Epitaxy-Free, Thin-Film, GaAs Solar Cells with V_{oc} Greater Than 900 mV

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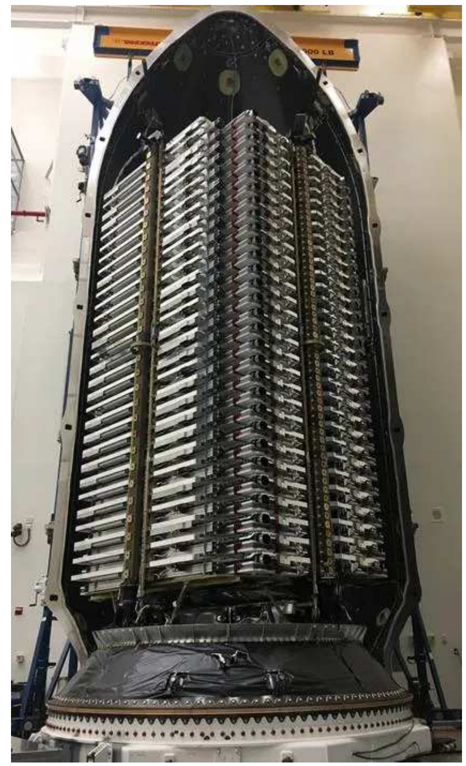
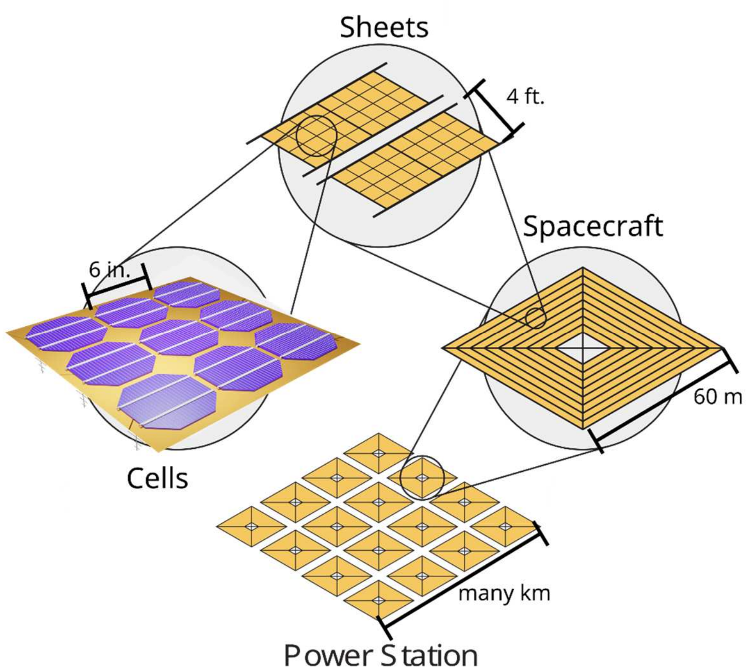
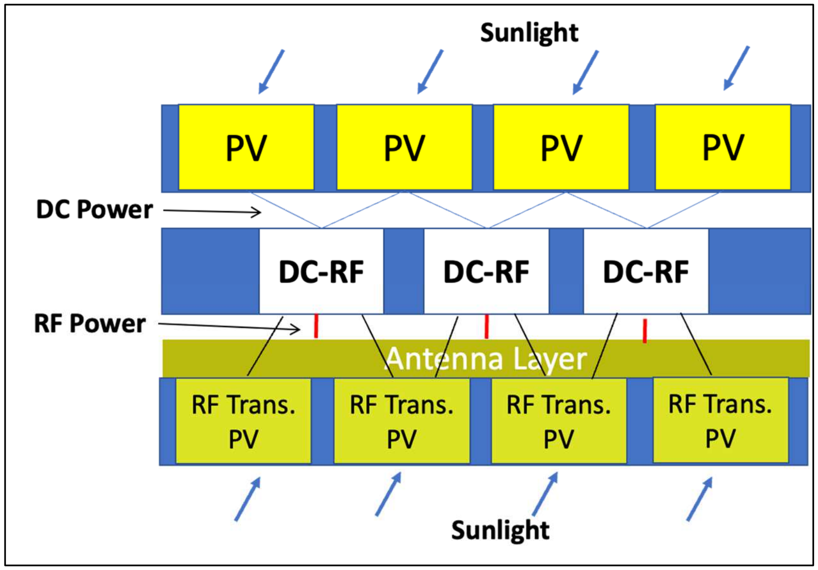
Solar Cells Are A Cost Driver For Mega Constellations

- Traditional III-V space cells cost $\sim\$100/\mathrm{W}$
- A Starlink satellite costs roughly $\$300\mathrm{k}$ and uses $6\ \mathrm{kW}$ of power
  - III-V cells for Starlink would cost $\$600\mathrm{k}$
    - III-V cell cost is twice the cost of the satellite
    - This is why Starlink uses silicon cells at $\$0.5/\mathrm{W}$



