Update of Photovoltaic CdTe Development at Sivananthan Laboratories, Inc.

Alexander Goldstone

6th US CdTe Workshop

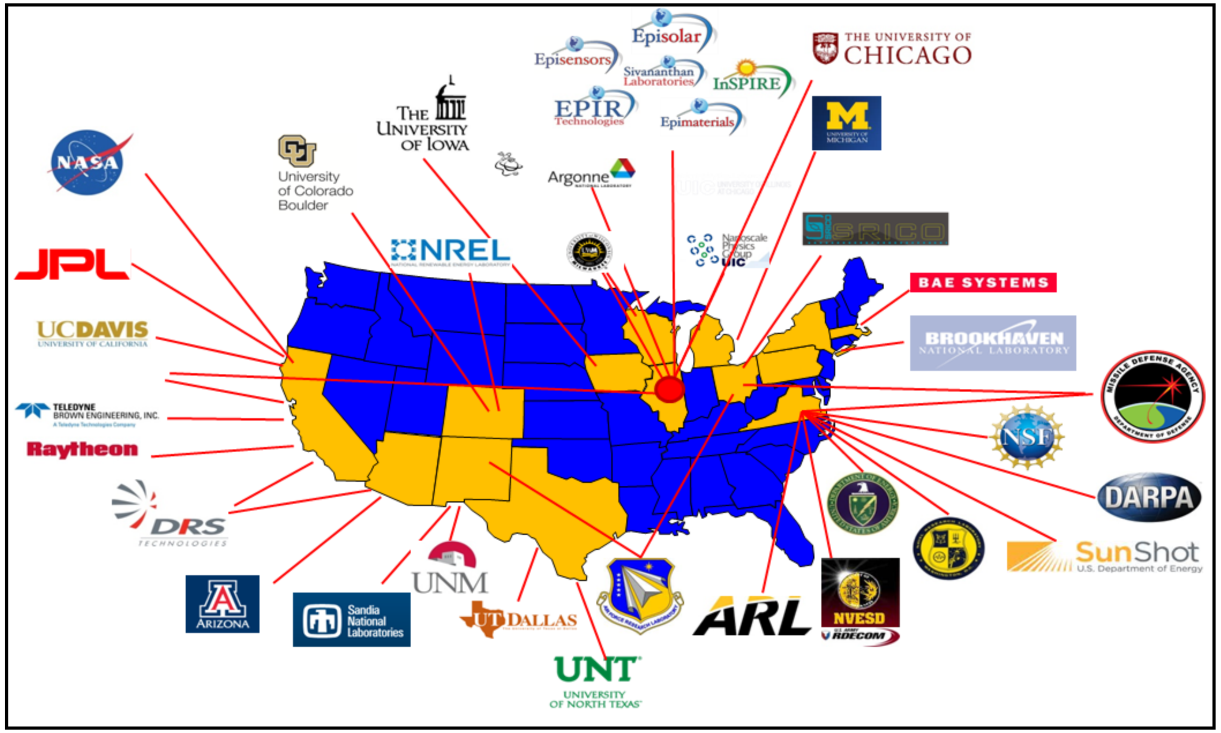
October 20 – 21, 2022

Sivananthan Laboratories

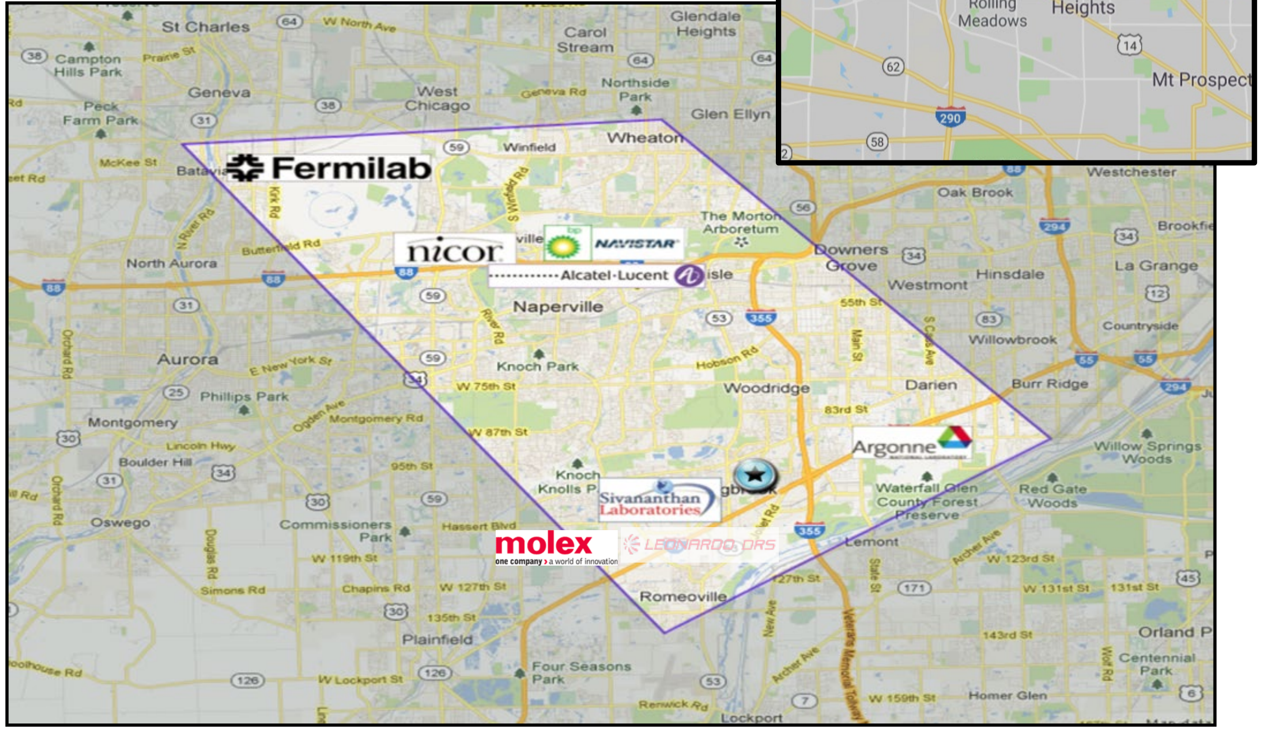
Intelligent and Automatic Decision-Making Sensors and Imagers

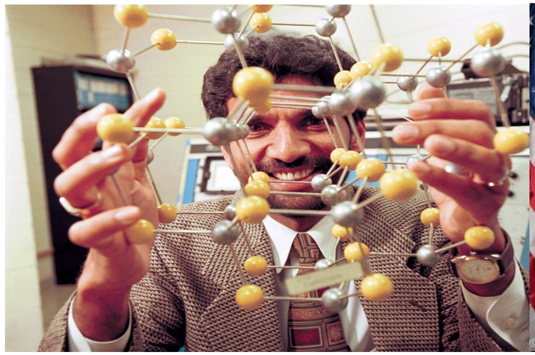
Sivananthan Laboratories – Key Midwest Positioning

Collaborators



Chicagoland's "High-Tech Corridor"





Sivananthan Laboratories

Intelligent and Automatic-Decision Making Sensors and Imagers

Community Outreach

Investment

Fundamental Research

Material Technology Development

Sensor Analytics

Spin-off Companies

Ideas

Prototypes

Products

Areas of Focus

Infrared

- **EPIR**: Infrared Material and Sensor Fabrication
- **Episensors**: Infrared Cameras


Solar

Episolar

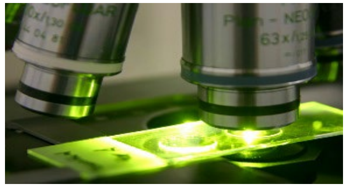
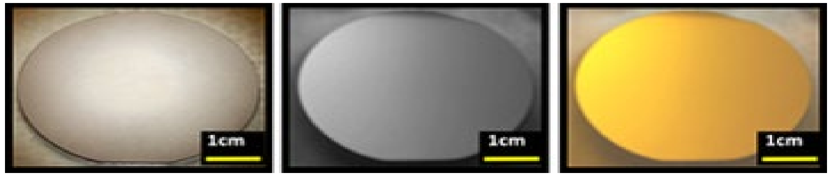
- Solar PV Sales and Manufacturing
- R&D for Flexible, High-Efficiency PV


Community Service

- InSPIRE
- STEM-focused education and training initiatives
- Outreach to underserved communities

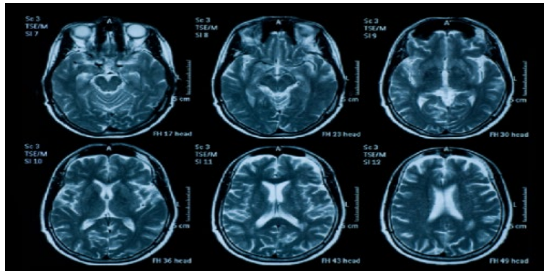
Research & Development

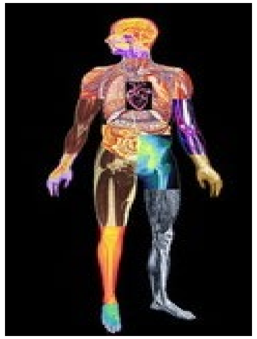
- Quantum Optics
- Radiation Detectors
- Type II Superlattices
- Colloidal Quantum Dots

Medical

- Biological Sensors
- Neuroscience
- Medical Imaging
- Social Medicine

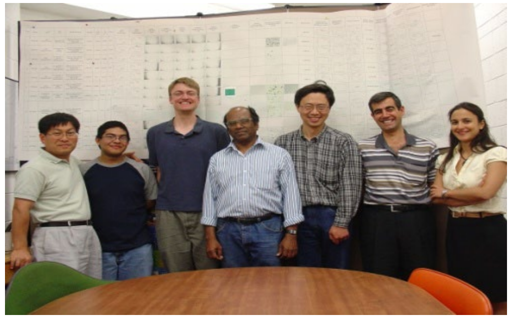


Global Outreach

Sivananthan Laboratories

R&D Training Exchange Program and Internships

India, China, Morocco, Sri Lanka



Solar Energy Workshops in Sri Lanka and Morocco

Establishing Sri Lanka as a Global Renewable Energy Hub in the Indian Ocean

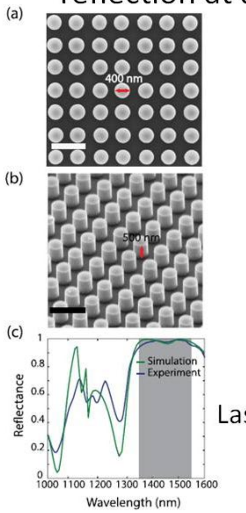
Solar PV installations donated to Universities

Passion to mentor and motivate interest in science, technology, engineering and mathematics among underrepresented communities across the world

