

Integrated, Flexible, High-efficiency Solar Cells: Epitaxial Lift-Off GaAs Solar Cells and Enabling Substrate Reuse

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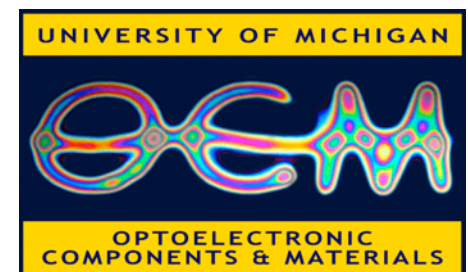
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Supported by

Army Research Laboratory MAST Program
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Report Documentation Page

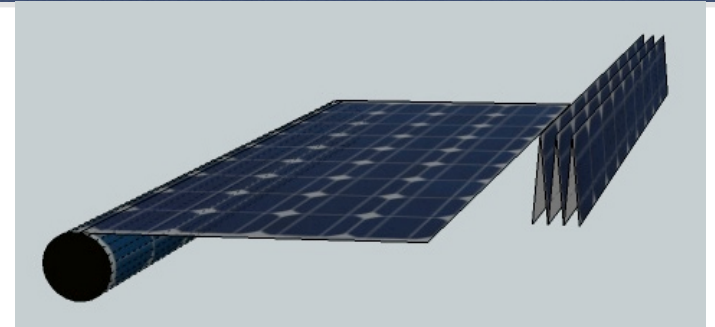
Form Approved
OMB No. 0704-0188

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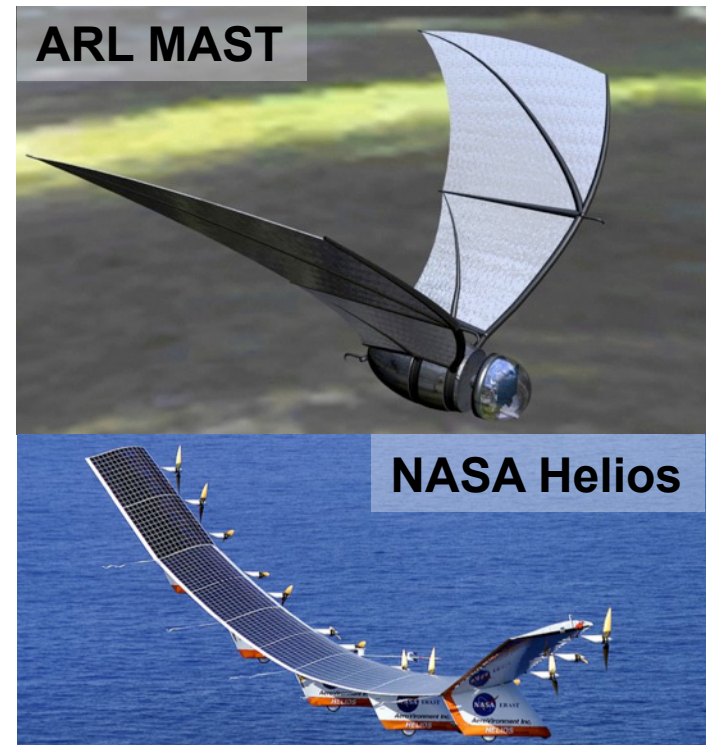
1. REPORT DATE AUG 2012	2. REPORT TYPE	3. DATES COVERED 00-00-2012 to 00-00-2012		
4. TITLE AND SUBTITLE Integrated, Flexible, High-efficiency Solar Cells: Epitaxial Lift-Off GaAs Solar Cells and Enabling Substrate Reuse		5a. CONTRACT NUMBER		
		5b. GRANT NUMBER		
		5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)		5d. PROJECT NUMBER		
		5e. TASK NUMBER		
		5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Michigan, Department of Electrical Engineering and Computer Science, Ann Arbor, MI, 48109		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)		
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited				
13. SUPPLEMENTARY NOTES Presented at the 2nd Multifunctional Materials for Defense Workshop in conjunction with the 2012 Annual Grantees'/Contractors' Meeting for AFOSR Program on Mechanics of Multifunctional Materials & Microsystems Held 30 July - 3 August 2012 in Arlington, VA. Sponsored by AFRL, AFOSR, ARO, NRL, ONR, and ARL. U.S. Government or Federal Rights License				
14. ABSTRACT				
15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified	Same as Report (SAR)	18. NUMBER OF PAGES 23
				19a. NAME OF RESPONSIBLE PERSON

Motivation

- Numerous uses for **lightweight, high-efficiency, flexible** photovoltaics:
 - Power at temporary off-grid locations.
 - Autonomous vehicles (e.g. UAVs).
 - Satellites.
- No available technologies provide high-efficiency, high power density photovoltaics on lightweight flexible substrates.
- III-V photovoltaics provide $>28\%$ power conversion efficiency (η_P).
- Specific power densities of >6 W/g & 280 W/m².
- Substantial reduction in III-V PV cost structure: wafer reuse.

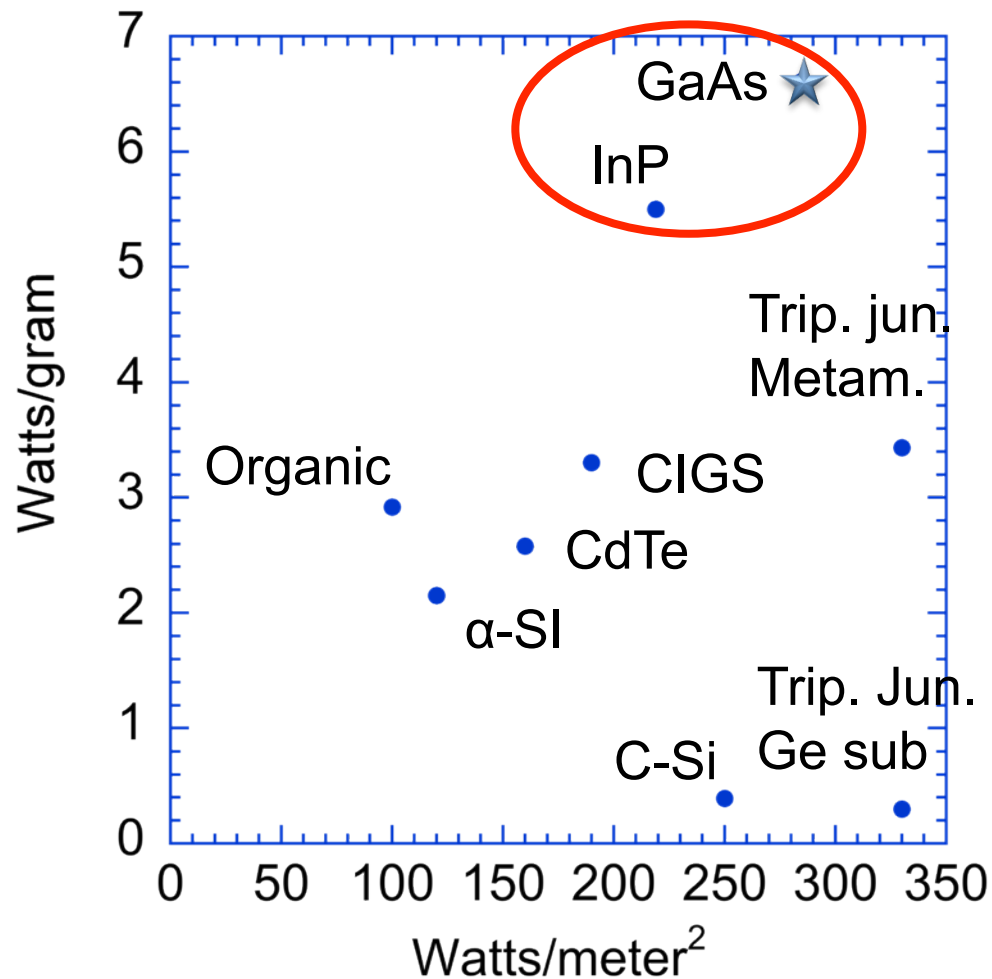


Rollable or foldable portable PV



Power for UAVs

Power/Weight Tradeoff



- Ideal cell: thin + high efficiency.
- Active layers for GaAs cell is ~2 μm .
- Lift-off uses back reflector \rightarrow active layer thickness reduced by ~50%.
- GaAs has highest power:area and power:weight ratios achievable.
- Lift-off cells have higher power conversion efficiency than substrate cells.

Technologies & Goals

Epitaxial Lift-Off (ELO)

- **Light Weight & Flexible Thin-Film Solar Cell**
E. Yablonovitch et al, Appl. Phys. Lett. **51**, 2222 (1987).

Epitaxial Protection Layers

- **Parent Wafer Reuse**
K. Lee et al, Appl. Phys. Lett. **97**, 101107 (2010)—[UM](#).

