Inverted GaInP/GaAs/InGaAs triple-junction solar cells with low-stress metamorphic bottom junctions

John F. Geisz, Sarah R. Kurtz, M.W. Wanlass, J.S. Ward, A. Duda, D.J. Friedman, J.M. Olson, W.E. McMahon, T.E. Moriarty, J.T. Kiehl, M.J. Romero, A.G. Norman, K.M. Jones

National Renewable Energy Laboratory

Golden, CO USA

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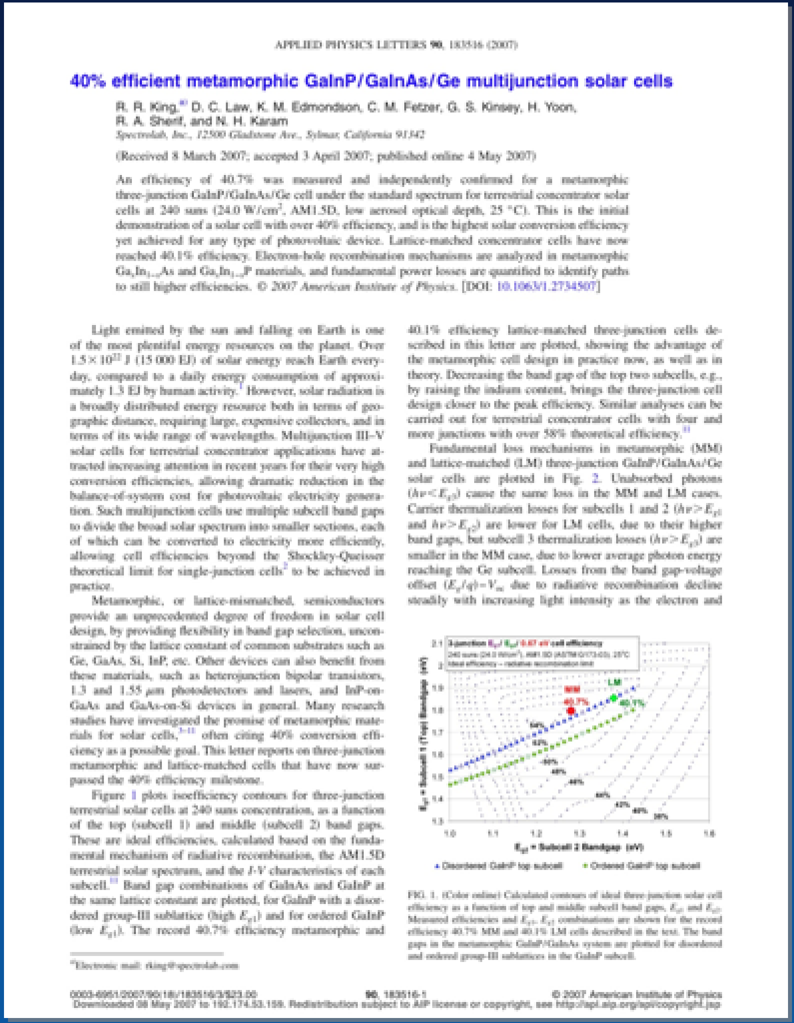
Outline

- Ge-based high-efficiency solar cells
- Theoretical basis for change
- Ge-free, inverted devices
- Strain control for metamorphic junctions
- High efficiency results
- Next step....”Band gaps without borders”

Spectrolab's World Record Results using Ge Bottom Junction



APPLIED PHYSICS LETTERS **90**, 183516 (2007)

40% efficient metamorphic GaInP/GaInAs/Ge multijunction solar cells

R. R. King,[a] D. C. Law, K. M. Edmondson, C. M. Fetzer, G. S. Kinsey, H. Yoon,
R. A. Sherif, and N. H. Karam
Spectrolab, Inc., 12500 Gladstone Ave., Sylmar, California 91342

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An efficiency of 40.7% was measured and independently confirmed for a metamorphic three-junction GaInP/GaInAs/Ge cell under the standard spectrum for terrestrial concentrator solar cells at 240 suns (24.0 W/cm², AM1.5D, low aerosol optical depth, 25 °C). This is the initial demonstration of a solar cell with over 40% efficiency, and is the highest solar conversion efficiency yet achieved for any type of photovoltaic device. Lattice-matched concentrator cells have now reached 40.1% efficiency. Electron-hole recombination mechanisms are analyzed in metamorphic $Ga_xIn_{1-x}As$ and $Ga_xIn_{1-x}P$ materials, and fundamental power losses are quantified to identify paths to still higher efficiencies. © 2007 *American Institute of Physics*. [DOI: 10.1063/1.2734507]

Light emitted by the sun and falling on Earth is one of the most plentiful energy resources on the planet. Over 1.5×10^{22} J (15 000 EJ) of solar energy reach Earth every-day, compared to a daily energy consumption of approximately 1.3 EJ by human activity.[1] However, solar radiation is a broadly distributed energy resource both in terms of geographic distance, requiring large, expensive collectors, and in terms of its wide range of wavelengths. Multijunction III–V solar cells for terrestrial concentrator applications have attracted increasing attention in recent years for their very high conversion efficiencies, allowing dramatic reduction in the balance-of-system cost for photovoltaic electricity generation. Such multijunction cells use multiple subcell band gaps to divide the broad solar spectrum into smaller sections, each of which can be converted to electricity more efficiently, allowing cell efficiencies beyond the Shockley-Queisser theoretical limit for single-junction cells[2] to be achieved in practice.

Metamorphic, or lattice-mismatched, semiconductors provide an unprecedented degree of freedom in solar cell design, by providing flexibility in band gap selection, unconstrained by the lattice constant of common substrates such as Ge, GaAs, Si, InP, etc. Other devices can also benefit from these materials, such as heterojunction bipolar transistors, 1.3 and 1.55 μm photodetectors and lasers, and InP-on-GaAs and GaAs-on-Si devices in general. Many research studies have investigated the promise of metamorphic materials for solar cells,[3–11] often citing 40% conversion efficiency as a possible goal. This letter reports on three-junction metamorphic and lattice-matched cells that have now surpassed the 40% efficiency milestone.

Figure 1 plots isoefficiency contours for three-junction terrestrial solar cells at 240 suns concentration, as a function of the top (subcell 1) and middle (subcell 2) band gaps. These are ideal efficiencies, calculated based on the fundamental mechanism of radiative recombination, the AM1.5D terrestrial solar spectrum, and the *I-V* characteristics of each subcell.[11] Band gap combinations of GaInAs and GaInP at the same lattice constant are plotted, for GaInP with a disordered group-III sublattice (high E_{g1}) and for ordered GaInP (low E_{g1}). The record 40.7% efficiency metamorphic and 40.1% efficiency lattice-matched three-junction cells described in this letter are plotted, showing the advantage of the metamorphic cell design in practice now, as well as in theory. Decreasing the band gap of the top two subcells, e.g., by raising the indium content, brings the three-junction cell design closer to the peak efficiency. Similar analyses can be carried out for terrestrial concentrator cells with four and more junctions with over 58% theoretical efficiency.[11]

Fundamental loss mechanisms in metamorphic (MM) and lattice-matched (LM) three-junction GaInP/GaInAs/Ge solar cells are plotted in Fig. 2. Unabsorbed photons ($h\nu < E_{g3}$) cause the same loss in the MM and LM cases. Carrier thermalization losses for subcells 1 and 2 ($h\nu > E_{g1}$ and $h\nu > E_{g2}$) are lower for LM cells, due to their higher band gaps, but subcell 3 thermalization losses ($h\nu > E_{g3}$) are smaller in the MM case, due to lower average photon energy reaching the Ge subcell. Losses from the band gap-voltage offset $(E_g/q) - V_{oc}$ due to radiative recombination decline steadily with increasing light intensity as the electron and

FIG. 1. (Color online) Calculated contours of ideal three-junction solar cell efficiency as a function of top and middle subcell band gaps, E_{g1} and E_{g2}. Measured efficiencies and E_{g1}, E_{g2} combinations are shown for the record efficiency 40.7% MM and 40.1% LM cells described in the text. The band gaps in the metamorphic GaInP/GaInAs system are plotted for disordered and ordered group-III sublattices in the GaInP subcell.

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[a] Electronic mail: rking@spectrolab.com

0003-6951/2007/90(18)/183516/3/$23.00

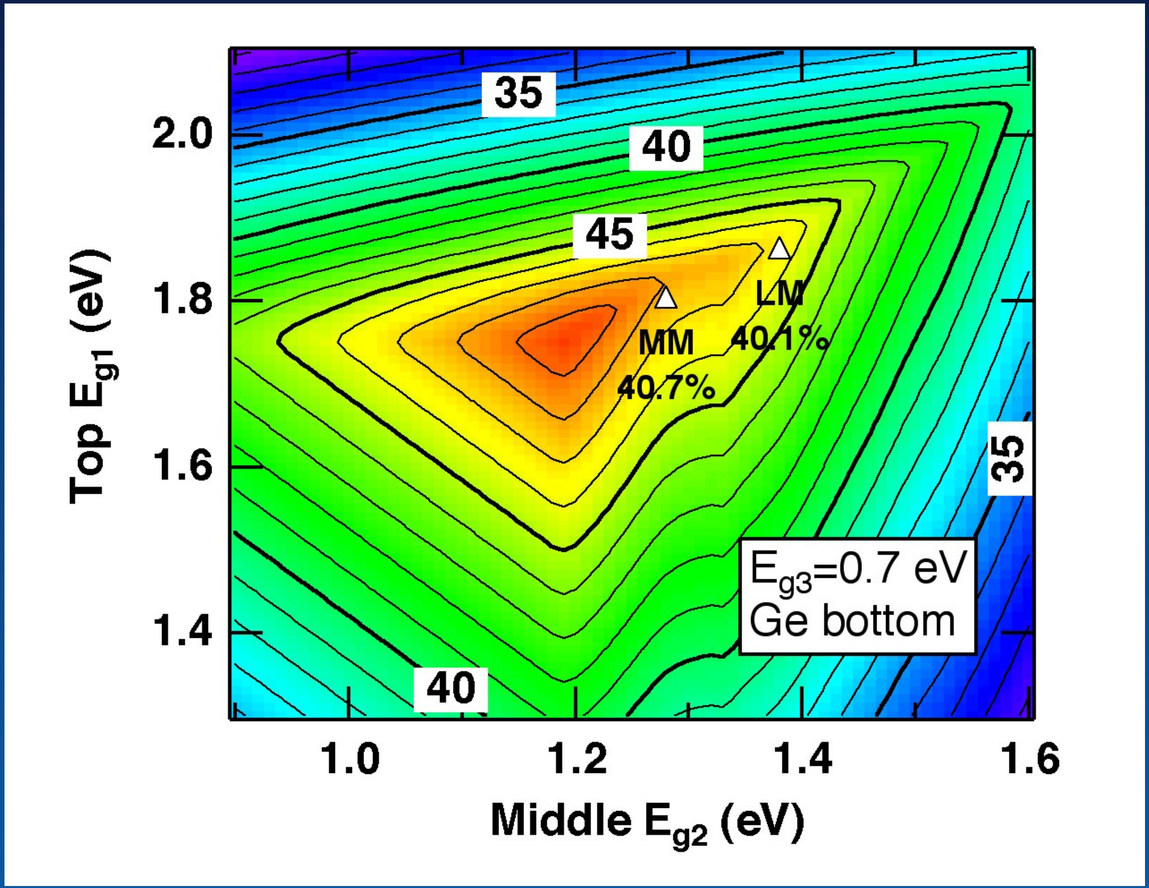
- Multijunction III-V solar cells under concentration
- Lattice-matched to Ge 40.1% efficiency (135X)
- Lattice-mismatched (metamorphic) on Ge 40.7% efficiency (240X)

Fixed bottom junction - Ge

E_{g1}

E_{g2}

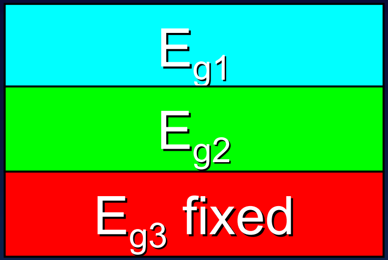
E_{g3} fixed



- Theoretical efficiency of series-connected 3 junction solar cells
- Isoefficiency plot shows highest theoretical efficiency on Ge far from lattice-matched
- Ge produces too much current, too little voltage
- LM 40.1% / 46.5%
- MM 40.7% / 47.7%