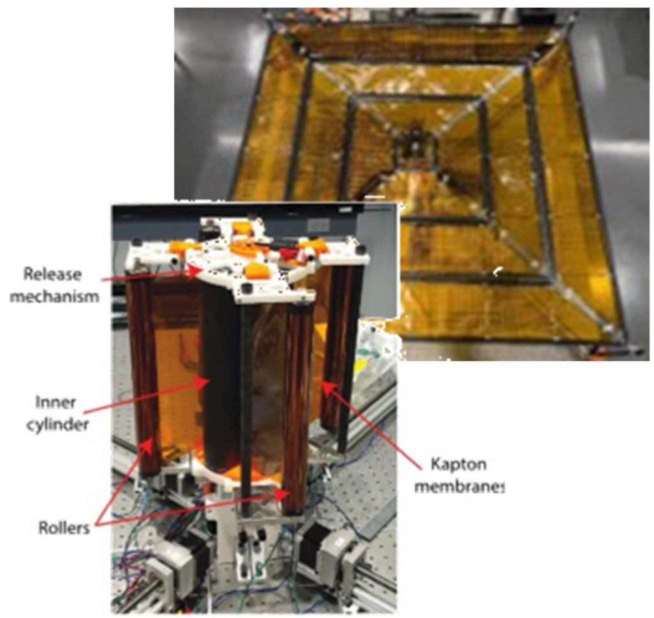
Space Solar Power Project Concept





Space Solar Power Project Prototyping

Atwater Group



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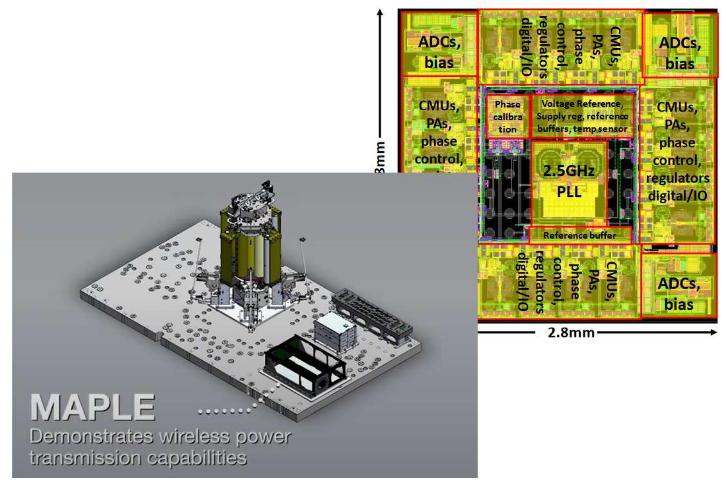


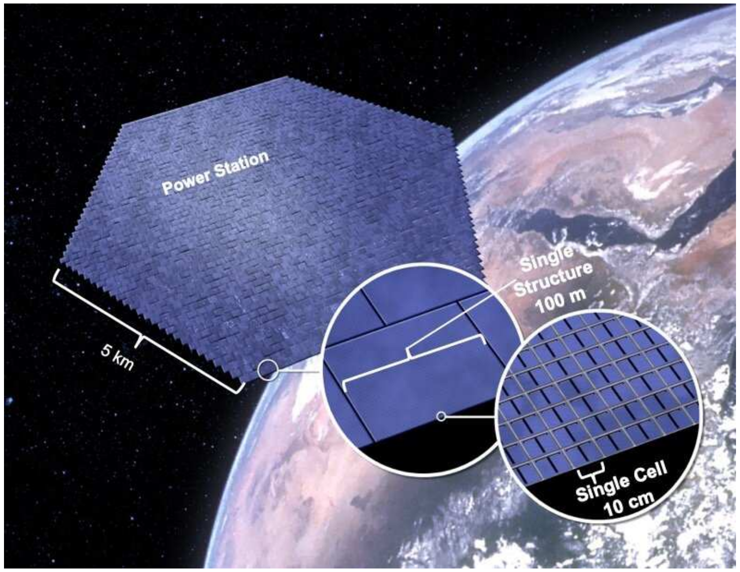
'Scientists beam solar power to Earth from space for 1st time ever'

- *Space.com*

Hajimiri Group

Space Solar Power Needs New Solar Cells

- Consider an Space Solar Power Station selling power to the grid for $5¢/\mathrm{kWhr}$
  - Basic technoeconomic analysis argues cells must be $< \$1/\mathrm{W}$, $< 50\mathrm{g/m^2}$, $\eta > 20\%$ and survive for 15 years at GEO
- No existing solar cell meets these requirements



Requirements for SSPP Solar Cells

Low Cost Devices

- Scalable and affordable III-V devices require the elimination of epitaxy in production
- Following a Si-style production mindset, we create the p/n junction through diffusion doping

