EPIR Technologies

The world leader in II-VI material technology and innovation

High Efficiency Single Crystal CdTe Solar Cells

Program Team: PV

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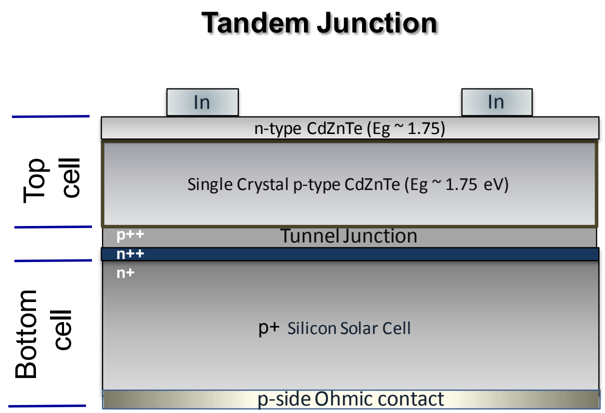
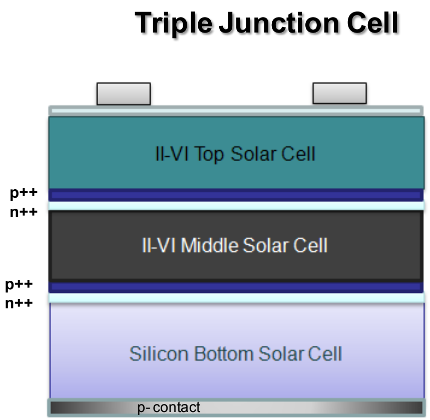
Objective

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Long Term Goal:

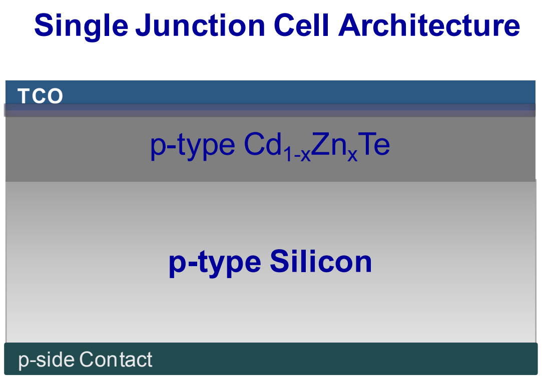
– Develop high efficiency multijunction, single crystal II-VI/Si solar cells.





Preincubator Program Goal:

– Develop high efficiency single junction single crystal II-VI on Si solar cells.



Program Overview

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Timeline

- Project start date: 11/19/2009
- Project end date: 11/18/2010
- Percent complete: 50%

Barriers

- Barriers addressed
  - Material Utilization and Cost: Reducing the cost of concentrator solar cells
  - Efficiency: Increasing the efficiency of CdZnTe-based solar cells

Budget

- Total project funding: $1,014,570
  - DOE share: $500,000
  - Contractor share: $514,570
- Funding received in FY09: $0
- Funding for FY10: $500,000

Partners

- *EPIR Technologies Inc.*
  Bolingbrook, Illinois

Why High Efficiency II-VI on Si?

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1. High absorption coefficient.
2. Ideal single junction bandgap (~ 1.5 eV).
3. Bandgap tunable from 1.5 to 2.24 eV ($Cd_{1-x}Zn_xTe$).
4. Higher accessible bandgaps than III-V's because of lattice matching issues.
5. II-VI devices appear to be less impacted by defects such as dislocations.
    - more ionic, less covalent nature of II-VI materials
    - greater screening that lowers the cross-section and capture rates of traps
    - impurity or defect states in more ionic materials should have substantially fewer deep energy levels and hence should not give rise to nearly as rapid carrier recombination (longer lifetimes)
6. Potential to grow on low cost large format substrates such as silicon.
    - lattice mismatch less important

Why High Efficiency II-VI on Si?

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Multijunction II-VI/II-VI/Si cells have the theoretical potential to reach higher efficiencies than their III-V counterparts because of the wider range of accessible bandgaps than the III-Vs.

Calculated Multijunction Cell Efficiencies (with C = 3 mA/cm^2-K^3)					
II-VI Multijunction Solar Cell Efficiencies			**III-V Multijunction Solar Cell Efficiencies (III-V junction $E_g \leq 1.88$ eV)**		
Cell (with Si optical path length and junction energies)	**One-sun efficiency (%)**	**500-suns efficiency (%)**	**Cell (with Ge optical path length and junction energies)**	**One-sun efficiency (%)**	**500-suns efficiency (%)**
II-VI/Si (500 µm) 1.78/1.12 eV	39.3	44.1	III-V/Ge (500 µm) 1.5-1.6/0.67 eV	33.6	40.2
II-VI/II-VI/Si (500 µm) 2.06/1.52/1.12 eV	45.3	51.5	III-V/III-V/Ge (500 µm) 1.68/1.18/0.67 eV	36.2	43.6
Inverted 3-junction 1.96/1.40/0.95 eV	46.0	54.0	Inverted 3-junction 1.88/1.35/0.94 eV	43.6	50.6

D. Xu et al., Appl. Phys. Lett. 96, 073508 (2010).

Potential Manufacturing Advantages of II-VI/Si vs. III-V/Ge Solar Cells

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MOCVD Growth of III-Vs

- Gas-based delivery system using arsine, phosgene, etc. => safety precautions, regulatory approval difficult => added expense, slow expansion of capacity
- High maintenance, much down time => added expense
- Small area, expensive Ge, GaAs or InP substrates => higher cost
- Doping and contacting are well solved problems

