# Update of Photovoltaic CdTe Development at Sivananthan Laboratories, Inc.

Alexander Goldstone

6<sup>th</sup> US CdTe Workshop

October 20 – 21, 2022



Intelligent and Automatic Decision-Making Sensors and Imagers

# Sivananthan Laboratories – Key Midwest Positioning











# Areas of Focus

.

**Community Service** 

STEM-focused education and training

Outreach to underserved communities

#### **Infrared**

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

### <u>Solar</u>

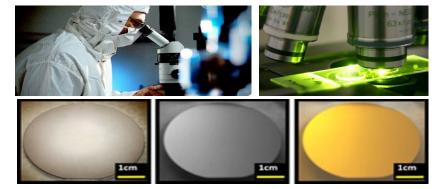
#### Episolar

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



#### **Research & Development**

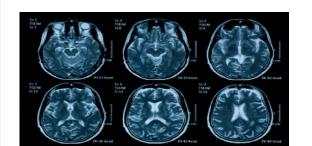
- Quantum Optics
- Radiation Detectors
- Type II Superlattices
- Colloidal Quantum Dots





InSPIRE

initiatives

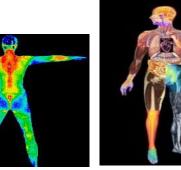




#### **Medical**

- Biological Sensors
- Neuroscience
- Medical Imaging
- Social Medicine







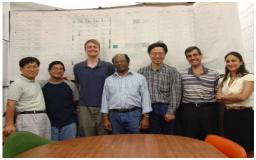
## **Global Outreach**



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

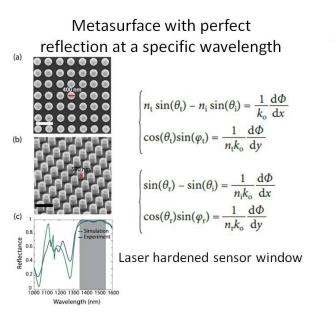
Passion to mentor and motivate interest in science, technology, engineering and mathematics among underrepresented communities across the world

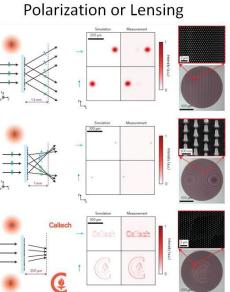
Sivananthan

### **Fundamental Research and Novel Ideas**

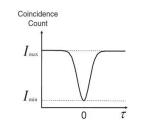
Features

### Flat Quantum Optics





- 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



### Ghost Imaging

ω

HWP QP

 $\omega_{p} = \omega_{s} + \omega_{i}$ 

 $\mathbf{k}_{n} = \mathbf{k}_{s} + \mathbf{k}_{i}$ 

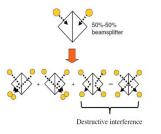
Scanning Detector A

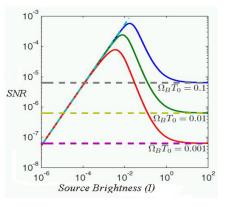
Bucket Detector B

a)

CW Laser

ω







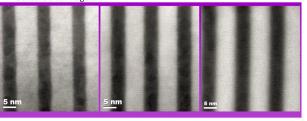
# Advanced Material Research and Prototyping

#### High Performance Superlattice Sensors and Imagers

Example:

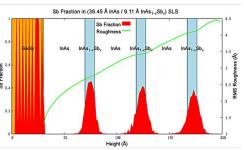
#### Infrared Materials By Design

- 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





Type III Type Type II HaCdTe/CdTe InAs/GaInSb HgTe/CdZnTe



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

320x256 30 µm ROIC

hour

R&D level

Compatible for SWIR to LWIR

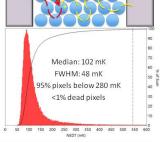
ROIC to FPA in approximately 1

Films cost about \$5 per FPA at the

Covers the SWIR, MWIR, and LWIR



#### MWIR SWIR 20 HgTe CQD Diameter (nm) Ultra-Low Cost Processing · FPAs fabricated using a commercial **Direct Photon Detection** · Photonic: Infrared photons Readily scaled to larger formats are detected as and wafer level processing.