Calculated for 500X @ 300K AM1.5D

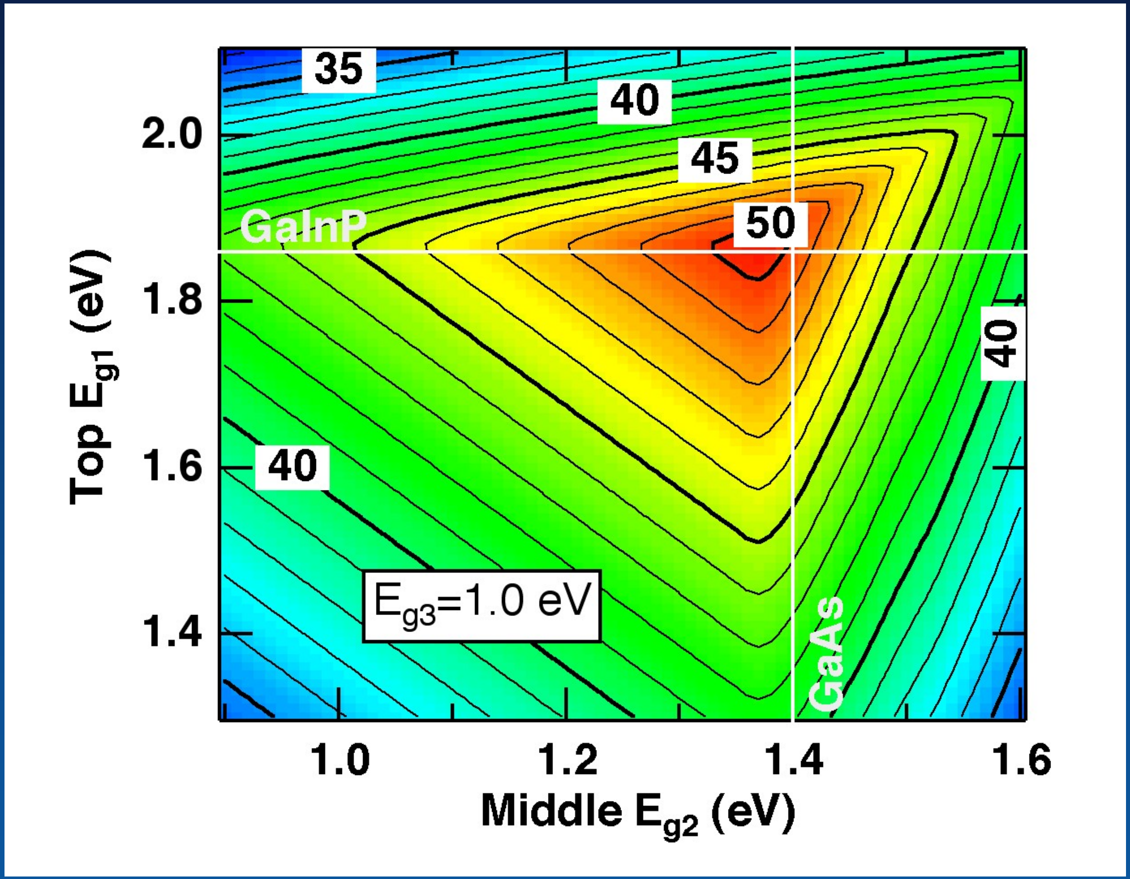
Fixed bottom junction - 1 eV



E_{g1}

E_{g2}

E_{g3} fixed



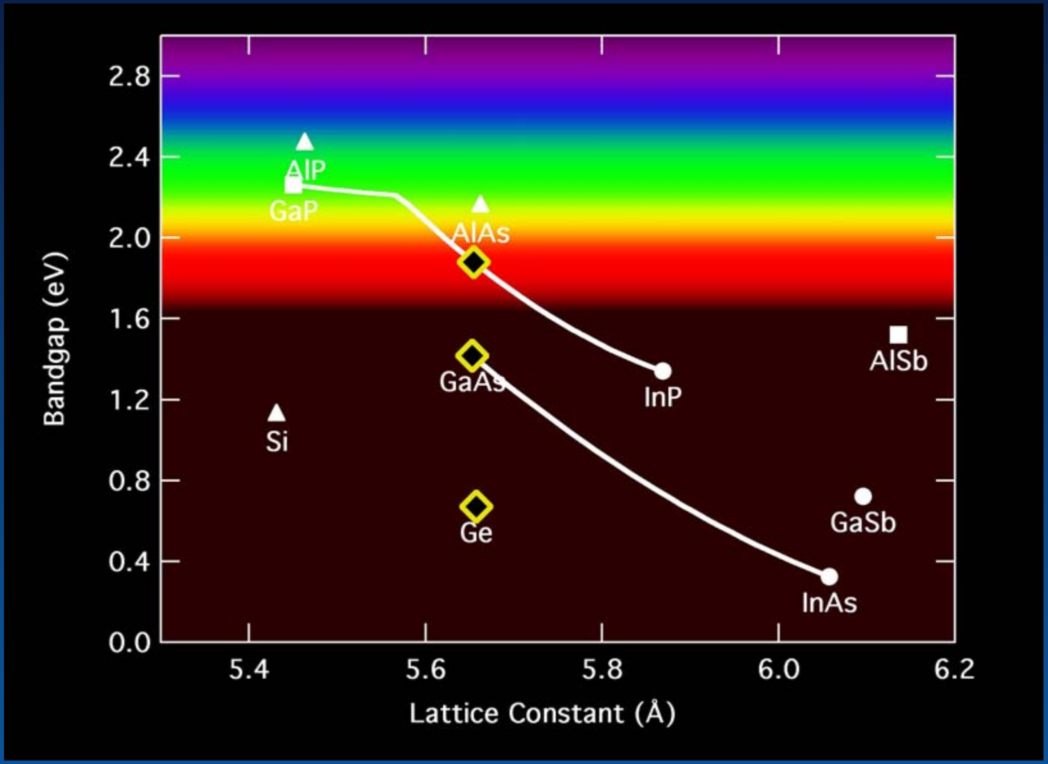
- Higher theoretical efficiency available near lattice-matched top junctions using 1.0 eV bottom junction

Calculated for 500X @ 300K AM1.5D

Constraints of Real Materials

Dislocations from lattice-mismatched materials degrade performance

- Current 3-junction solar cell is lattice-matched

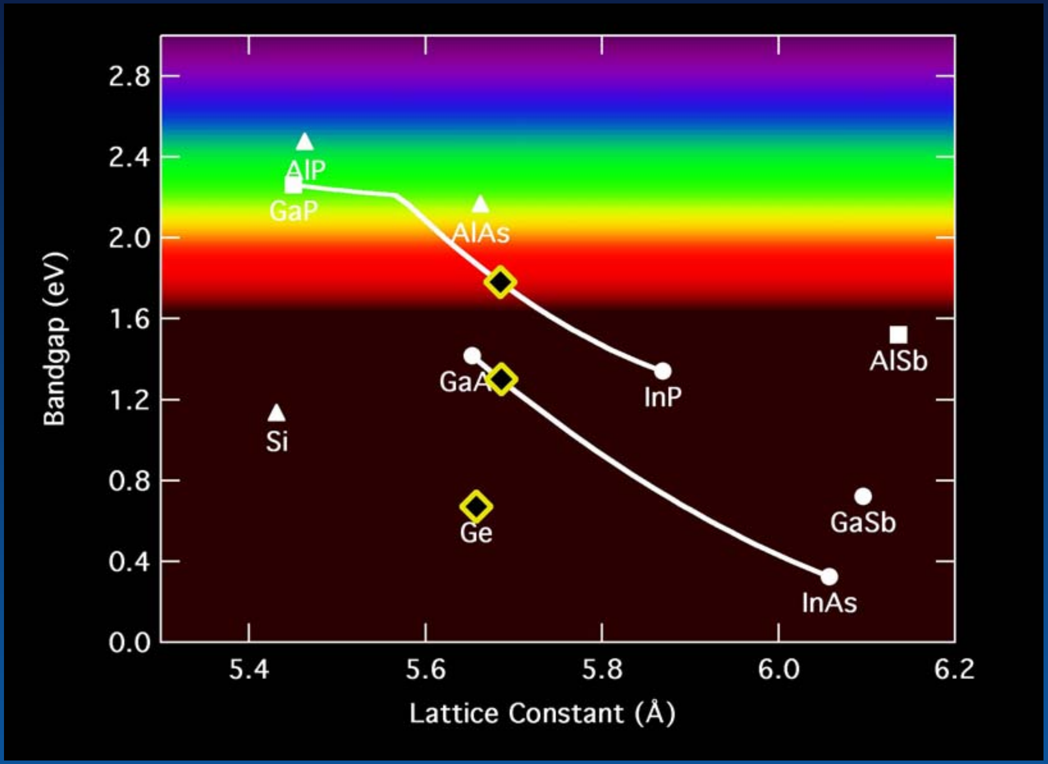


Standard Lattice Matched

Constraints of Real Materials

Dislocations from lattice-mismatched materials degrade performance

- Current 3-junction solar cell is lattice-matched
- Spectrolab's metamorphic design is slightly mismatched (0.5%)

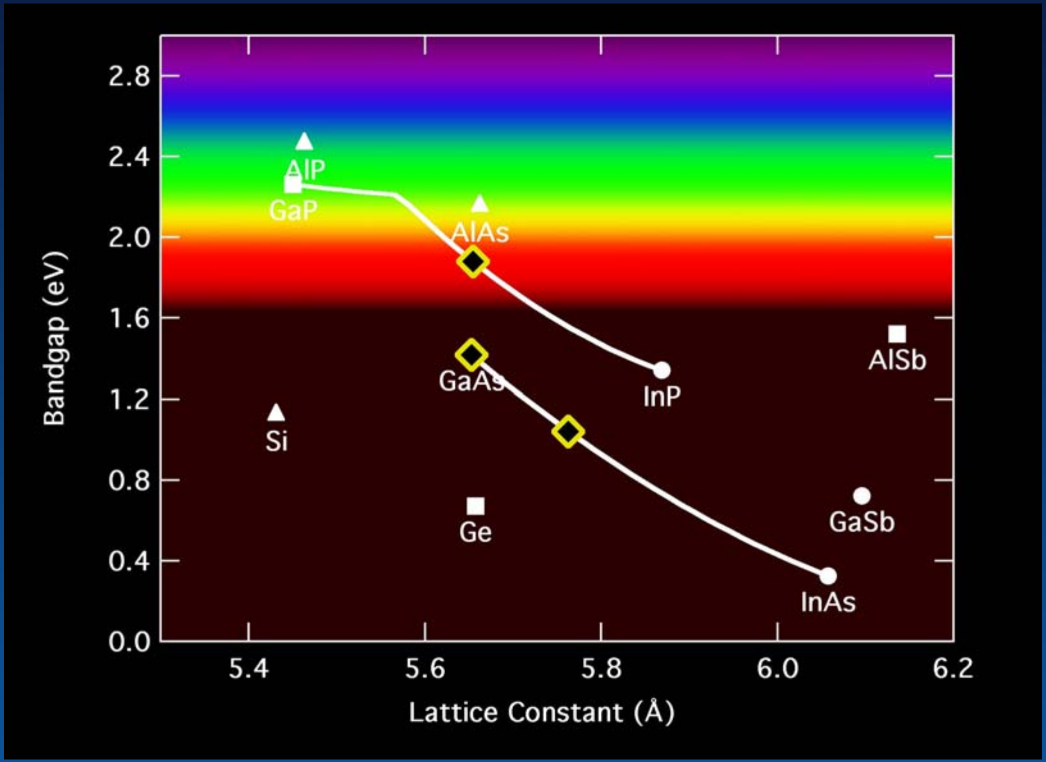


Spectrolab's Metamorphic

Constraints of Real Materials

Dislocations from lattice-mismatched materials degrade performance

- Current 3-junction solar cell is lattice-matched
- Spectrolab's metamorphic design is slightly mismatched (0.5%)
- Our design has a highly mismatched (1.9%) bottom junction

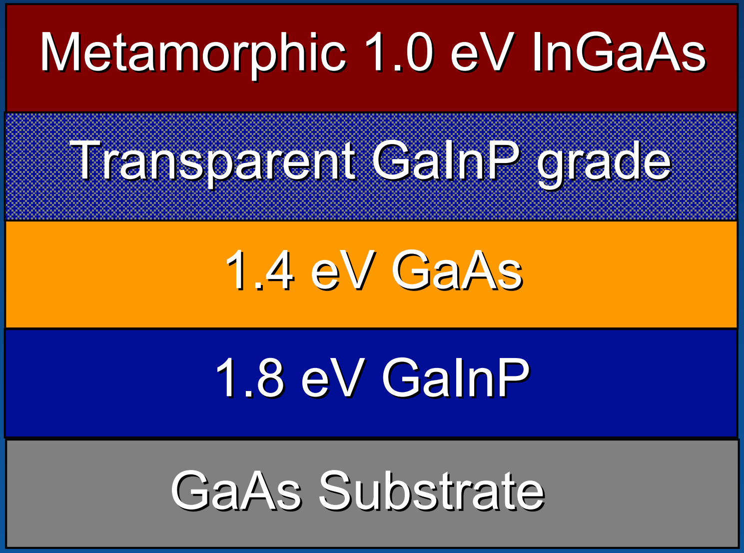


NREL's Inverted Design

Inverted Design

- OMVPE growth on GaAs
- Lattice-matched grown first
- Metamorphic grown last
- Mounted on Si or glass
- Substrate removed

- Descriptive names
  - Handle mounted
  - Inverted metamorphic (Emcore)
  - Flip-chip (LEDs)



