High dislocation densities in high efficiency GaN-based light-emitting diodes

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The electrical, optical, and structural properties of light emitting diodes (LEDs) fabricated from the III–V nitride material system have been studied. LEDs with external quantum efficiencies as high as 4% were characterized by transmission electron microscopy and found to contain dislocation densities in excess of 2×10^{10} cm^{-2}. A comparison to other III–V arsenide and phosphide LEDs shows that minority carries in GaN-based LEDs are remarkably insensitive to the presence of structural defects. Dislocations do not act as efficient nonradiative recombination sites in nitride materials. It is hypothesized that the benign character of dislocations arises from the ionic nature of bonding in the III–V nitrides. © *1995 American Institute of Physics.*

It is widely recognized that dislocations introduce nonradiative recombination centers in III–V arsenides and phosphides. Even moderate dislocation densities can impose an upper limit to minority carrier lifetimes for GaAs or InP-based compounds.[1–6] These recombination centers reduce the efficiency of light-emitting diodes (LEDs) and lasers by effectively competing with radiative recombination paths. Additionally, they migrate during device operation, shortening excess carrier lifetimes, and limiting the usable operating life of optical devices.

Recently, high-brightness LEDs based on GaN have become commercially available from Nichia Chemical Industries. We have characterized the electrical, optical, and structural properties of these devices and obtained some surprising results. Compared to LEDs fabricated using III–V arsenides and phosphides or II–VI materials, recombination in GaN-based LEDs is found to be remarkably insensitive to structural dislocations.

The LEDs in this study were grown on basal plane sapphire substrates by metalorganic chemical vapor deposition (MOCVD).[7] The device layers consist of ~4 μm of Si-doped *n*-type GaN, followed by a GaN:Si/InGaN:(Si+Zn)/AlGaN:Mg double heterostructure, and a *p*-type GaN:Mg cap, as determined by secondary ion mass spectroscopy (SIMS). The InGaN active layer was heavily doped with Zn to provide recombination centers that emit at ~450 nm. The active areas of the LEDs were $\sim3\times10^{-4}$ cm^2.

Figure 1 shows the external quantum efficiency and power output of a typical LED as a function of drive current. As the forward current is increased the quantum efficiency rises and reaches a maximum of ~4% at 0.8 mA. At higher currents the efficiency gradually decreases, falling to 1.3% at 100 mA dc. The total optical output power increases steadily with drive current, and is as high as 3.3 mW at 100 mA. The efficiency of these LEDs is far higher than commercially available GaAsP, GaP:N, or SiC LEDs, and somewhat lower than high-brightness AlGaAs and GaInAlP-based LEDs.

The decrease in quantum efficiency above 1 mA is attributed to the saturation of impurity recombination centers in the InGaN active layer. This is clearly seen in electroluminescence (EL) spectra. Figure 2 shows EL spectra measured over a wide range of currents. For currents below 1 mA the spectra consist of a single, broad emission band. The peak wavelength of this emission shifts toward shorter wavelengths as the drive current increases. The microscopic origin of this impurity band is unknown, but it arises from Zn doping in the active region. This emission saturates as the current is increased and band-to-band recombination at 379 nm is observed. Combining measurements of LED efficiency and spectral line shape, the external efficiency of band-to-band recombination at 100 mA is estimated to be ~0.3%.

The key finding we report here is that these LEDs are highly efficient in spite of an extremely high density of structural defects. Figure 3 consists of TEM images of the epitaxial nitride film. The images were taken under two-beam bright-field conditions. Figure 3(a) shows a cross section of the device, and highlights the dislocation distribution across the film. Stacking faults are evident in the vicinity of the substrate interface. Evidence of three-dimensional growth is

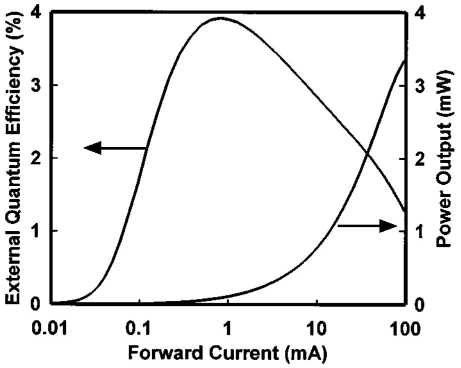

FIG. 1. External quantum efficiency and total emitted power vs current for a typical GaN-based LED.

