Development of HVPE-Grown III-V Solar Cells Passivated with AlInP

Jacob T. Boyer, Kevin L. Schulte, Aaron J. Ptak, John Simon
National Renewable Energy Laboratory, Golden CO

PVSC 49 - Philadelphia, PA

Outline

1. HVPE Needs AlInP for Low-Cost Potential
2. Challenges of Growing AlInP in HVPE → Solutions
3. Developing AlInP for HVPE Solar Cells
4. Assessing AlInP Passivation → 1J GaAs Solar Cells
5. Implementing AlInP in 2J GaInP/GaAs Solar Cells
6. Progress of HVPE-Grown PV
7. Conclusions & Future Directions

Low-cost precursors /high utilization
→ *raw material/Wp*

→ See Simon *et al.*, *Crystals* 2019 *http://dx.doi.org/10.3390/cryst9010003 for* ***technoeconomic analysis*** *of* ***production-scale*** *HVPE*

High throughput
→ *wafers/h; MW/tool*

→ See Simon *et al.*, *Crystals* 2019 *http://dx.doi.org/10.3390/cryst9010003 for* ***production-scale HVPE concept***

Low-cost substrate
→ reuse via spalling

→ *See John Mangum – next talk: " High Efficiency solar cells grown on spalled germanium without polishing"*

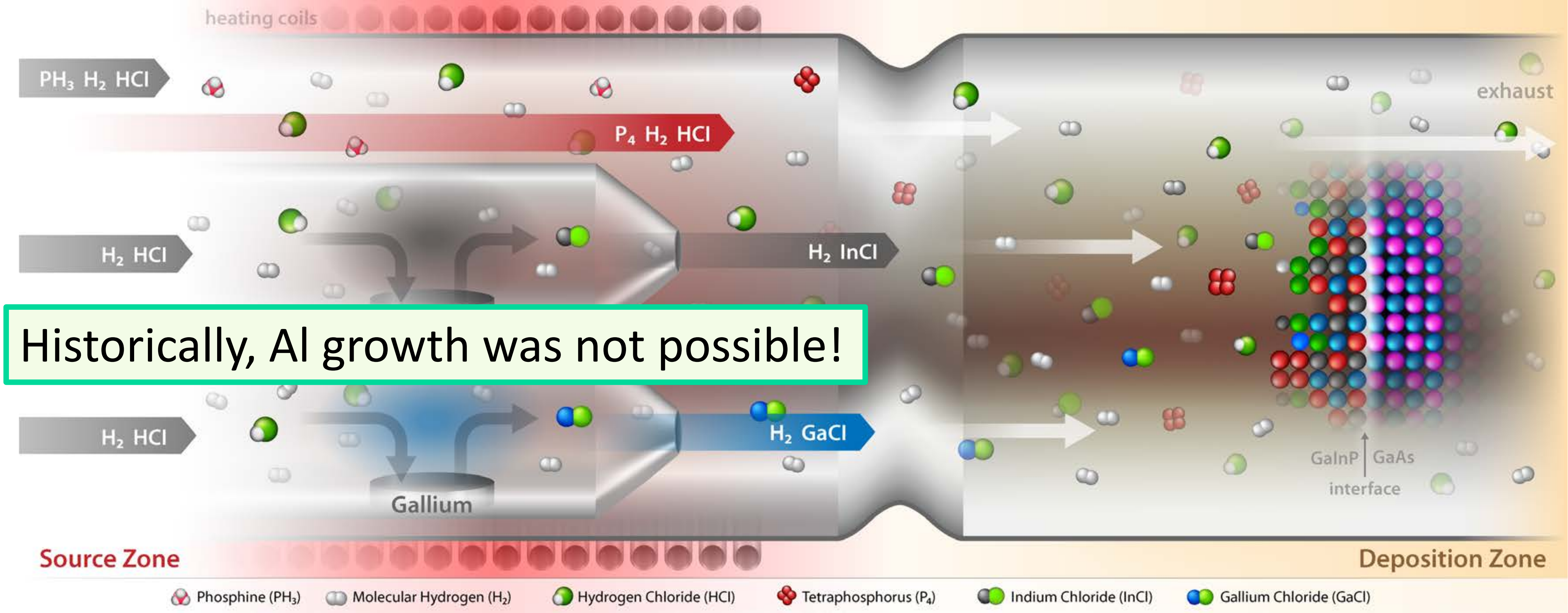
→ *See Anna Braun at 9:30a: "Planarizing HVPE growth on GaAs substrates produced by controlled spalling"*

Parity efficiency with state-of-the-art (OMVPE-grown PV)

→ *This talk: achieving passivating AlInP removes last barrier(s) to parity efficiencies*

What is needed to produce III-V PV at low cost?

→ Hydride Vapor Phase Epitaxy (HVPE) can address these



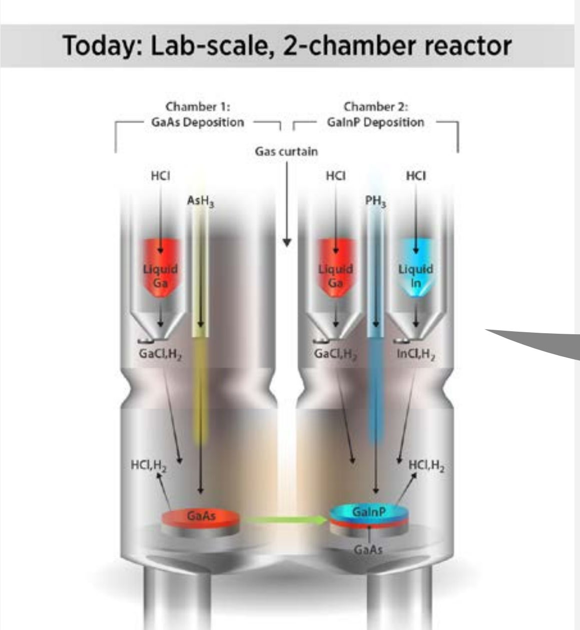
Historically, Al growth was not possible!

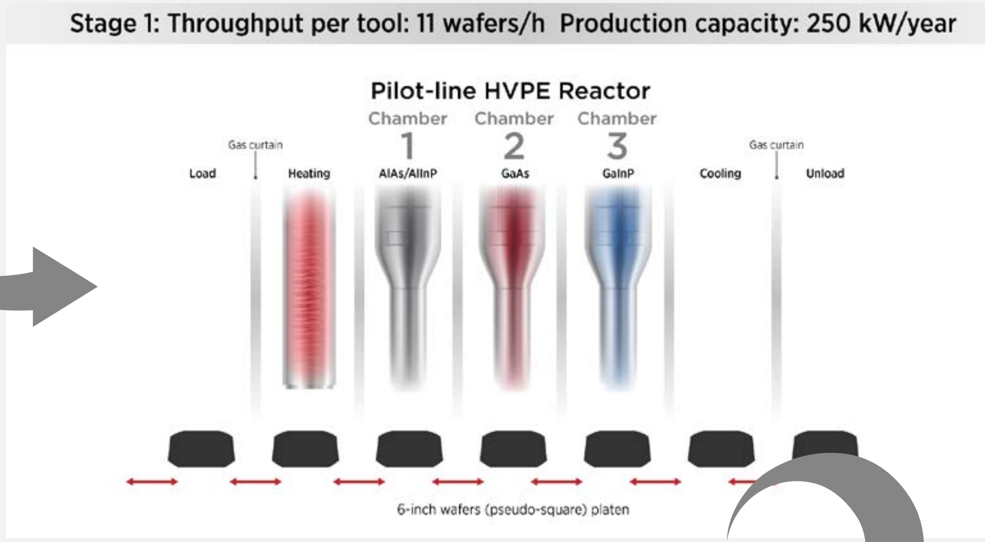
HVPE enables low-cost precursors

- Hot wall, atmospheric pressure epitaxial deposition
- Group V via hydride; Group III transport via chloride
- High precursor utilization (low V/III)
- Low-cost precursors (10x lower cost than organometallics)
- High growth rates (~530 µm/h)*

*McClure et al., Appl. Phys. Lett. **116**, 182102 (2020)

Towards High Throughput: Future HVPE reactor scale-up plans





High R_{growth} (µm's/min!)

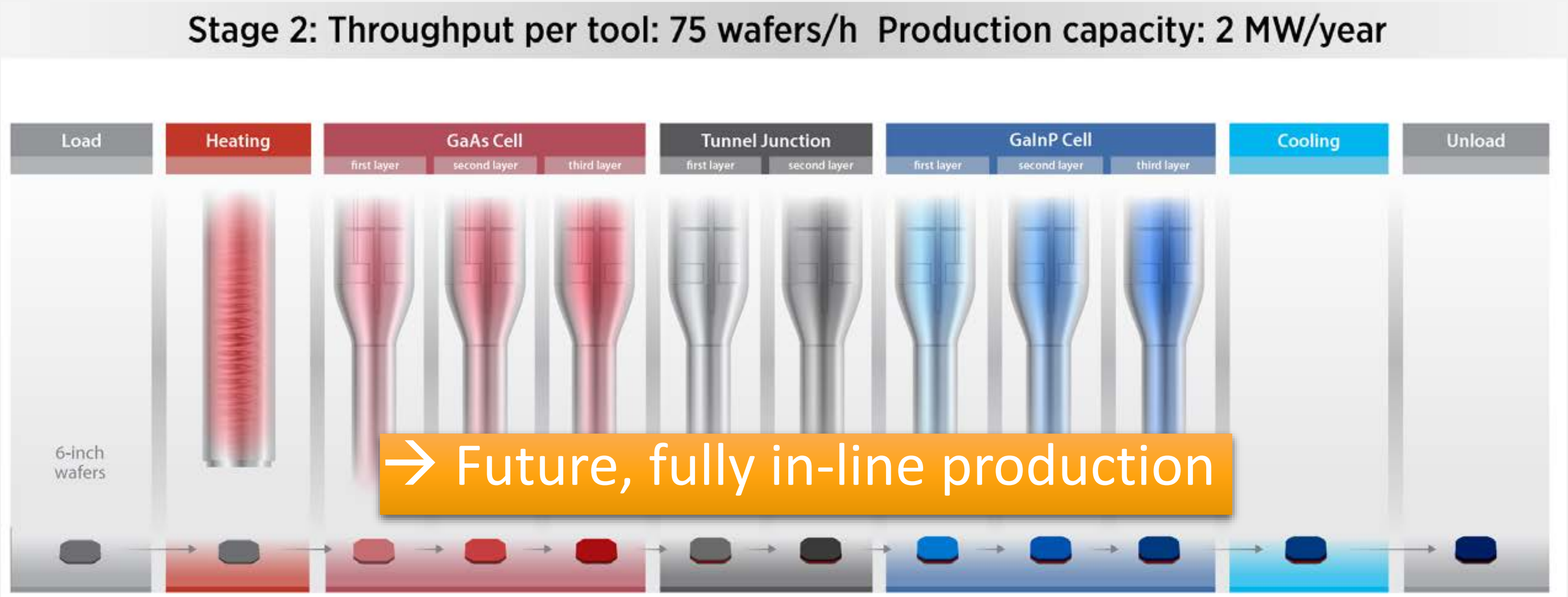
\+

In-line tool design

=

high throughput

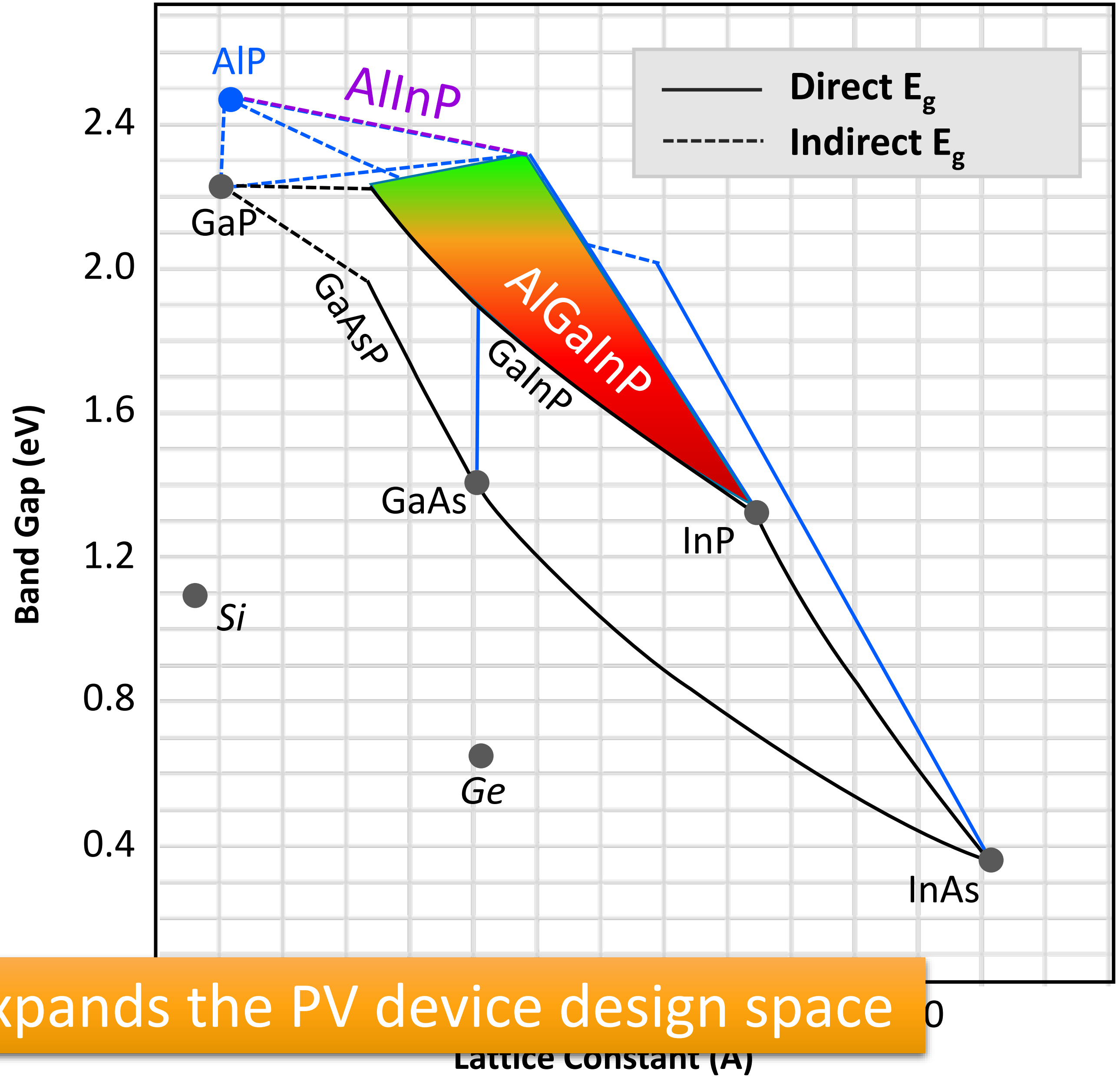
≈ 70 OMVPE's!



→ Future, fully in-line production

Benefits of Al-containing III-V materials

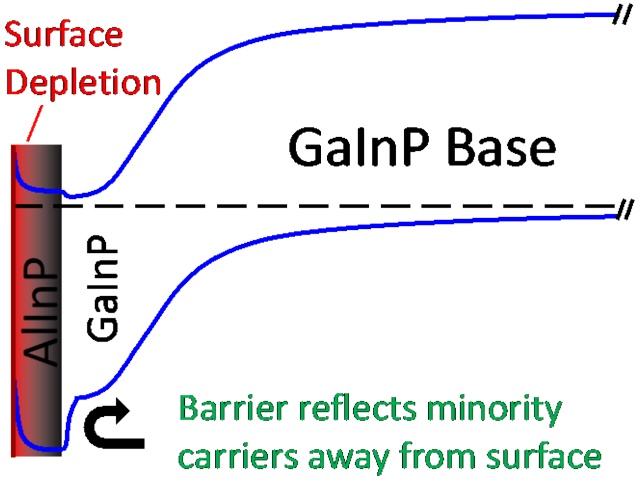
- Al greatly expands III-V As/P material palette
- AlInP enables widest E_G @ GaAs lattice constant
- AlGaInP has large region of tunable direct E_G



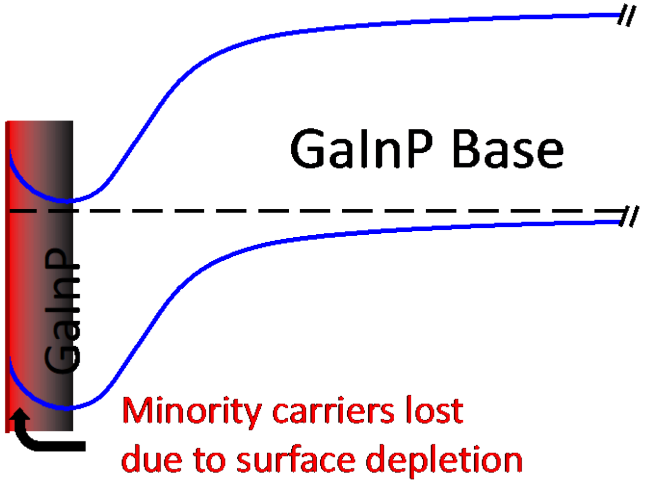
Adding Al to HVPE expands the PV device design space

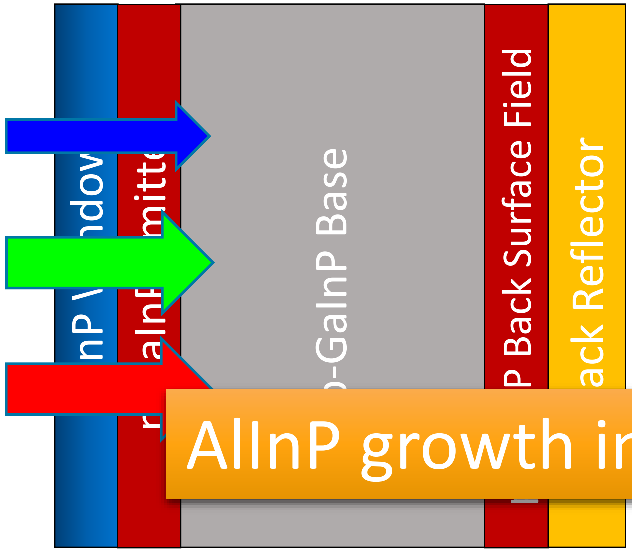
Need for AlInP – Passivated Solar Cells

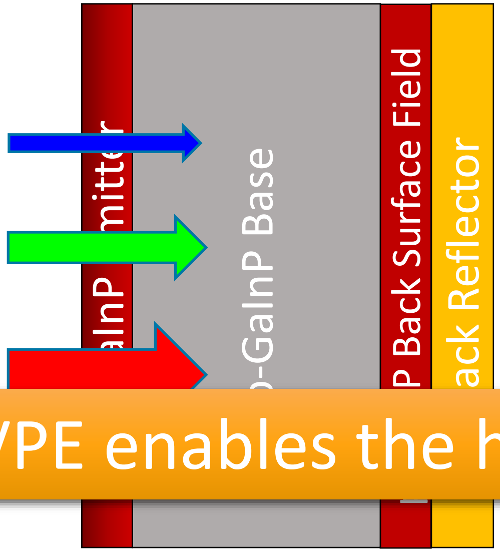
AlInP-passivated

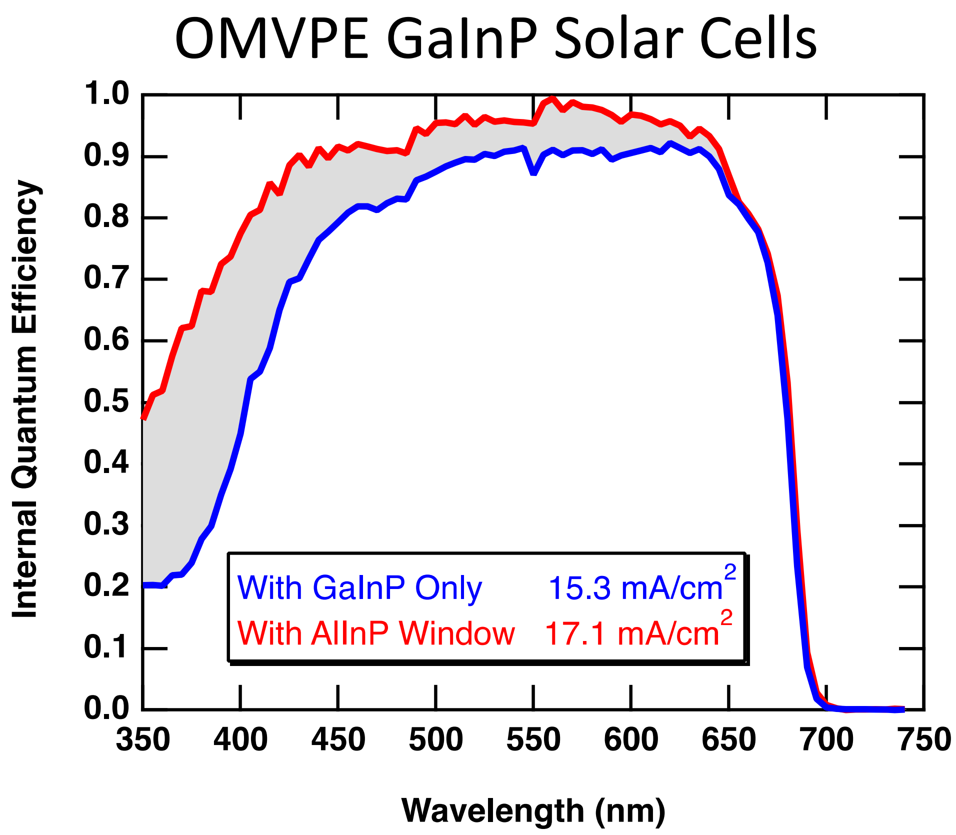


GaInP-'passivated'









