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InGaN-based Photovoltaic Devices for High-Efficiency Mechanically Stacked Multijunction Cell Structures

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Outline

- Sandia's Multijunction PV Effort.
- Difficulties of growing high indium composition InGaN layers.
- Sandia's InGaN PV cell with $In_{0.09}Ga_{0.91}N$ absorbing layers.
- Methods to achieving higher In composition InGaN layers.

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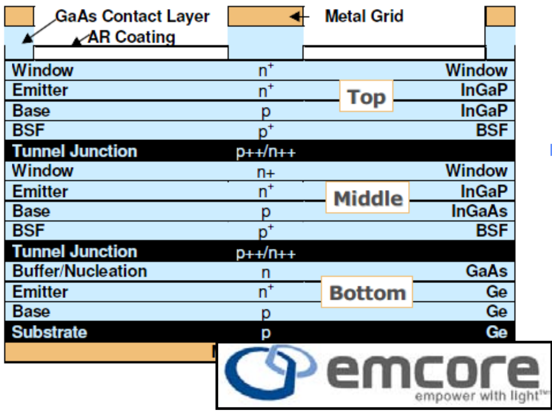
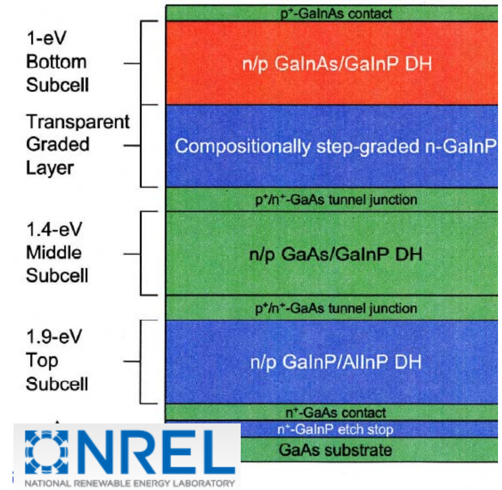
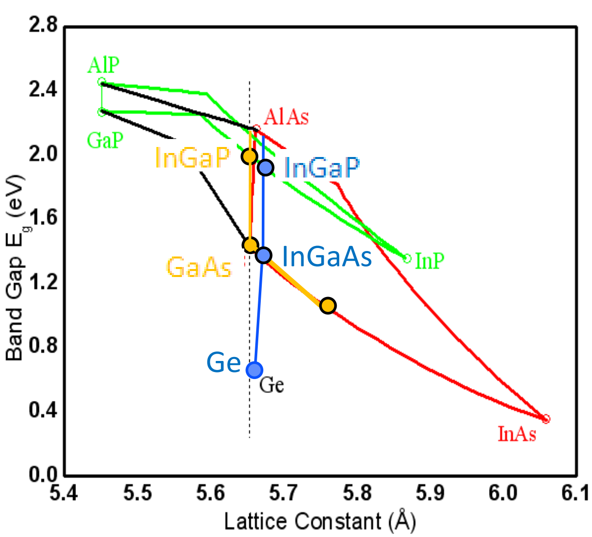
High-Efficiency Monolithically Grown Triple-Junction Photovoltaics







- Multijunction solar cells efficiencies are just over 40%.
  - Challenges exist for further advances with this technology.
- Lattice matching limits bandgaps to non-ideal values.
  - Adding cells/gaps to increase efficiency is difficult.
- Current matching requirements limit efficiency by designing to a specific spectrum.
  - On earth the spectrum changes with time weather, seasons.
- System level requirements further limit efficiency.

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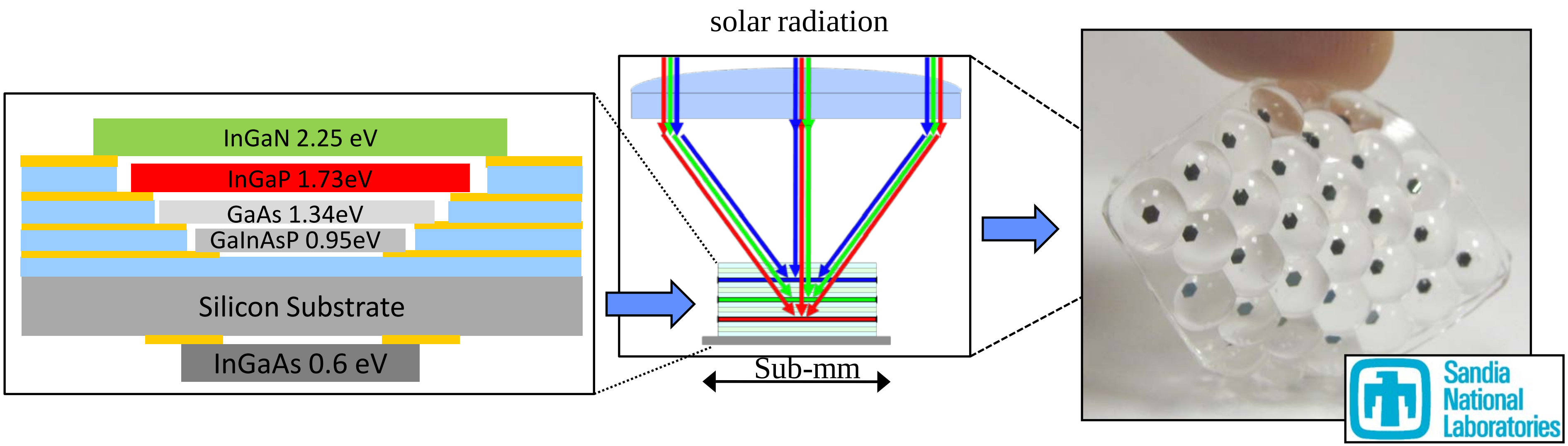
Mechanically Stacked Multijunction Photovoltaic Structure



- This structure removes or reduces many of the constraints on current multijunction cells.
- Stack of solar cells are grown independently, out of ideal materials, and proper thickness for efficient energy absorption and transmission.
- Apply Sandia's advanced microsystem technologies to create and assembly the cell.
- Developing new technology for individual control of PV junctions, efficient optical collection and utilization.
- Small dimensions allow high-quality, molded refractive optics and over-all cheaper module.

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Mechanically Stacked Multijunction PV Benefits

- **Cell Level Scale Benefits**
  - Reduced thickness significantly reduces the use and cost of c-Si/GaAs material
  - Backside contacts allows improved efficiency (no shading) and makes contacting simpler
  - Small scale cells better utilize wafer area (hexagons vs. squares and edge exclusion area)
  - Small PV cells tend to be more efficient (until surface recombination at edges becomes significant).
- **Module Level Scale Benefits**
  - Modules can be assembled with low-cost automated tools such as pick-and-place tools.
  - Modules can be assembled at very low costs by using self-assembly concepts in a manner that mirrors roll-to-roll printing.
  - Since all high-temp processing is performed on the wafer, the materials for the module can be low-temp, low-cost materials.
  - Concentration can be performed with low-cost and optically efficient refractive microlens arrays.
  - Small cell size allows short focal lengths for concentrating optics, providing for direct lamination of optics to PV cells without a cavity between.
  - Small cell size provides significant temperature reductions as compared to larger scale concentrating systems at the same concentration ratios.
- **System Level Scale Benefits**
  - High-voltage output directly from modules is possible due to the large number of cells comprising the module, eliminating the need for DC to DC converters and reducing the cost of system wiring.
  - High-efficiency panels reduce racking and installation costs
  - Integration of health monitoring and power conditioning ICs can be performed using same low-cost module assembly techniques already proposed.
  - Small in-plane motion can provide high-accuracy, low-cost tracking built into the thin module reducing tracking cost and system complexity.
  - Small-motion, high-bandwidth tracking can account for wind and other environmental vibrations.

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Ideal Multijunction Cell Structure

# Junctions	Junction #1	Junction #2	Junction #3	Junction #4	Junction #5
3	*0.6eV (InGaAs)*	*1.14eV (Si)* *1.1eV (GaInAsP)*	1.81eV (InGaP)		
4	*0.6eV (InGaAs)*	*0.97eV (GaInAsP)*	1.42eV (GaAs)	2.00eV (InGaP)	
4	*0.6eV (InGaAs)*	*1.12eV(Si)* *1.1eV (GaInAsP)*	1.64eV (AlGaAs)	2.22eV (InGaN)	
5	*0.6eV (InGaAs)*	*0.95eV (GaInAsP)*	1.34 (GaAs)	1.73eV (InGaP)	2.28eV (InGaN)

- Leveraging Sandia's semiconductor growth expertise to cover all the materials.
- Most of the III-V compound systems are well developed and present a low risk for achieving solar cells with good PV performance.
- Higher number of cells requires a wide-gap cell, and theoretically InGaN can be use
    - We need to overcome the difficulties of growing quality high indium composition (x~0.3-0.35)$In_xGa_{1-x}N$ layers (non-QW).