Fundamental Research and Novel Ideas

Flat Quantum Optics

Metasurface with perfect reflection at a specific wavelength

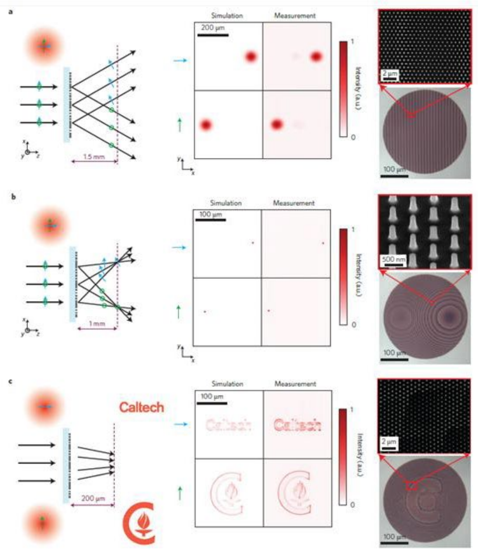


$$\begin{cases} n_t \sin(\theta_t) - n_i \sin(\theta_i) = \dfrac{1}{k_o}\dfrac{d\Phi}{dx} \\ \cos(\theta_t)\sin(\varphi_t) = \dfrac{1}{n_t k_o}\dfrac{d\Phi}{dy} \end{cases}$$

$$\begin{cases} \sin(\theta_r) - \sin(\theta_i) = \dfrac{1}{n_i k_o}\dfrac{d\Phi}{dx} \\ \cos(\theta_r)\sin(\varphi_r) = \dfrac{1}{n_r k_o}\dfrac{d\Phi}{dy} \end{cases}$$

Laser hardened sensor window

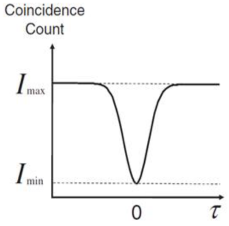
Polarization or Lensing

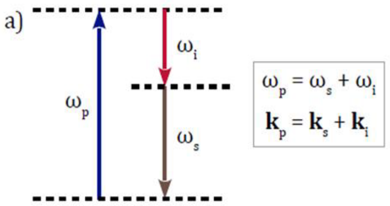


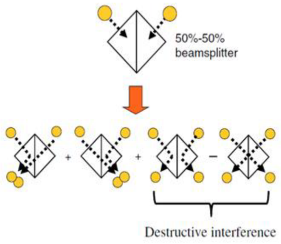
Ghost Imaging

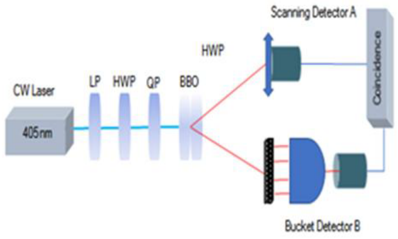
Features

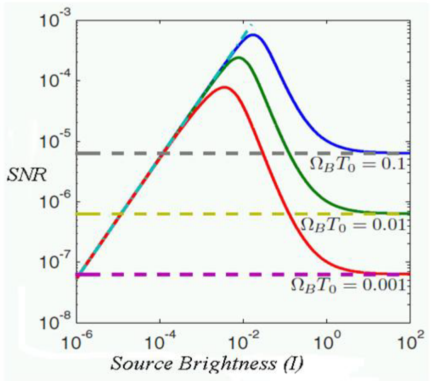
- Strong noise rejection due to high dimensional entanglement, noise photons cannot masquerade as signal.
- Promises higher range/target resolution due to strong time correlation of the signals
- Stealth due to ultra-low intensity.
- Can't be jammed due to noise/background rejection









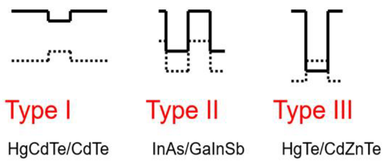


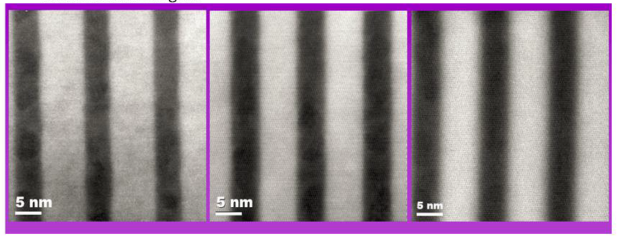
Advanced Material Research and Prototyping

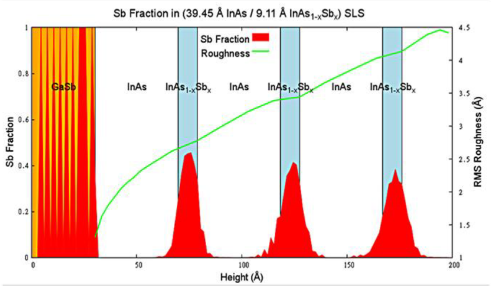
High Performance Superlattice Sensors and Imagers

Infrared Materials By Design

- Optical and electronic material properties can be engineered using layered semiconductor structures called superlattices (SLs)
- Quantum-engineered "material by design" can overcome intrinsic limitations of traditional high performance infrared sensors raising the theoretical ceiling of future infrared systems
- In addition to material property engineering, sophisticated SL device designs can be engineered to further improve the performance of sensors and imagers





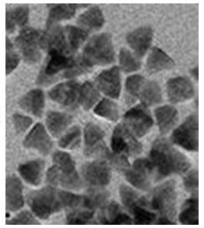


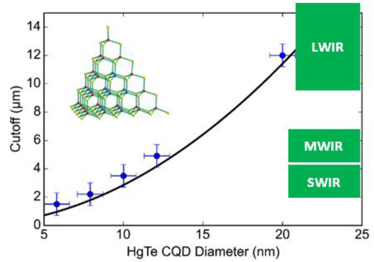
A.J. Ciani, C.H. Grein, B. Irick, M. Miao and N. Kioussis, Opt. Eng. **56** 091609 (2017).

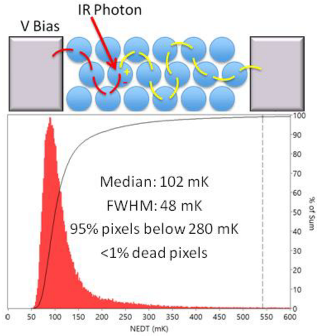
Low-Cost IR Imaging with Colloidal Quantum Dots

What are CQDs?

- Colloidal Quantum Dots (CQDs) are semiconducting nanoparticles made through wet chemical synthesis
- Tunable material properties
- Covers the SWIR, MWIR, and LWIR







Ultra-Low Cost Processing

- FPAs fabricated using a commercial 320x256 30 µm ROIC
- Readily scaled to larger formats and wafer level processing.
- Compatible for SWIR to LWIR
- ROIC to FPA in approximately 1 hour
- Films cost about $5 per FPA at the R&D level

Direct Photon Detection

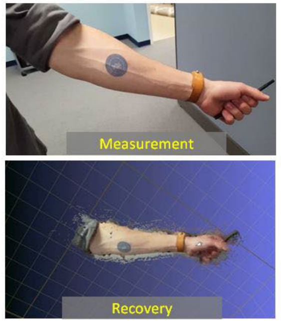
- Photonic: Infrared photons are detected as photocurrent, PC or PV
- Carriers transverse the CQD film via tunneling/hopping, like a barrier device

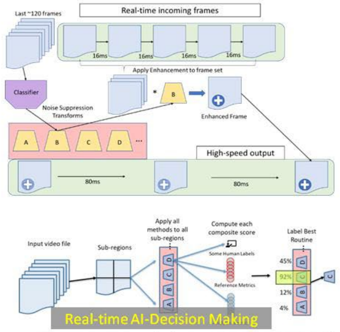
Integrated Sensor Intelligence

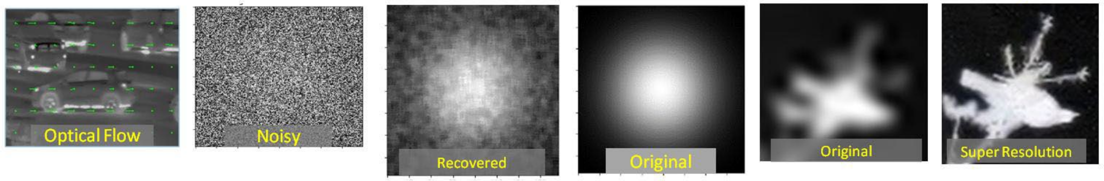
Intelligent Image Enhancement

Sensor Analytics

- Reveal information contained within images beyond what human eyes can detect
- Image enhancement is **valuable for human and machine consumption**
- Image processing is highly beneficial for machine vision applications to increase detection speed and accuracy



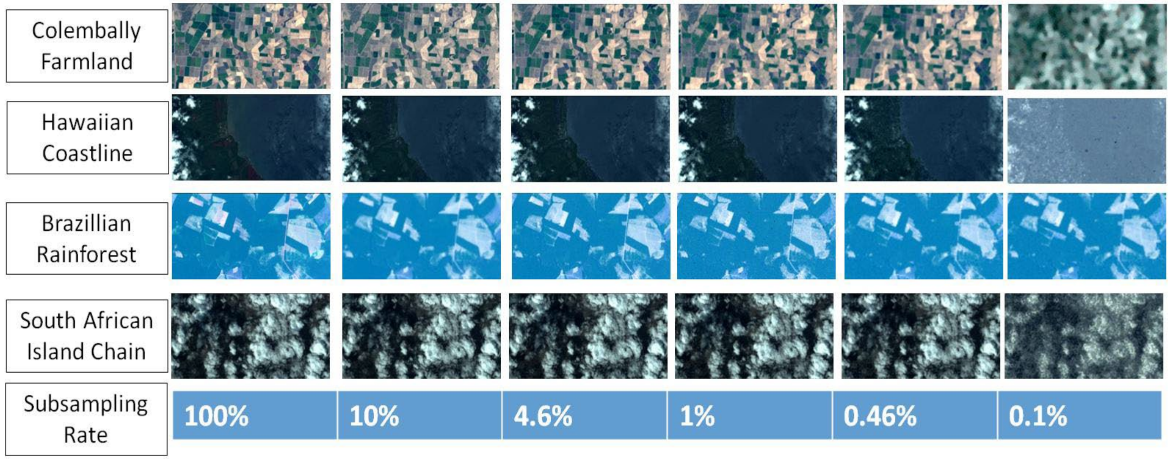




Hyperspectral Compressive Sensing

Sensor Analytics

Sub-sampling and reconstruction provide major benefits for minimal loss



Lower sampling rates allow for higher frame-rate, spectral resolution, spatial resolution, or signal to noise ratio

Integrated Modeling Capabilities

$$V_{if} = \iint d^3r_1 d^3r_2 [\phi_1^*(\vec{r}_1)\phi_2^*(\vec{r}_2)\Delta_{21} - \phi_2^*(\vec{r}_1)\phi_1^*(\vec{r}_2)\Delta_{12}] \frac{e^2 \exp[-\lambda|\vec{r}_1-\vec{r}_2|]}{\varepsilon|\vec{r}_1-\vec{r}_2|} \times \phi_{1'}(\vec{r}_1)\phi_{2'}(\vec{r}_2)$$