- photocurrent, PC or PV
- Carriers transverse the CQD film via tunneling/hopping, like a barrier device

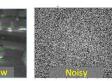


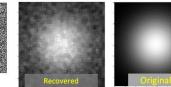
### Integrated Sensor Intelligence

#### Intelligent Image Enhancement

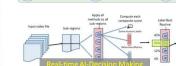
- Reveal information contained within images beyond what human eyes can detect
- Image enhancement is valuable for human and machine consumption
- Image processing is highly beneficial for machine vision applications to increase detection speed and accuracy









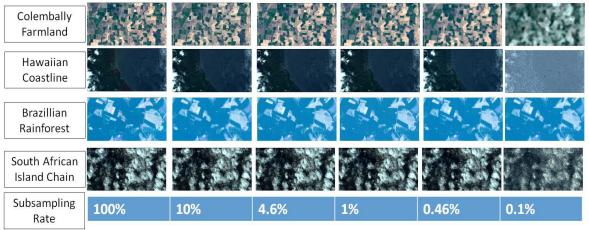




#### Hyperspectral Compressive Sensing



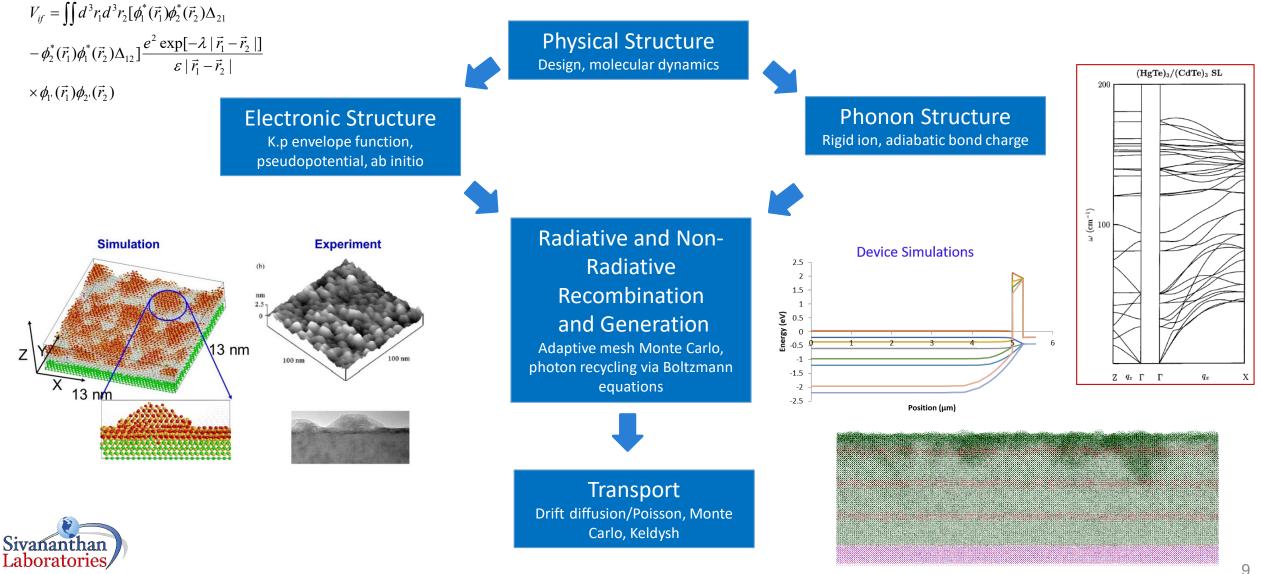
Sub-sampling and reconstruction provide major benefits for minimal loss



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



### **Integrated Modeling Capabilities**

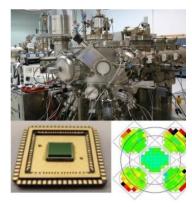


Sivananthan Laboratories, Inc. Proprietary Information

# Investments/Spin-offs







• Infrared Materials • Focal Plane Arrays



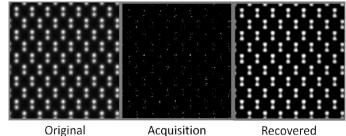


- High-efficiency CdTe
- Thin-Film Solar Panels
- Next Generation **Flexible Solar Panel** R&D