AlInP growth in HVPE enables the highest efficiency potential of PV

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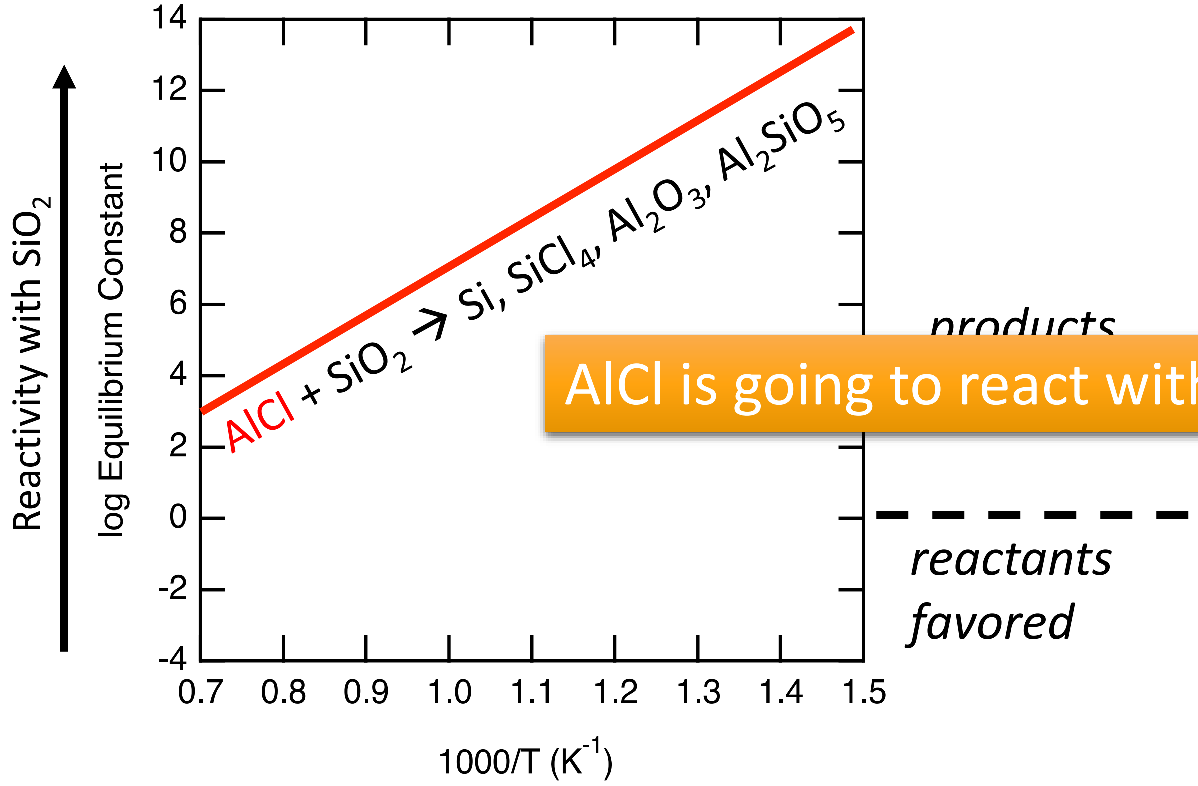
Challenge of Growing Al-Containing Materials by D-HVPE

Al(Ga)InP thought to be impossible by HVPE

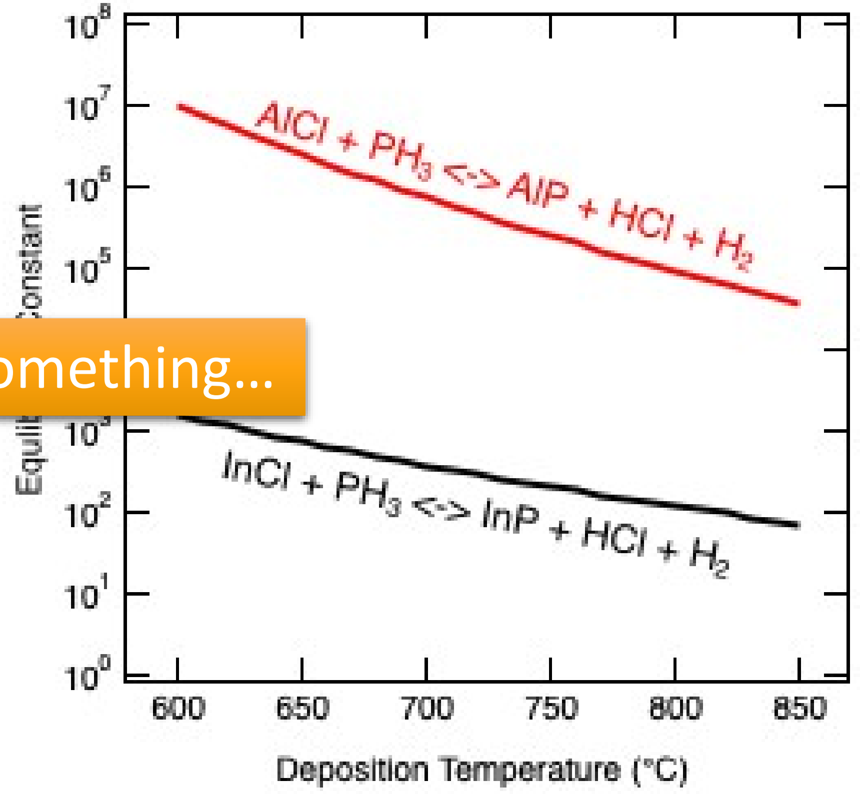
"Likewise, **(HVPE) growth of all Al** containing alloys is also **practically impossible** due to the chemistry of the chlorides of Al, the large Al distribution coefficient and the extremely reactive nature of Al chlorides. Thus, it was recognized that AlGaInP alloys would be grown only using either molecular beam epitaxy (MBE) or organometallic vapor phase epitaxial (OMVPE)..."

Yuan and Stringfellow, et al., J. Appl. Phys. **57**, 1380 (1985)



AlCl is going to react with something...

Kumagai *et al*. phys. stat. sol. (c) 0, No. 7, 2498 – 2501 (2003)

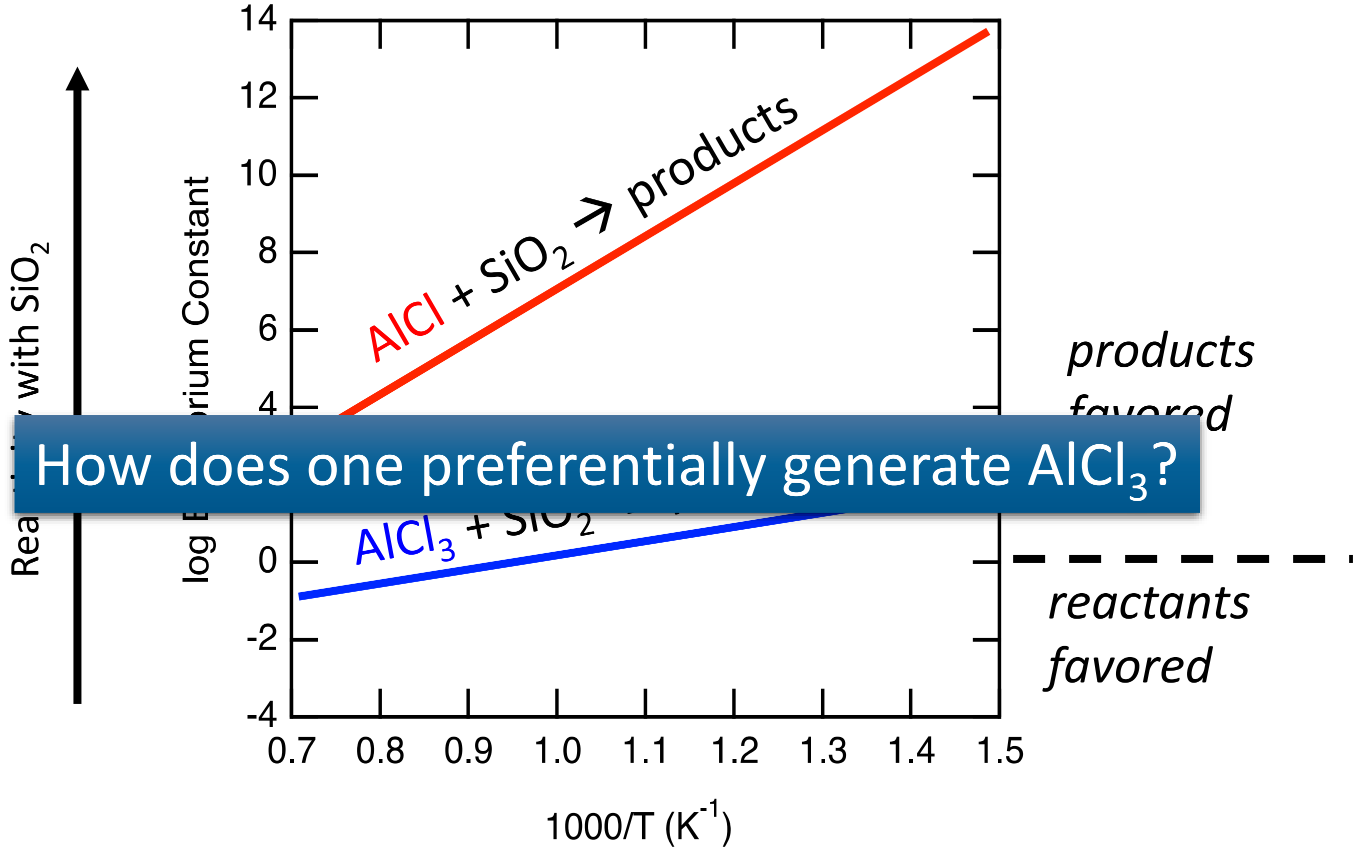


Schulte et al., *ACS Appl. Energy Mater*. **2**, 8405-8410 (2019)

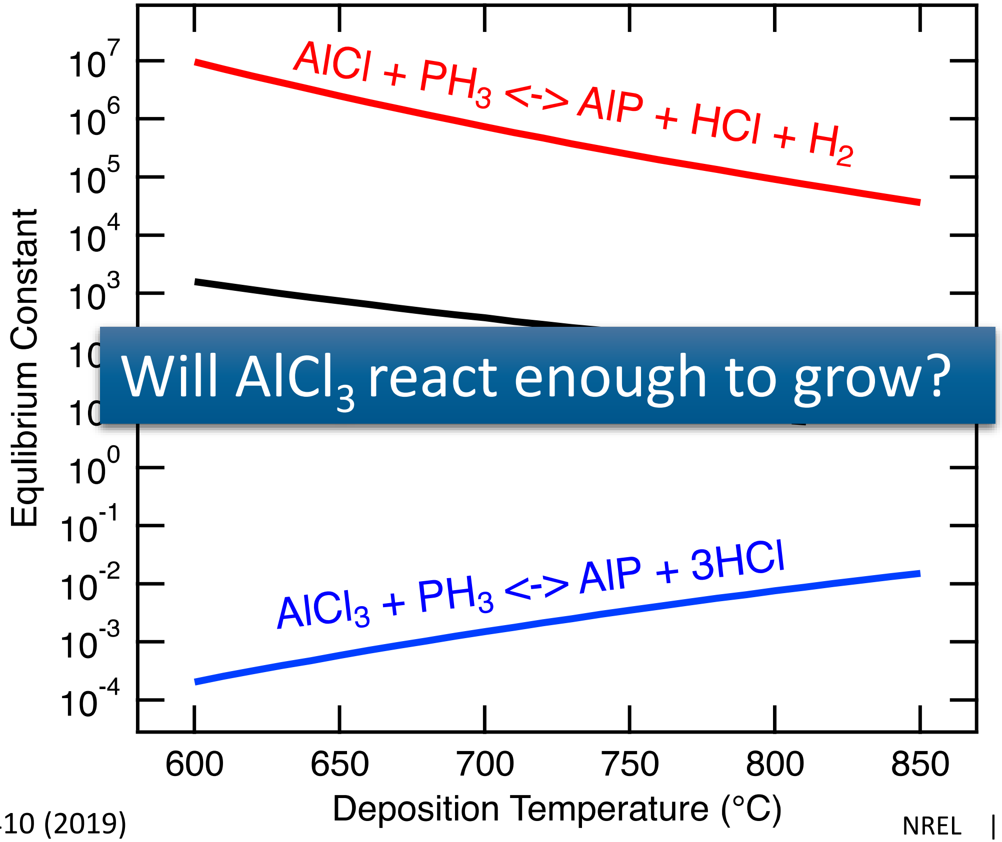
$AlCl_3$ – A Less Reactive Al Precursor

$AlCl_3$ - 'good' precursor
→ low reactivity with reactor quartz

AlCl - 'bad' precursor
→ high reactivity with reactor quartz
→ Can contribute to Si and O impurities



How does one preferentially generate $AlCl_3$?

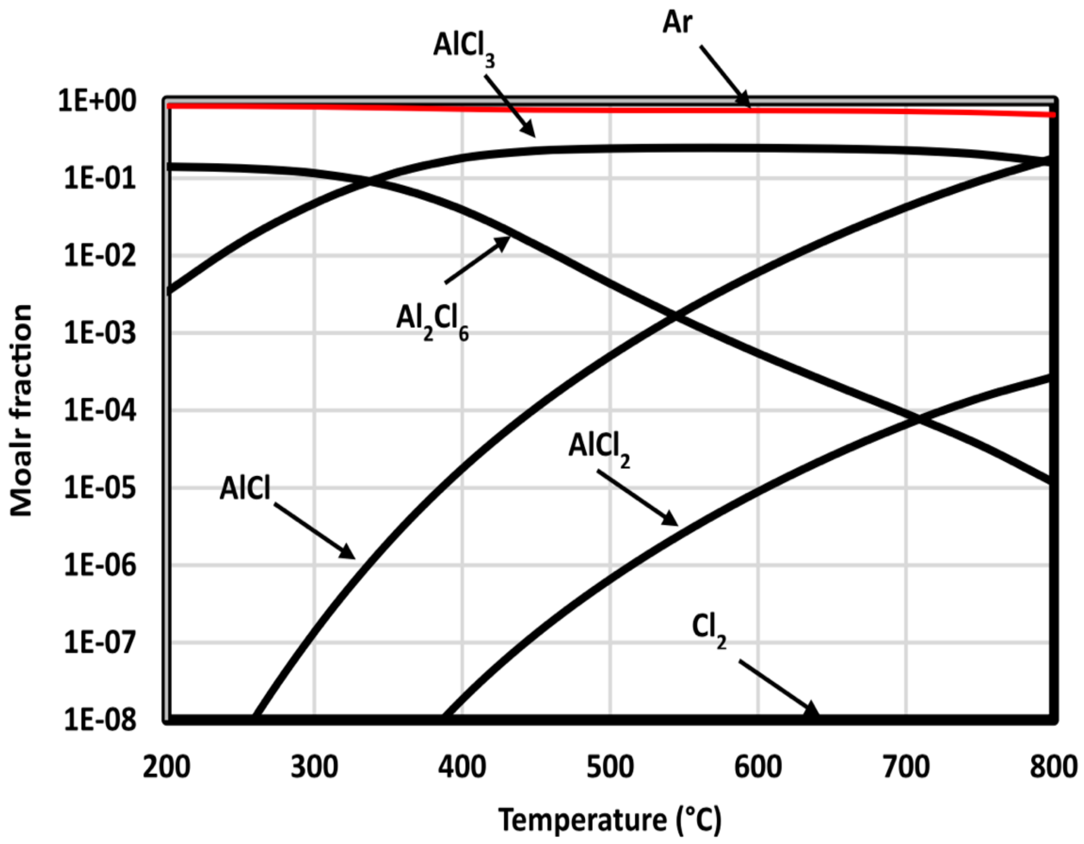


Will $AlCl_3$ react enough to grow?

