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Innovation for Our Energy Future

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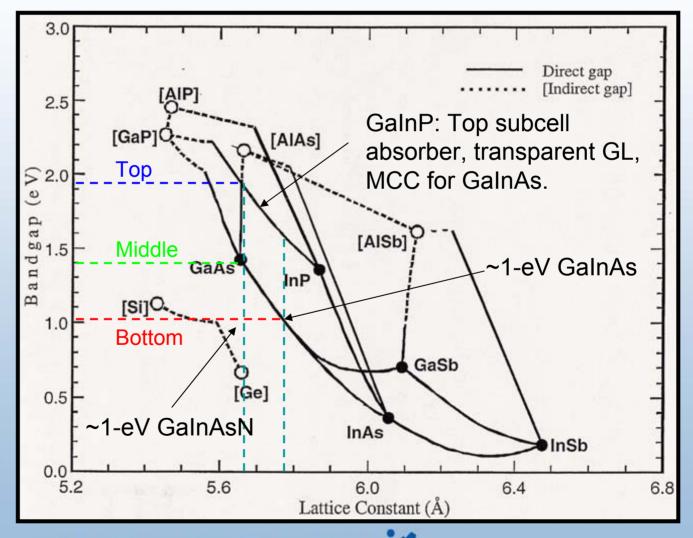
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### Monolithic, Ultra-Thin GaInP/GaAs/GaInAs Tandem Solar Cells

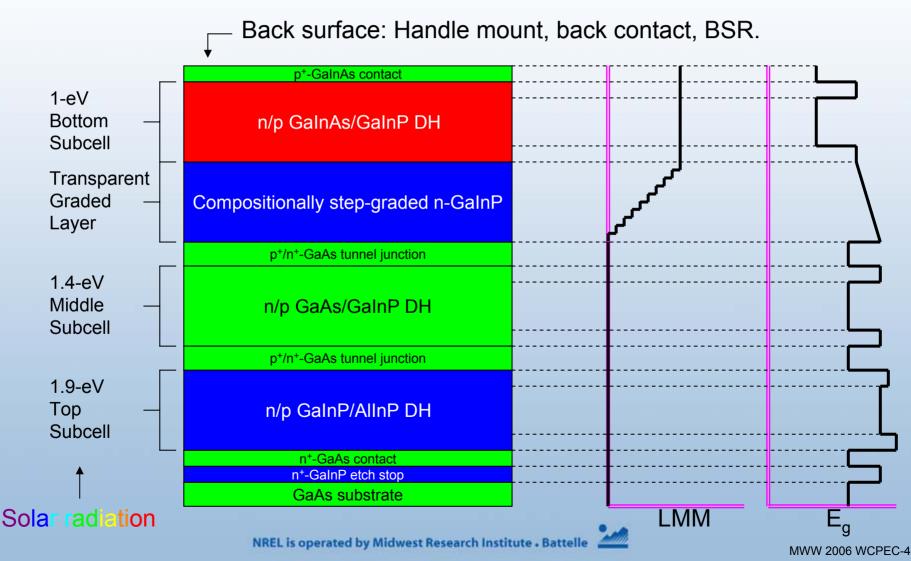
- NREL IR # 05-05, patent pending.
- Near-optimum subcell bandgaps.
- ~300 mV voltage output boost compared to conventional Ge-based triple-junction tandems.
- Bottom subcell E<sub>g</sub> is variable.
- Basic approach is expandable to 4-6 subcells.







### Inverted GaInP/GaAs/GaInAs Tandem Structure





### Ultra-thin Tandem Cell Processing Sequence

Back contact/BSR Contact layer		Parent substrate
Multi-bandgap device layers		Etch-stop layer Contact layer
Contact layer Etch-stop layer	1	Multi-bandgap device layers
Parent substrate		Contact layer Back contact/BSR
1) Inverted tandem structure is grown on the parent substrate, and the back contact/BSR is formed.		Handle (support substrate) 2) Epistructure is mounted upside down on a
Contact layer	*	handle material (secondary support substrate).
Multi-bandgap device layers	Contact layer —	Top contact ARC
Contact layer		Multi-bandgap device layers
Back contact/BSR Handle (support substrate)		Contact layer
		Back contact/BSR
3) Parent substrate is removed.		Handle (support substrate)

4) Front-surface processing is completed.