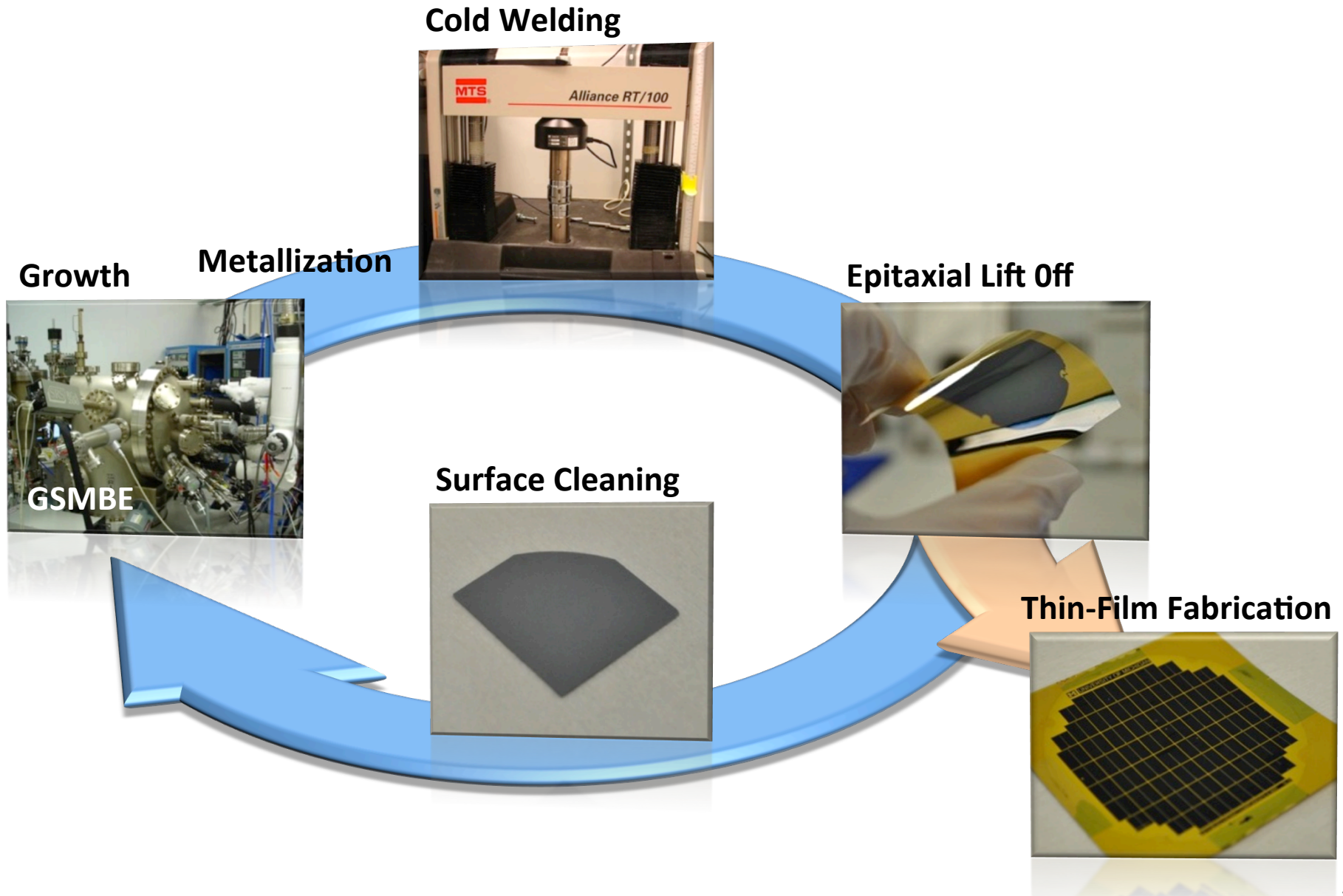
Cold Welding

- **Simplified Transfer Process**
K. T. Shiu et al, Appl. Phys. Lett. **95**, 223503 (2009)—[UM](#).

Multiple Growths on Single Wafer

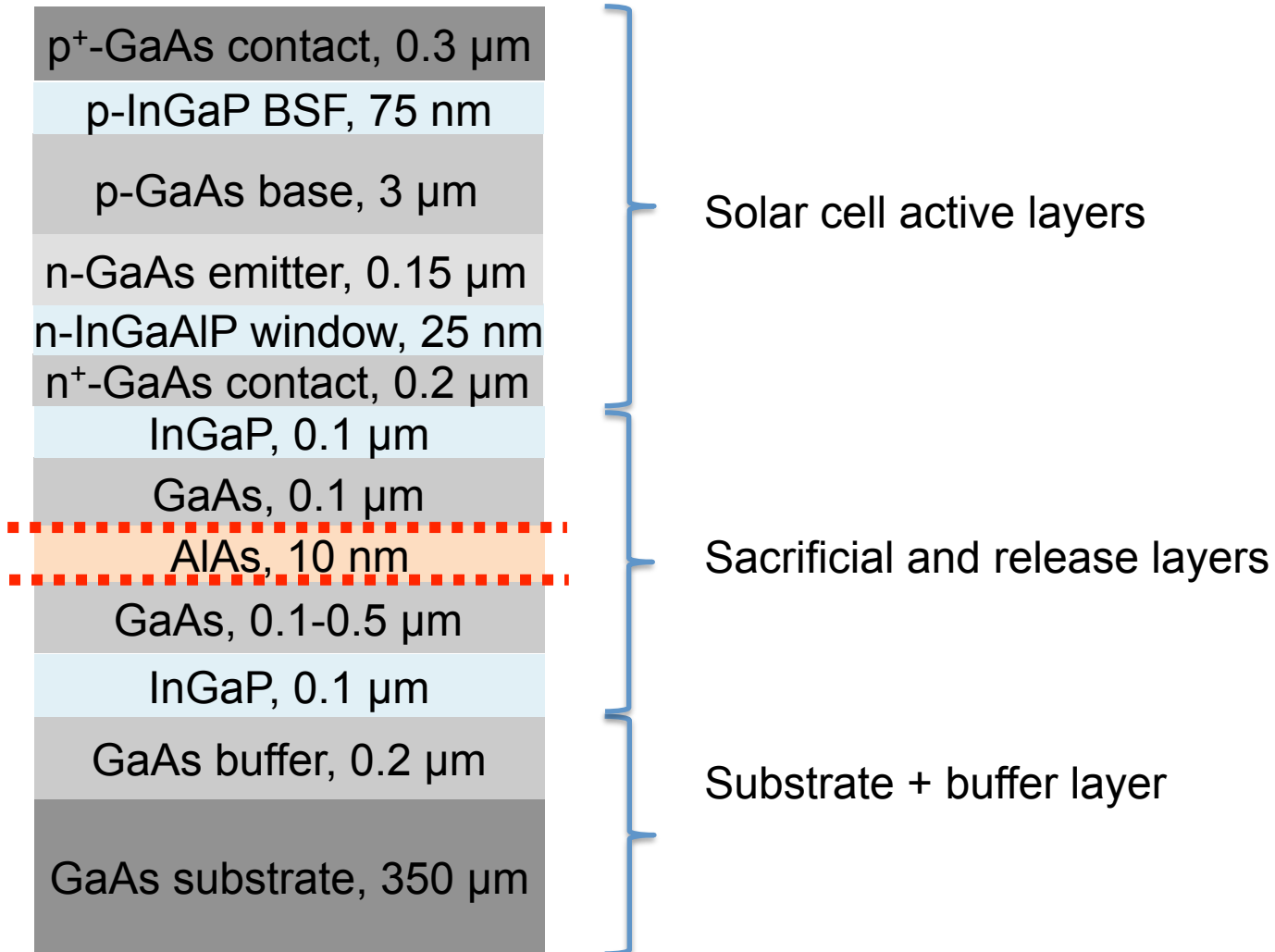
Low-Cost Solar-to-Electrical Energy Conversion

Non-Destructive Wafer Reuse for Thin-Film PV Cells



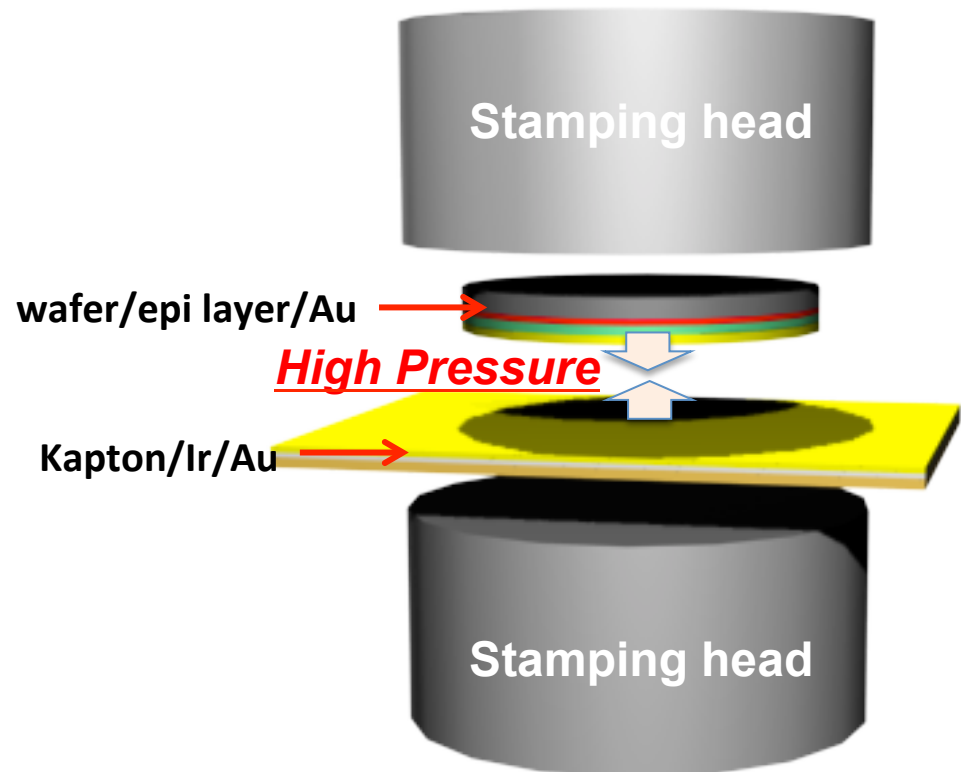
MBE Growth of Epi-layers

Molecular beam epitaxy used to grow:



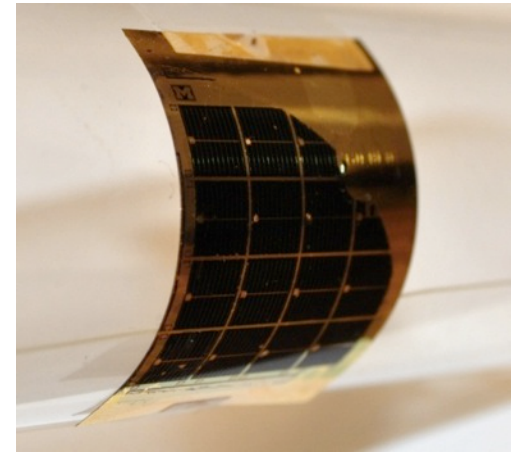
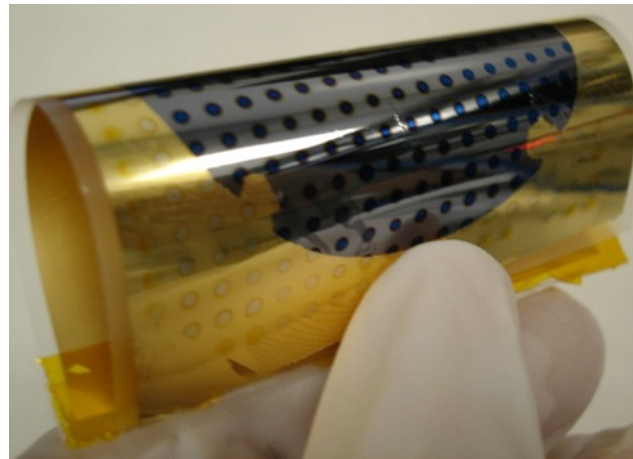
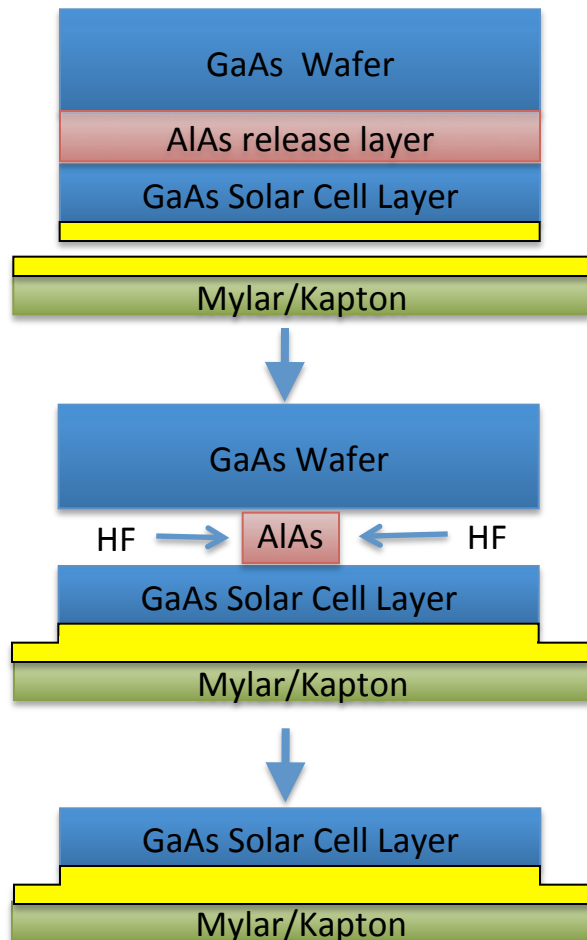
Cold Welding

- Au deposited on wafer and plastic handle.
- Au surfaces bonded by applying pressure.
 - Metallic bonds formed at room temperature.
 - Adhesive-free bonding technology.
- Simple transfer process.



Transferring III-V PV Cells to Plastic

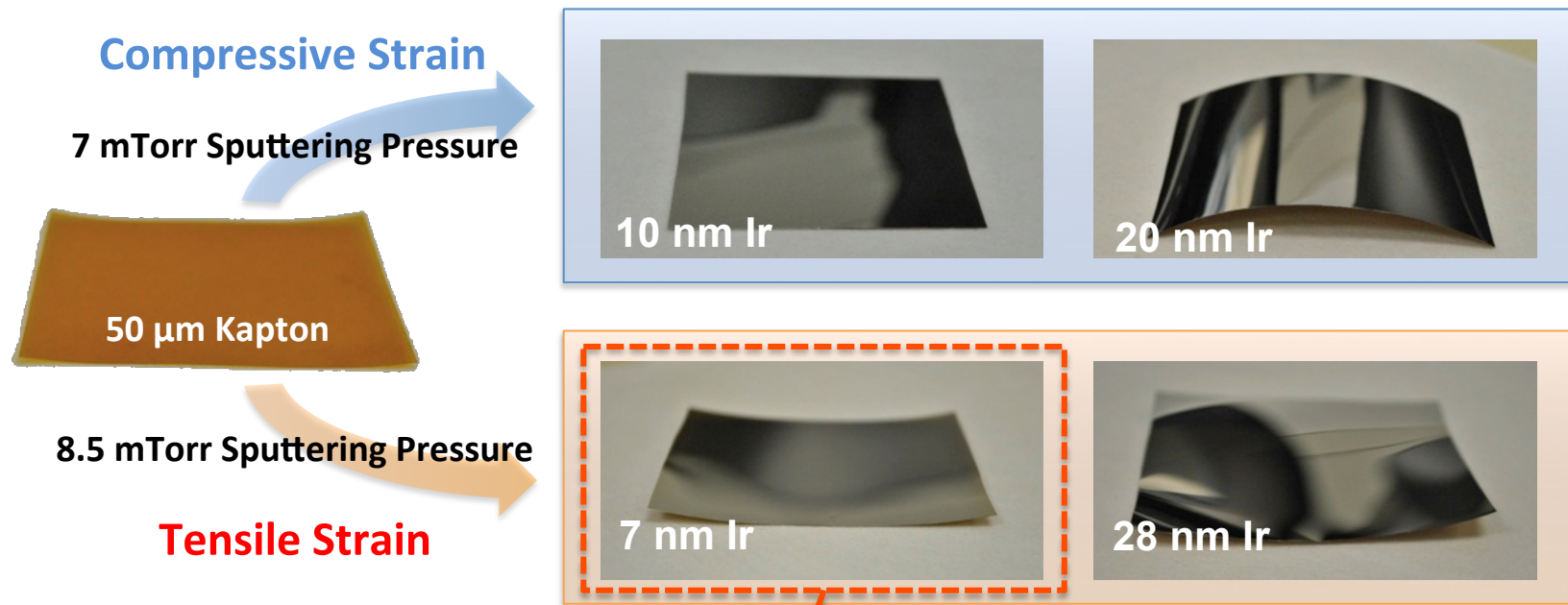
Epitaxial lift-off



- Wafer cold welded to Kapton®.
- Lift off performed with HF.
 - Etch selectivity is $\sim 10^7:1$ (AlAs:GaAs).
 - Epitaxial lift-off enables wafer reuse.
 - Efforts are focused on improving quality and speed of lift-off process.
- Fabrication performed on Kapton® substrate.
- Flexible without degradation to radius < 1 cm.