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

Episensors





Original

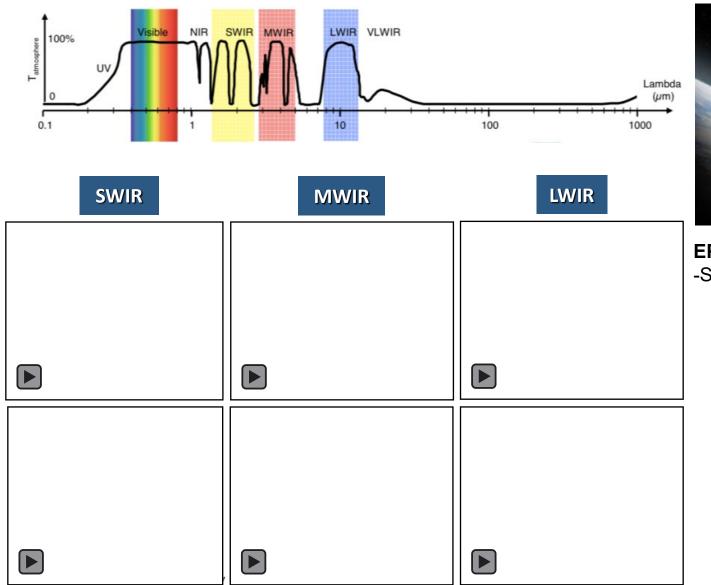
Recovered

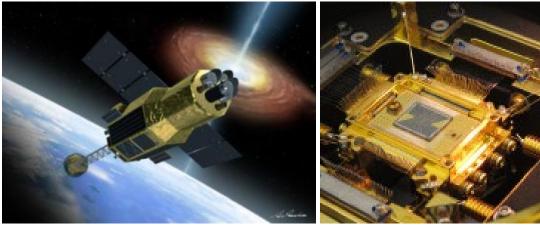
• High-speed imaging Compressive sensing



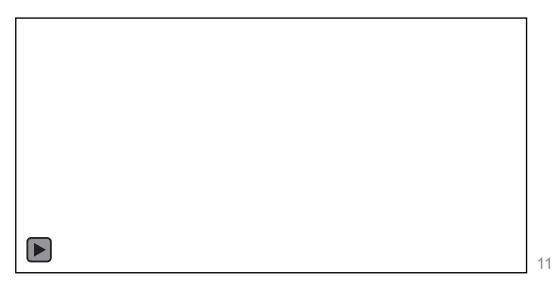
### High Performance HgCdTe Sensors and Imagers





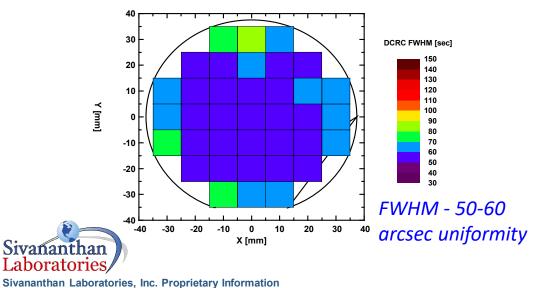


EPIR's HgTe material layers are the detectors in the SXS -SXS was fabricated with NASA Goddard team

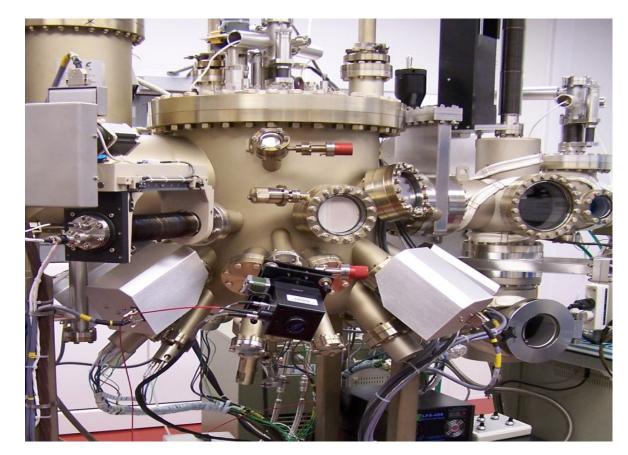


### MBE Growth of CdTe and Its Alloys

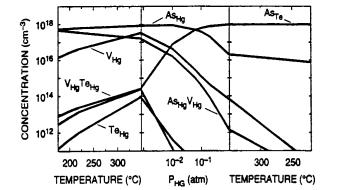
- •Bandgap engineering
- •In situ doping control
- Precise film thickness
- •Low T -> little diffusion
- •Low maintenance cost
  - Non-volatile sources
  - Low vapor pressures
  - Non-flammable
- •Low downtime
- •High throughput
- •Scalable for low cost



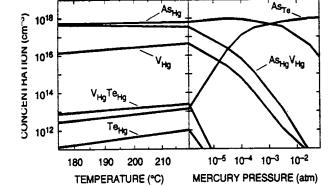
### II-VI MBE Thin Film Growth – Key EPIR Technology for IR and Multijunction Solar Cell Materials



