NREL
NATIONAL RENEWABLE ENERGY LABORATORY

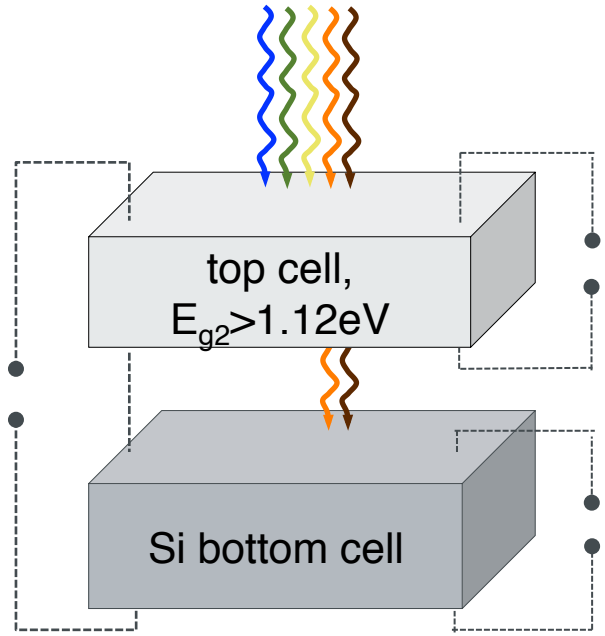
Opportunities in III-V/Si Integration and New Materials for High Efficiency PV

Adele Tamboli

October 6, 2016

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

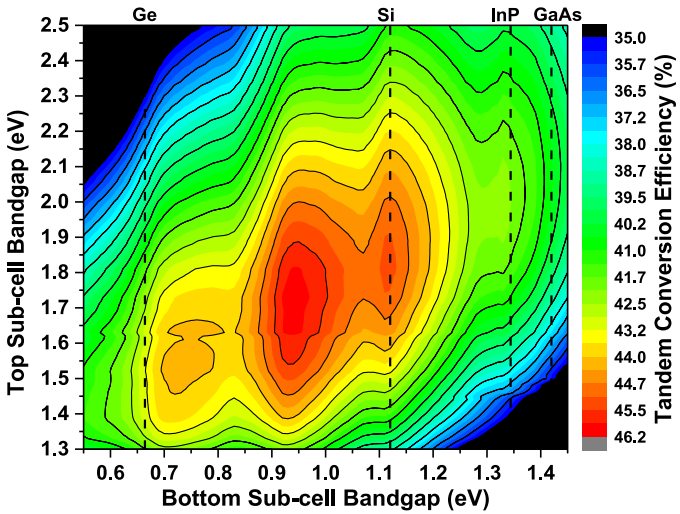
Efficiency potential of tandems on Si



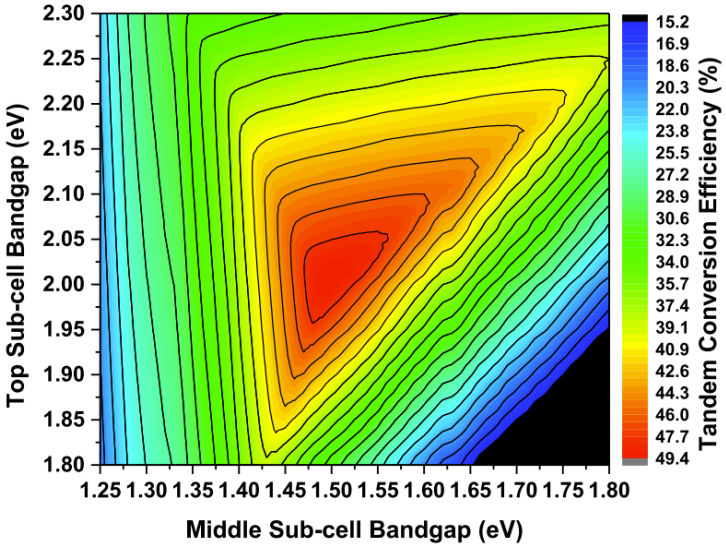
serially connected (2-terminal)

Independent operation of cells (4-terminal)

Detailed balance limit for multijunctions on Si



2J



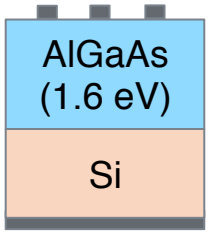
3J

I. Almasouri, *JPV,* 5, 3 (2015)

Realizing III-V/Si tandem solar cells

Epitaxial growth

+ Few process steps
+ Lowest costs
+ Simple module integration
- Mismatch of lattice (4%) thermal expansion coefficients → defects in top cell
- Performance of Si subcell can be reduced



eff.= 21.2%
(1-sun)

T. Soga et al., J. Cryst. Growth (1997)

Direct wafer-bonding

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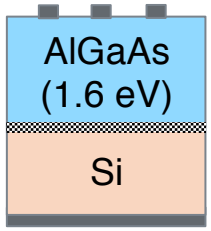
+ Simpler module integration
- Lift-off and re-use of growth substrates required
- Mirror-polished clean surfaces required (RMS < 0.5nm) → CMP necessary



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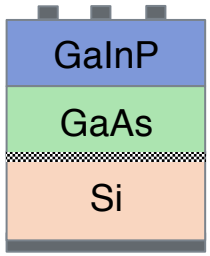

eff. = 30.0%
(112-suns)

S. Essig et al., IEEE JPV (2015)

Mechanical stacking

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+ Any Si bottom cell (textured) can be used
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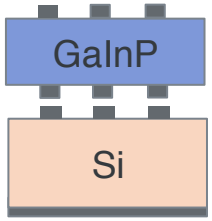

eff. = 29.8%
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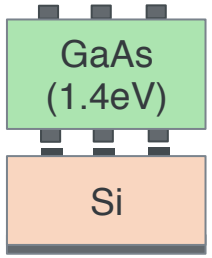
S. Essig, NREL & CSEM, JPV 2016



