Inorganic Thin Films: Future Perspectives

Global Climate Energy Project

Solar Energy Workshop: Thin-Film Photovoltaics

October 19, 2004

John P. Benner
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National Center for Photovoltaics

Future Perspectives from 1975

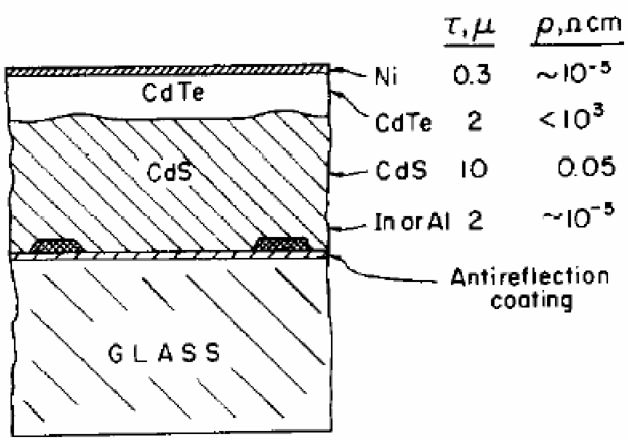
Structure and electrical properties of CdS and CdTe thick films for solar cell applications*

Kim Mitchell, Alan L. Fahrenbruch, and Richard H. Bube

Department of Materials Science and Engineering, Stanford University, Stanford, California 94305

(Received 6 January 1975; in final form 27 January 1975)

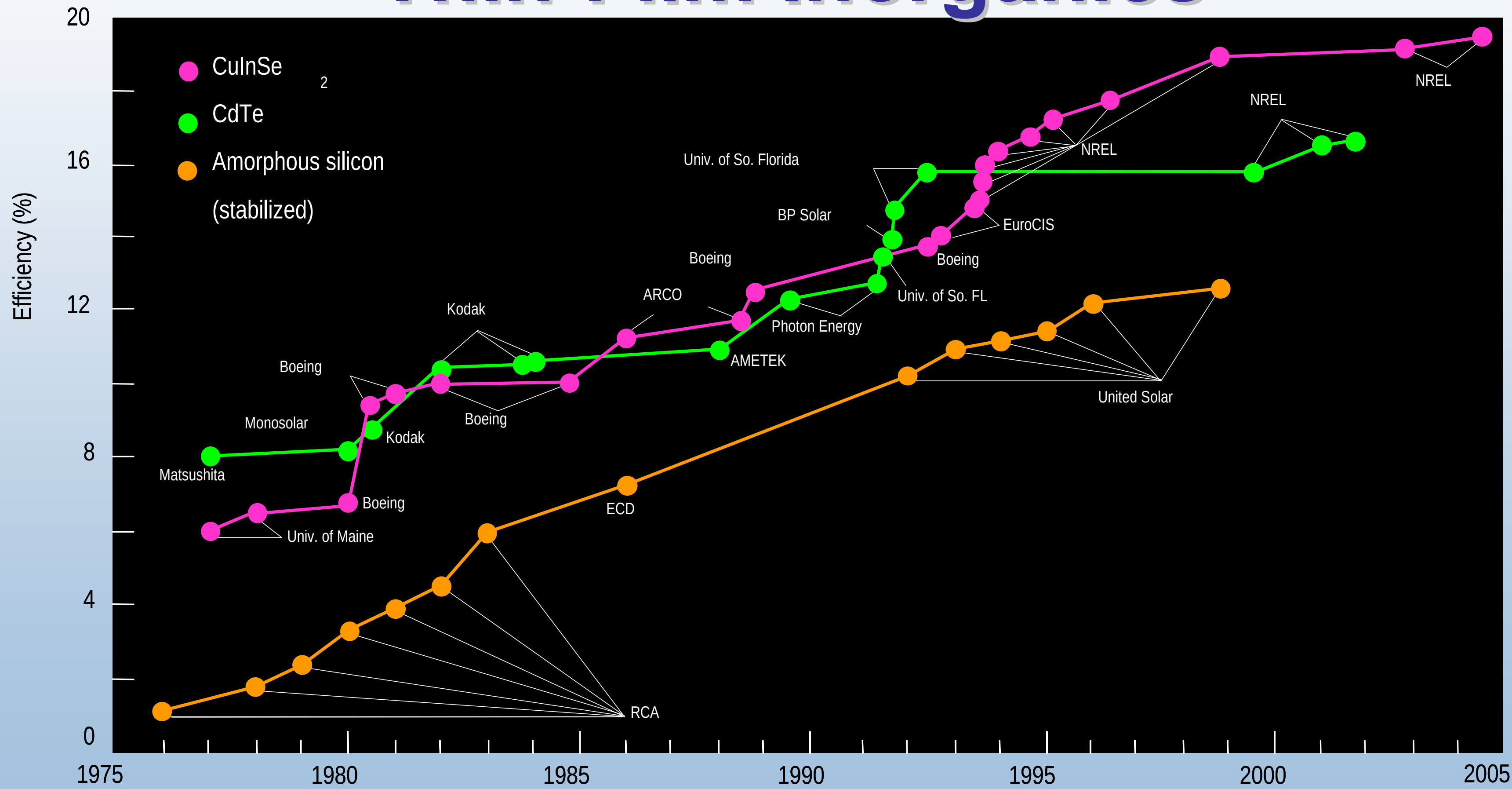
CdTe/CdS heterojunction solar cells show particular promise for large-scale terrestrial use. To evaluate these cells, thick films of CdTe and CdS have been