Schulte et al., *ACS Appl. Energy Mater.* **2**, 8405-8410 (2019)

Solution: Generate $AlCl_3$ without AlCl at lower temperature

Molar fraction of Al-chlorides generated from HCl

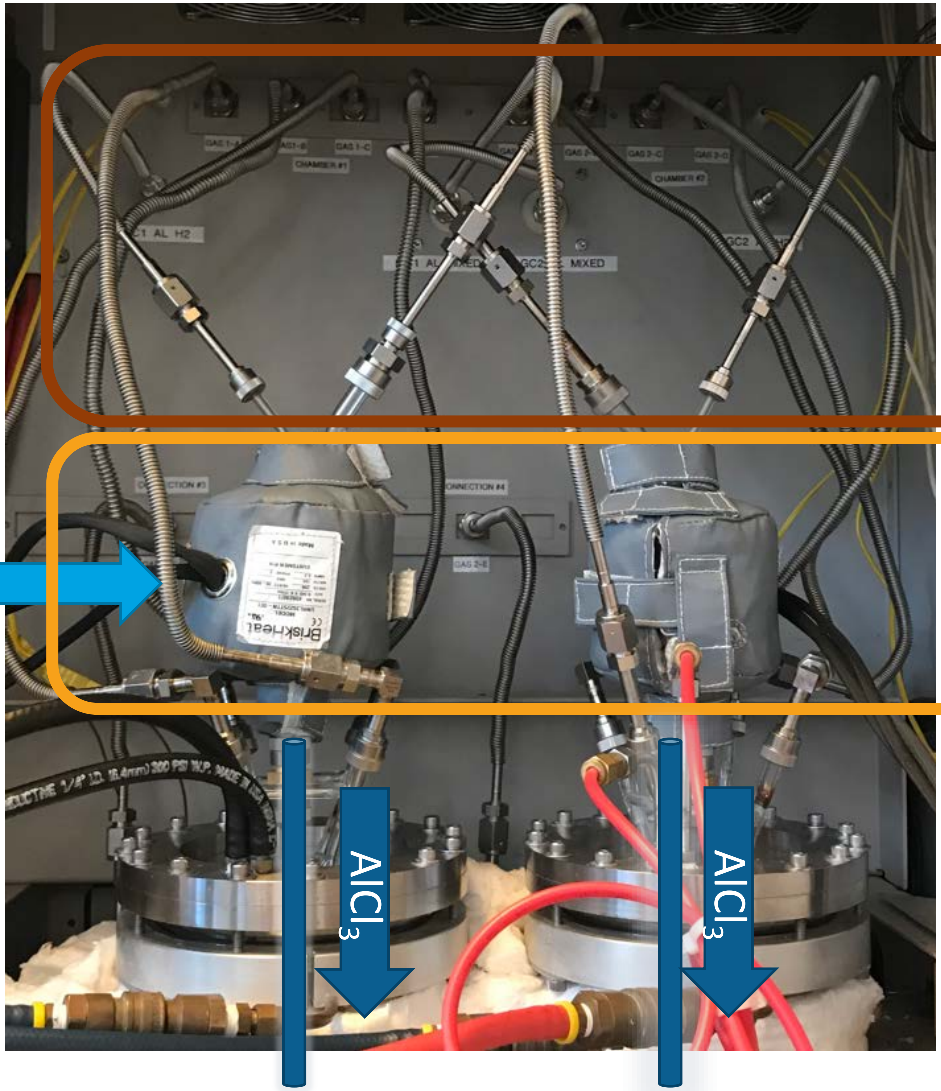


M. Pons et al. Journal of Crystal Growth 468 (2017) 235–240236

Ex-Situ $AlCl_3$ Source

- React Al and HCl @ 400°C to favor $AlCl_3$ generation
- 4 orders of magnitude less AlCl

Solution: Generate $AlCl_3$ without AlCl at lower temperature



HCl and H_2 gas inlets

Heaters held at 400°C

Quick flow $AlCl_3$ in quartz tube past 800°C source zone

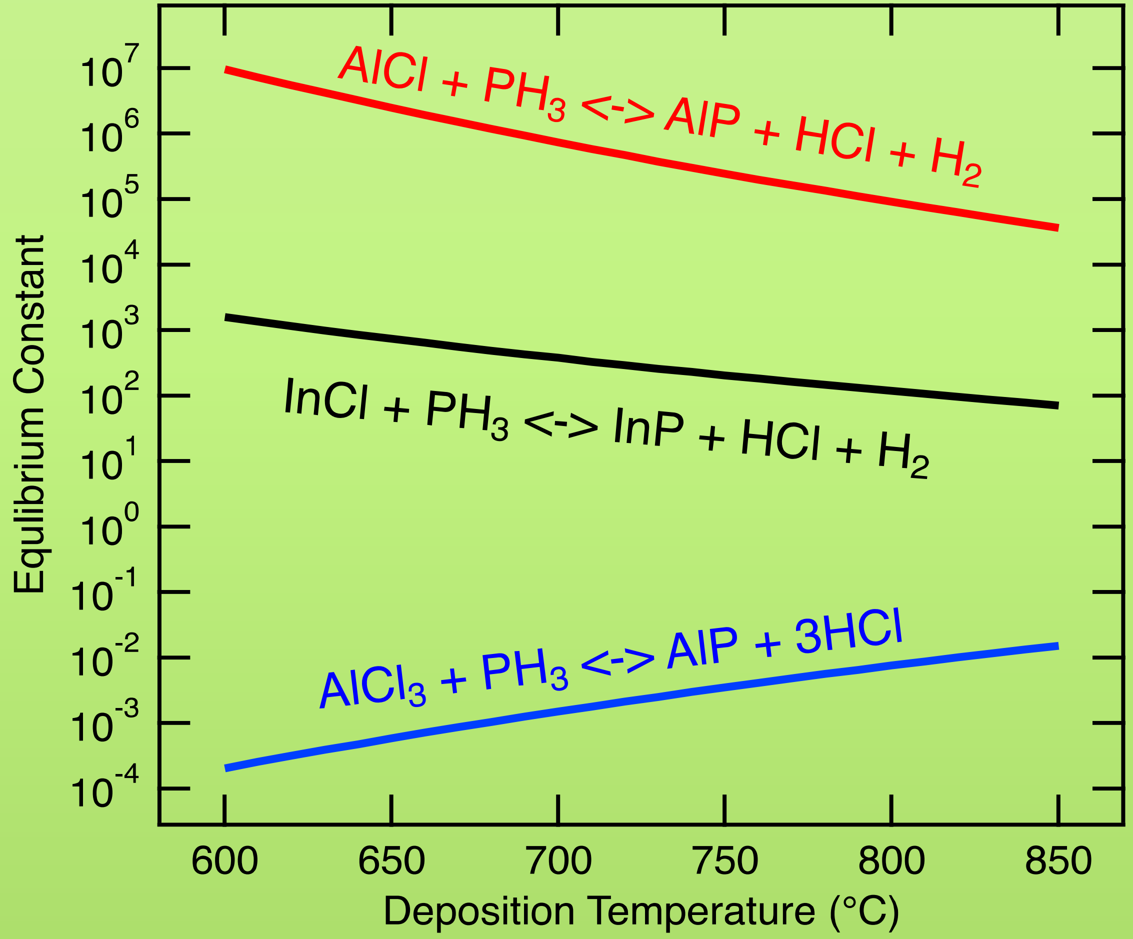
Ex-Situ $AlCl_3$ Source

Generate $AlCl_3$ just above reactor at colder temperature

Al ampoule renovated – closer to reactor for easier operation with less maintenance

Solution: Use Uncracked Hydrides and $AlCl_3$ to Grow AlInP

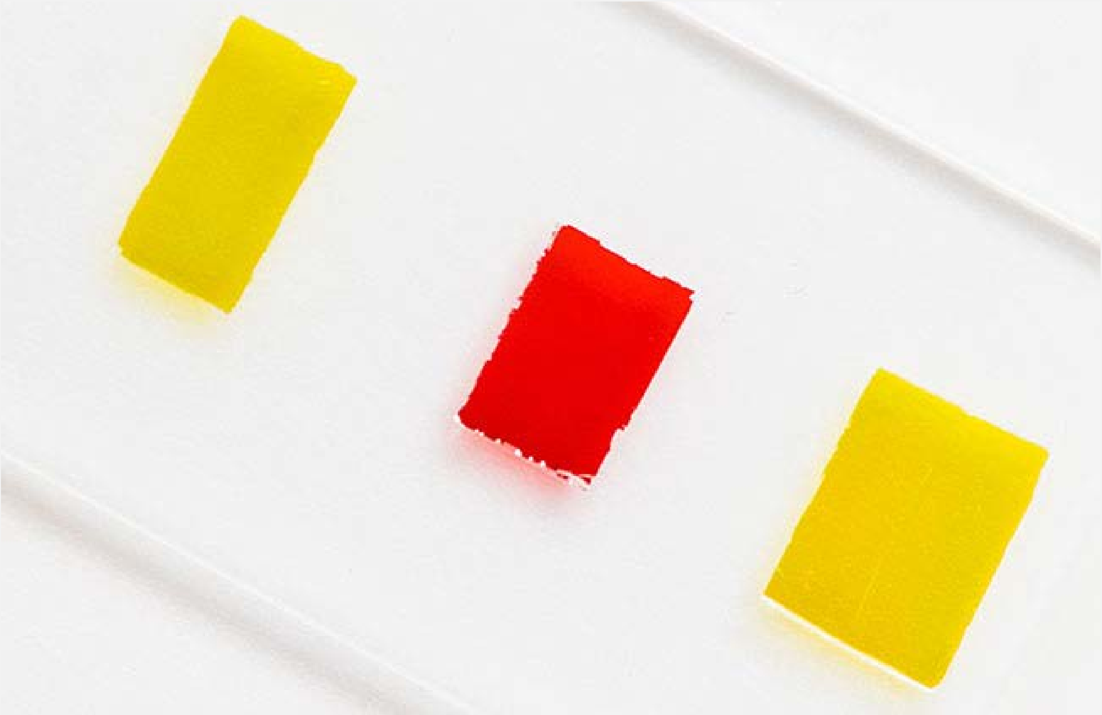
Thermodynamics predicts $AlCl_3$ is too stable to grow AlInP



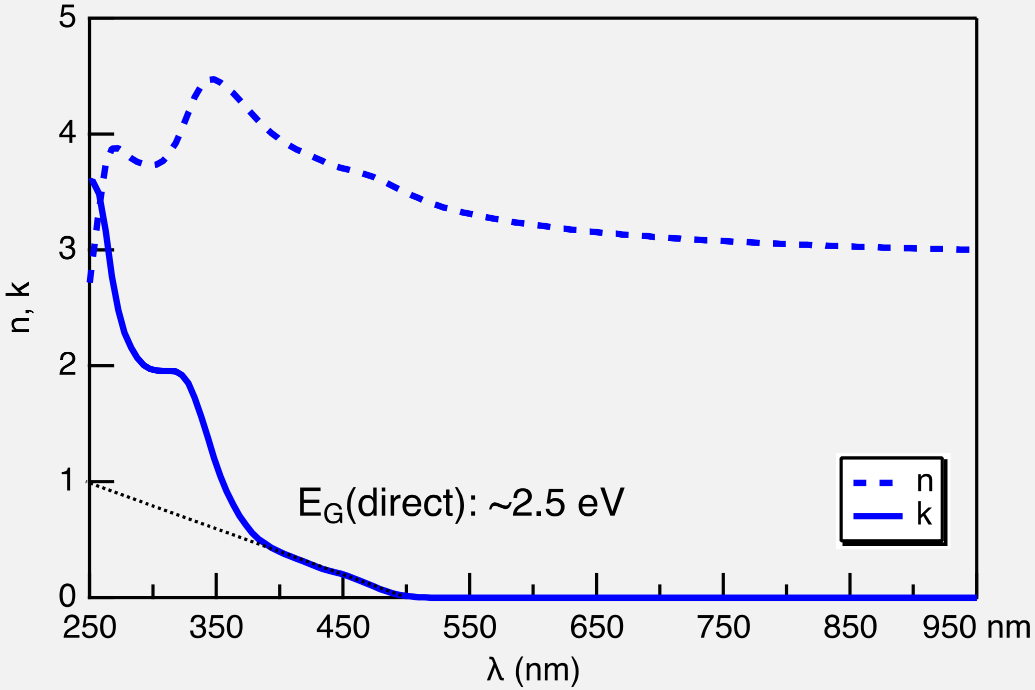
Schulte et al., *ACS Appl. Energy Mater*. **2**, 8405-8410 (2019)

Solution: Use Uncracked Hydrides and $AlCl_3$ to Grow AlInP

Transmission Samples – HVPE Al(Ga)InP



Spectroscopic Ellipsometry – HVPE AlInP



Verified that we have wide bandgap material commensurate with Al(Ga)InP!

Schulte et al., *ACS Appl. Energy Mater.* **2**, 8405-8410 (2019)

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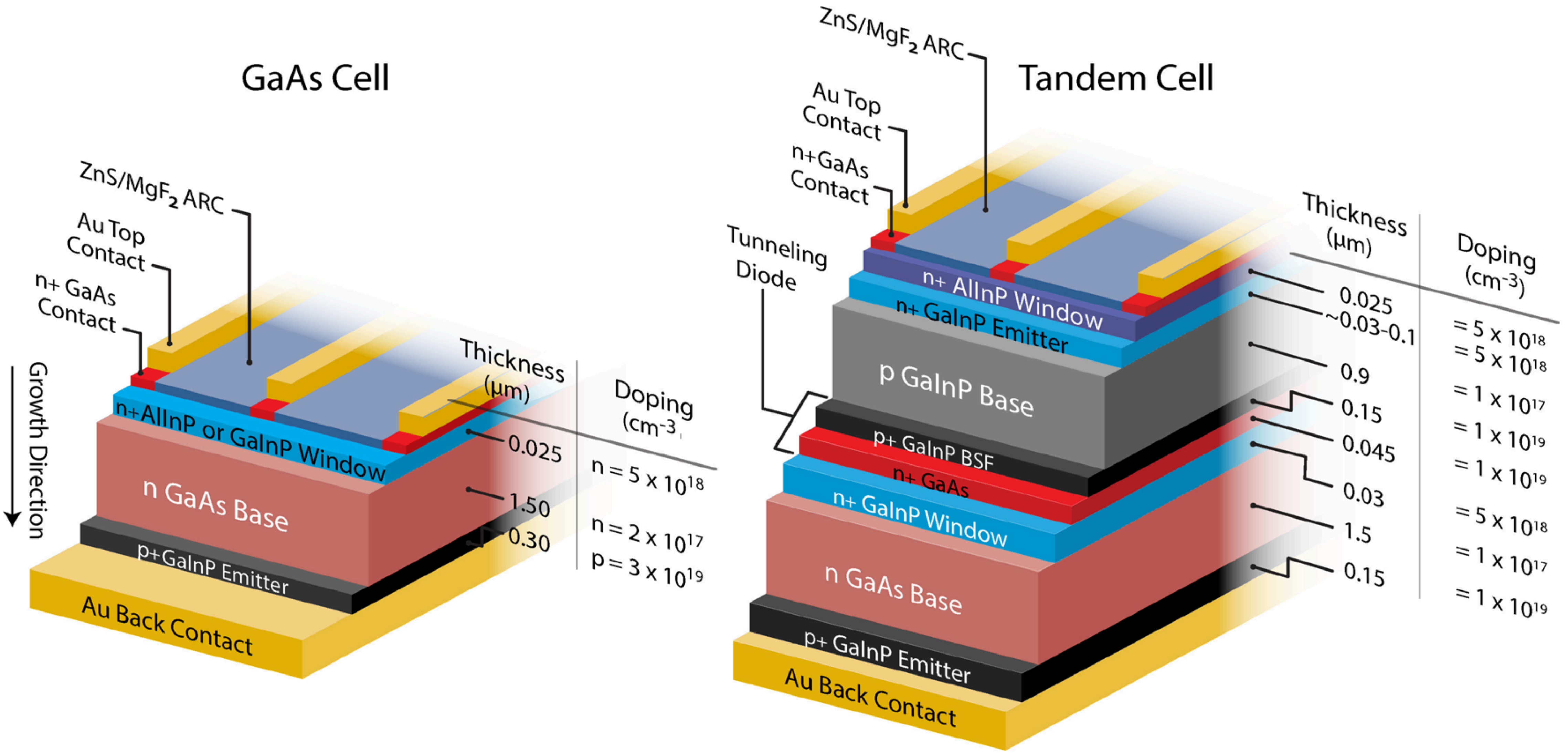


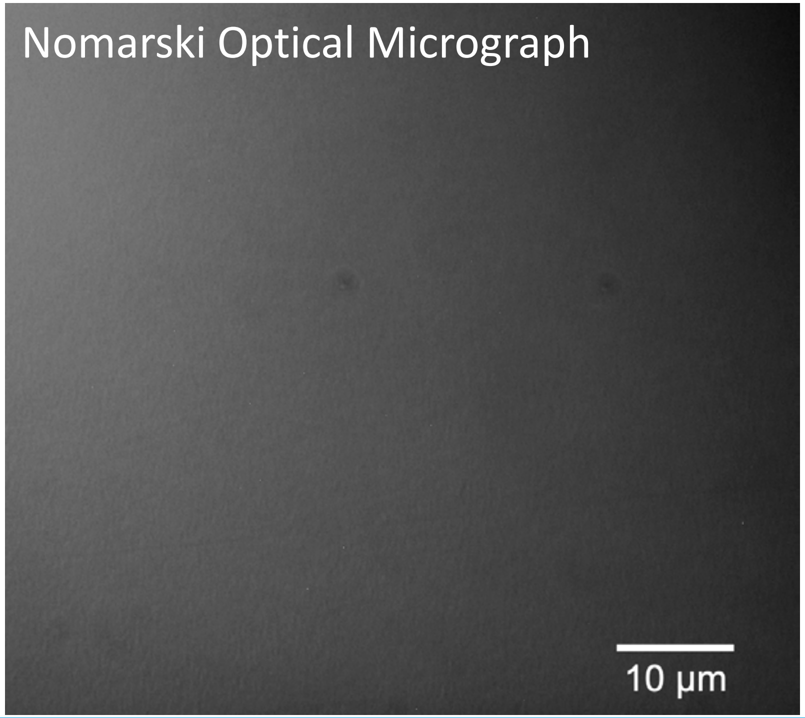
AlInP in HVPE-Grown PV Device Structures

AlInP window requirements:

- Smooth morphology for inverted growth
- Doping to n = 5 x 10^{18} cm^{-3} or higher

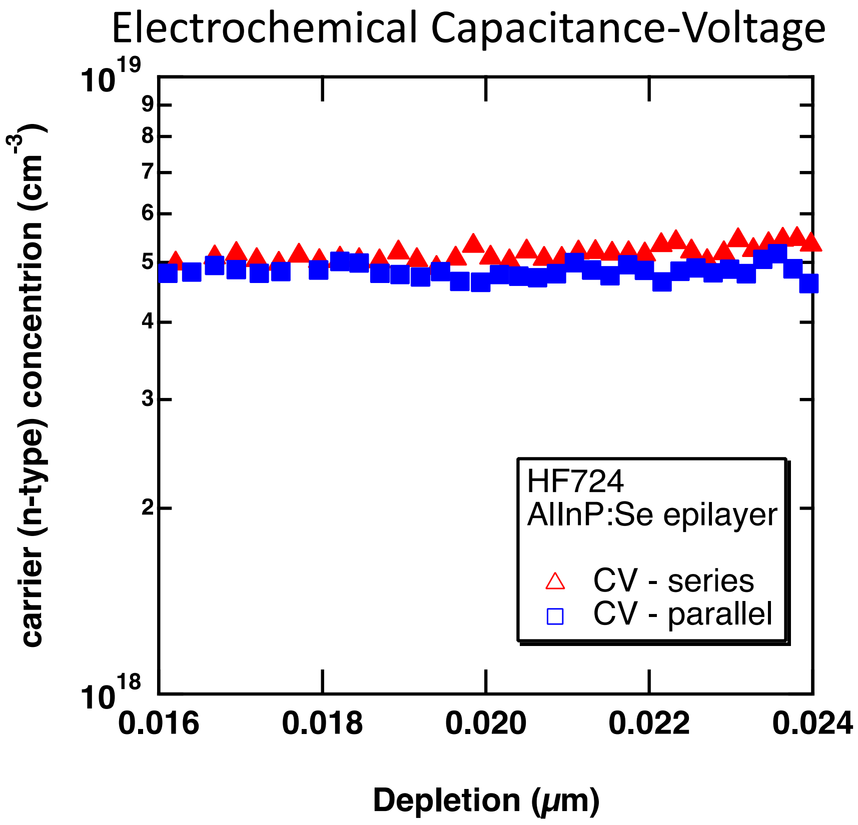
Surface Morphology

- Smooth morphology good for inverted devices (grown before active layer)
- R_q: 1.66 nm from 5x5 µm atomic force micrograph