Physical Structure
Design, molecular dynamics

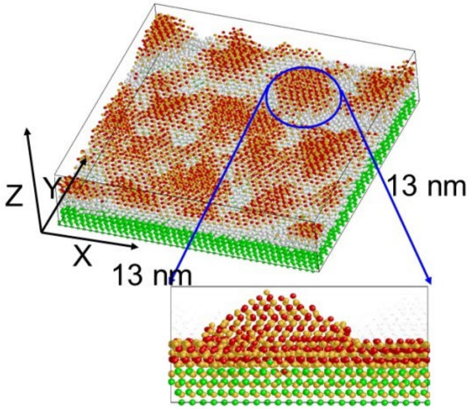
Electronic Structure
K.p envelope function, pseudopotential, ab initio

Phonon Structure
Rigid ion, adiabatic bond charge

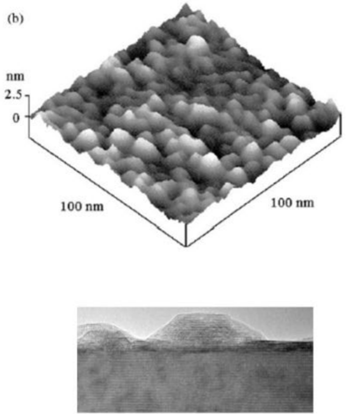
Radiative and Non-Radiative Recombination and Generation
Adaptive mesh Monte Carlo, photon recycling via Boltzmann equations

Transport
Drift diffusion/Poisson, Monte Carlo, Keldysh

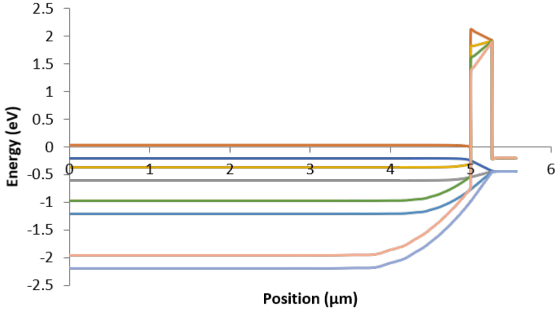
Simulation

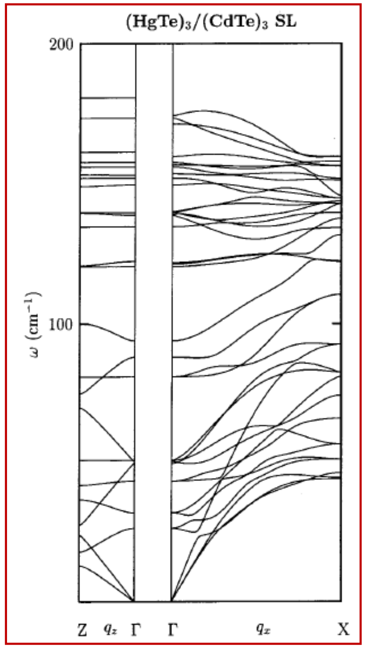


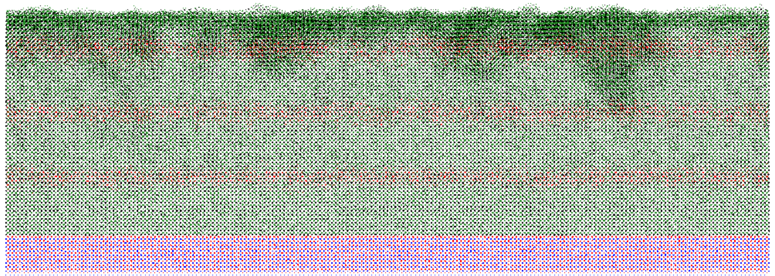
Experiment



Device Simulations

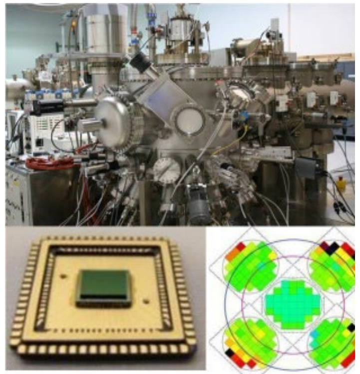






Investments/Spin-offs

EPIR Technologies



- Infrared Materials
- Focal Plane Arrays

Episolar

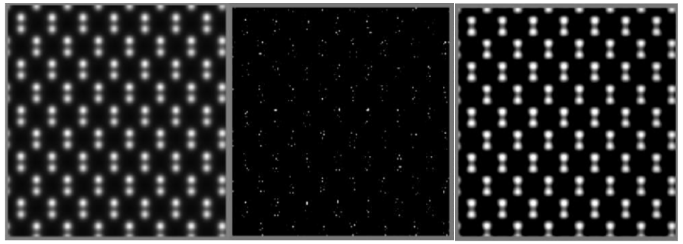
- High-efficiency CdTe
- Thin-Film Solar Panels
- Next Generation Flexible Solar Panel R&D

Episensors

- Low-cost, high-performance cameras and imaging systems

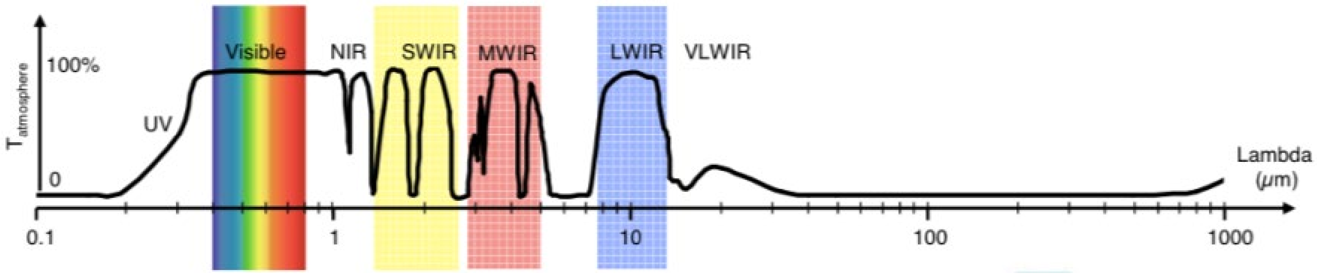
NUXUTRA

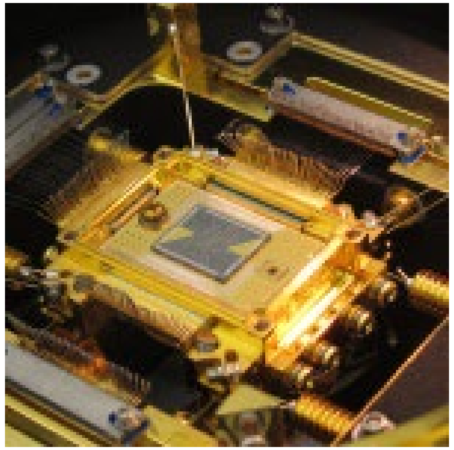
innovation



- High-speed imaging
- Compressive sensing

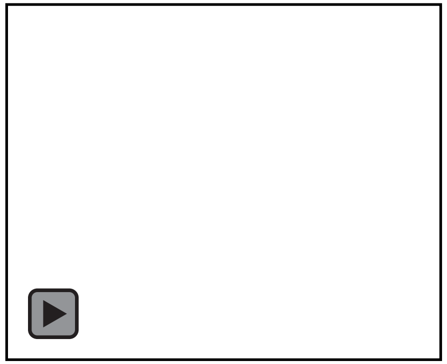
High Performance HgCdTe Sensors and Imagers

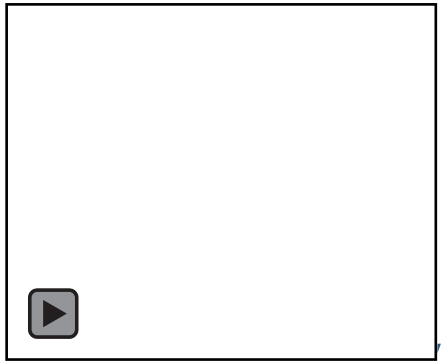




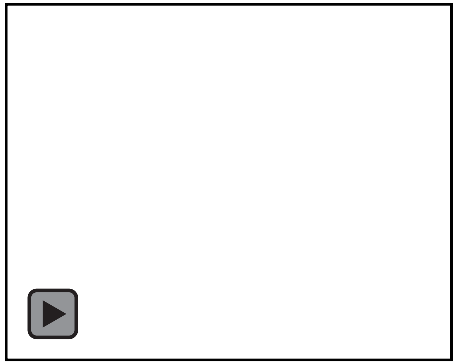
EPIR's HgTe material layers are the detectors in the SXS
-SXS was fabricated with NASA Goddard team