Metamorphic 1.0 eV InGaAs

Transparent GaInP grade

1.4 eV GaAs

1.8 eV GaInP

GaAs Substrate

Inverted Design

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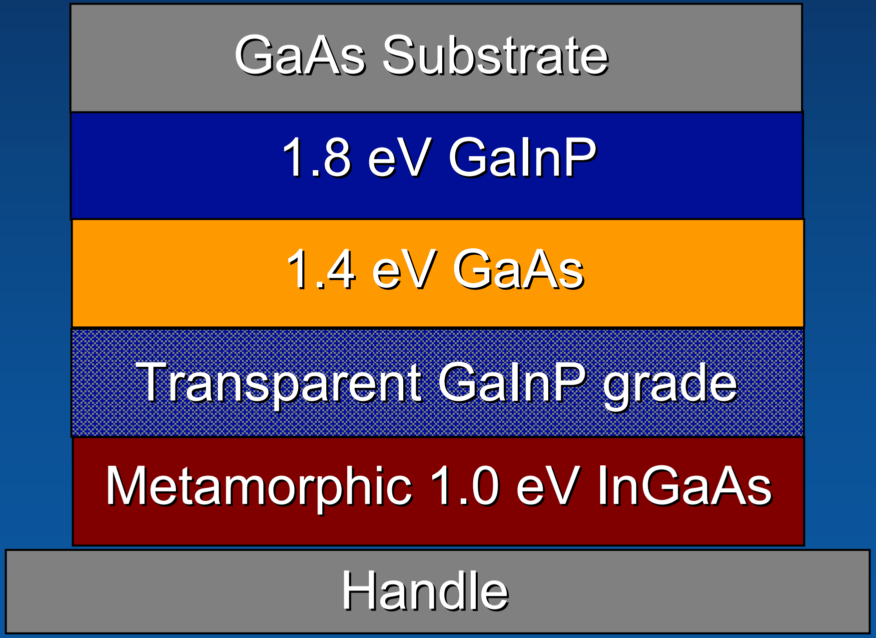

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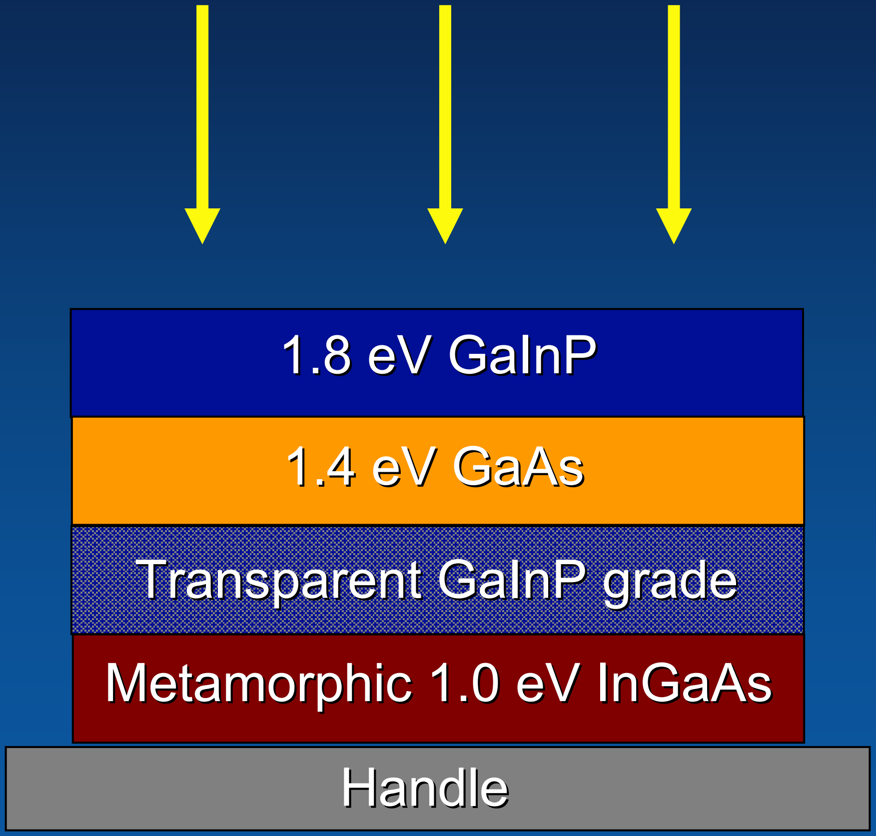

Advantages of Inverted Design

- Monolithic - one growth process
- Thin device – handle properties dominate
  - weight
  - heat removal
  - mechanical robustness
  - flexible
  - cheap (reuse substrate)
- Efficient
  - more band gap choices
  - top junction (most power producing) is lattice-matched
- Requires good metamorphic growth
  - minimize defects
  - transparent buffers

More Details of the Structure

APPLIED PHYSICS LETTERS **91**, 023502 (2007)

High-efficiency GaInP/GaAs/InGaAs triple-junction solar cells grown inverted with a metamorphic bottom junction

J. F. Geisz,[a] Sarah Kurtz, M. W. Wanlass, J. S. Ward, A. Duda, D. J. Friedman,
J. M. Olson, W. E. McMahon, T. E. Moriarty, and J. T. Kiehl
National Renewable Energy Laboratory, Golden, Colorado 80401

(Received 27 April 2007; accepted 11 June 2007; published online 10 July 2007)

The authors demonstrate a thin, Ge-free III–V semiconductor triple-junction solar cell device structure that achieved 33.8%, 30.6%, and 38.9% efficiencies under the standard 1 sun global spectrum, space spectrum, and concentrated direct spectrum at 81 suns, respectively. The device consists of 1.8 eV $Ga_{0.5}In_{0.5}P$, 1.4 eV GaAs, and 1.0 eV $In_{0.3}Ga_{0.7}As$ *p-n* junctions grown monolithically in an inverted configuration on GaAs substrates by organometallic vapor phase epitaxy. The lattice-mismatched $In_{0.3}Ga_{0.7}As$ junction was grown last on a graded $Ga_xIn_{1-x}P$ buffer. The substrate was removed after the structure was mounted to a structural "handle." The current-matched, series-connected junctions produced a total open-circuit voltage over 2.95 V at 1 sun. © 2007 *American Institute of Physics*. [DOI: 10.1063/1.2753729]

Currently, state-of-the-art high efficiency III-V solar cells[1] utilize a three-junction design that includes a Ge bottom junction formed in the Ge substrate in conjunction with lattice-matched $Ga_{0.5}In_{0.5}P$ and GaAs top junctions.[2] However, the Ge junction absorbs approximately two times more low energy photons than are needed for current matching with the $Ga_{0.5}In_{0.5}P$ and GaAs junctions. Ideally, the Ge bottom junction would be replaced with a 1.0 eV junction that is lattice matched with the other junctions.[3] The dilute nitride alloy $Ga_xIn_{1-x}N_yAs_{1-y}$ initially appeared to satisfy these requirements, but proved to be limited by what appears to be intrinsic defects.[4] $In_{0.3}Ga_{0.7}As$ could also be used as the 1.0 eV junction, but it has a larger lattice constant than GaAs by about 2%. The dislocations generated by this large lattice mismatch (LMM) can be reduced through the use of graded composition buffer layers[5,6] (sometime referred to as "metamorphic" growth), but the remaining threading dislocations would significantly degrade any subsequently grown junctions with higher band gaps. By growing in an inverted configuration,[7,8] this degradation of the top junctions can be avoided.

In this letter, we demonstrate excellent solar cell performance in an inverted, monolithic triple-junction structure that combines a metamorphic 1.0 eV $In_{0.3}Ga_{0.7}As$ junction with lattice-matched 1.8 eV $Ga_{0.5}In_{0.5}P$ and 1.4 eV GaAs junctions. These devices outperform or rival all previously reported solar cell efficiencies for both terrestrial and space applications. The inverted triple-junction device structure is shown schematically in Fig. 1. It was grown by atmospheric-pressure organometallic vapor phase epitaxy (OMVPE) on a (001) GaAs substrate miscut 2° toward (111)*B*. Growth conditions are similar to those described elsewhere.[9] The top $Ga_{0.5}In_{0.5}P$ and middle GaAs lattice-matched junctions were grown before any lattice-mismatched layers, preventing the threading dislocations that originate during mismatched growth from degrading their performance. Thus, the top two junctions, which produce most of the power, were grown with high crystal perfection for optimal solar cell performance. The three junctions were series connected with two $Al_{0.3}Ga_{0.7}As:C/GaAs:Se$ tunnel junctions. In order to minimize the dislocations in the bottom junction, a graded $Ga_xIn_{1-x}P$ layer, which is transparent to the light intended for the bottom junction, was grown. The composition of the $Ga_xIn_{1-x}P$ was step graded from $Ga_{0.51}In_{0.49}P$, with a nominal lattice constant (a_0=5.66 Å) equal to that of GaAs, to $Ga_{0.22}In_{0.78}P$ (a_0=5.78 Å) using eight 0.25-μm-thick intermediate compositions of $Ga_xIn_{1-x}P$. After the growth of 1.0 μm of $Ga_{0.22}In_{0.78}P$, the composition was then dropped back to $Ga_{0.25}In_{0.75}P$ (a_0=5.76 Å) which is lattice matched to the $In_{0.3}Ga_{0.7}As$ active junction. This $Ga_{0.25}In_{0.75}P$ composition was used as the passivating window and back-surface-field layers.

FIG. 1. Schematic of inverted triple-junction structure. The band gap of the semiconductor layers is indicated by a rainbow color scale (violet=high and red=low). The GaInP junction base thickness was 0.45 μm for the AM0 device.

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[a] Electronic mail: john_geisz@nrel.gov

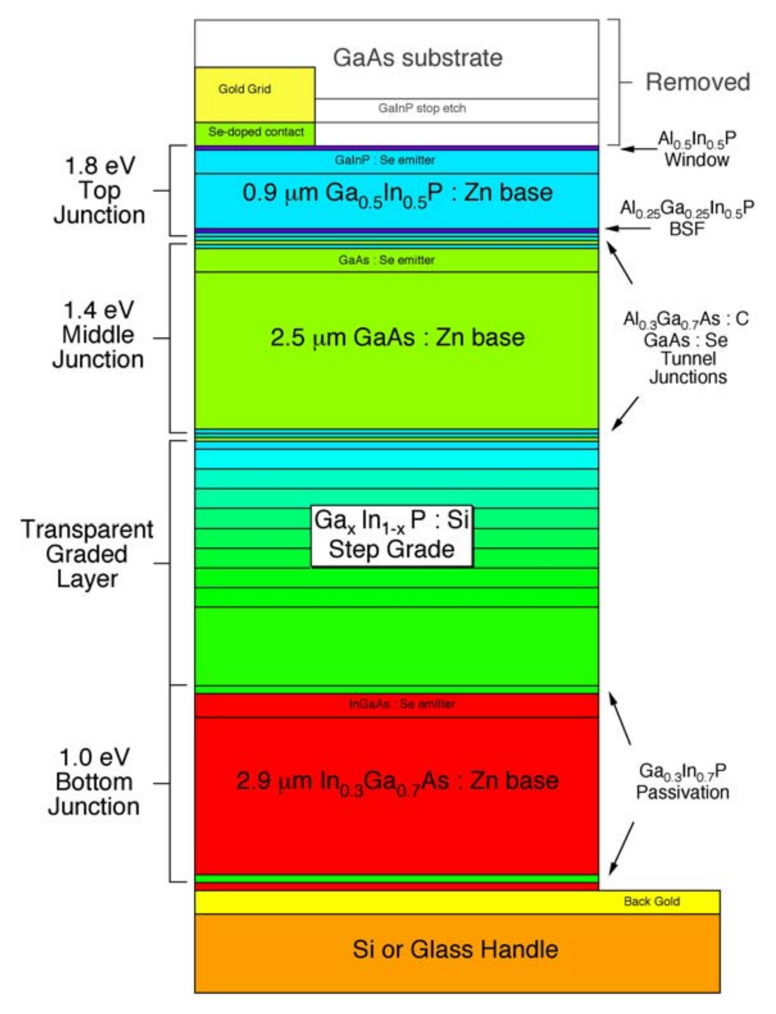
0003-6951/2007/91(2)/023502/3/$23.00 **91**, 023502-1 © 2007 American Institute of Physics

More details can be found in Geisz et al., APL, 91, 023502 (2007)

Complicated structure includes
- –tunnel junctions
- –contact layers
- –p/n junctions
- –back-surface-field layers
- –window layers
- –metal grids

Subtle difference in inverted growth (see Steiner's talk)

More Details of the Structure



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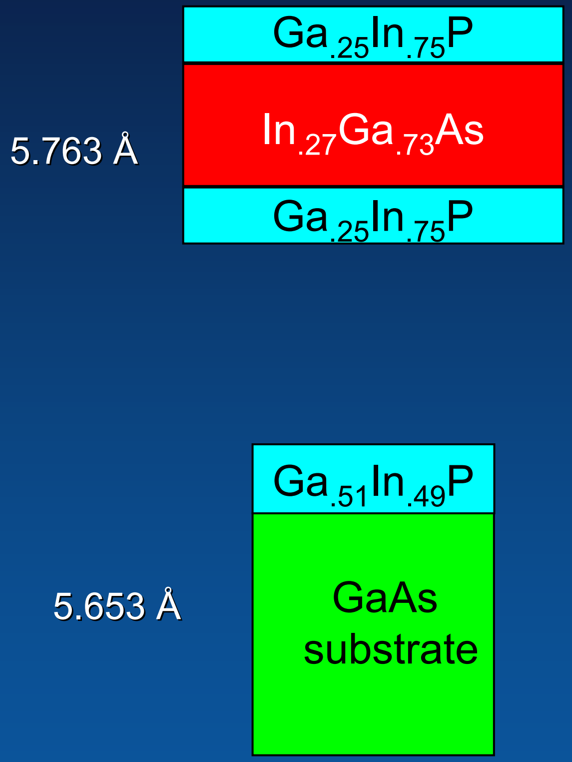
Stress/Strain Control of Metamorphic $In_{.27}Ga_{.73}As$ Junction