Acceleration of ELO Using Strained Handles

Strain Control by Sputtered Ir

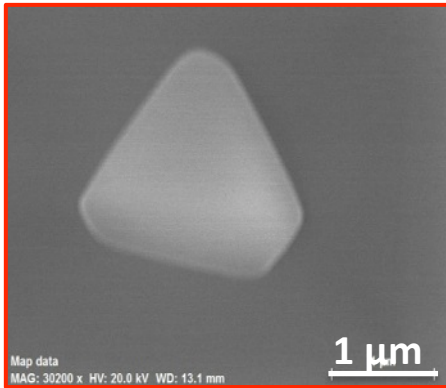


Substrate
10nm AIAs
Kapton/epi layer

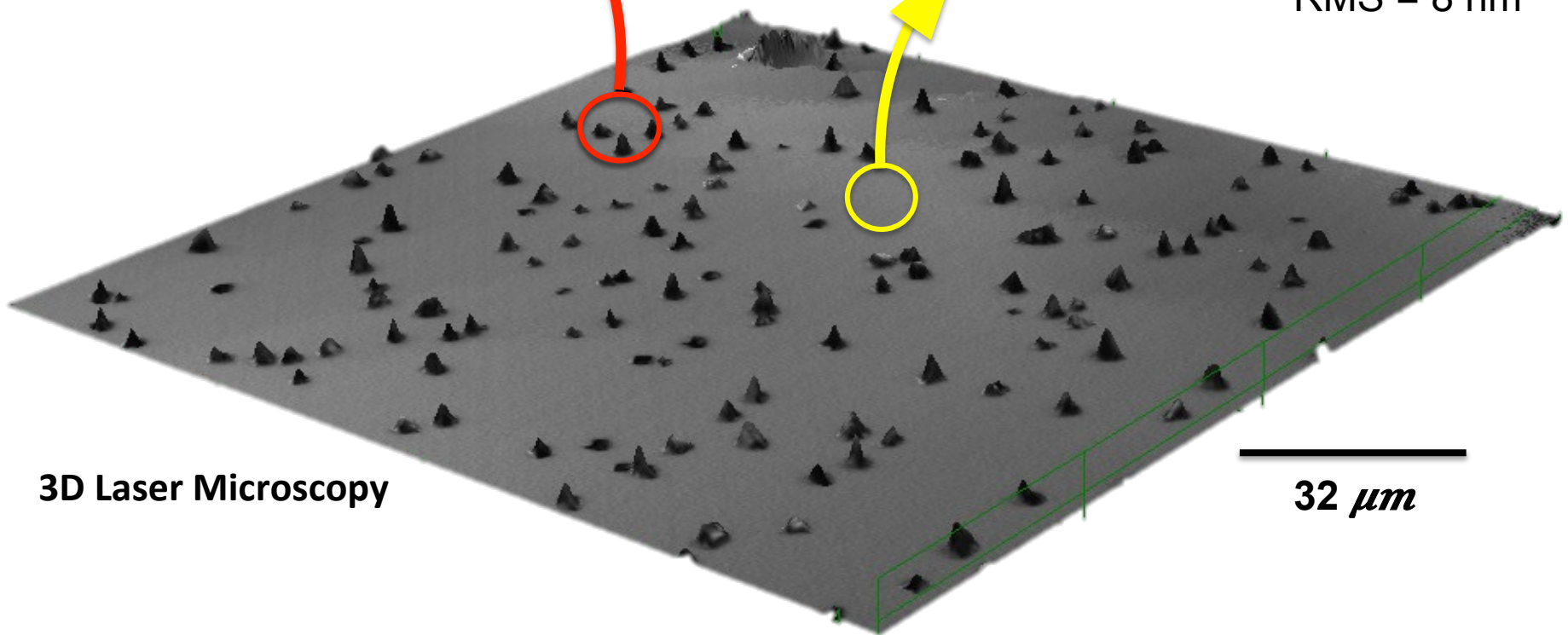
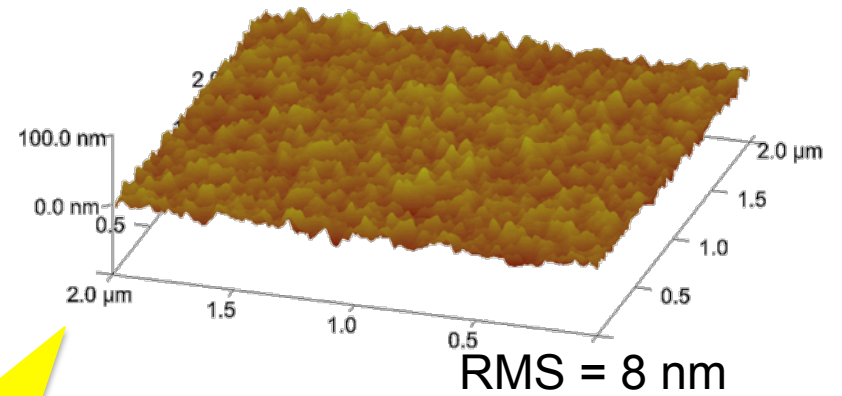
Strain State (Ir thickness)	Etch time
Neutral	~10 days
Compressive (21 nm)	~24 hrs
Tensile (7 nm)	<8 hrs