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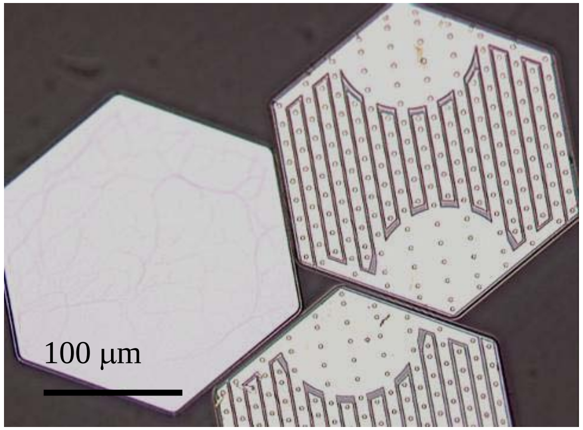
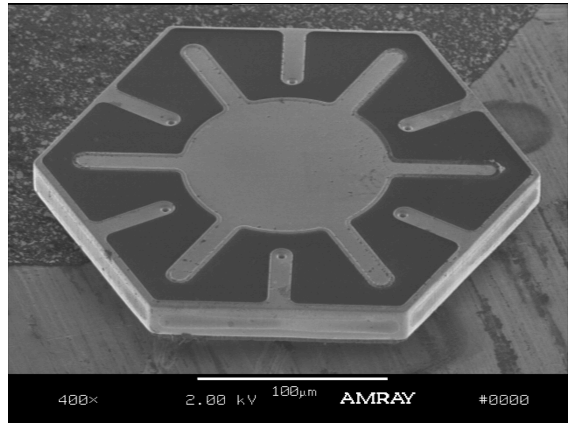
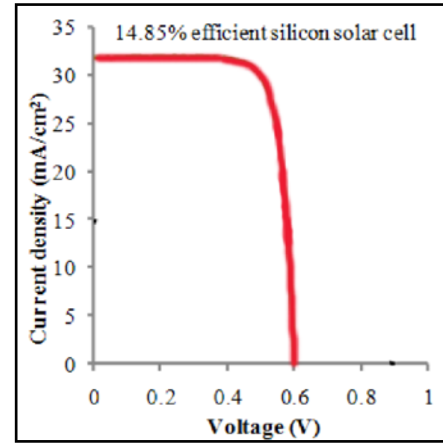
Silicon (1.1eV) Solar Cells

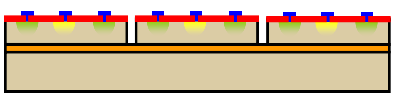




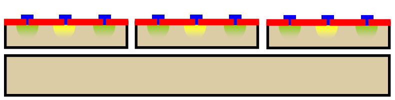


SOI wafer (HF Release)

Create micro-PV cell then anisotropically etch between cells to buried oxide layer.



Release from handle wafer using an HF based release etch.



After release, the handle wafer can be reused to create a new SOI wafer.

- We can produce thin (~20 mm), back-contacted crystalline silicon PV cells with various lateral dimensions and contact designs.
- Si cells will need to be further optimized and modified to allow light to pass through (i.e. move metallization to the edges). We have achieved 14.9% efficient cells with a 14 micron thick c-Si cell.

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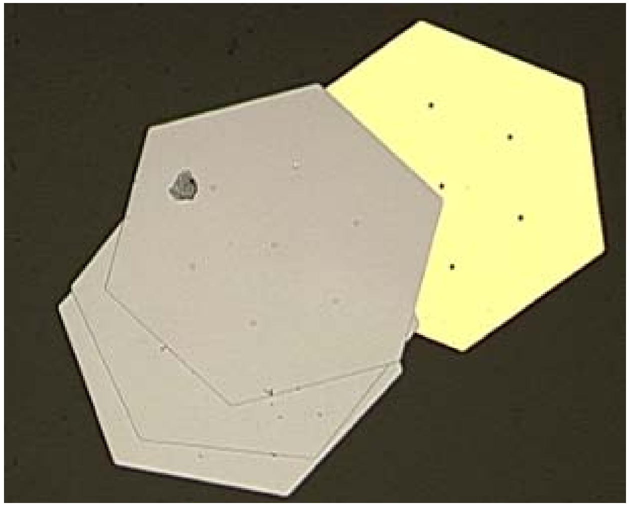
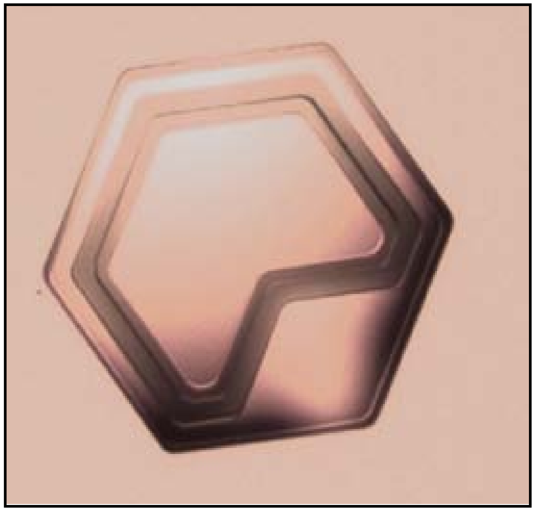
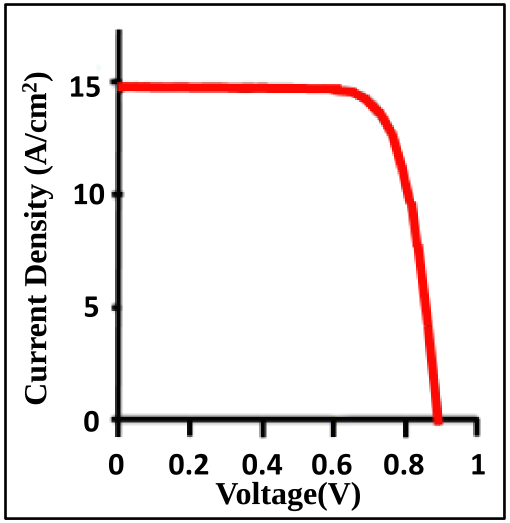
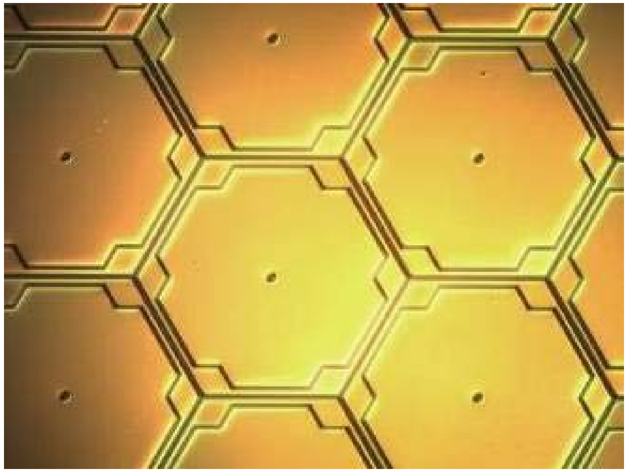
GaAs (1.43eV) Solar Cells