$Ga_{.25}In_{.75}P$

$In_{.27}Ga_{.73}As$

$Ga_{.25}In_{.75}P$

5.763 Å

$Ga_{.51}In_{.49}P$

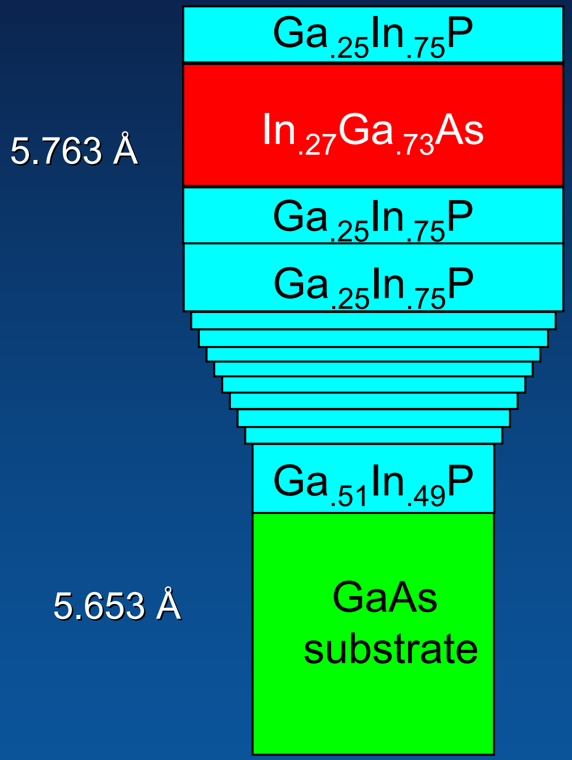
GaAs substrate

5.653 Å

(width represents lattice constant)

Geisz et al., J Crystal Growth, **310** (2008) 2339

Stress/Strain Control of Metamorphic In$_{.27}$Ga$_{.73}$As Junction



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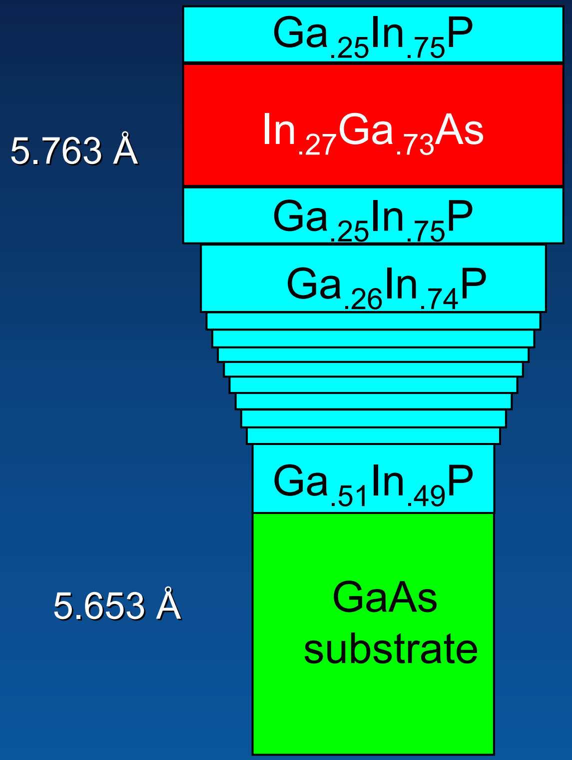

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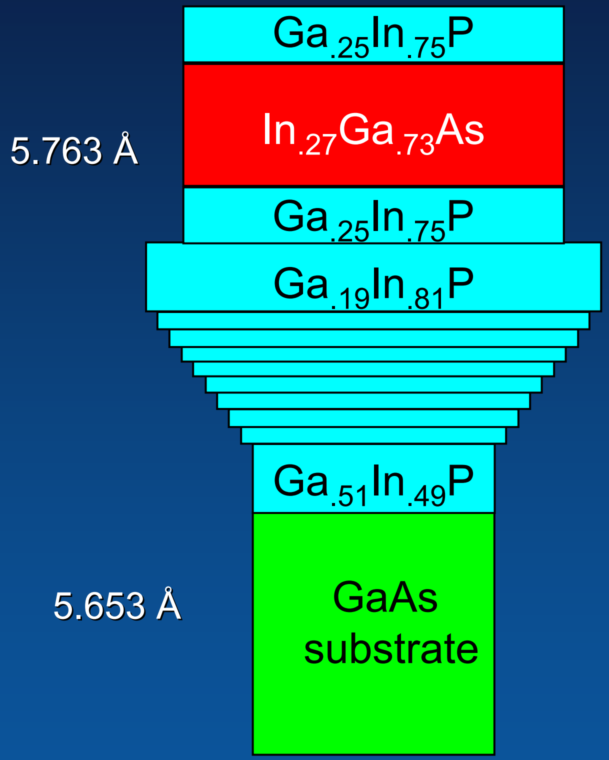

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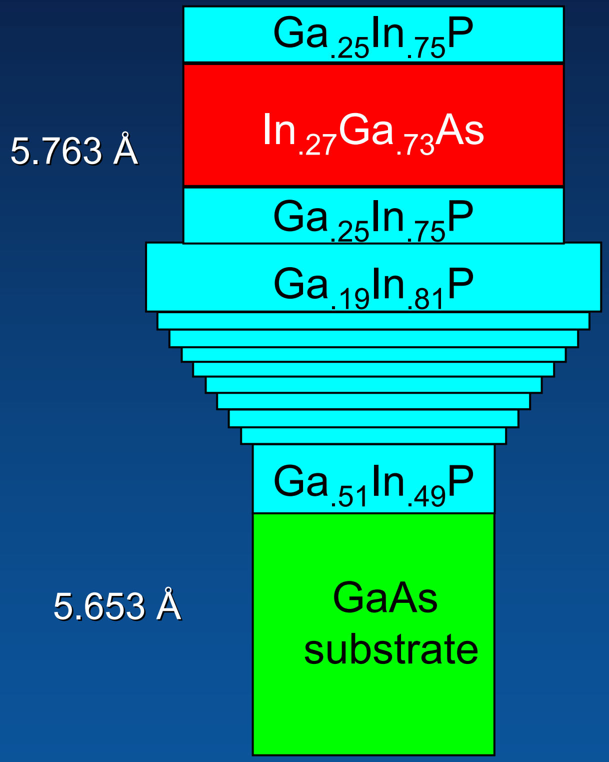

$Ga_{.25}In_{.75}P$

5.763 Å

$In_{.27}Ga_{.73}As$

$Ga_{.25}In_{.75}P$

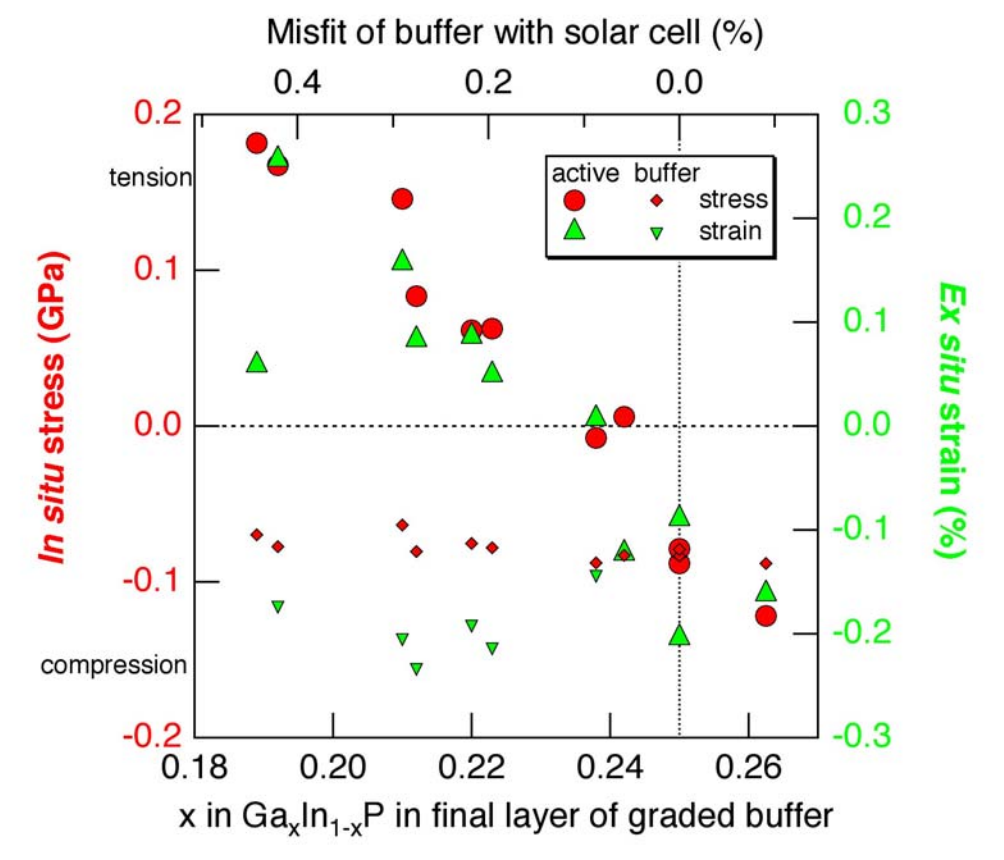
$Ga_{.19}In_{.81}P$

$Ga_{.51}In_{.49}P$

5.653 Å

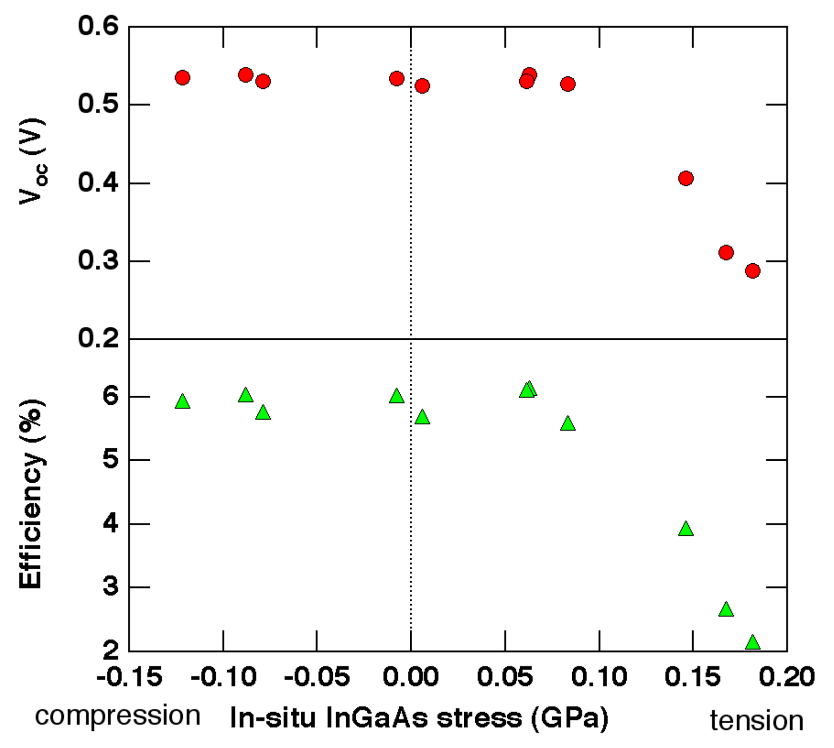
GaAs substrate

(width represents lattice constant)



Geisz et al., J Crystal Growth, **310** (2008) 2339

1.0 eV Solar Cell Performance



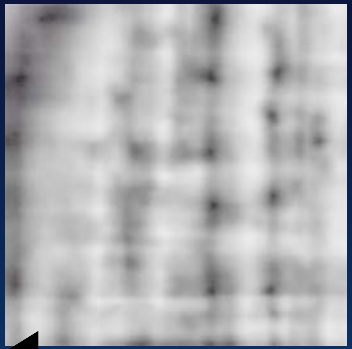
Excellent results when grown under low stress (no driving force for dislocation generation or glide)