Influence of ELO on GaAs Wafer

Scanning Electron Microscopy



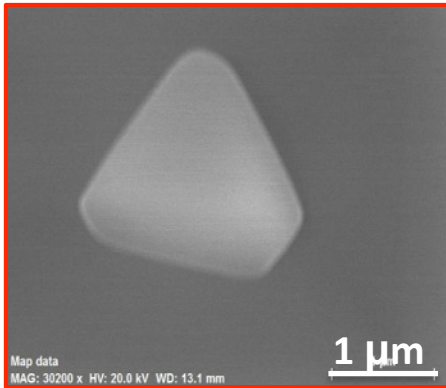
Atomic Force Microscopy



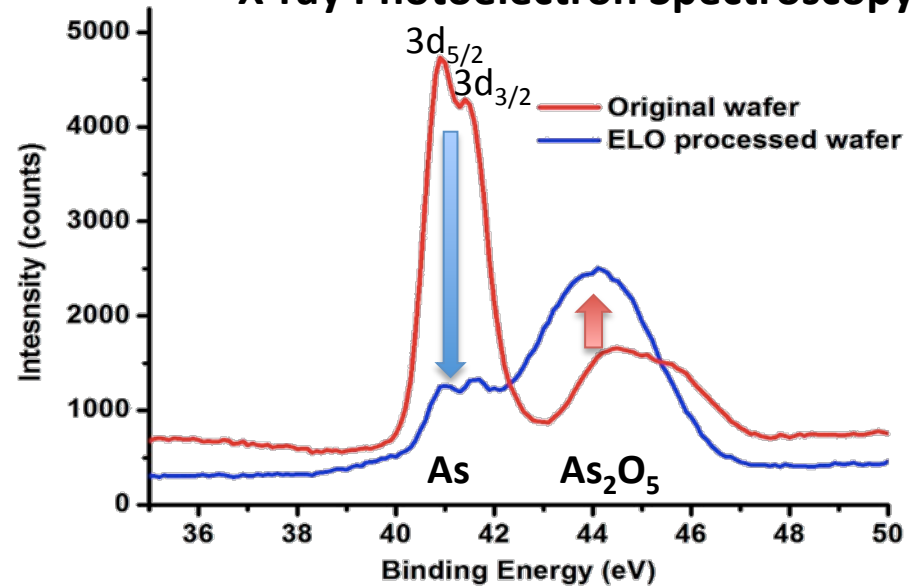
3D Laser Microscopy

Influence of ELO on GaAs Wafer

Scanning Electron Microscopy

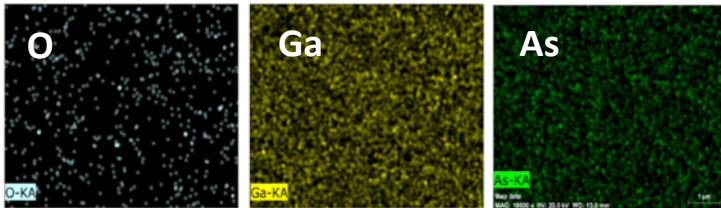


X-ray Photoelectron Spectroscopy

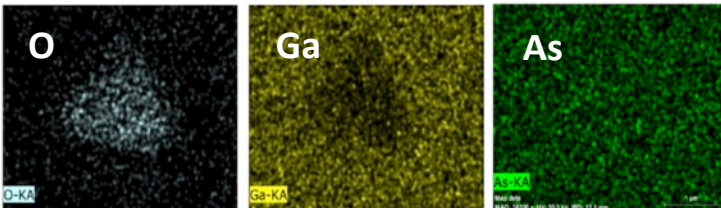


Energy Dispersive Spectroscopy

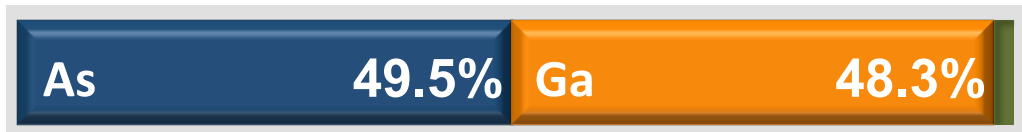
Original Wafer



ELO Processed Wafer



Atomic Concentration Near Surface Original Wafer

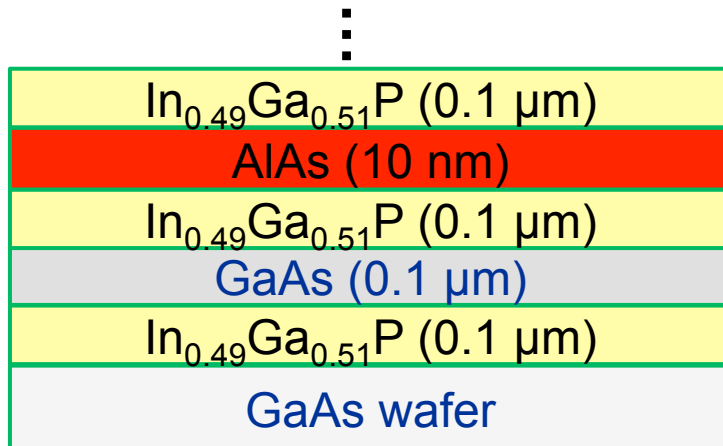


ELO Processed Wafer

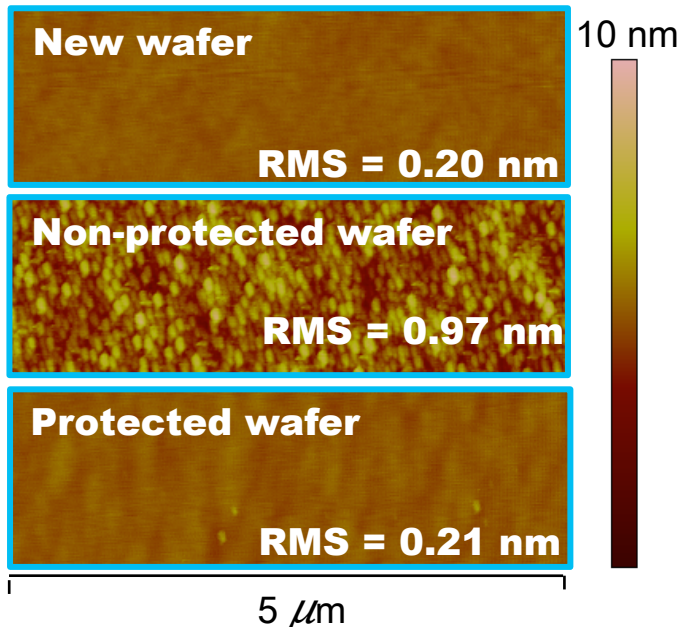


Protection Layers

Protection Layer Structure



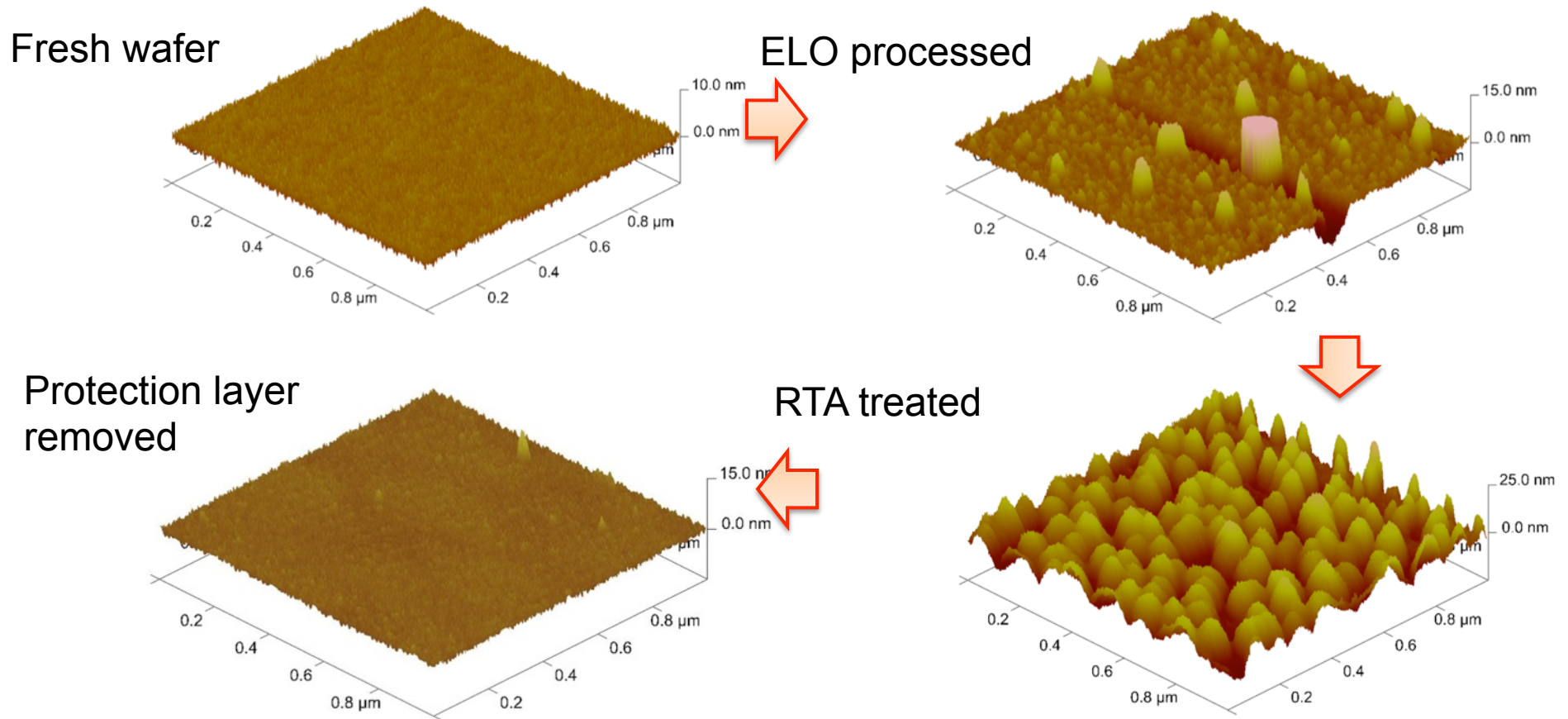
Atomic Force Microscopy



- Protection layers
 - Inserted between AIAs and wafer or active layers.
 - Prevent HF from contacting the wafer.
 - InGaP removed with H₃PO₄:HCl or HCl:H₂O.
 - GaAs removed with H₃PO₄:H₂O₂: H₂O.
 - Reduces RMS roughness to that of original wafer.
- As₂O₅ particles difficult to remove
 - Tri-layer necessary.
 - Over-etched to undercut particulates.

K. Lee et al, APL **97**, 101107 (2010).
K. Lee et al, JAP **111**, 033527 (2012).

Thermal Decomposition

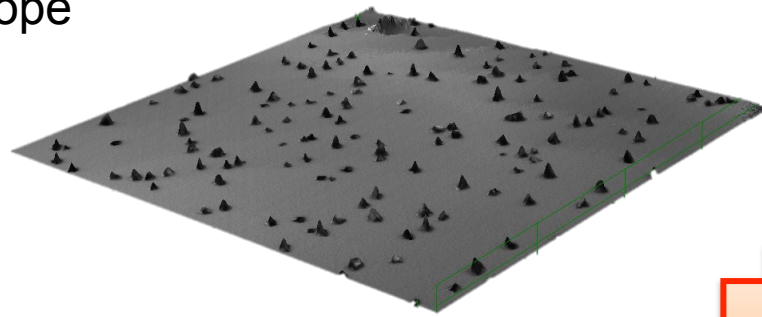


- RTA in N_2 at 600 °C for 1 min.
- GaAs/InGaP bilayer protection removed with wet etches.
- Surface returned to like-new condition.

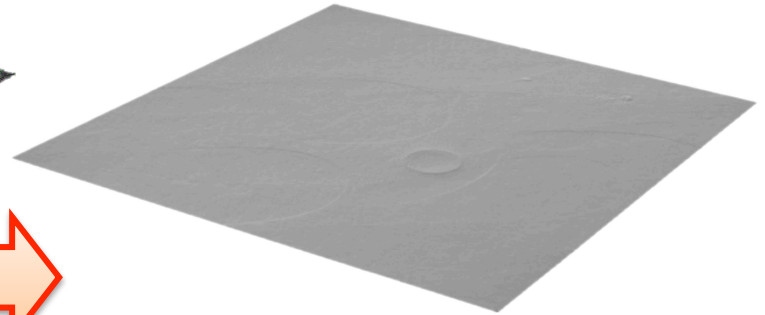
Plasma Pre-clean

3d laser microscope

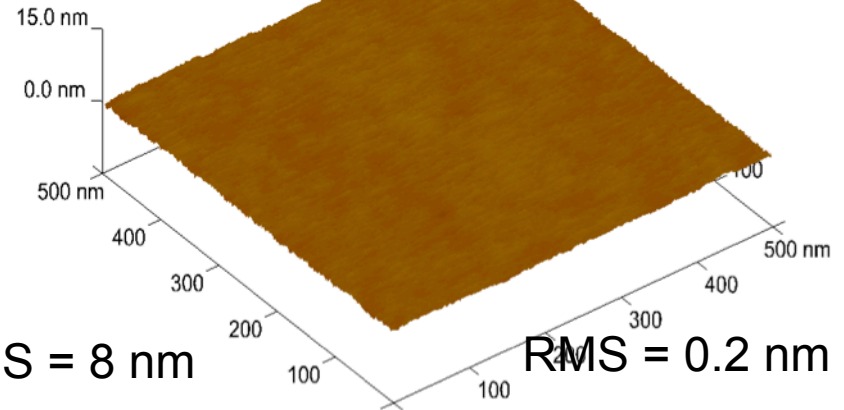
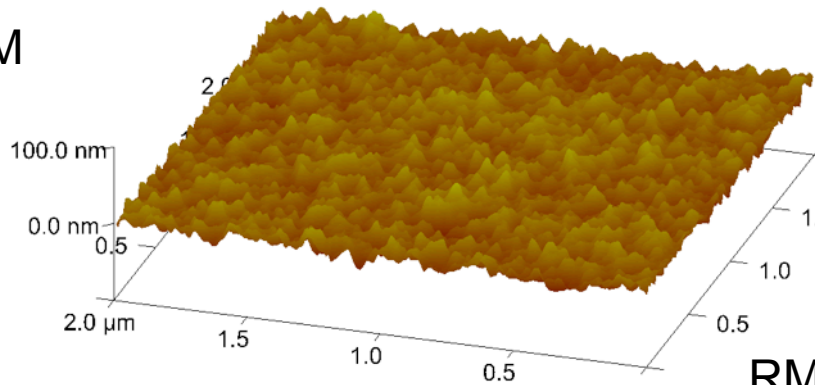
After ELO