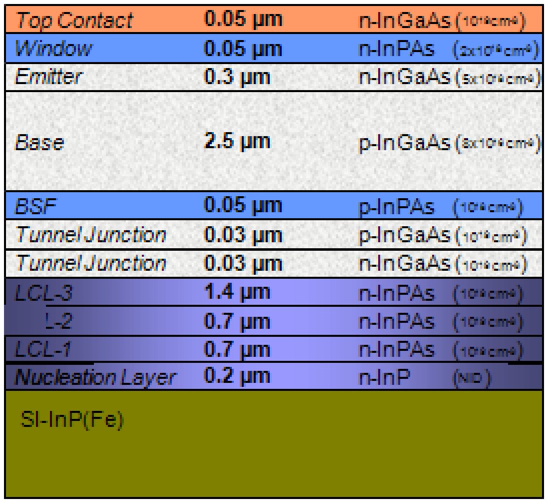


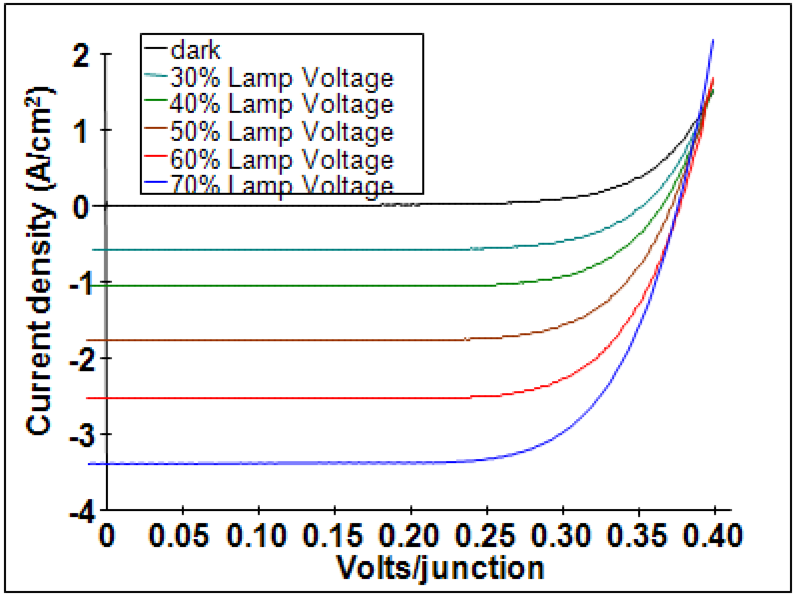


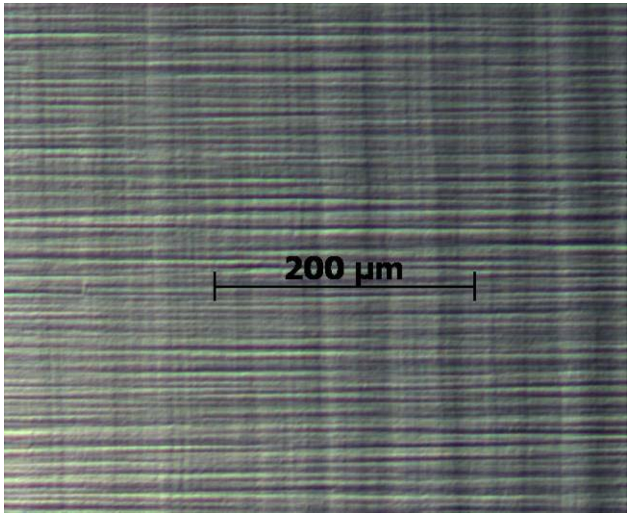


- We have demonstrated fully back-contacted, 10% efficient, 2.6 micron thick GaAs PV cells.
- Epitaxial lift-off with AlAs as the sacrificial material is used to create the thin cell.

InGaAs (0.6eV) Solar Cell







- Surface dominated by cross-hatch from strain relaxation
- 5-junction cells (series connected)
  - V_{oc}= 1.9 (380 mV/junction)
  - Fill factor = 71%
  - External QE = 80%

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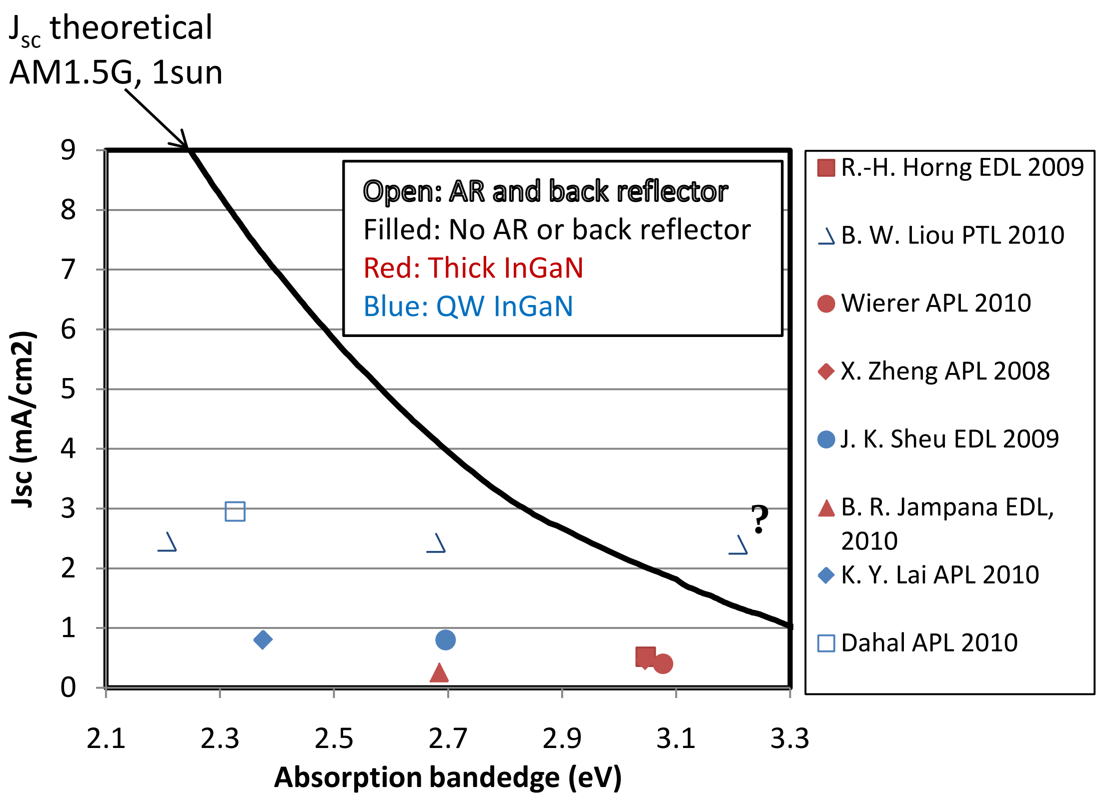
InGaN Photovoltaic Performance



$$\eta_{sc} = \eta_{photon\text{-}collection} \times \eta_{absorption} \times \eta_{carrier\text{-}collection}$$

η_{sc} = 100% for J_{sc} theoretical

- Theoretical short circuit current density (J_{sc}) increases rapidly with decreased band edge.
- Clear performance difference when collection efficiency is enhanced (AR and back reflector).
- So far reducing the bandgap of the InGaN absorption region by increasing the indium concentration has not resulted in increased performance.
- Clearly the difficulties of growing high indium concentration InGaN layers is the cause.

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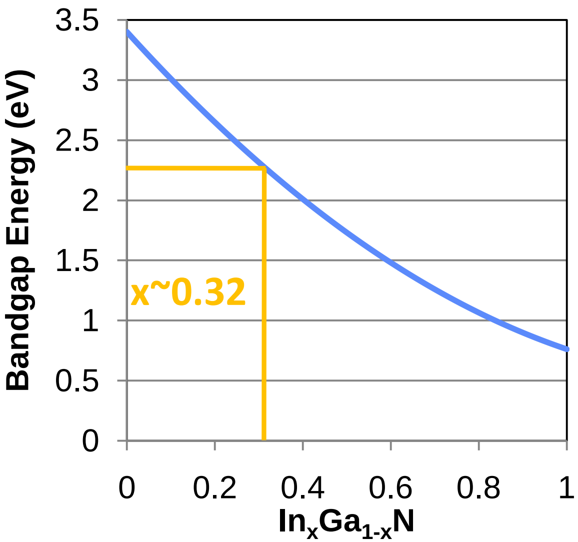
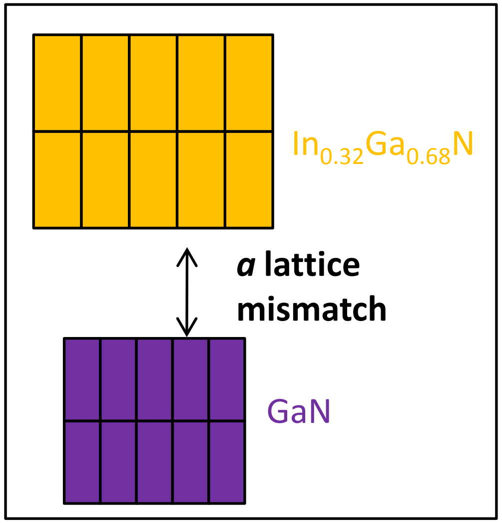
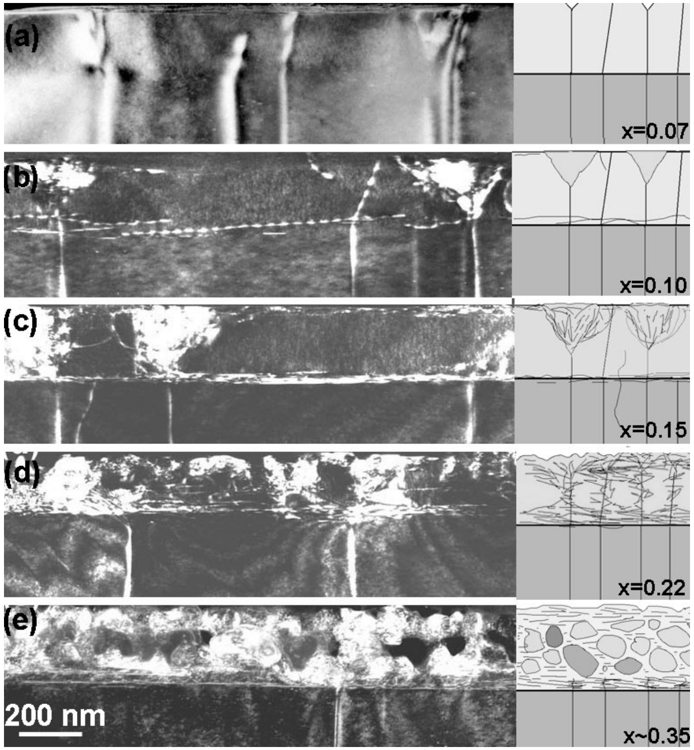
InGaN strained on GaN



Data from Wu et al., APL 80 (2000).





Ponce et al., phys. stat. sol. (b) 240, No. 2 (2003).