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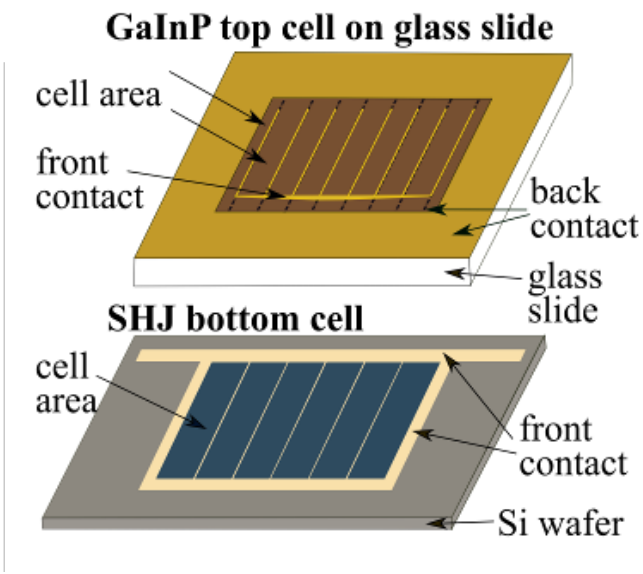
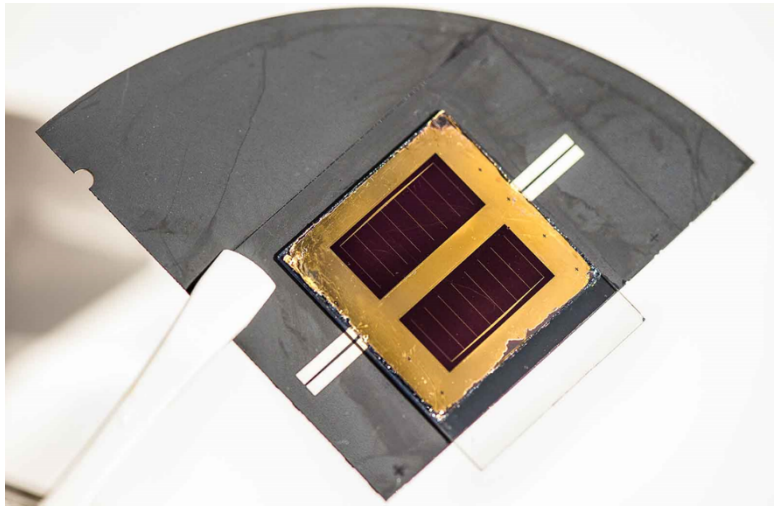
T. Soga et al., J. Crys. Gro. 1997)