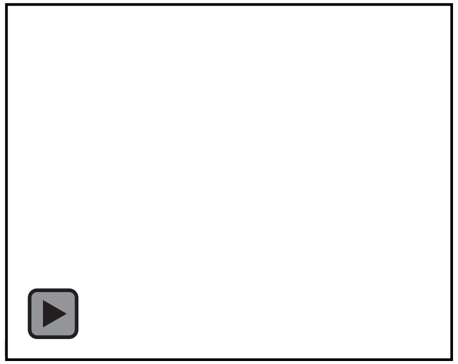
SWIR



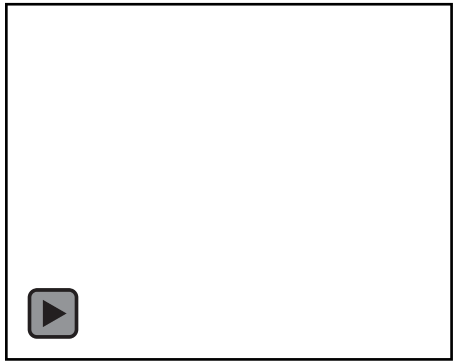


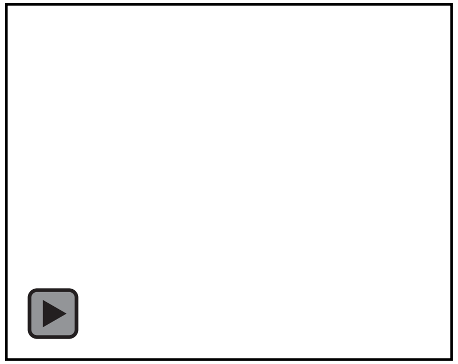
MWIR

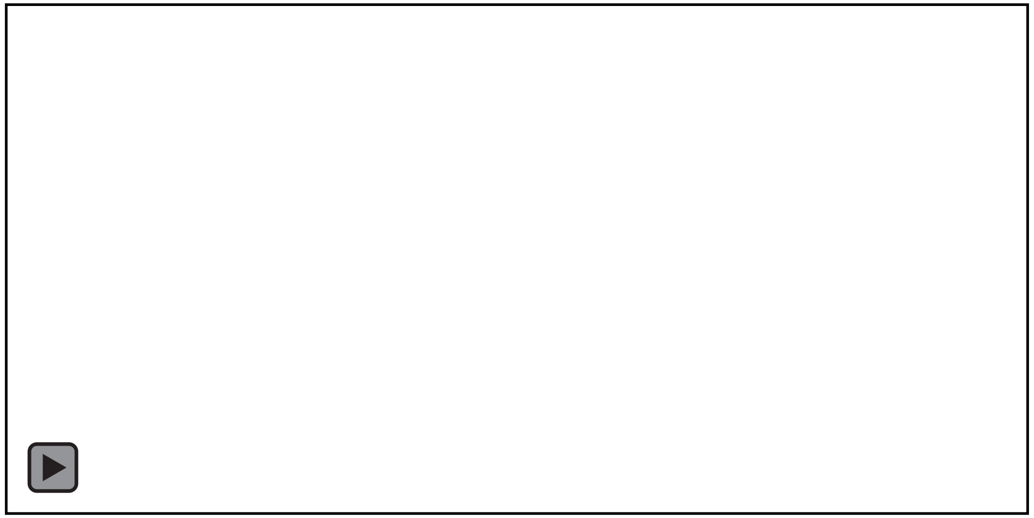




LWIR

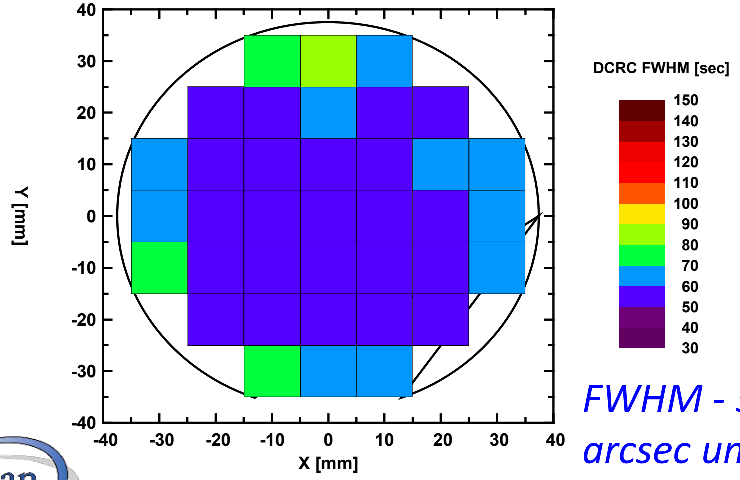






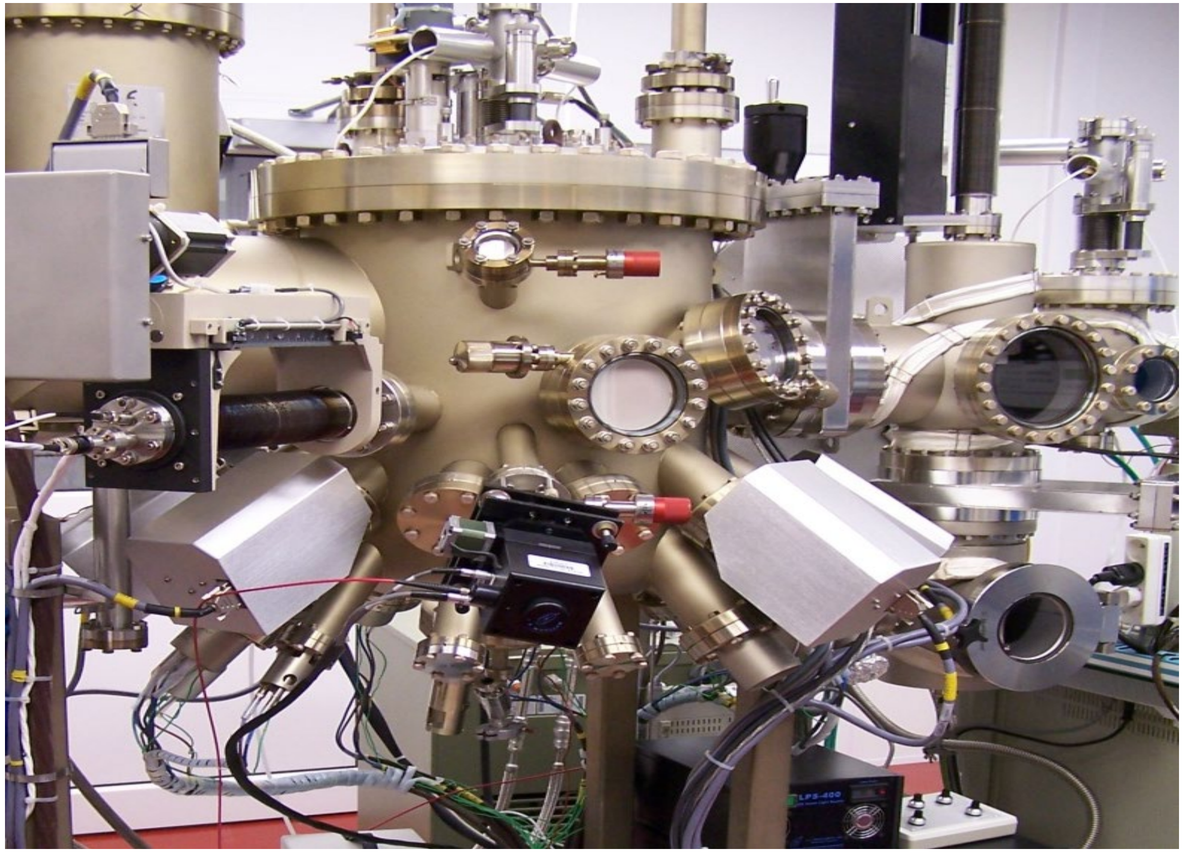
MBE Growth of CdTe and Its Alloys

- Bandgap engineering
- In situ doping control
- Precise film thickness
- Low T -> little diffusion
- Low maintenance cost
    - Non-volatile sources
    - Low vapor pressures
    - Non-flammable
- Low downtime
- High throughput
- Scalable for low cost



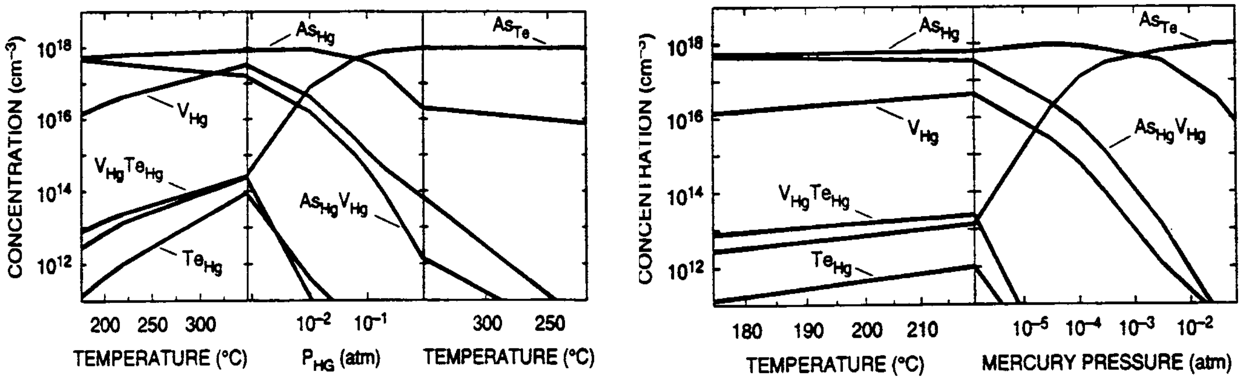
FWHM - 50-60 arcsec uniformity

II-VI MBE Thin Film Growth – Key EPIR Technology for IR and Multijunction Solar Cell Materials



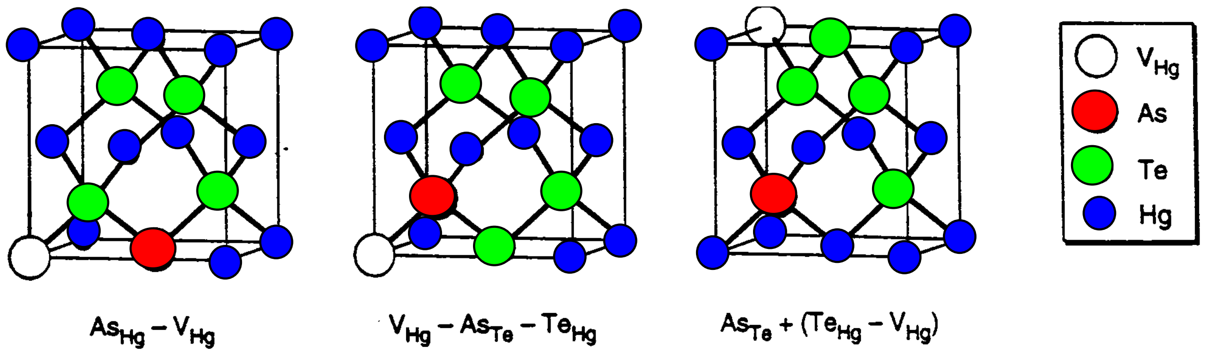
Arsenic Incorporation and Activation in HgCdTe

Low temperature annealing



Arsenic concentration: 10^{18} cm^{-3}

Density of native point defects during annealing, after Berding et al, J Electr. Mat. 27 (1998)



Berding et al, J Electr. Mat. 27 (1998)

Co-evaporation (cracked and non-cracked As)

- As_2 and As_4 - neutral

Arsenic incorporation in MBE grown $Hg_{1-x}Cd_xTe$; Grein, C.H., Garland, J.W., Sivananthan, S.; Journal of Electron Mater **28,** 789 (1999)

Evidence that arsenic is incorporated as As_4 molecules in the molecular beam epitaxial growth of $Hg_{1-x}Cd_xTe:As$; J. W. Garland, C. H. Grein, B. Yang, P. S. Wijewarnasuriya, F. Aqariden, and S. Sivananthan Appl. Phys. Lett. **74**, 1975 (1999)

Cd_2As_3

- Forcing As into the Te lattice
- May not require annealing

L.H. Zhang, S.D. Pearson, W. Tong, B.K. Wagner, J.D. Benson and C.J. Summers, J. Electron. Mater., **27**, 600 (1998)