- $In_xGa_{1-x}N$ is typically grown on GaN (no $In_xGa_{1-x}N$ substrates).
- Strain limits $In_xGa_{1-x}N$ composition and thickness (x~0.1-0.12 for ~200nm).
- Exceeding these limits leads to defect formation and poor material quality.
- Bandgap of ~2.25eV requires $In_xGa_{1-x}N$ (x~32 %) layers <u>≥ 200 nm thick.</u>

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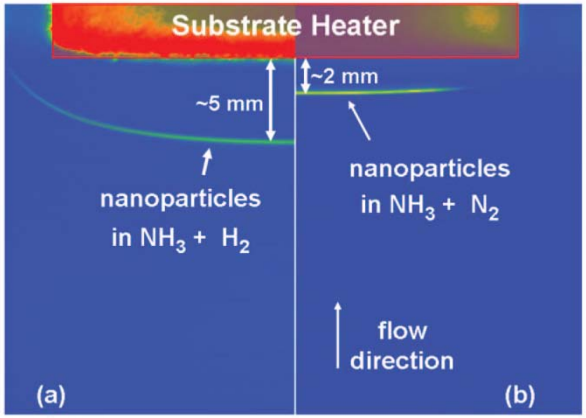
Other Issues for the MOCVD growth of InGaN films

- **InGaN Thermal Stability**
  - GaN growth best at 1000-1100 C – InGaN is best at 700-850 C. Low InN solubility in GaN.
  - Lower growth temperatures are necessary to decrease Indium desorption, but introduces defects, impurities, morphology changes.
  - InGaN decomposition occurs when QWs and InGaN films are heated.

- **MOCVD Growth Environment**
  - Gas phase parasitic reactions – decreases metal organics reaching surface.
  - Indium incorporation depends strongly on growth temperature – accurate temperature measurement difficult due to transparency of GaN and sapphire.
  - Low growth temperature limits NH_3 dissociation possibly leaving excess indium metal on the surface.



Creighton et al., APL, **93,** 171906 (2009).

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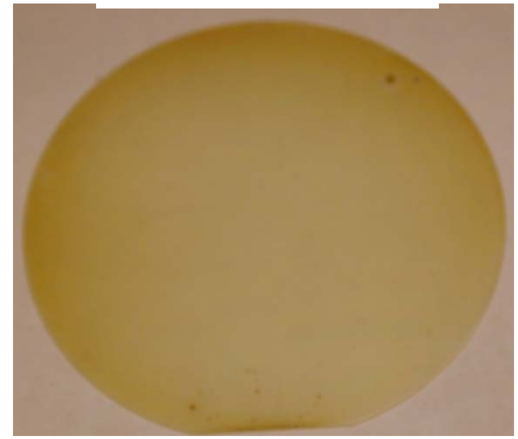
Visual appearance of InGaN growth problems

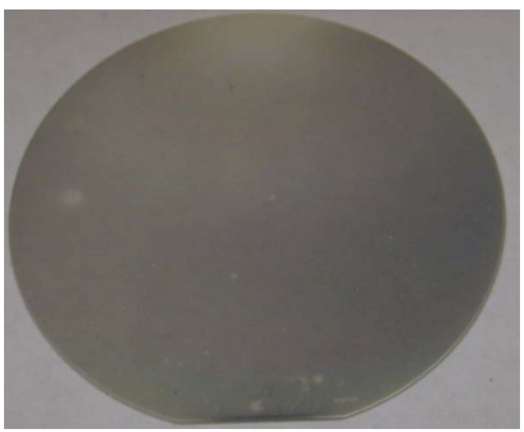
MQW, $In_{0.15}Ga_{0.85}N$

MQW, $In_{0.2}Ga_{0.8}N$

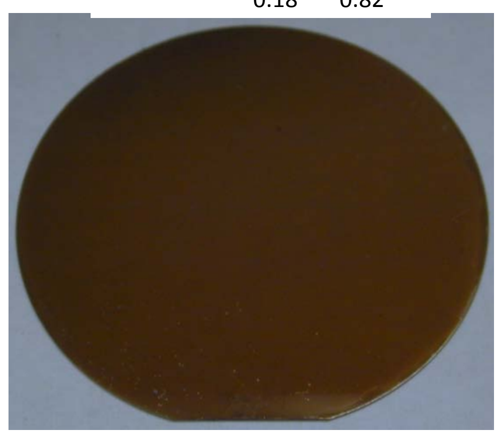
~180nm, $In_{0.1}Ga_{0.9}N$



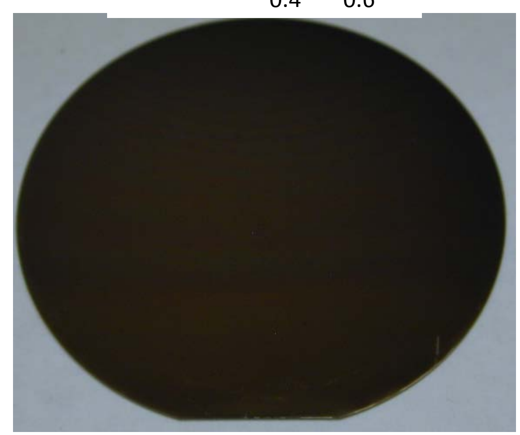
MQW, $In_{0.15}Ga_{0.85}N$, high temp p-GaN



200nm $In_{0.18}Ga_{0.82}N$



150nm $In_{0.4}Ga_{0.6}N$



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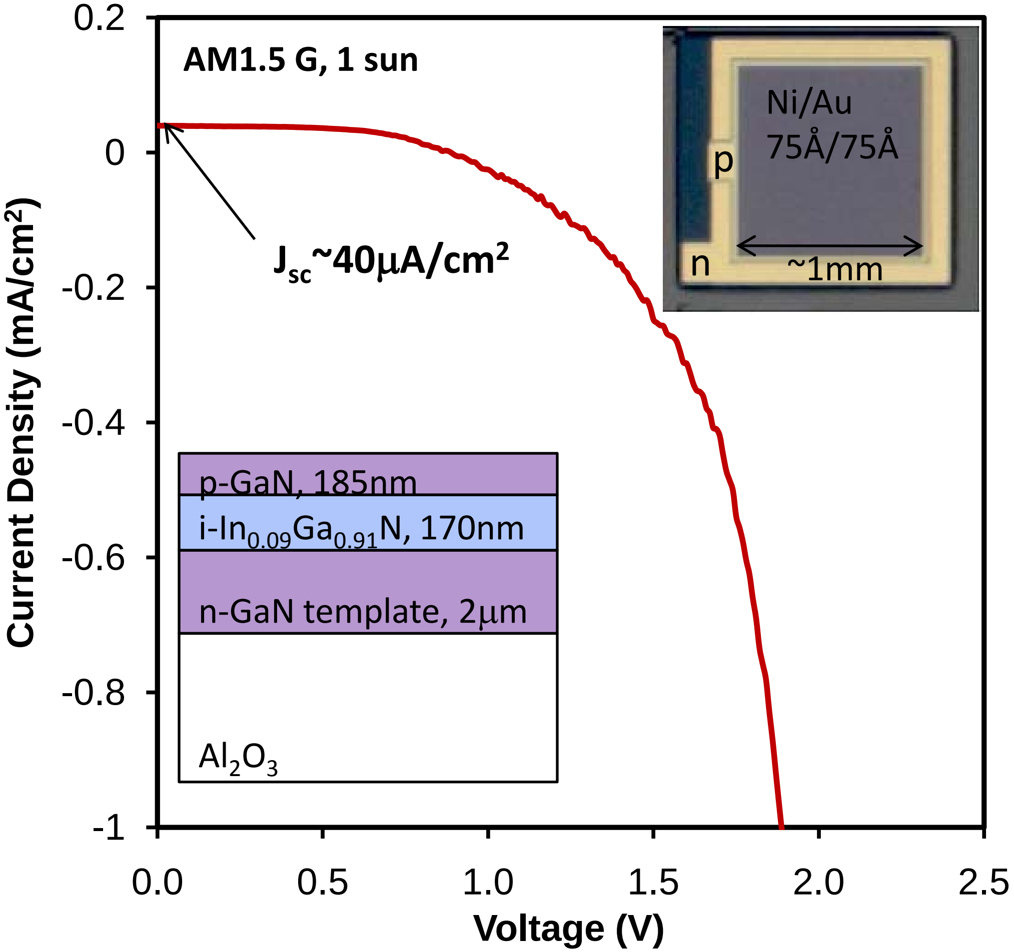
PIN Solar Cells with i-$In_{0.09}Ga_{0.91}N$ layers



- PIN structure consisting of p-GaN/i-InGaN on an (0001)-face n-GaN template layer.
- Performed a simple device fabrication process with square ~1mm² device with a surrounding n-contact and a Ni/Au p-contact/spreading layer. No anti-reflection coating or back-reflector.
- The device performs poorly with a low short-circuit current density (J_{sc}).