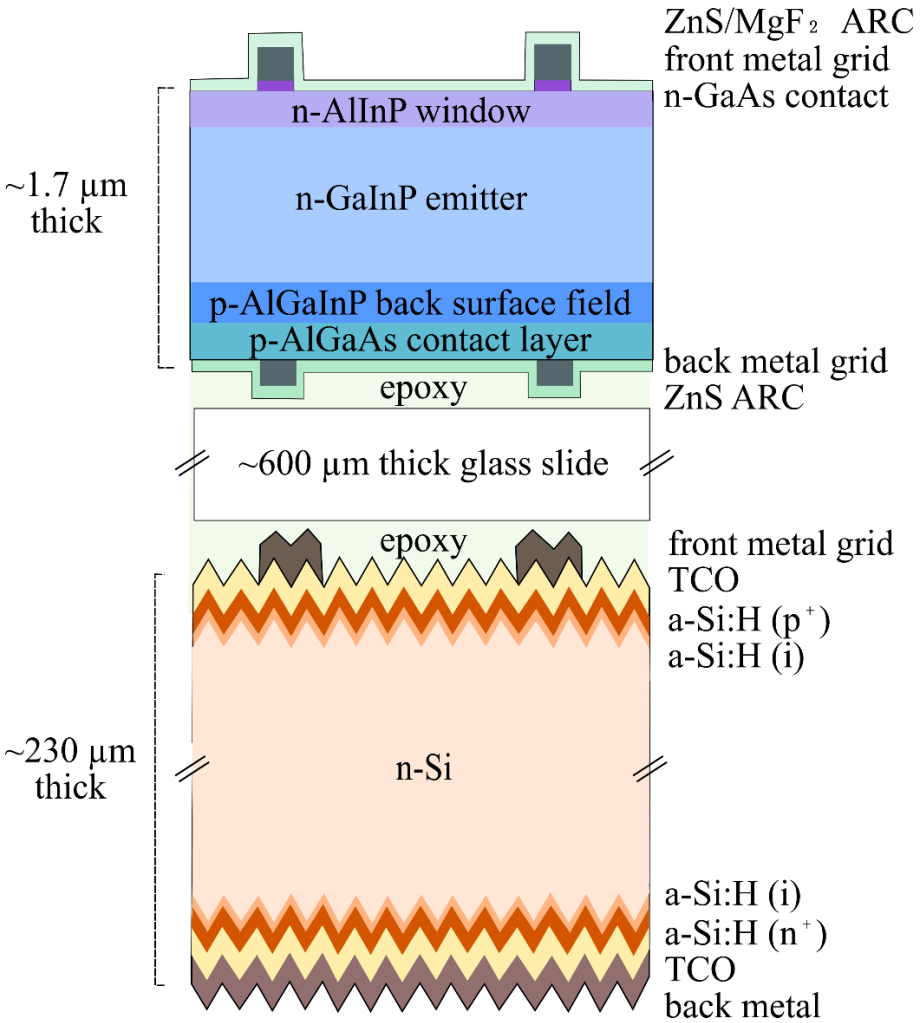
NREL is working on all three approaches

Mechanically stacked GaInP/Si tandem solar cells



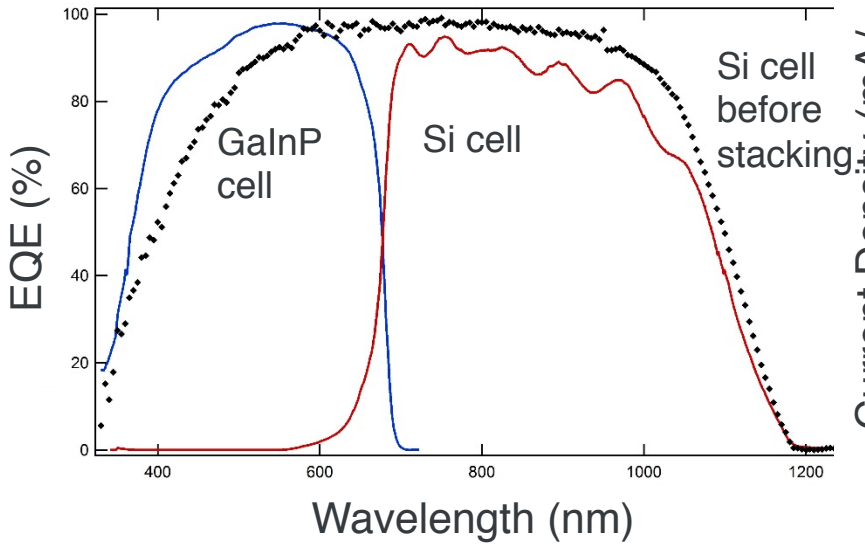


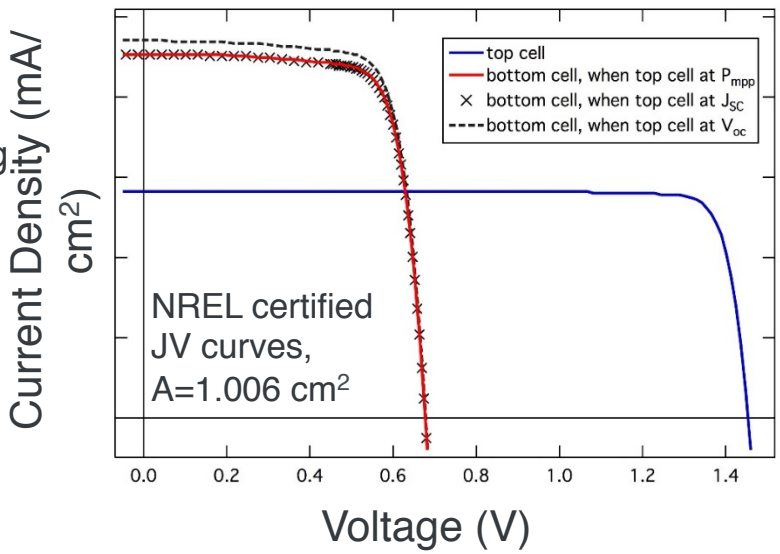
[Photo by Dennis Schroeder]



S. Essig et al., *IEEE JPV* 2016

Characteristics of GaInP/Si tandem cell (1 Sun)



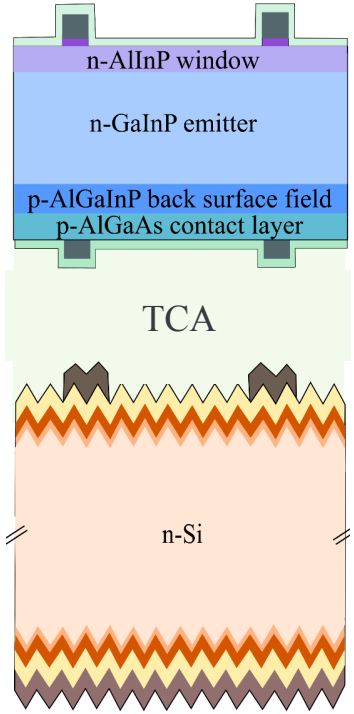


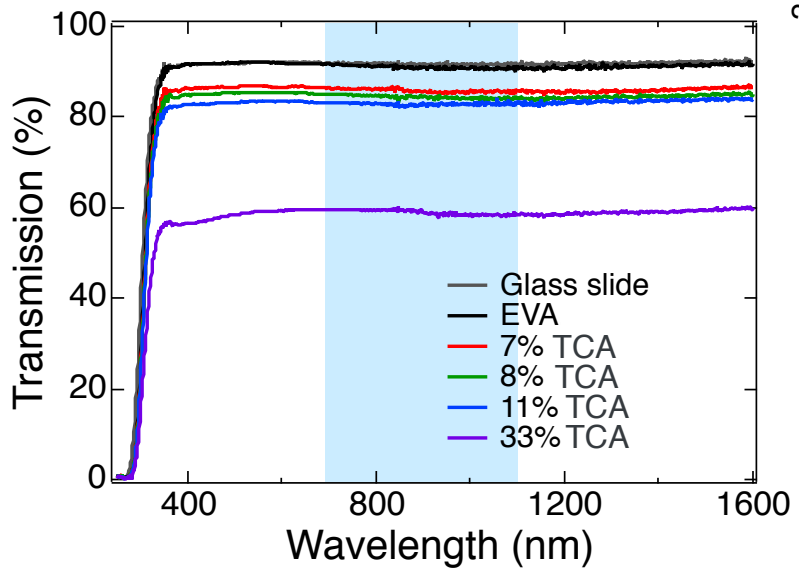
cell	J_{SC} [mA/cm²]	V_{OC} [mV]	FF [%]	eff. [%]
GaInP top cell	14.15	1456	87.9	18.1 ± 0.5
bottom cell when top cell at V_{OC}	23.53	678	75.9	12.1 ± 0.4
bottom cell when top cell at J_{sc}	22.68	677	76.0	11.7 ± 0.4
bottom cell when top cell at P_{mpp}	22.70	677	76.2	11.7 ± 0.4
			cumulative eff.	**29.8 ± 0.6**