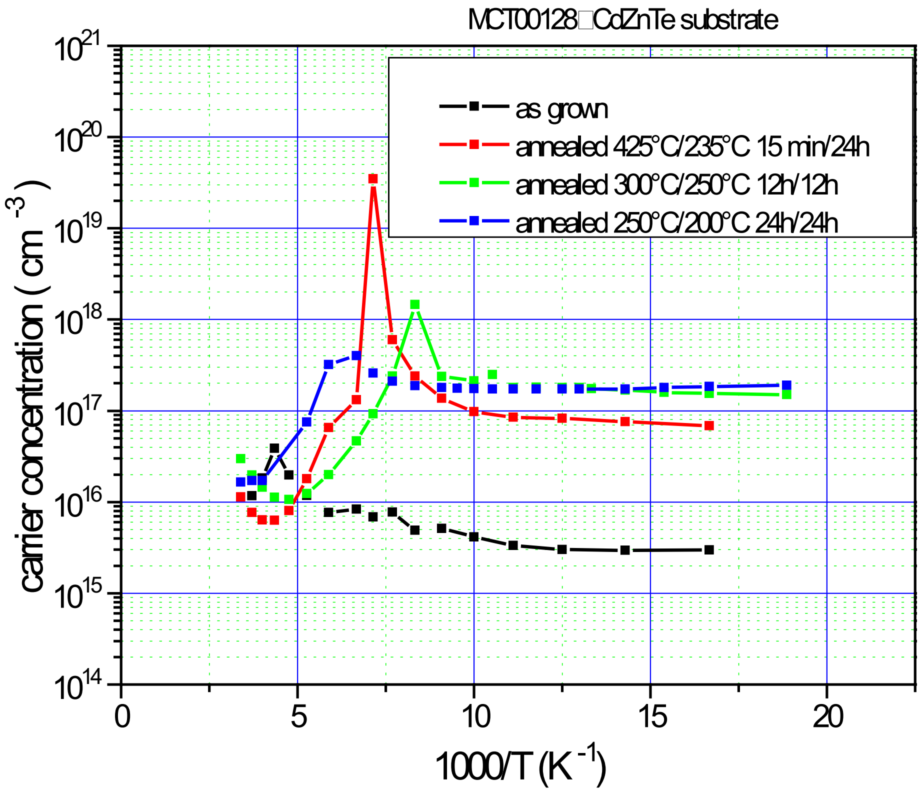
Planar (Delta) Doping

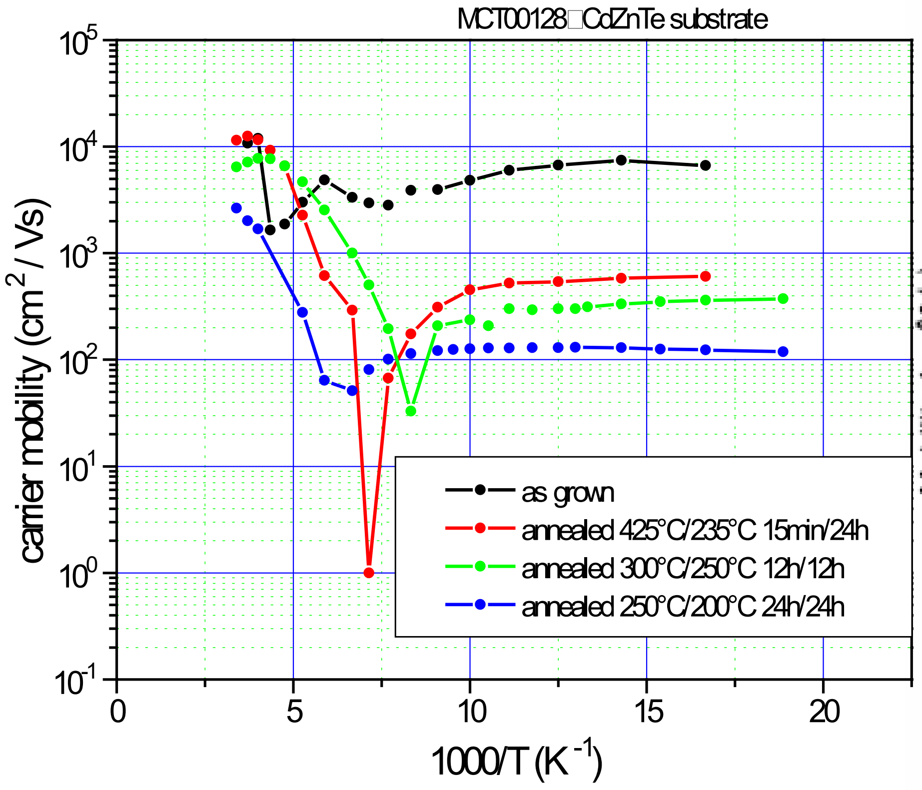
- Activation 85%
- Doping concentration $1x10^{17}$ cm^{-3}

P.S. Wijewarnasuriya, F. Aqariden, C.H. Grein, J.P. Faurie and S. Sivananthan, J. Cryst. Growth, **175/176**, 647 (1997)

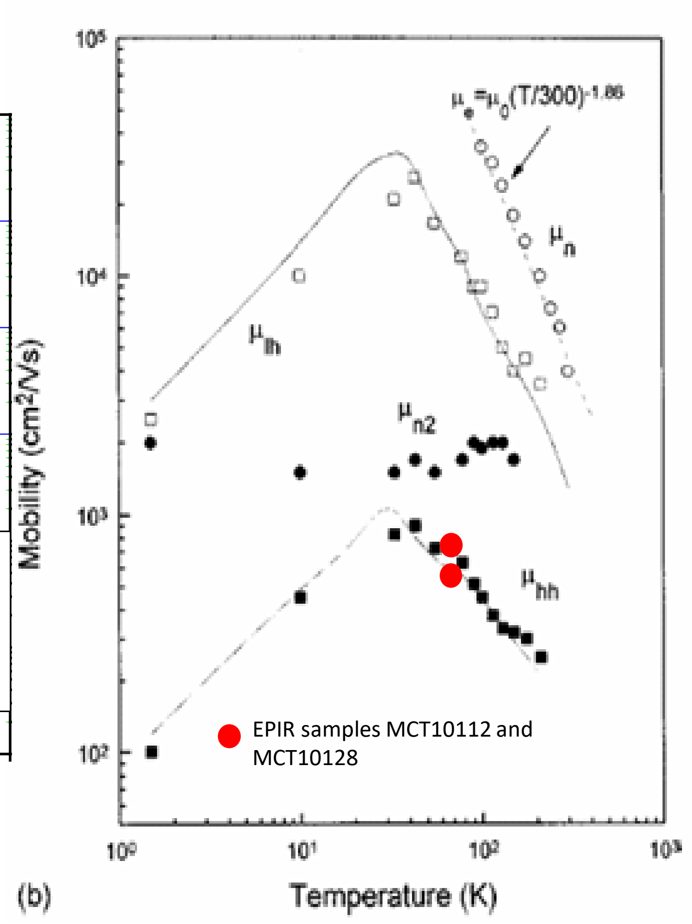
F. Aqariden, P.S. Wijewarnasuriya, S. Rujirawat and S. Sivananthan, Mat. Res. Soc. Symp. Proceeding **450**, 251 (1997)

Results of Arsenic Doping of HgCdTe





Arsenic activation in molecular beam epitaxy grown, in situ doped HgCdTe(211);
P. Boieriu, C. H. Grein, H. S. Jung, and J. Garland; Appl. Phys. Lett. 86, 212106 (2005)



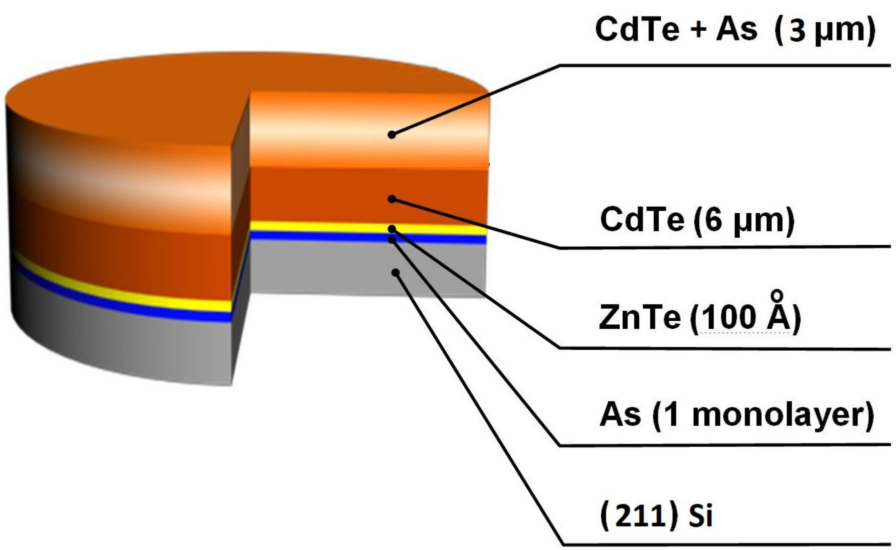
Gui et al.: QMSA study of p-type HgCdTe
J. Appl. Phys., Vol. 84, No. 8, 15 October 1998

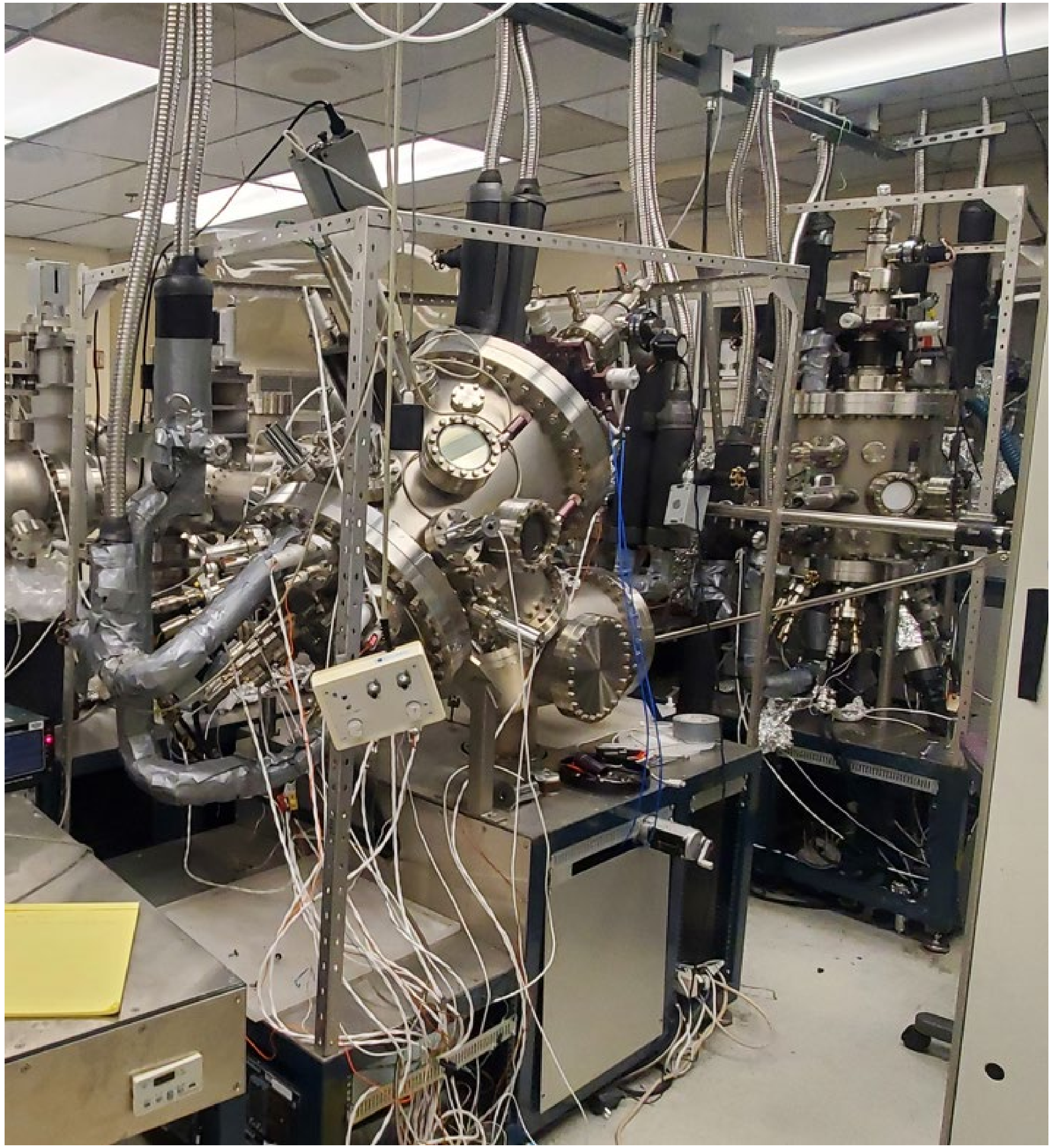
Sivananthan Laboratories, Inc. Proprietary Information