After plasma cleaning



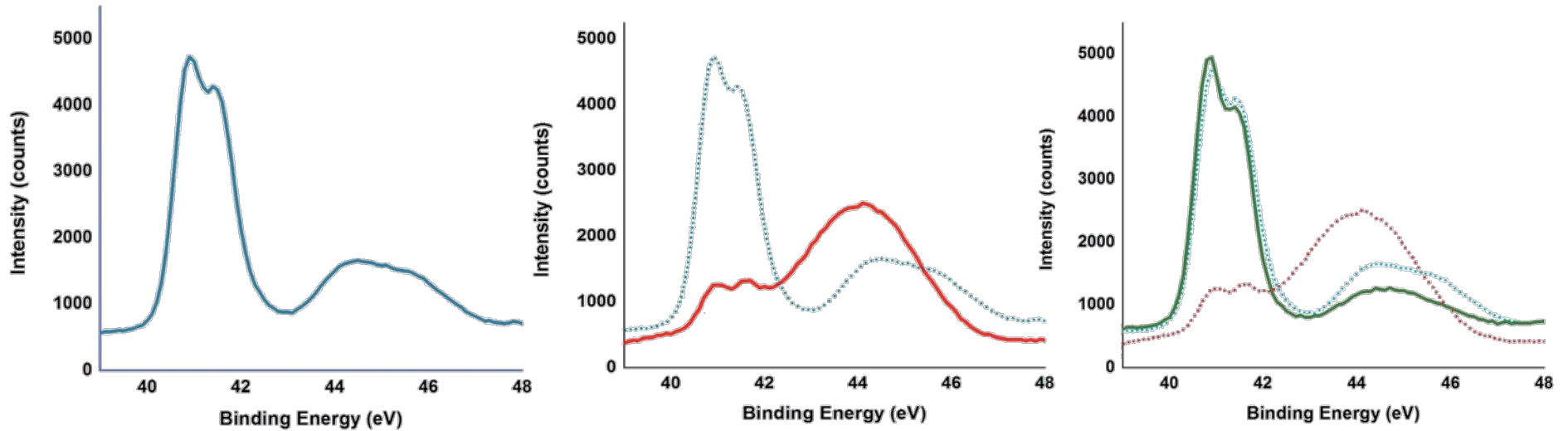
AFM



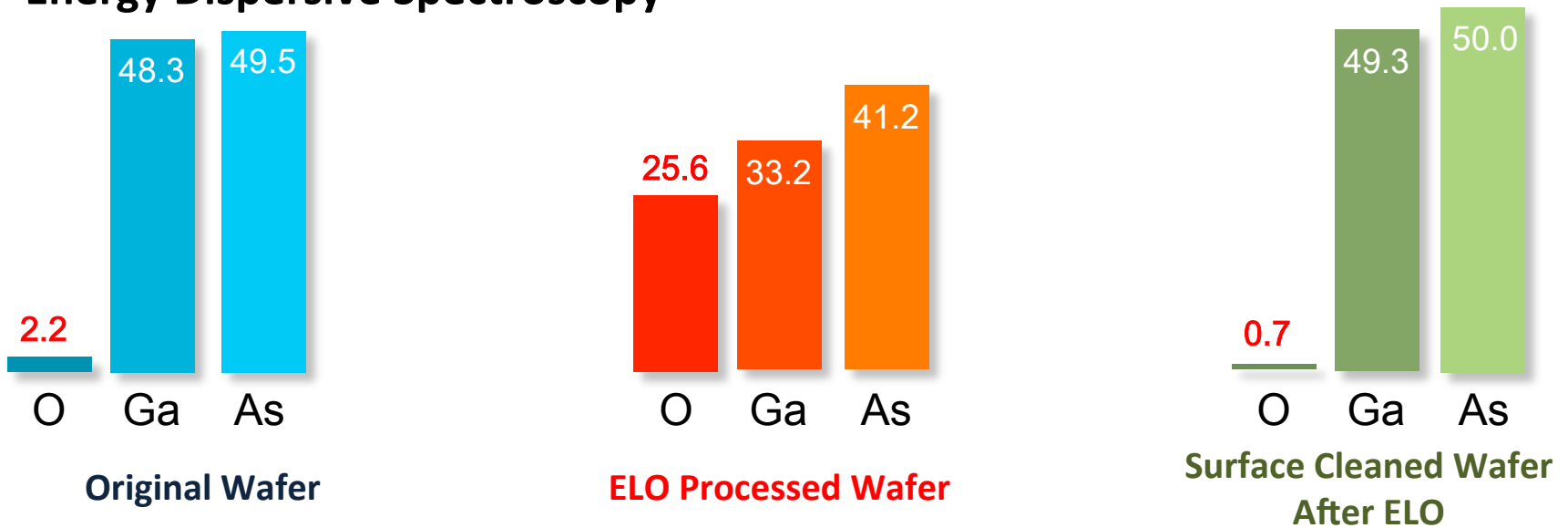
- SF_6 +Ar ICP plasma for 1 min.
- GaAs/InGaP bilayer protection removed with wet etches.
- Surface returned to like-new condition.