Radiative limit not much higher V_{oc} than 0.6 V

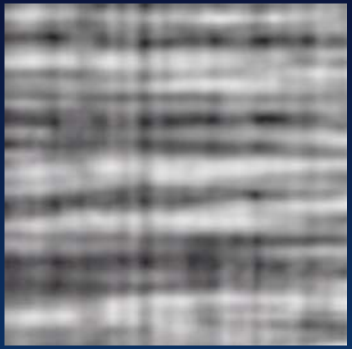
1.0 eV Solar Cell Performance

Plan-view CL

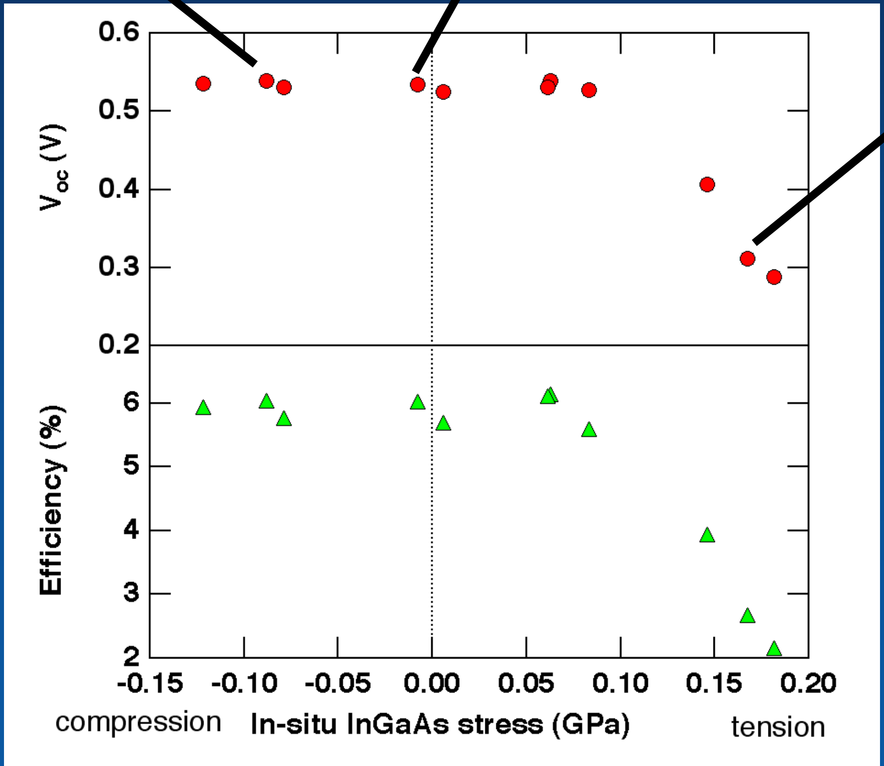
Low 10^6 cm^{-2}



Low 10^6 cm^{-2}



High 10^6 cm^{-2}



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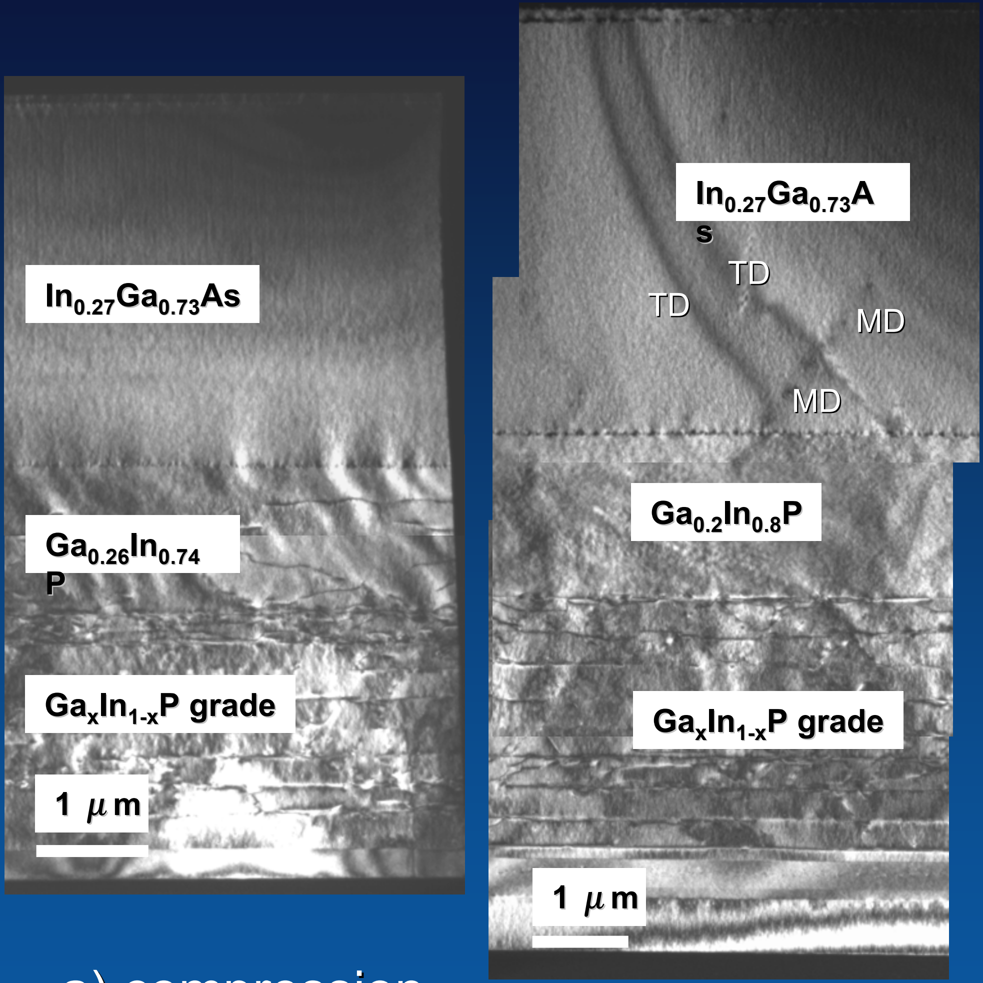
Radiative limit not much higher V_{oc} than 0.6 V

TEM of 1.0 eV Metamorphic Junction

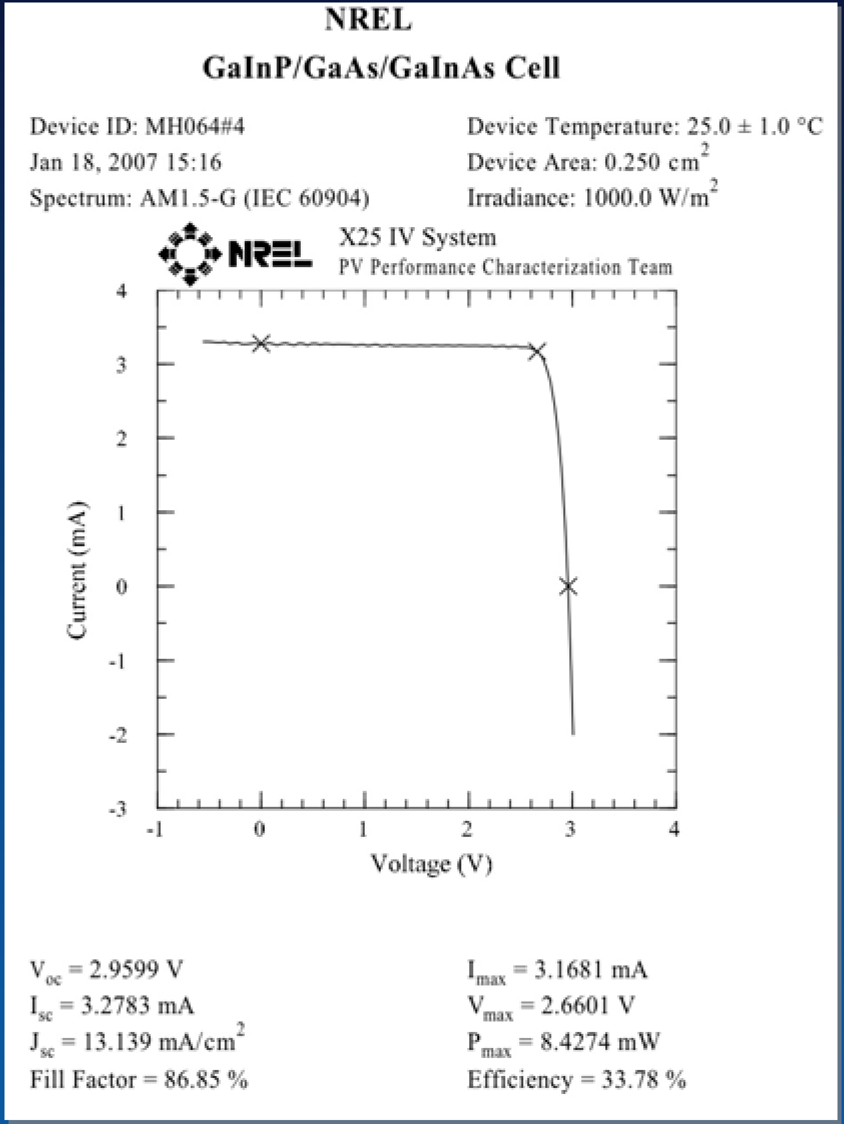


a) compression

b) tension

220 dark field

One-Sun Global Results (AM1.5G)



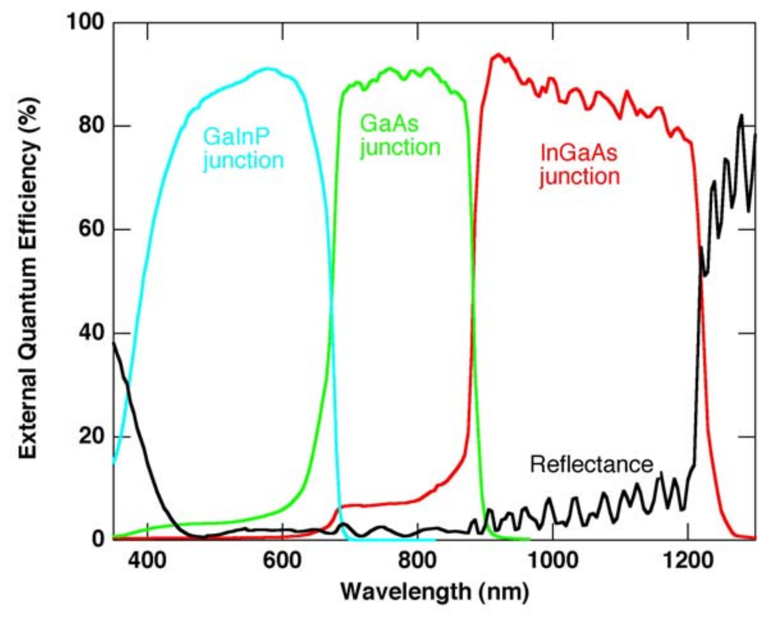
NREL

GaInP/GaAs/GaInAs Cell

Device ID: MH064#4	Device Temperature: 25.0 ± 1.0 °C
Jan 18, 2007 15:16	Device Area: 0.250 cm^2
Spectrum: AM1.5-G (IEC 60904)	Irradiance: 1000.0 W/m^2

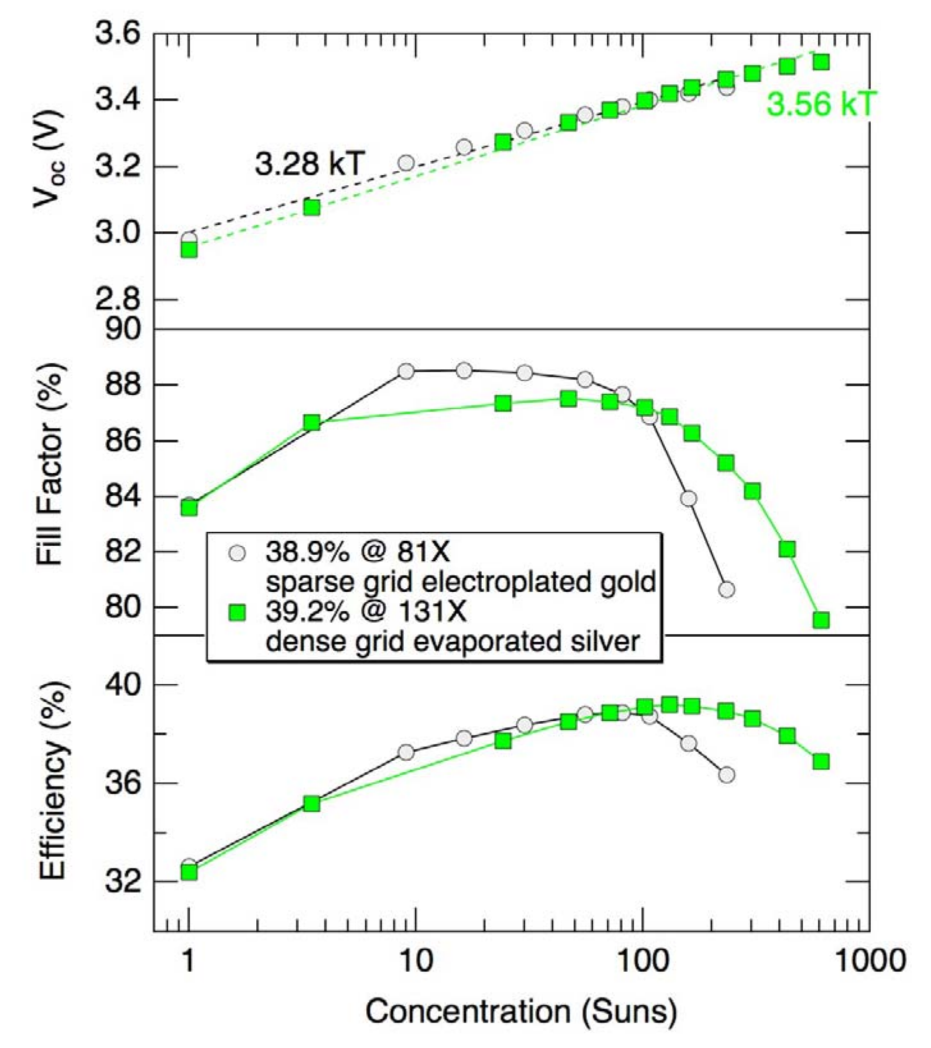
NREL X25 IV System
PV Performance Characterization Team

