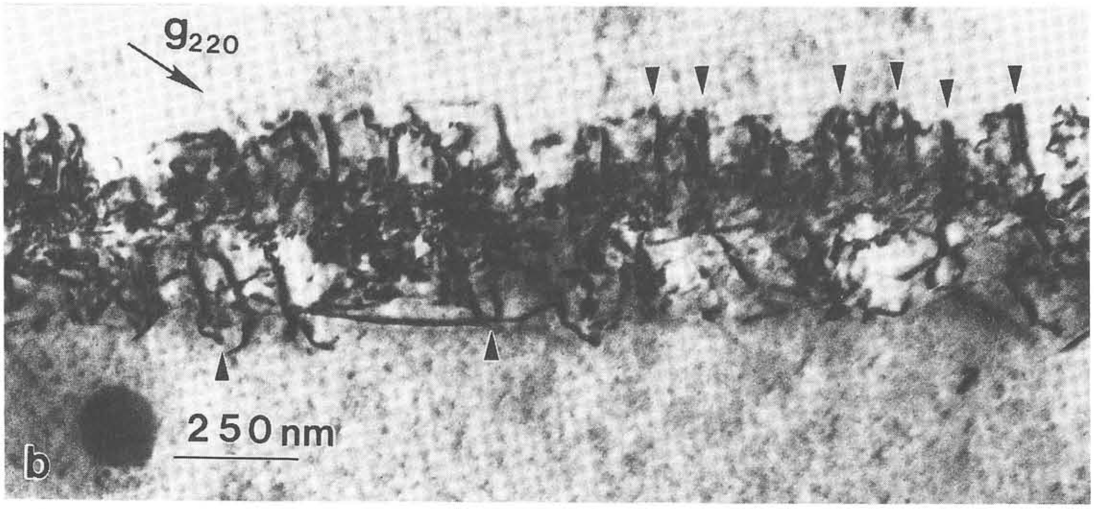




Fig. 1 a) ($\bar{2}20$) bright field image of a photodegraded sample showing a DLD and a faulted defect b blocked by a stacking fault T. b) (220) plan view image of a DLD. Small and extended dislocation loops are marked by arrowheads in (a) and (b), respectively.

Figure 2 is a TEM plan-view image that was also obtained at the end of a trace. This figure shows the remaining of a Frank-type stacking fault S that has almost completely collapsed and become a dense tangle of dislocations upon photodegradation. The remaining segments of the Frank partial dislocations are marked F. Traces (marked by arrowheads) are observed in Fig 2 originating at the degraded stacking fault. It is interesting to note, however, that the density and structure of Shockley partials were essentially the same in the degraded and non-degraded samples. This result indicates that for the photodegradation conditions studied the Shockley partials are more stable than the Frank partials. These results confirm that the Frank-type stacking faults are the main sources for the ⟨100⟩ DLDs.

A possible mechanism for the generation of DLDs based on our TEM observation is as follows. Illumination with light of energy close to the band gap produces photoelectrons from the valence band which may be trapped at the dislocation levels resulting in an increase in the charge accumulated at the dislocations[8]. It has been reported that an increase in flow stress under illumination is correlated with an increase in the dislocation charge for ZnSe and CdS[9]. Thus, during electron-hole recombination from the QW charge may be absorbed and accumulated in the faults inducing local damage to the stacking faults. The charge accumulation gives rise to local degradation and instability in the region of the QW until a mobile defect is emitted from the Frank-type fault. Upon further illumination the degradation propagates toward the II-VI/GaAs interface and the film surface. The mobile defects are clusters of vacancies that form since II-VI compounds have a low stacking fault energy[10], and the supersaturation of local clusters of vacancies can be reduced by fault climb to form steps in different portions of a simple faulted defect[11]. Thus, the small faulted defect b in Fig. 1a) is believed to be a mobile defect that traveled until it was blocked (or absorbed) by a pre-existing stacking fault (T).

The dissipation of the flow stress associated with the emission of the mobile defects may contribute to the residual strain contrast observed along the path of the mobile defects. Along the path of the mobile defect very small dislocation loops can nucleate and expand upon further light emission from the QW. More dislocation loops form and expand by cross slip and glide on the {111} planes upon further electron- hole recombination until a DLD is formed. With continued light emission the density of DLDs and their lengths and widths increase until the area of light emission is covered with these defects.

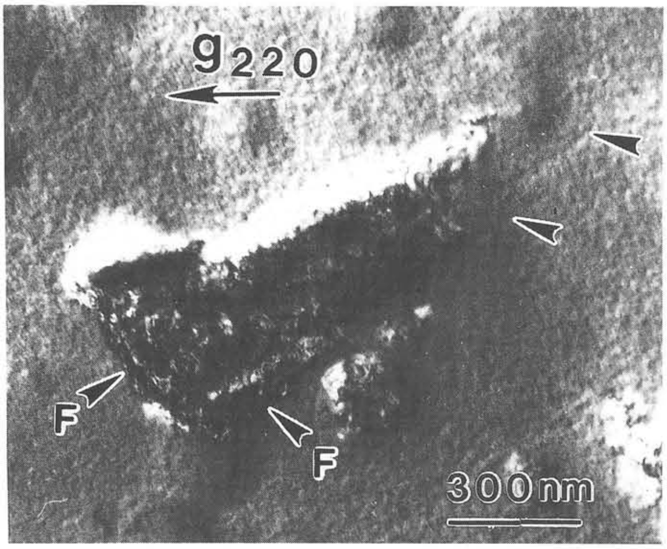



Fig. 2 (220) plan-view image of a degraded Frank-type stacking fault. The fault has become a dense network of dislocations. Traces of the mobile defects are marked by arrowheads.

### Conclusions

Photodegradation gives rise to the collapse of Frank-type stacking faults. These faults become dense networks of dislocations and are sources of the mobile defects. The DLDs are hair-pin-like dislocation loops or half loops that form primarily along the ⟨100⟩ directions. The mechanism for the photodegradation still needs to be investigated. A possible mechanism is by the accumulation of charge on the Frank-type stacking faults that eventually causes the emission of a faulted defect. As the faulted defect moves through the lattice it produces distortions that facilitate the formation of dislocation loops. Upon further light emission from the quantum well the dislocation loops expand until they become hair- pin-like dislocation loops or half loops. The loops continue to extend until they form a network of dislocations along the ⟨100⟩ directions.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