Radiation Hard

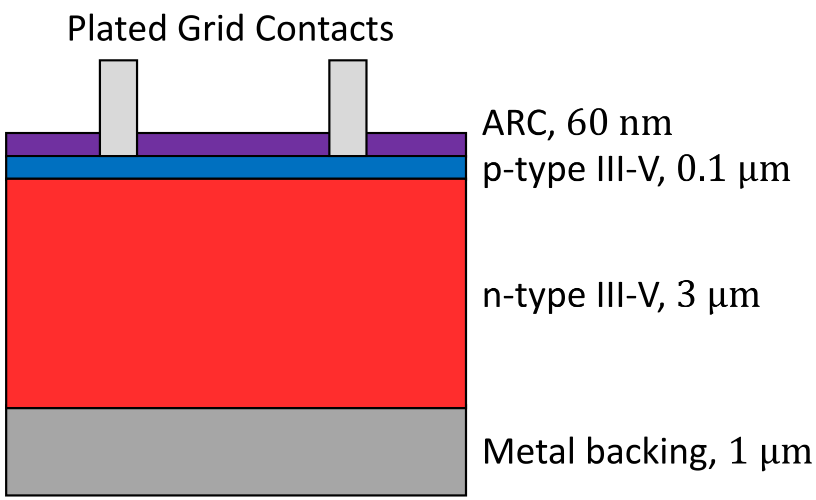
- 15 years at GEO
- Thin film, III-V devices are intrinsically radiation hard
- Prolonged space environmental testing performed with ALBA payload on SSPD-1
  - Mike Kelzenberg Thursday at 10:15

<50 $^{g}/_{m^2}$ Devices

- Spalling is a demonstrated method to yield continuous, thin films from bulk
- Spalled thin films reduce materials cost substantially
- We demonstrate preliminary spalled, non epitaxial devices from commercial GaAs

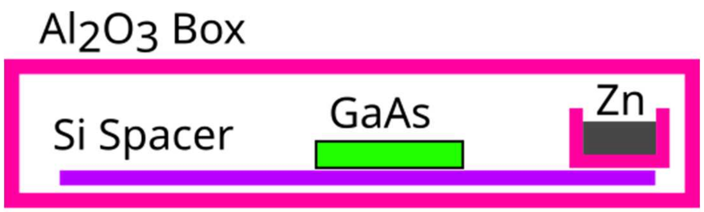
Our Vision for Low-Cost III-V PV

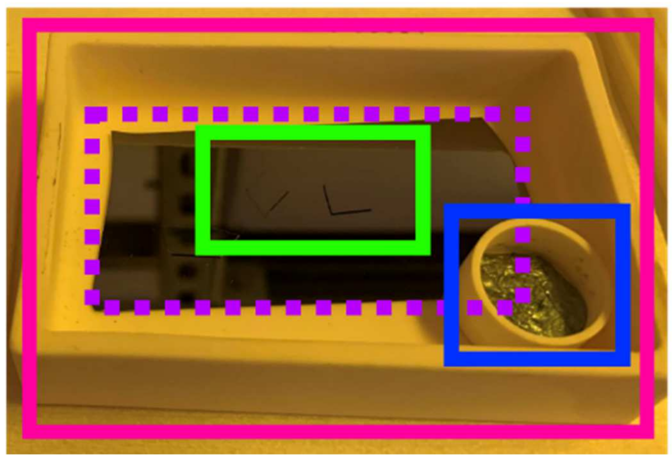
- Use diffusion doping to make the p/n junction without epitaxy
- Spall thin films to reduce capital and materials cost per Watt by turning a single melt-grown wafer into many solar cells
- Change III-V device philosophy
  - "The best device possible"
  - "The best device possible, with Si-style processing"



Simplified GaAs Diffusion Doping Process

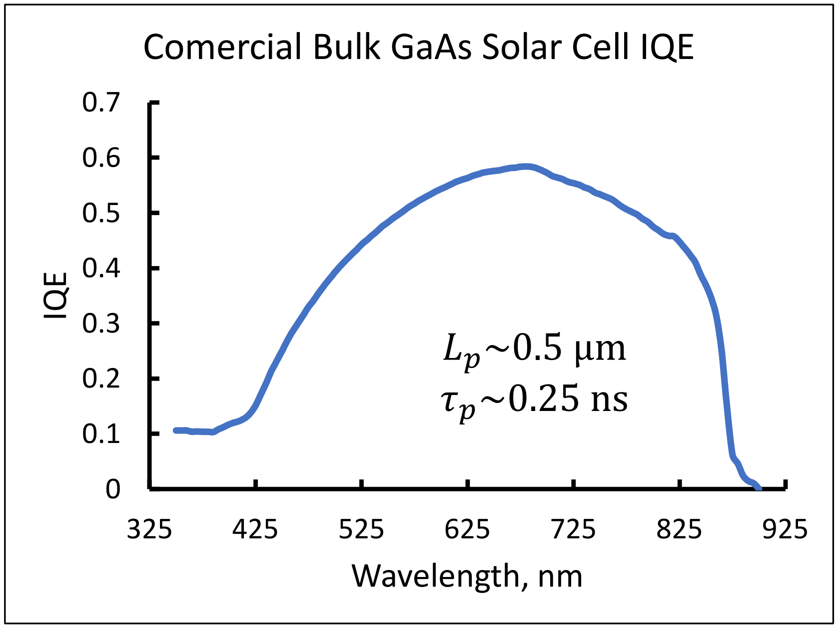
- Source is simply zinc metal
- $400^\circ\text{C} > 2\,\text{hr}$ to $550^\circ\text{C} < 15\,\text{min}$ in 5% H_2
  - Sheet resistances between $10\ \text{k}\Omega/\square$ and $100\ \Omega/\square$
  - Surfaces stay mirror-smooth
- Process is reliable and repeatable
  - Process has worked for over 100 runs excluding gross contamination issues