MBE Growth of II-VIs

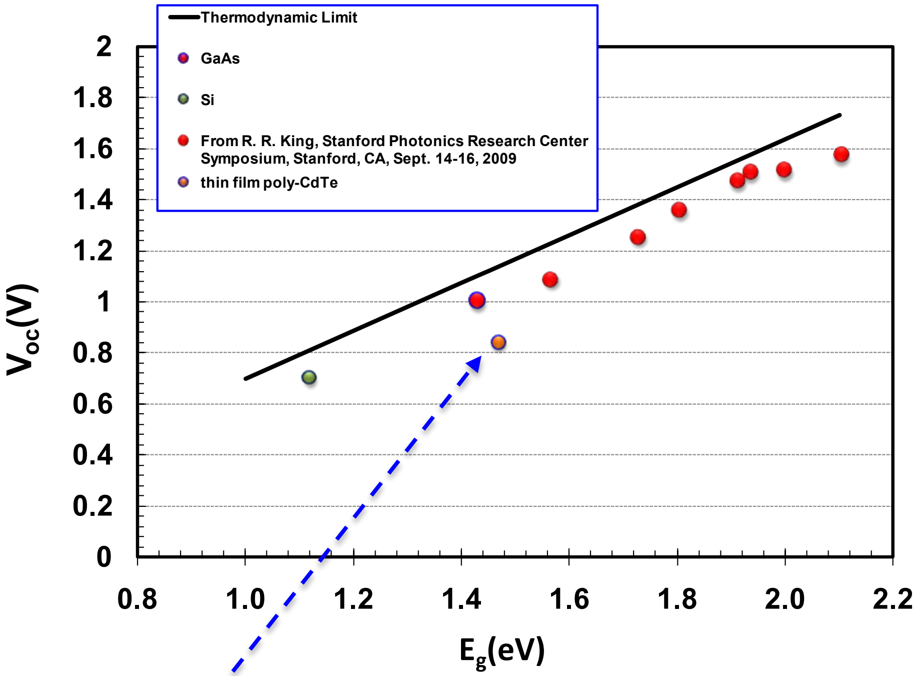
- Delivery system based on molecular beams => easier safety precautions and regulatory approval
- Much lower maintenance requirements and downtime
- Larger area, much less expensive and more robust Si substrates can be used
- Slower growth rate, but high throughput, ~24,000 6 in. wafers for Riber 7000 MBE machine (10 MW/yr at 500 suns, 4 MW/yr at 200 suns)

The II-VI V_{oc} Challenge

$$\eta = \frac{J_{sc}V_{oc}FF}{P_{in}}$$

Single junction GaAs 1-sun efficiency record - 24.7% - 2008 IMEC

Single junction CdTe 1-sun efficiency record - 16.5% - 2001 NREL



Current thin film CdTe cells have suppressed V_{oc} relative to Si and III-V based cells

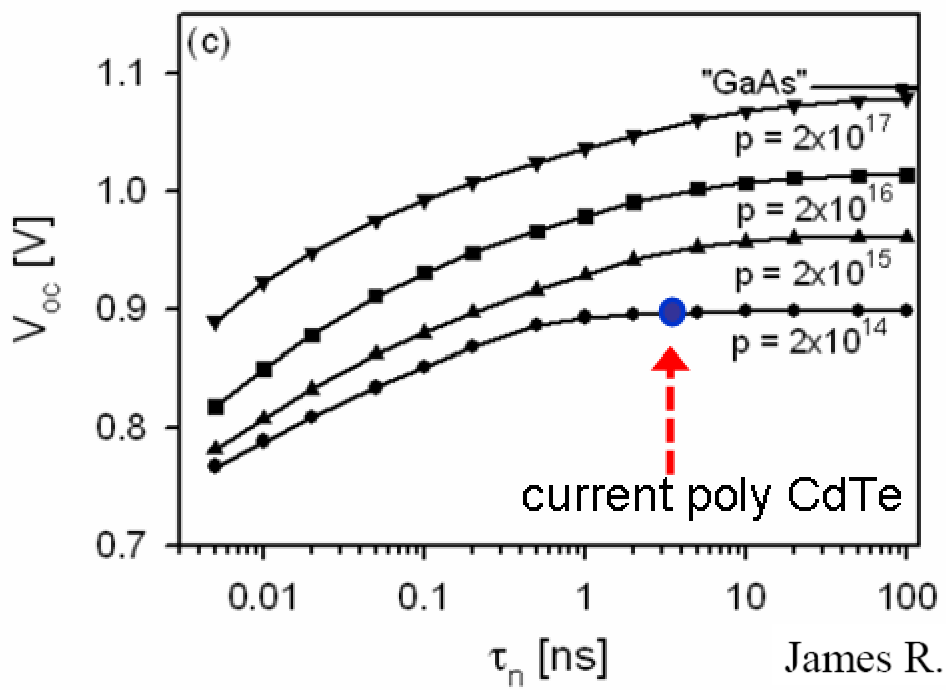
Current CdTe Thin Film Cells

- **low carrier concentration < 10^{15} cm^{-3} p-type**
- **low minority carrier lifetime (< 10 ns)**
- **V_{oc} significantly lower than bandgap predicts**

$E_g - qV_{oc}$ measures the intrinsic cell quality

J_{sc} and FF depend on extrinsic factors

How do we increase the V_{oc} of II-VI Cells?



