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Advanced Materials and Designs for High Efficiency Multijunction Photovoltaic Devices

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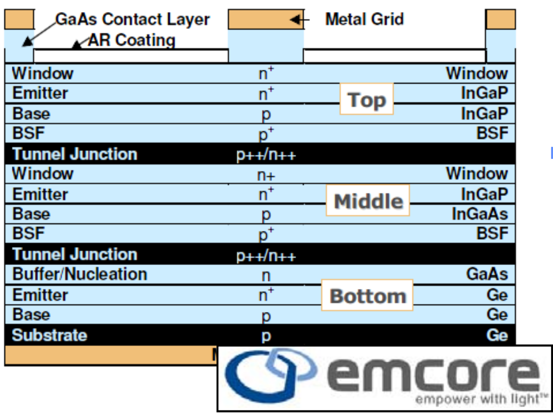
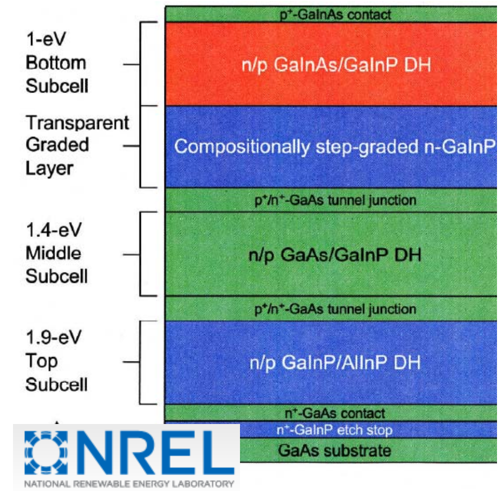
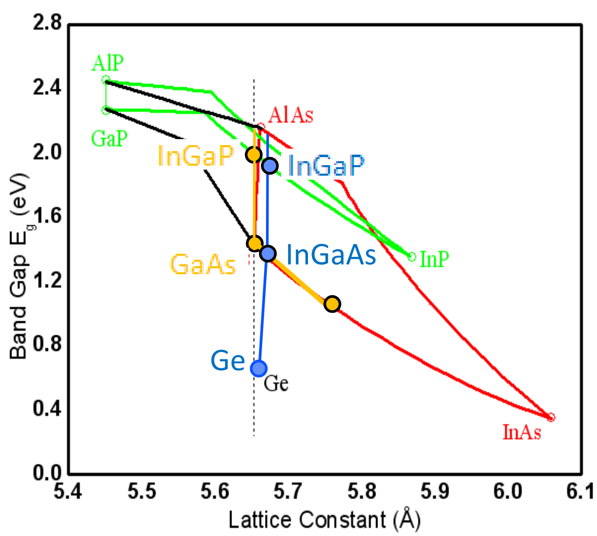
High-Efficiency Monolithically Grown Triple-Junction Photovoltaics







- 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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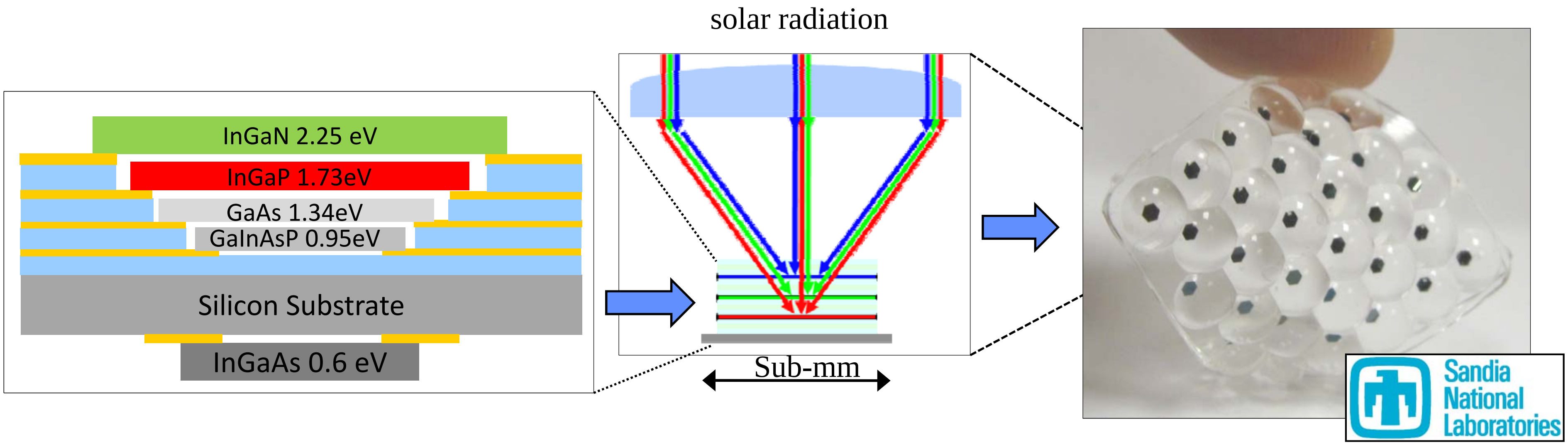
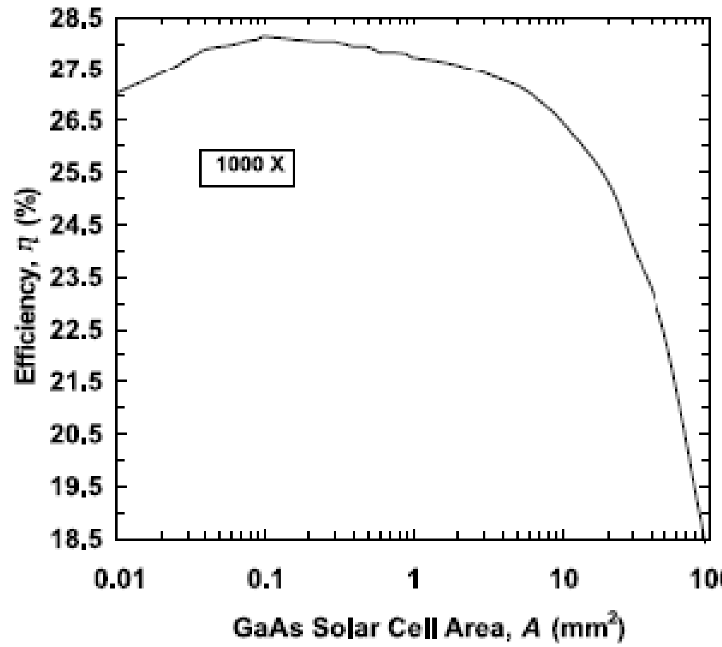
Mechanically Stacked Multijunction Photovoltaic Structure



- Not a new idea! 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 assemble 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.

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 the cells simpler
- Small scale and backside contacts provides for low cost automated assembly (self-assembly or pick-and-place)
- Small scale cells better utilize wafer area (hexagons vs. squares and edge exclusion area)
- Small cells can use any size wafer while one cell/wafer manufacturing model has a wafer size limitation. (Increased wafer size decreases processing costs.)
- The high-quality processing provided with IC fabrication tools should allow near-ideal cell performance (>20%).
- Small PV cells tend to be more efficient (until surface recombination around edge becomes significant).
- Carrier collection improves with reduced size.



C. Algora, *Concentrator Photovoltaics (*ed. W. T. Rhodes*)*, ch. 5, 2007.

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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 (bulk).

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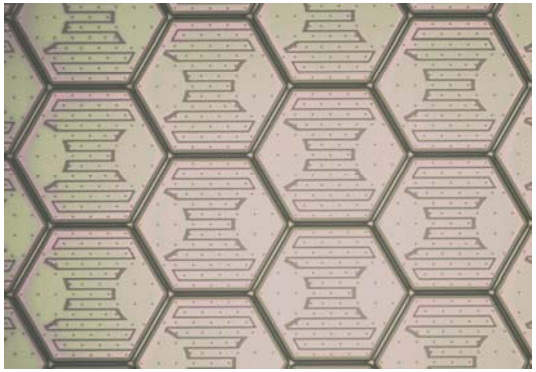
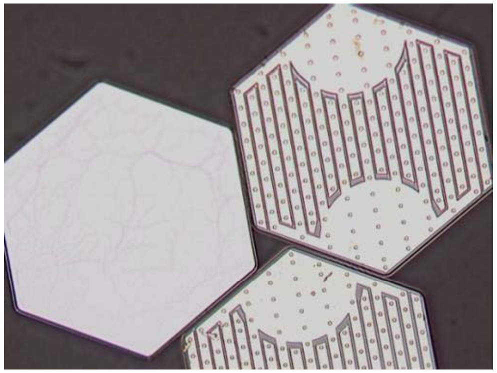
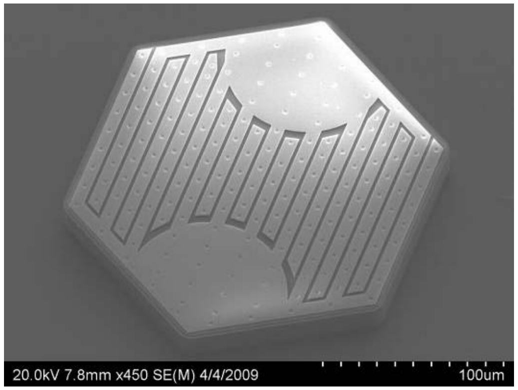
Experimental Results:Si