V_{oc} = 2.9599 V	I_{max} = 3.1681 mA
I_{sc} = 3.2783 mA	V_{max} = 2.6601 V
J_{sc} = 13.139 mA/cm^2	P_{max} = 8.4274 mW
Fill Factor = 86.85 %	Efficiency = 33.78 %



- 33.8% efficiency at AM1.5G World record!(previously 32.0% on Ge)
- All 3 junctions current matched

High Concentration Results



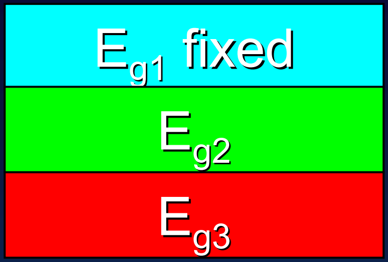
- High intensity flash simulator
- V_{oc} rises logarithmically (expect 3kT for 3 ideal junctions)
- Series resistance limits fill factor increase
- Improved metal grids reduced series resistance
  - 38.9% @ 81X old
  - 39.2% @ 131X new

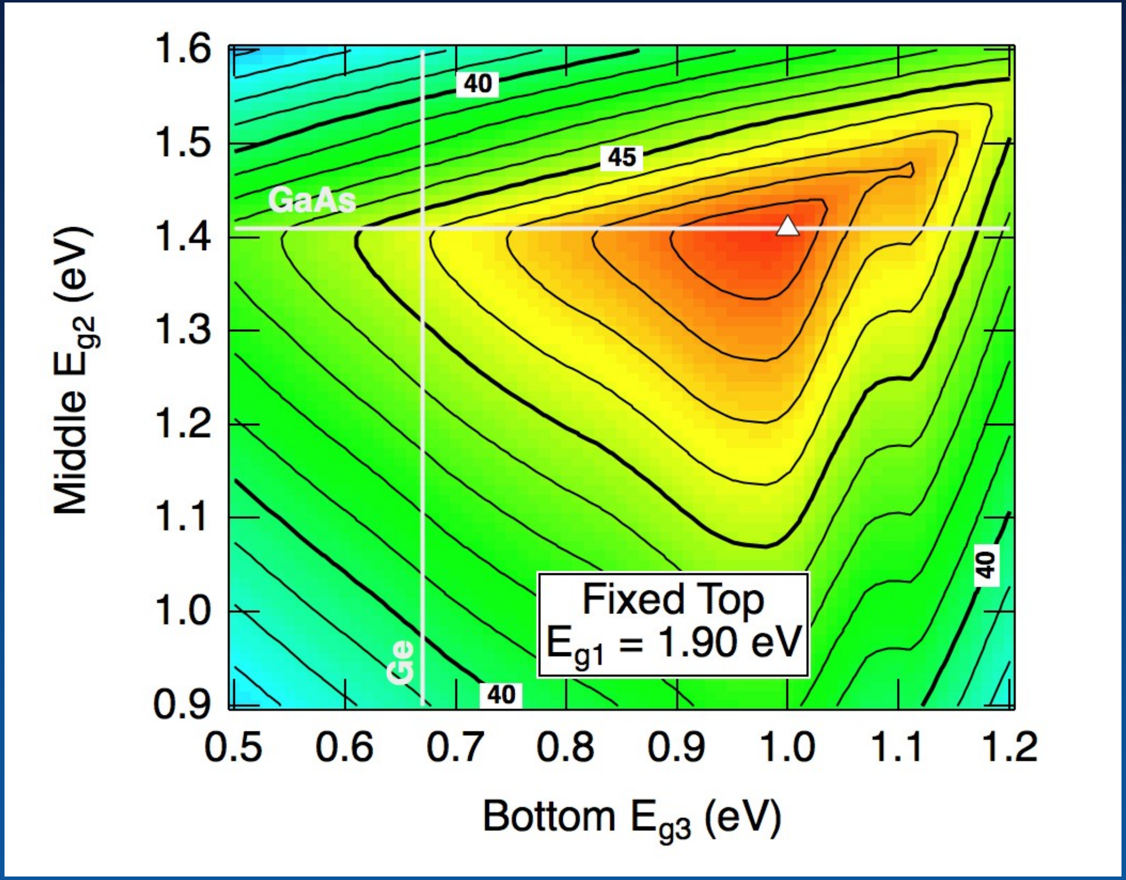
And One More Thing.......

New Inverted Triple Junction Design

- More Optimal Band Gaps
- Two Metamorphic Junctions

Fixed top junction - high E_g

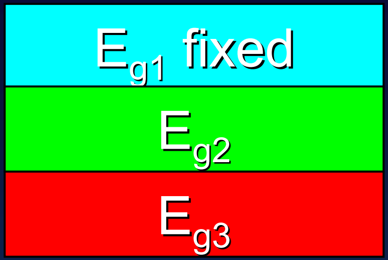


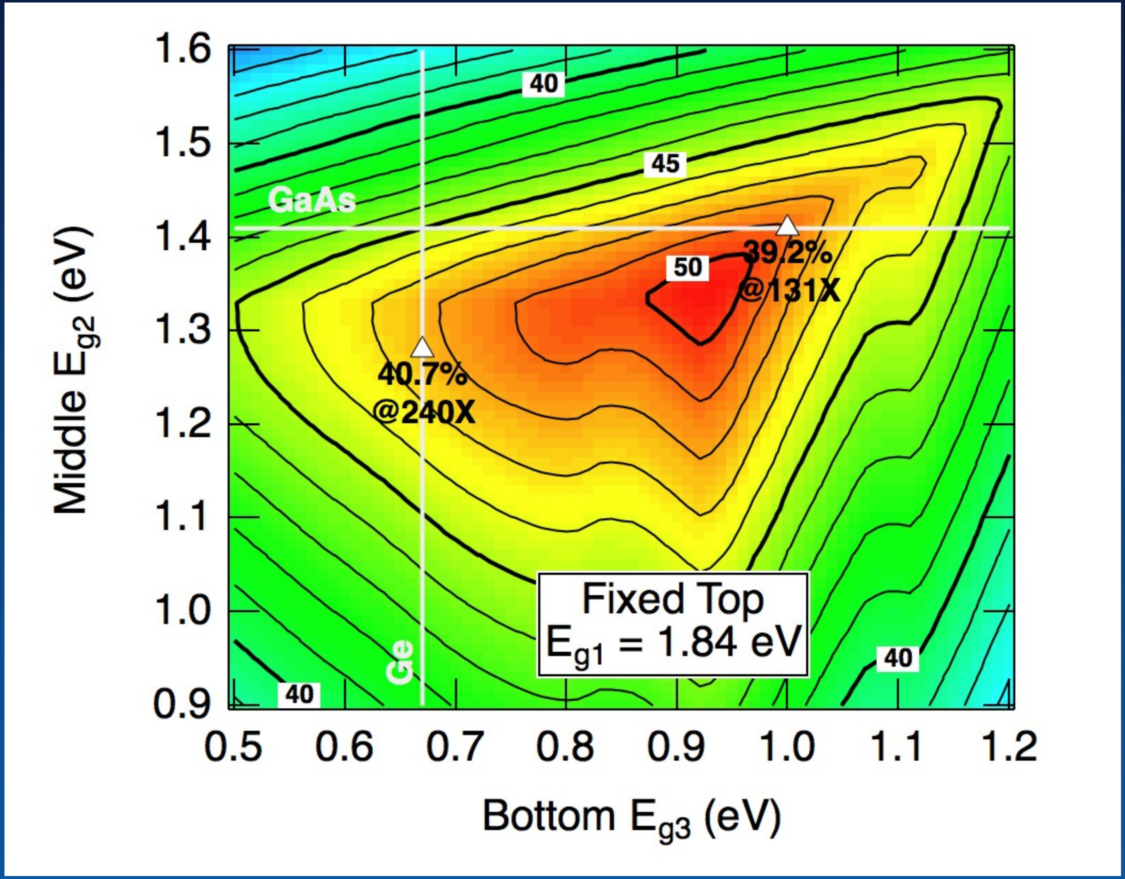


- High E_g (disordered) GaInP top junction best for lattice-matched triple
- 1.0 eV bottom junction better