Carrier Concentration

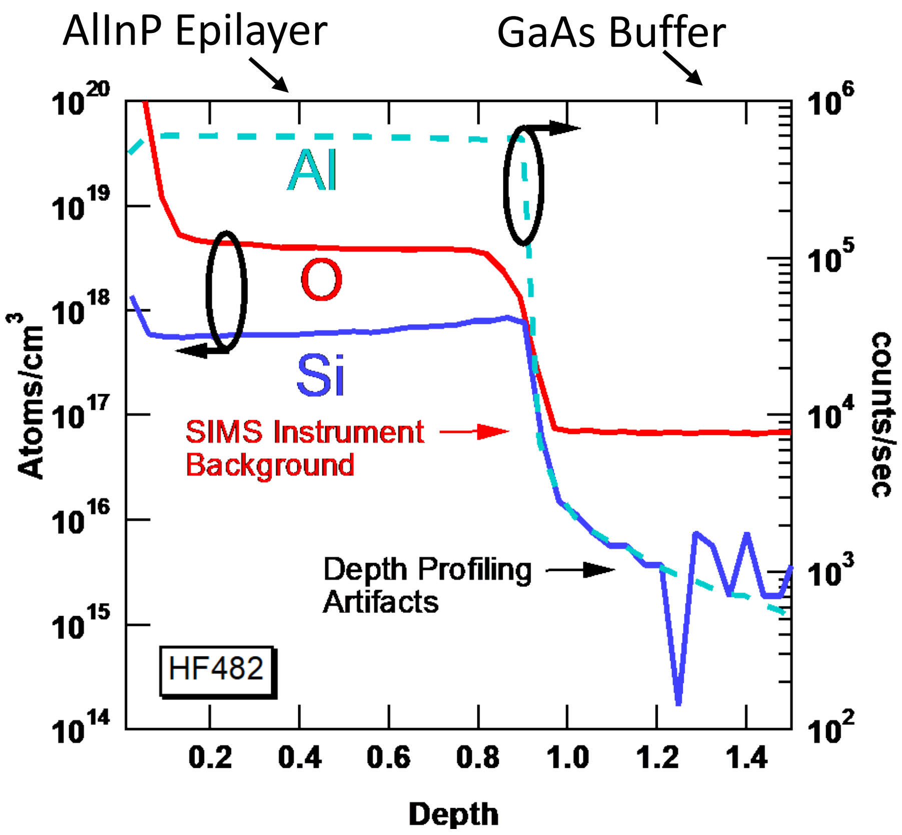
- *N*-type doping at 5 x 10^{18} cm^{-3} achieved with H_2Se



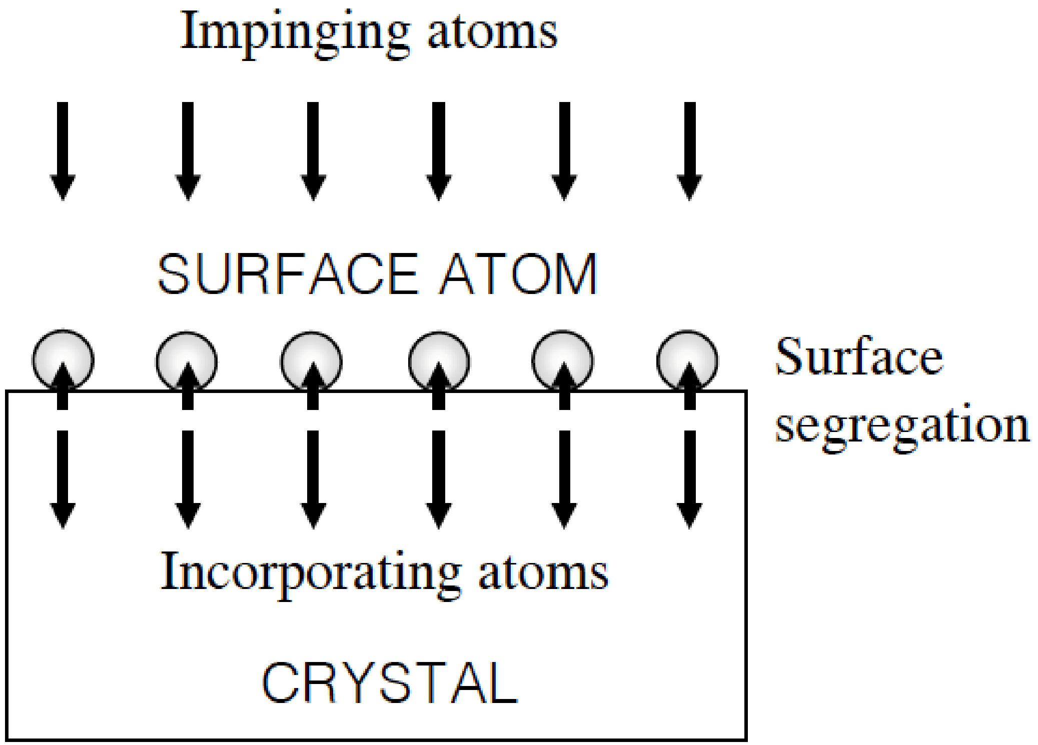
Towards Implementing AlInP in PV Devices

- Achieved smooth AlInP with target doping for use as window layers

Thick AlInP epilayer



Surface [O] saturates after ~100 nm of growth
→ O incorporation rate = O impingement rate



Dynamic Secondary Ion Mass Spectrometry

- Significant [Si] and [O] observed in AlInP
- AlInP growth has minimal effect on other layers
- Less [O] in thinner layers – surface segregation likely

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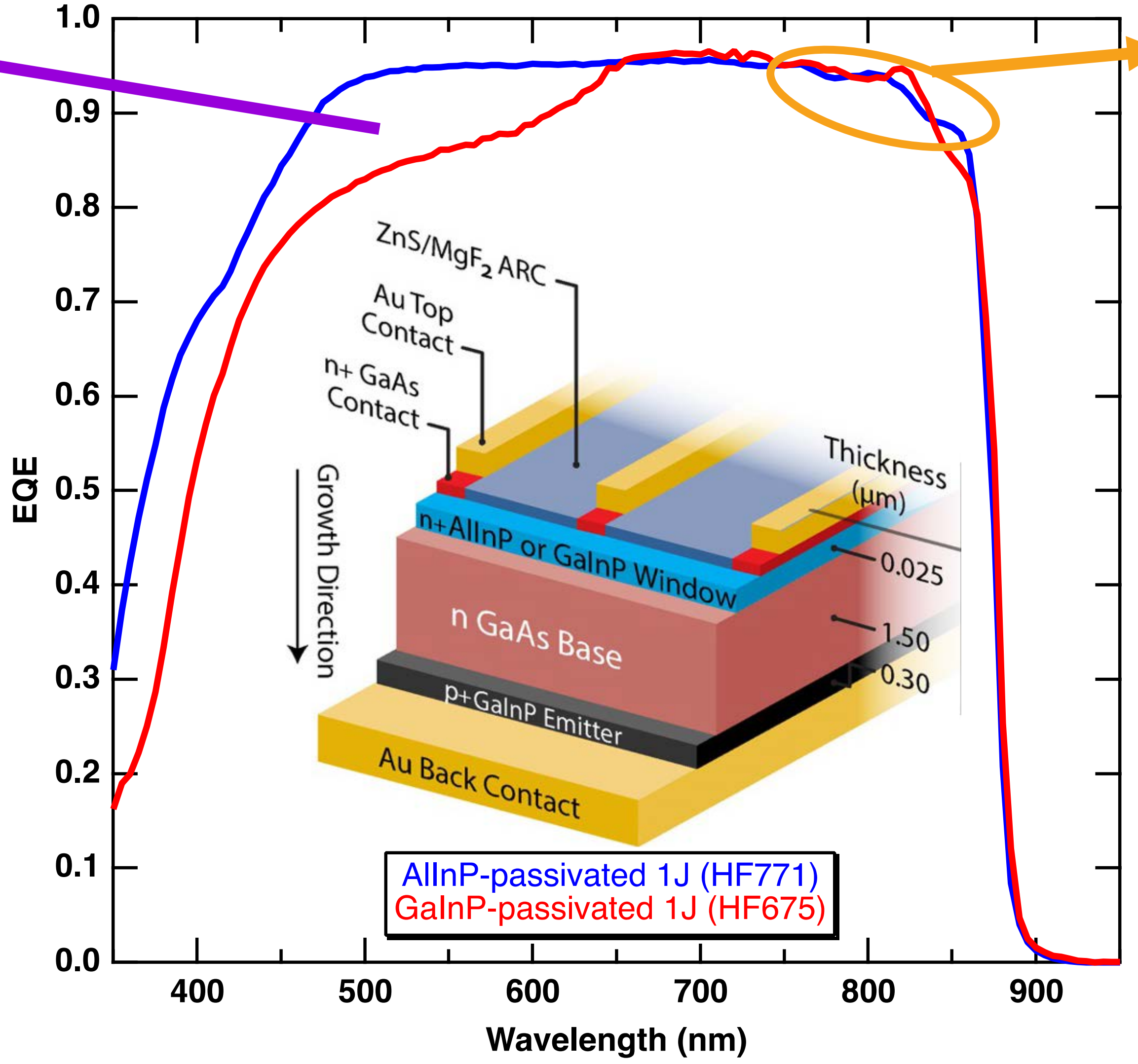
Improved short wavelength current collection

→ Reduced parasitic absorption of AlInP window

→ Accounts for 1.3 mA/cm² boost



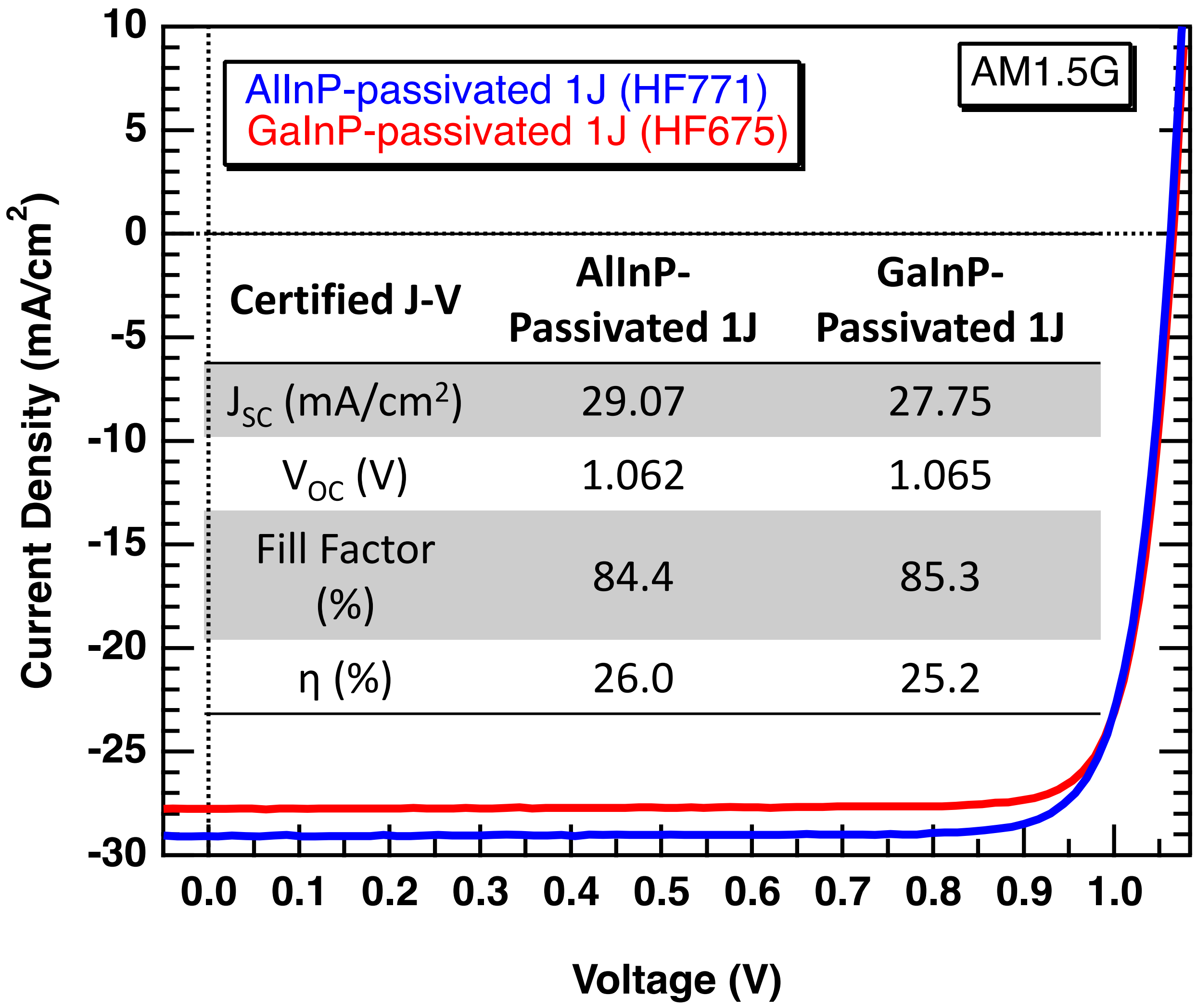
Unchanged long wavelength current collection

→ Equivalent passivation & no degradation of other layers

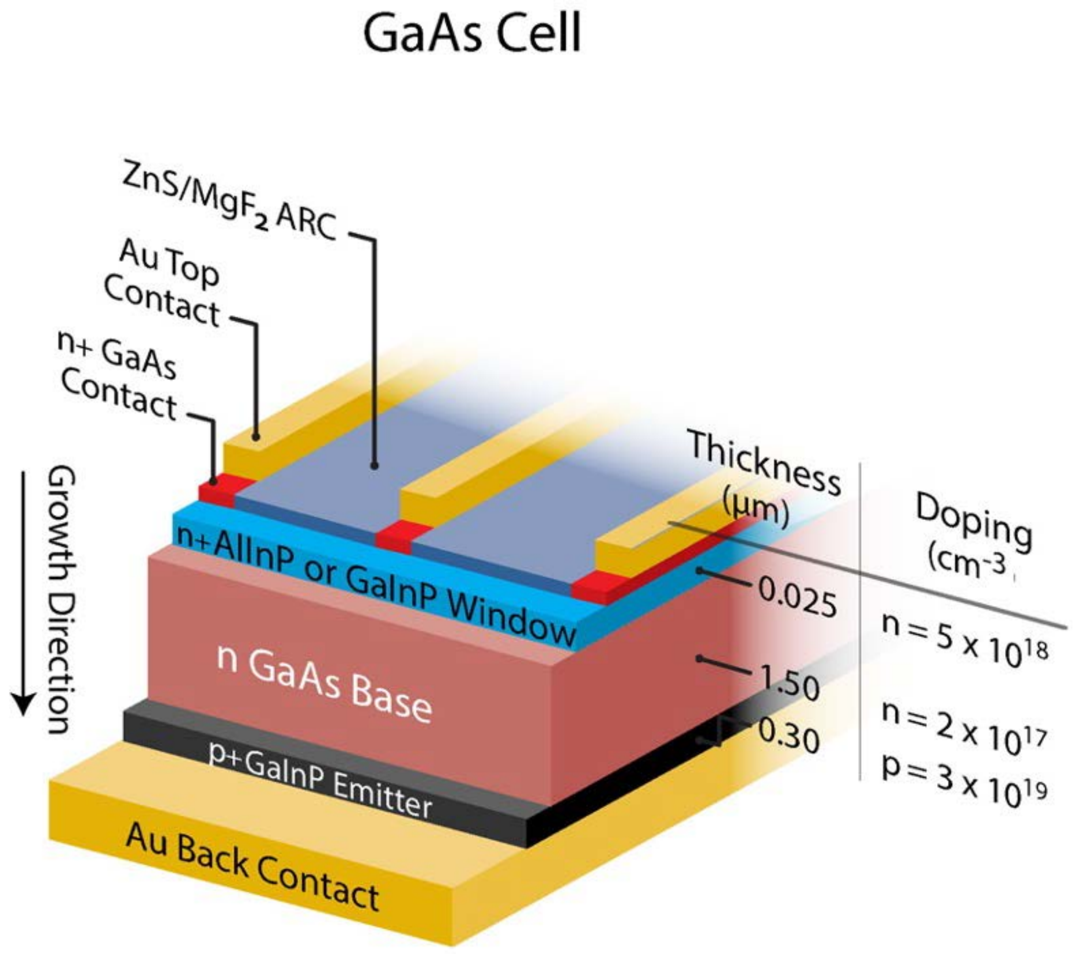
→ Rear junction cells especially sensitive to passivation

GaAs Solar Cells with AlInP Passivation

- Unchanged EQE at long wavelengths demonstrates equivalent passivation ability of AlInP
- Short wavelength EQE accounts for J_{SC} boost



Certified J-V	AlInP-Passivated 1J	GaInP-Passivated 1J
J_{SC} (mA/cm²)	29.07	27.75
V_{OC} (V)	1.062	1.065
Fill Factor (%)	84.4	85.3
η (%)	26.0	25.2



GaAs Solar Cells with AlInP Passivation

- GaInP previously demonstrated good passivation; no O or Si impurities
- AlInP passivation improves J_{SC} & η; no change in V_{OC} & FF