James R. Sites

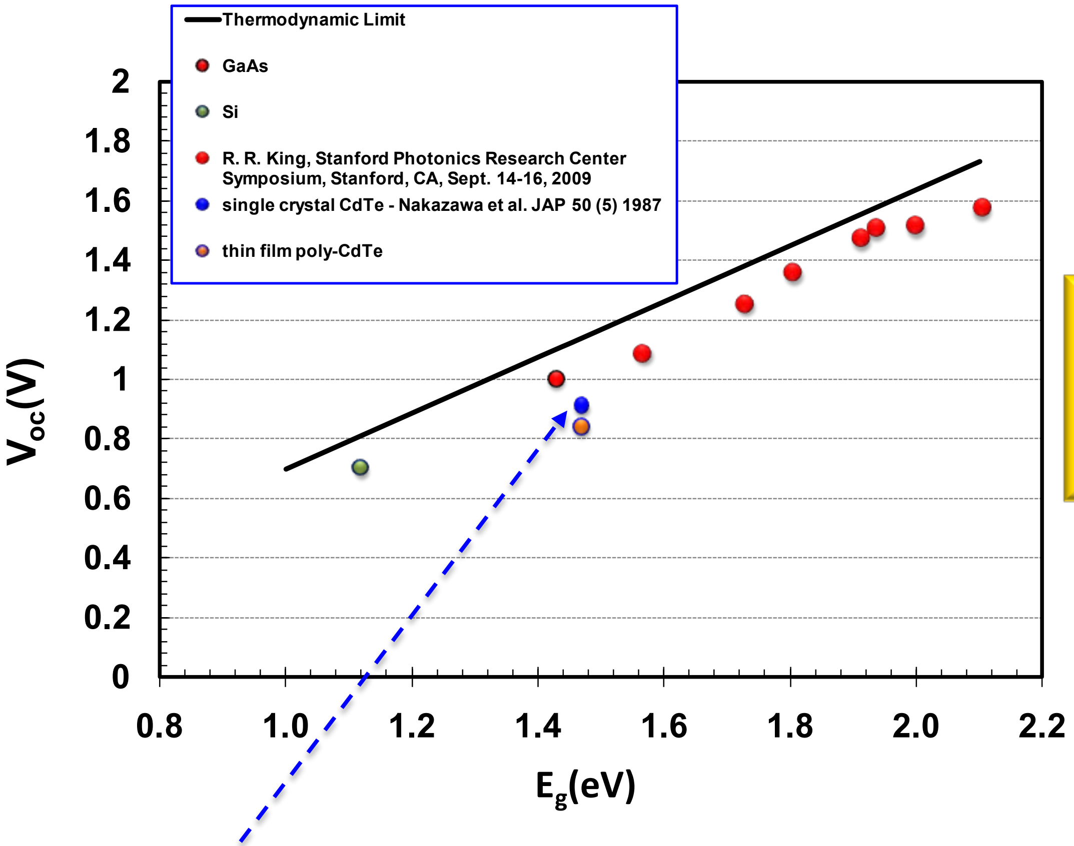
CHARACTERIZATION AND ANALYSIS OF CIGS AND CdTe SOLAR CELLS

Increasing V_{oc}:

- Higher carrier concentration
- Higher minority carrier lifetime
- Bandgap engineering

  ternary $Cd_{1-x}Zn_xTe$

Single Crystal CdTe



Highest reported CdTe V_{oc} (0.91 V) reported by 1987 by Nakazawa *et al.* for single crystal CdTe homojunction

Single Crystal CdTe Potential

- High crystal quality
- No-grain boundaries
- Doping control
- High minority carrier lifetime

Improved performance of single crystals demonstrated in other material systems and other II-VI PV devices

1. Bulk single II-VI crystal too expensive.
2. Need for epitaxial thin film single crystal CdTe.
3. Si ideal low cost large format scalable substrate if you can make it work.

Program Tasks

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Task 1: MBE growth and characterization of single-crystal epitaxial CdTe/Si.

Task 2: Establish low resistance Ohmic contacts for n-type CdTe.

Task 3: Perform controlled n- and p-doping in plain CdTe and measure the dopant densities and carrier concentrations.

Task 4: Measurement of the CdTe minority carrier recombination lifetimes.

Task 5: Model the photon absorption and electrical carrier transport in CdTe/Si solar cells and their efficiencies.

Task 6: Fabricate CdTe p-n homojunctions and characterize them with I-V and C-V.

Task 7: Fabricate and test CdTe/Si homojunction solar cells.

Key Program Milestones

The internal decision milestones:

(1) Doping Development;

> 2×10^{15} cm^{-3} p-type

> 2×10^{16} cm^{-3} n-type

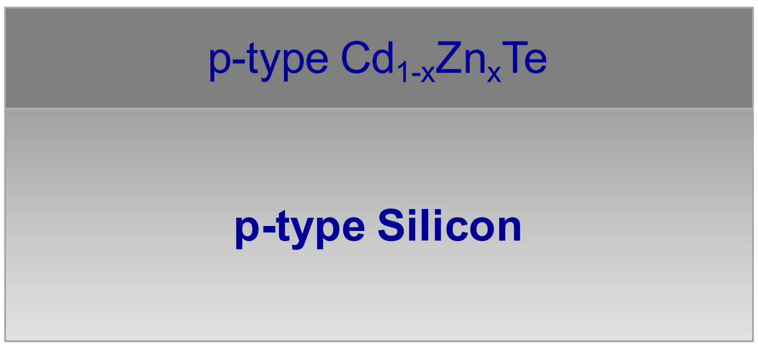
(2) Minority carrier recombination lifetime in p-doped material ≥ 50 ns

(3) The achievement of a diode ideality factor < 2

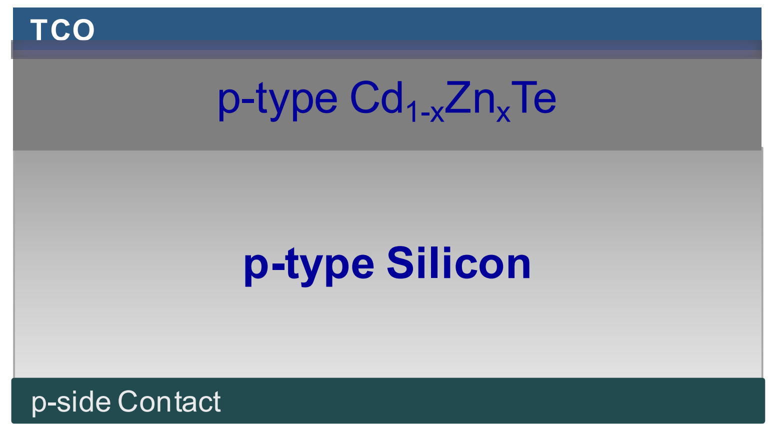
(4) The achievement of a solar cell with an efficiency >10%