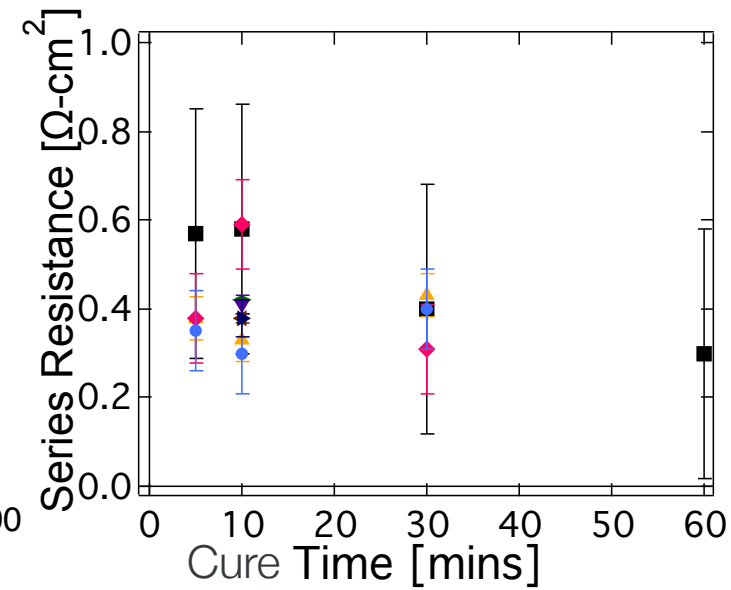
S. Essig et al., *IEEE JPV* 2016

Conductive Adhesives for 2T Stacked Tandems

Developing new transparent, conductive adhesives (TCA) for mechanically stacked, two-terminal tandems







Promising initial properties demonstrated

- Next: initial devices, modeling in Sentaurus Device

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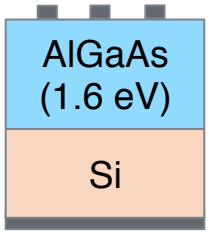

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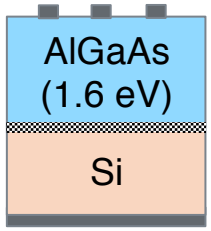

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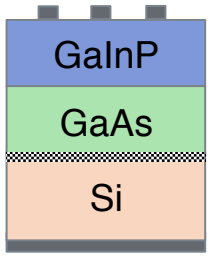

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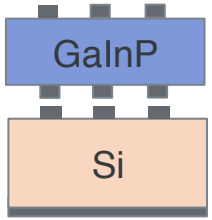

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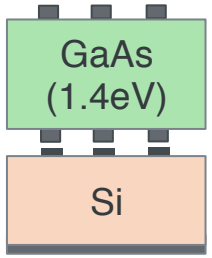

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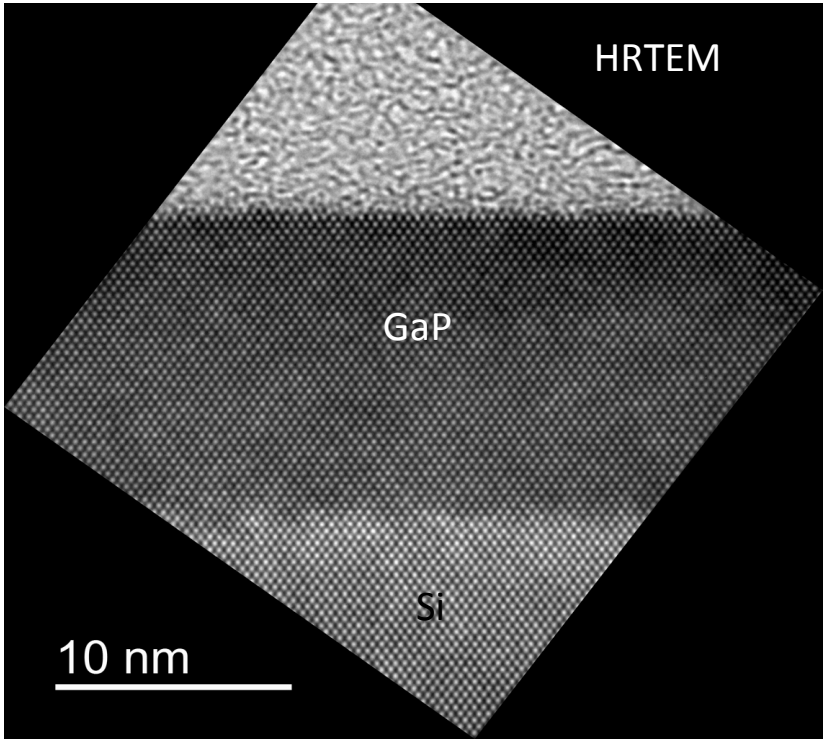
GaP Nucleation on AsH_3 pretreated Si

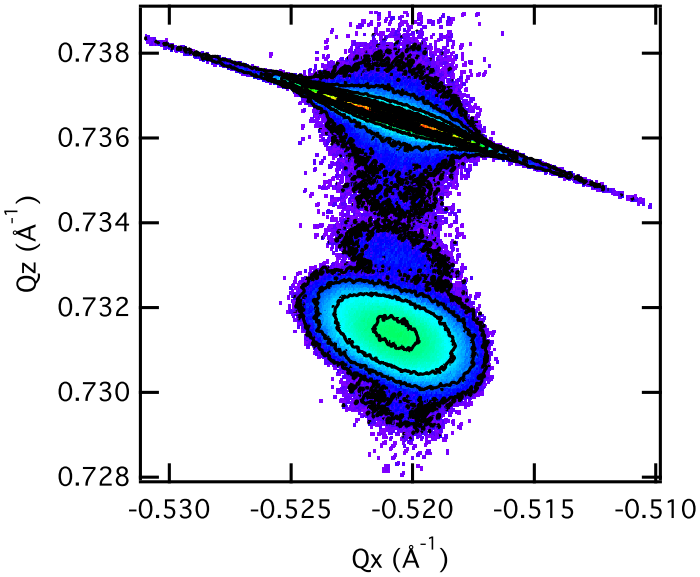
- Cross-section TEM shows flat GaP/Si interface
- Plan-view TEM
  - No APDs observed (upper limit 6 x10^5 cm^{-2})
  - No misfit dislocations observed (upper limit 2 x10^6 cm^{-2})



E. Warren, et al. *APL.* **107**, 8 (2015)

- Reciprocal space maps show that ~75nm film is coherently strained
  - No significant relaxation through misfit dislocations
  - Visible Pendellsung fringes indicates flat interface