Calculated for 500X @ 300K AM1.5D

Fixed top junction - low E_g

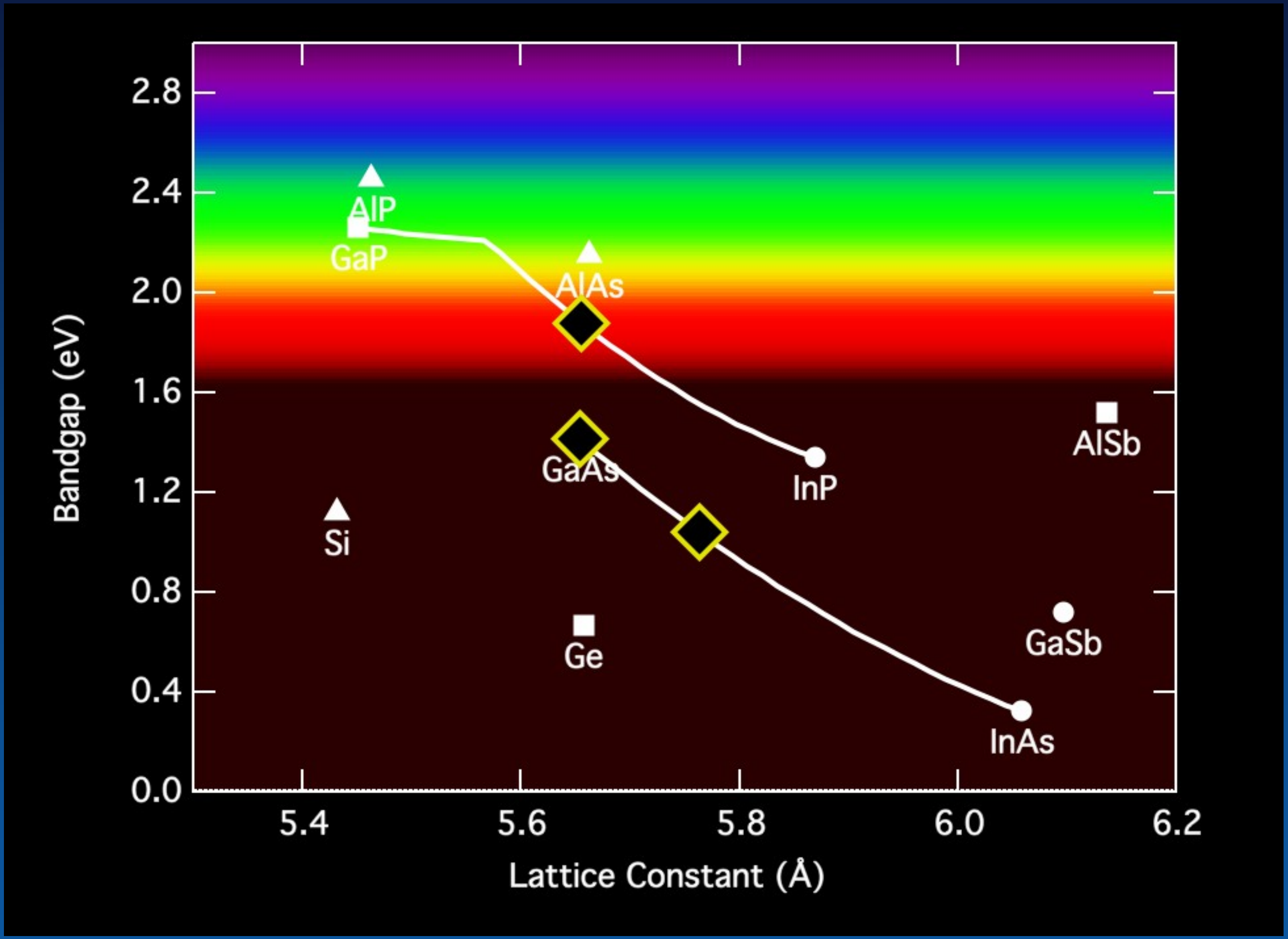




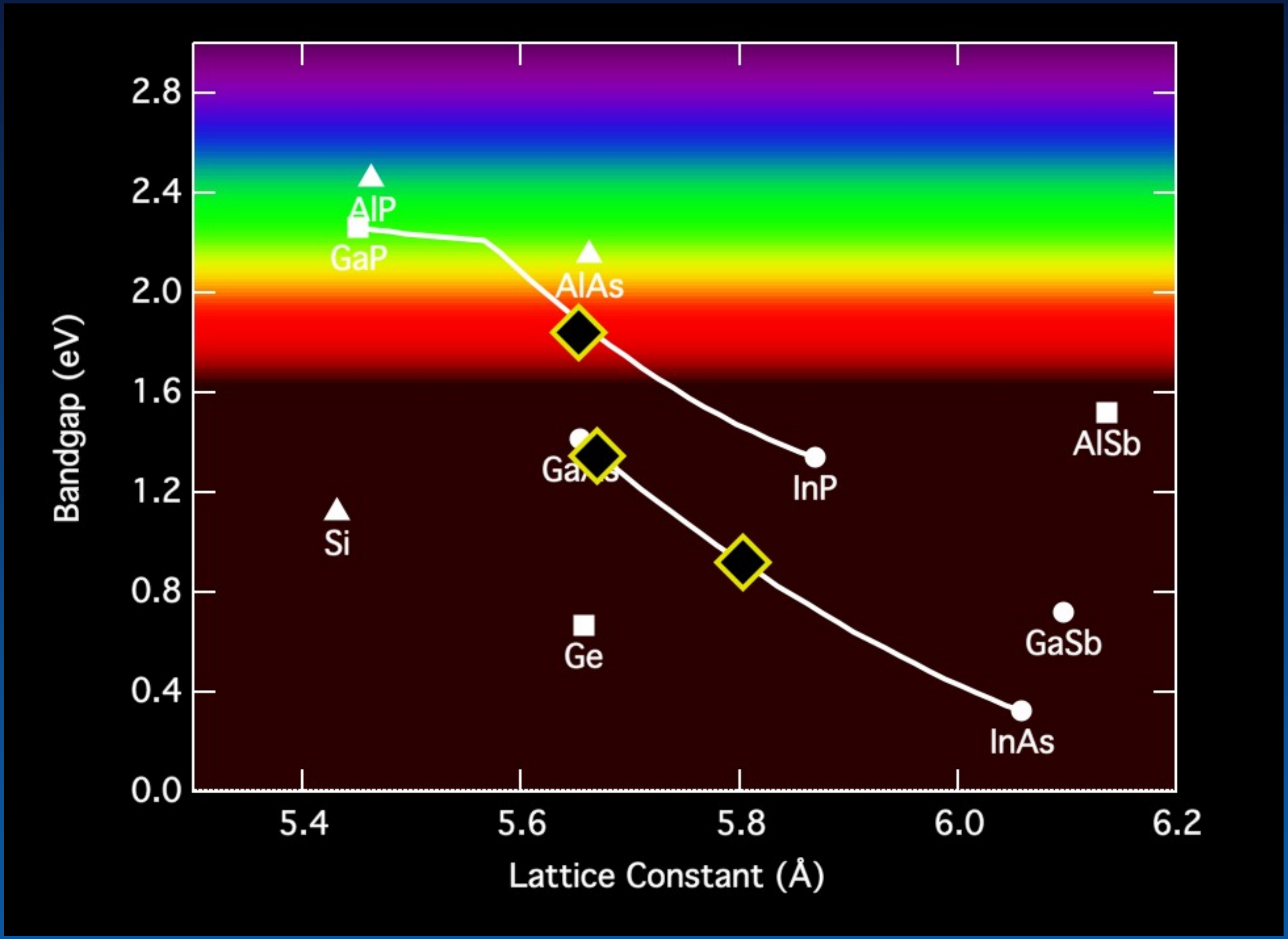
- Higher theoretical efficiency available using lower E_g (ordered) GaInP top junction
- Global maximum at 1.85 / 1.34 / 0.93 eV

Calculated for 500X @ 300K AM1.5D

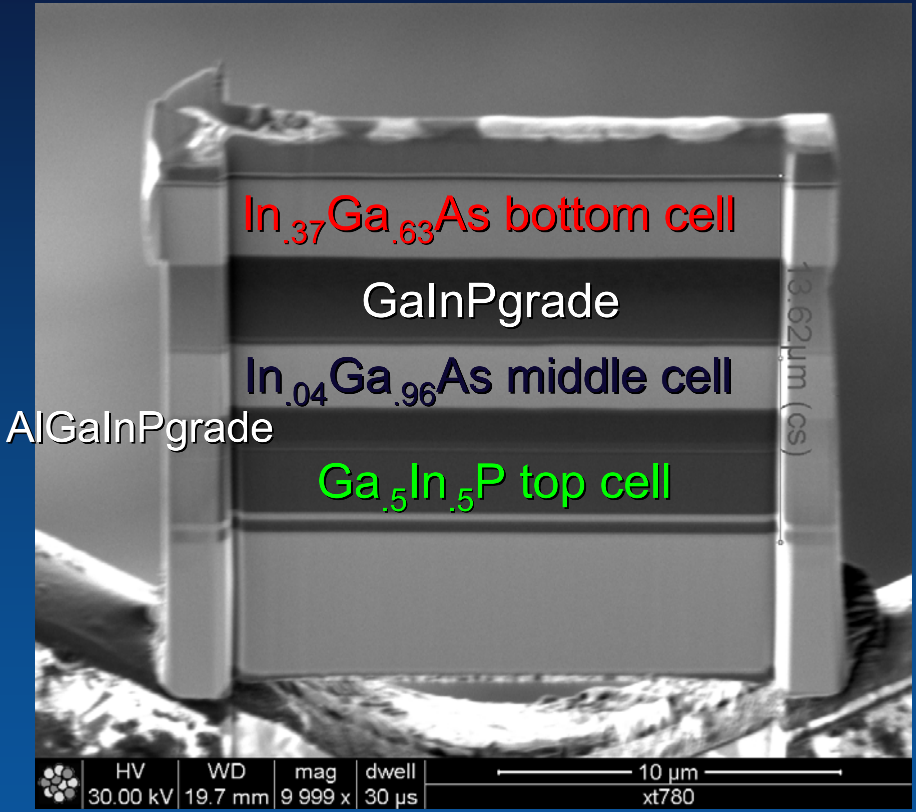
One Metamorphic Junction (1MMJ)



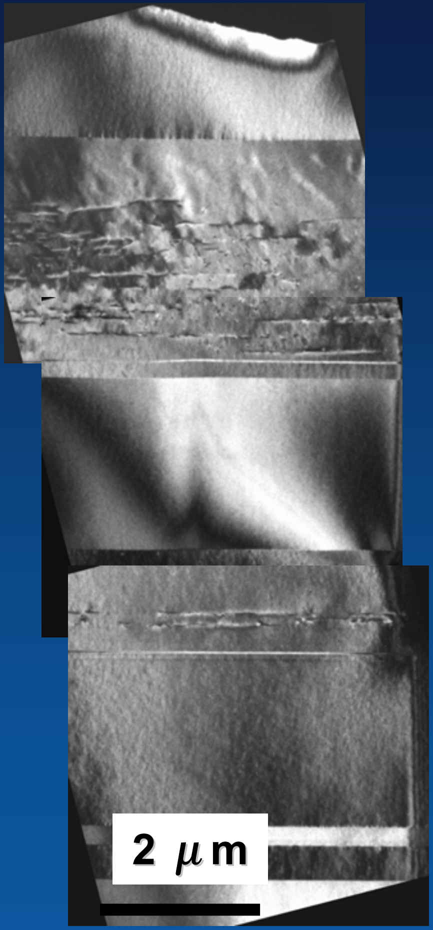
Two Metamorphic Junctions (2MMJ)



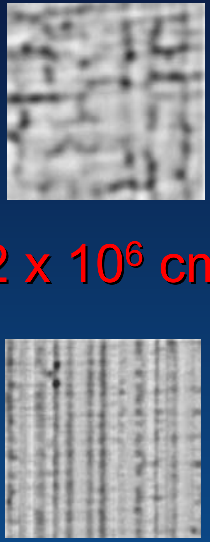
Dislocations in Inverted Triple with Two Mismatched Junctions



