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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 ($10^8 - 10^{10}$ cm^{-2}) that act as non-radiative recombination channels. This perceived contradiction can be been explained by small (< 100 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) 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 nm volume in GaN. The diffusion length for bound excitons (D°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°h) emission at 300 K and donor acceptor pair (DAP) emission at 100 K. Panchromatic CL images at 5 K of undoped ($n_e \approx 1.0 \times 10^{16}$ cm^{-3}) and GaN:Si ($n_e \approx 3.5 \times 10^{18}$ cm^{-3}) collected under identical excitation conditions are shown in Figure 2 (undoped GaN) and Figure 3 (GaN:Si). A D°X diffusion length of ≈ 50 nm was observed in the GaN:Si compared to ≈ 90 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 (≈ 80 nm) and for minority carriers (≈ 100 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 ≈ 1 eV, depletion layer depths of ≈ 17 nm for GaN:Si and ≈ 100 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 ($E_i = E_B/a_B = 1.1 \times 10^5$ V/cm). E_i is exceeded at depths up to ≈ 15 nm in GaN:Si and ≈ 46 nm in the undoped sample, suggesting that at 1 kV no FX or D°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.

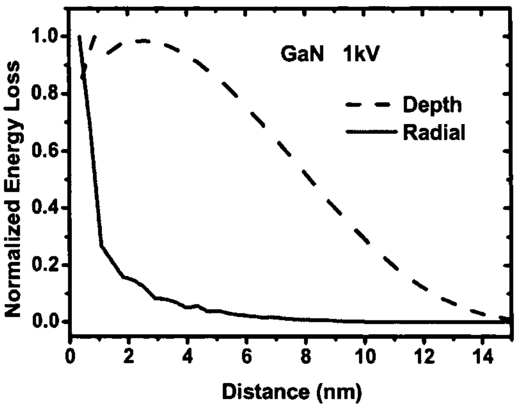

Fig. 1. Normalized depth and radial energy loss profiles for GaN at 1 kV including a 1 nm surface layer of Ga_2O_3

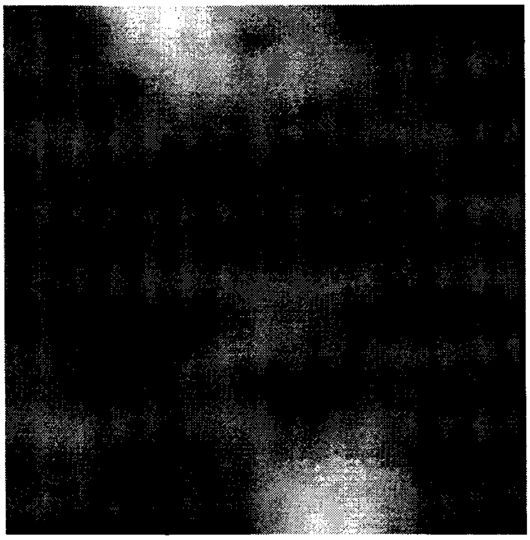

Fig. 2. Panchromatic D°X CL image of threading dislocations undoped GaN 1kV, 0.4 nA, 2 μm x 2 μm

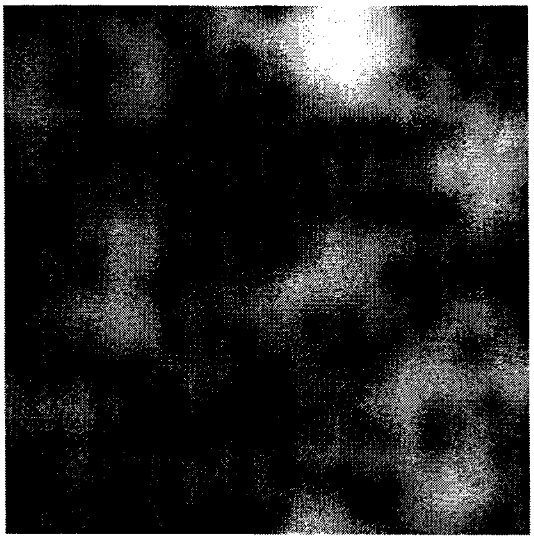

Fig. 3. Panchromatic D°X CL image of threading dislocations in GaN:Si 1 kV, 0.4 nA, 2 μm x 2 μm

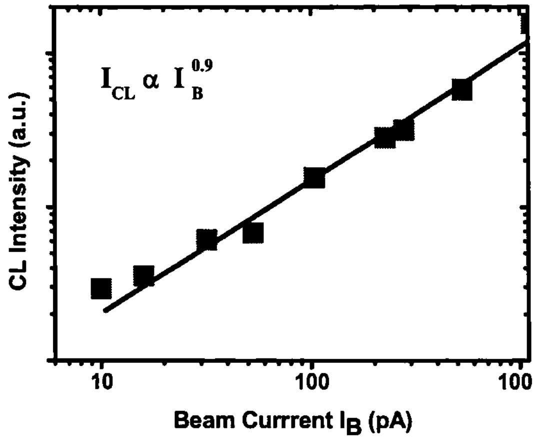

Fig. 4. FX CL intensity versus I_B at 1 kV and 300 K

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