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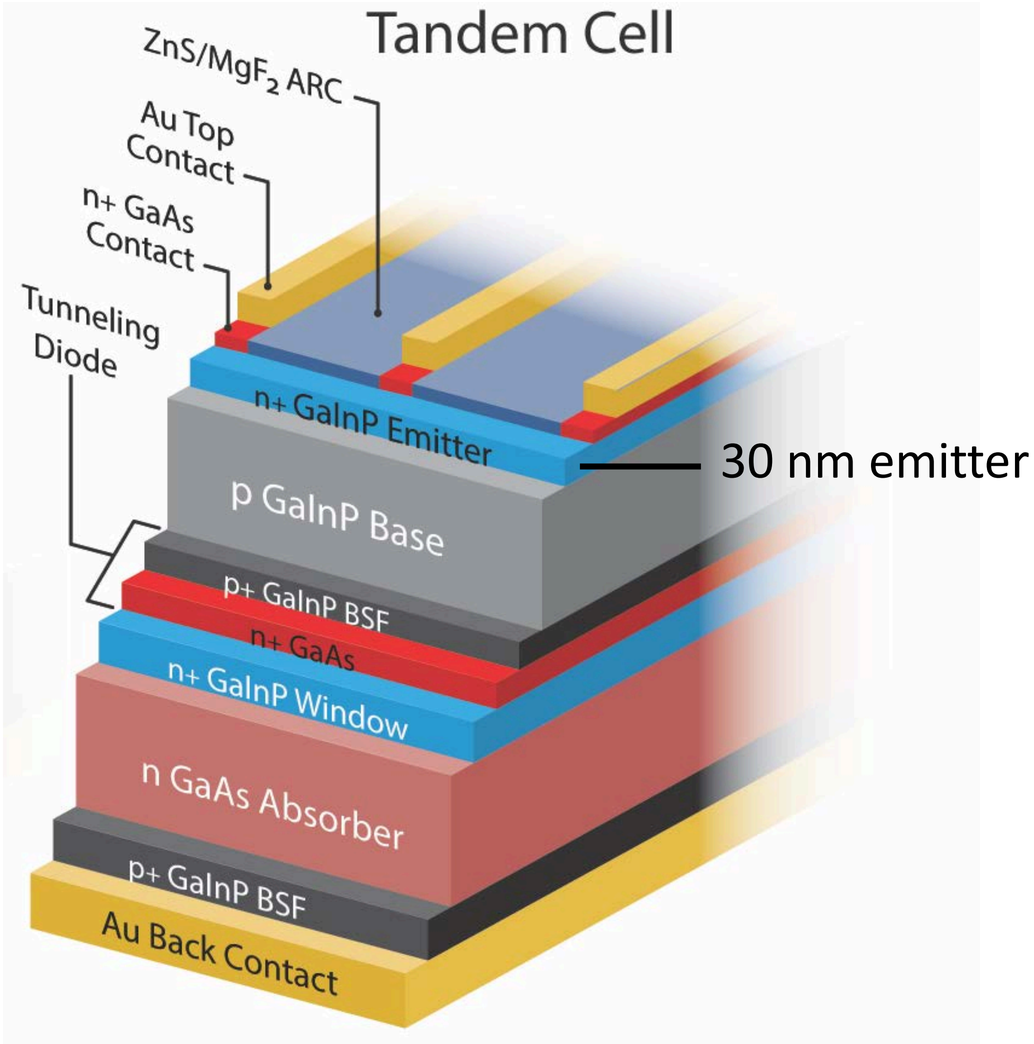
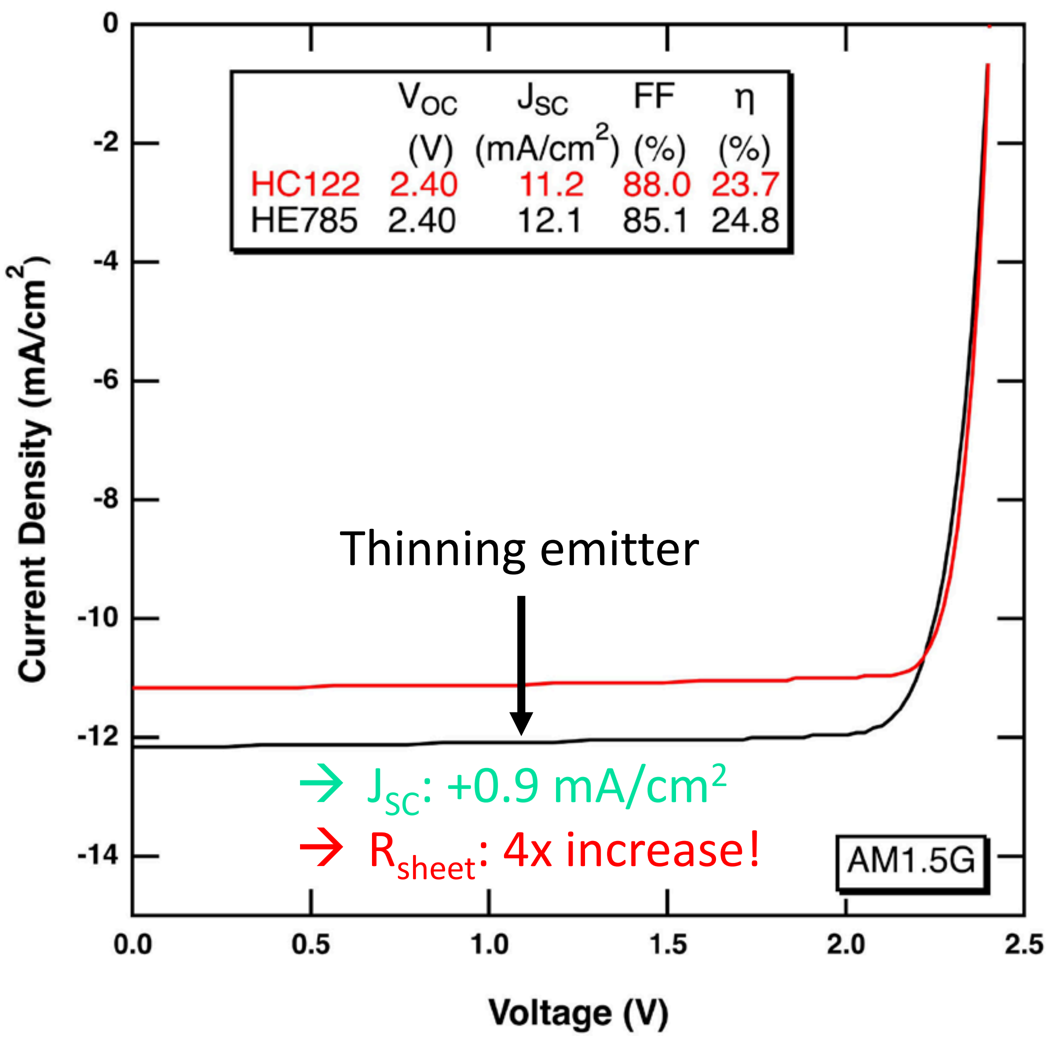


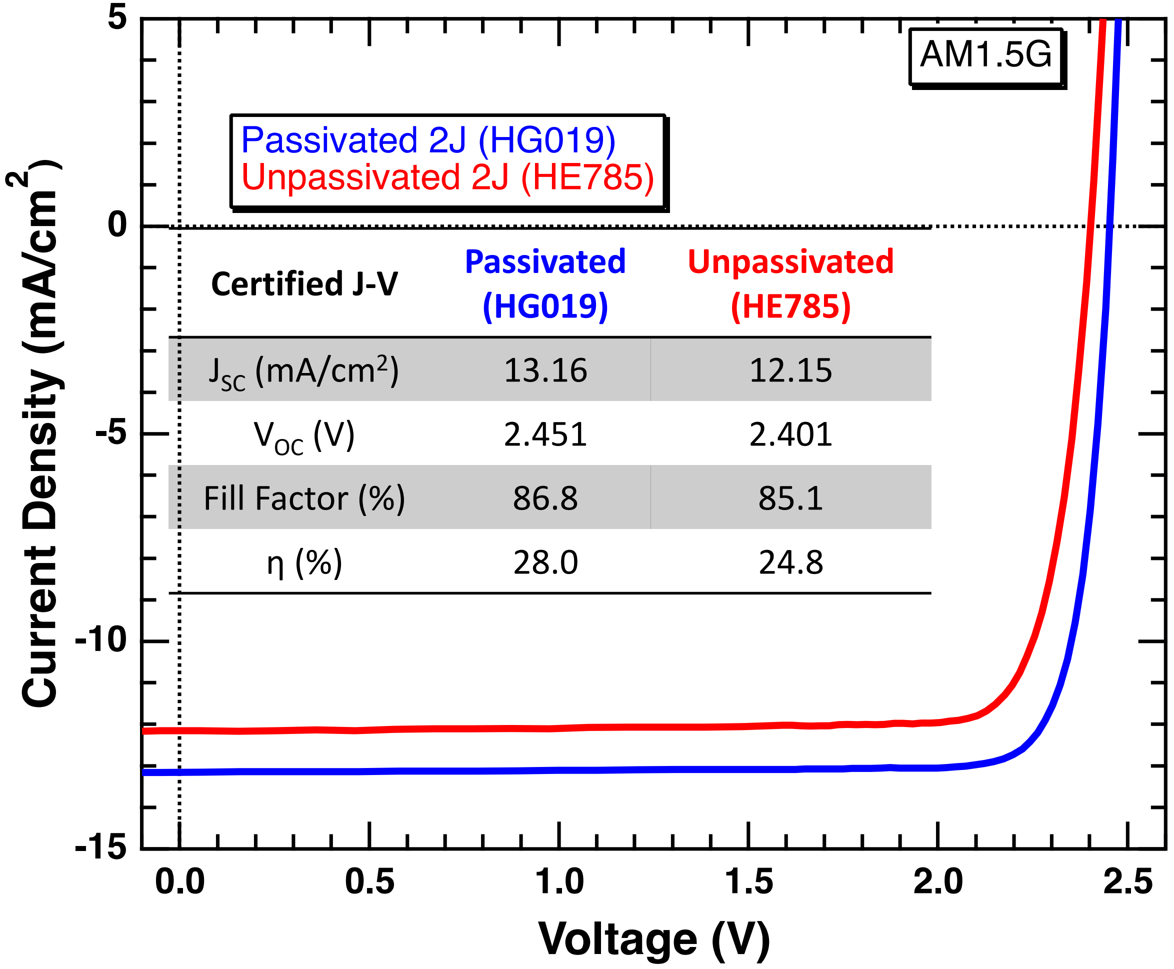
Roberts et al., *JPV*. **11**, 5 (2021)

Schulte et al. *Prog Photovolt Res Appl.* 26:887–893 (2018)

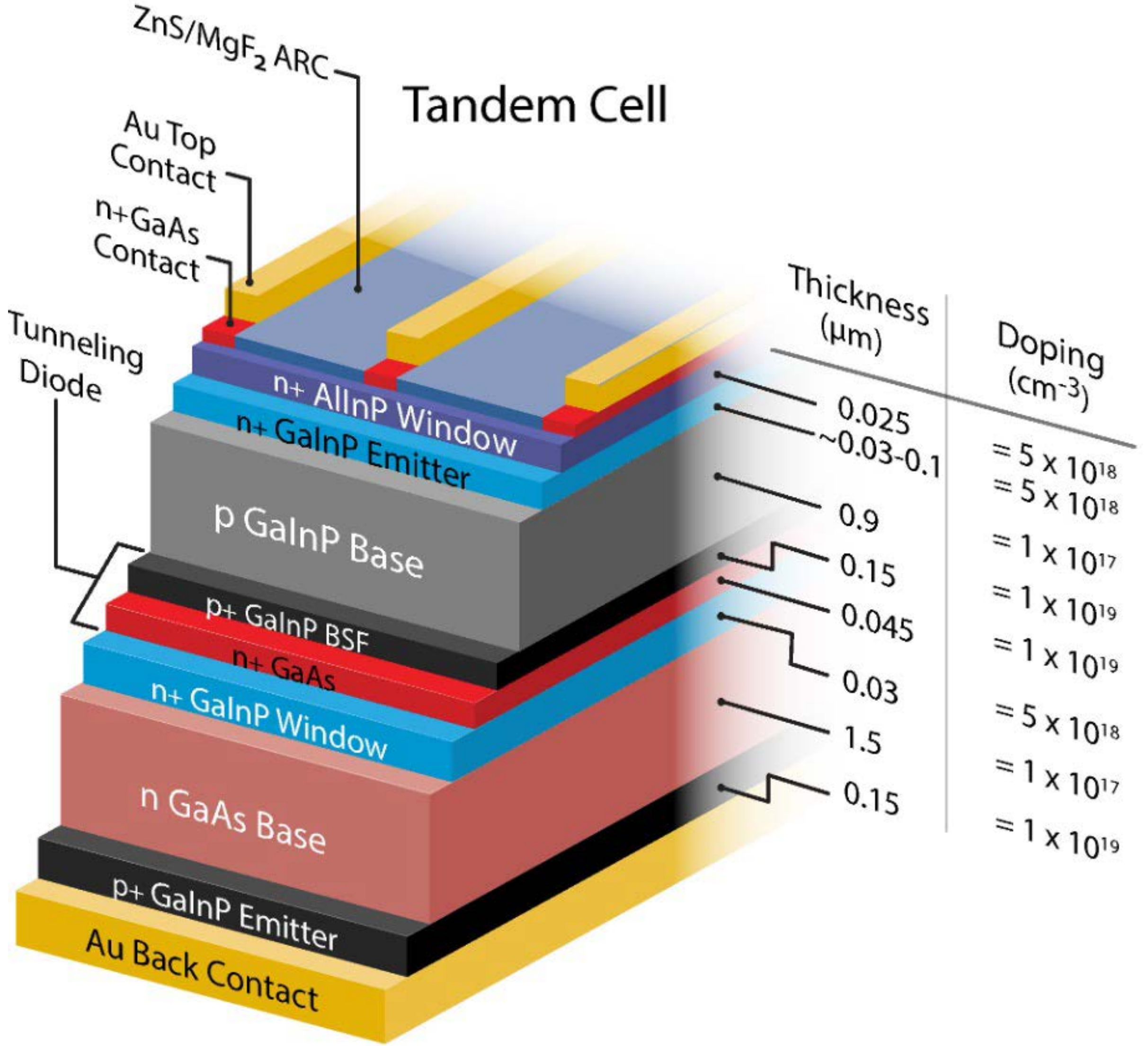


Unpassivated GaInP/GaAs (2J) Solar Cells

- Without AlInP, use thin 30 nm emitter to optimize current collection, lose R_{sheet}



Certified J-V	Passivated (HG019)	Unpassivated (HE785)
J_{SC} (mA/cm^2)	13.16	12.15
V_{OC} (V)	2.451	2.401
Fill Factor (%)	86.8	85.1
η (%)	28.0	24.8



AlInP Passivated GaInP/GaAs (2J) Solar Cells

- Passivated 2J:

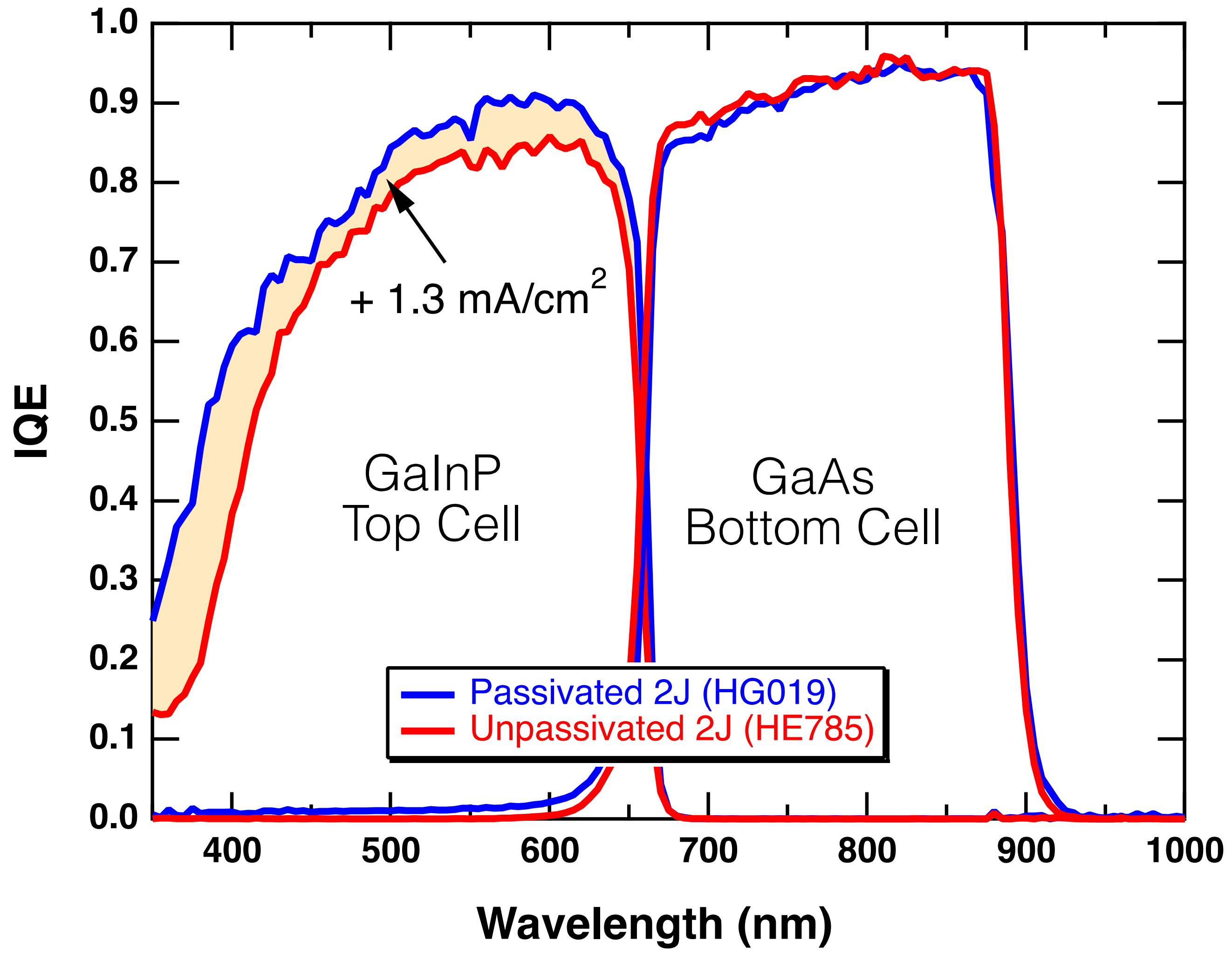
→28.0% efficiency, certified AM1.5G

GaInP/GaAs (2J) Solar Cells with AlInP Passivation

Subcell IQE

- AlInP improves top cell current potential by 1.3 mA/cm^2
- Bottom cell is unchanged, no effect on layers grown after
- Slope suggests some parasitic absorption from TJ – **add Al to future 2J**

Adding passivation improves top cell current at **all wavelengths**

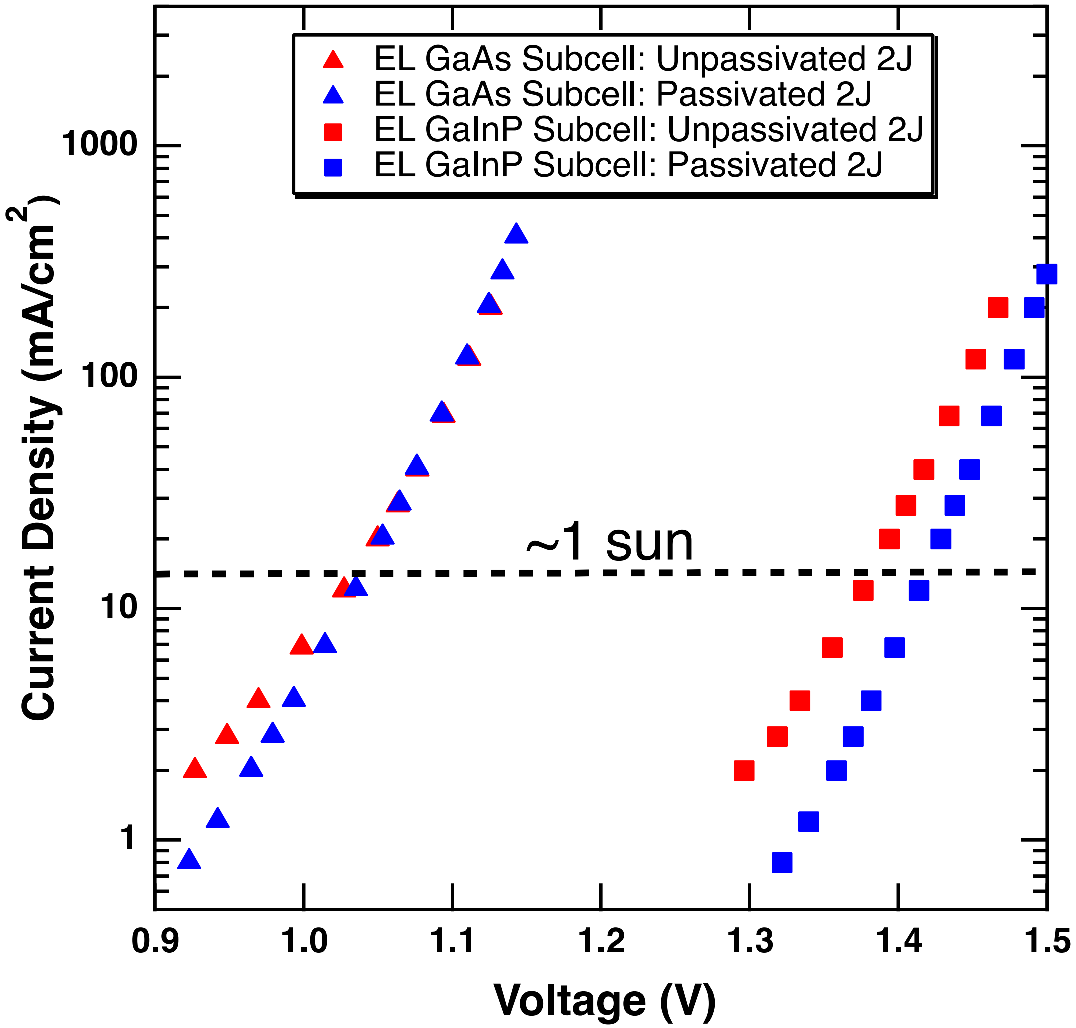


GaInP/GaAs (2J) Solar Cells with AlInP Passivation

Subcell Electro-luminescence (EL)

- AlInP Passivation improves top cell V_{OC} by 40 mV – **majority of V_{OC} boost**