Cells attached to the wafer



Released cells



SEM of released cell

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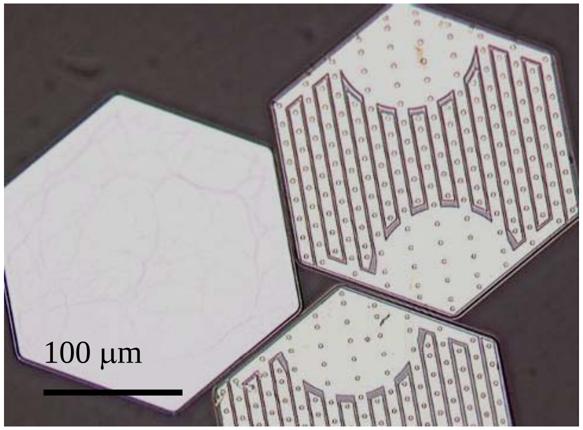
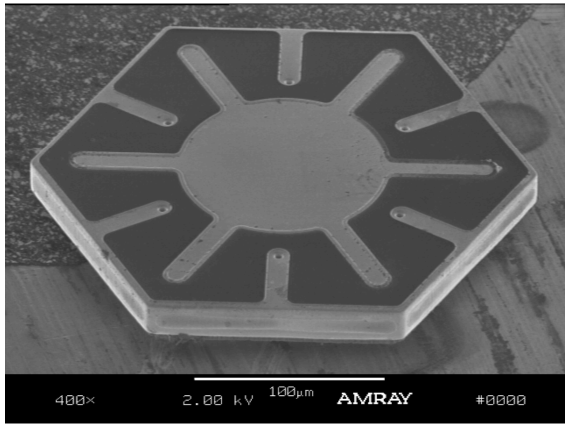
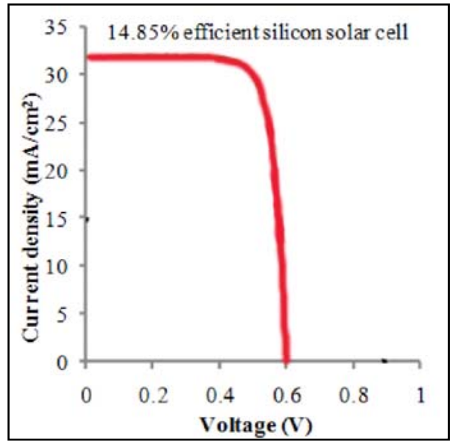
Silicon (1.1eV) Solar Cells

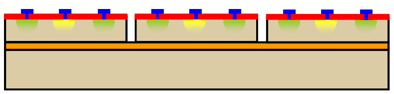




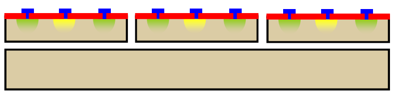


SOI wafer (HF Release)

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



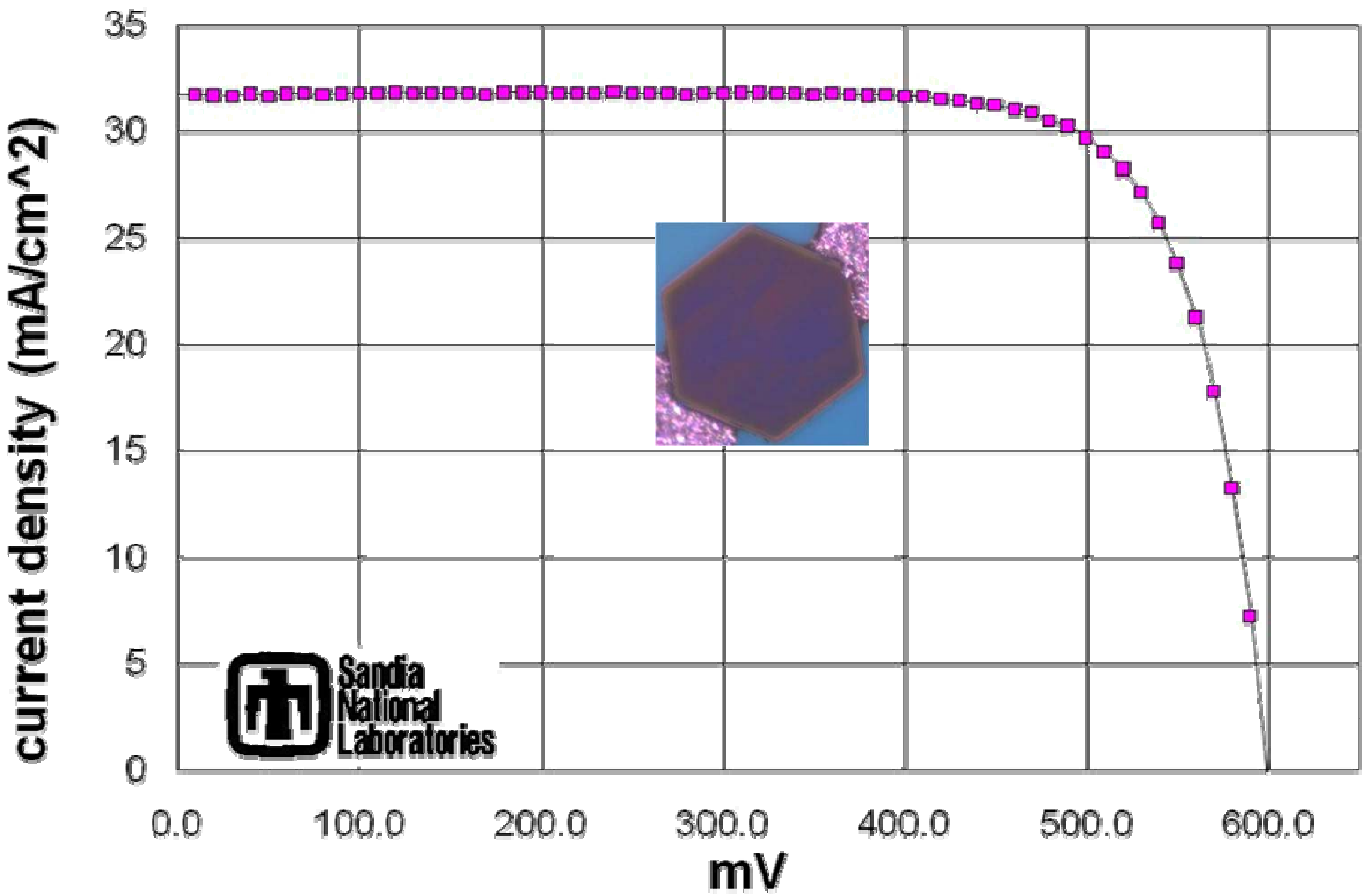
Release from handle wafer using an HF based release etch.



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 15% efficient cells with a 14 micron thick c-Si cell.

Thin c-Si PV Cell Performance



08/20/09 2:18 PM	25.0 °C	0.0003763 cm^2	31.75 J_{sc}(mA/cm^2)	0.784 FF	AM1.5G
LN3_2_250k	1.0000 M'	597.3 V_{oc}(mV)	11.946 I_{sc}(uA)	14.86 % Eff	1.00 Suns
	1.0000 S'	501. V_{mp}(mV)	11.161 I_{mp}(uA)		

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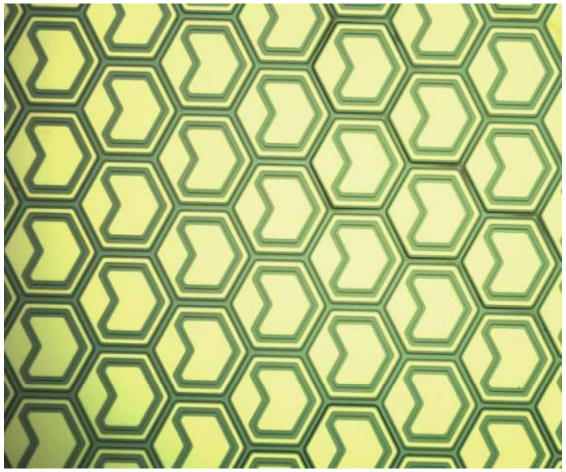
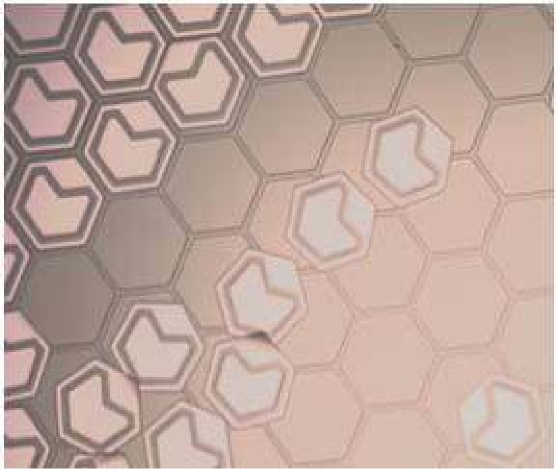
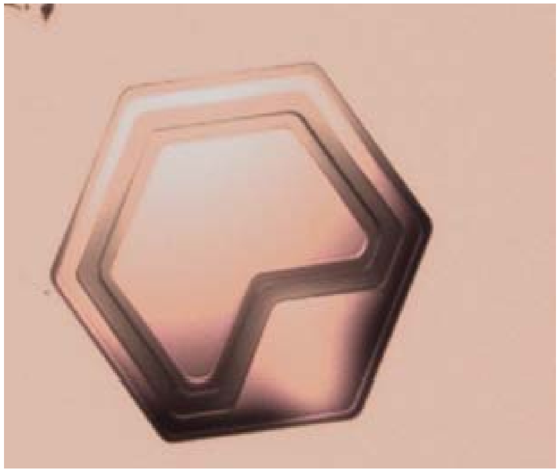
Experimental Results:GaAs