In-situ As doping of CdTe/Si Grown via MBE

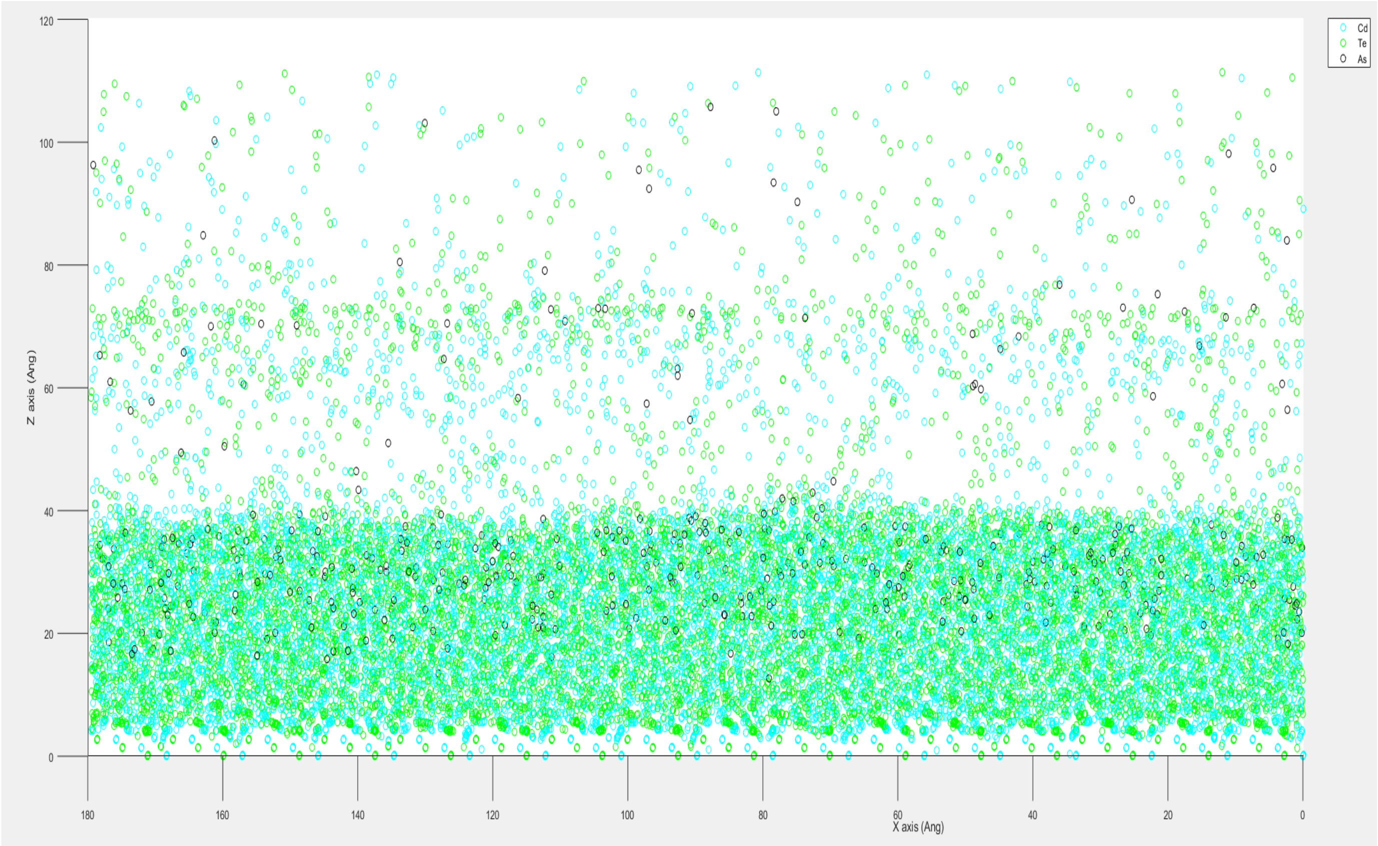
Sivananthan Laboratories

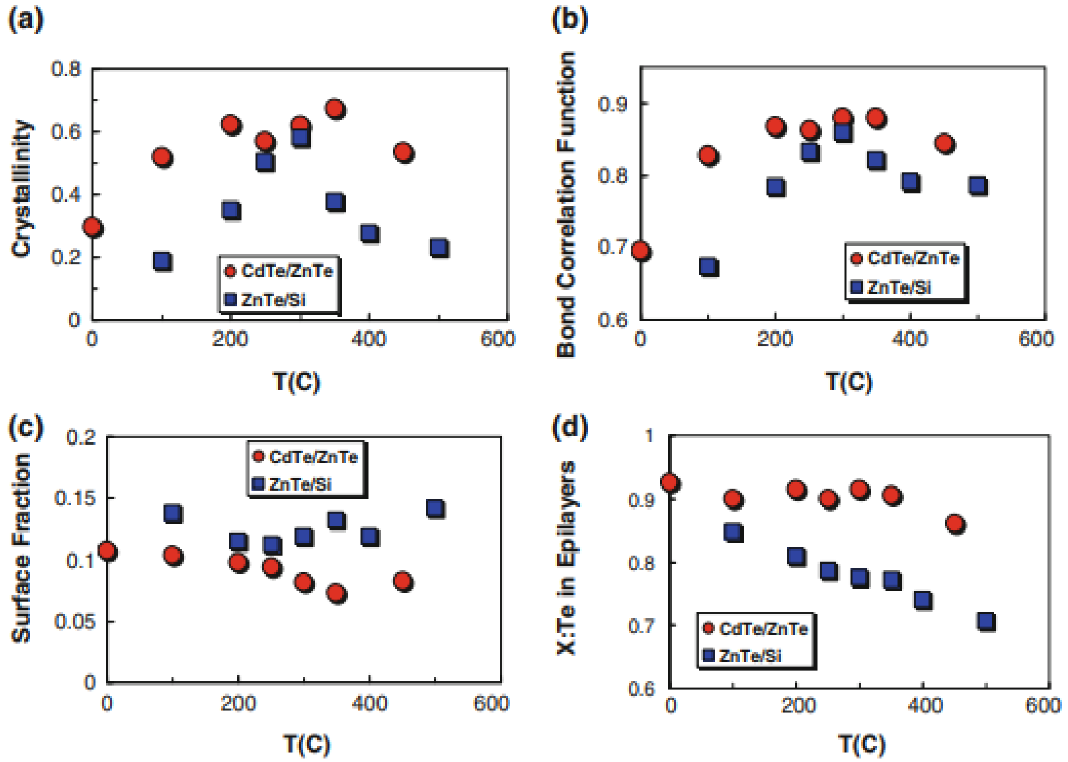
- Developing novel MBE growth recipes for high activation and incorporation of in-situ As in single crystal CdTe/Si
- Dedicated MBE chamber for material growth specific to CdTe solar applications
- Consistently achieve FWHM of ~75 arcsec for CdTe/Si using refined 3-cycle spike anneal recipe
- Target goal of 50% CdTe activation at concentrations of 2 x 10^{16} cm^{-3} by end of year





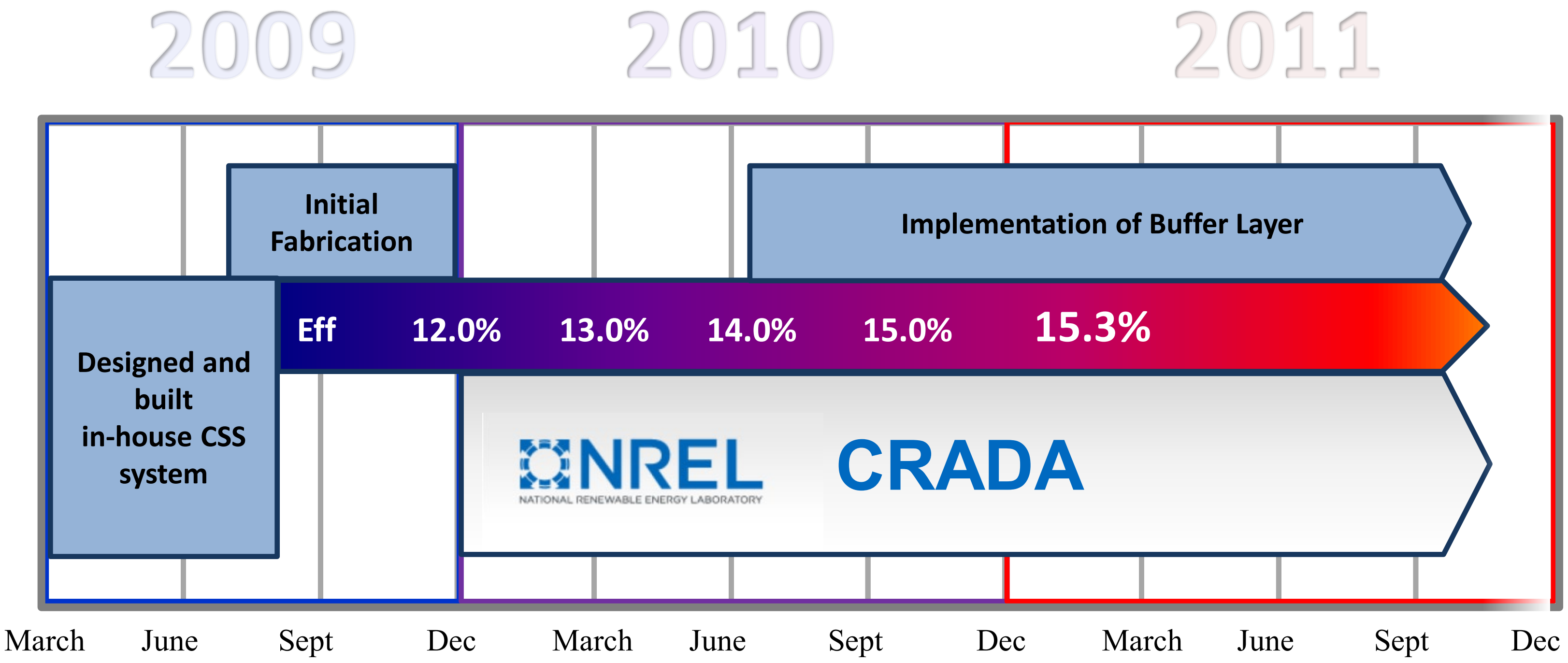
Advanced MD Modeling of CdTe Deposition Processes