Subcell:	GaAs Bottom Cell		GaInP Top Cell	
Device:	Unpassivated 2J	Passivated 2J	Unpassivated 2J	Passivated 2J
V_{OC} (V)	1.027	1.037	1.376	1.416



GaInP/GaAs (2J) Solar Cells with AlInP Passivation

J-V @ diode turn on

- Increased emitter thickness possible with AlInP passivation

→ Fill factor improvement due to reduced R_{series} and R_{sheet}

	Passivated 2J (HG019)	Unpassivated 2J (HE785)
J_{SC} (mA/cm²)	13.16	12.15
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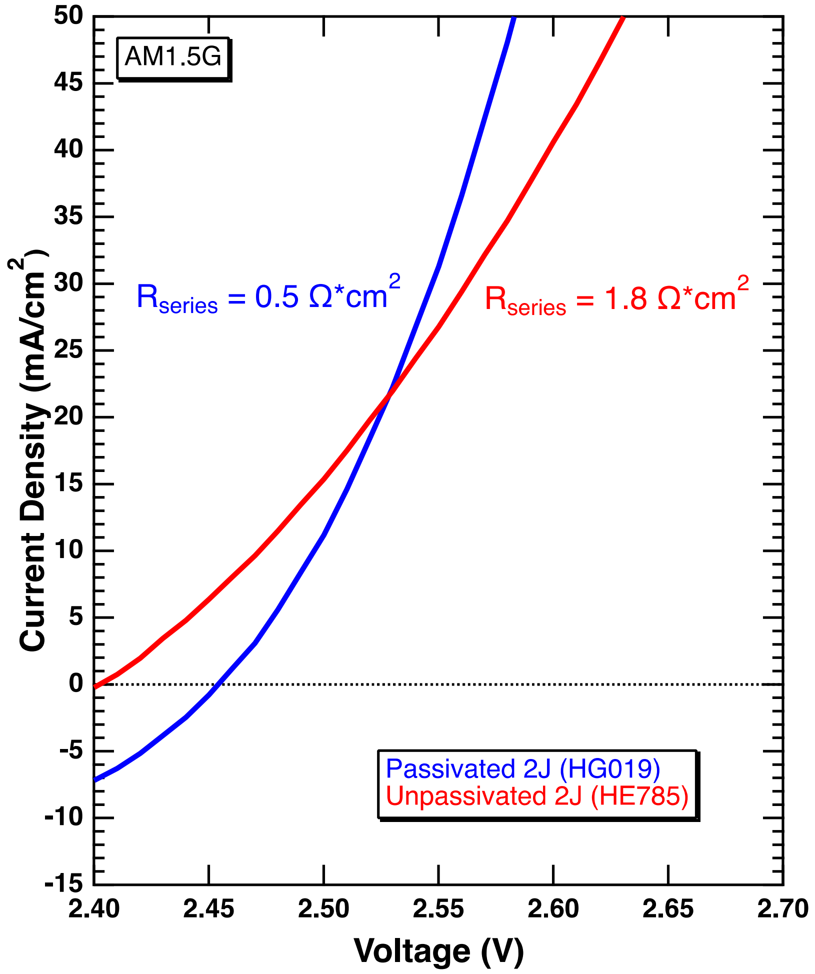
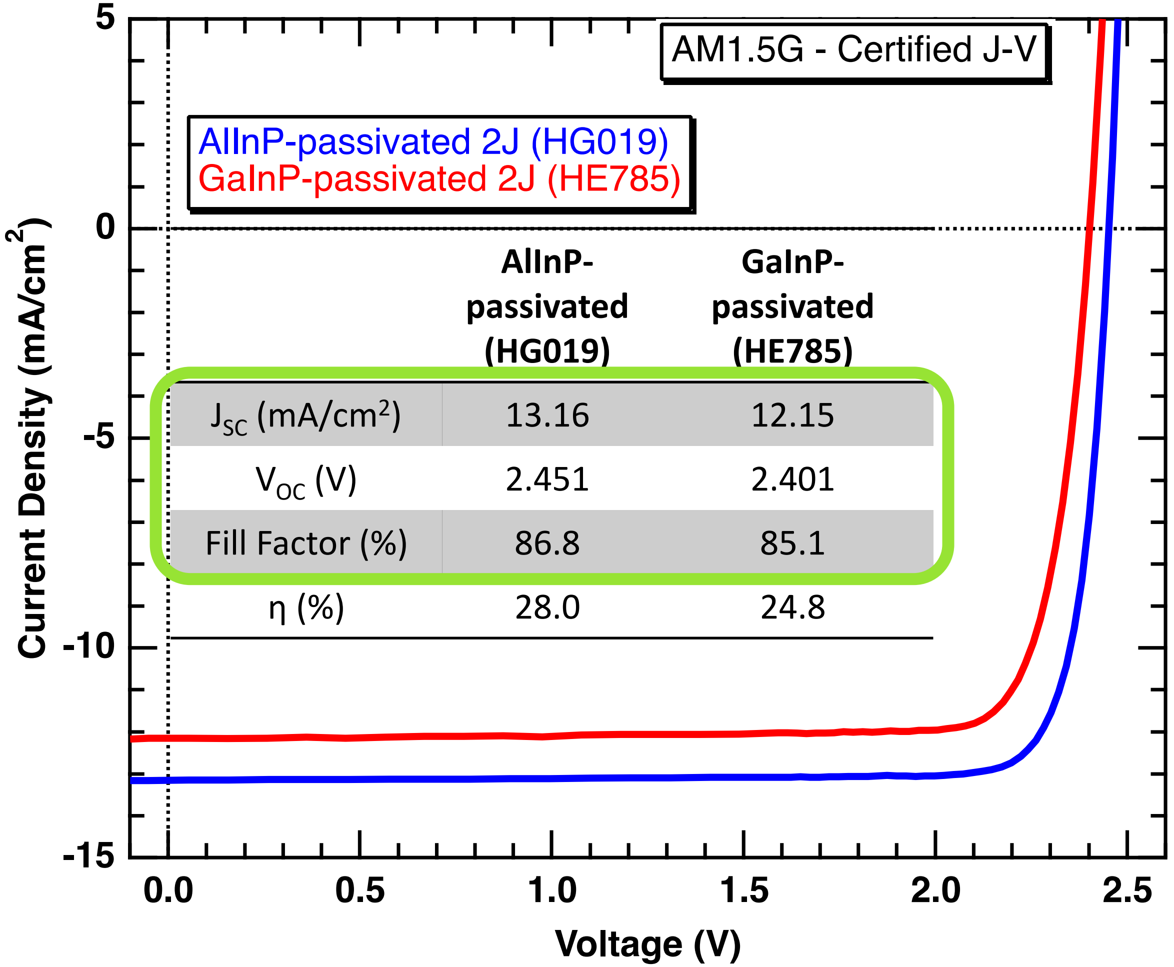
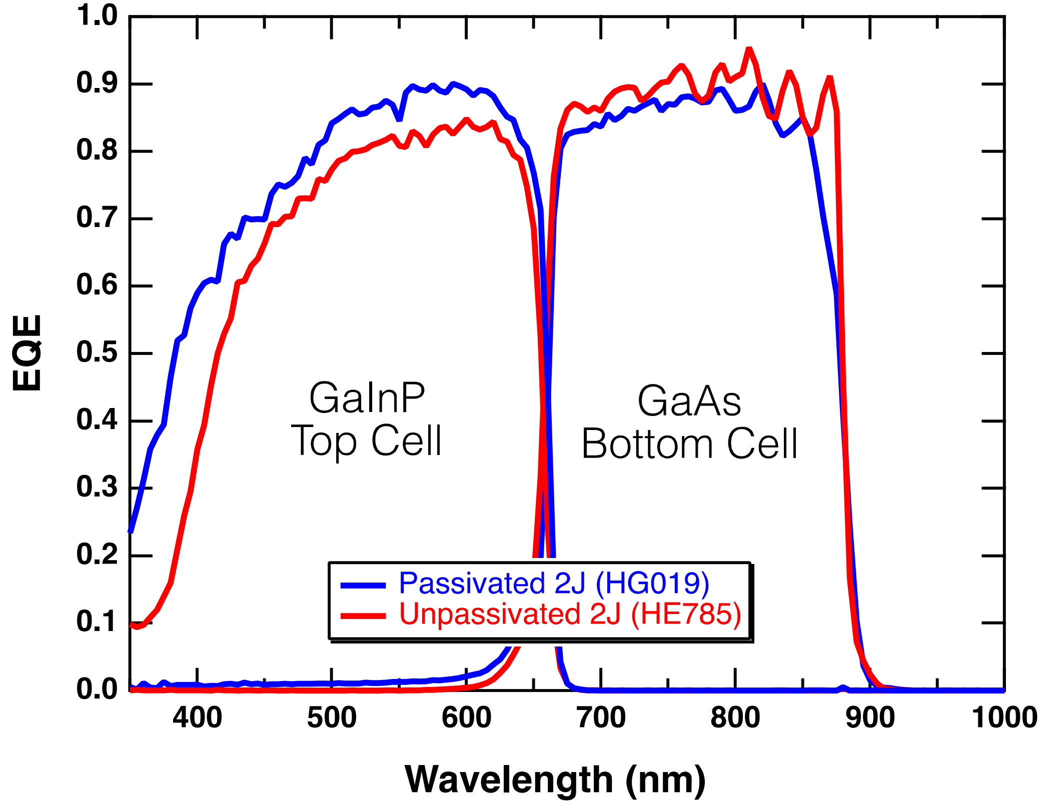




	AlInP-passivated (HG019)	GaInP-passivated (HE785)
J_{SC} (mA/cm^2)	13.16	12.15
V_{OC} (V)	2.451	2.401
Fill Factor (%)	86.8	85.1
η (%)	28.0	24.8

AlInP enables:
+1 mA/cm^2; +50 mV; +1.7% FF



GaInP/GaAs (2J) Solar Cells with AlInP Passivation

- Jsc, Voc, FF improved with AlInP passivation

→ 28% efficiency, certified AM1.5G

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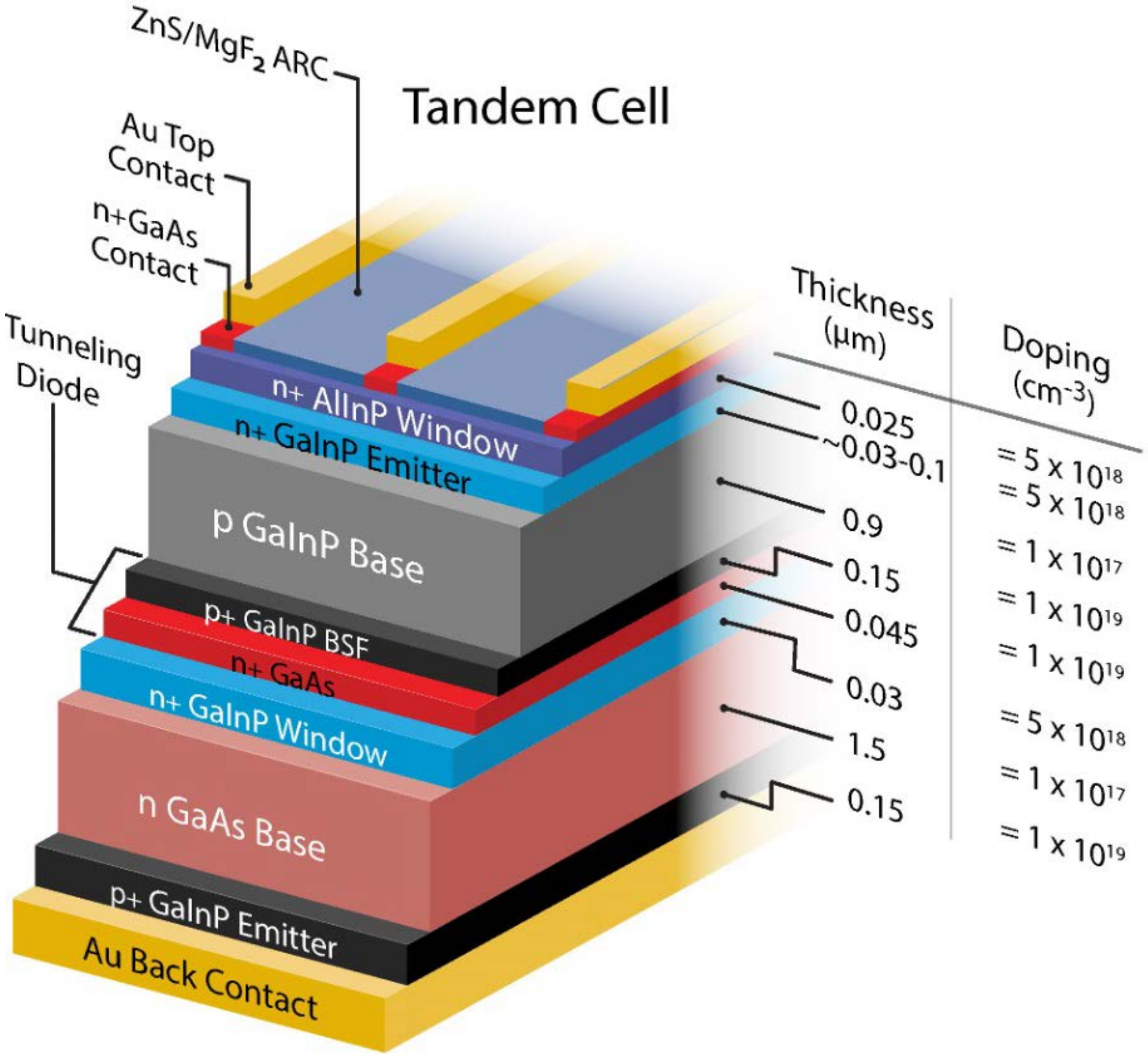
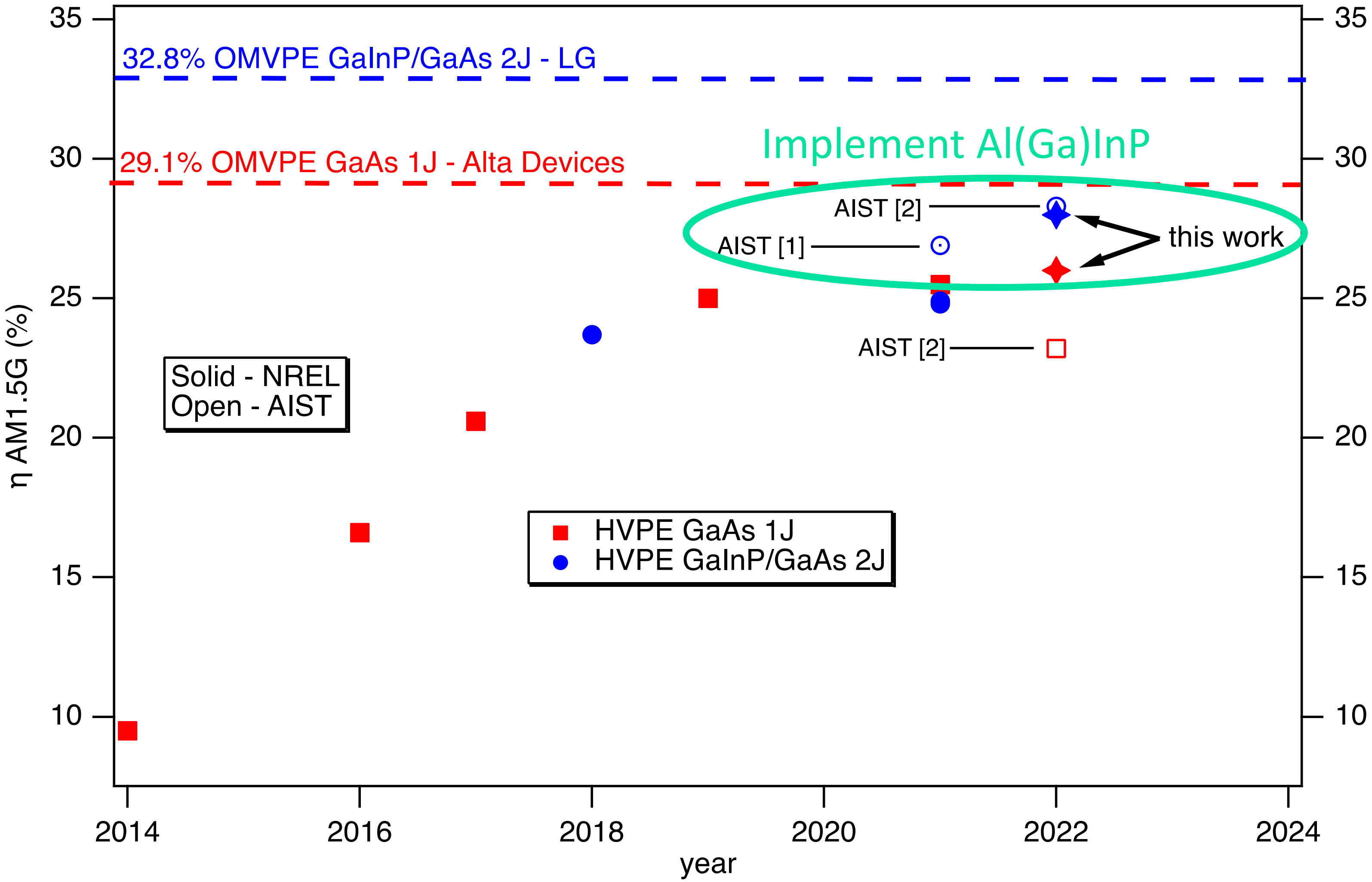
- Initial demonstration of AlInP within PV by HVPE reaches 26%(1J)/28%(2J)
- Add Al to other layers, top cell BSF and tunneling diode
  - *Shoji et al. already demonstrated V_{OC} boost by using AlGaInP BSF*
- Optimize GaInP with passivation



Y. Shoji, et al., *Solar RRL*, p. 2100948, Dec. 2021

Pathways toward higher η

- Room to expand upon this initial demonstration with AlInP



[1] Y. Shoji, et al. *Prog Photovolt Res Appl*, pip.3454, Jul. 2021
[2] Y. Shoji, et al., *Solar RRL*, p. 2100948, Dec. 2021

Learning curve of PV grown in D-HVPE

- Steady progress in D-HVPE-grown PV
- AlInP enables further growth

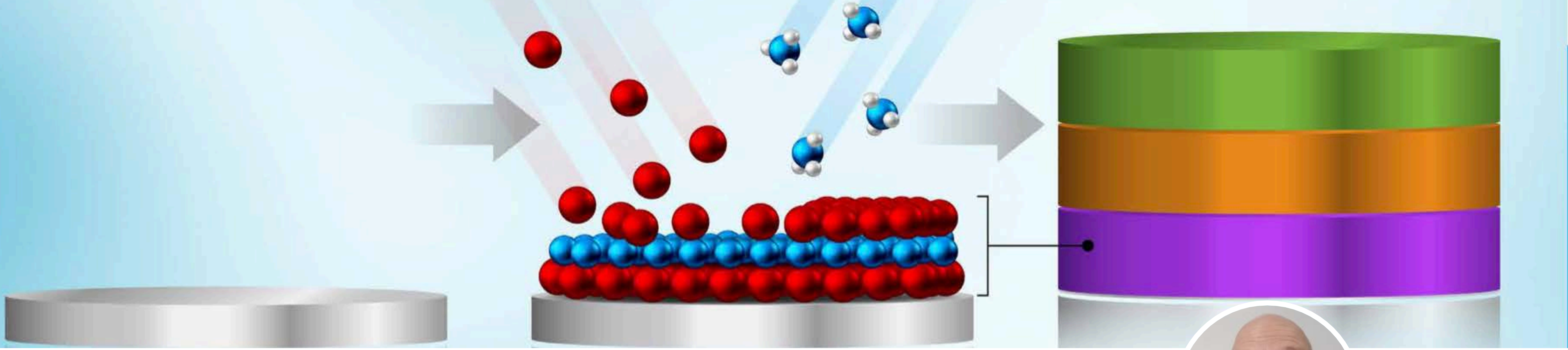
Conclusions & *Further Directions*

- *Incorporate Al in other layers within PV structure to increase transparency*
- *Understand origin and incorporation of O/Si impurities*
- *Exploring Al generation temperature, carrier flow rates, V:III, etc.*

- Initial demonstration of HVPE-PV with AlInP reaches 26% (1J Record) and 28% (2J) with room to improve
- Current AlInP material yields the anticipated cell improvements without any degradation or barriers to further development

→ Addresses last major barrier to achieving D-HVPE-grown PV at parity efficiency with state of the art III-V PV

Current HVPE team at NREL



Anna Braun

Dennice Roberts

John Simon

Kevin Schulte

Jacob Boyer

Evan Wong

Allison Perna

David Guiling

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

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Questions?