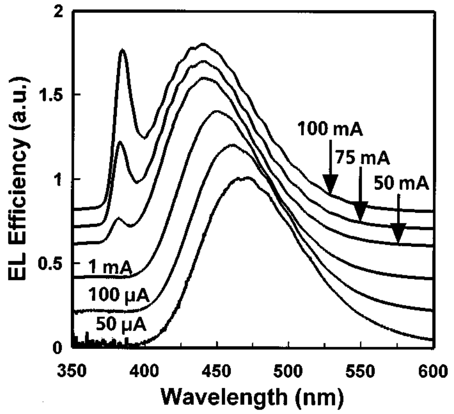

FIG. 2. Electroluminescence spectra taken at various drive currents. The peak at 379 nm is due to band-to-band recombination in the InGaN active region. The longer-wavelength peak is due to recombination through impurity centers.

also noted along most of the film, extending to different distances from the substrate. Dislocations are seen as dark lines propagating in a direction normal to the substrate. Figure 3(b) shows the top region of the device, which includes the metal contact layer and the active region. Dislocations are observed which cross the double heterostructure, and some are seen to bend and follow the layers for a short distance before threading out to the surface. The density of dislocations reaching the top surface of the film has been measured to be the same as the rest of the film.

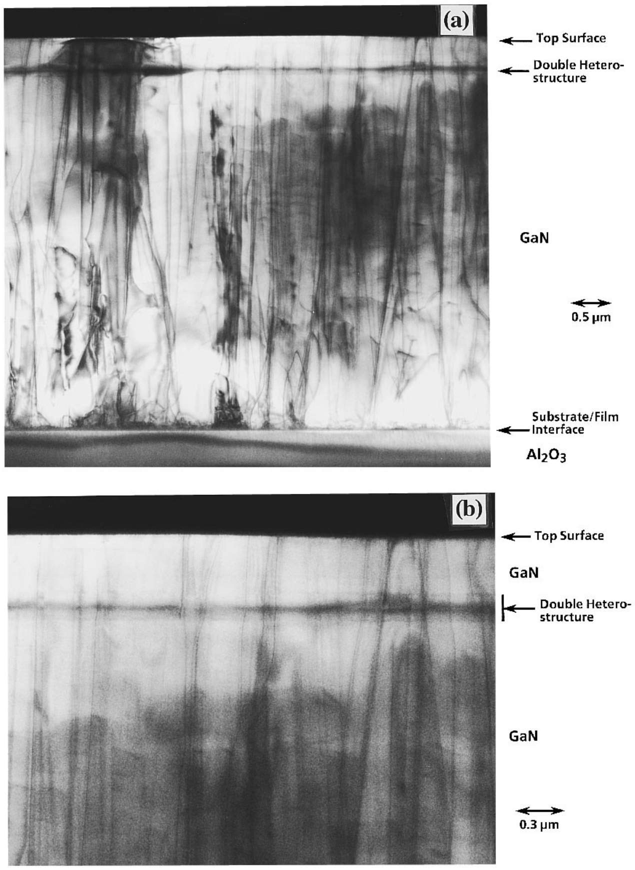

FIG. 3. Bright-field two-beam TEM micrographs showing the defect distribution along the device. (a) Cross section of full thickness of device, (b) top region of device including the double heterostructure active region. The dislocation density is in the range $2-10\times10^{10}$ dislocations/cm^2.