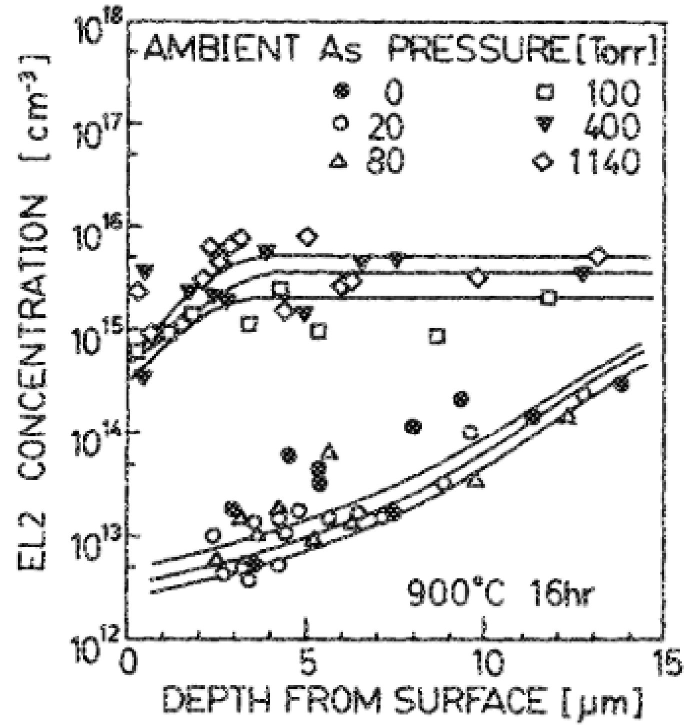
Commercial Wafers limited by Hole Diffusion Lengths

- Substrate quality determines minority hole diffusion length, L_p, and long-wavelength response
- Want $L_p > 5\ \mu m$ for J_{sc}
- Commercially available bulk GaAs has $L_p \leq 1\ \mu m$
- Limited by the EL2 ($V_{Ga}As_{Ga}$) defect