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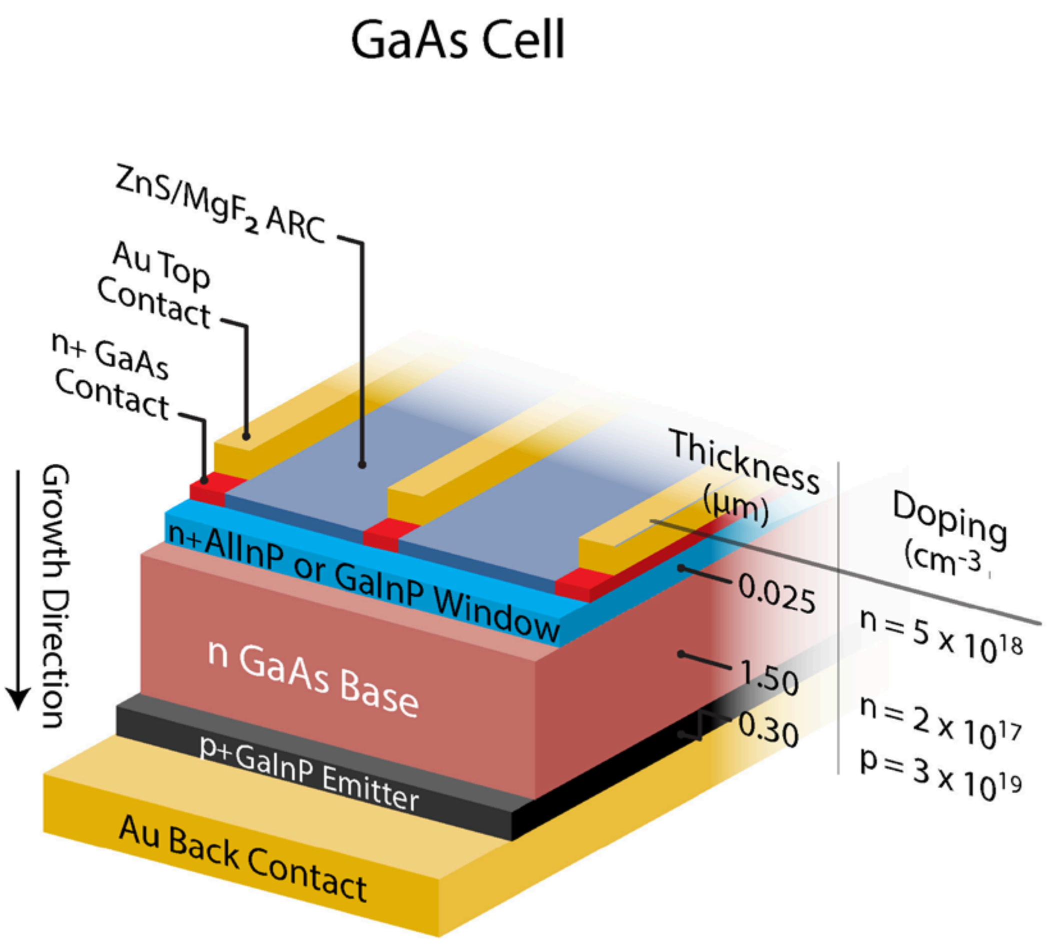
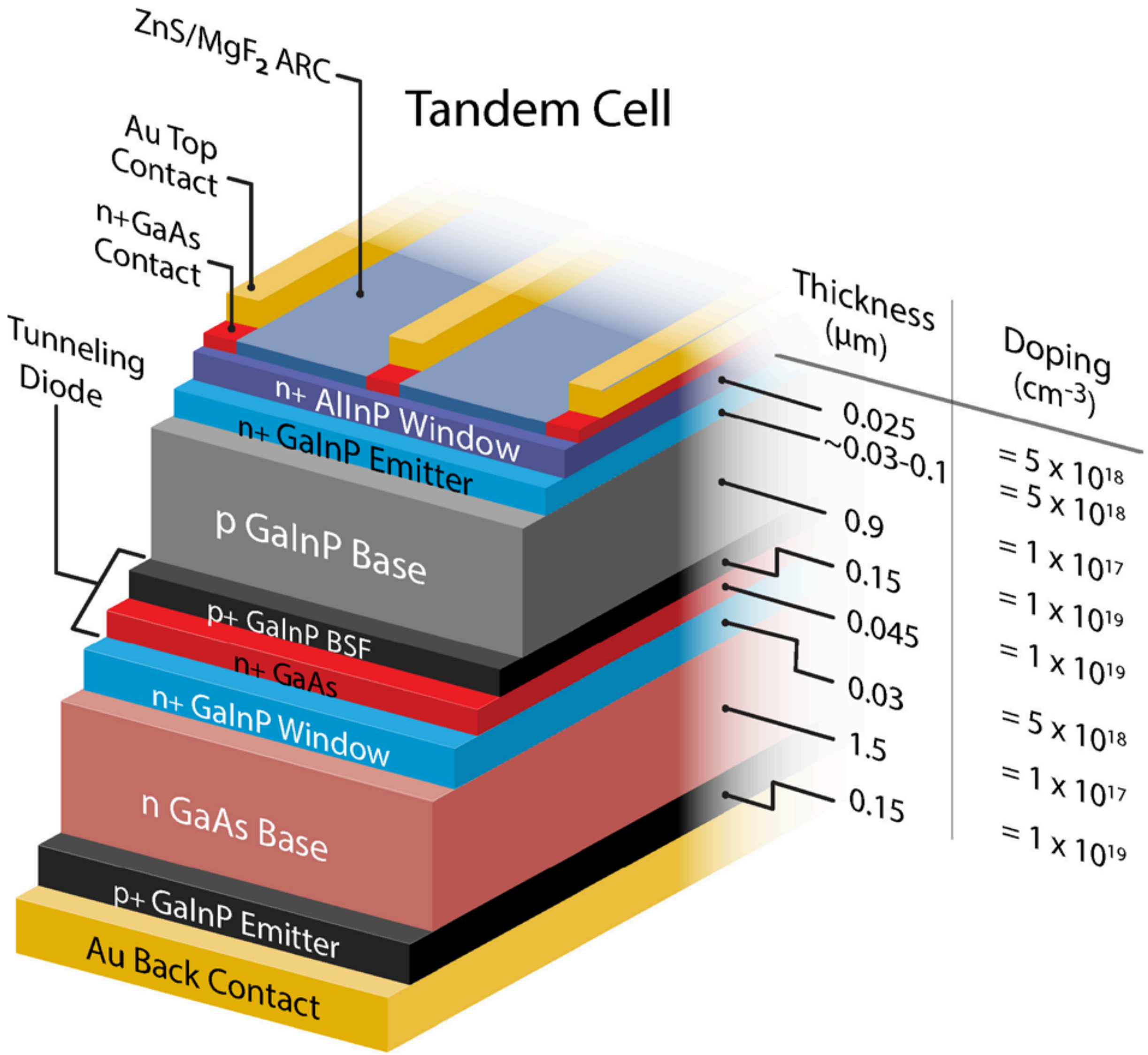
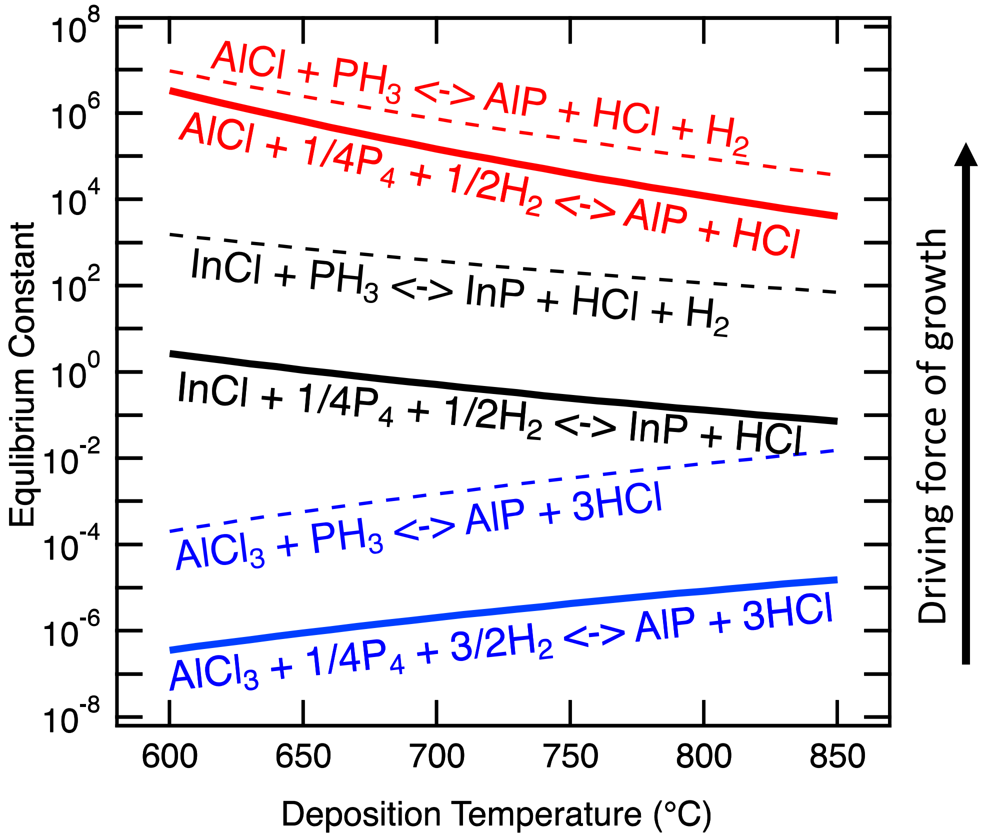


GaAs Cell
ZnS/MgF2 ARC
Au Top Contact
n+ GaAs Contact
Growth Direction
Thickness (μm)
Doping (cm-3)
n+AlInP or GaInP Window
n GaAs Base
p+GaInP Emitter
Au Back Contact
0.025
1.50
0.30
n = 5 x 1018
n = 2 x 1017
p = 3 x 1019

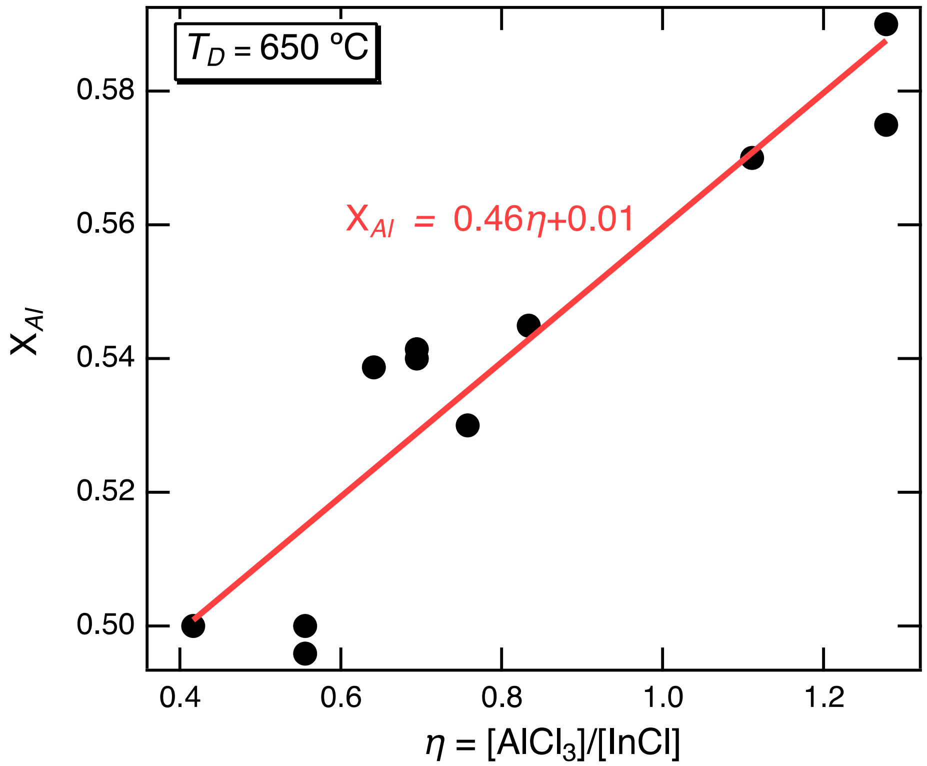


Tandem Cell
ZnS/MgF2 ARC
Au Top Contact
n+GaAs Contact
Tunneling Diode
Thickness (μm)
Doping (cm-3)
n+ AlInP Window
n+ GaInP Emitter
p GaInP Base
p+ GaInP BSF
n+ GaAs
n+ GaInP Window
n GaAs Base
p+ GaInP Emitter
Au Back Contact
0.025
~0.03-0.1
0.9
0.15
0.045
0.03
1.5
0.15
= 5 x 1018
= 5 x 1018
= 1 x 1017
= 1 x 1019
= 1 x 1019
= 5 x 1018
= 1 x 1017
= 1 x 1019

Using Uncracked Hydrides and $AlCl_3$ to Grow AlInP

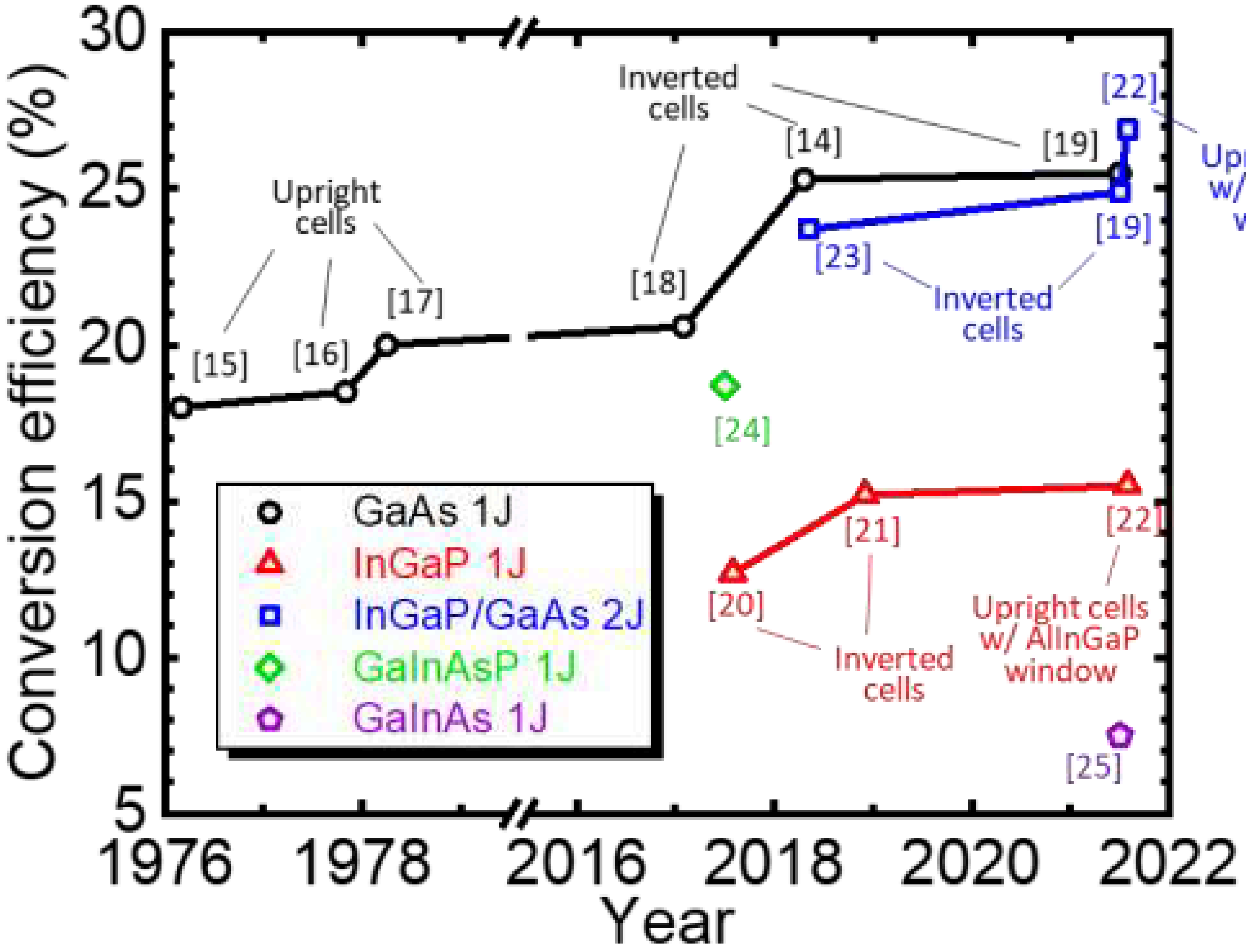


- *However,* kinetics enable near unity $[AlCl_3]/[InCl]$ to grow LM $Al_{.53}In_{.47}P$



- Uncracked PH_3 raises the thermodynamic driving force of growth, especially for $AlCl_3$
- Difference in growth from InCl vs. $AlCl_3$

Schulte et al., *ACS Appl. Energy Mater.* **2**, 8405-8410 (2019)



Y. Shoji, et al., *Solar RRL*, p. 2100948, Dec. 2021

Learning curve of PV grown in D-HVPE

- Many PV architectures demonstrated by HVPE

Challenges of Growing AlInP in HVPE

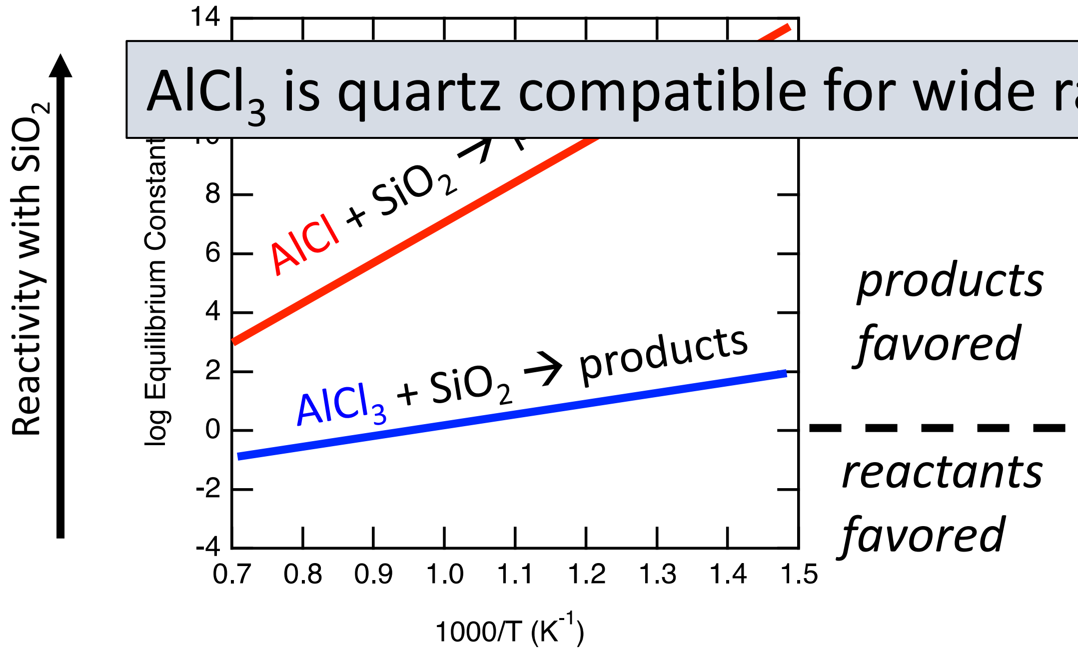
Al Precursor Reactivity with Quartz

- AlCl **reacts strongly with quartz (SiO_2) reactor**
- $AlCl_3$ has low reactivity with quartz at typical growth temperatures