224(GI) RSM

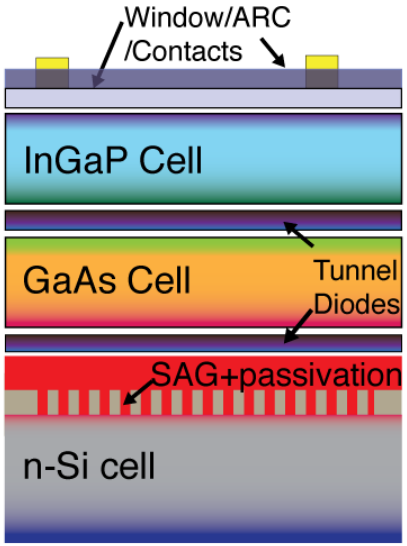


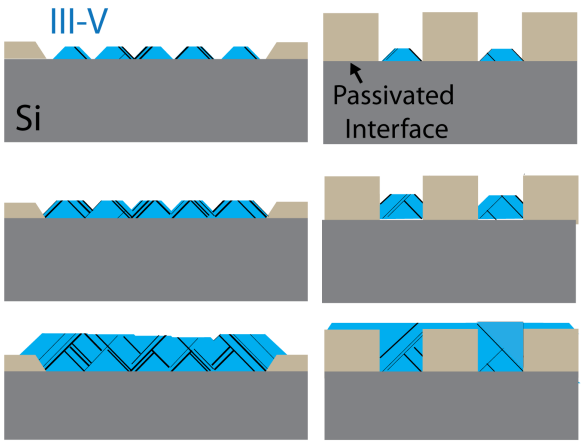
Goal: Incorporate in metamorphic tandem

Selective Area Growth of GaAs on Si

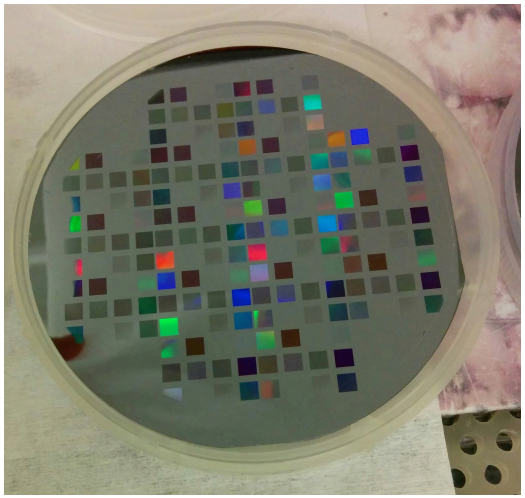
Goal: *Cheap* III-V/Si triple junction

- Compress graded buffer into nanometers using nanoscale aspect ratio trapping
- Enable Si surface passivation
- Use soft nanoimprint lithography for cheap large-area nanopatterning