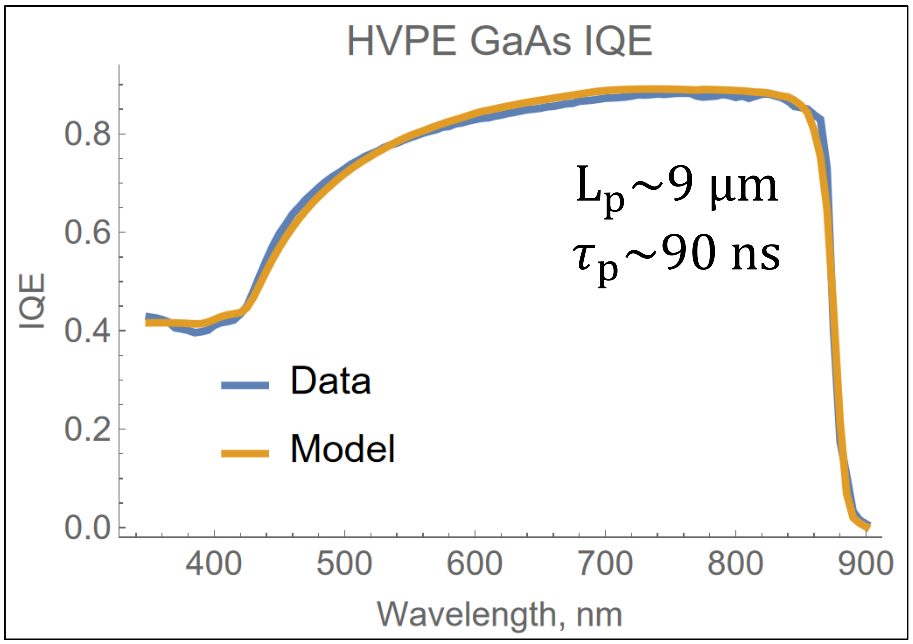
Low EL2 Concentration GaAs

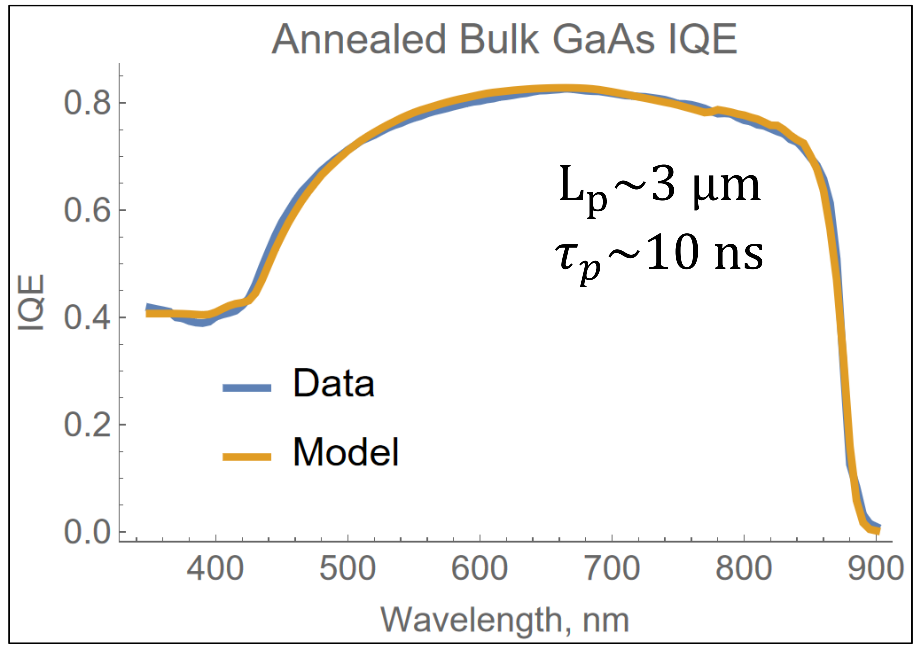
- Growth from vapor
  - Growth temperature, 650 °C, is below the EL2 formation reaction temperature of 700 °C
  - $[\mathrm{EL2}] < 5 * 10^{14}\mathrm{cm}^{-3}$
- Growth from Ga-rich melt
  - As_i readily absorbed by the melt
  - Remote As source maintains melt stoichiometry
- Out-diffusion of EL2
  - Annealing in As-poor ambient removes EL2
  - $\mathrm{GaAs} \rightarrow \mathrm{V_{As}} + 1/2\mathrm{As_2}$
  - $\mathrm{V_{As}} + \mathrm{As_{Ga}} \rightarrow \mathrm{V_{Ga}}$
  - $\mathrm{V_{As}} + \mathrm{V_{Ga}} \leftrightarrow 0$



Kiessling, F. M., (2004). Growth of GaAs crystals from Ga-rich melts by the VCz method without liquid encapsulation. *Journal of Crystal Growth*
Chichibu, S., (1998). Effects of controlled As pressure annealing on deep levels of liquid-encapsulated Czochralski GaAs single crystals. *Journal of Applied Physics*

HVPE Growth or Annealing Melt-Grown Wafers Improves L_p up to 9 μm

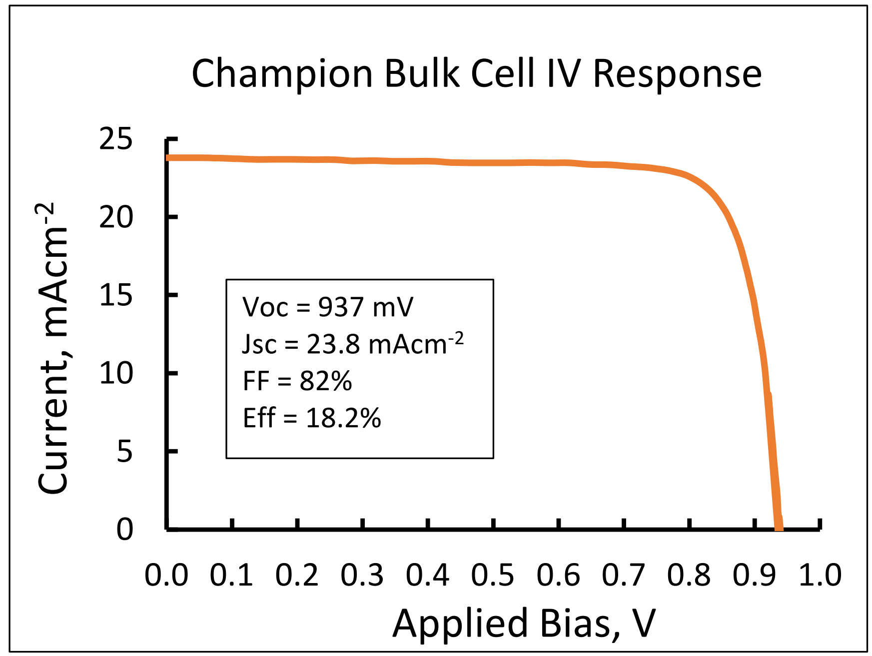




HVPE material
provided by NREL

Champion Bulk Cell Results

- With emitter thinning, passivation, and ARC
- Best cell is 18.2% efficient
  - Comparable to Al-BSF Si cells
- Measured at NREL
- Previous literature best is 14.1%



Garozzo, M., Parretta, A., Maletta, G., Adoncecchi, V., & Gentili, M. (1986). GaAs shallow homojunction solar cells fabricated on thin epitaxial films by a simple Zn solid state diffusion method. *Solar Energy Materials*, *14*(1), 29–49. https://doi.org/10.1016/0165-1633(86)90011-0