unreleased array of cells

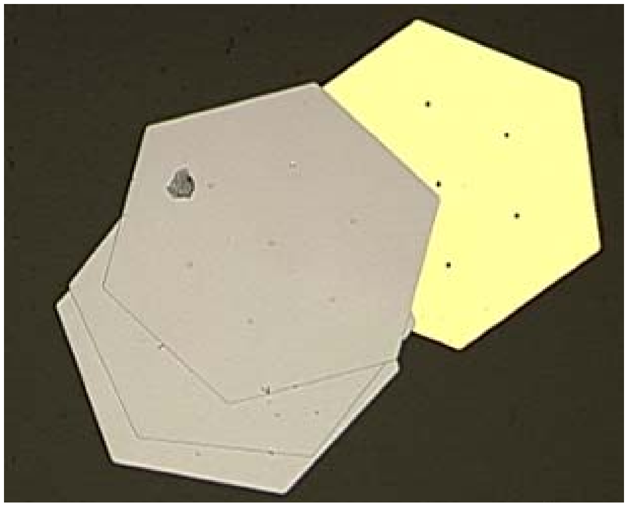


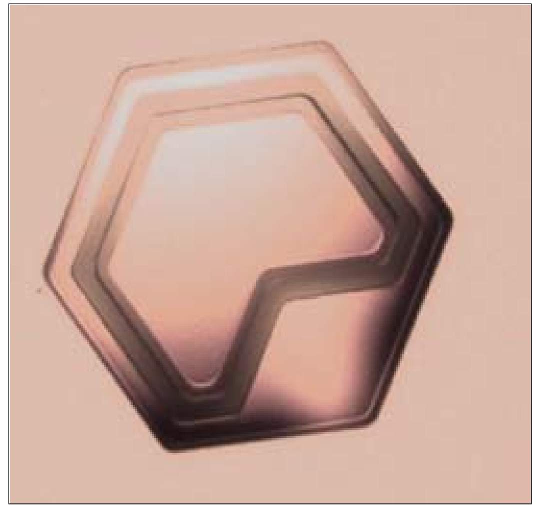
cells in the process of being released

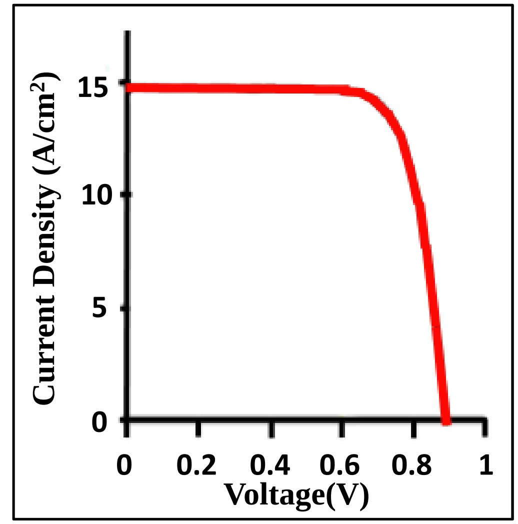


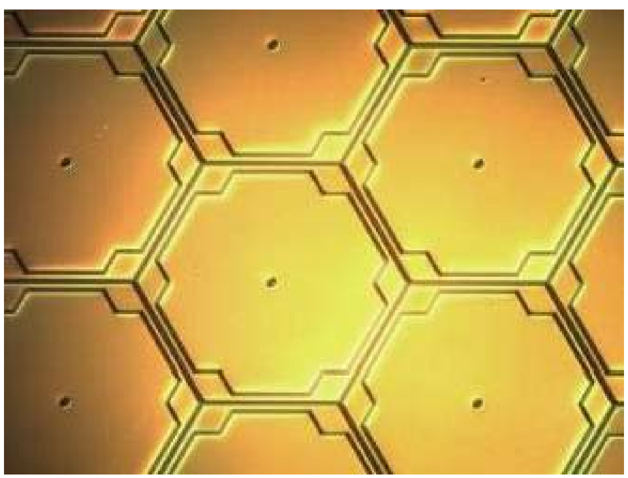
released cell

GaAs (1.43eV) Solar Cells









- We have demonstrated fully back-contacted, 11% efficient, 5 micron thick GaAs PV cells.
- Epitaxial lift-off with AlAs as the sacrificial material is used to create the thin cell.

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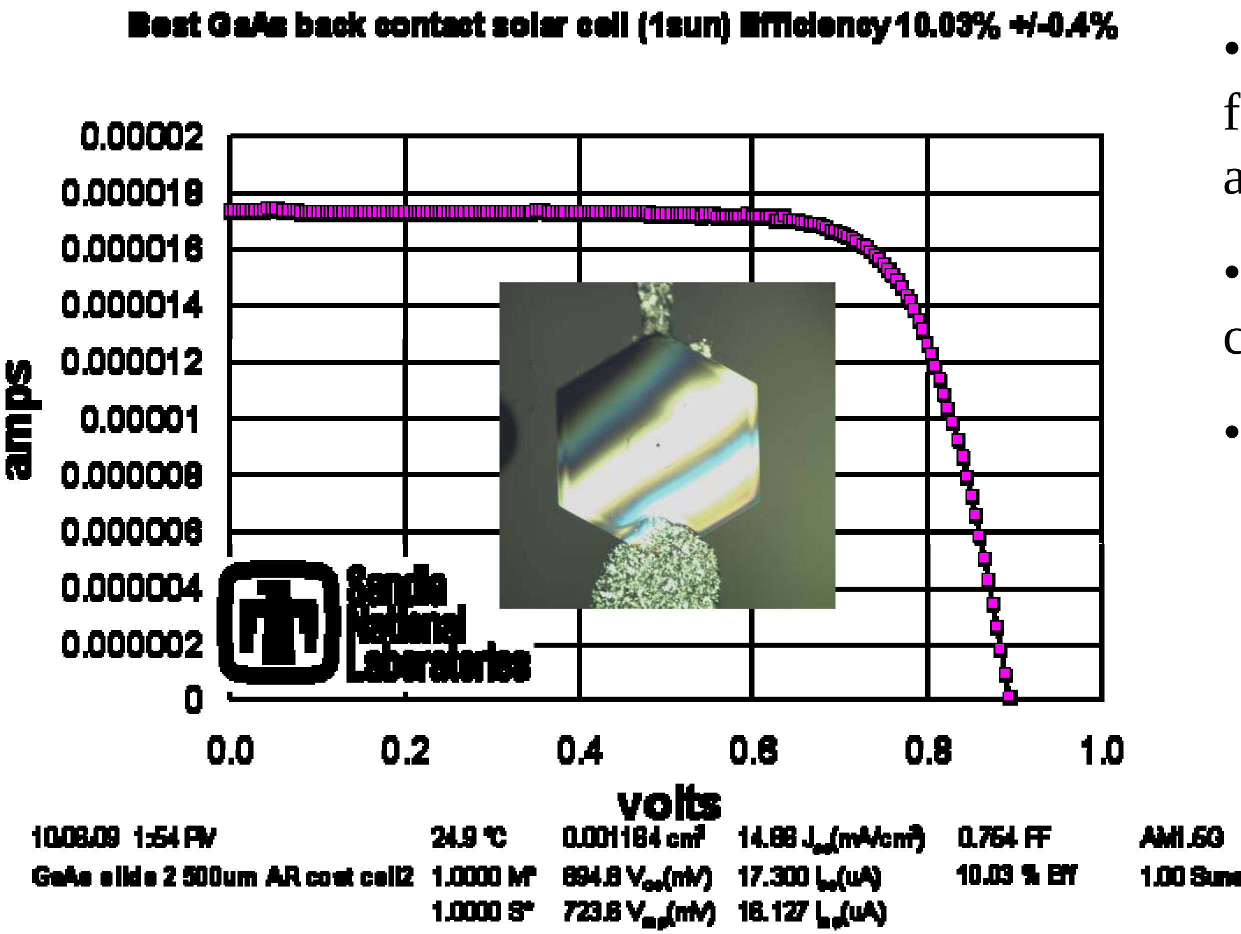
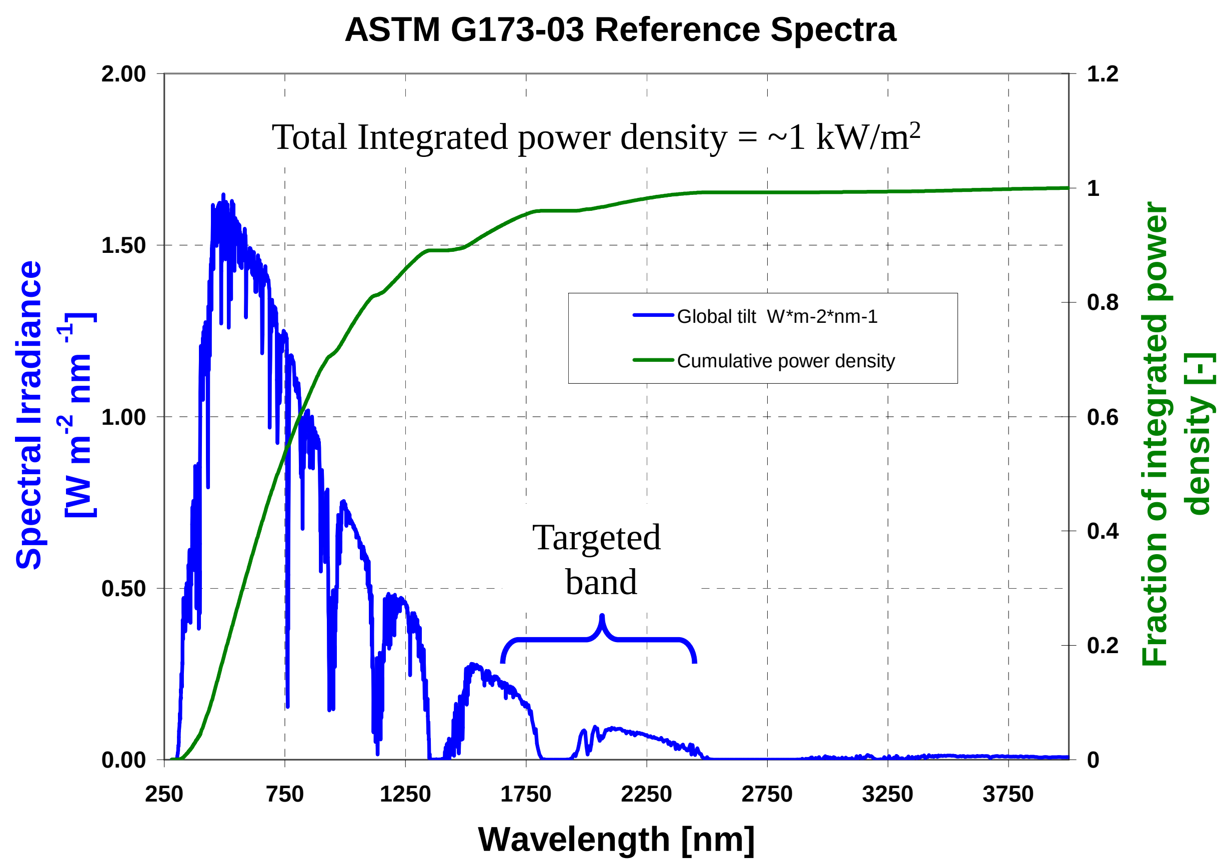
Experimental Results