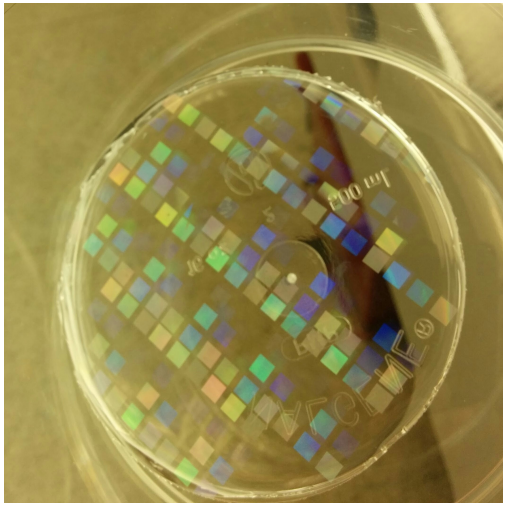




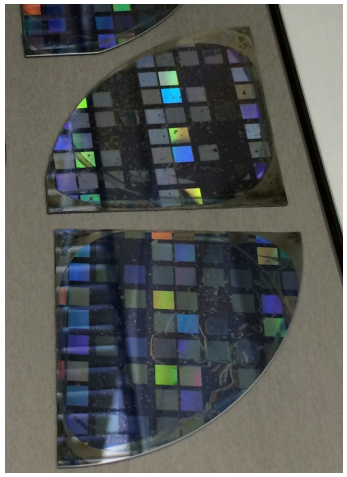
Silicon master



PDMS stamp

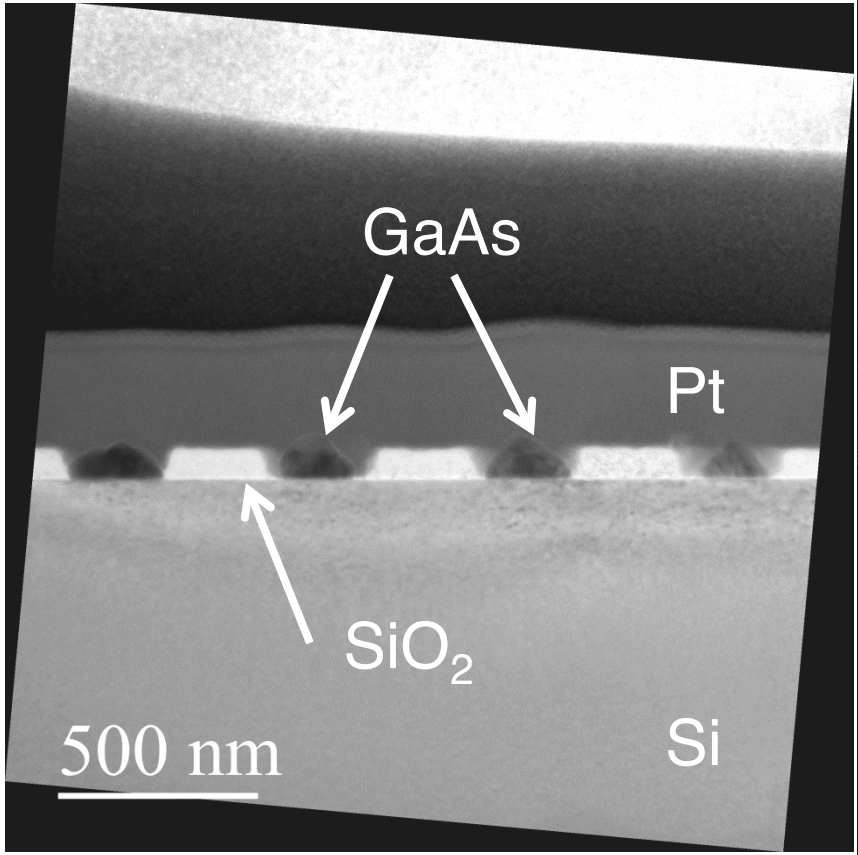


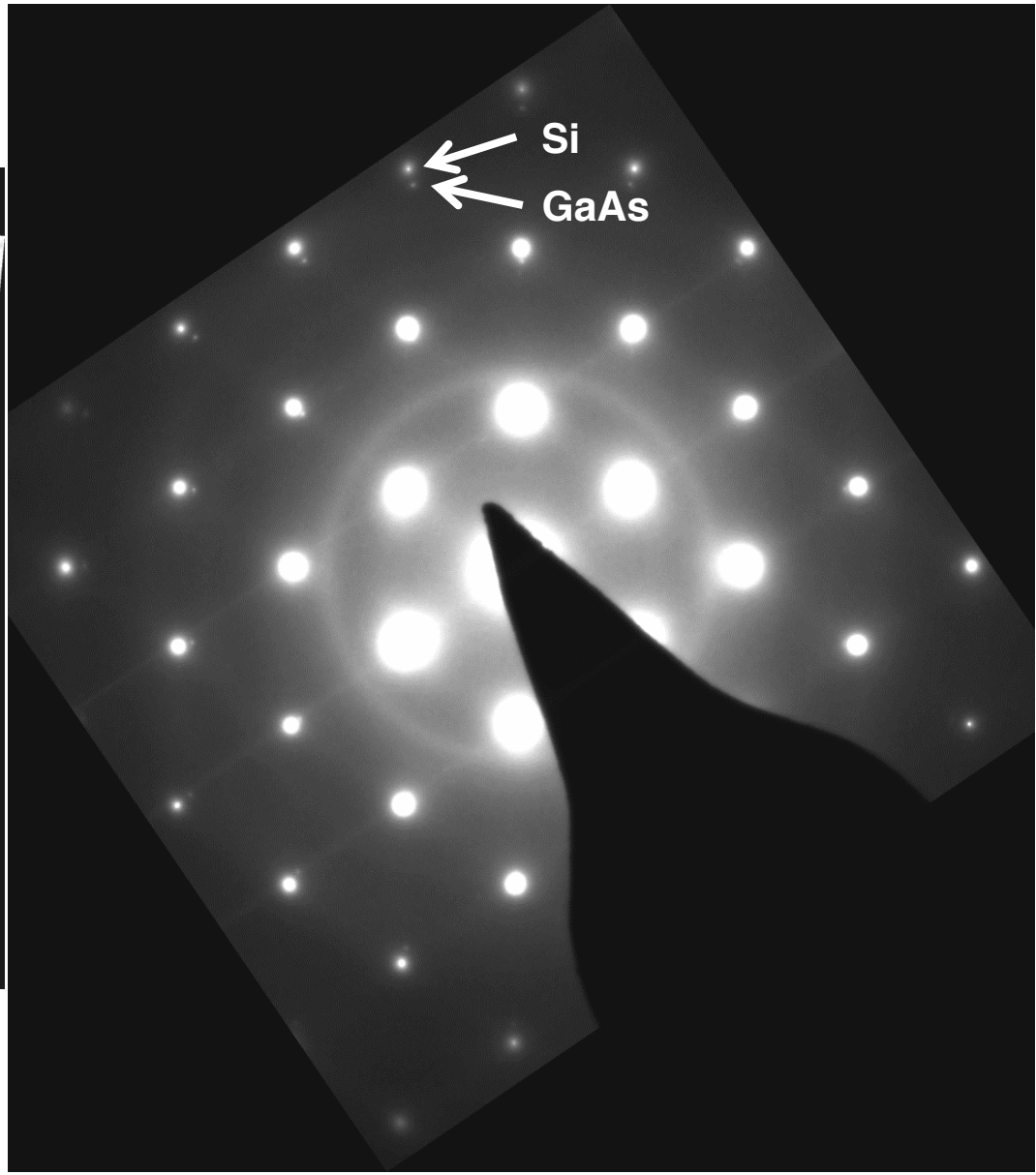
Patterned sol gel SiO_2 on Si samples



Nanoscale selective area growth of GaAs on Si

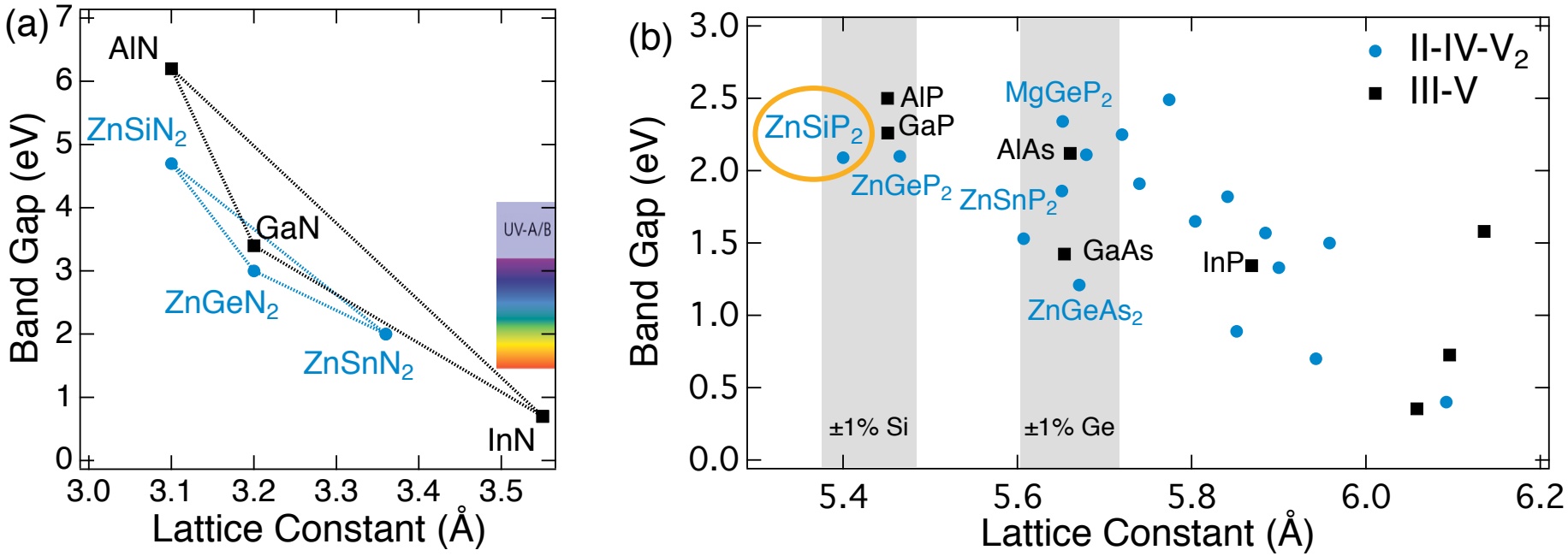
GaAs grows selectively, is epitaxial and partially relaxed