# Advantages of Ultra-Thin, Handle-Mounted Tandem Solar Cells

- Handle material can be engineered to have a wide range of advantageous characteristics.
- Thermal management can be optimized.
- Highest specific power (W/kg) for space applications.
- Reuse and/or reclamation of the parent substrate also possible, reducing cost.
- Parent substrate can be impure to reduce cost.
- Benefits of BSR: thin GaInAs subcell, lower  $J_0$ , improved radiation hardness, reduced operating temperature.





# Semi-Realistic Performance Modeling GaInP/GaAs/GaInAs

Low-AOD Direct Spectrum, 250 suns, 25°C QE = 0.95, realistic  $J_0(E_g)$ , no parasitic losses

Subcell parameters

Series-connected tandem parameters

Subcell Absorber	E <sub>g</sub> (eV)	V <sub>oc</sub> (V)	J <sub>sc</sub> (A/cm²)	FF (%)
GalnP	1.87	1.53	3.40	91.57
GaAs	1.42	1.12	3.40	89.23
GalnAs	1.01	0.74	3.63	85.21

V <sub>oc</sub> (V)	Jsc (A/cm²)	FF (%)	V <sub>max</sub> (V)	J <sub>max</sub> (A/cm²)	P <sub>max</sub> (W/cm²)
3.38	3.40	90.32	3.11	3.34	10.38

Tandem efficiency: 41.5%





# Semi-Realistic Performance Modeling

#### Subcell parameters

<u>Conditions</u> AM0, one sun, 25°C QE = 0.95, Realistic  $J_0(E_g)$ 

Subcell Absorber	E <sub>g</sub> (eV)	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA/cm²)	FF (%)
GalnP	1.87	1.393	17.00	90.94
GaAs	1.42	0.981	17.00	88.09
GalnAs	1.02	0.608	18.13	83.01

Tandem efficiency ~33% (one sun) ~36% (10 suns)

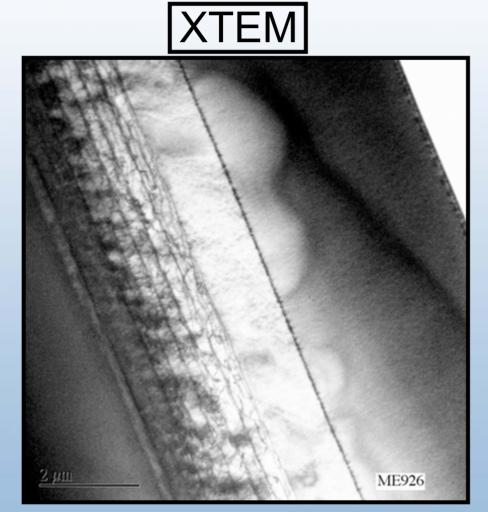
#### Series-connected tandem parameters

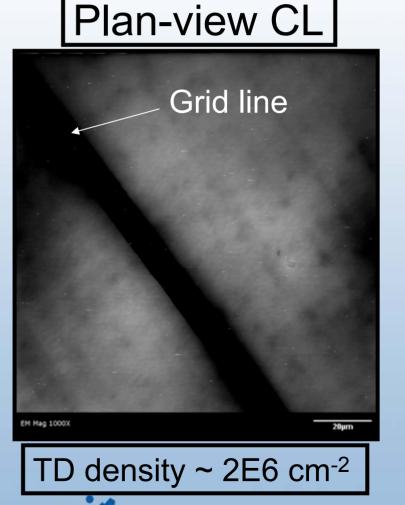
V <sub>oc</sub> (V)	Jsc (mA/cm²)	FF (%)	V <sub>max</sub> (V)	J <sub>max</sub> (mA/cm²)	P <sub>max</sub> (mW/cm²)
2.98	17.00	89.27	2.72	16.65	45.26