- Efficiency calculated using full cell area (includes active and inactive area).
- Cell tested without an AR coating
- One-sun illumination

Efficient IR cells are needed to achieve high efficiency

- **Target infrared band**
  - **1.65 to 2.35 μm**
  - **6% of integrated power density**
- **III-V materials can efficiently capture this portion of the spectrum**
- **Use InGaAs cells on InPAs strain-relaxed buffer developed for thermophotovoltaics**



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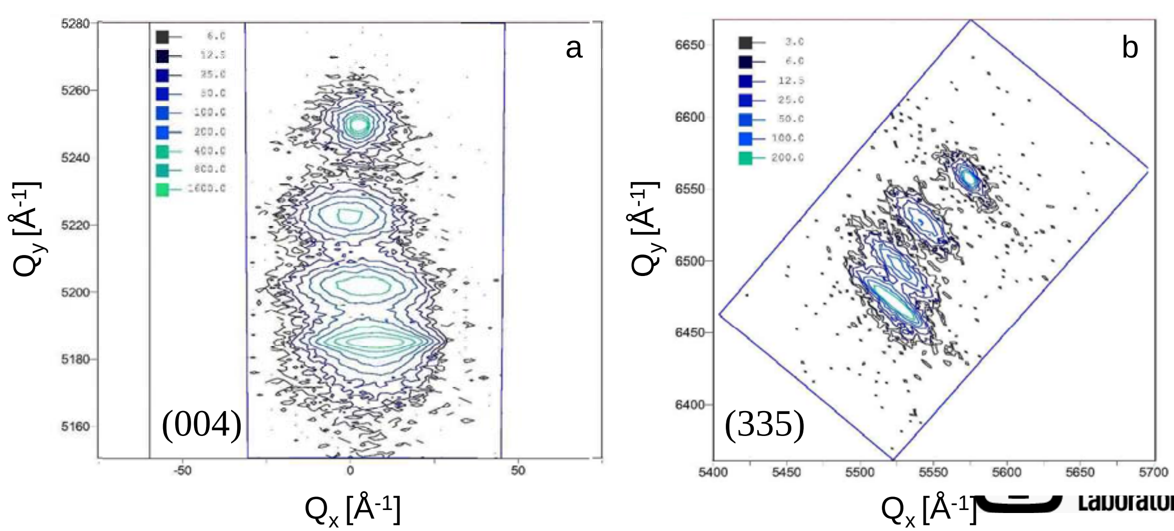
InGaAs (0.6eV) Solar (TPV) Cell Epitaxy

- **Epitaxy performed by MOCVD at 620°C and 70 Torr**
  - **Using methyl substituted metal-organics and hydride sources**
- **Utilized x-ray diffraction reciprocal space mapping to determine buffer lattice constant.**
  - **Experimentally lattice-match InGaAs cell to strain-relaxed InPAs buffer.**

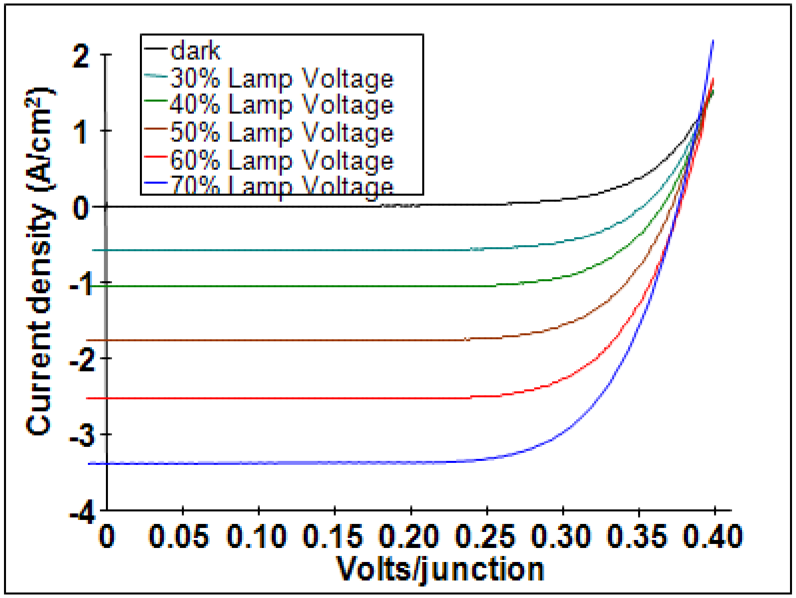
Top Contact	**0.05 µm**	n-InGaAs (10^{19} cm^{-3})
Window	**0.05 µm**	n-InPAs ($2x10^{18}$ cm^{-3})
Emitter	**0.3 µm**	n-InGaAs ($5x10^{18}$ cm^{-3})
Base	**2.5 µm**	p-InGaAs ($8x10^{16}$ cm^{-3})
BSF	**0.05 µm**	p-InPAs (10^{18} cm^{-3})
Tunnel Junction	**0.03 µm**	p-InGaAs (10^{19} cm^{-3})
Tunnel Junction	**0.03 µm**	n-InGaAs (10^{19} cm^{-3})
LCL-3	**1.4 µm**	n-InPAs (10^{19} cm^{-3})
LCL-2	**0.7 µm**	n-InPAs (10^{19} cm^{-3})
LCL-1	**0.7 µm**	n-InPAs (10^{19} cm^{-3})
Nucleation Layer	**0.2 µm**	n-InP (NID)
Semi-Insulating InP (Fe)		

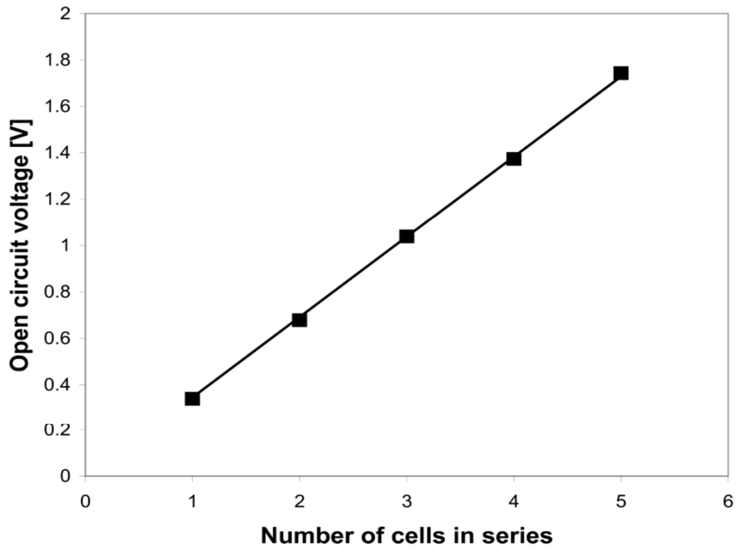
"The development of (InGa)As TPV cells on InP using Strain-relaxed In(PAs) buffers"
J.G. Cederberg, *et al.*,
J. Crystal Growth,
310, (2008), 3453

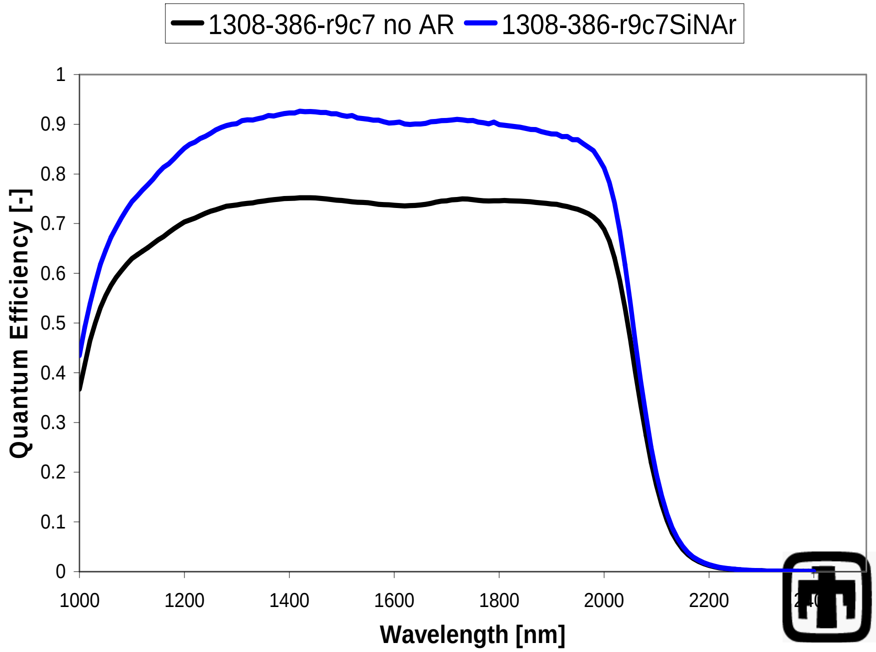


TPV cell performance

- 5-junction cells connected in series
  - Open circuit voltage = 1.9 V
    - 380 mV/junction
  - Fill factor = 71%
- External Quantum Efficiency as high as 90%
- Voltage builds linearly







