# Deep Level Optical Spectroscopy of GaN Nanowires

*by* ***A. Armstrong, G. T. Wang, Q. Li and A. A. Talin***

**Motivation**—GaN-based nanowire (NW) applications include chemical sensing and light emitters spanning the IR to UV spectrum. An advantage of GaN NWs compared to thin films is their lack of threading dislocations. However, point defects still impact the electrical and optical properties of GaN NWs. Therefore, quantitative defect spectroscopy has been developed for GaN NWs to study the atomistic origin and role of defects.

**Accomplishment**—Deep level spectroscopy of GaN NWs has been limited mainly to luminescence, which is not quantitative in defect energy level ($E_o$) or defect density ($N_t$). Thus, we have demonstrated the applicability of deep level optical spectroscopy (DLOS) for GaN NWs. DLOS provides quantitative values for $E_o$ and $N_t$, but is a photocapacitance technique that was originally developed for macroscopic diodes with planar geometry. We have extended DLOS to a photoconductivity technique for NWs with three-dimensional depletion regions.

GaN NWs were grown by metal-organic chemical vapor deposition (MOCVD) via the vapor-liquid-solid mechanism using Ni particles as a growth catalyst. The NWs were transferred to a Si substrate, and electrical contacts were made using optical lithography to form individual devices. DLOS measurements were performed by scanning the energy $h\nu$ of sub-bandgap light incident upon the NWs. When $h\nu$ is large enough to photoionize deep levels, a photoconductivity transient is measured. Majority carrier photoemission reduces the surface depletion region, which in turn increases the conductive, quasi-neutral NW cross-sectional area. The GaN NW DLOS spectrum is shown in Fig. 1. The spectral dependence of the deep level optical cross-section $\sigma_o(h\nu)$ is found by taking the derivative of the photoconductivity transient at the beginning of illumination. Abrupt onsets in the DLOS spectrum demarcate individual deep levels, and saturation occurs at the band gap $E_g$. $E_o$ and the Franck-Condon shift ($d_{FC}$) are extracted by fitting $\sigma_o(h\nu)$ to a theoretical model. Since the NWs are *n*-type, positive photoconductivity indicates electron photoemission to the conduction band minimum $E_c$. Deep levels are observed at $E_c - 1.71$ ($d_{FC} = 0.77$ eV), $E_c - 2.81$ ($d_{FC} = 0.28$ eV), and $E_c - 3.19$ eV. The large $d_{FC}$ of the former two defects indicates strong phonon coupling. The NW deep levels are similar to those observed in bulk GaN, suggesting the defects are not particular to the surface but pervade the NW volume.

$N_t$ was estimated from the change in photoconductivity $\Delta I$ relative to the dark value $I_0$. Based on the electrostatics for cylindrical NWs,[1] $\Delta I/I_0$ is predicted to increase sharply with decreasing diameter, and $N_t$ can be extracted from a fit to the model (Fig. 2). Measurements of several NWs show good agreement with the model, suggesting $N_t \sim 1.4 \times 10^{16}$ cm$^{-3}$.

**Significance**—DLOS has been extended to GaN NWs, enabling quantitative defect spectroscopy in nanoscale devices. An important application will be investigating defect incorporation as a function of NW growth method and impurity incorporation. This will provide important insight to the atomistic origin of defects in GaN NWs.

1. Calarco, *et al. Nano Lett. 5*, 981 (2005).

**Sponsors for various phases of this work include:** DOE Office of Basic Energy Sciences, and Laboratory Directed Research & Development

**Contact:** Andrew Armstrong, Semiconductor Material and Device Science, Dept. 1123
Phone: (505) 284-7757, Fax: (505) 844-3211, Email: aarmstr@sandia.gov

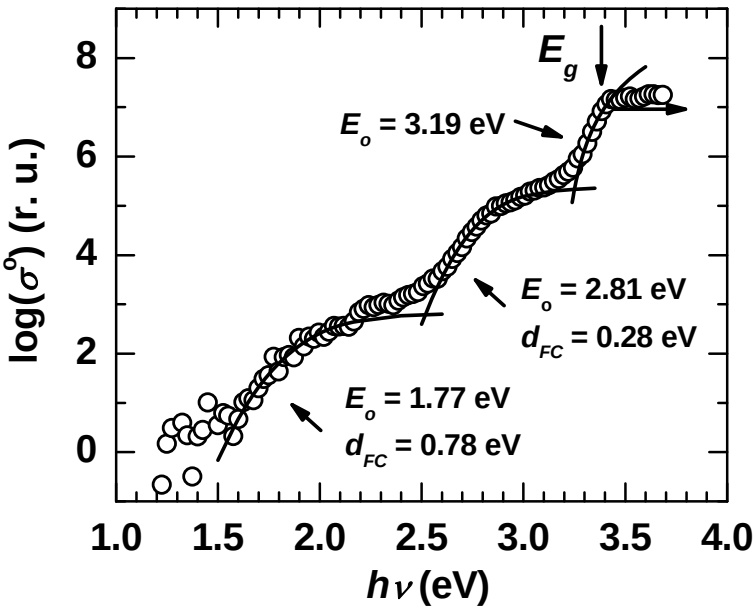


**Figure 1.** DLOS spectrum of a GaN NW. The symbols are experimental data and the lines are theoretical fits.

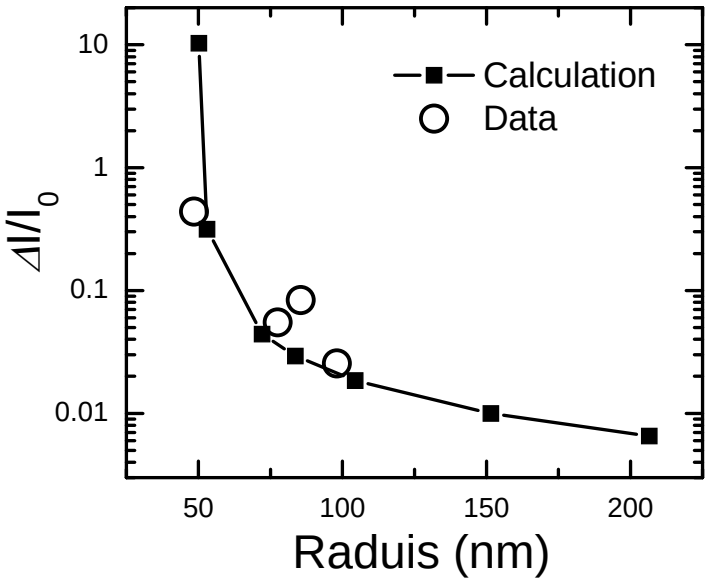


**Figure 2.** GaN NW photoconductivity as a function of size. The data are well fit using a model for cylindrical NWs.