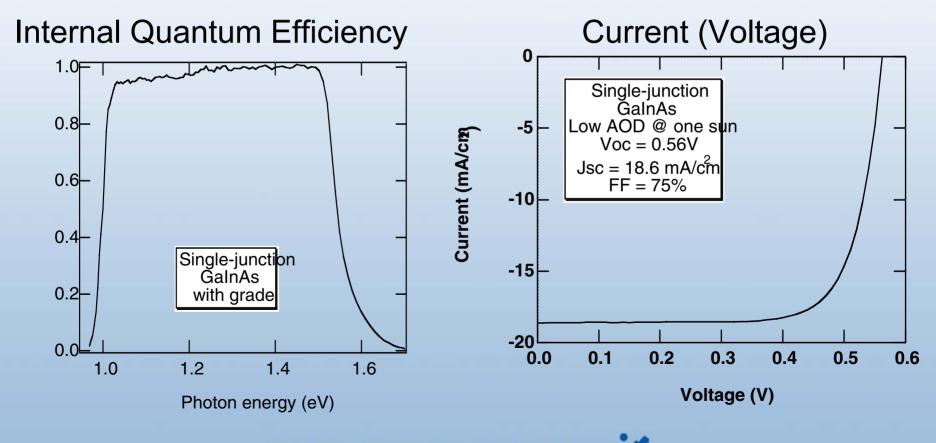
# Defects in LMM, ~1-eV GalnAs







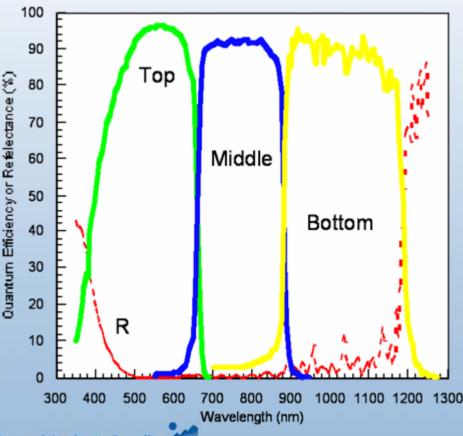
### ~1-eV, LMM (2.2%) GalnAs/GalnP DH Cell Performance





### Ultra-Thin, Handle-Mounted GaInP/GaAs/GaInAsTandem AEQE & R Data

- QE is excellent for all subcells, but some improvement is still possible (reduce parasitic absorption and reflection).
- ZnS/MgF<sub>2</sub> ARC is not optimal.
- Interference evident in thin bottom subcell.





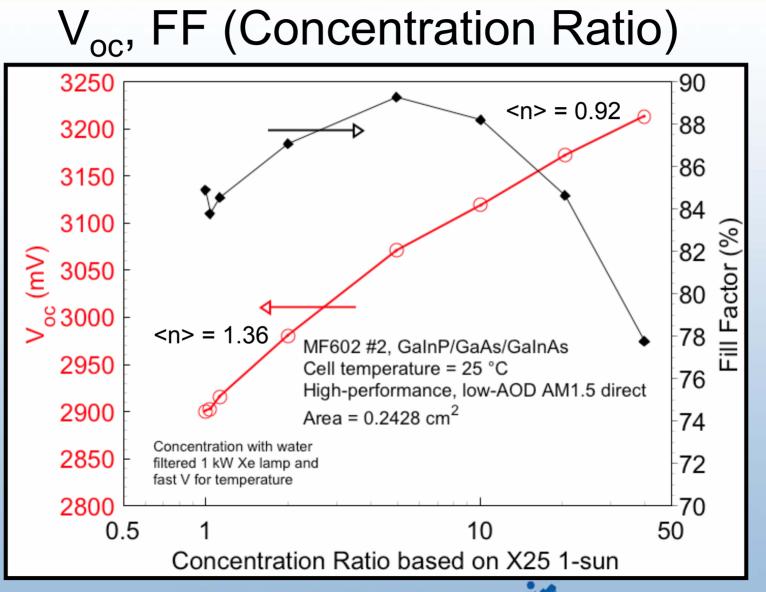
# **Reported Performance**

PVSC	1/3-7/05	Global, 25°C	31.1%
SPW	4/18-21/05	AM0, 1 sun, 25°C	29.7%
ISCC	5/1-5/05	Direct, 10.1 suns, 25°C	37.9%
SPRAT	9/20-22/05	AM0, 1 sun, 25°C Kapton handle	26.5%
SPRAT	9/20-22/05	AM0, 8.9 suns, 25°C	31.4%