Transitioning from Wafer to Thin-Film Devices

- Epitaxy free GaAs device
  - Front junction cell
  - 300 μm thick GaAs from wafer
  - 18.2% efficient champion performance

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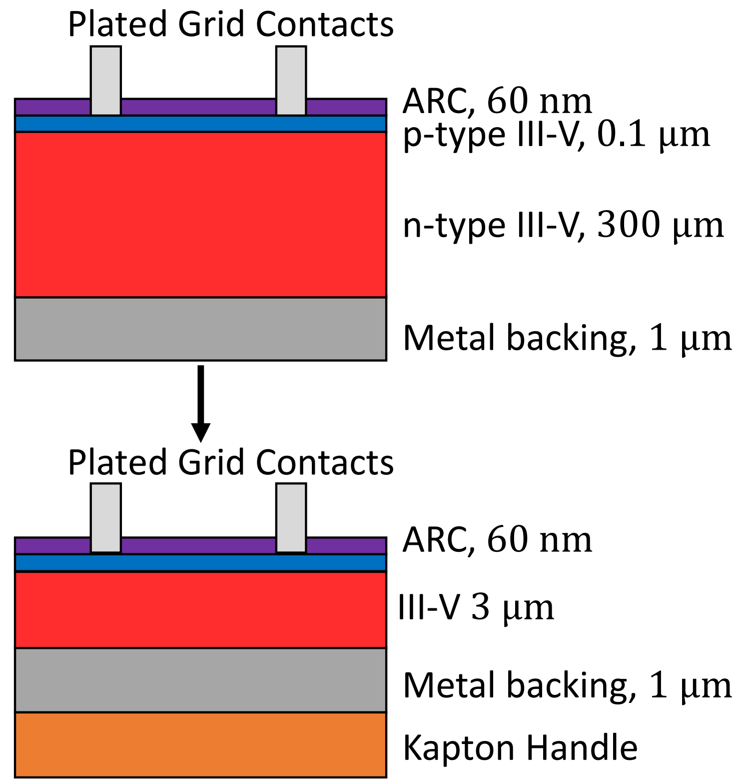
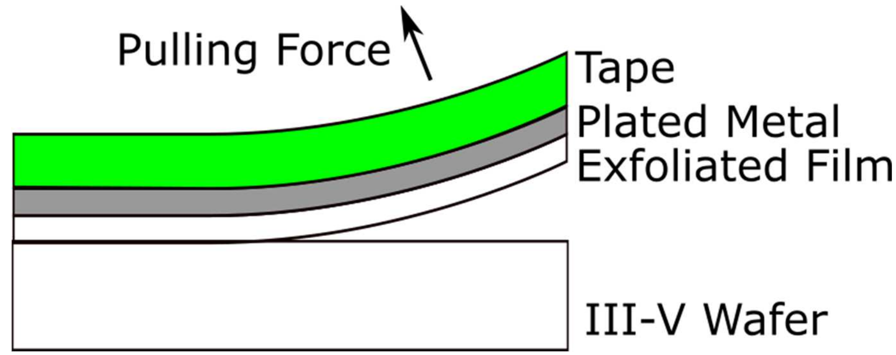
- Spalled GaAs cells
  - 3 μm thick spalled GaAs
  - Kapton back handle layer