## Arsenic Incorporation and Activation in HgCdTe

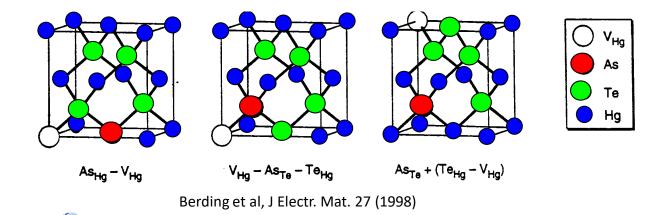


#### Low temperature annealing



Arsenic concentration: 10<sup>18</sup> cm<sup>-3</sup>

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



#### Co-evaporation (cracked and non-cracked As)

• As<sub>2</sub> and As<sub>4</sub> - 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

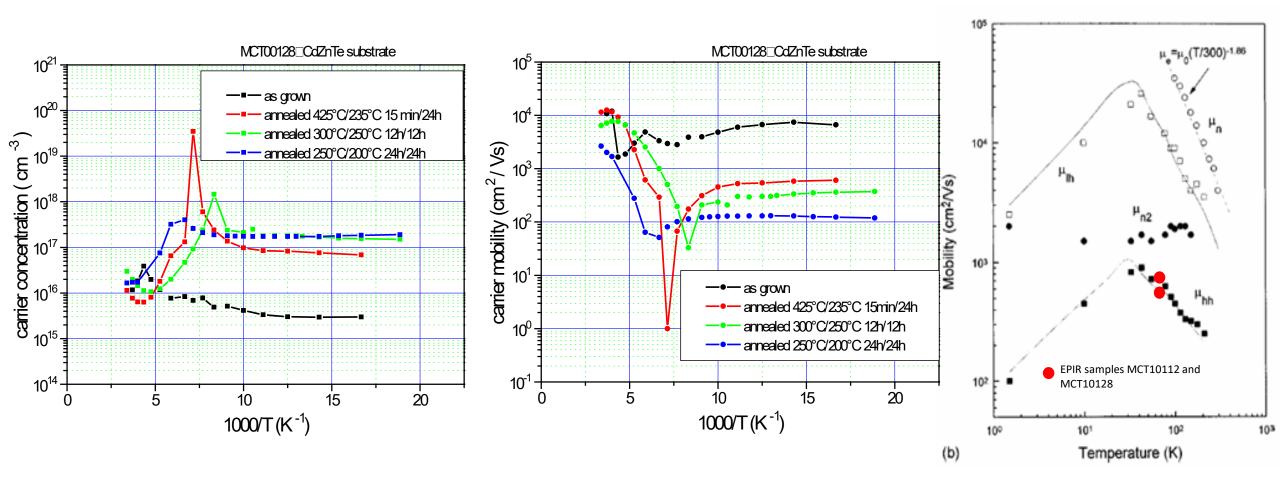
- Activation 85%
- Doping concentration 1x10<sup>17</sup> cm<sup>-3</sup>

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)

Sivananthar

### 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

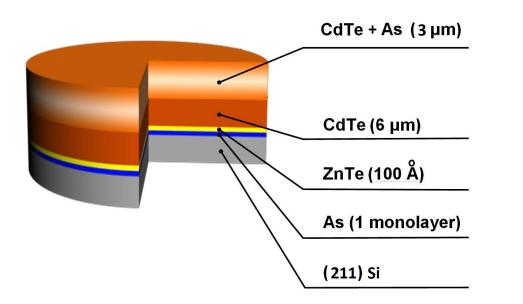
Laboratories// Sivananthan Laboratories, Inc. Proprietary Information

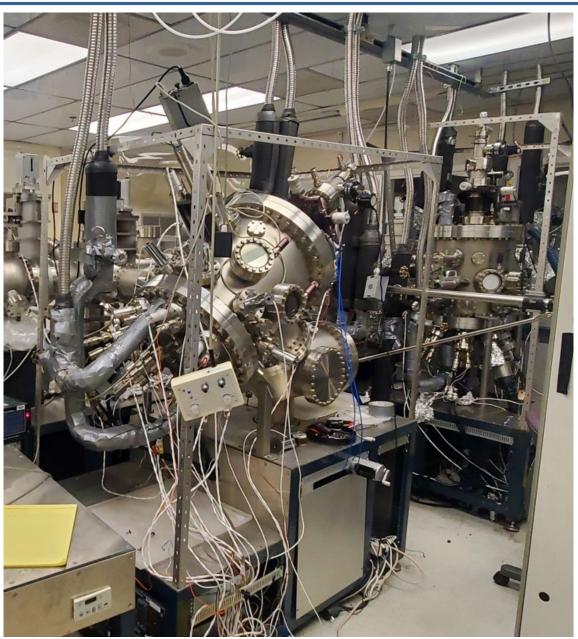
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### In-situ As doping of CdTe/Si Grown via MBE