Architecture Approach

As-grown



Single Junction Cell Architecture



n-on-p homojunction in the single crystal CdTe or CdZnTe cell

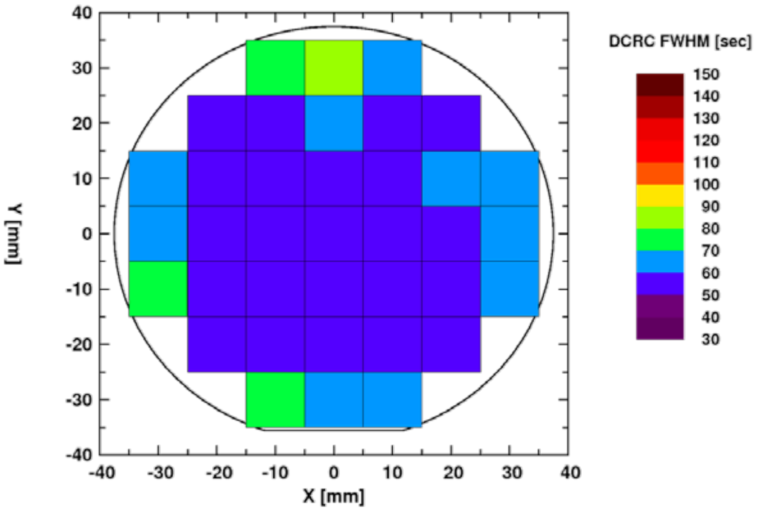
Deposition Technology - MBE

MBE Crystal Growth of II-VI on Si

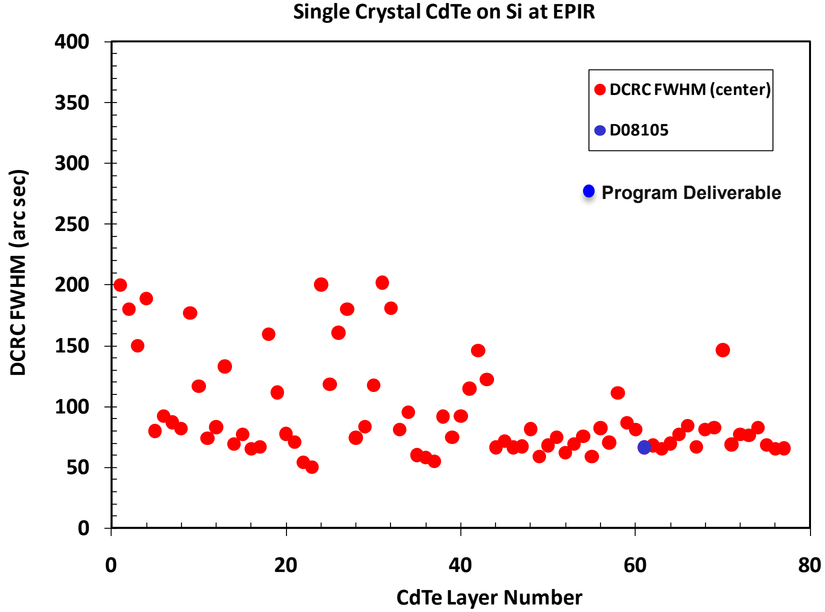
Low Temperature Growth

1. doping control in II-VI semiconductors
2. advanced structures
   - heterojunctions
   - bandgap grading
   - doping grading

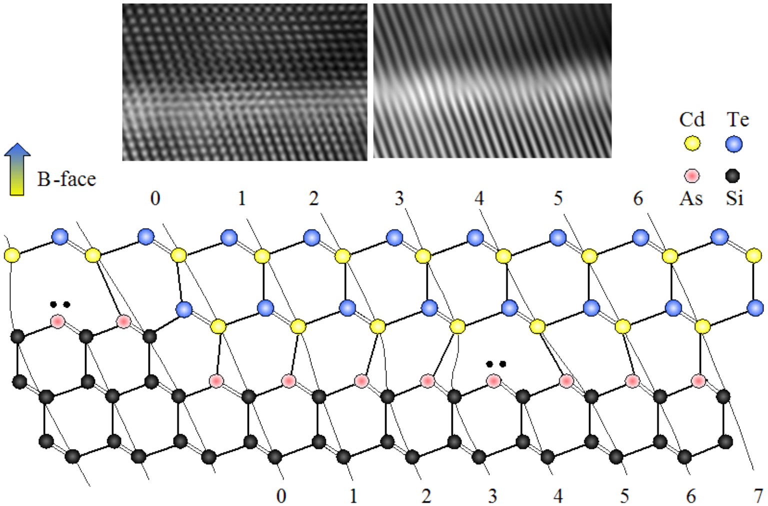
XRD DCRC FWHM Map – 3” CdTe on Si



Program Deliverable



CdTe/As/Si(111) interface



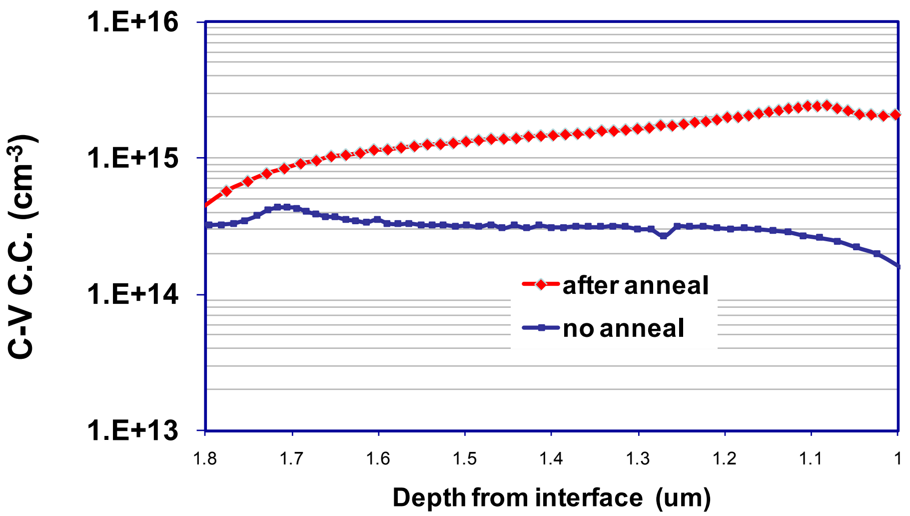
Doping Control

Both p and n type doping control required for PV devices

Doping control traditionally a challenge in CdTe based cells.

- **Cd vacancy influence on doping in CdTe**
- **Cd and Zn vacancy controls doping in CdZnTe**

C-V Depth Profile of Vacancy Doped CdTe



"as-grown" CdTe layers slightly p-type

Post growth anneals
- increase the Cd or Zn vacancy conc.