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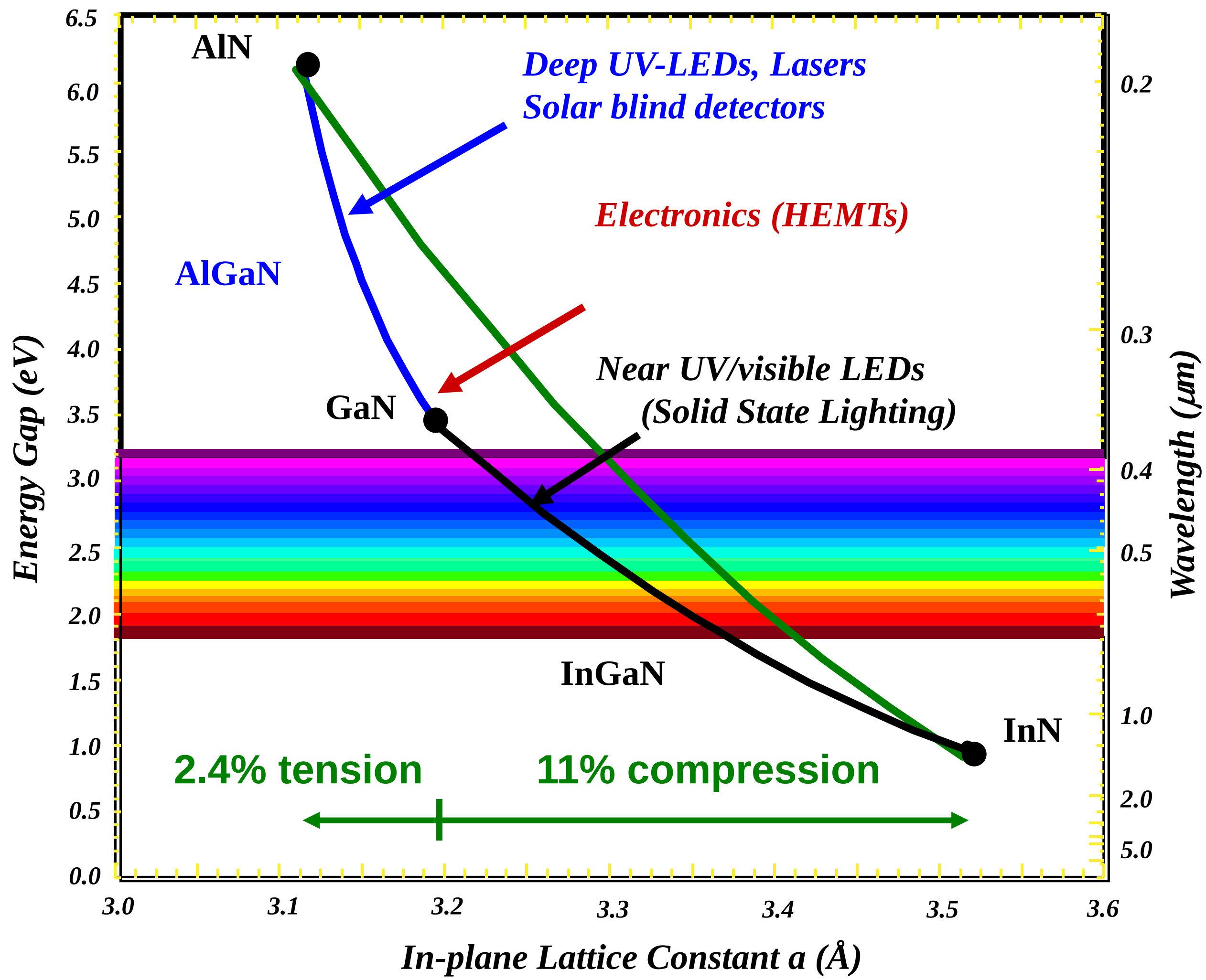
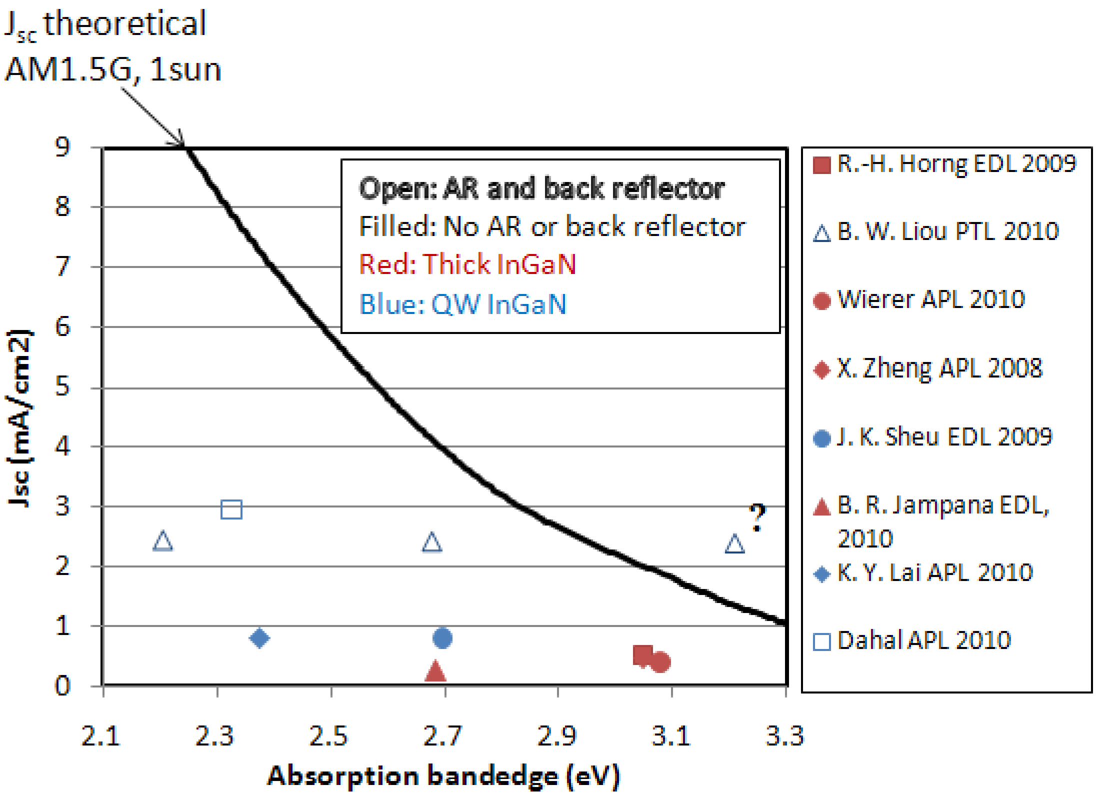
Bandgap versus Lattice Constant for AlGaInN Alloys



InGaN Photovoltaic Performance



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

$\eta_{sc} =$ 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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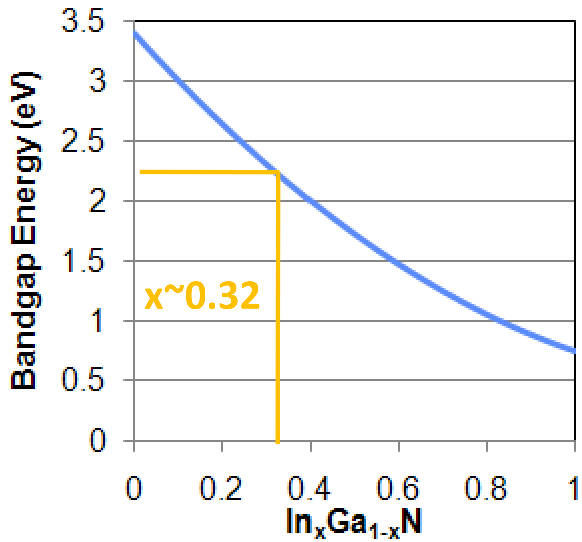
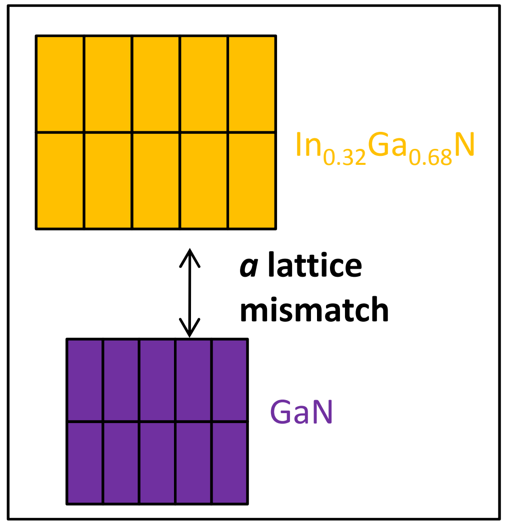
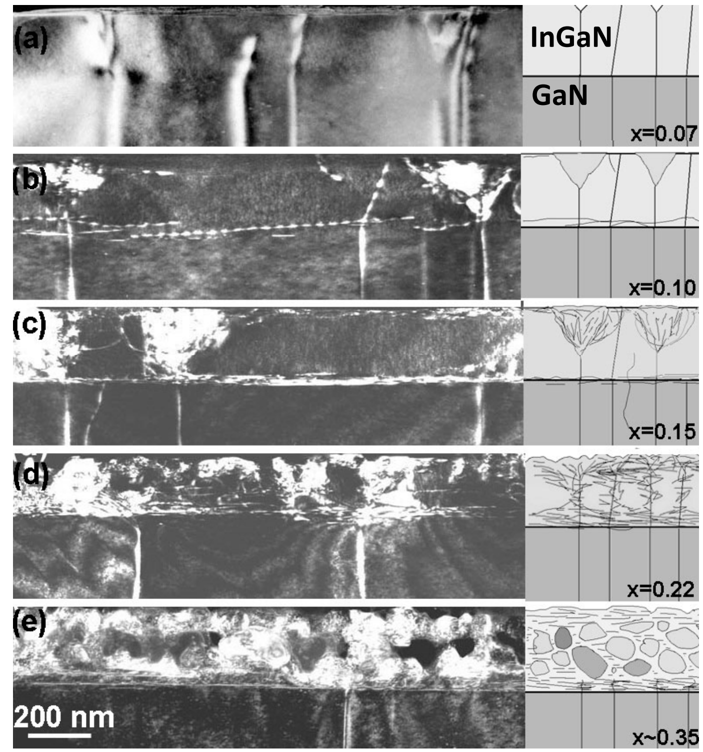
InGaN strained on GaN