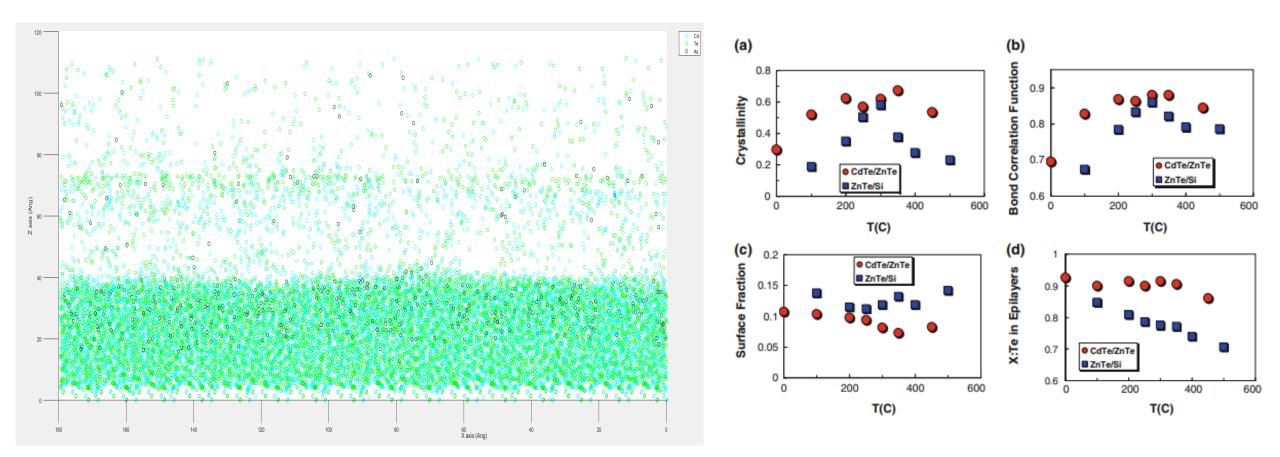


- Developing novel MBE growth recipes for high activation and incorporation of in-situ As in single crystal CdTe/Si
- Dedicated MBE chamber for material growth specific to CdTe solar applications
- Consistently achieve FWHM of ~75 arcsec for CdTe/Si using refined 3-cycle spike anneal recipe
- Target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





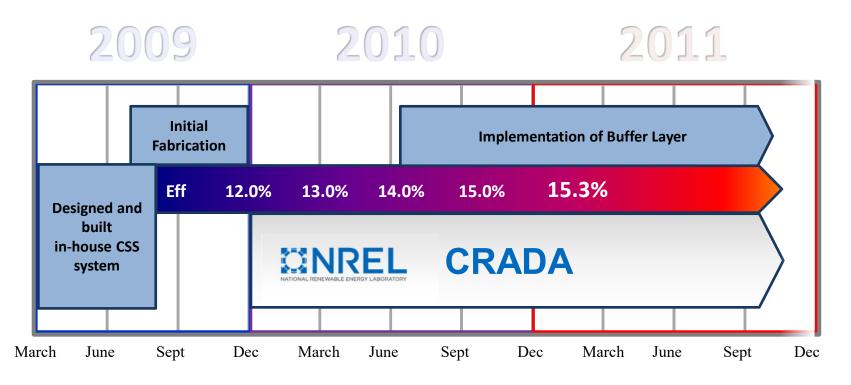
### Advanced MD Modeling of CdTe Deposition Processes