Ion beam image
of FIB sample



220DF TEM



2×10^6 cm^{-2}

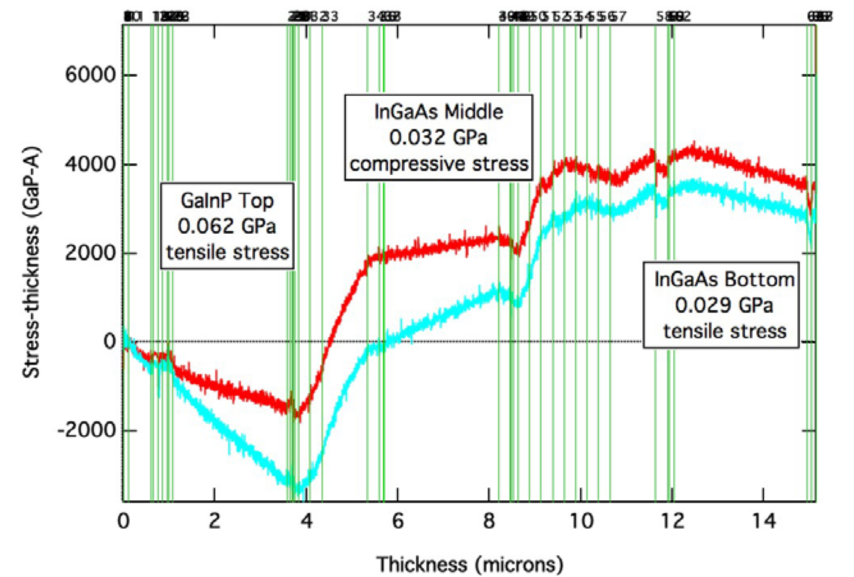
1×10^5 cm^{-2}

none

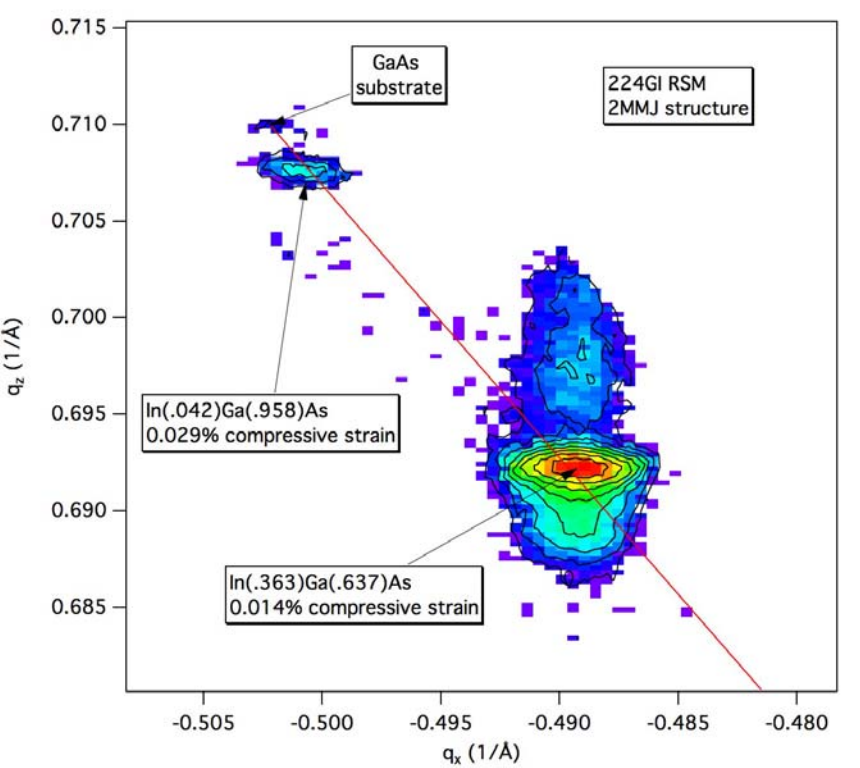
Plan-view CL

Stress and Strain of 2MMJ

Near zero in both metamorphic junctions

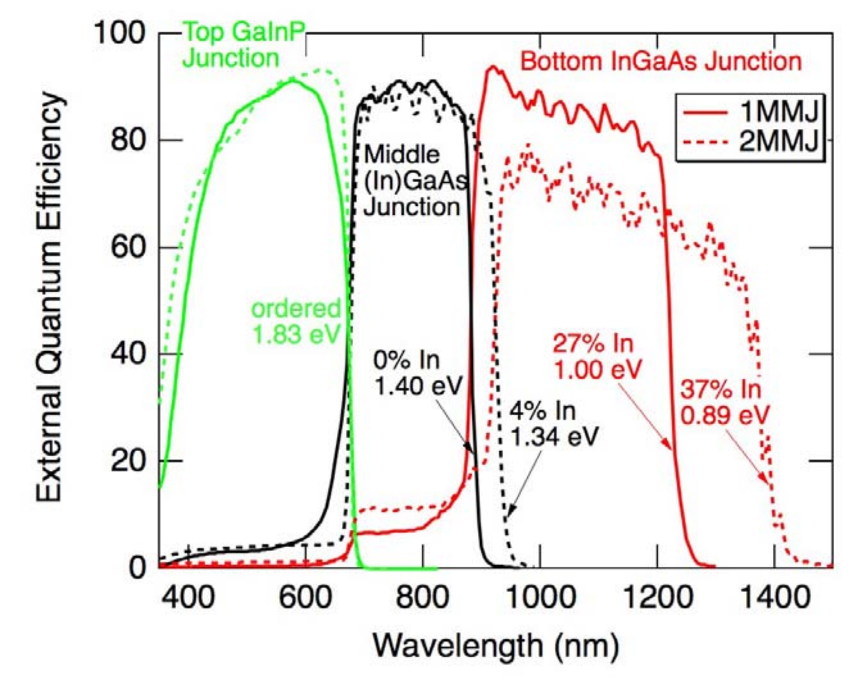


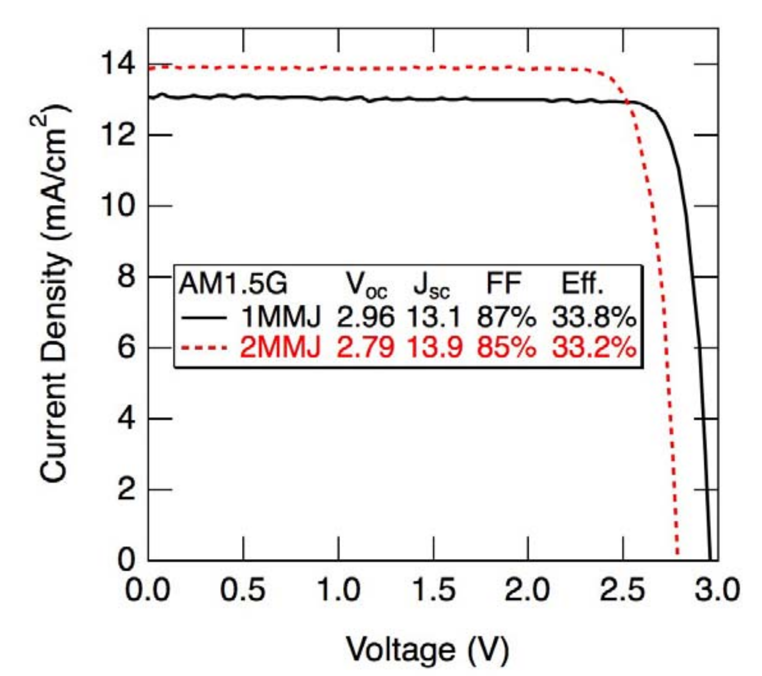
in situ stress
by MOS



ex situ strain
by XRD

Inverted Solar Cell Comparison AM1.5G

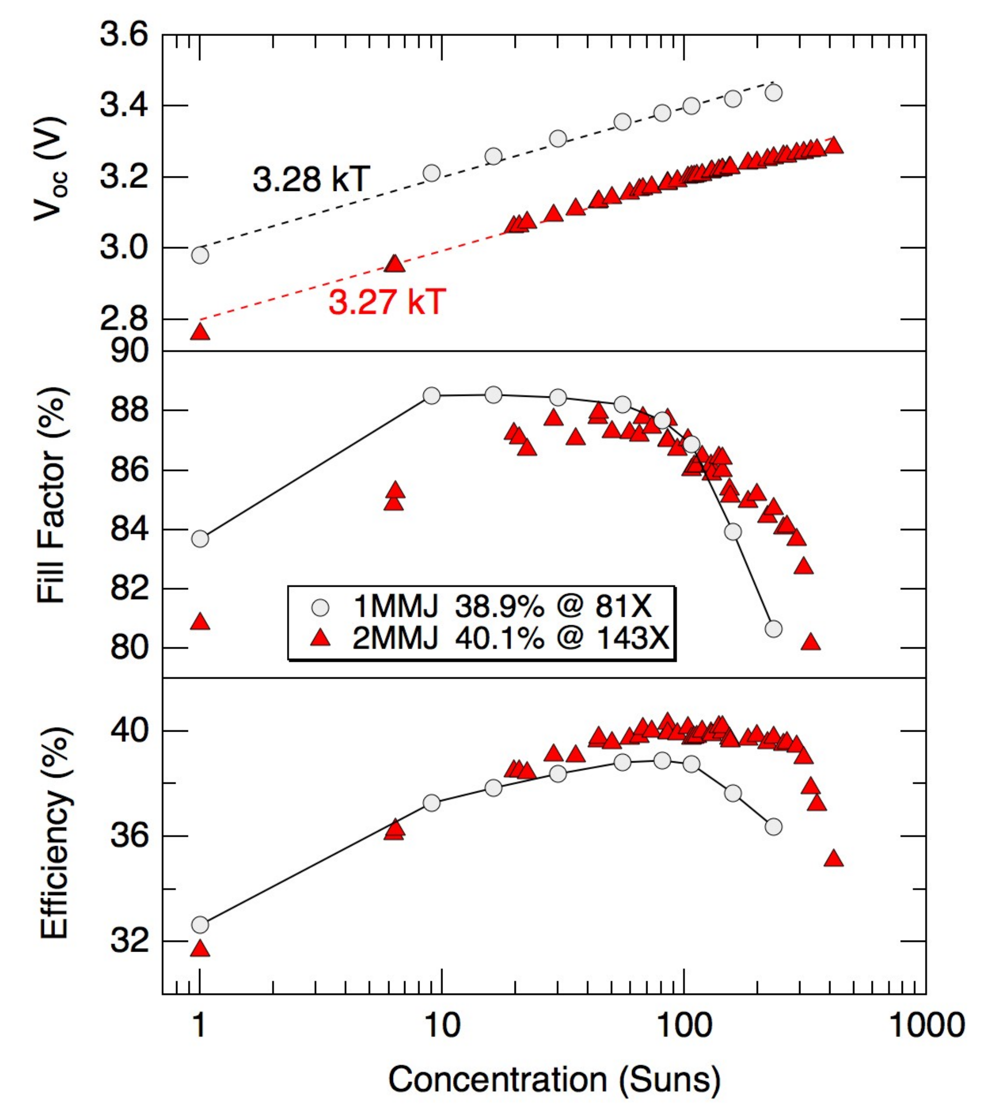




AM1.5G	V_{oc}	J_{sc}	FF	Eff.
— 1MMJ	2.96	13.1	87%	33.8%
---- 2MMJ	2.79	13.9	85%	33.2%

- New 2MMJ design has higher current, lower voltage
- >33% AM1.5G efficiencies from both inverted designs

Inverted Solar Cell Comparison



AM1.5D Concentration

40.1% efficiency at 143X in triple-junction with 3 different lattice constants

using sparse grid electroplated gold

NREL National Renewable Energy Laboratory

Challenges

- Series resistance
- Broadband antireflective coatings
- Long term reliability of lattice mismatched devices
- Measurements of current matched multi-junctions
- More junctions
- Substrate reuse

Conclusions

- Ge-based devices are great, but nearing full potential
- Lattice-mismatched (metamorphic) growth becoming more important for further improvements - requires dislocation and stress control
- Inverted approach has many advantages
- 33.8% at AM1.5G WORLD RECORD
- Great for space too (see Emcore's talk)
- 39.2% at 131 suns concentration (1 metamorphic)
- 40.1% at 143 suns concentration (2 metamorphic)

Acknowledgements

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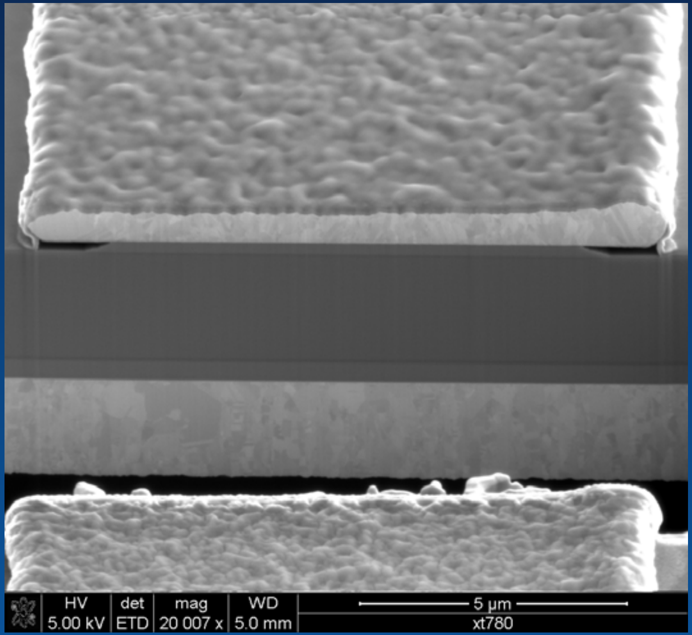
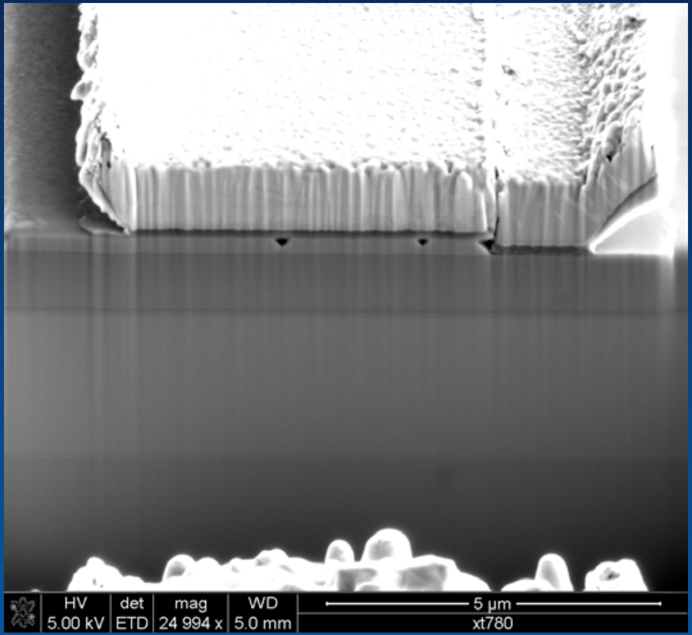
Charlene Kramer - MOVPE growth
Waldo Olavarria - MOVPE growth
Alejandro Levander - summer intern
Keith Emery - measurements leadership

III-V Industry - Spectrolab, Emcore, others

Resistance losses from metallization

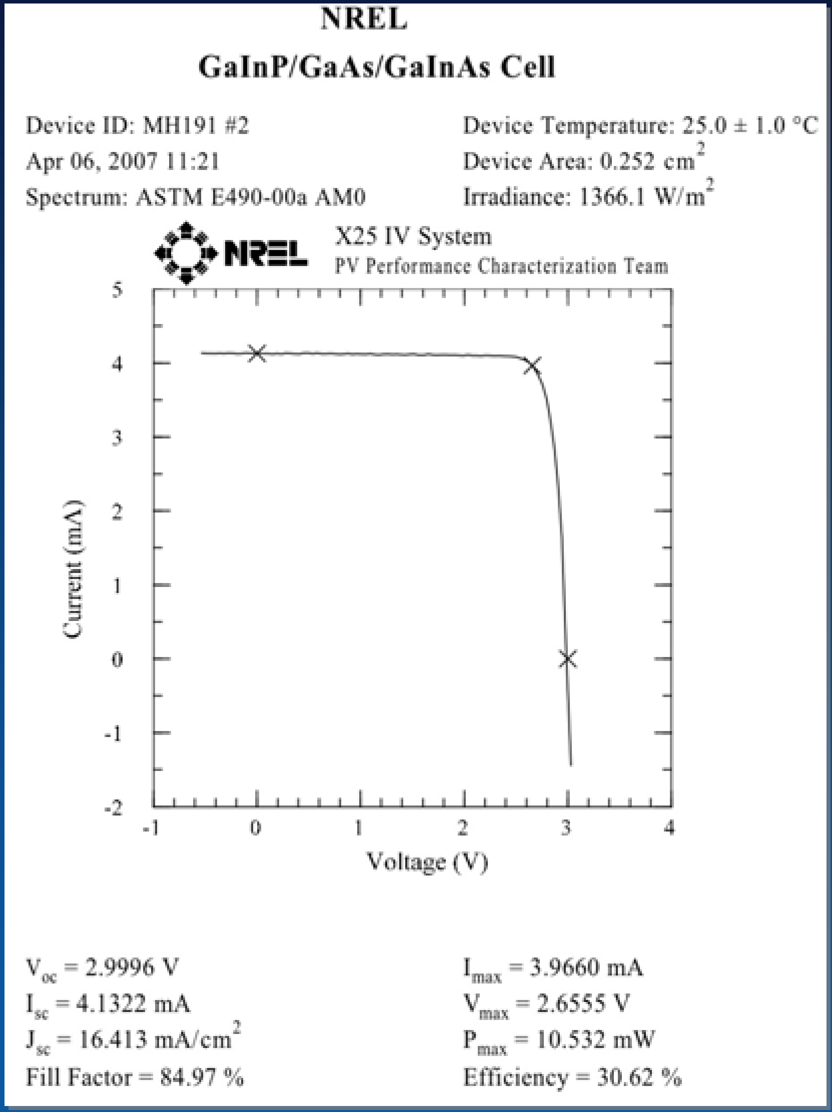


Severe catalytic undercutting of electroplated gold fingers used as etch mask



Misalignment of evaporated metal on pre-etched contact layer

One-Sun Space Results (AM0)



NREL

GaInP/GaAs/GaInAs Cell

Device ID: MH191 #2	Device Temperature: 25.0 ± 1.0 °C
Apr 06, 2007 11:21	Device Area: 0.252 cm^2
Spectrum: ASTM E490-00a AM0	Irradiance: 1366.1 W/m^2

X25 IV System
PV Performance Characterization Team

V_{oc} = 2.9996 V	I_{max} = 3.9660 mA
I_{sc} = 4.1322 mA	V_{max} = 2.6555 V
J_{sc} = 16.413 mA/cm^2	P_{max} = 10.532 mW
Fill Factor = 84.97 %	Efficiency = 30.62 %

30.6% AM0 efficiency
V_{oc} = 3.0 V
Fill Factor = 85%

Independent confirmation
NASA Glenn (30.8%)

Technology transfer to Emcore:
31.9% AM0 efficiency on 4 cm^2 device