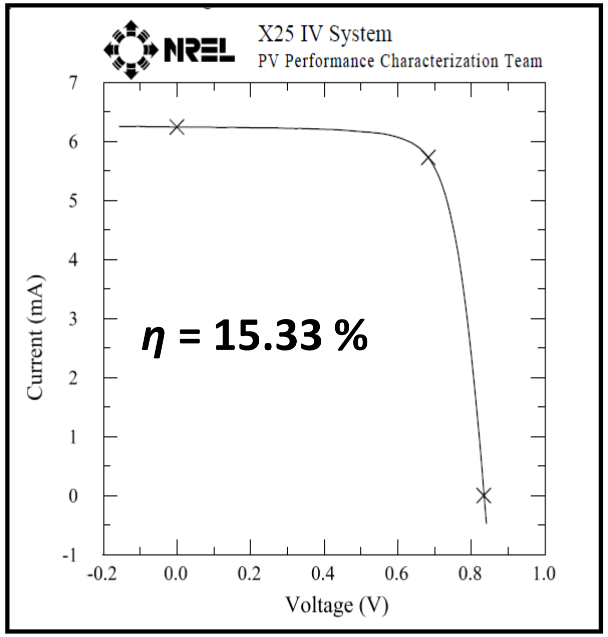


2009-2011 EPIR PolyCdTe Project

- Goal: *Improve cell efficiencies by means conducive to low cost manufacturing*
  - Improve device efficiency on commercial TCOs
    - Optimize CdS material quality and SnO_2 buffer layer
    - Maintain repeatability



EPIR Efficiencies above 15%



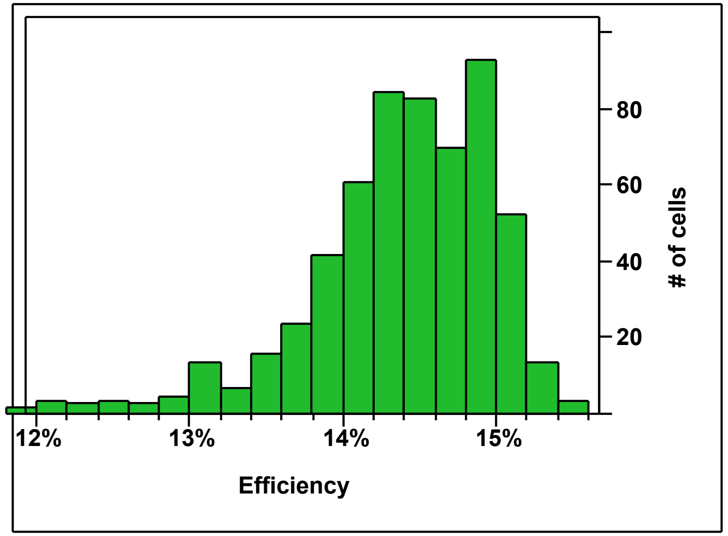
NREL verified I-V parameters

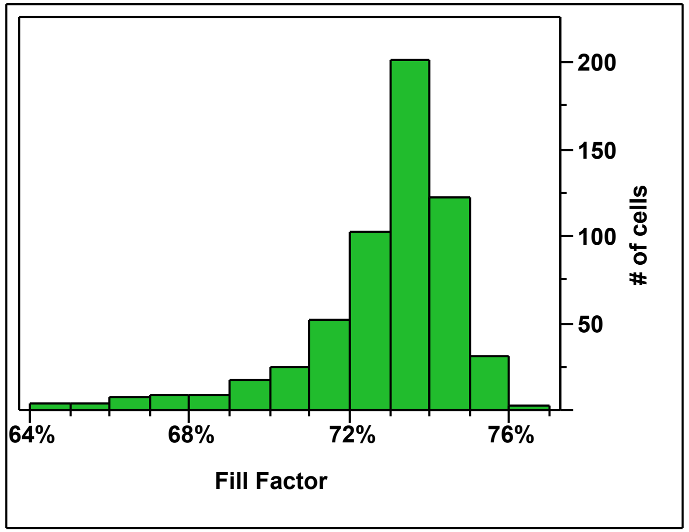
Month of Verification	η	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF
Jul-2010	**12.02 %**	**802**	**21.97**	**68.19 %**
Dec-2010	**15.21 %**	**815**	**24.03**	**77.64 %**
Apr-2011	**15.08 %**	**829**	**23.87**	**76.16 %**
Apr-2011	**15.33 %**	**834**	**24.47**	**75.16 %**

- Achieved above 15% efficiencies with V_{oc} between 820 - 835 mV, J_{sc} approximately 24 mA and FF between 75 - 78%

Among the highest CdS/CdTe solar cell efficiencies on commercial TCO substrates in 2011

Performance Distribution





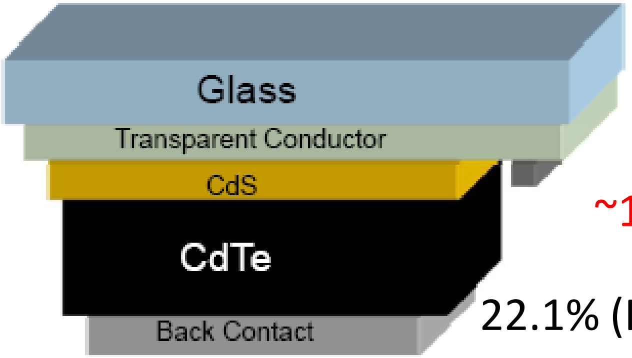
- Hundreds of devices processed between July 2010 and August 2011
- Mean efficiency > 14.4% (std dev of 0.6 percentage points)
- Mean FF > 73%

Polycrystalline CdTe Solar Cells Architectures

- **Most CdTe photovoltaic (PV) device work in the last 30 years has focused on the superstrate configuration**
  - Early success in producing devices of reasonable efficiency
  - Access to CdTe back surface to enable optimization of back contact
- **Limited CdTe substrate configuration PV device work has been described in literature (≈20 articles)**

  Limited performance in past
  - Strong rollover indicating poor back contact (low V_{oc}, fill factor)
  - Typically <8% (unofficial) efficiency reported

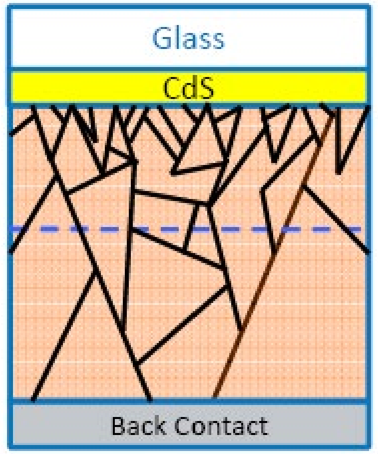
Superstrate Configuration



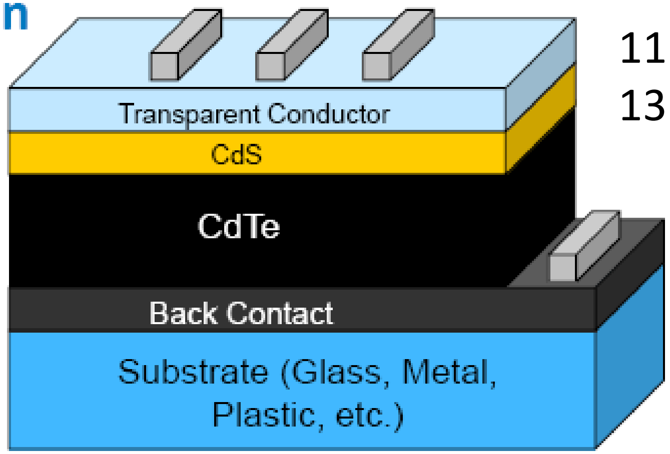
~10 W/Kg

22.1% (First Solar, 2016)

Superstrate



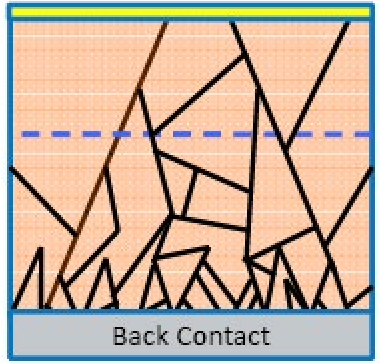
Substrate Configuration



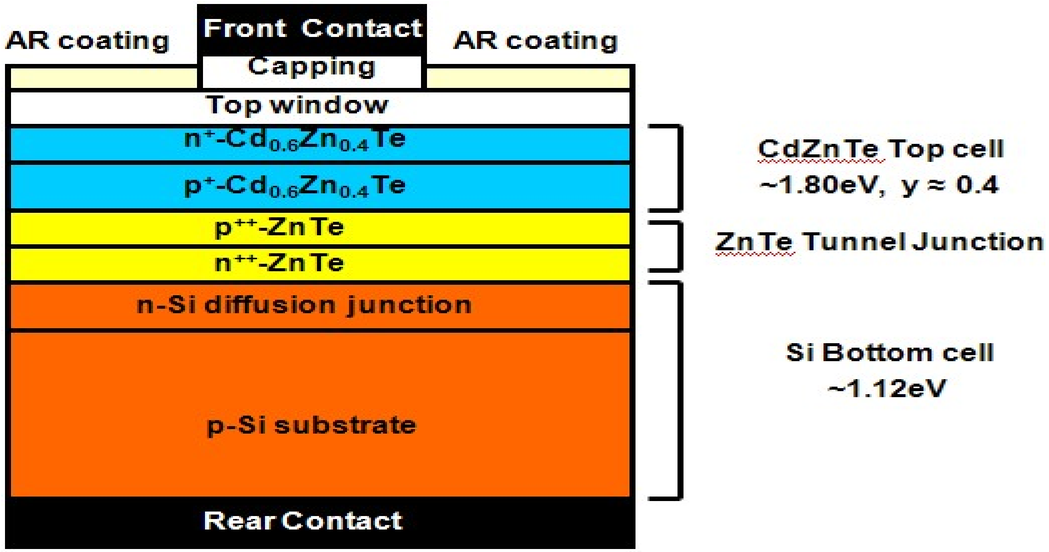
11.0% (NREL, 2010)
13.6% (EMPA, 2013)