J. J. Wierer, Jr., A. J. Fischer, and D. D. Koleske, APL, **96**, 051107 (2010).

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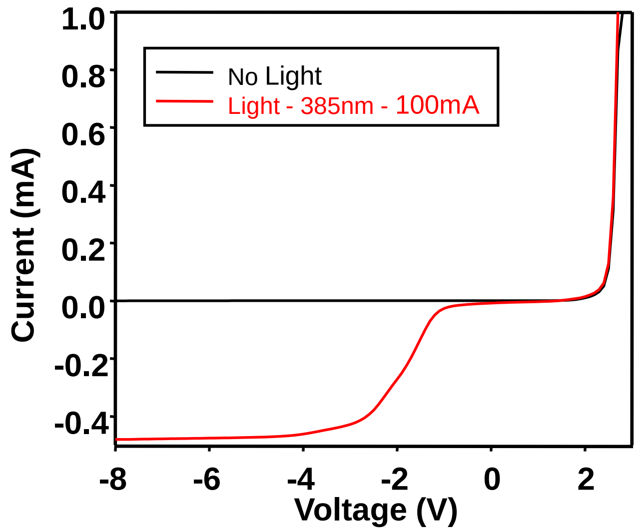
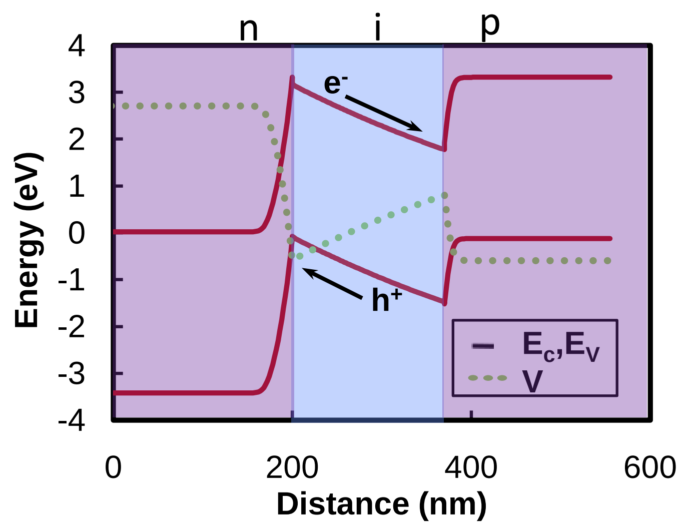
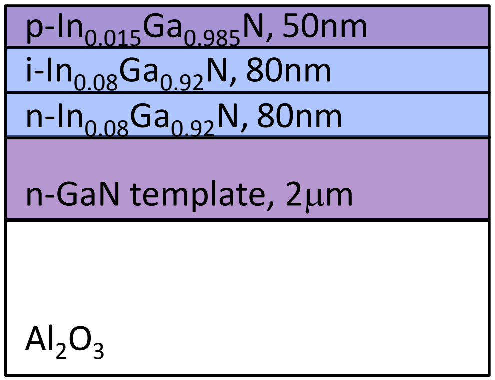
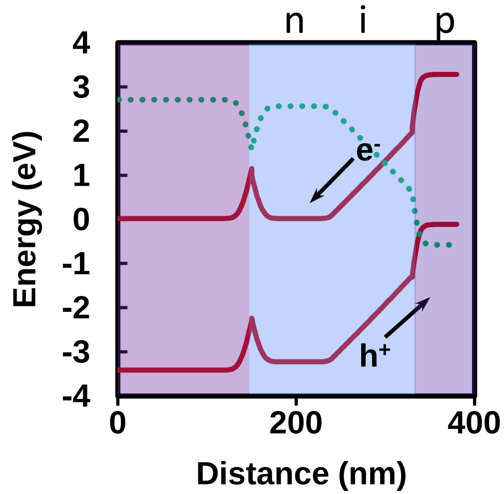


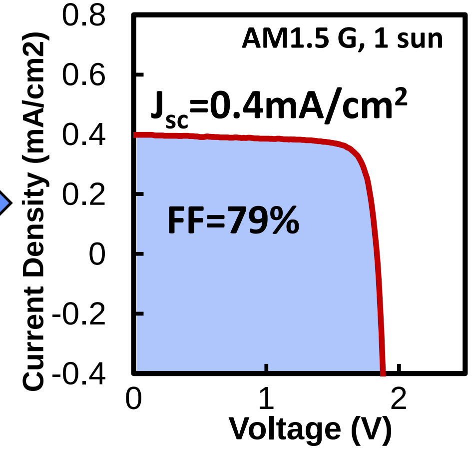


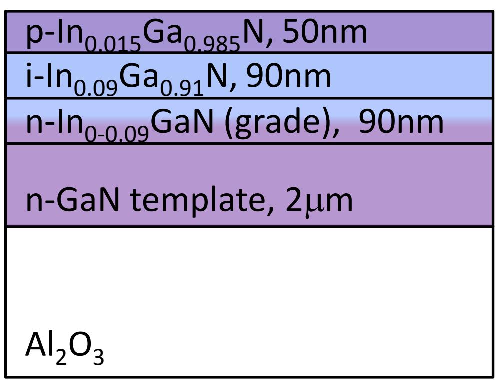
- When reverse biasing the device under illumination we can see an appreciable increase in the current beyond at -2 to -4V.
- Modeling of the band diagram shows the piezoelectric polarization creates a detrimental field within the intrinsic region forcing carriers the wrong way.
    - Note: structures grown on non-polar structures will not have this problem.
- The reverse bias most likely overcomes this field and allows the carriers to drift in the proper direction and be collected.

Polarization Engineered PIN InGaN Solar Cells









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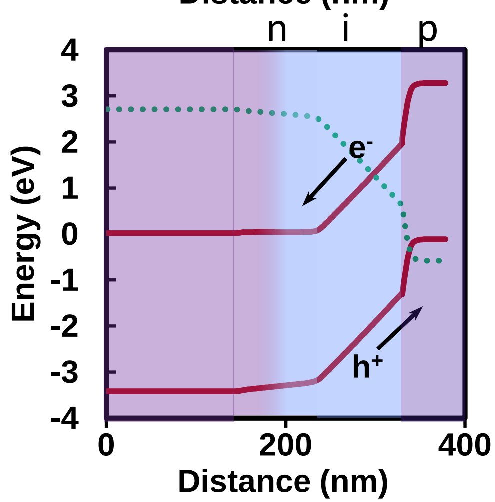

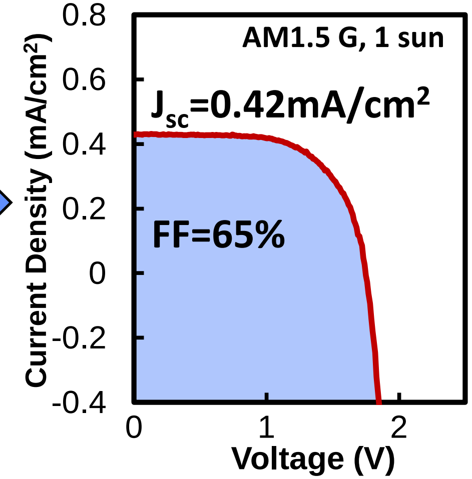

- Removing/displacing polarization fields at the i-InGaN interfaces allows carriers to drift in the proper direction improving performance.

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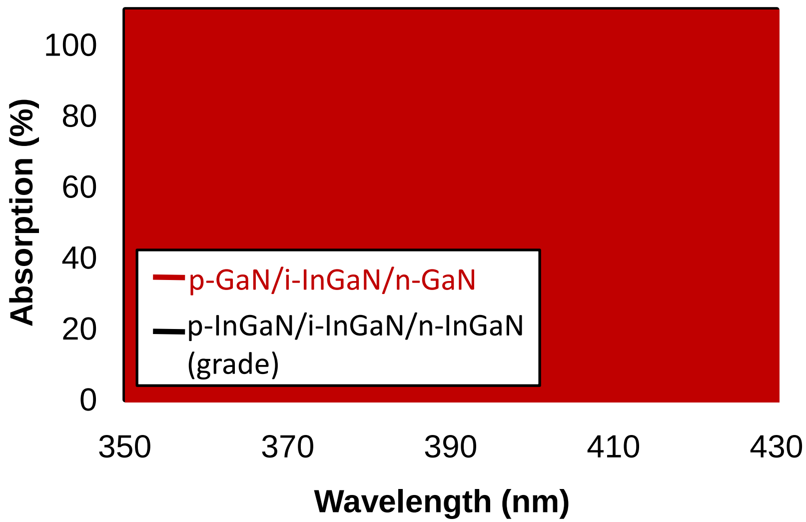
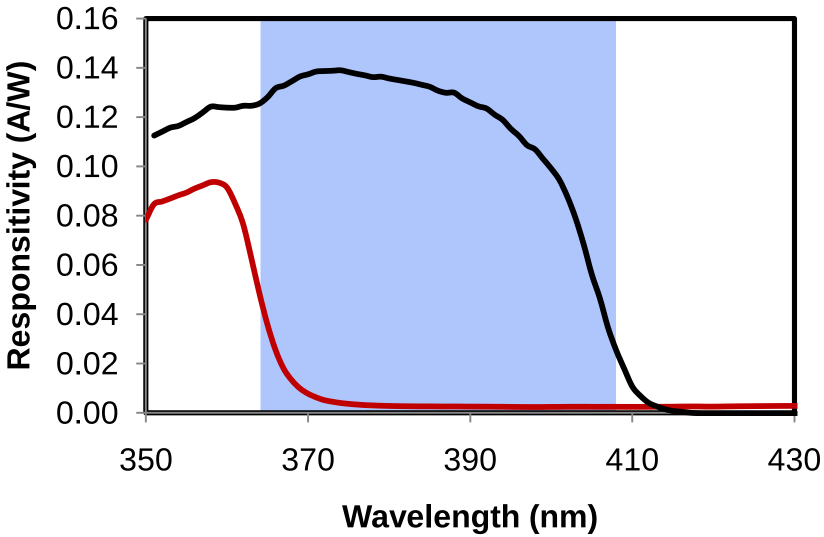
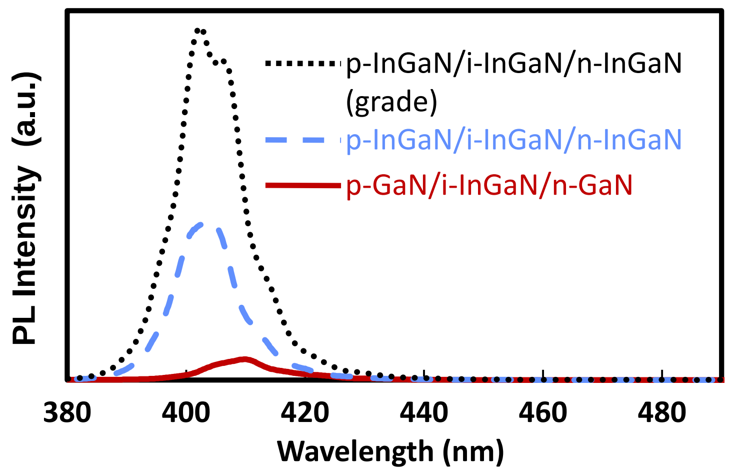
Polarization
Engineered PIN InGaN Solar Cells

