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Strain at Coalescence of Patterned (Al)GaN Nanorod Arrays Formed by Selective Area Growth for Optoelectronic Devices

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Efficient deep UV light-emitting diode (LED) and laser diode emitters are recently showing some noticeable progress due to the improvement in crystalline quality of (Al)GaN growth [1]. Various bottom-up fabrication techniques, such as the selective area growth of nanostructured semiconductors, are some of the recent solutions that enable to produce isolated structures with relatively low defect density and high uniformity [2]. Within nanorods (NRs), strain can relax elastically because of the high surface-to-volume ratio reducing the formation of dislocations, which are classically visible in highly lattice-mismatched layers during planar heteroepitaxial growth. However, the free surfaces commonly act as non-radiative recombination centers and could potentially affect the overall emission efficiency. Moreover, the coalescence of adjacent NRs can generate defects and induce additional strain detrimental to the electronic properties, making the study of localized strain in such structures of interest.

Here, vertical arrays of GaN/AlGaN NR structures are grown by plasma-assisted molecular beam epitaxy through selective area growth using nanoscale hole mask defined by typical e-beam lithography methods on planar *c*-plane GaN template on sapphire substrates. Through well-chosen patterning and growth parameters, sidewall incorporation of adatoms can be controlled to engineer a specific lateral growth rate, leading to a controlled progressive coalescence of NR arrays. This generates a pseudo-planar configuration that allows for a reduced free surface density, while maintaining good crystalline quality to function as a planar template for further growth. The purpose of this work is to study the boundary between NRs upon coalescence using scanning transmission electron microscopy (STEM), in order to provide information on the quality of atomic arrangement, strain accommodation, and elemental distribution. Additional insight on the nature of the coalescence boundaries, in particular near the active layers, enables further understanding of the formation and the resulting optical and electrical properties of such structures.

Individual NRs exhibit a hexagonal geometry with top facets terminated by semi-polar pyramidal planes, as visible in the focused ion beam cross-section (Figure 1(a)). The atomic-number sensitive high-angle annular dark-field (HAADF) image shows Z-contrast variation in the active region that consists of an $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ double heterostructure (DH, where $y > x$) grown on GaN NR bases. Elemental mapping using electron energy-loss spectroscopy (EELS) further illustrates the compositional differences within the AlGaN DH (Figure 1(b)). Some variation in the degree of coalescence was observed between different NRs, but overall, the coalescence boundary shows good coherency in its atomic arrangement (Figure 2(a)). Lattice mismatch is expected from Al-content differences between layers that lead to variations in relative strain distribution in isolated NRs, as evaluated using geometric phase analysis (GPA) on atomically-resolved images (Figure 2). Furthermore, additional constraints are imposed upon coalescence that shows localized changes in lattice distortion across the coherent boundary, such as the shear strain component (Figure 2(f)). It is revealed that, depending on the quality and degree of the coalescence boundary, the relative lattice deformation shows distinguishable variations between NRs and can be related to the epitaxial quality [3].

References:

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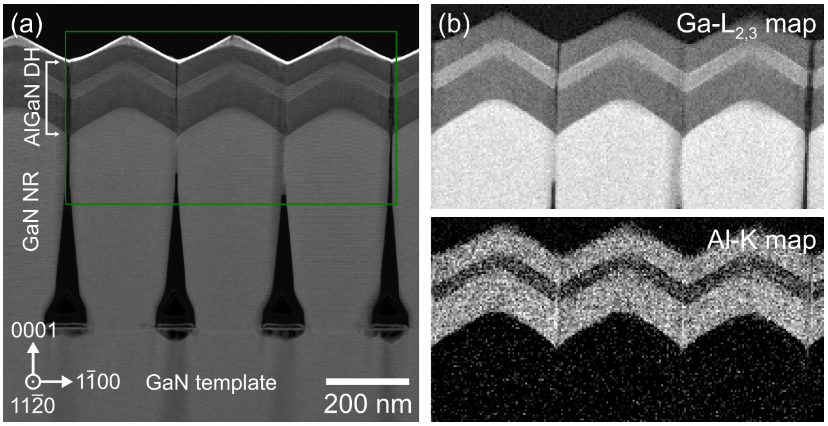

Figure 1. (a) STEM-HAADF image of the AlGaN/GaN coalesced NRs in cross-sectional view along *a*-plane with the different layers labeled. (b) STEM-EELS elemental maps (Ga and Al from Ga $L_{2,3}$ and Al K-edges, respectively) showing the chemical composition difference between layers. Weighted principal components analysis was used as noise reduction in the EELS maps.