~100-200 W/Kg

Substrate



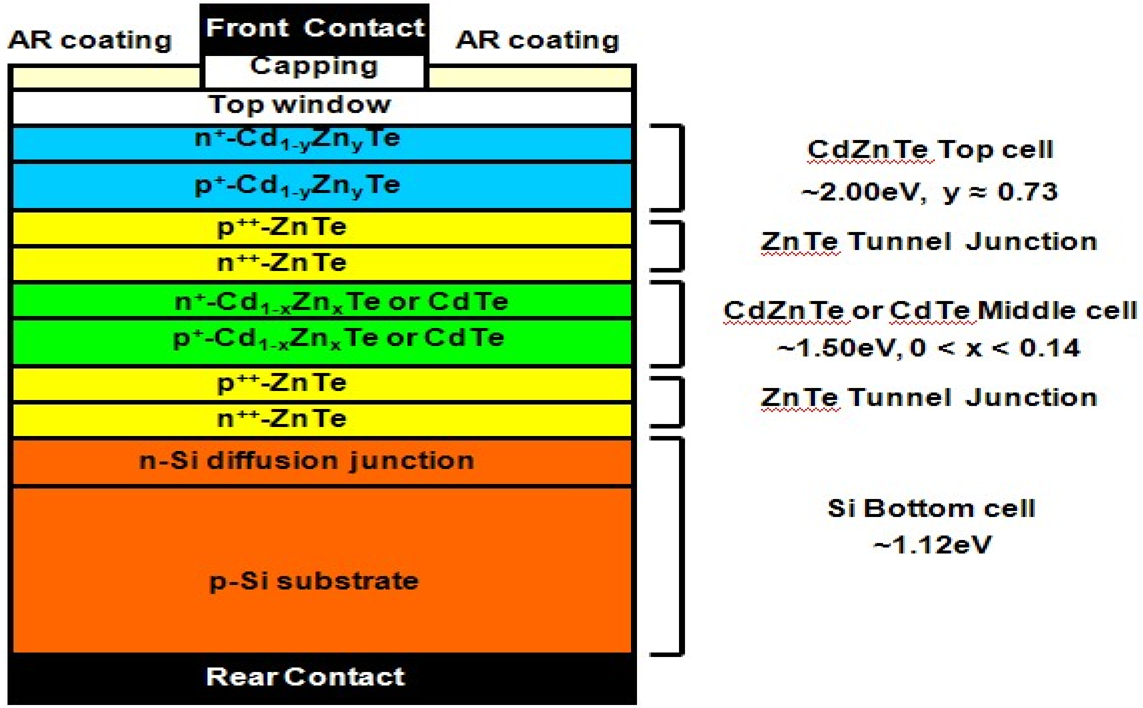
II-VI 2- and 3-Junction Single Crystal Solar Cells



Two-junction CdZnTe/Si solar cell

Projected optimal production-line efficiency ~38%

Projected large-scale production cost < $1/cm²



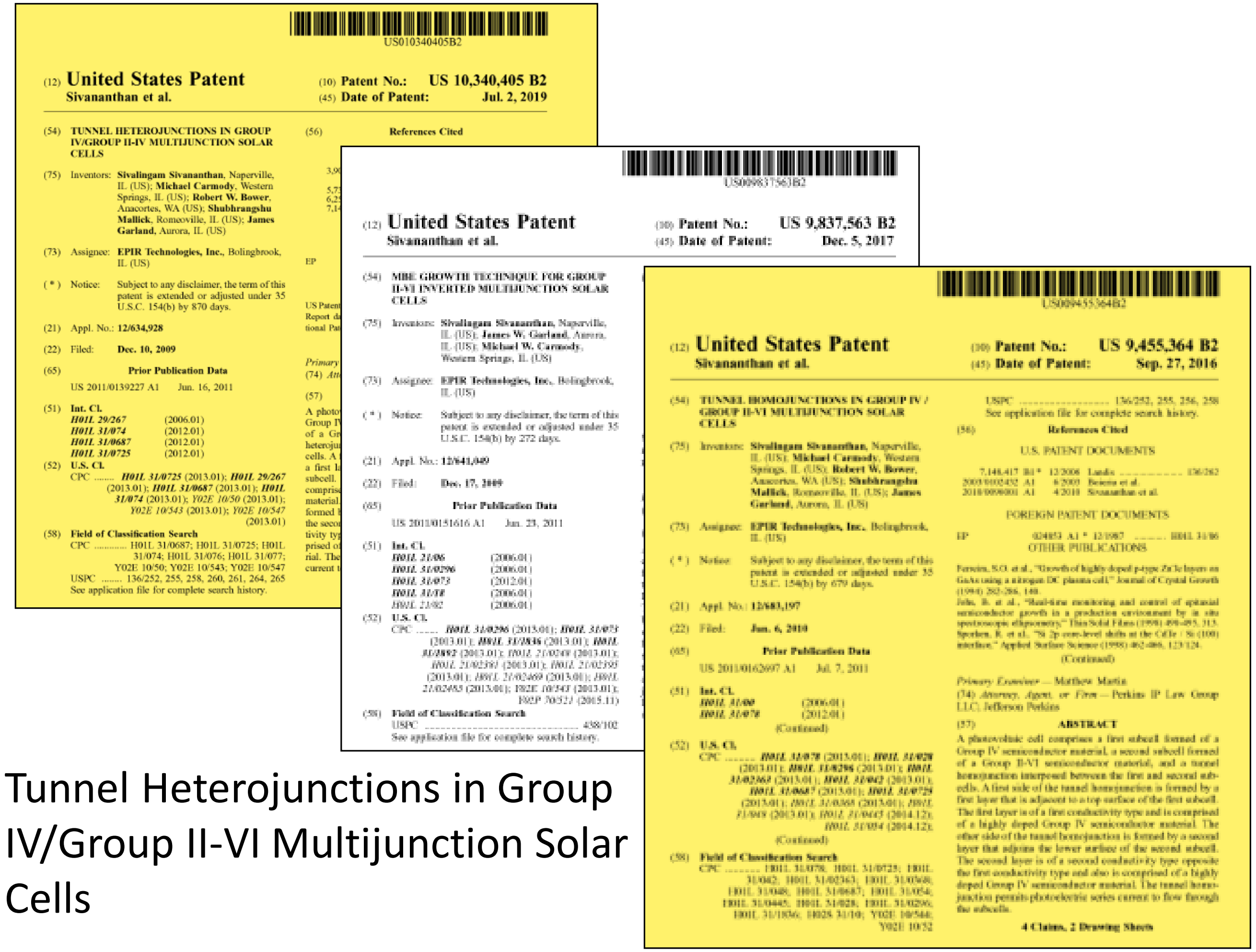
Three-junction CdZnTe/CdTe/Si solar cell

Projected optimal production-line efficiency ~42%

Projected large-scale production cost < $1.50/cm²

Inverted II-VI four-junction production-line efficiency → 50%

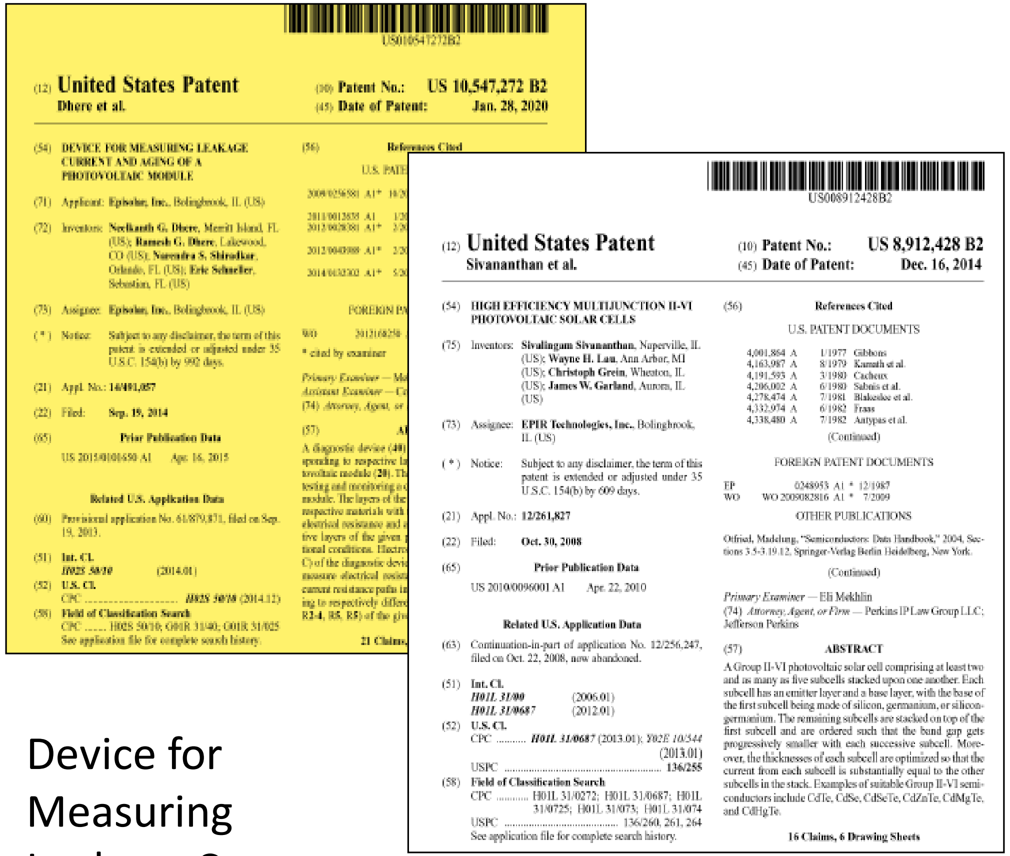
Patented Solar Technology



Tunnel Heterojunctions in Group IV/Group II-VI Multijunction Solar Cells

MBE Growth Technique for Inverted Multijunction Solar Cells

Tunnel Homojunctions in Group IV/Group II-VI Multijunction Solar Cells



Device for Measuring Leakage Currents

High-efficiency Multijunction II-VI Solar Cells

Summary

- V_{oc} values must be increased to obtain highest efficiencies
- Increase p-doping of CdTe with long carrier lifetimes
- Long-term module longevity increases with doping reliability
- Higher doping yield improved contacts
- Atomistic modeling of co-evaporation of dopants, grain/crystal growth and annealing is mandatory
- Sivananthan Laboratories and its affiliates have extensive expertise in incorporation and activation of Gr V dopants in II-VI materials