N-type Doping Control

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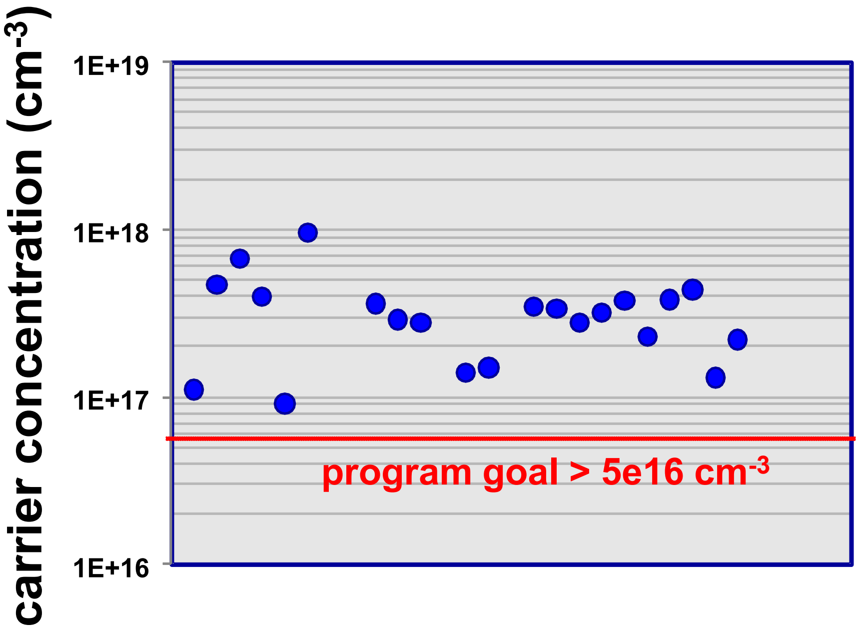
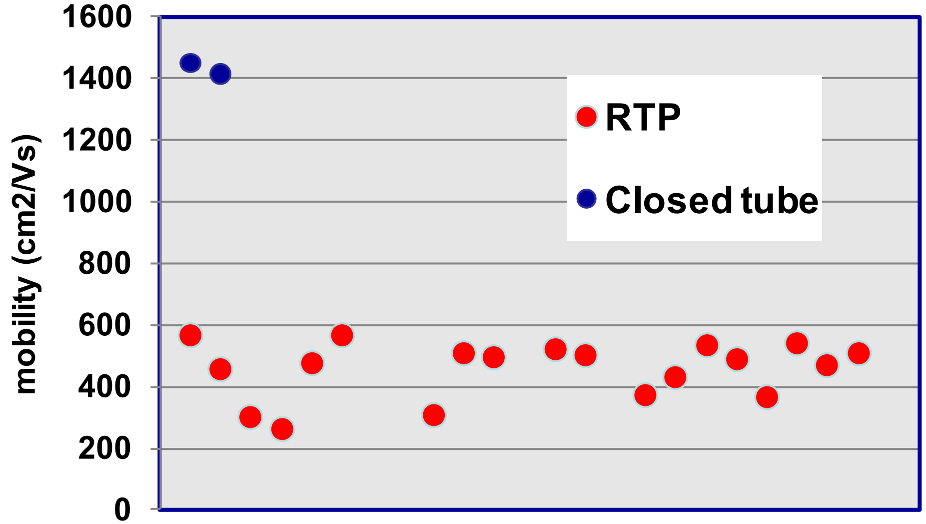
n-type doped CdTe

Hall Carrier Concentration



*SIMS dopant level ~ 10^{18} cm^{-2}

Hall Mobility



*State of the art CdTe n-type mobility ~ 1500 cm^2/Vs

P-type Doping Control

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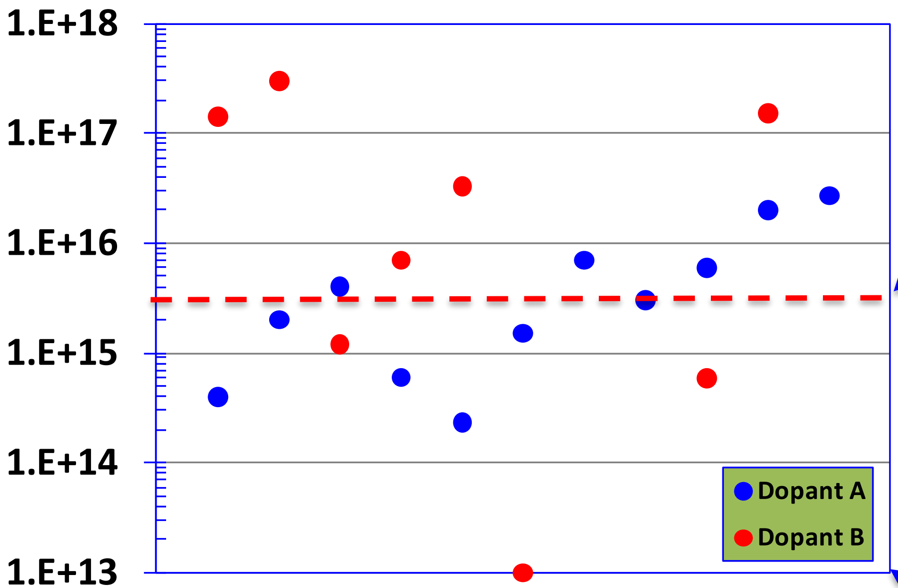
P-type carrier concentration measured at room temperature by C-V