## 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<sub>2</sub> buffer layer
    - Maintain repeatability



### EPIR Efficiencies above 15%

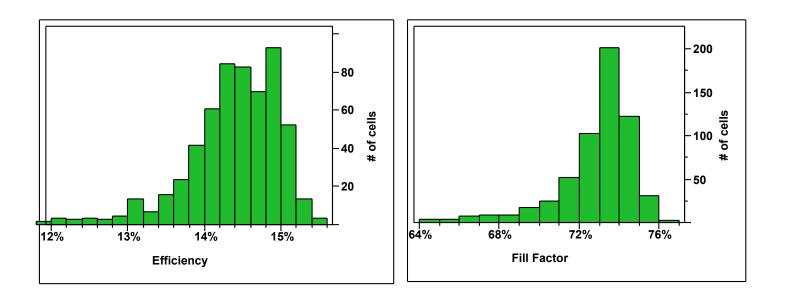
	X25 IV System		NREL	NREL verified I-V parameters			
7 6 5			Month of Verification	η	V <sub>oc</sub> (mV)	J <sub>sc</sub> (mA/cm²)	FF
4 (Ym) 3	η = 15.33 %		Jul-2010	12.02 %	802	21.97	68.19 %
Current (mA)			Dec-2010	15.21 %	815	24.03	77.64 %
1		Apr-2011	15.08 %	829	23.87	76.16 %	
-1 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 Voltage (V)			Apr-2011	15.33 %	834	24.47	75.16 %

Achieved above 15% efficiencies with V<sub>oc</sub> between 820 - 835 mV,
 J<sub>sc</sub> 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%

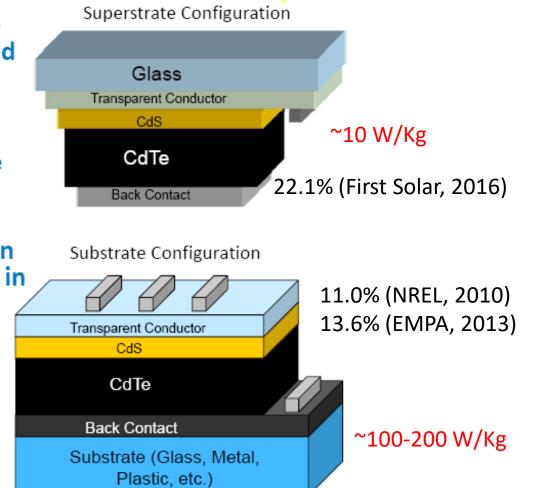


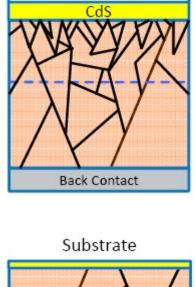
# Polycrystalline CdTe Solar Cells Architectures

- 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

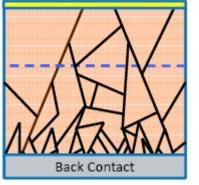
- Strong rollover indicating poor back contact (low V<sub>oc</sub>, fill factor)
- Typically <8% (unofficial) efficiency reported





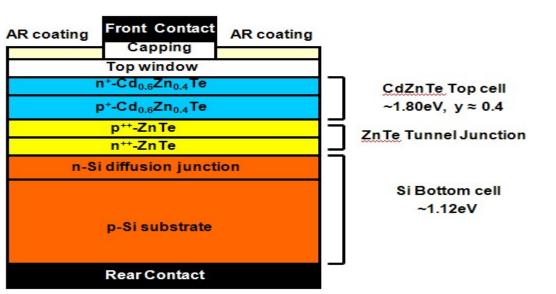
Superstrate

Glass

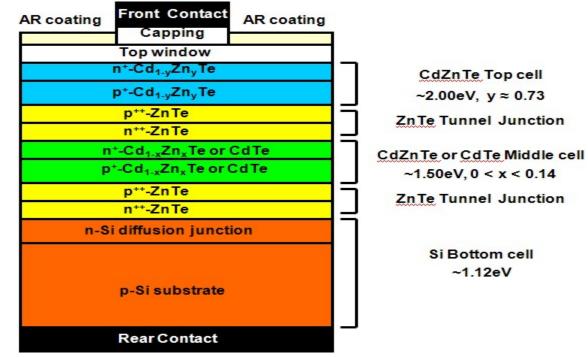




## II-VI 2- and 3-Junction Single Crystal Solar Cells



**Two-junction CdZnTe/Si solar cell** *Projected optimal production-line efficiency* ~38% *Projected large-scale production cost* < \$1/cm<sup>2</sup>

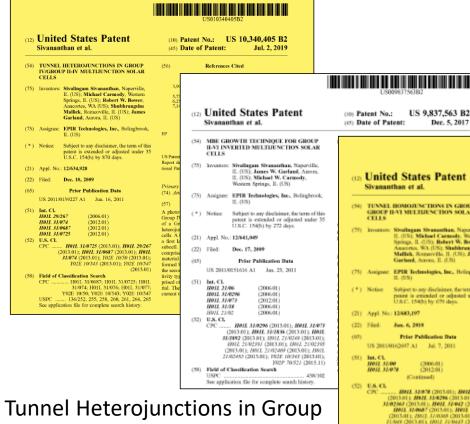


Three-junction CdZnTe/CdTe/Si solar cell Projected optimal production-line efficiency ~42% Projected large-scale production cost < \$1.50/cm<sup>2</sup>



