Observation of [100] and [010] Dark Line Defects in Optically Degraded ZnSSe-Based LEDs by Transmission Electron Microscopy

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We have used transmission electron microscopy to study the [100] and [010] 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 grown-in or pre-existing Frank-type stacking faults become tangles of dislocations. In contrast, the Shockley-type stacking faults remained unchanged for the photodegradation conditions studied indicating that they are more resistant to photodegradation than the Frank-type stacking faults. Our results suggest that the Frank-type stacking faults are the sources of the DLDs. The mechanism for degradation probably starts by the emission of very small clusters of vacancies from the Frank-type faults. Upon further illumination the dislocation loops bounding the vacancies grow by gliding on {111} planes and become hairpin-like dislocation loops.

Key words: Dark line defects, mechanism for photodegradation, photodegradation, Zn_{1-x}Cd_xSe quantum well

INTRODUCTION

ZnSSe-based/GaAs heterostructures have become very important for the fabrication of blue-green light emitting diodes (LEDs) and lasers. Great improvements in the performance of devices based on these materials have recently been obtained. At first, the devices would only last a few seconds or minutes. At present typical devices last approximately 100 h (LEDs) and 90 min (laser diode). The failure of the device takes place by the generation of defects in the active region. 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 that appear during device operation. The dark patches are triangular in shape and also form during device operation. Both DLDs and patches have been observed to form during operation under optical microscopes and cathodoluminescence imaging. Both defects start small and grow during device operation until the whole surface of the emitting region is dark and the device fails.

Both DLDs and dark patches form from pre-existing defects. The dark patches have been identified to be dislocation networks developed at the QW region and originating from V-shaped stacking faults. The DLDs form along traces left by mobile defects emitted from pre-existing defects (or dark spots). Upon further illumination, the DLDs widen until the whole emitting area is dark making the device fail. DLDs have also been observed in III-V semiconductor laser diodes along either the [100] or [110] directions. In order to increase the lifetime of the devices, it is important to understand the mechanism of generation of the DLDs and dark patches and to identify their sources so that they can be eliminated. In this
work, we report a transmission electron microscopy (TEM) study of the DLDs produced during photodegradation of a ZnSSe/CdZnSe quantum well (QW)/ZnSSe/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) and consisted of 0.16 μm ZnS₀.₅₅Se₀.₄₄/5 nm Cd₀.₂Zn₀.₈Se QW/0.84 μm ZnS₀.₀₅₅Se₀.₉₄/ZnSe/GaAs buffer layer/GaAs heterostructures. The films were grown at 280°C. Under these conditions, the ZnS₀.₀₅₅Se₀.₉₄ cladding layers are lattice matched to GaAs while the Cd₀.₂Zn₀.₈Se QW are under a ~2% compressive strain.

The QW was mostly pseudomorphic with a density of misfit dislocations of ~1 x 10⁶/cm² at the QW/cladding layer interfaces. The films were doped with Cl and had a net carrier concentration of N_d - N_s ~1 x 10¹⁸/cm³. The photodegradation was carried out by illuminating regions of the samples of ~50 μm in diameter along a straight line using the 351.1 and 363.8 nm lines of an argon ion cw laser with a power density of 140W/cm². The laser was focused on the film to produce the luminescence by photopumping the ZnS₀.₀₅₅Se₀.₉₄ cladding layers and the Cd₀.₂Zn₀.₈Se QW above their band gap energies, thus, producing electron hole recombination. Prior to TEM analysis, cathodoluminescence (CL) imaging was carried out to observe the photodegraded regions. For TEM studies, plan-view specimens were prepared from the photodegraded and undegraded 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 is a CL image that shows areas, A, photodegraded and, B, nondegraded of a ZnS₀.₃₅Se₀.₆₅/Cd₀.₂Zn₀.₈Se QW/ZnS₀.₀₅₅Se₀.₉₄/ZnSe/GaAs heterostructure. The dark spots in this figure correspond to grown-in defects (Frank and Shockley stacking faults) since their density is the same as that of stacking faults observed by TEM. These defects extend from the ZnSe/GaAs interface to the film surface cutting through the Cd₀.₂Zn₀.₈Se QW and act as nonradiative recombination centers for the luminescence. The radius of the degraded area is ~50 μm which corresponds to the area of degradation observed with photoluminescence imaging. Illumination from the recombination between electrons and holes at the QW caused the photodegradation in the area marked A.

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**Fig. 2.** TEM (3 2 0) bright field image showing a faulted defect b blocked by a stacking fault T. Along the trace of the faulted defect, very small dislocation loops (marked by arrowheads) formed during photodegradation.