

## Probing Carrier Behavior at the Nanoscale in Gallium Nitride using Low Voltage Cathodoluminescence

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The increasing application of GaN in blue and UV light emitting diodes and lasers has generated considerable interest in its optical and electrical properties. These optical devices exhibit extremely high emission efficiencies despite the presence of a very high concentration of threading dislocations ( $10^8 - 10^{10} \text{ cm}^{-2}$ ) that act as non-radiative recombination channels. This perceived contradiction can be explained by small ( $< 100 \text{ nm}$ ) carrier diffusion lengths which effectively negate the effect of the threading dislocations on the radiative recombination efficiency. These short exciton and minority carrier diffusion lengths in GaN can be explored by cathodoluminescence (CL) microscopy and spectroscopy using a SEM equipped with a Schottky field emission gun operating at 1 kV.

The recombination length ( $L$ ) can be estimated by analyzing the CL contrast around isolated threading dislocations which varies as  $C(r) \propto \exp(-r/L)$ , where  $r$  is the distance of the electron probe from the dislocation core. Monte Carlo simulation of the normalized depth and radial total energy loss profiles (Figure 1) reveal that at 1 kV minority carriers are injected into a  $< 10 \text{ nm}$  volume in GaN. The diffusion length for bound excitons ( $D^{\circ}X$ ) and free excitons (FX) can be determined by using the near band edge CL emission at 5 K and 300 K, respectively. Minority carrier diffusion can be measured using deep level CL, such as free-to-bound ( $D^{\circ}h$ ) emission at 300 K and donor acceptor pair (DAP) emission at 100 K. Panchromatic CL images at 5 K of undoped ( $n_e \approx 1.0 \times 10^{16} \text{ cm}^{-3}$ ) and GaN:Si ( $n_e \approx 3.5 \times 10^{18} \text{ cm}^{-3}$ ) collected under identical excitation conditions are shown in Figure 2 (undoped GaN) and Figure 3 (GaN:Si). A  $D^{\circ}X$  diffusion length of  $\approx 50 \text{ nm}$  was observed in the GaN:Si compared to  $\approx 90 \text{ nm}$  in undoped GaN. This difference can be accounted for by higher donor concentration in GaN:Si. Larger recombination lengths were found for the FX ( $\approx 80 \text{ nm}$ ) and for minority carriers ( $\approx 100 \text{ nm}$ ). The FX recombination length is essentially determined by how quickly the FX loses its kinetic energy by phonon emission whereas the minority carrier diffusion length is strongly affected by carrier mobility.

Since GaN has a bare surface potential of  $\approx 1 \text{ eV}$ , depletion layer depths of  $\approx 17 \text{ nm}$  for GaN:Si and  $\approx 100 \text{ nm}$  for the undoped GaN are expected at the GaN surface. The exciton binding energy ( $E_B$ ) and Bohr radius ( $a_B$ ) of the 1S state in GaN is 25 meV and 2.3 nm respectively. Consequently excitons will be separated into electron hole pairs when the surface field surpasses the exciton ionization field ( $E_i = E_B/a_B = 1.1 \times 10^5 \text{ V/cm}$ ).  $E_i$  is exceeded at depths up to  $\approx 15 \text{ nm}$  in GaN:Si and  $\approx 46 \text{ nm}$  in the undoped sample, suggesting that at 1 kV no FX or  $D^{\circ}X$  CL emission should be observed as all carriers injected within the exciton ionization range will be separated by the surface field. The FX CL intensity versus  $I_B$  at 300K (Figure 4) shows no indication of exciton dissociation,

exhibiting a power density dependence,  $I_{CL} \propto I_B^n$ , with a power law exponent of  $n \approx 0.9$  over a wide range of  $I_B$  (100 to 1000 pA). This result suggests that flat band conditions exist during electron irradiation. Since all carriers are injected within the depletion layer, holes are rapidly swept to the surface by the in-built surface field and captured by surface states, reducing the depletion layer width towards zero.