### Inverted II-VI four-junction production-line efficiency $\rightarrow$ 50%

### Patented Solar Technology



tates Patent et al.	(10) Patent No.: US 9,455,364 B2 (45) Date of Patent: Sep. 27, 2016					
JUNCTIONS IN GROUP IV / ULTIJUNCTION SOLAR	USPC					
	(56) References Clied					
ngam Sivanaerthan, Naperville, 5): Michael Carmody, Western	U.S. PATENT DOCUMENTS					
s, IL (US); Robert W. Bower, rtes, WA (US); Shubhrangshu &, Romeoville, IL (US); James nd, Acrons, IL (US)	7,146,417 Bit* 12/2006 Landis					
	FOREIGN PATENT DOCUMENTS					
Technologies, Inc., Bolingbrook, 5)	EP 02485 A1 * 121987					
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1,197	John, B. et al., "Real-time monitoring and control of epitaxial semiconductor growth in a production cervitonment by in situ					
2414	<ul> <li>spectroscopic ellipsoenetry," Thin Solid Films (1990) 490–495, 313.</li> <li>Sporken, R. et al., "Si 2p core-level shifts at the Celle / Si (100).</li> </ul>					
er Publication Data	interface," Applied Surface Science (1998) 462-466, 123/124.					
A1 361.7, 2011	(Continued)					
(2006-01)	Primary Econology – Matthew Mattia (74) Atterney, Agent, or Firm – Perkins IP Law George LLC: Jefferson Perkins					
(2012.01) Continued)	(37) ABSTRACT					
2. J24079 (2013.06); HOLE J24020 E. J24079 (2013.06); HOLE J44020 HOLE J4025 (2013.01); HOLE HOLE (2013.06); HOLE J407 HOLE J40406 (2013.01); HOLE HOLE J40408 (2013.01); HOLE HOLE J40408 (2014.12); HOLE J40408 (2014.12); HOLE J40408 (2014.12); HOLE J40408 (2014.12); HOLE J40408 (2014.12); HOLE J40408 (2014.12); HOLE J40408 (2014.12); HOLE HOLE J40487; HOLE J40742; HOLE B4015 J40487; HOLE J40748; HOLE J40487; HOLE J	A photovchiac cell comprises a first undved formed of a forego IV semiconducer material, a second sub-cell formed of a Group TAVI semiconducer material, and a more bench method interpreted between the second ad- observation interpreted between the second ad- observation of the standard home parameter of the second of a highly deeped Group IV seconduced material. The other share the standard the second conductivity type expected object that adjoints the lever architect of the second second the transformer the second conductivity type expected for the photoe the lever architect of the second second. The fore second conductivity type expected for the second lever a material. The transformers photoe the second second conductivity type expected for the second lever a material. The transformers photoe the second second conductivity type expected for the second lever a material. The transformers photoe the second second conductivity type expected for the second lever a material. The transformers photoe the second lever a material. The transformers photoe the second lever a material is the second lever the second lever and the second lever the second lever the second lever the second lever and the second lever the second lever the second lever and the second lever the second lever the second lever and the second lever					
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(12)	United States Patent Dhere et al.	(10) Patent No.: (45) Date of Patent		),547,27 Jan. 28					
(54)	DEVICE FOR MEASURING LEAKAGE CURRENT AND AGING OF A PHOTOVOLIAIC MODULE	U.S. PATE	ices Cited						
(71)	Applicant: Episolar, Inc., Bolingbrook, IL (US)	2008/0256581 A1* 18/20						US008912428B2	
(72)	Inventors: Neekanth G. Dhere, Mamit Island, FL. (US): Bannesh G. Dhere, Lakewood, CO (US): Narendra S. Shiradkar, Orlando, FL (US): Erie Schneller, Sebastion, FL (US):	2011/0012638 A1 1/2 2012/062088 A1* 2/2 2012/0640988 A1* 2/2 2014/0122002 A1* 5/2	(12)		ed States othan et al.	Patent	(10) Patent (45) Date of		
(73)	Assignee: Episolan Inc., Bolingbrook, IL (US)	FOREKON PA	(54)			JULTIJUNCTION II-VI	(56)	References Cited	