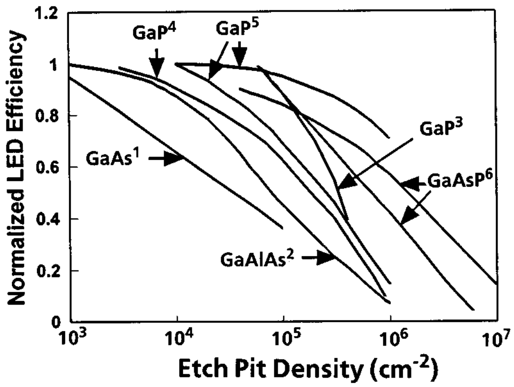

FIG. 4. Dependence of LED efficiency on dislocation density for devices made with a wide range of III–V materials. The numbers on the figure next to the material indicate the reference numbers from which the data were taken. (In some cases the original data were not normalized. The curves shown here were obtained by extrapolating the data to low dislocation densities and estimating a normalization constant.)

The dislocation density is calculated by counting along a plane normal to the growth direction. The thickness of the TEM sample is estimated from the contrast distribution in the image. The error in thickness estimation can be as large as 100%. Several measurements have been made in this manner at various positions along the film and at various distances above the substrate interface. We conclude that the dislocation density is $2-10\times10^{10}$ cm^{-2} and that is does not vary substantially with distance from the sapphire interface. In addition to dislocations propagating in the direction of growth, number of dislocations are observed to lie in the basal planes (parallel to the substrate).

The defect densities observed here are far higher than those measured in working LEDs made from any other III–V or II–VI material system. In fact, GaAs LEDs with dislocation densities of 10^{10} cm^{-2} would not be expected to emit any band edge light at all. Careful studies by Herzog[1] and Roedel[2] have shown that the efficiencies of GaAs and AlGaAs:Si LEDs are limited by dislocations at densities of only $\sim10^4$ cm^{-2}, six orders of magnitude lower than the densities observed here. Figure 4 shows the relationship between the efficiency of LEDs and their corresponding dislocation densities for LEDs fabricated from a wide variety of materials. This figure includes direct band-gap materials, direct gap materials that rely on recombination through impurities, indirect gap GaP devices, and GaP LEDs doped with isoelectronic nitrogen centers. Dislocations limit the efficiency of LEDs made from all of these materials and do so at far lower densities than those seen in the GaN-based LEDs.

The fact that efficient GaN-based LEDs can be made with such high densities of structural defects indicates a critical difference between the III–V nitrides and the arsenides and phosphides. That is, dislocations in III–V nitrides are not efficient nonradiative recombination centers, as they are in other materials. This is an important difference, and means it should be possible to fabricate a wide range of minority carrier devices without the high degree of crystalline perfection necessary in other III–Vs.

We hypothesize that the relatively benign behavior of dislocations in GaN stems from the ionic character of bonding in these materials. Based on a variety of empirical observations, Kurtin *et al.*[8] reported that the electronic properties of ionic materials (such as GaN) are fundamentally different from those of more covalent materials such as Si, GaAs, or InP. These differences arise from the localization of valence band excitations (holes) in ionic materials. Specifically, they reported that the surfaces of ionic materials do not exhibit Fermi level pinning. That is, states associated with the lattice disruption at the surface are either few in number or energetically located outside the energy gap of the material. Indeed, Foresi and Moustakas recently reported evidence that the surface of GaN is unpinned, based on the I–V characteristics of metallized contacts.[9] Dislocations can be viewed as lattice interruptions, somewhat like internal crystalline surfaces. In fact, similar models can be used to describe minority carrier recombination at both dislocations and surfaces.[10] If minority carriers are insensitive to the presence of a nearby surface, it follows that they may also be insensitive to dislocations.

In summary, we have characterized highly efficient GaN-based LEDs. The devices were found to contain extremely high dislocation densities ($2-10\times10^{10}$ cm^{-2}) in the active layer. This density is far in excess of what could be tolerated in any working III-As or III-P minority carrier device. The key finding is that dislocations in III–V nitrides do not act as efficient minority carrier recombination sites. This fundamental property may arise from the more ionic character of bonding in nitride materials compared to other III–Vs.

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