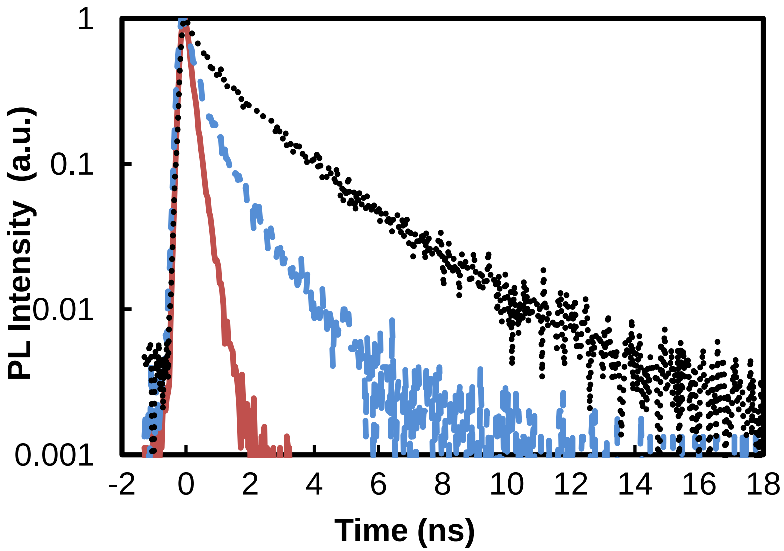




- Both the standard p-GaN/i-InGaN/n-GaN and polarization engineered p-InGaN/i-InGaN/n-InGaN(grade) structures absorb in the InGaN layer (below the gap of the GaN).
- The p-GaN/i-InGaN/n-GaN device does not display a photo response at these energies though.
- Further evidence that carriers generated in i-InGaN layer of the p-GaN/i-InGaN/n-GaN device are drifting the wrong way and cannot be collected.

Polarization
Engineered PIN InGaN Solar Cells





J. J. Wierer, Jr., A. J. Fischer, and D. D. Koleske, APL, **96**, 051107 (2010).

- Further characterization shows there is also a materials quality improvement.
- Both the polarization engineered structures have emit more light and have longer lifetimes.
- Internal fields will also influence the PL but it is not easy to determine how much.
- The improved structures have lower non-radiative recombination also contributing to the better performance.

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Methods to achieve InGaN layers with higher indium composition

- Create InGaN template layers on which to grow the InGaN solar cell structure.
  - Removes the growth problem of strained InGaN on GaN.
  - How does one create such a template?
- Grow multiple quantum well or superlattice structures.
  - Target absorption energy can be achieved with lower indium composition InGaN layers.
  - Absorption layer is thicker and carriers will need to travel farther to be collected.
- Grow InGaN on GaN nanowires.
  - Alleviates some of the strained growth, and higher In composition InGaN layers can be achieved compared to planar films.
  - The final device needs to be a collection of nanowires. Can the necessary uniformity from nanowire to nanowire be achieved so that they can all be run in parallel?

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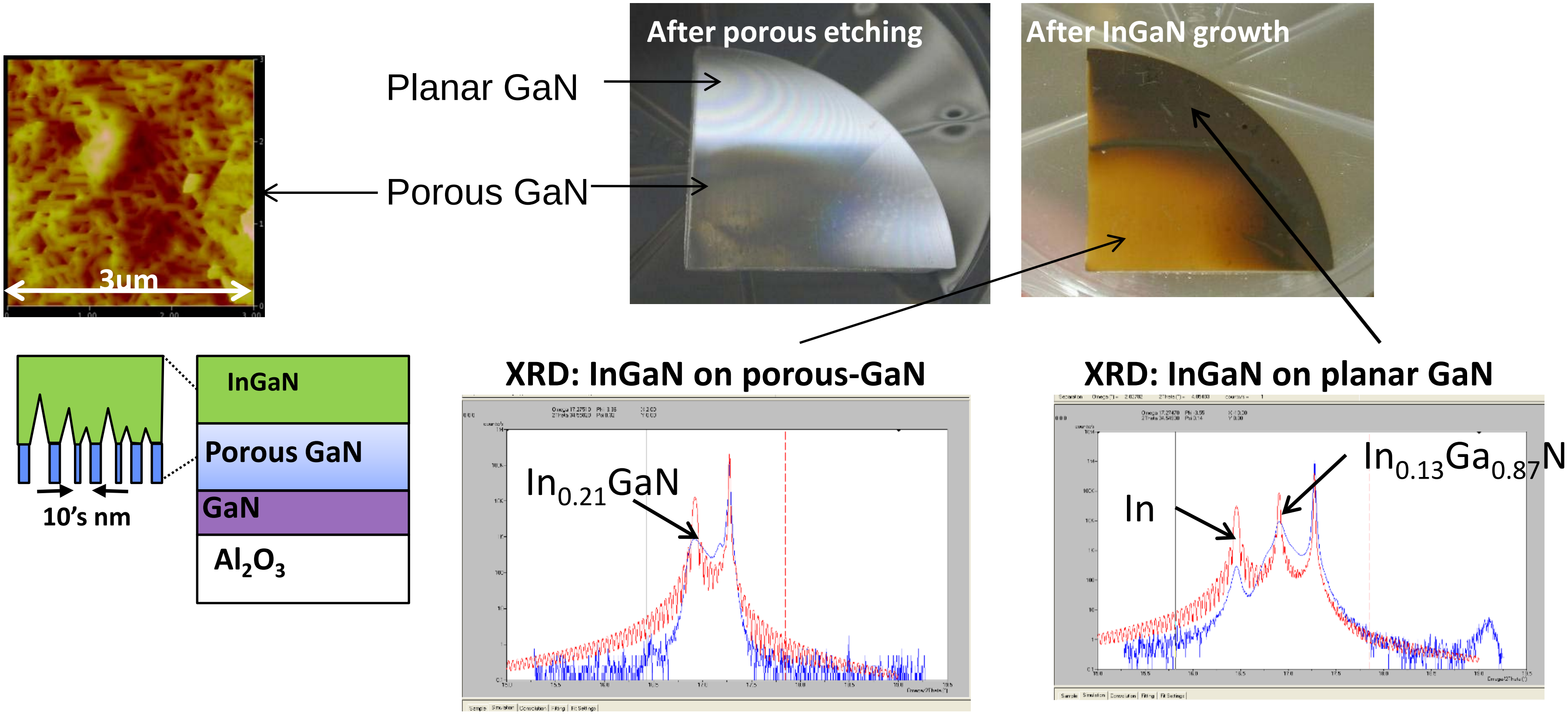
InGaN Templates Grown From Porous GaN



- InGaN growth on porous GaN produces inhomogeneous strain that promotes InGaN relaxation.
- Demonstrated 1μm thick $In_{0.21}Ga_{0.79}N$ films (E_g~2.5) that are fully relaxed and not grey.
- Questionable if this is suitable as a growth template.