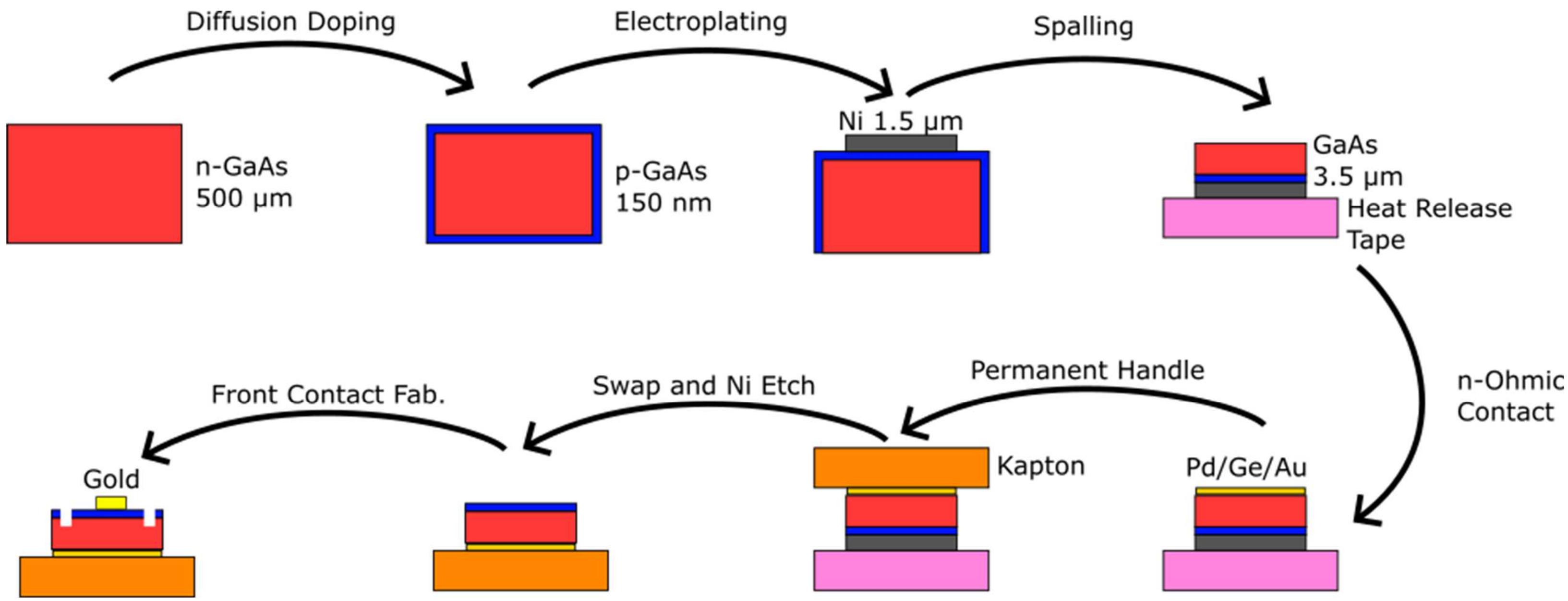
Semiconductor Spalling

- Can make thin III-V films by electroplating a stressed layer and removing with tape
- Have demonstrated 2 μm thick GaAs so far
- Spalled films are flexible
- Spall reveals 110 surface



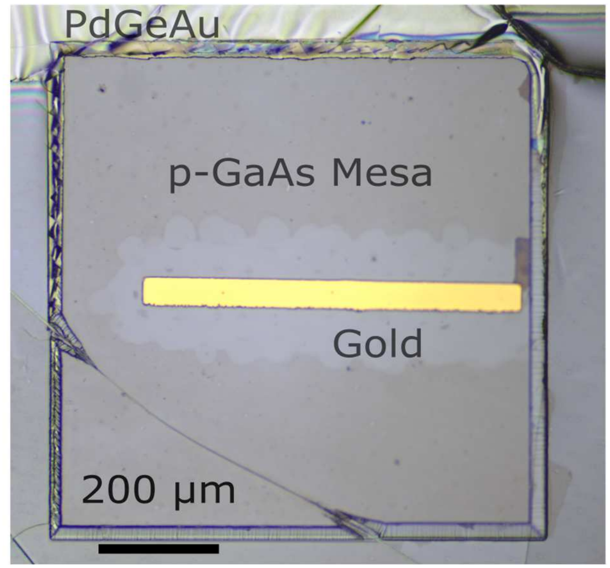
https://publishing.aip.org/publications/latest-content/thinking-thin-brings-new-layering-and-thermal-abilities-to-the-semiconductor-industry/