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 ≥ 200 nm thick.

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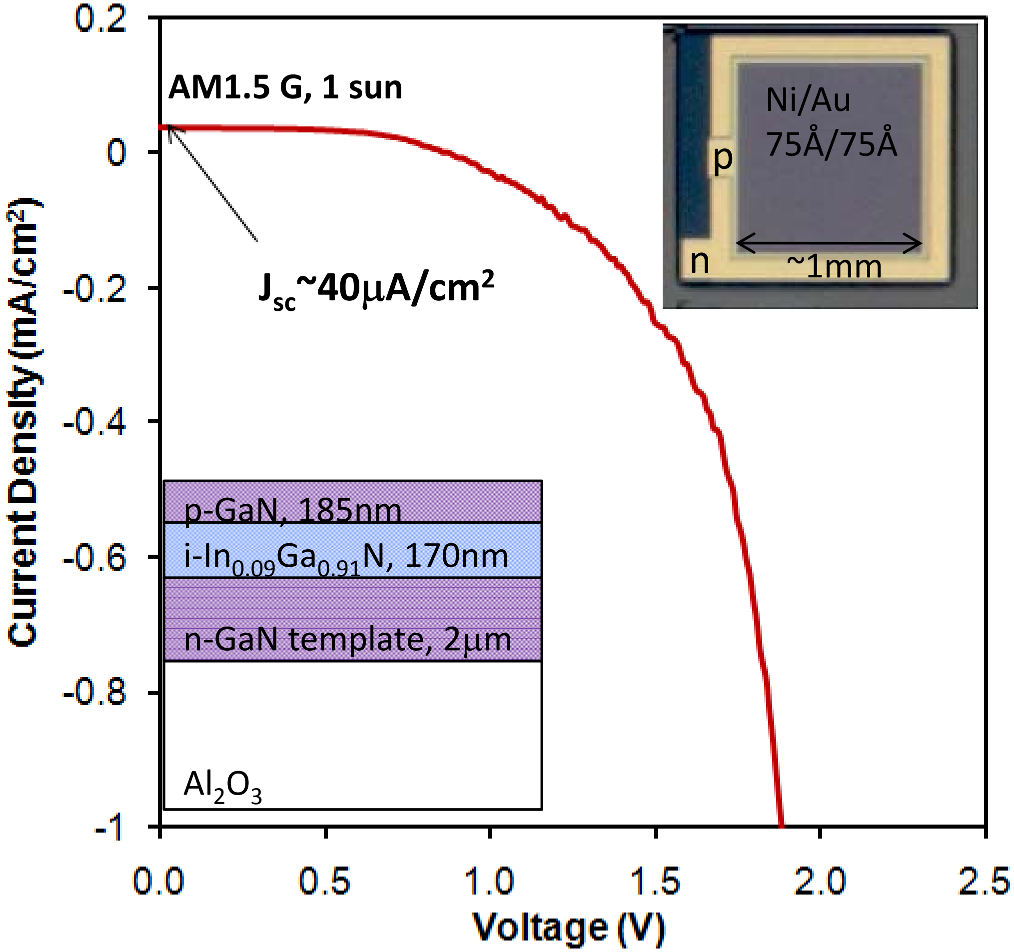
PIN Solar Cells with i-$In_{0.09}Ga_{0.91}N$ layers



- PIN structure consisting of p-GaN/i-InGaN on an (0001)-face n-GaN template layer.
- Performed a simple device fabrication process with square ~1mm^2 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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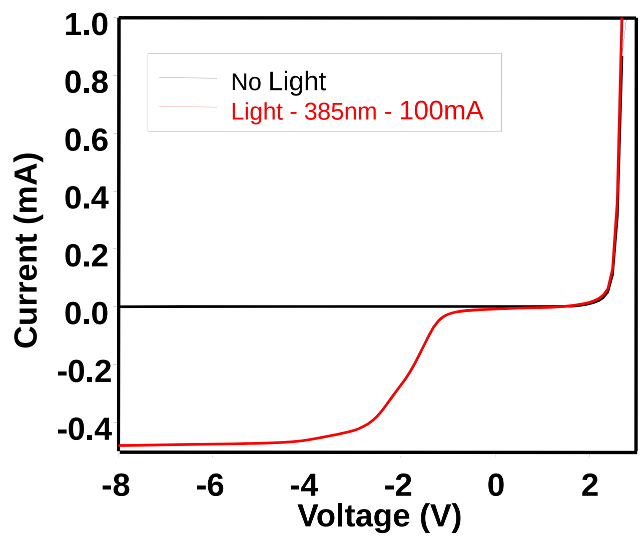
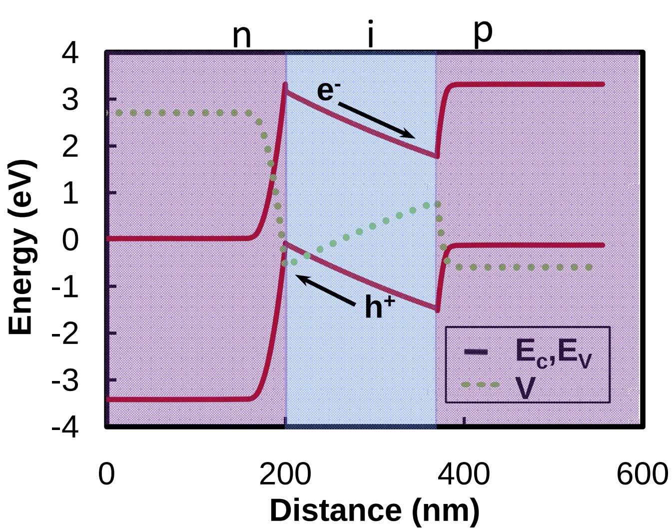
PIN Solar Cells with i-$In_{0.09}Ga_{0.91}N$ layers





- 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: Doping can screen these fields to some degree.

- The reverse bias most likely overcomes this field and allows the carriers to drift in the proper direction and be collected.