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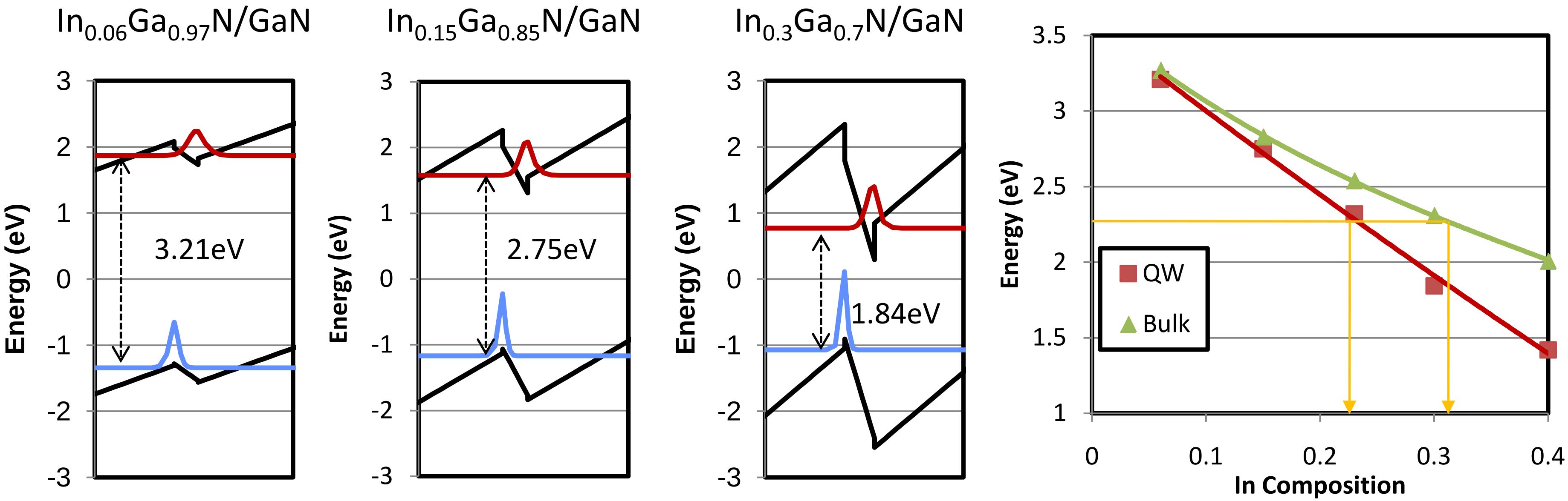
InGaN/GaN Multiple Quantum Wells as Absorption Layers



- Modeled band diagrams of multiple quantum wells of $In_xGa_{1-x}N/GaN$ with 3nm/13nm thicknesses and x varying.
- The piezoelectric polarization at the $In_xGa_{1-x}N/GaN$ heterointerfaces tilts the quantum wells, shifting the wavefunctions with respect to each other (Stark Effect).
- This tilt also brings the wavefunctions closer in energy, and we can achieve a lower absorption energy with a lower indium composition InGaN layer compared to bulk.
- Is absorption strong enough?

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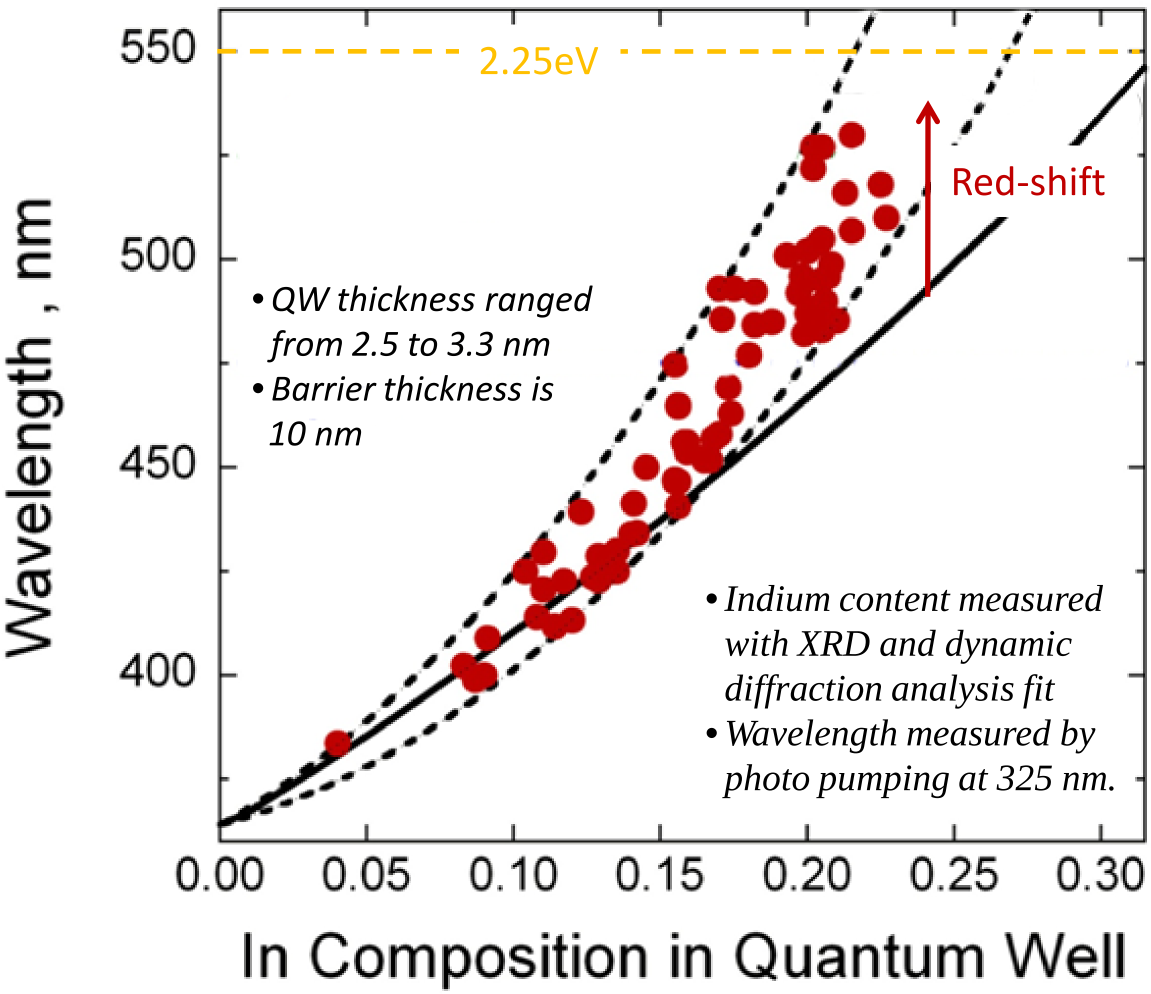
Influence of Stark Effect on Quantum Well Emission Wavelength



- Solid line- Bulk InGaN emission wavelength vs. indium content
  - In~0.32 for 550nm/2.25eV.
- Dotted lines- bracketed the necessary indium composition to achieve each wavelength.
- A single InGaN composition can yield multiple wavelengths because of MQW design considerations.
- Piezoelectric induced tilted bandstructure reduces the transition energy *red-shifting* the QW emission; this energy change is called the *Stark shift.*
- Lower energy absorption in InGaN may be easier to achieve with QWs!

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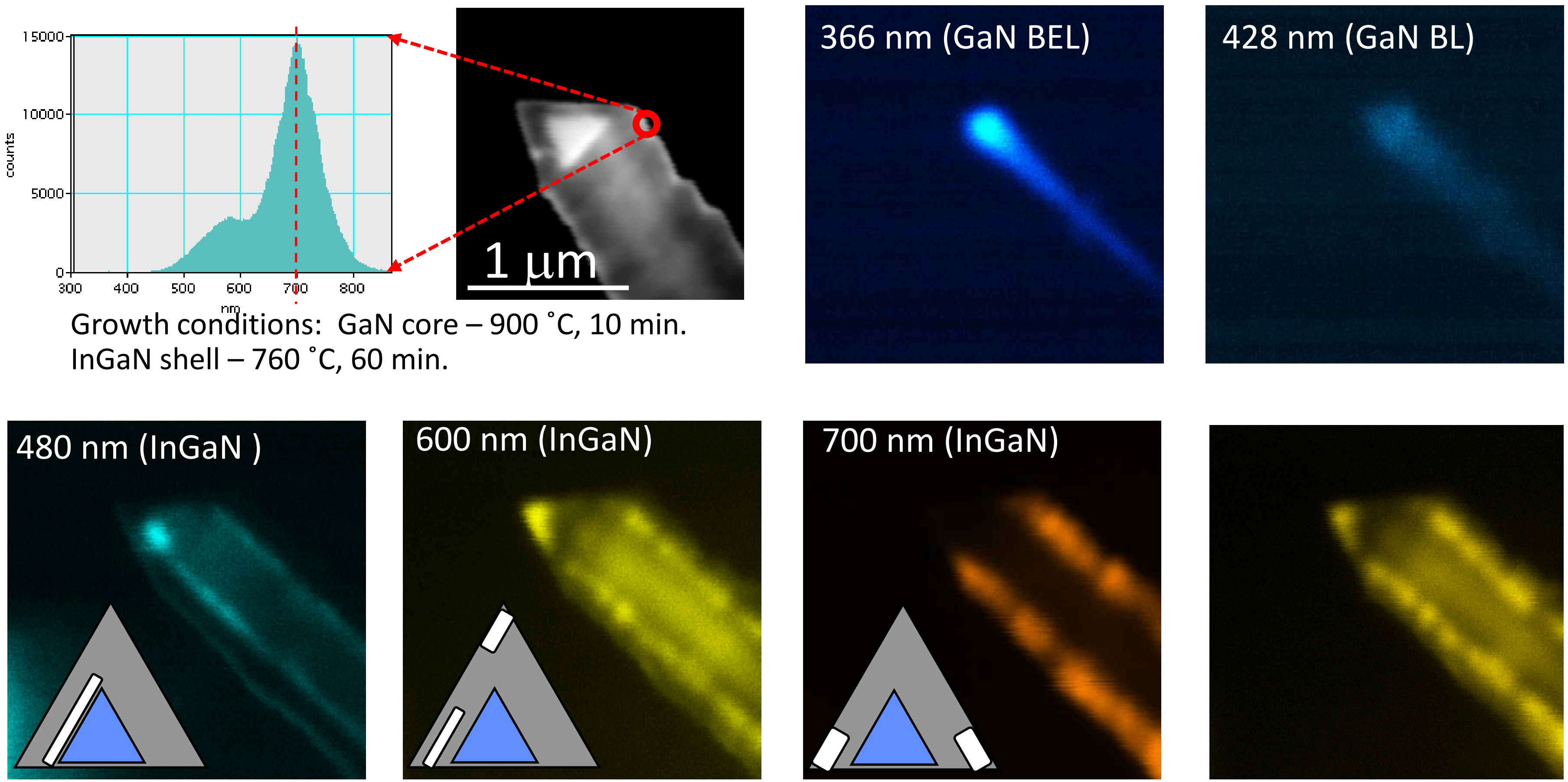
High Indium Incorporation in GaN/InGaN Core/Shell Nanowires