Surface Chemistry Comparison

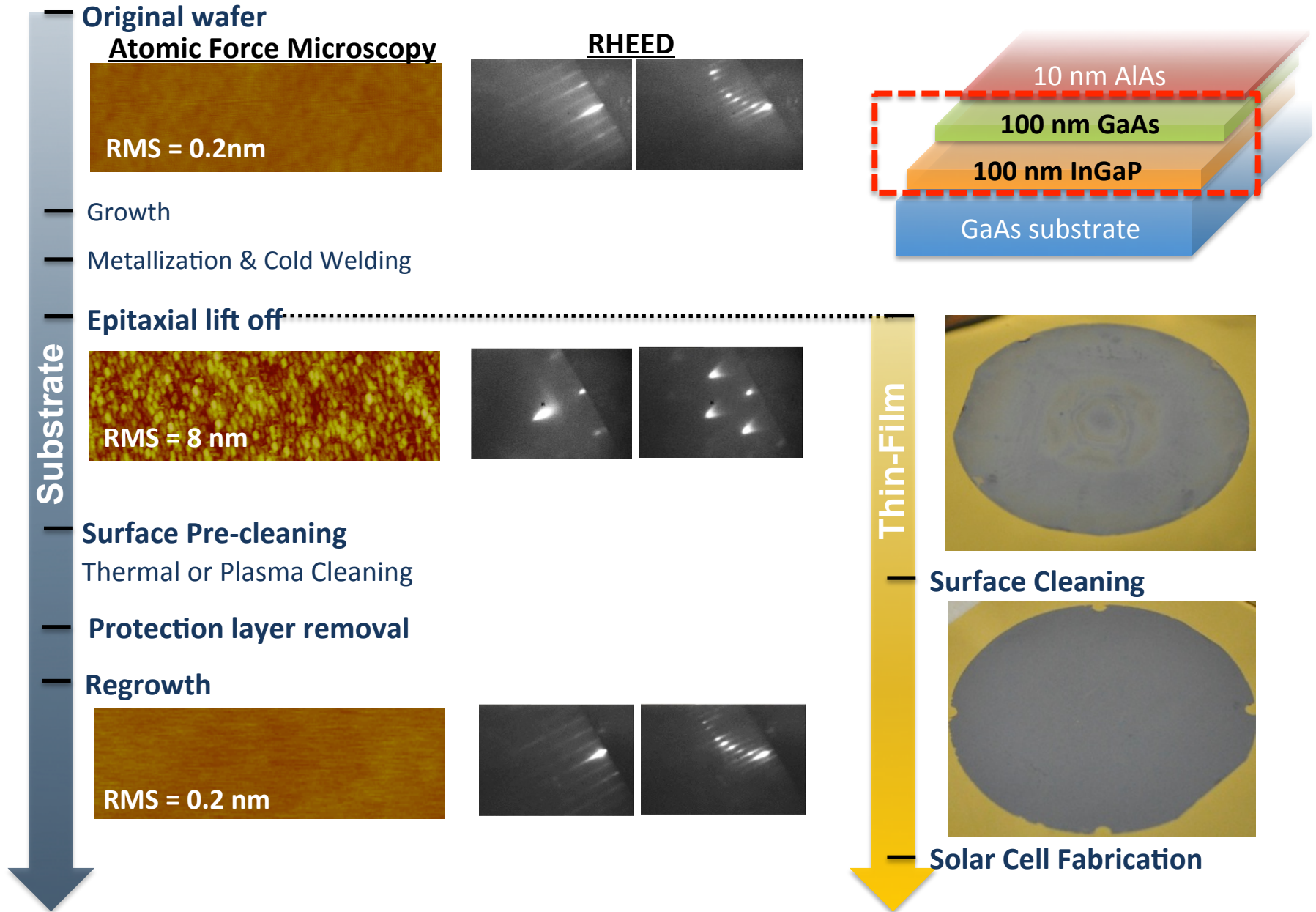
X-ray Photoelectron Spectroscopy



Energy Dispersive Spectroscopy

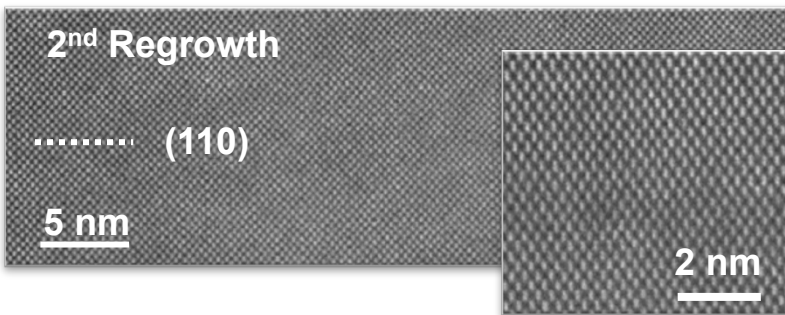
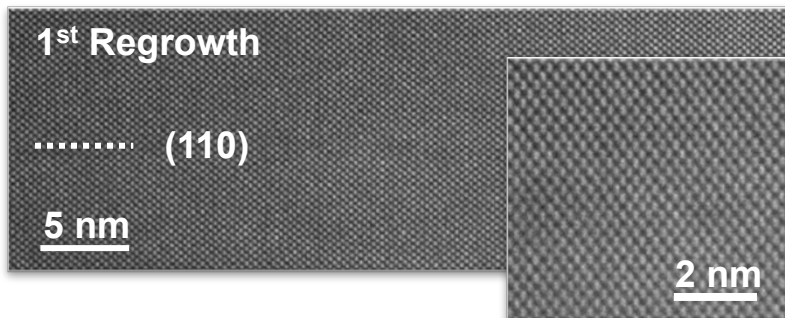
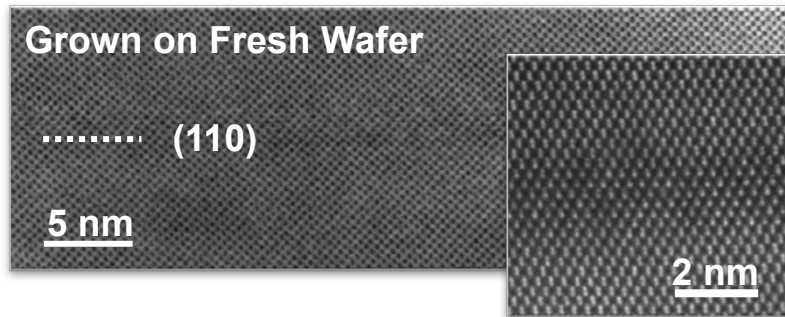


Epitaxial Protection Layer & Surface Cleaning



Growth Quality Comparison

Cross-Sectional Transmission Electron Microscopy



Hall Effect Measurement

Original Growth

Doping concentration
 $1.67 \times 10^{18} / \text{cm}^3$

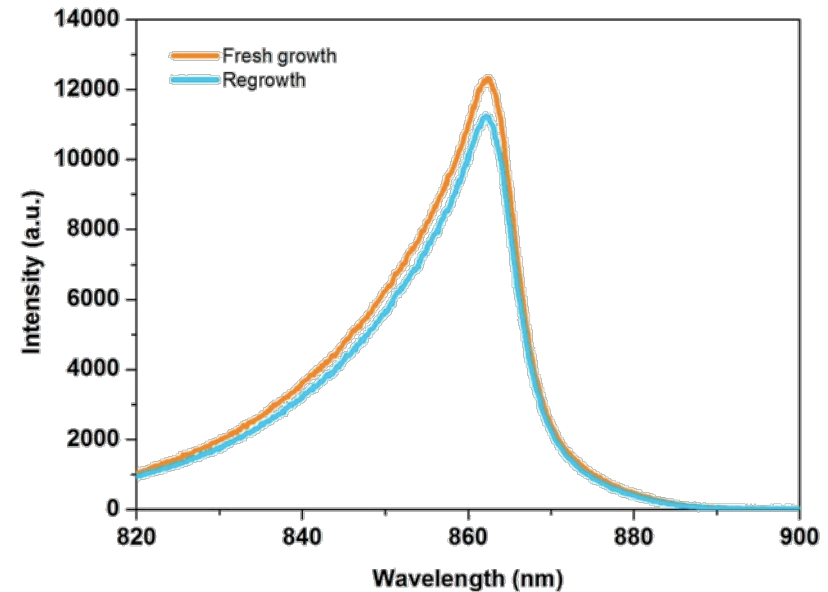
$1950 \text{ cm}^2/\text{Vs}$

Regrowth

Doping concentration
 $1.78 \times 10^{18} / \text{cm}^3$

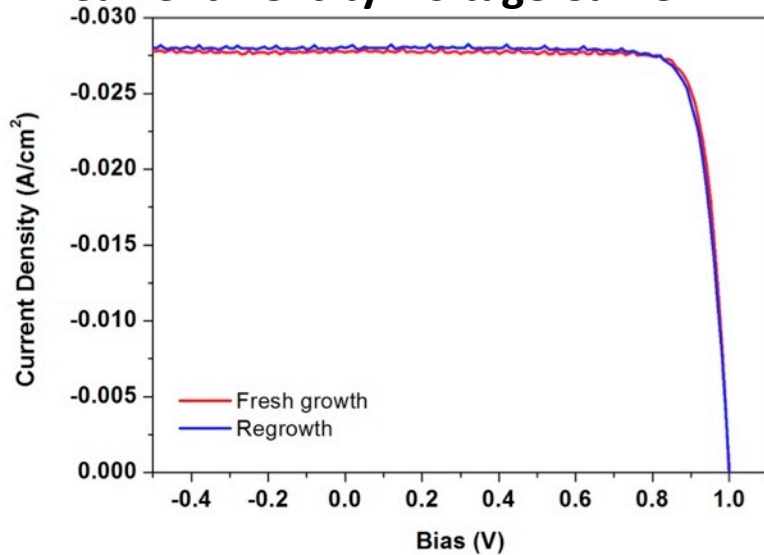
$1930 \text{ cm}^2/\text{Vs}$

Photoluminescence Measurement

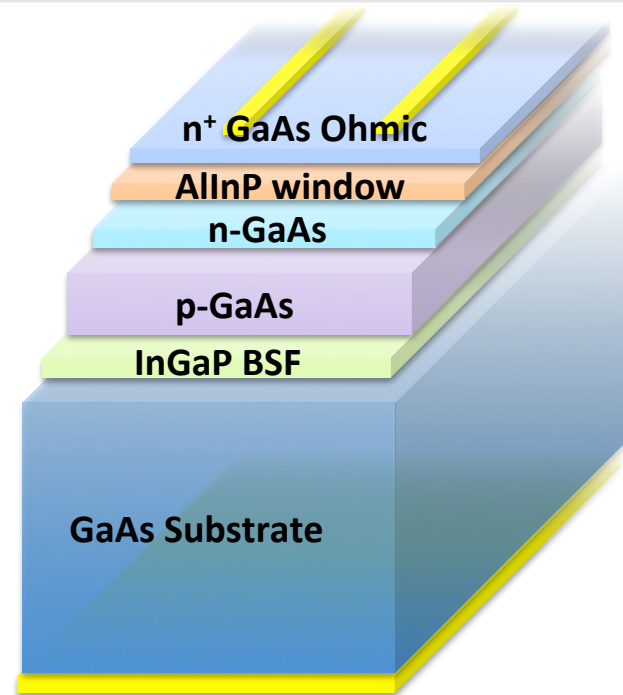
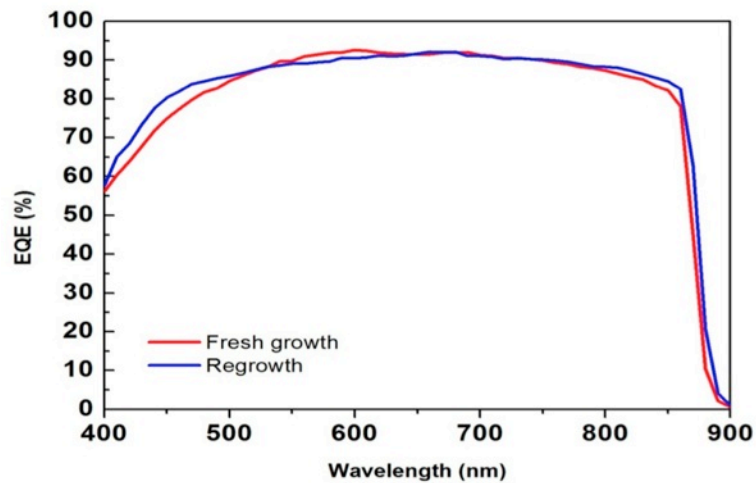