Scatter plot of recent p-type CdTe samples

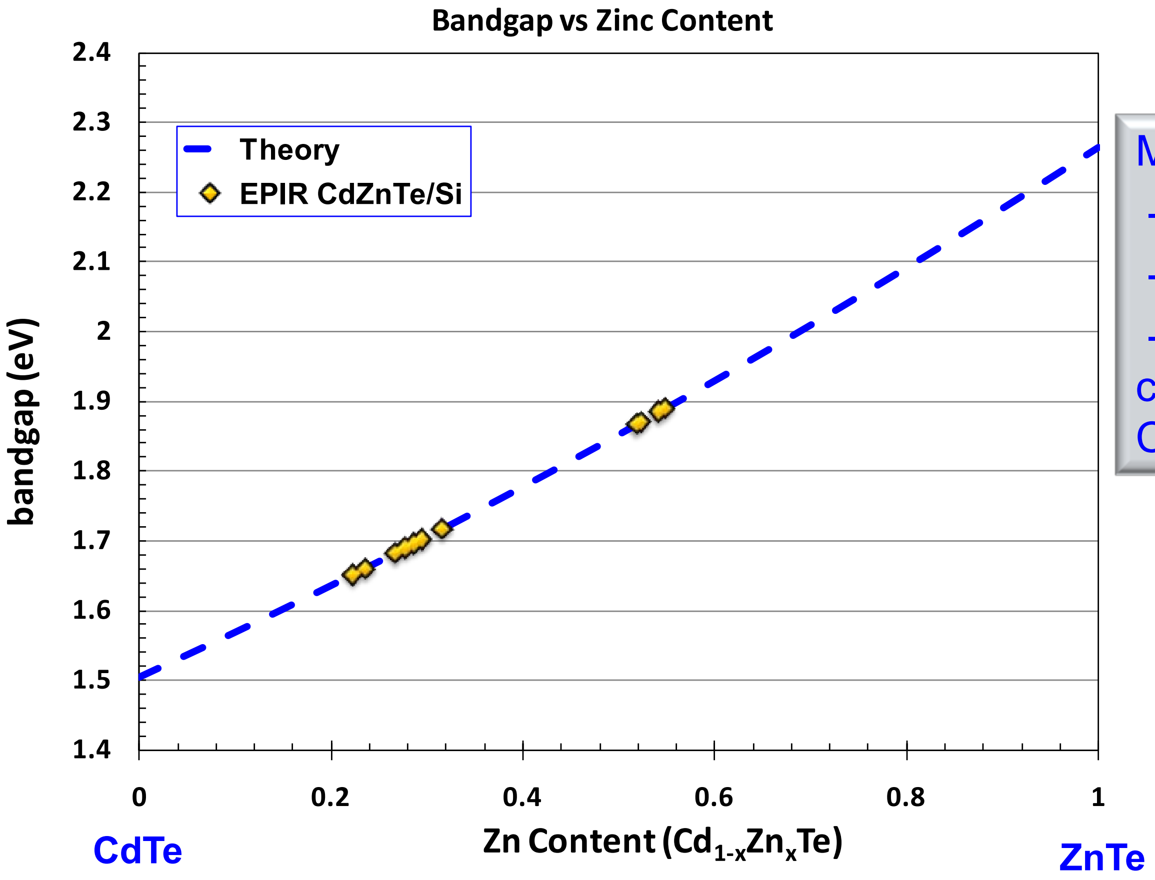
EPIR's Preincubator Program Milestone

p-type doping in CdTe > $3 \cdot 10^{15}$ cm^{-2}

For p-type doping of CdTe
- developing multiple dopant options

proprietary p-type dopants

Bandgap Engineering – $Cd_{1-x}Zn_xTe$

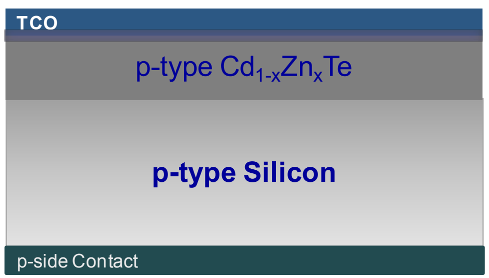


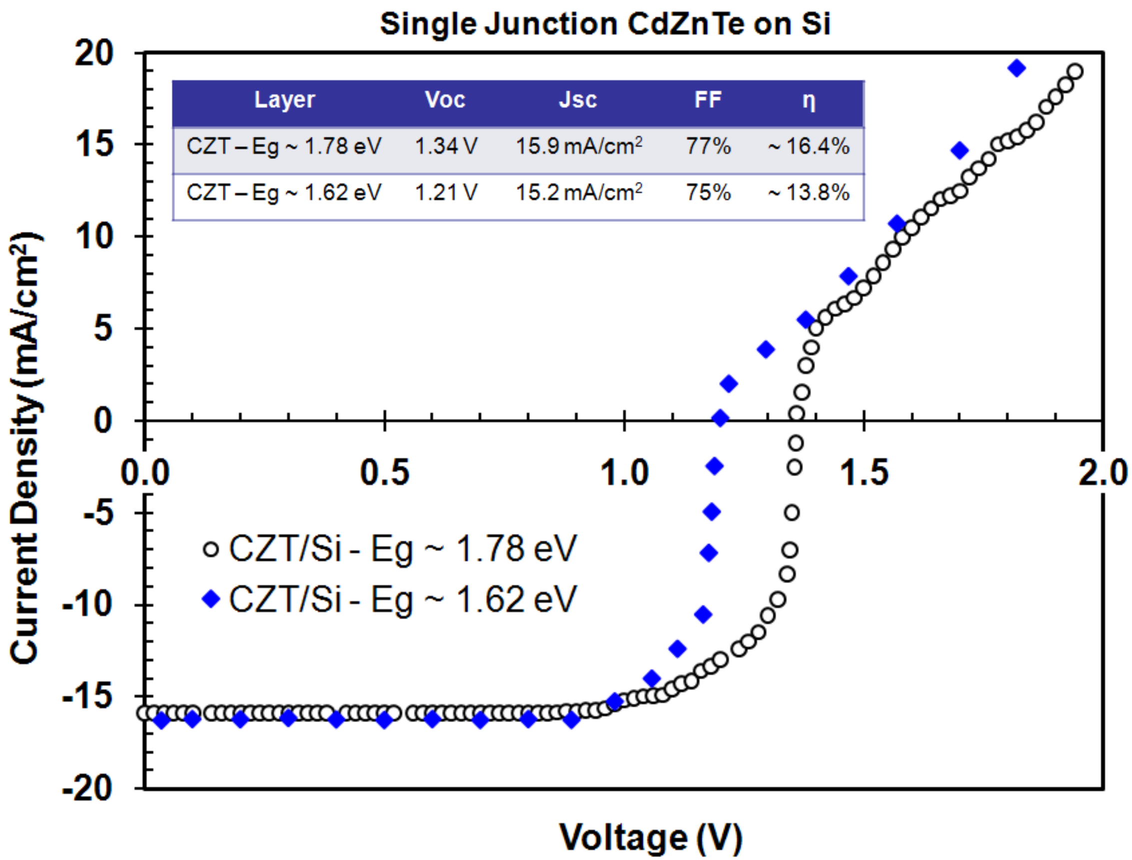
MBE CdZnTe/Si

- Low temperature growth
- Eliminates Zn segregation
- Capable of growing any composition (bandgap) along the CdTe–ZnTe binary phase diagram.