(*)	Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35	WO 2012168250 ; * cited by examiner	(75)		OLTAIC SOLA Sivalingam Siv	unanthan, Naperville, IL	U.S 4,001.854 A	S. PATENT DOCUMENTS U1977 Gibbons	
(21)	U.S.C. 154(b) by 992 days. Appl. No.: 14491,057	Primary Economy – Ma Arctitum Economy – Ca			(US); Christop (US); James W	L Lau, Ann Arbor, MI sh Grein, Wheaton, IL & Garland, Aurora, IL	4,163,987 A 4,191,593 A 4,206,002 A	8/1979 Kannath et al. 3/1980 Cacheux 6/1980 Sabnis et al.	
(22)	Filed: Sep. 19, 2014	(74) disensey, Agent, or			(US)		4,278,474 A 4,332,974 A 4,338,480 A	7/1981 Blakeslee et al. 6/1982 Fraas 7/1982 Antypas et al.	
(65)	Prior Publication Data	(57) Al	(73)	Assignee:	EPIR Technol IL (US)	ogles, Inc., Bolingbrook,	4,730,000 75	(Continued)	
	US 2015/0101650 AI Apr. 16, 2015	A diagnostic device (40) sponding to respective la tovoltaic modulo (20). The testing and monitoring a c	(*)	Notice:	patent is exten	disclaimer, the term of this ded or adjusted under 35		GON PATENT DOCUMENTS 248953 A1 * 12/1987	
	Related U.S. Application Data	module. The layers of the respective materials with			U.S.C. 154(b) I	oy 009 days.	WO WO 20090	082816 Al * 7/2009	
(60)	Provisional application No. 61/879,871, filed on Sep. 19, 2013.	electrical resistance and a tive layers of the given p tional conditions. Histro-	(21) (22)		: 12/261,827 Oct. 30, 2008		Otfried, Madelung,	OTHER PUBLICATIONS "Semiconductors: Data Handbook," 2004, S	
(51)	Int. Cl. 1025 50/10 (2014.01)	C) of the diagnostic devic measure electrical resista	(65)		Prior Public	cation Data	tions 3.5-3.19.12, Sp	pringer-Verlag Berlin Heidelberg, New York. (Continued)	
	U.S. CI. CPC	current resistance paths in ing to respectively differe R2-4, R5, R5) of the give				Apr. 22, 2010	Primary Examiner (74) Attorney, Age Jefferson Perkins	r — Eli Mekhlin ent, or Firm — Perkins IP Law Group LL	
	CPC H02S 50/10; G01R 31/40; G01R 31/025 See application file for complete search history.	21 Chilms,	(63)		slated U.S. Appli ion-in-part of ap	plication No. 12/256,247,	(57)	ABSTRACT	
				filed on O Int. Cl.	et. 22, 2008, now	abandoned.	A Group II-VI pho and as many as fiv	otovoltaic solar cell comprising at least to e subcells stacked upon one another. Ea	
			(21)	H01L 31/ H01L 31/		06.01) 12.01)	the first subcell bei	itter layer and a base layer, with the base ing made of silicon, germanium, or silico	
D	Device for		(52)	(52) U.S. CL CPC Holf. 31/0687 (2013.01); Y02E 10/544 (2013.01)			germanium. The remaining subcells are stacked on top of the first subcell and are ordered such that the band gap gets progressively smaller with each successive subcell. More- over, the thicknesses of each subcell are optimized so that the		
			(58)	USPC		urch 72; H01L 31/0687; H01L	<sup>5</sup> current from each subcell is substantially equal to the other subcells in the stack. Examples of suitable Group II-VI semi- conductors include CdTe, CdSe, CdSeTe, CdZnTe, CdMgTe,		
١V	leasuring					01L 31/073; H01L 31/074 	and CdHgTe.	Claims, 6 Drawing Sheets	
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RACT lar cell comprising at least two icked upon one another. Each a base layer, with the base o ilicon, germanium, or silicon cells are stacked on top of the such that the band gap gets ich successive subcell. More beell are optimized so that the bstantially equal to the other of suitable Group II-VI semie, CdSeTe, CdZnTe, CdMgTe rawing Sheets High-efficiency

Multijunction II-VI Solar Cells

MBE Growth Technique for **Inverted Multijunction Solar Cells** 

(58) Field of Chavilles CPC ...... 130 11,006

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

Sivananthan Laboratories, Inc. Proprietary Information

Cells

Sivananthan

Laboratories

IV/Group II-VI Multijunction Solar

## Summary

- V<sub>oc</sub> 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