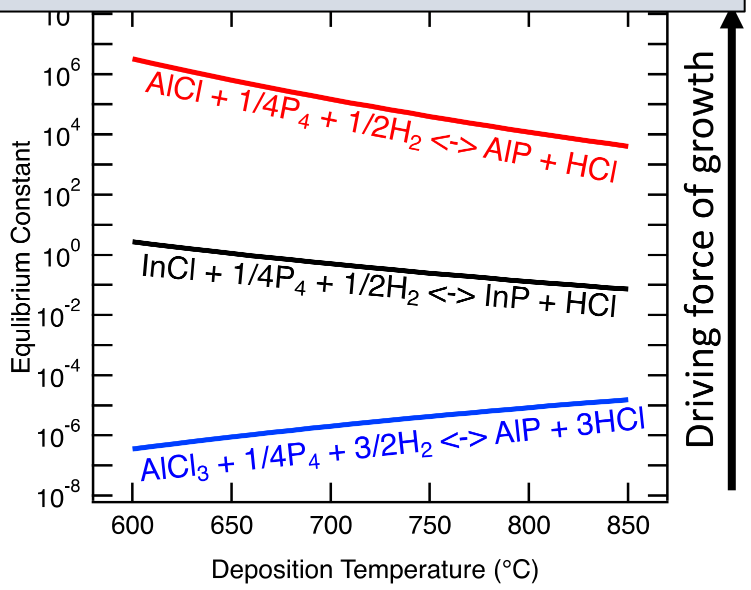
Precursor Growth Thermodynamics

- **AlCl:** large driving force for growth
→ **AlP predeposition**
- **$AlCl_3$:** small driving force for growth
→ **needs kinetic boost**
- **InCl:** far from either AlCl or $AlCl_3$
→ **theoretically impossible to grow AlInP**

$AlCl_3$ is quartz compatible for wide range of T; but less driving force to grow



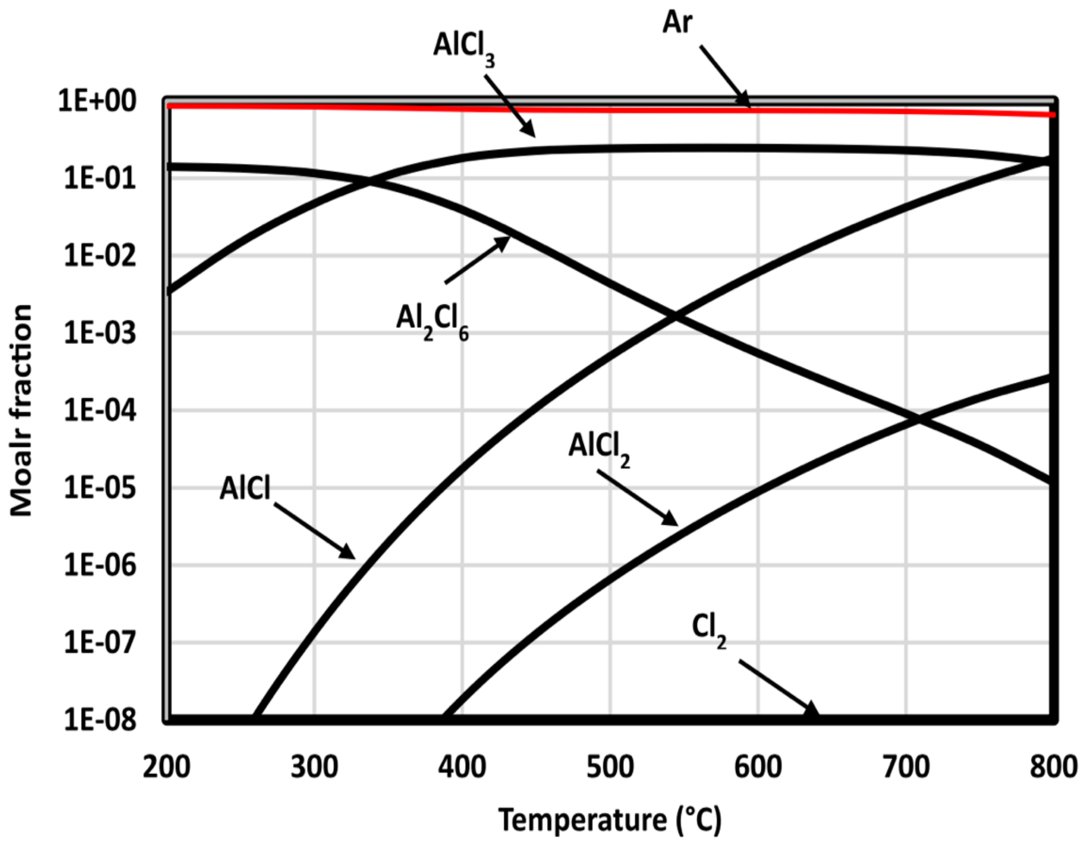
Kumagai *et al*. phys. stat. sol. (c) 0, No. 7, 2498 – 2501 (2003)



Schulte et al., *ACS Appl. Energy Mater*. **2**, 8405-8410 (2019)

Solution: Generate $AlCl_3$ without AlCl at lower temperature

Molar fraction of Al-chlorides generated from HCl

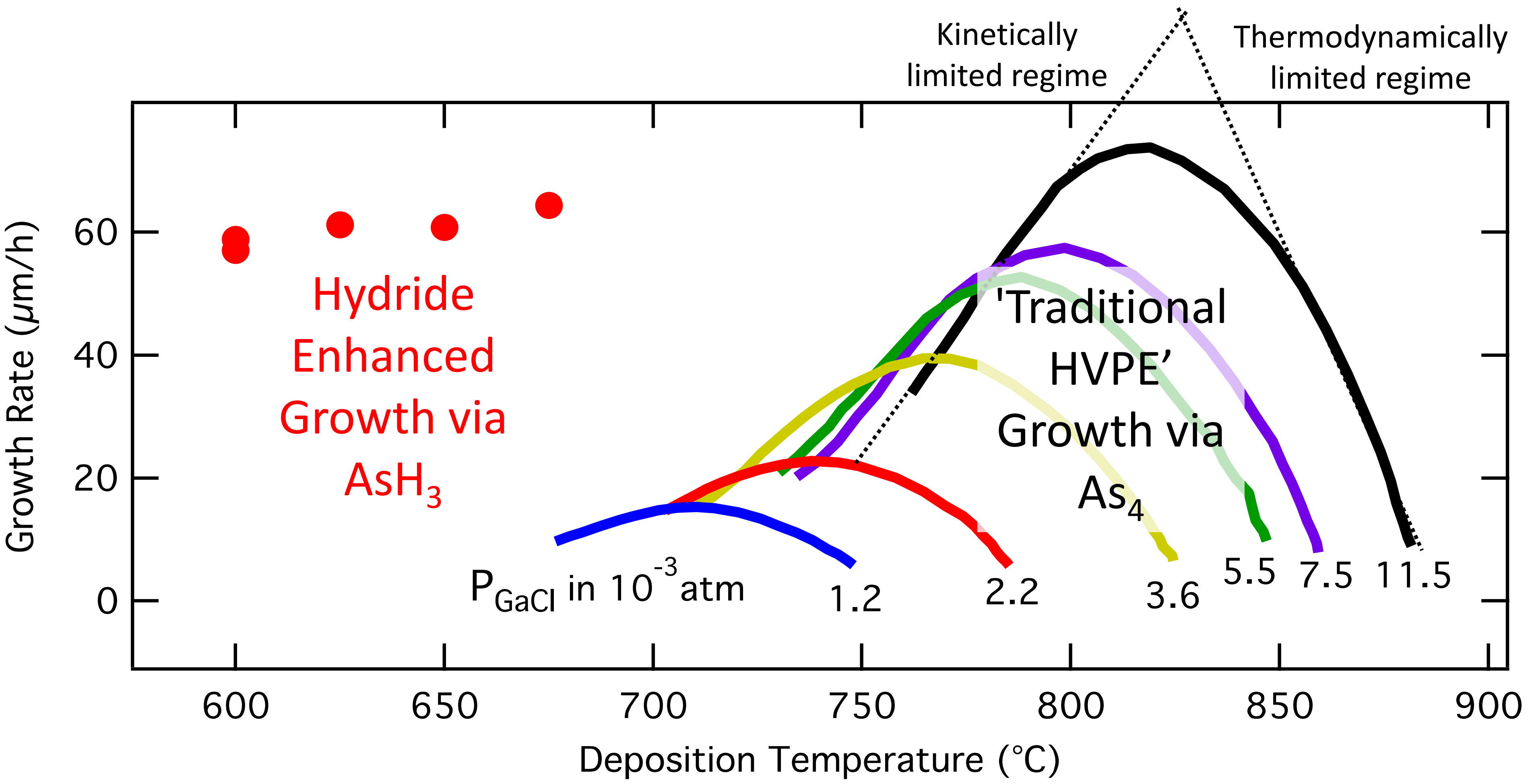


M. Pons et al. Journal of Crystal Growth 468 (2017) 235–240236

Ex-Situ $AlCl_3$ Source

- Generate $AlCl_3$ just above reactor at colder temperature
- React Al and HCl @ 300 – 400°C to favor $AlCl_3$ generation
- 4 orders of magnitude less AlCl

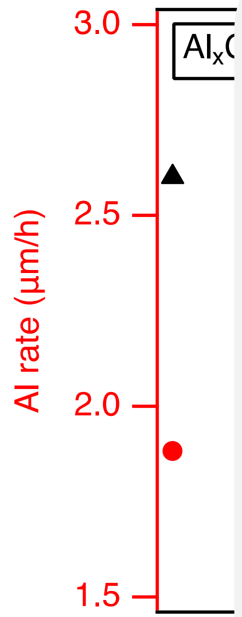
Solution: Hydride Enhanced Growth to Enhance Kinetics

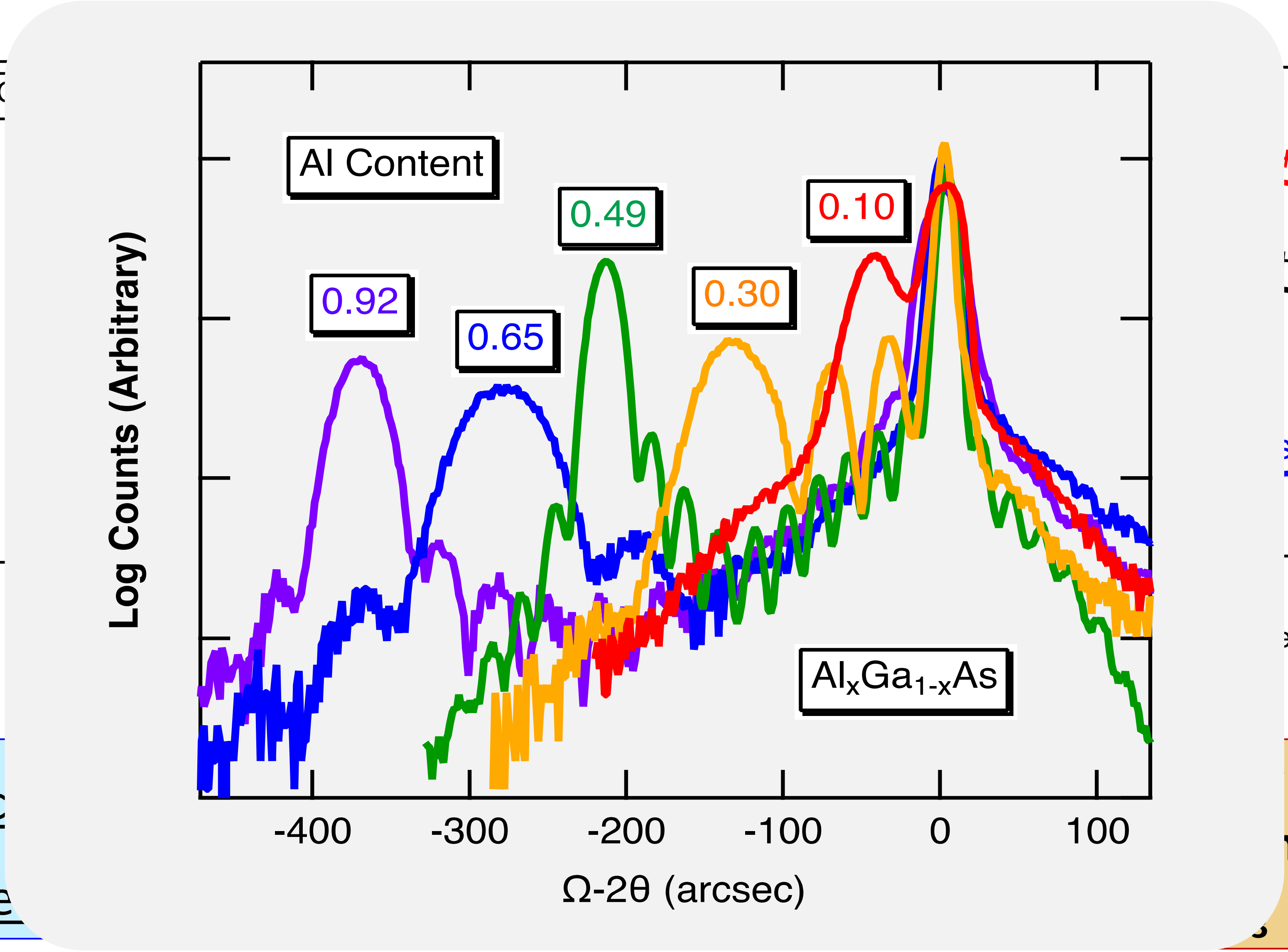


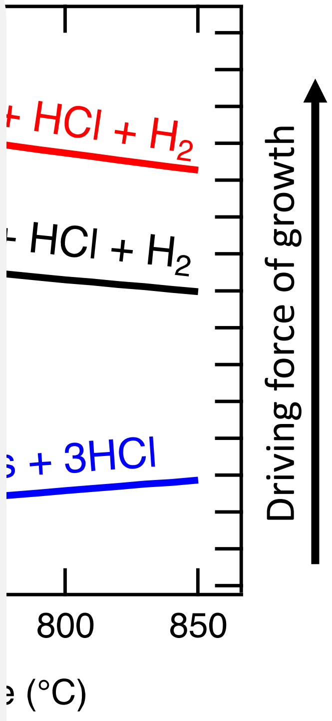
→Apply hydride enhanced growth kinetics to growth of Al - materials!

Shaw, D.W., *J. Electrochem. Soc.* **117**(5) pp. 683-687, (1970).

Demonstrating Growth of AlGaAs via $AlCl_3$ & Uncracked AsH_3



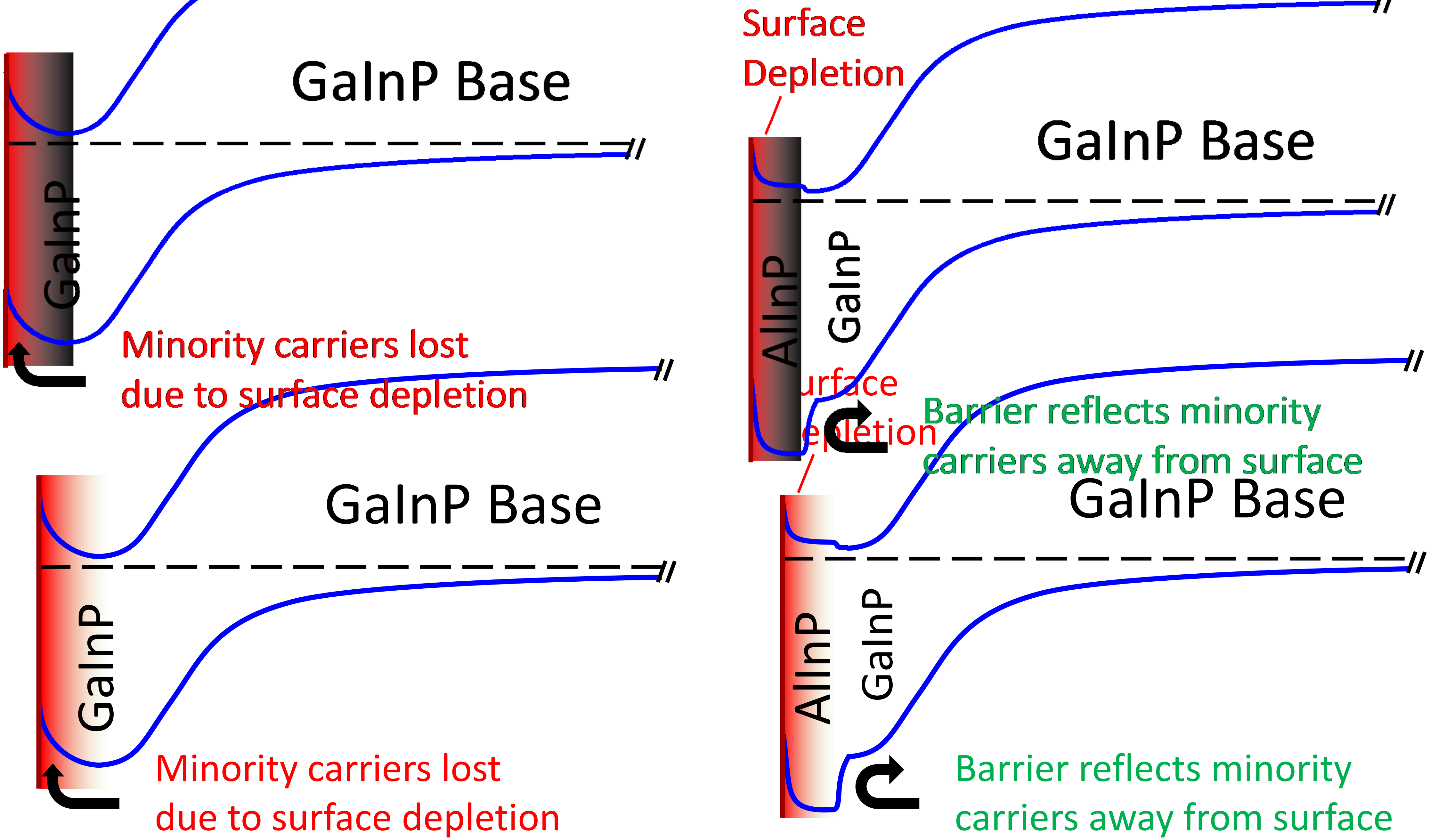




- Al rate inc
- Ga rate de

namic
ning

Schulte et al., *ACS Appl. Energy Mater*. **2**, 8405-8410 (2019)


GaInP Base
GaInP
Minority carriers lost
due to surface depletion
Surface
Depletion
GaInP Base
AlInP
GaInP
Barrier reflects minority
carriers away from surface
GaInP Base
GaInP
Minority carriers lost
due to surface depletion
GaInP Base
AlInP
GaInP
Barrier reflects minority
carriers away from surface