Growth conditions: GaN core – 900 ˚C, 10 min.
InGaN shell – 760 ˚C, 60 min.

- Strain limits practical In incorporation in InGaN thin films
- InGaN shell layers on GaN core nanowires an overcome those limitations.

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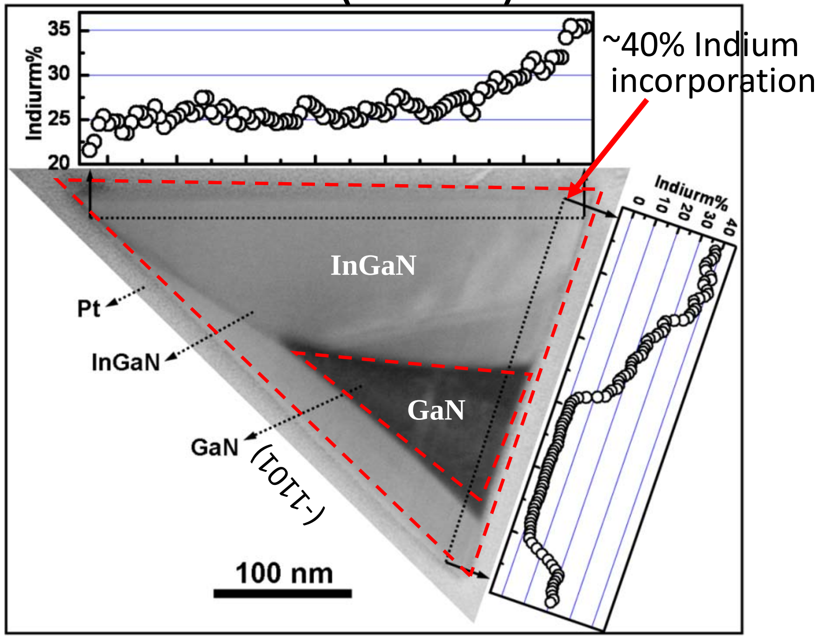
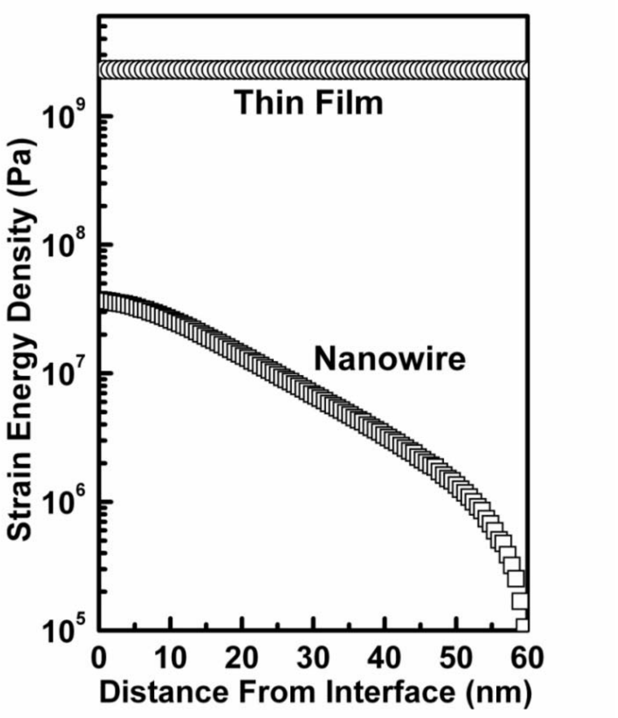
In incorporation
in GaN/InGaN core-shell Nanowires

EDX(STEM)





- InGaN shell growth highly facet-dependent -- no growth on (000-1) c-plane facet
- In concentration increases away from GaN/InGaN interface, highest at corners
- Low amont dislocations observed despite very high In concentration
- Strain in InGaN NW shell much lower than for InGaN thin film

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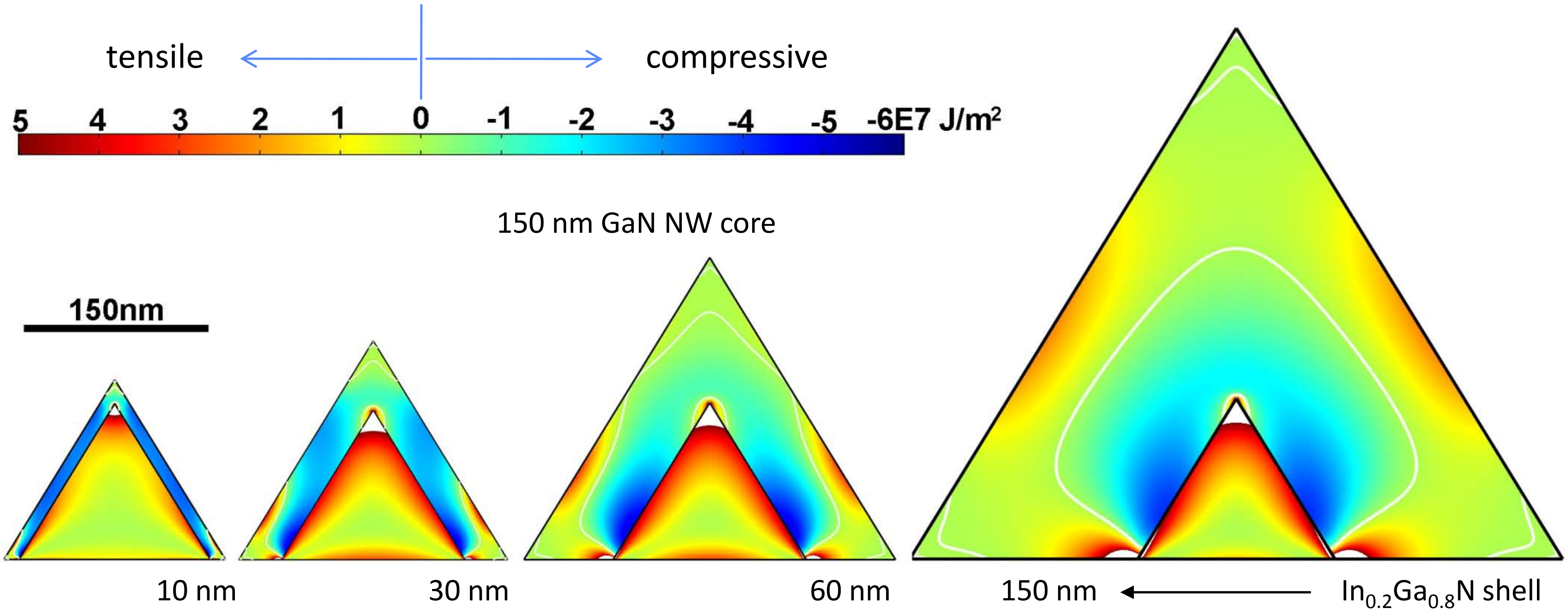
Strain-dependent In incorporation in GaN/InGaN core-shell NWs



- Finite element models show compressive/tensile strain in GaN core and InGaN shell
- Compressive strain dominates in thinner shells, decreases away from interface and becoming tensile for thicker shells
- Higher In incorporation correlated with lower (compressive) strain regions

Conclusion

- **Sandia is working on a high–efficiency mechanically stacked multijunction solar cell with InGaN as the highest energy cell.**
- **Growing InGaN layers with high indium compositions is difficult because of strain mismatch with GaN, thermal stability, and growth environment issues.**
- **The performance of III-nitride PIN solar cells with i-$In_{0.09}Ga_{0.91}N$ absorbing layers is affected by piezoelectric polarization and materials quality.**
- **Showed three potential ways to achieve lower bandgap absorption: InGaN templates, MQW absorbing layers, and GaN/InGaN core/shell nanowires.**