Device Performance Comparison

Current Density-Voltage Curve



External Quantum Efficiency

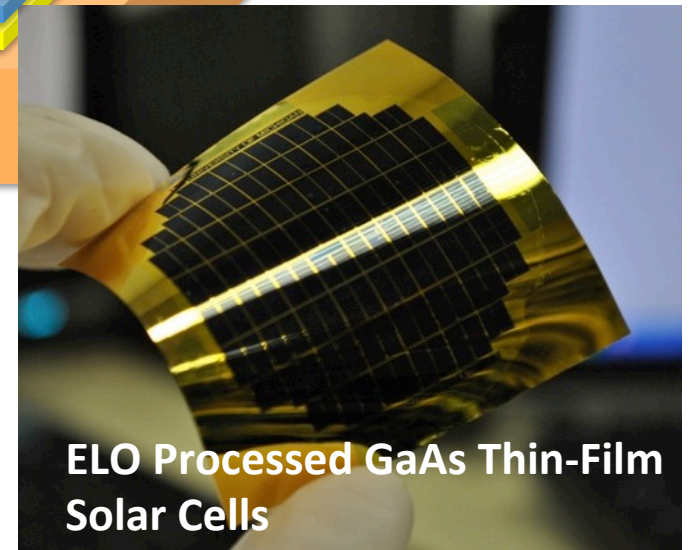
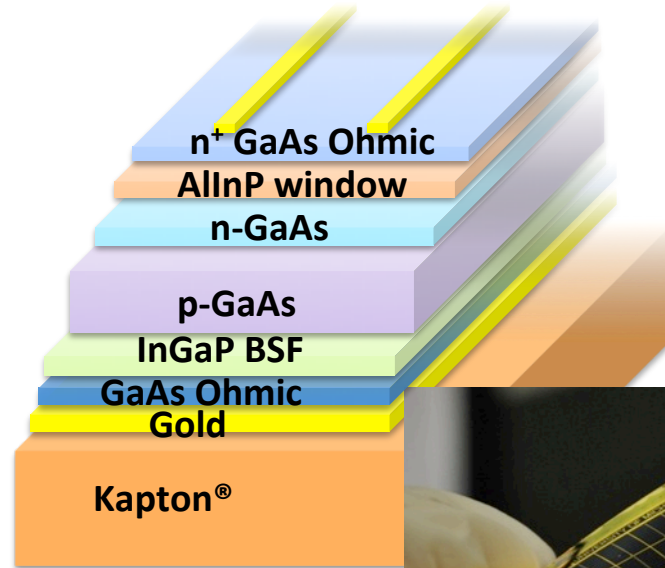
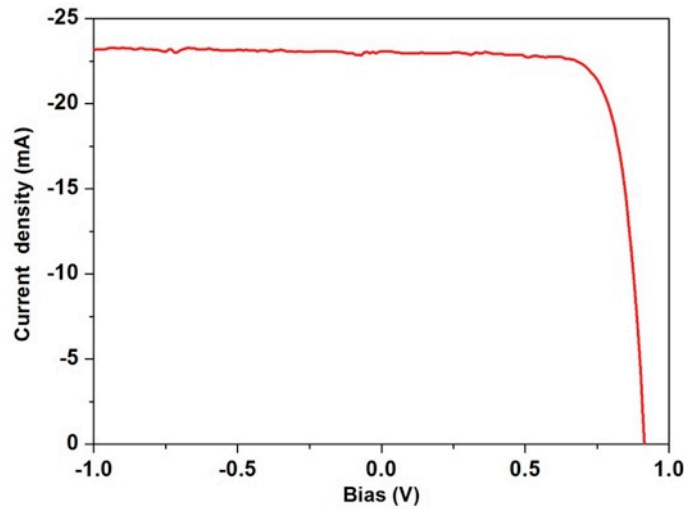


Device Efficiency Parameters

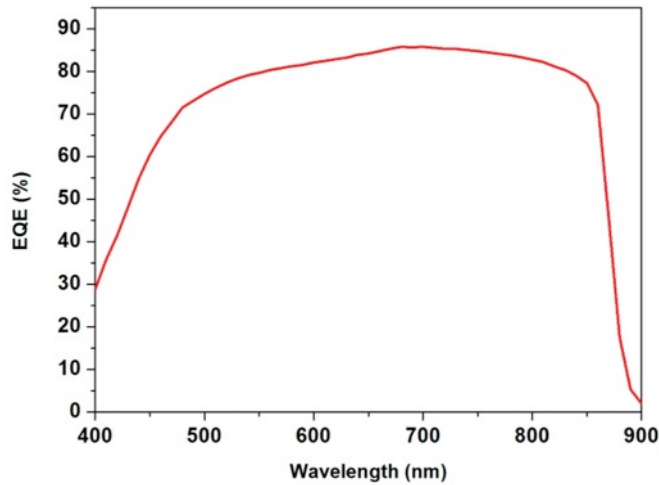
	J_{SC} [mA cm ⁻²]	V_{OC} [V]	FF [%]	PCE [%]
Fresh Wafer	27.7±0.5	1.00	83.4	23.1±0.6
Reused wafer	28.0±0.4	1.00	81.6	22.8±0.5

GaAs Thin-Film Solar Cells

Current Density-Voltage Curve



External Quantum Efficiency



Device Efficiency Parameters

J_{sc}	V_{oc}	FF	PCE
23.1 mA/cm ²	0.92 V	75.6%	16.1%

Cost Estimate: Substrate-Based III-V PV

1 m² GaAs PV Cells:

• Substrates (56 x 6")		\$17,000
• Source material (4 μm GaAs growth)		\$80
• Liquid nitrogen for cryo panels		\$400
• Electricity (~120 kW-hr)		\$15
• Wafer processing		\$75
– Conventional Au contacts	\$40	
– AR coating (ZnS/MgF ₂)150nm	\$10	
– Lithographic patterning	\$25	
• Total		\$17,570
• Cost/Wp @ 23%		\$76

(assumptions: Standard **MBE** design, no large reductions in price for bulk quantities, and labor and capitol cost not included.)

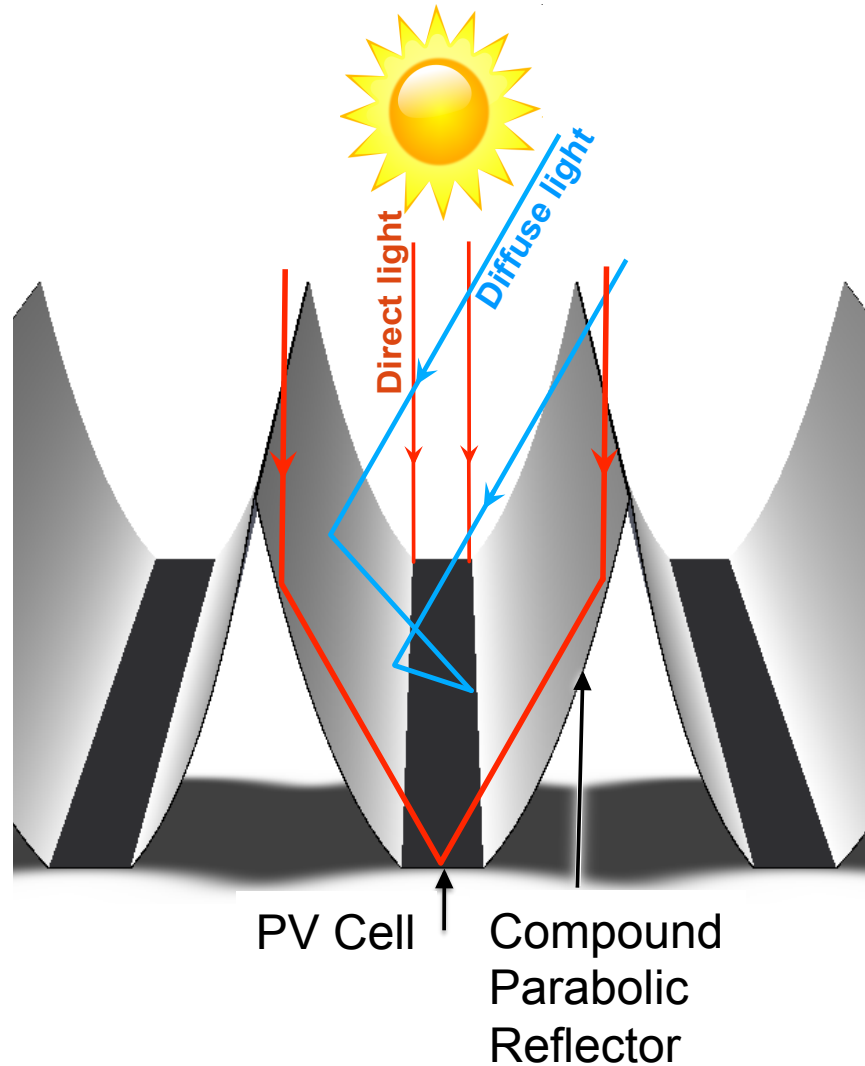
Cost Estimate for *Flexible III-V PV*

1 m² GaAs PV Cells:

- Substrates (56 x 6"): **50 uses** **\$340**
- Source material (**2 μm** GaAs growth) **\$40**
- Electricity (~120 kW-hr) **\$15**
- Wafer processing **\$35**
 - Metal/Kapton[®] foil **\$10**
 - Ag/Cu contacts **\$10**
 - AR coating (ZnS/MgF₂)150nm **\$5**
 - HF etchant (HF:AlAs >106:1), 1 L 10% **\$5**
 - Non-Lithographic patterning **\$5**
- Total **\$430**
- **Cost/Wp @ 30%** **\$1.43**

(assumption: **No LN₂**—requires MBE redesign.)

Concentration



- Grid parity possible by using concentrators.
- 4x concentration: ~\$0.70/Wp.
- 10x concentration: ~\$0.45/Wp.
- Requires solar tracking.

Summary

- **Solar Cell Fabrication**

- Via cold-welding & epitaxial lift-off.
- Expedited lift-off process using strained handle.

- **Reuse of GaAs Wafers**

- Lattice matched epitaxial protection layer.
- Thermal & plasma surface cleaning.
- GaAs regrowth after protection layer removal.
- Identical solar cell performance.

K. Lee et al, J. Appl. Phys. **111**, 033527 (2012).

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