Thin-Film Device Fabrication



Preliminary Thin-Film Devices

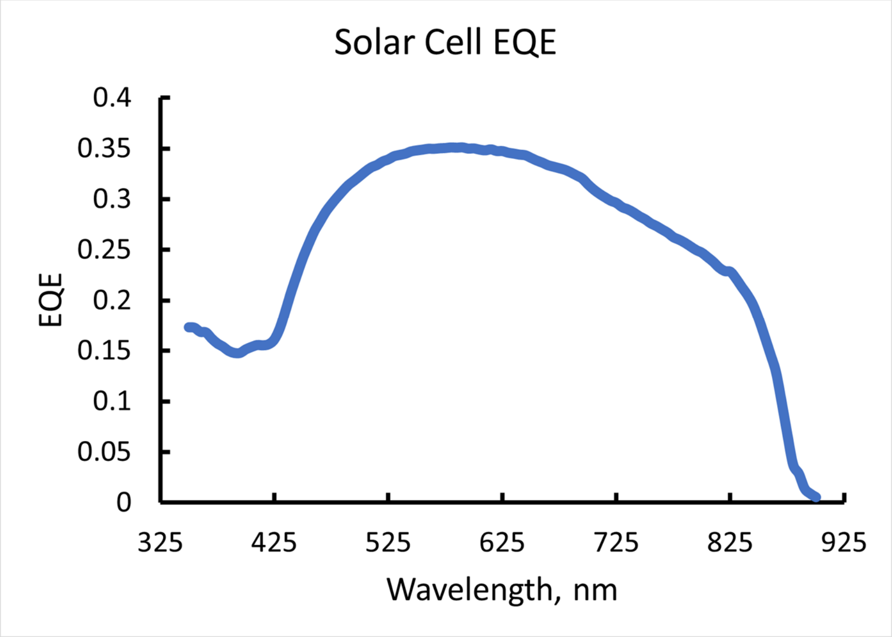
Spalled Film with deposited contacts



Finished spalled device

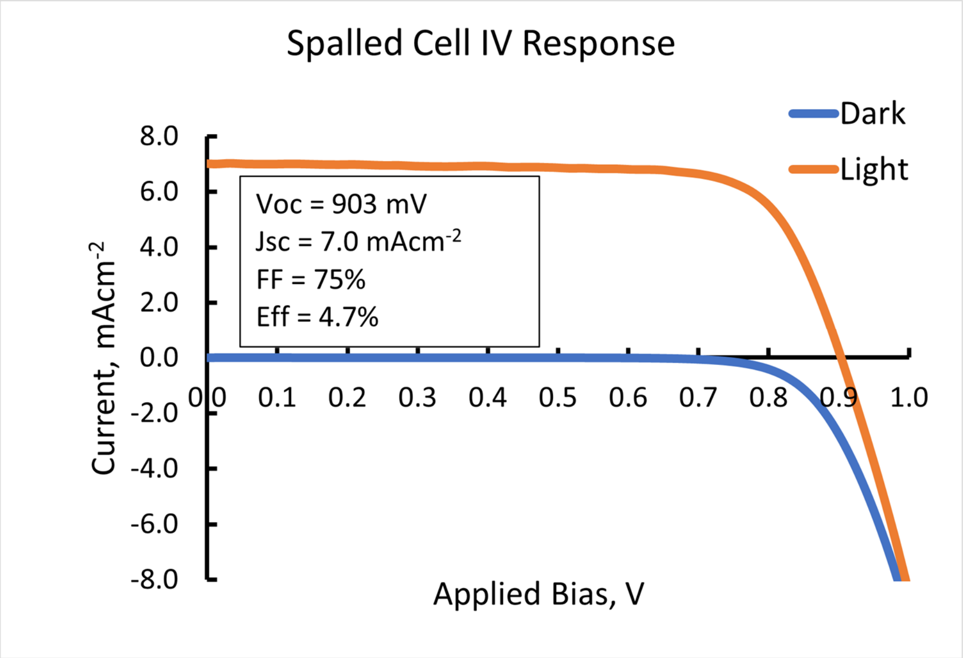
Preliminary Thin-Film Device Performance

- EQE is consistent with front-junction device
- Short hole diffusion length
  - $< 1\ \mu m$
  - Expected from using melt-grown, unannealed GaAs



Preliminary Thin-Film Device Performance

- 4.7% efficiency, 903 mV V_{oc}
- IV is consistent with a diffused junction device
- Free from shunting
- Ideality factor of 2 due to low-quality bulk GaAs
- Specific power of 500 W/kg including tape backing
- Still very early days

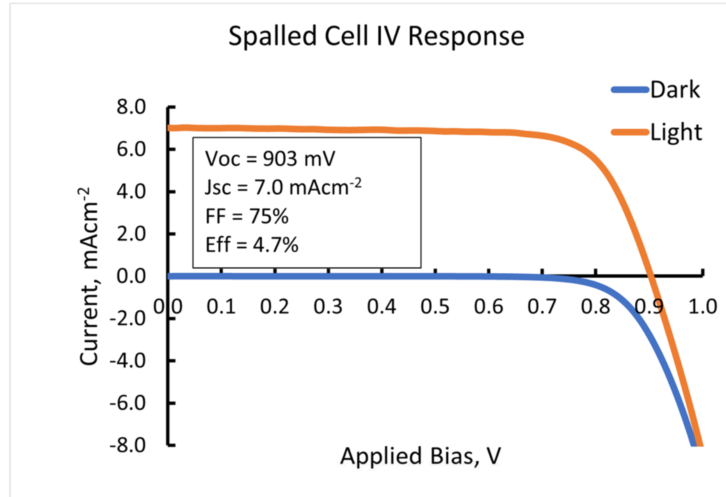


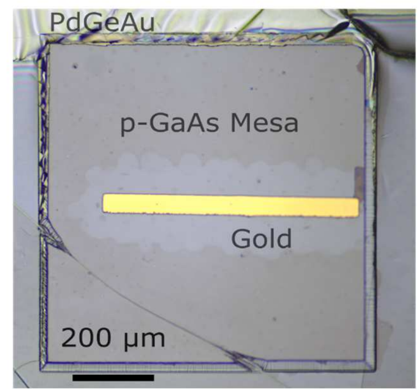
Future Work

- Fabricate devices on annealed GaAs to improve photocurrent
- Refine spalling process to be able to produce larger devices
- Develop optoelectronic simulations for calculating efficiency limits of thin-film devices

Summary

- Proposed a non-epitaxial III-V cell concept motivated by near-term space demands
- A simple, reliable method for p-type GaAs diffusion doping
- Long diffusion lengths in bulk GaAs
- High performance devices on HVPE-grown GaAs
- Preliminary fabrication and performance of thin-film, diffusion doped cells





Simplifying GaAs Diffusion Doping

- Historically done at $> 650°C$ to make junctions $> 1\mu m$ deep
- At $> 650°C$:
  - Arsenic pressure is large; need to use sealed ampoule or capping film
  - Vapor is mostly As; hard to get rid of Ga_i
    - Use Zn_3As_2 source or SiO_2 capping film
- Simply diffusing at lower temperatures fixes all these problems
  - Arsenic pressure is manageable
  - GaAs preferentially evaporates Ga, so doping stays favorable
  - Zn still has a good vapor pressure