### NREL National Renewable Energy Laboratory

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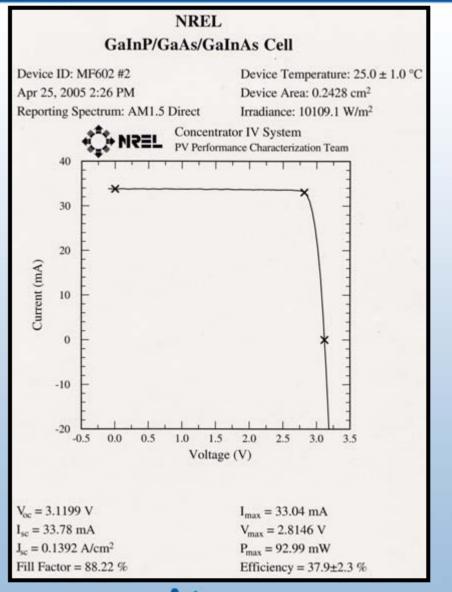


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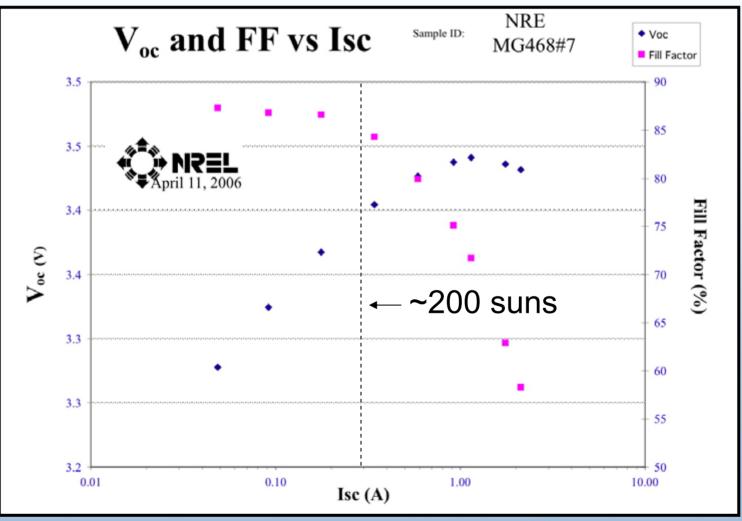
# I-V Data at Peak Efficiency

- η = 37.9% (10.1 suns).
- On 4/25/05, a new record for solar PV conversion.
- With continued development,  $\eta > 40\%$  possible at higher concentration ratios.





### Recent progress





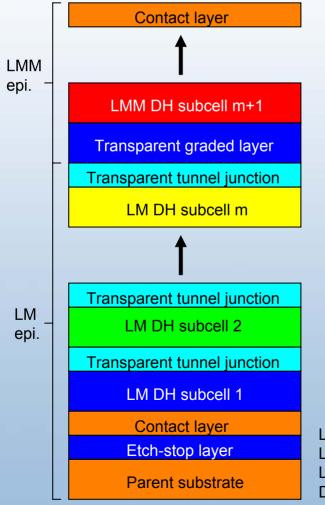


# **Research Issues**

- High-yield processing of handle-mounted, ultra-thin devices.
- Develop process enabling reuse of parent substrate.
- Tandem cell efficiency testing more difficult w/ 1-eV subcell even more difficult as we consider more than three subcells.
- Inverted tunnel junctions.
- Radiation effects.
- Push efficiency limits by including more subcells can we achieve 40-50% (terr. conc.), 35-40% (AM0)?



## **Advanced Design Options**



- Concept applies to two, or more, subcells.
- A wide range of substrates, subcell materials, tunnel junction materials, and transparent compositional grades are possible.
- Substrates: GaAs, Ge, Si, SiGe.
- Subcells, etc.: AlGaInPAsSb.

Legend: LM = lattice matched. LMM = lattice mismatched. DH = double heterostructure.