Device Development Pathway

Single Junction Cell Architecture

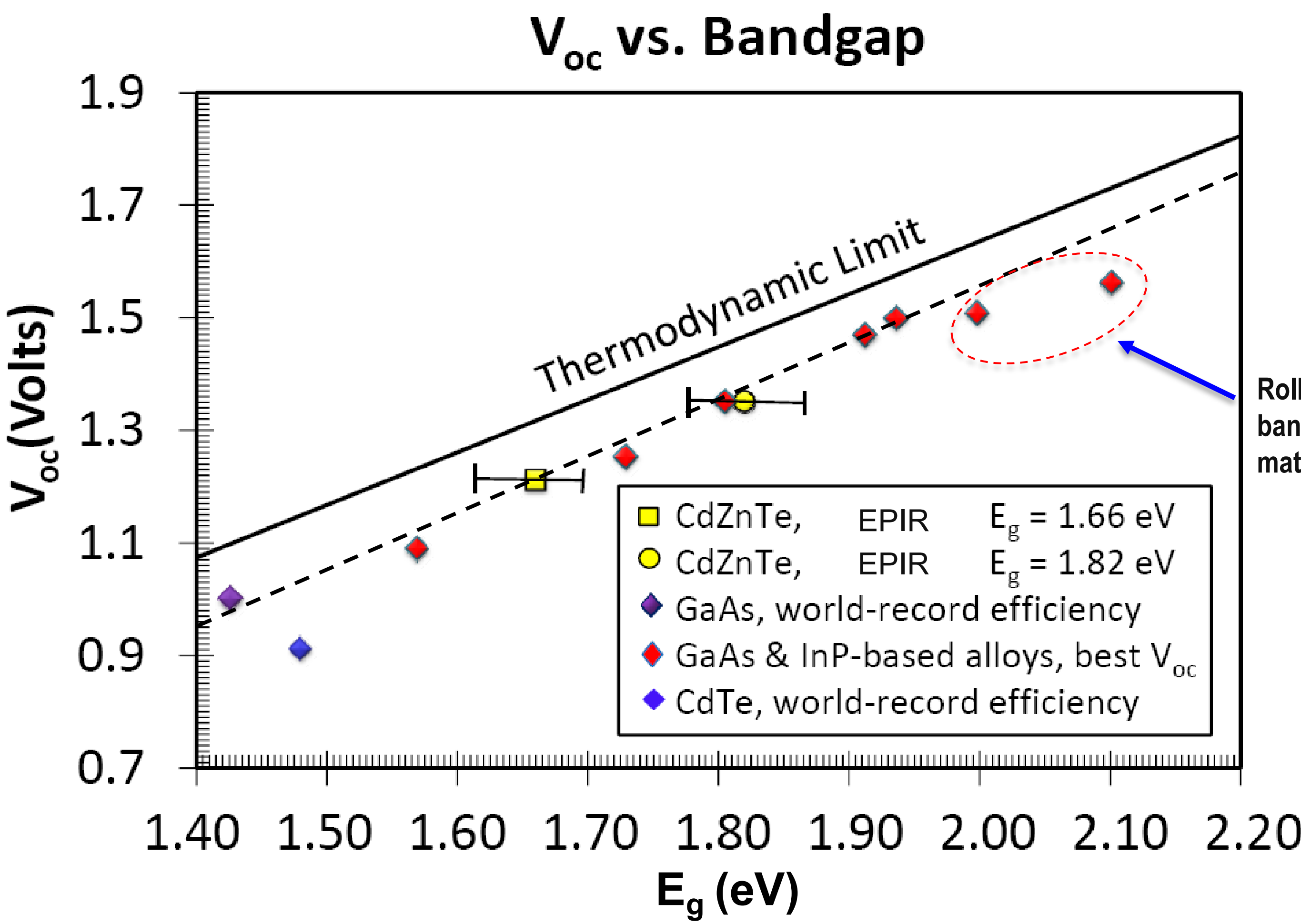




Layer	Voc	Jsc	FF	η
CZT – Eg ~ 1.78 eV	1.34 V	15.9 mA/cm^2	77%	~ 16.4%
CZT – Eg ~ 1.62 eV	1.21 V	15.2 mA/cm^2	75%	~ 13.8%

Measured under AM1.5

V_{oc} vs. Bandgap



Roll off of III-V V_{oc} at higher bandgaps because of lattice matching challenges

$(E_g - qV_{oc})$ – direct measure of cell quality

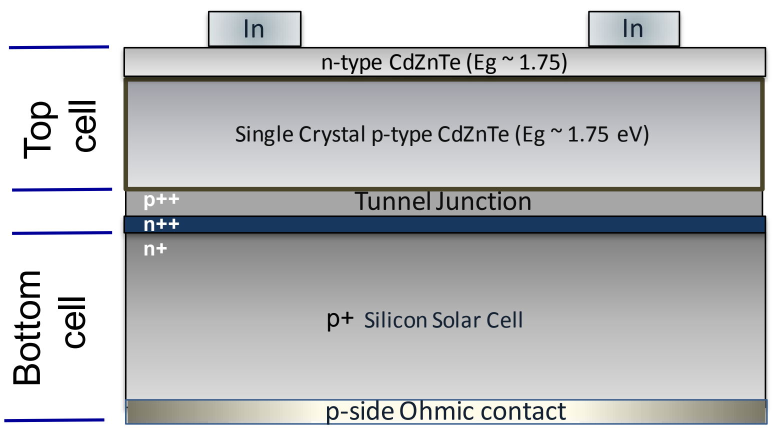
Red diamonds from R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sept. 14-16, 2009