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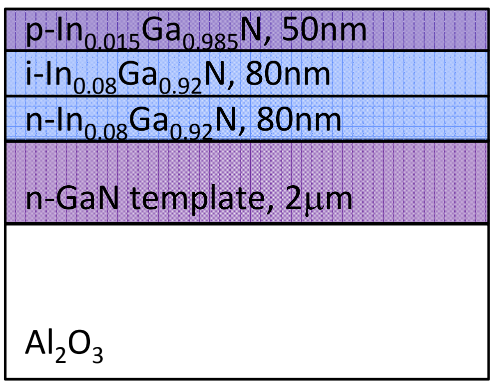
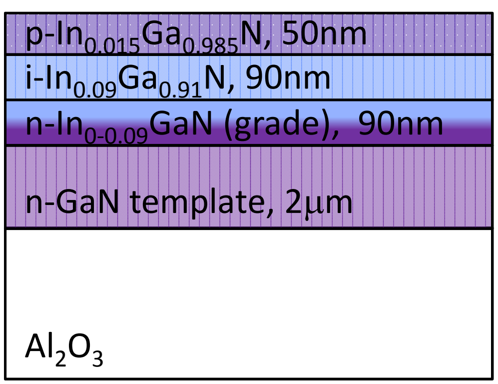
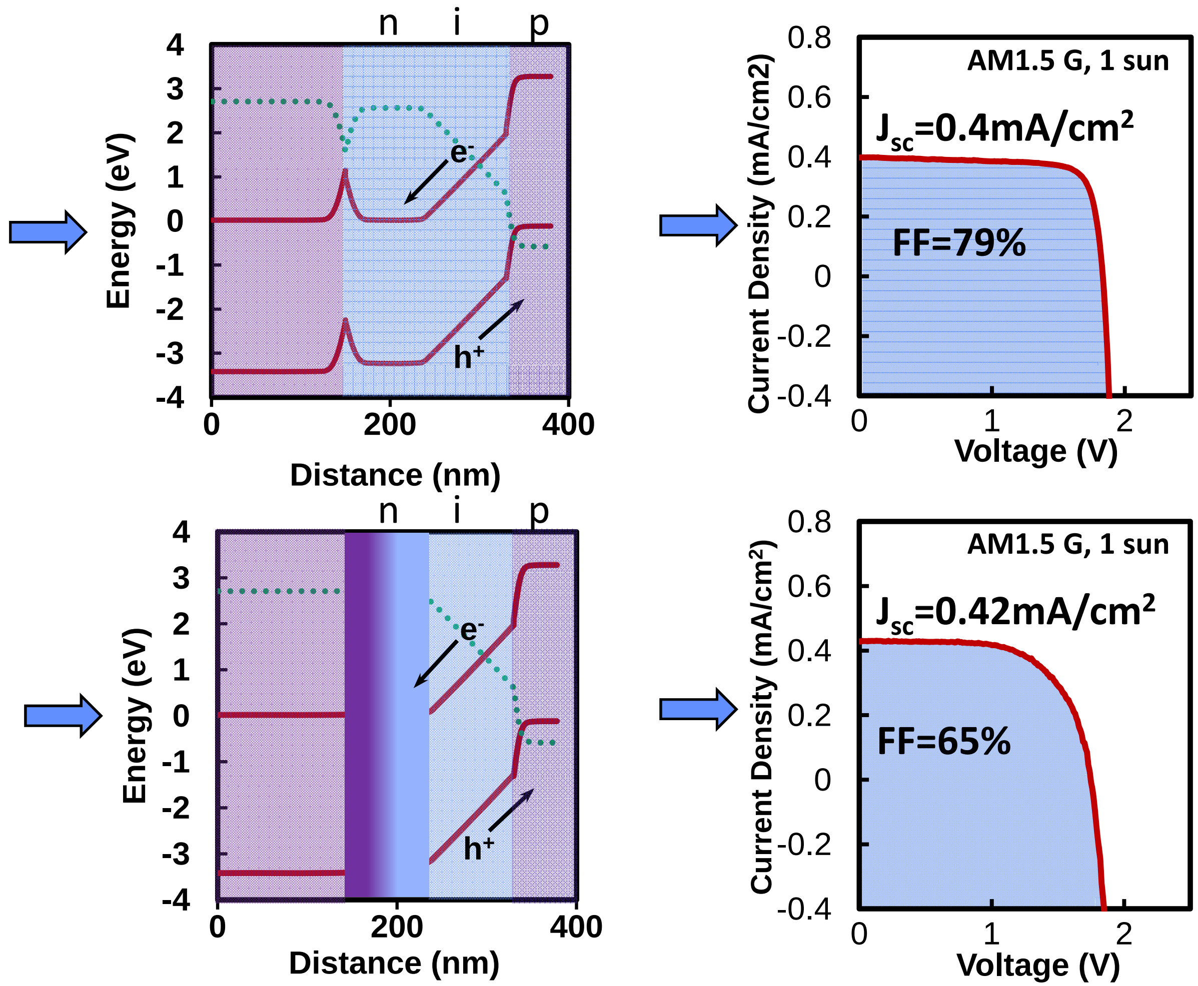
Polarization
Engineered PIN InGaN Solar Cells







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

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

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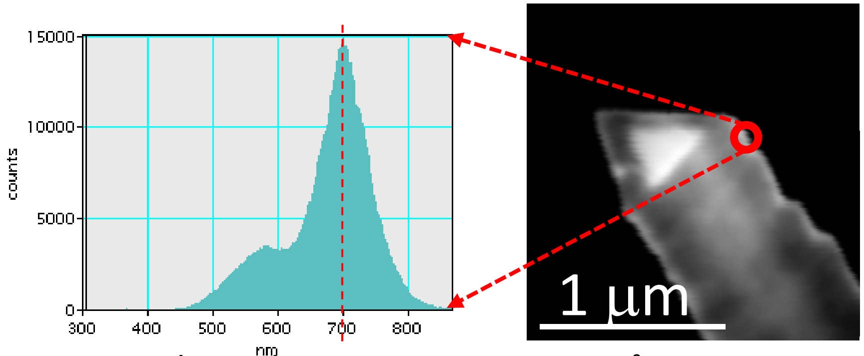
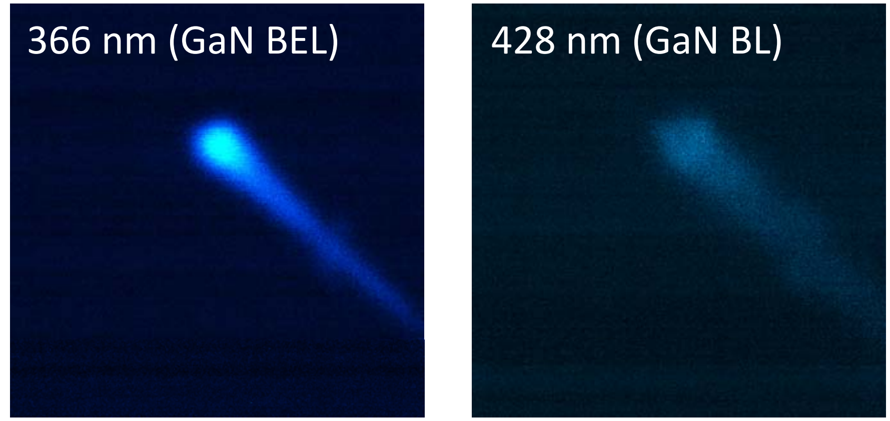
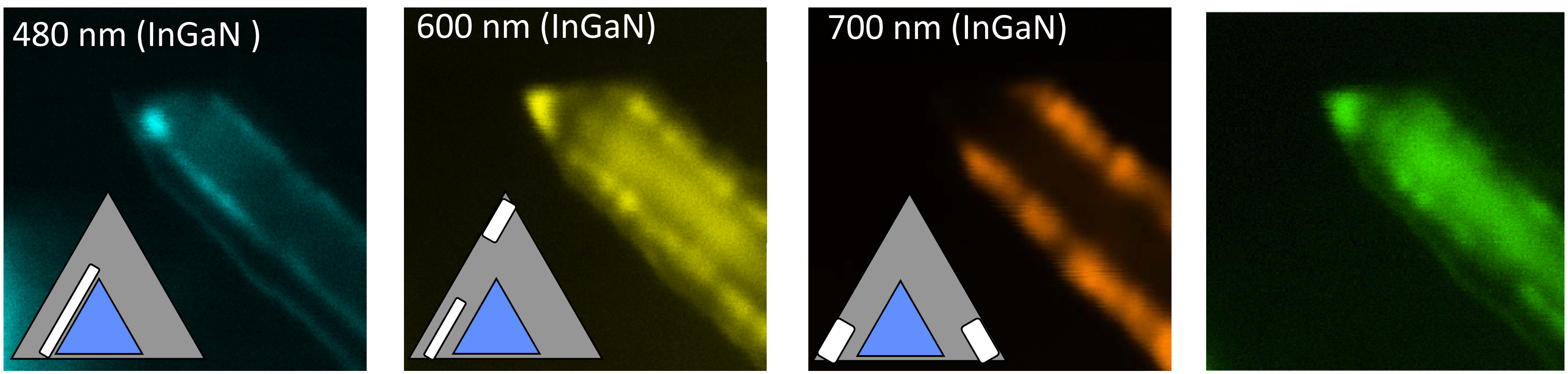
High Indium Incorporation in GaN/InGaN Core/Shell Nanowires



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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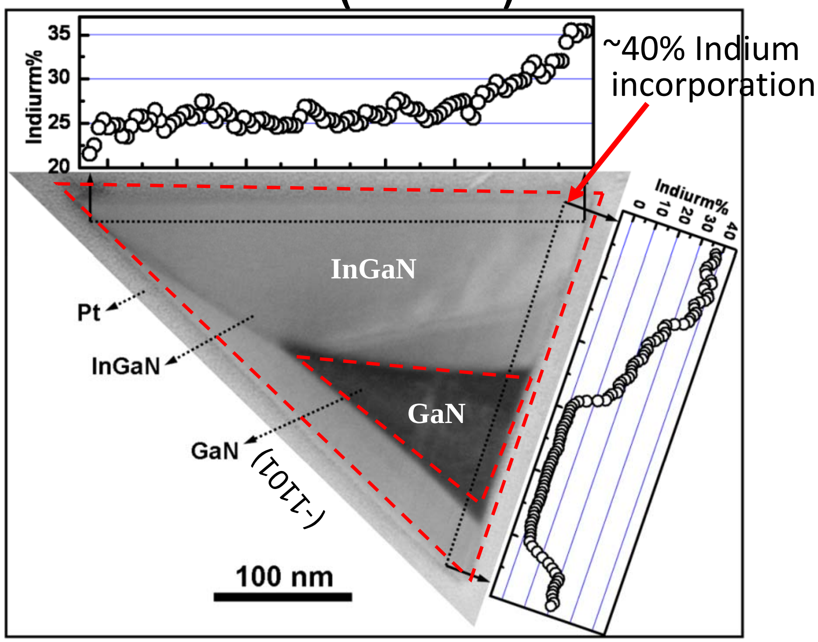
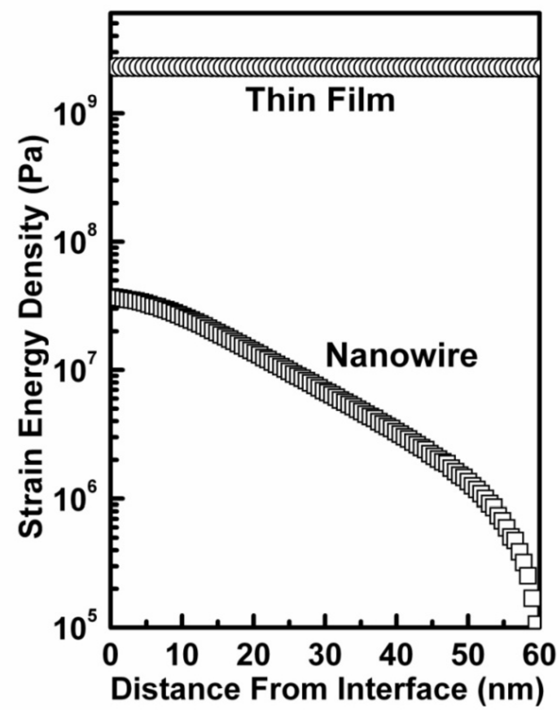
In incorporation in GaN/InGaN core-shell Nanowires