Next steps: optimize growth, patterns for high quality GaAs devices on Si

Beyond III-Vs: II-IV-V_2 materials



Moving to ternary basis increases tunability, phase space

- Nitrides: materials in visible space
- Phosphides: materials lattice matched to Si

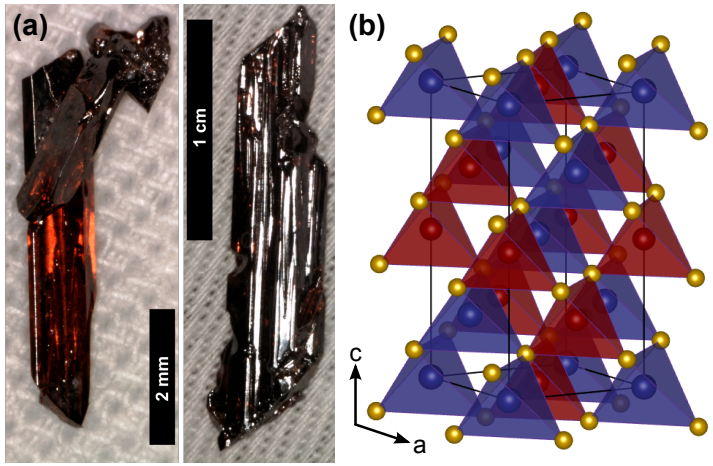
$ZnSiP_2$ – Possible Top Cell Material

Growing films of a new material is hard

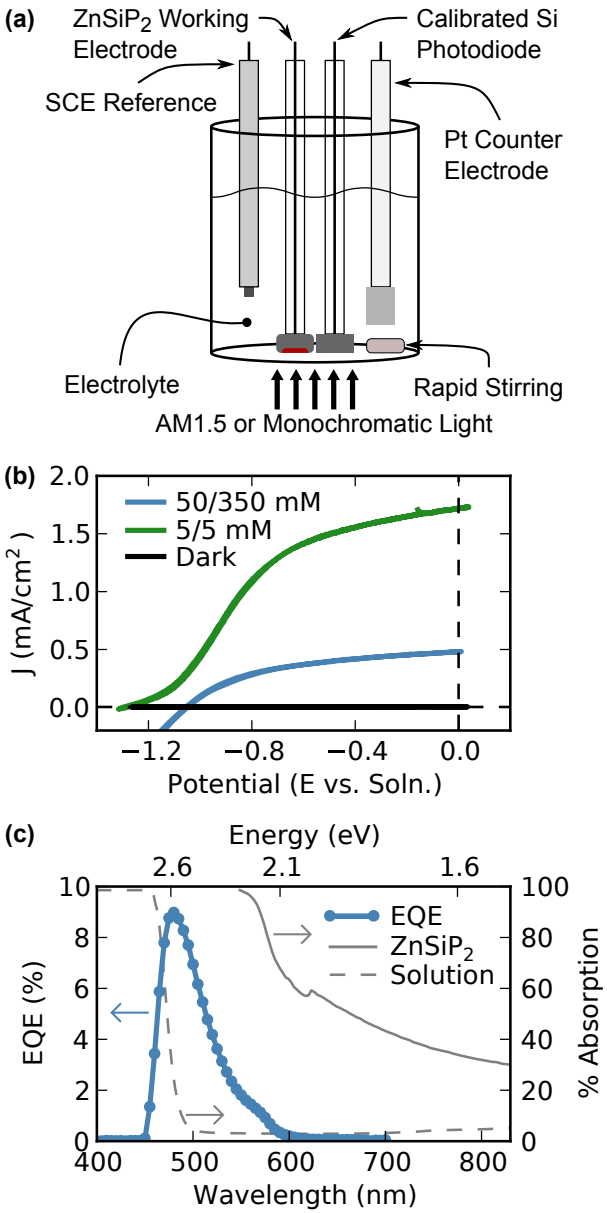
➔ Start by using bulk samples

Measured PV properties of bulk single crystals in a photoelectrochemical configuration

- Conversion efficiency ~ 1%
- Limited by parasitic absorption in solution, wide band gap
- High V_{OC} measured – shallow defects

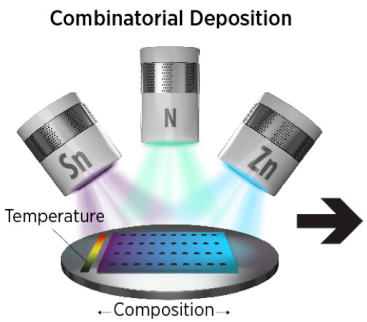


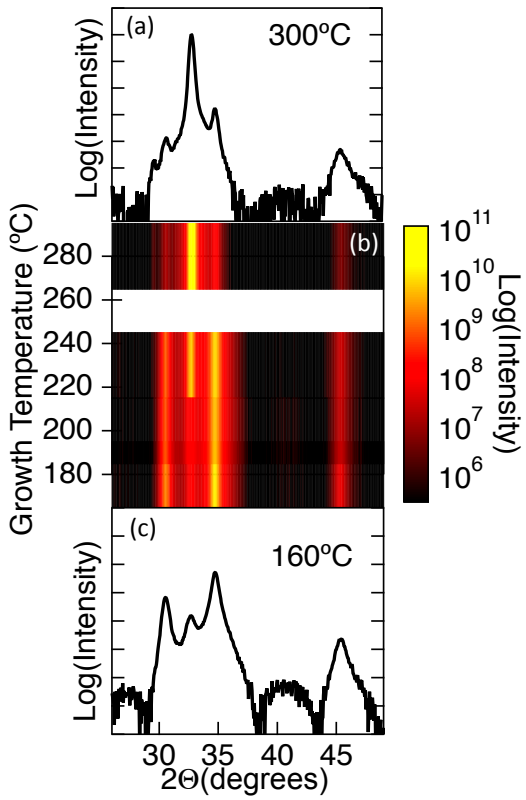
A. Martinez et al., Energy Environ. Sci. 9, 1031 2016



