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Original research article

# Threading dislocation density effect on the electrical and optical properties of InGaN light-emitting diodes

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ABSTRACT

The electrical and optical properties of InGaN LEDs with different threading dislocation densities (TDDs) were investigated. LEDs with low TDDs exhibited low forward voltage and high injection efficiency compared with LEDs with high TDDs. The effect of TDDs on the electrical properties of InGaN LEDs was attributed to efficient carrier injection into the QWs brought about by increased transverse carrier mobility in the InGaN layer resulting from reductions in carrier scattering around dislocation cores. In terms of optical properties, LEDs with low TDDs exhibited high peak efficiency and substantial efficiency droops under increased current densities, whereas LEDs with high TDDs showed low peak efficiency and minimal droops under the same condition. These trends can be explained by the correlations of high TDDs with increased dominance of nonradiative recombination and pronounced suppression of peak efficiency under low current densities.



## 1. Introduction

Light-emitting diodes (LEDs) based on InGaN multiple quantum well (MQW) and produced by metal-organic chemical vapor deposition (MOCVD) are increasingly being used as white light sources [1,2]. However, several factors affecting the internal quantum efficiency (IQE) of these LEDs remain poorly understood [3,4]. InGaN MQWs have no native GaN substrates, thus, they are grown conventionally on commercially available sapphire wafers. As these sapphire wafers are highly lattice-mismatched with nitride, threading dislocations (TDs) normally appear in the epitaxial layers. LED structures typically contain between five and ten QWs. Deposition of increasing numbers of QWs results in accumulation of misfit strain and subsequent relaxation of this strain by defect formation in the active region [5]. Typical threading dislocation densities (TDDs) in the epilayers produced by MOCVD were in the range of $\sim 10^9$–$10^{10}$ cm$^{-2}$ in the 1990s; today, these TDDs have been reduced to $\sim(4\text{–}5) \times 10^8$ cm$^{-2}$ [6,7].

High TDDs ($10^8$–$10^{10}$ cm$^{-2}$) in epitaxial layers present a major function in the leakage current source of III-nitride-based LEDs [8]. TDs in GaN-based LEDs have been reported to strongly affect decreases in light output power with changes in current density and temperature [9,10]. High TDDs cause a decrease in the saturation drift velocity of GaN carriers because of intensive impurity scattering of the carriers, which results in reduced current spreading during LED operation [11,12]. Most research efforts have been devoted to reducing GaN TDDs by lateral epitaxial overgrowth in the homoepitaxial layers of GaN on sapphire [13] and low-defect bulk GaN [14] substrates. Several studies have also investigated the influence of TDDs on the structure and properties of GaN-based LEDs [9,15–18].

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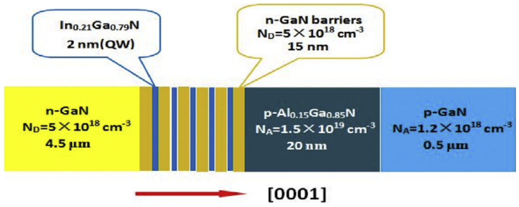


**Fig. 1.** Schematic of the light-emitting diode (LED)and its associated parameters.

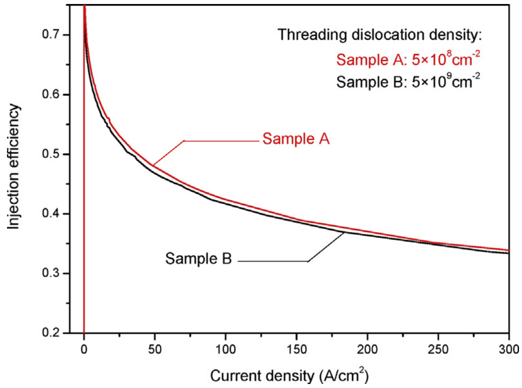


**Fig. 2.** Injection efficiency of the two samplesas a function of current density under different dislocation densities.

This paper reports the effect of TDDs on the electrical and optical properties of InGaN LEDs. The results of this study will improve the current understanding of the effect of TDDs on the reliability and lifetime of GaN-based optoelectronic devices and help increase the efficiency of these devices.

## 2. Calculation model and parameters

In this study, the optical and electrical properties of InGaN LEDs with a high dislocation density of $5 \times 10^8\,cm^{-2}$ (sample A) and a low dislocation density of $5 \times 10^9\,cm^{-2}$ (sample B) were numerically investigated using SiLENSe simulation software (STR Group Inc.). Fig. 1 shows aschematic of the LED designs. A 3 μm-thick *n*-GaN layer (*n*-doping = $6 \times 10^{18}\,cm^{-3}$) was used as the LED template. The active region consisted of five-period $In_{0.18}Ga_{0.82}N$(3.6 nm)/GaN(12 nm) MQWs. On top of the active region, a 20 nm-thick *p*-$Al_{0.15}Ga_{0.85}N$ EBL (*p*-doping = $5 \times 10^{17}\,cm^{-3}$) and 0.2 μm-thick *p*-GaN cap layer (*p*-doping = $1.2 \times 10^{18}\,cm^{-3}$) were installed. Aband offset ratio of $\Delta Ec/\Delta Ev = 0.7/0.3$ served as the default parameter during simulation. The electron mobility, hole mobility, and operating temperaturewere assumed to be $100\,cm^2\,V^{-1}\,s^{-1}$,$10\,cm^2\,V^{-1}\,s^{-1}$, and 300 K, respectively. Other material parameters of the semiconductors and a detailed description of the simulation model are reported elsewhere [19,20].

## 3. Results and discussion

TDDs effect on the electrical properties was performed by injection efficiency and *I–V* characteristics. Fig. 2 compares the injection efficiencies of samples A and B as a function of current density. Sample A exhibited higher injection efficiency than sample B under the same current density. The influence of current injection can be explained as a suppression of lateral carrier transport by the ionized impurity scattering of carriers in GaN with high TDDs. Open-core dislocations with edge components become negatively charged because of captured electrons resulting from Coulomb repulsion. A schematic of the current flow in samples A and B is shown in Fig. 3(a) and (b). In sample B, which features high TDDs, carrier injection into the InGaN QWs near the *n*-electrode can be barely achieved because of intensive carrier scattering in the *n*-GaN [17]. By contrast, in sample A, which features with low TDDs, lateral carrier transport in the *n*-GaN is scarcely affected,thereby resulting in uniform current spreading and high injection efficiency, as shown in Figs. 3 (a) and 2 .

Fig. 4(a) compares the characteristic *I–V* curves of the LEDs fabricated using the two samples. The forward voltages of samples A and B at 200 mA were 5.62 and 5.51 V, respectively. A forward voltage drop of 0.11 V was also observed; this phenomenon is attributed to uniform current injection in the entire *n*-GaN layer with low TDDs. The *n*-GaN layer with low TDDs provides tunnels for electron transport in the lateral direction,which improves current spread in the active region. Improved lateral current spreading allows uniform current injection throughout the entire *n*-GaN layer, which eventually decreases the forward voltage and increases the light output power. The forward *I–V* curves are replotted in semilogarithmic scale in Fig. 4(b). Sample A exhibits larger leakage current (more than one order of magnitude) than sample B in the region