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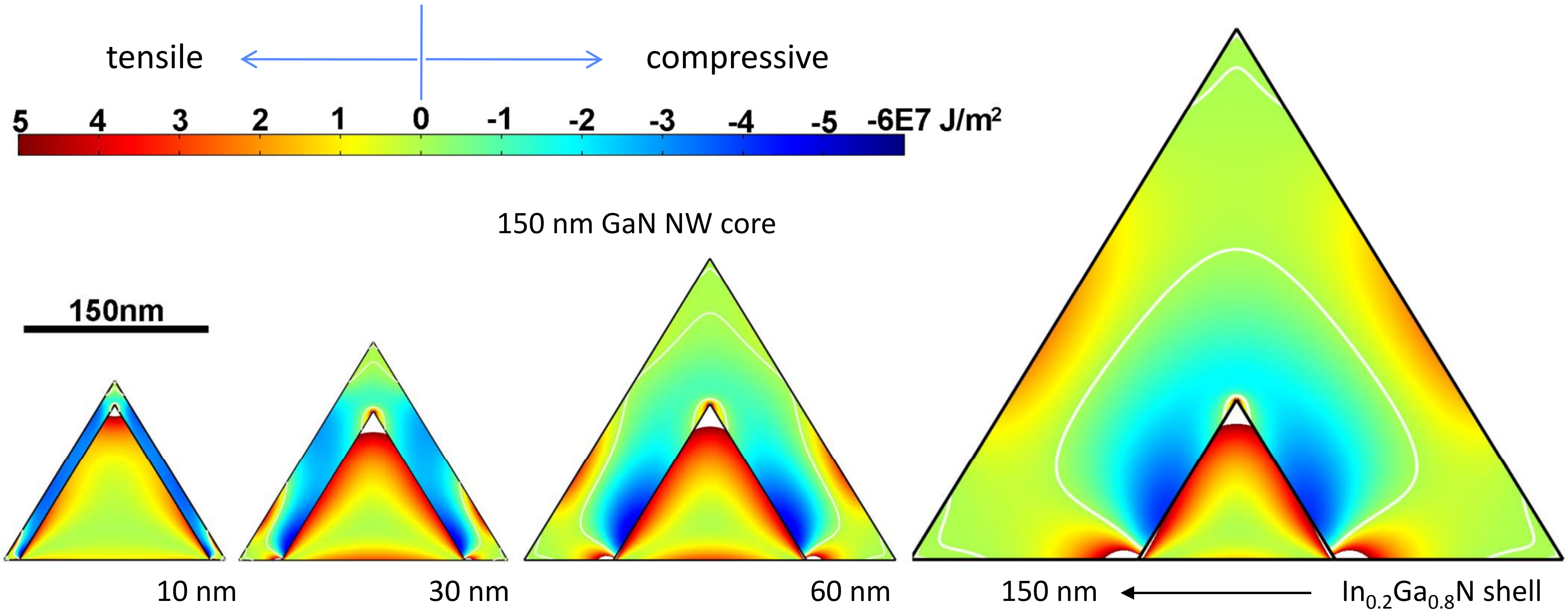
Strain-dependent In incorporation in GaN/InGaN core-shell NWs

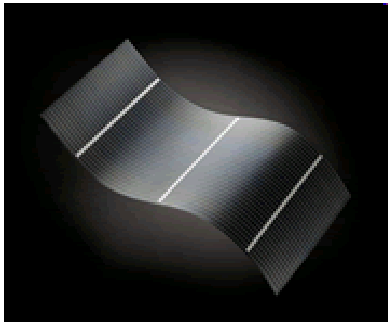


- Finite element models show compressive/tensile strain in GaN core and InGaN shell
- Compressive strain dominates in thinner shells, decreases away from interface and becoming tensile for thicker shells
- Higher In incorporation correlated with lower (compressive) strain regions

Roll-to-Roll Assembled High-Efficiency PV Modules

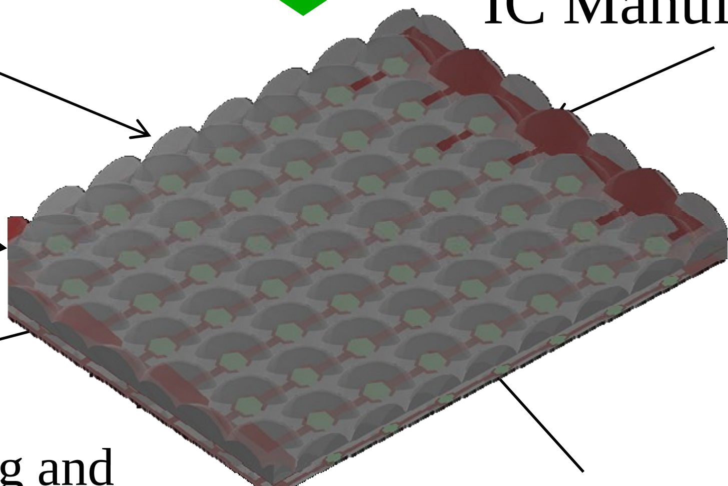
Concentrated PV

Thin-film PV



c-Si PV

Sandia's silicon and III-V fabrication facility



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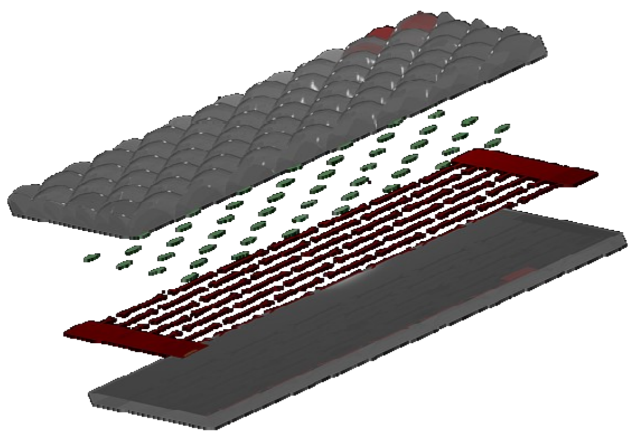
Module Level Scale Benefits

- Modules can be assembled with low-cost automated tools such as pick-and-place tools used for electronics assembly.
- 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.
- Because of the small cell size, modules can be highly flexible.
- Modules that conform to a variety of shapes can be manufactured.
- Building Integrated PV (BIPV) panels of a variety of sorts are possible, reducing material costs and installation costs.
- 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.



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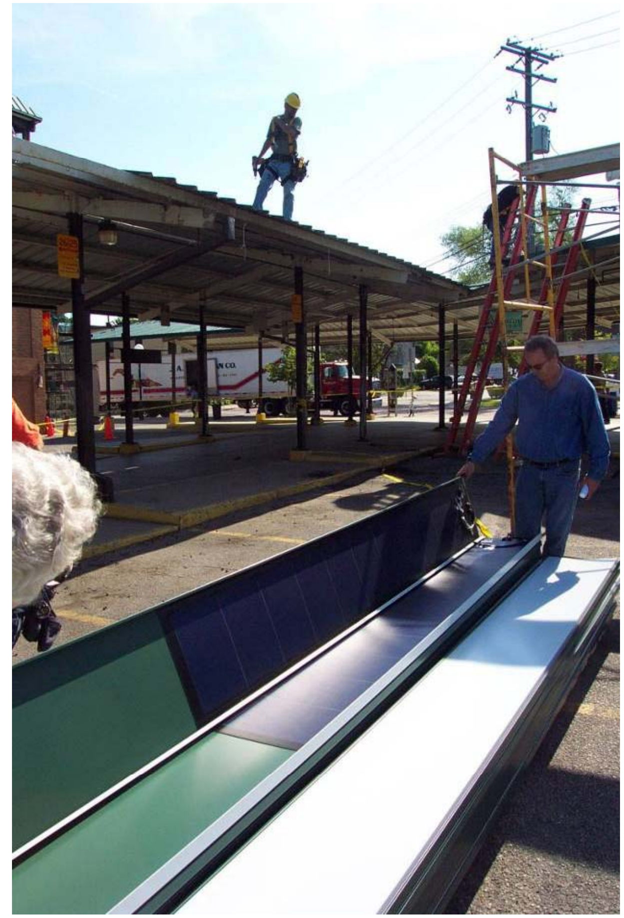
System Level Scale Benefits

- 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
- BIPV modules reduces installation labor
- 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, high-bandwidth tracking; reducing tracking cost and complexity.
- High-bandwidth tracking can account for wind and other environmental vibrations.
- System designs are possible that provide improved shading performance of modules/systems as compared to conventional systems.



UNI-SOLAR building integrated a-Si PV metal roof panels being installed.

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Conclusion

- Sandia is working on a high–efficiency mechanically stacked multijunction solar cell with InGaN as the highest energy cell.
- We have demonstrated Si, GaAs, InGaAs, and InGaN photovoltaic cells as part of this project
- Both Si and GaAs cells have been prepared that are less than 0.1 mm^2 (Solar Glitter)
- InGaN nanowires are being explored for use in solar cells
- Refractive optics have been developed for small size cells
- Si manufacturing techniques are being used to demonstrate concept

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Power at the Point of Use:
High-efficiency Flexible/Conformal
Photovoltaic Modules
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