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Full-scale Characterization of UVLED $Al_\chi Ga_{1-\chi}N$ Nanowires via Advanced Electron Microscopy

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Due to the wide range of wavelengths at which they can emit light, there is great interest in III-N semiconductor heterostructures for use in optoelectronic applications. However, the lack of a suitable substrate upon which to grow thin films leads to poor epitaxy and a subsequent high density of extended defects, which lead to states in the bandgaps and thus recombination centers and a loss of efficiency. Nanowires are of particular interest to the GaN community as they effectively solve the "substrate issue" presented by conventional thin film growth. The large free-surface area of a nanowire allows the structure to relax out much of the remnant strain, and thus nanowires have become a viable solution to grow low-strain, defect-free III-N material; high quality $AlxGa1_{-\chi}N$ structures have been repeatedly presented. Furthermore, due to their low defect concentration, more efficient photoluminescence has been demonstrated in nanowires as compared to planar structures.
Specifically, compositionally graded $Al_\chi Ga1_{-\chi}N$ ultraviolet light emitting diode (UVLED) nanowires are the focus of the present contribution. The structures in question (first presented in [1]) are rather unique in that they do not rely on impurity doping, but rather on polarization-induced electron and hole doping. Hence, by linearly grading a non-centrosymmetric crystal (such as GaN) from $\chi=0$ to $\chi=1$ and then back to $\chi=0$ with a quantum well (QW) or active region placed in between the two graded regions, a pn-junction results. Uniquely, these UVLEDs do not freeze-out at low temperatures, but still exhibit rectification and UV light emission at the bandgap, which can be tuned based on the composition and thickness of the QW. In the present case, device efficiency is intimately linked with various physical properties at both the atomic and more macroscopic scales. For example, it is well-known that dislocations and other defects can act as recombination centers, reducing luminescent efficiency, so basic imaging via high-resolution scanning transmission electron microscopy (HR STEM) is called for. Additionally, the active region's diameter, thickness, and residual strain are known to directly influence the structure's electronic properties, and as the material's bandgap will directly depend on its composition (3.4 -6.2 eV in $AlxGa1_{-\chi}N$), obtaining quantitative chemical data from the QW is required. In short, by applying the many available facets of a STEM instrument, such as electron energy loss (EEL) and energy-dispersive X-ray (EDX) spectroscopies, one can complete a full-scale structural, chemical, and even electronic characterization of a wide range of relevant nanomaterials.

All STEM-based techniques were performed on a probe-corrected JEOL JEM ARM-200CF equipped with a cold field emission (CFEG) gun, operated at either 80 or 200 kV. Specifically, a given nanowire's structural properties (QW layer thicknesses, etc.) can be probed via large scale STEM imaging and EDX mapping, while defect identification is possible through HR HAADF STEM. ABF STEM is used to image light elements (nitrogen in this case) and is therefore useful for characterizing both the AlN shell as well as for determining the nanowire's polarity [2]. Electronic properties, on the other hand, can be fleshed out of both perfect and defected regions with local (position sensitive) EELS fine structure (N K-edge) and low loss (bandgap) analyses. The application of the aforementioned techniques (see Fig. 1) will be discussed at length in regards to the full-scale characterization of these UVLED $AlxGa1_{-\chi}N$ nanowires, with emphasis on practically using the results to drive the growth of more efficient devices. Additionally, STEM image simulations will be discussed as a method to probe GaN/AlN ordering effects.

References

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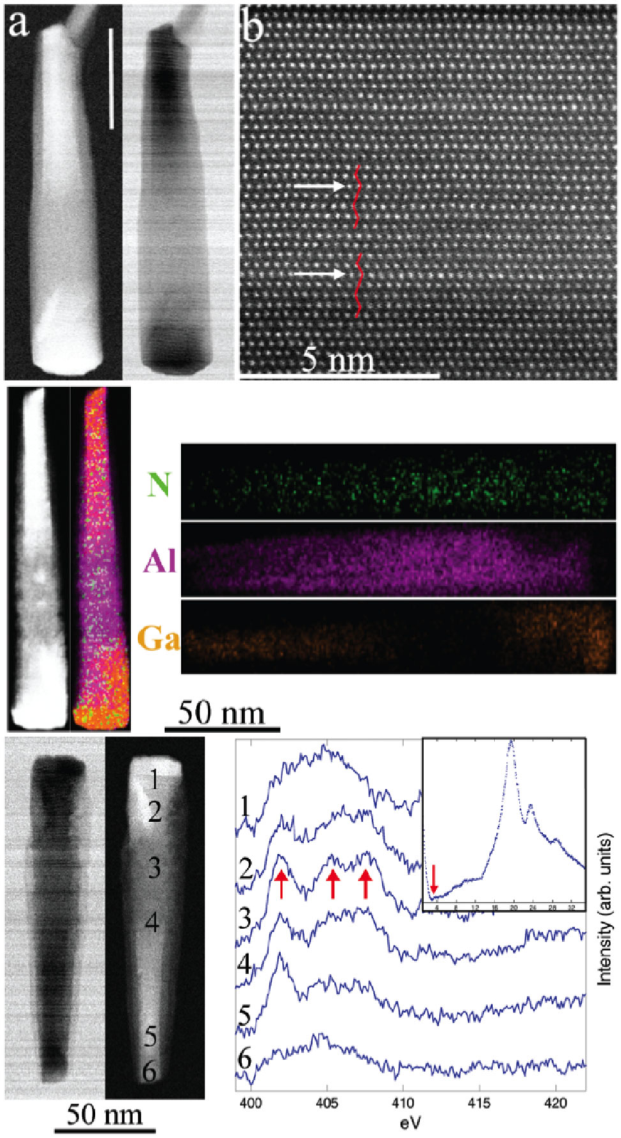

Figure 1: Overview HAADF/ABF images of a double-graded Al$_x$Ga$_{1-x}$N nanowire (a) and a high-resolution HAADF image of a region containing multiple stacking faults (b). Also presented are EDX (middle) and EELS (lower) results which probe the composition gradient. In the case of EELS, the N K-edge is sensitive to x in Al$_x$Ga$_{1-x}$N while low-loss measurements can be used to probe the bandgap, which should also be a function of x. Inset: low-loss measurement of the ≈ 3.4 eV bandgap of a GaN reference film. Note that the heavier species (GaN) images as “brighter” in HAADF.