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# Nanostructured solar cells employ wide-band-gap materials

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*The range of energies accessible to nitride semiconductor materials provides unique flexibility in designing quantum-dot photovoltaic structures.*

The solar-electric conversion efficiency of traditional semiconductor solar cells is limited by a fundamental trade-off between the current generated by photon absorption and the operating voltage. Photons with energies below the semiconductor band gap pass straight through the device and do not contribute to the photocurrent. High-energy photons can be absorbed, but the resulting electrons are collected and extracted at a lower voltage, limited by the intrinsic energy gap. Any difference in energy between the photon and the semiconductor band gap is lost as heat. The conversion efficiency of single-junction devices using optimal materials with mid-range energy gaps (∼1–1.5eV) is typically limited to less than 25% of the incident solar power.

Quantum effects in nanostructured materials enable the development of new device concepts that can radically enhance the operation of traditional semiconductors. For example, a larger fraction of the optical spectrum can be harnessed while maximizing the solar-cell operating voltage by using quantum wells and quantum dots embedded in a higher-band-gap barrier material.[1,2] Nanostructured devices thus allow bypassing of the usual dependence of short-circuit current on open-circuit voltage, which limits conventional solar-cell design. Ultra-high conversion efficiencies are also predicted for photovoltaic devices that collect low-energy photons through a two-step process that pumps electrons from the valance to the conduction band via an intermediate stage.[3] Theoretically, the maximum efficiency of a single-junction intermediate-band solar cell matches that of a three-junction tandem cell while avoiding the limitations of current matching and subcell interconnection.[4]

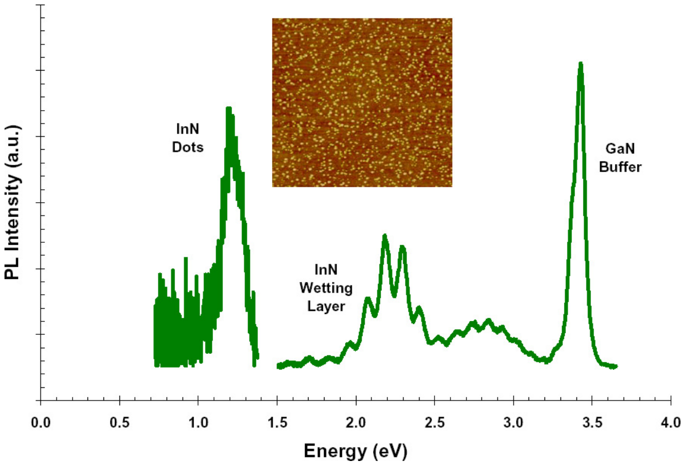

***Figure 1.*** *Room-temperature photoluminescence (PL) spectra (in arbitrary intensity units, a.u.) and a 5×5μm atomic force microscope image from an indium-nitride (InN) sample with a high density of dots (∼$5\times10^9 cm^{-2}$). A strong response is shown for both the InN dots and the wetting layer, as well as the gallium-nitride (GaN) buffer layer.*

Previous experimental work involving the use of either quantum wells or quantum dots in solar photovoltaics has almost exclusively employed gallium-arsenide-based (GaAs) material as the wide-band-gap matrix.[5,6] We take a different approach, instead employing wide-band-gap gallium nitride (GaN) as the barrier material and indium nitride (InN) as the quantum-dot substrate. Nitride semiconductors possess a number of unique properties applicable to solar cells, including a large range of energy gaps, superior radiation resistance, and tolerance to high temperatures. The well-known wide-band-gap properties of GaN have enabled the creation of new solid-state lighting and high-power electronic technologies. InN is a less well-developed material with a significantly lower energy gap, possibly as low as 0.7eV.[7] Thus, an unprecedented range of absorption energies, ranging from the IR to the UV, can potentially be obtained by embedding InN-based quantum dots in a wide-band-gap GaN

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barrier. The combination of energy gaps accessible to type III–V nitride materials may also potentially be used to reap the benefits of even more advanced design concepts involving hot-carrier effects.

The ordered-crystalline (epitaxial) growth of InN represents a great challenge for modern deposition techniques due to a lack of lattice-matched substrates, a low dissociation temperature, and a high-equilibrium-indium partial-pressure atmosphere at elevated temperatures. These difficulties in the growth of indium-containing nitride materials have limited the success of using indium-gallium-nitride (InGaN) materials in traditional bulk solar-cell devices. However, preliminary work indicates that self-assembled InN quantum dots can be formed on GaN by using the Stranski–Krastanov growth mode, a naturally occurring growth mechanism induced by lattice strain.[8] Moreover, under the right conditions, InN dots exhibit excellent structural and optical properties. Figure 1 shows the photoluminescence (PL) spectrum and an atomic-force-microscope image from the surface of a sample with InN islands approaching a density of $5\times10^9\text{cm}^{-2}$. Strong InN-dot emission at 1.2eV is clearly observed, along with the GaN-band edge near 3.4eV and a weak InN wetting-layer signal around 2.2eV. The 1.2eV PL signal associated with these smaller dots is higher in energy than the 0.7–1.0eV emission observed in samples with larger islands,[8] which likely results from quantum confinement in the InN dots between the underlying GaN buffer layer and the top surface potential.

In summary, InN dots have been synthesized on GaN templates through metalorganic chemical vapor deposition. Strong room-temperature PL has been observed, with peak emission energies ranging from the IR to the UV. These promising properties suggest that it may be possible to build structures incorporating InN quantum dots within a well-developed GaN semiconductor device. The unique properties of nitride material make it an excellent system with which to test the basic concepts of quantum-dot solar cells. We will next focus on improving both the InN quantum-dot stability and the quality of the capping material.

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