Early Tandem Cell Development at EPIR

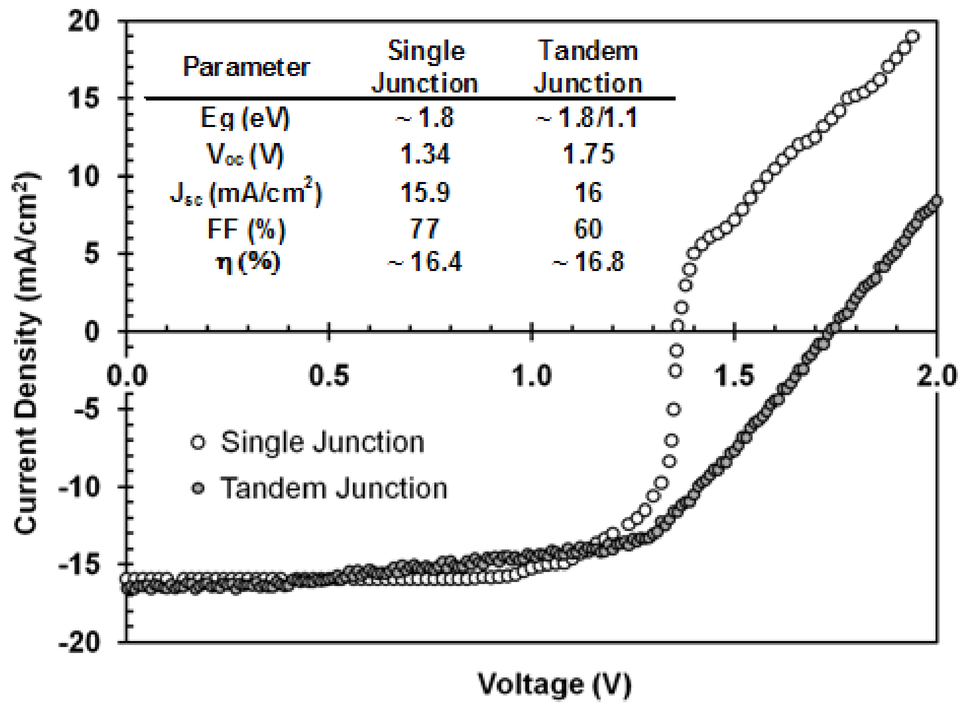
CdZnTe top cell (Eg ~ 1.8 eV) – Voc ~ 1.3 eV

Si – bottom cell – Voc ~ 0.45 eV

Tandem Junction



Voltage addition demonstrated on early EPIR tandem cell device



Related Work

Future Plans

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Deliverable 1. **(Complete)** An epitaxial CdTe film on a 3-inch Si wafer representing the baseline of the proposed technology will be delivered during month one. The CdTe/Si wafer will be delivered with a high resolution XRD data mapping across the entire wafer to show the uniformity of the structural quality.

Deliverable 2. **(Complete)** A single-crystal, extrinsically doped *n*-type CdTe/Si piece cut from a 3" wafer with data obtained from adjacently cut pieces showing an n-type carrier concentration within the range 3×10^{16} cm^{-3} to 3×10^{18} cm^{-3}.

Remaining 2010 Deliverables

Deliverable 3. **on track** **(due June 18th)** A single-crystal, extrinsically doped *p*-type CdTe/Si piece cut from a 3" wafer with data obtained from adjacently cut pieces showing a p-type carrier concentration within the range 3×10^{15} cm^{-3} to 3×10^{17} cm^{-3}.

Deliverable 4. A single-crystal, extrinsically doped *p*-type CdTe/Si piece cut from a 3" wafer with data obtained from adjacently cut pieces showing a minority carrier lifetime longer than 100ns.

Deliverable 5. A prototype CdTe solar cell with a 15% efficiency will be delivered during month 12 – November 2010

Future Plans Schedule

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Task	Month											
	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov
Quarterly Reports			Δ			Δ			Δ			Δ Final Report
Hardware Deliverables	Δ			Δ			Δ			Δ		Δ

- Dec: CdTe/Si baseline **complete**
- Feb: submitted **complete**
- Mar: n-type Sample **complete**
- June: p-type Sample on-track
- Sept: lifetime Sample on-track
- Nov: II-VI prototype Cell on-track

Budget

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- Total project funding: $1,014,570
  - DOE share: $500,000
  - Contractor share: $514,570
- Funding received in FY09: $0
- Funding for FY10: $500,000
- Project is on time and on budget.
- Tasks to be added if additional funding were made available:
  - Multijunction cell development
    a. CdZnTe growth and optimization
    b. Tunnel junction optimization - Si/Si, Si/CZT and CZT/CZT
- Project ends in 2010. Thus no changes for 2011 exist.

Summary

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- Single crystal CdTe and CdTe based alloys have the potential to dramatically increase the efficiency of single junction CdTe based solar cells with efficiencies comparable to single crystal GaAs cells.

- Single crystal CdTe and CdTe based alloys grown on Si have the potential to act as a platform for low cost high performance multijunction solar cells with theoretical efficiencies greater than comparable III-V cells.

- The Preincubator program is on track with all program deliverables met to date and the remaining program deliverables are on track to be delivered on time and on budget.

- Preliminary cell results serve as a proof of concept that the single crystal II-VI on Si approach is a viable technology pathway for future high efficiency cell development.

Summary

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Program Performance Metric	Parameter or Deliverable	Status in FY09	Result in FY10	Notes
FHWM < 200 arcsec	Rocking curve FWHM CdTe/Si	Completed	NA	Sample delivered to NREL for verification
> 3e16 cm^{-3}	N-type carrier concentration	Completed	NA	Sample delivered to NREL for verification
> 3e15 cm^{-3}	P-type carrier concentration	In progress	In progress	Demonstrated Internally – samples to be sent to NREL for verification June 2010
> 50 ns	Minority carrier lifetime	In progress	In progress	Working with NREL to test
> 15%	Single junction cell efficiency	In progress	In progress	Demonstrated preliminary devices