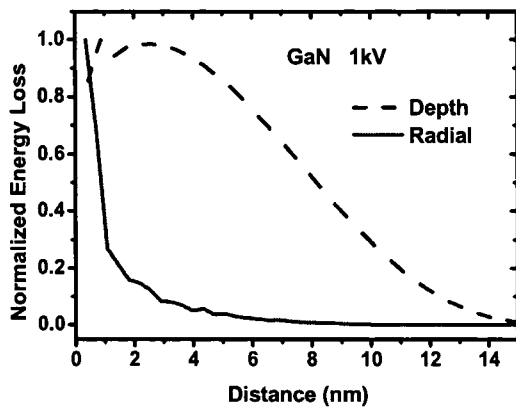


Fig. 1. Normalized depth and radial energy loss profiles for GaN at 1 kV including a 1 nm surface layer of Ga<sub>2</sub>O<sub>3</sub>

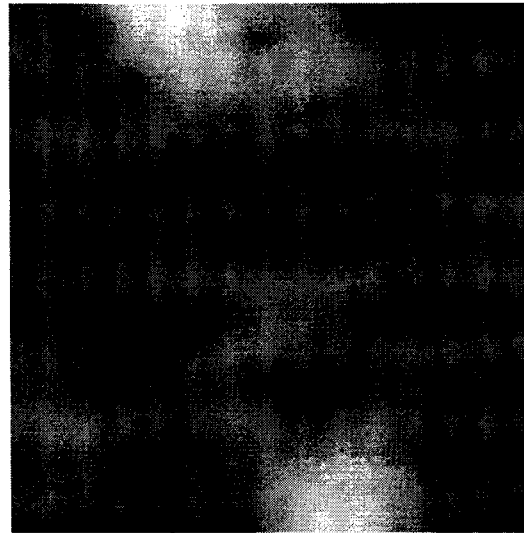


Fig. 2. Panchromatic D°X CL image of threading dislocations undoped GaN 1kV, 0.4 nA, 2 μm x 2 μm

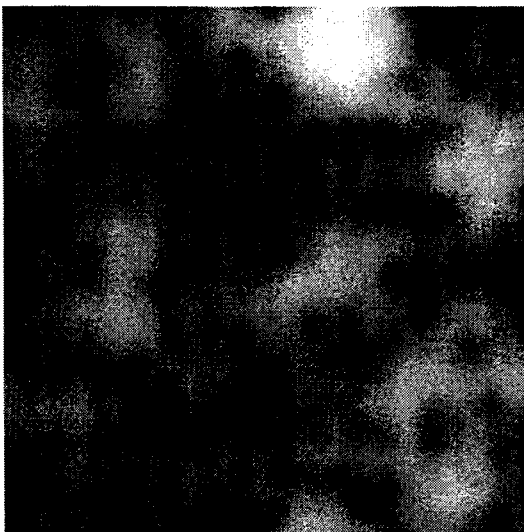


Fig. 3. Panchromatic D°X CL image of threading dislocations in GaN:Si 1 kV, 0.4 nA, 2 μm x 2 μm

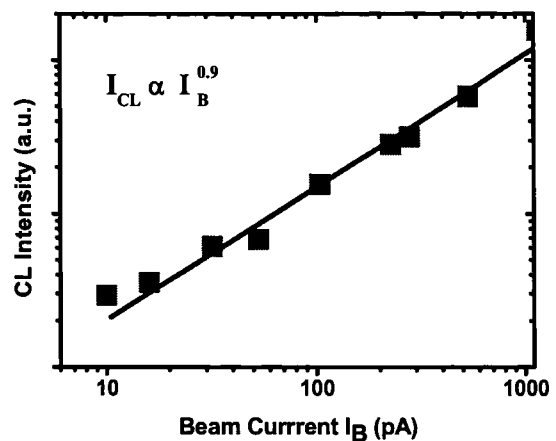


Fig. 4. FX CL intensity versus  $I_B$  at 1 kV and 300 K

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