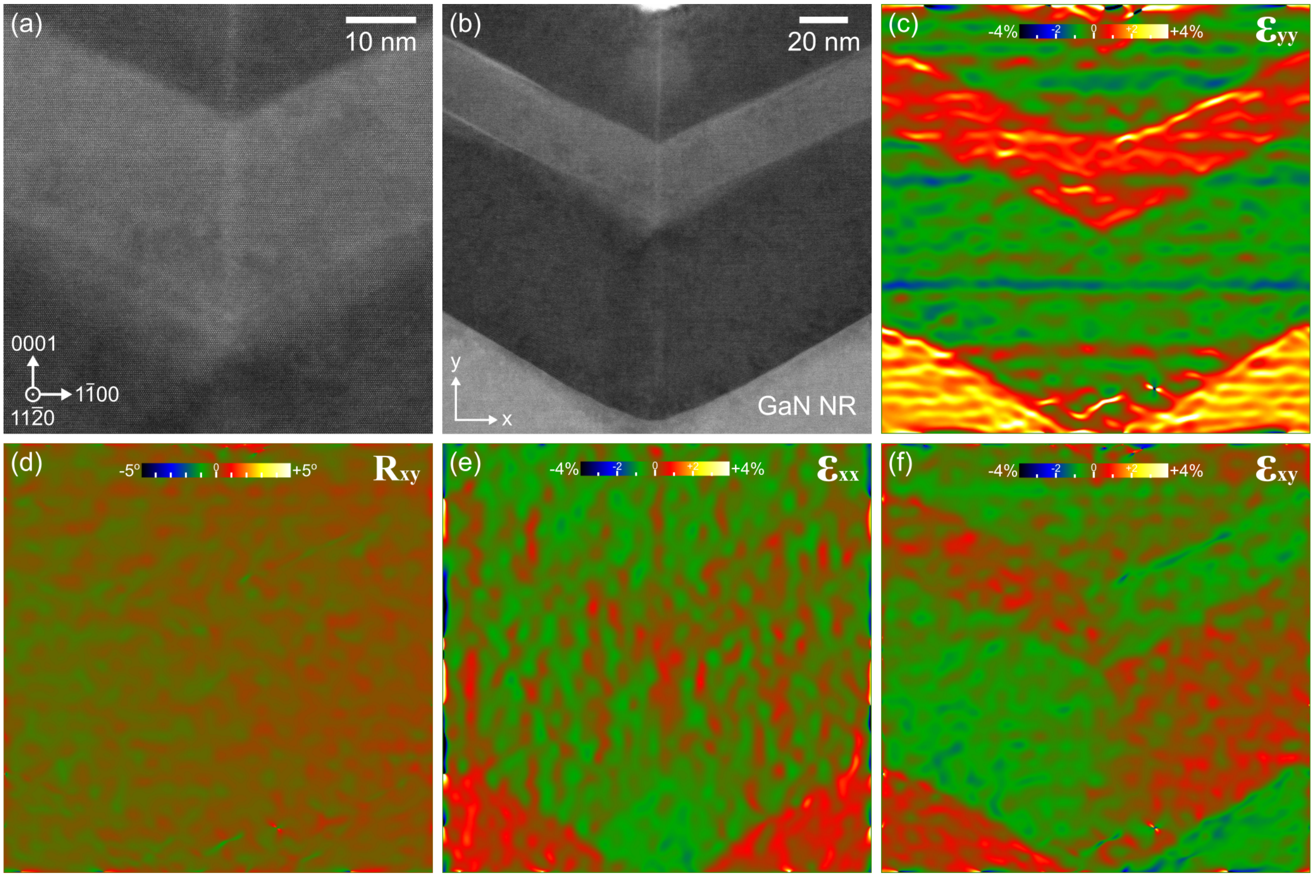

Figure 2. (a) High magnification image of a highly coherent coalescence boundary at the AlGaN DH. GPA processing of image in (b) with (c, e, f) corresponding to the strain components from the strain matrix and (d) the rotation component to visualize the relative local lattice deformation.