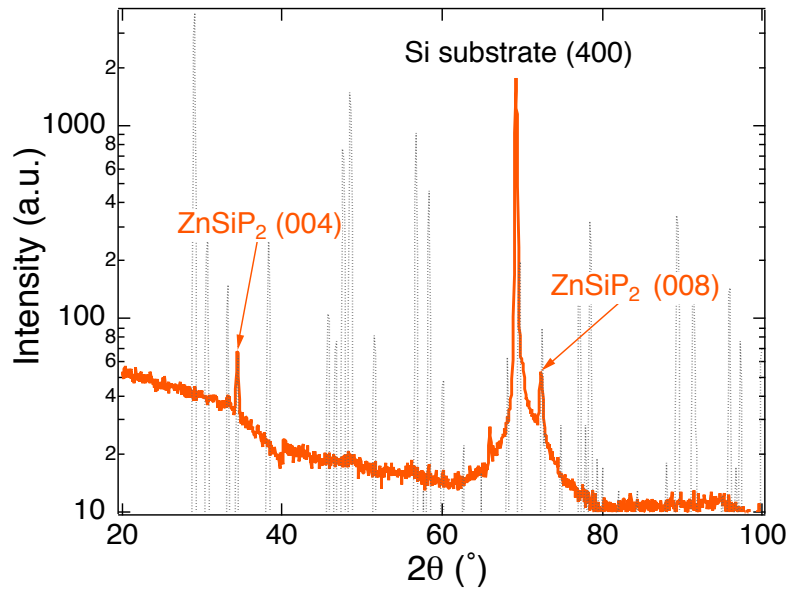
II-IV-V_2 film growth: Methods

Combinatorial Sputtering





Epitaxial Growth on Oriented Substrates

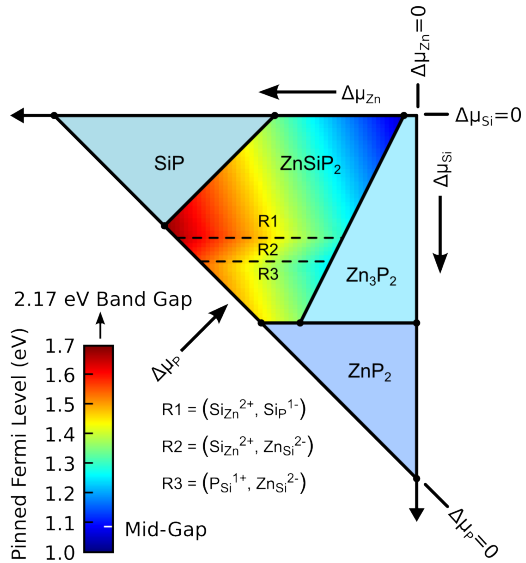


A. Fioretti et al., J. Mat. Chem. C 3, 11017 2015; see also talk by A. Zakutayev on Oct. 18

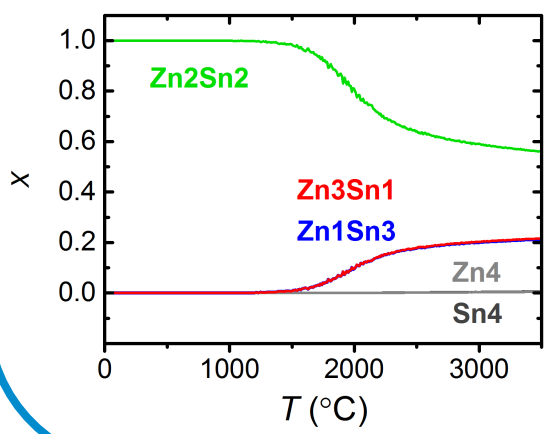
Collaborations

Theory: *S. Lany, V. Stevanović (NREL)*

Phase space, antisite formation energies

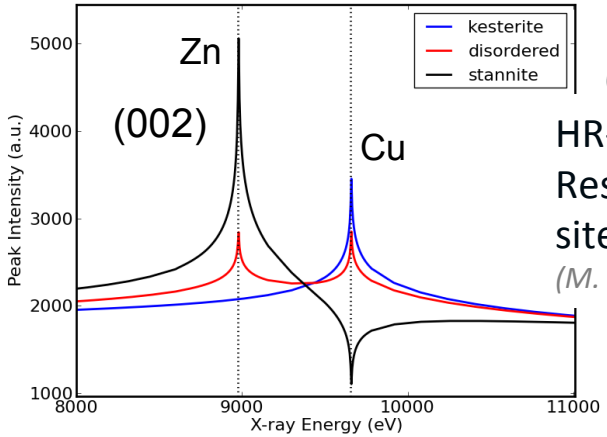


Martinez et al., *Energy Environ. Sci.* 2016



Motif-based disorder model

Advanced Characterization:



@ SLAC:

HR-XRD, Resonant X-ray: site disorder

(M. Toney, SSRL)

@ NREL:

- Photoelectrochemical measurements
- Microscopy: TEM, etc
- XPS
- Raman, PL, TRPL

Logistics

- Time frame: at least 3 months, up to several years
  - Currently: 6 students doing their PhD work with me, all plan to spend at least 2 years at NREL
- Start date: Summer 2017 or later

Contact:

Adele Tamboli – adele.tamboli@nrel.gov

- (any topic covered here)

Emily Warren – emily.warren@nrel.gov

- (III-V/Si growth, tandem device modeling)