Toward third-generation solar cells

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A new approach to growing indium nitride nanowires has produced nearly intrinsic indium nitride and opens the way to novel optoelectronic devices.

Recently, indium nitride (InN) nanowires have emerged as a promising candidate for a range of nanoscale electronic, photonic, and biochemical devices. Extensive studies have shown that they exhibit a small direct energy bandgap (~0.6–0.7 eV), high electron mobility, and small electron effective mass. However, application devices require precise control of the charge properties of InN nanostructures. The currently reported InN nanowires and films are generally n-type degenerate with a residual doping of ~1×10^{18} cm^{-3} or higher.1–3 The uncontrollable electron density has made it extremely difficult to achieve p-type doping and to accurately determine many fundamental properties of InN, thereby severely limiting practical device applications. We have succeeded in growing, for the first time, nearly intrinsic (that is, undoped, or extremely pure) InN. In addition, we have experimentally demonstrated InN nanowire solar cells, opening up exciting possibilities for indium gallium nitride (InGaN) nanowire-based, full-solar-spectrum, third-generation solar cells.

Conventional InN nanowires grown on silicon (Si) generally exhibit a tapered morphology, with the presence of large densities of dislocations and stacking faults due to the uncontrolled wire nucleation associated with spontaneous growth, as well as the formation of an amorphous silicon nitride (SiNx) layer at the InN/Si heterointerface.4,5 In our approach, we first deposited a thin (~0.5 nm) In layer on the substrate surface before introducing any nitrogen species, which forms nanoscale In liquid droplets at elevated temperatures and can promote the nucleation and growth of vertically aligned InN nanowires.6 The wires are remarkably straight, with identical top and bottom sizes, compared to any previously reported InN nanowires (see Figure 1a). Detailed transmission electron microscopy studies further confirm that the wires are nearly free of dislocations and stacking faults.6

Figure 1. (a) Scanning electron microscopy image of nearly intrinsic InN nanowires grown on an Si(111) substrate using a Veeco Gen II molecular beam epitaxial system equipped with a radio frequency (RF) plasma source. Nitrogen flow rate: ~1.5 standard cm^3/min. RF plasma forward power: 400 W. In flux: ~1.0×10^{-7} Torr. Substrate temperature: ~480°C. (b) Photoluminescence spectrum of nearly intrinsic InN nanowires measured at 5 K under an excitation power of 15 μW.

Continued on next page
The photoluminescence emission spectrum of an undoped InN nanowire sample exhibits an extremely narrow spectral linewidth (~8meV) under an excitation power of ~15μW at 5K (see Figure 1b). This is nearly 10 times smaller than commonly reported values (~50–100meV) of InN nanowires in this temperature range.\textsuperscript{2,4,7} If we assume an inhomogeneous broadening of ~5meV for the present InN sample, which is the lower limit of the commonly reported values of III–V compound semiconductor nanowires grown on Si substrates, then we can calculate the electron concentration to be ~2×10\textsuperscript{15}cm\textsuperscript{-3}, which is nearly 1,000 times smaller than the commonly reported values for InN nanowires and films.\textsuperscript{1–3,7}

The achievement of nearly intrinsic InN nanowires on Si opens an entirely new avenue for the development of a range of InN-based optoelectronic devices. To this end, we studied the epitaxial growth, fabrication, and characterization of InN:Mg/i-InN/InN:Si nanowire axial structures on n-type Si(111) substrates and demonstrated the first InN nanowire solar cells. We passivated the InN:Mg/i-InN/InN:Si nanowire homojunction solar cells with a CdS layer using a chemical bath deposition method to effectively suppress nonradiative carrier recombination associated with the presence of surface states (see Figure 2a). Under one-sun (AM 1.5G) illumination, the devices exhibit a short-circuit current density of ~14.4mA/cm\textsuperscript{2}, open circuit voltage of 0.14V, fill factor of 34.0%, and energy conversion efficiency of 0.68% (see Figure 2b for the measured characteristics under dark and illuminated conditions).

The present work constitutes important progress for the realization of InGaN-based third-generation solar cells. It has also mitigated some of the major barriers for the future development of InN-based nanoelectronic and nanophotonic devices. Work is currently in progress to drastically improve device performance by optimizing the wire density and diameters, by using indium gallium nitride nanowires with an optimum energy bandgap, and by fabricating multi-junction nanowire solar cells.

This work is being supported by the Natural Sciences and Engineering Research Council of Canada, the Hydro-Quebec Nano-Engineering Program at McGill University, and the Nano-Quebec Biosensor Program.

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Continued on next page
References