	p-CdTe/n-CdS	p-CdTe/n-$Zn_{0.35}Cd_{0.65}S$	2004 CdTe
J_0 (A/cm^2)	3×10^{-10}	2×10^{-10}	
J_{sc} (mA/cm^2)	19.8	25.3	25.9
V_{oc} (V)	0.90	0.93	0.845
$V_P{}^b$ (V)	0.77	0.79	
$J_p{}^c$ (mA/cm^2)	19.3	24.9	
Fill factor	0.83	0.84	0.755
Efficiency (%)	17.0	22.6	16.5

J. Vac. Sci. Technol., Vol. 12, No. 4, July/Aug. 1975

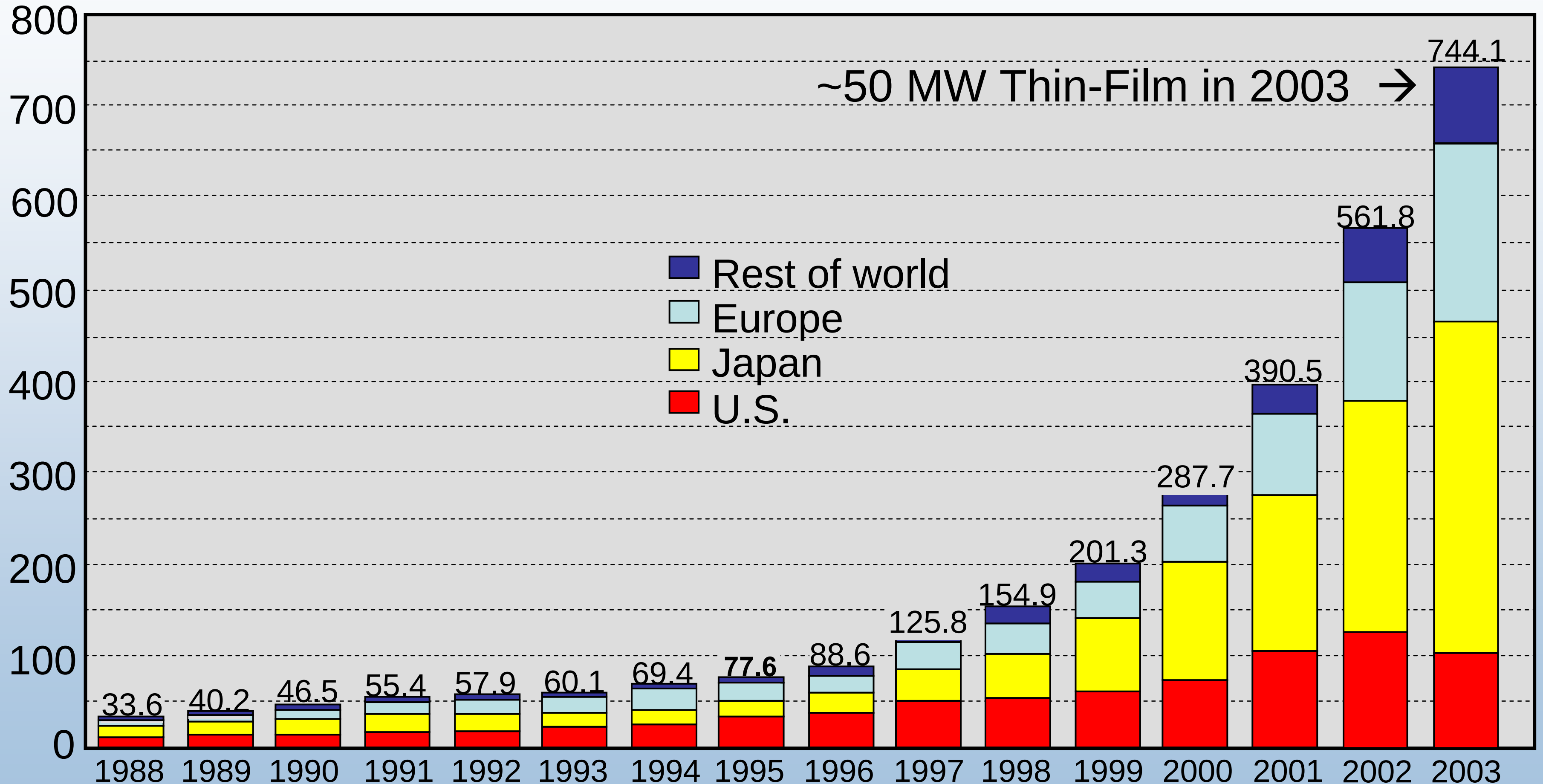
Best Research-Cell Efficiencies
Thin-Film Inorganics



National Renewable Energy Laboratory

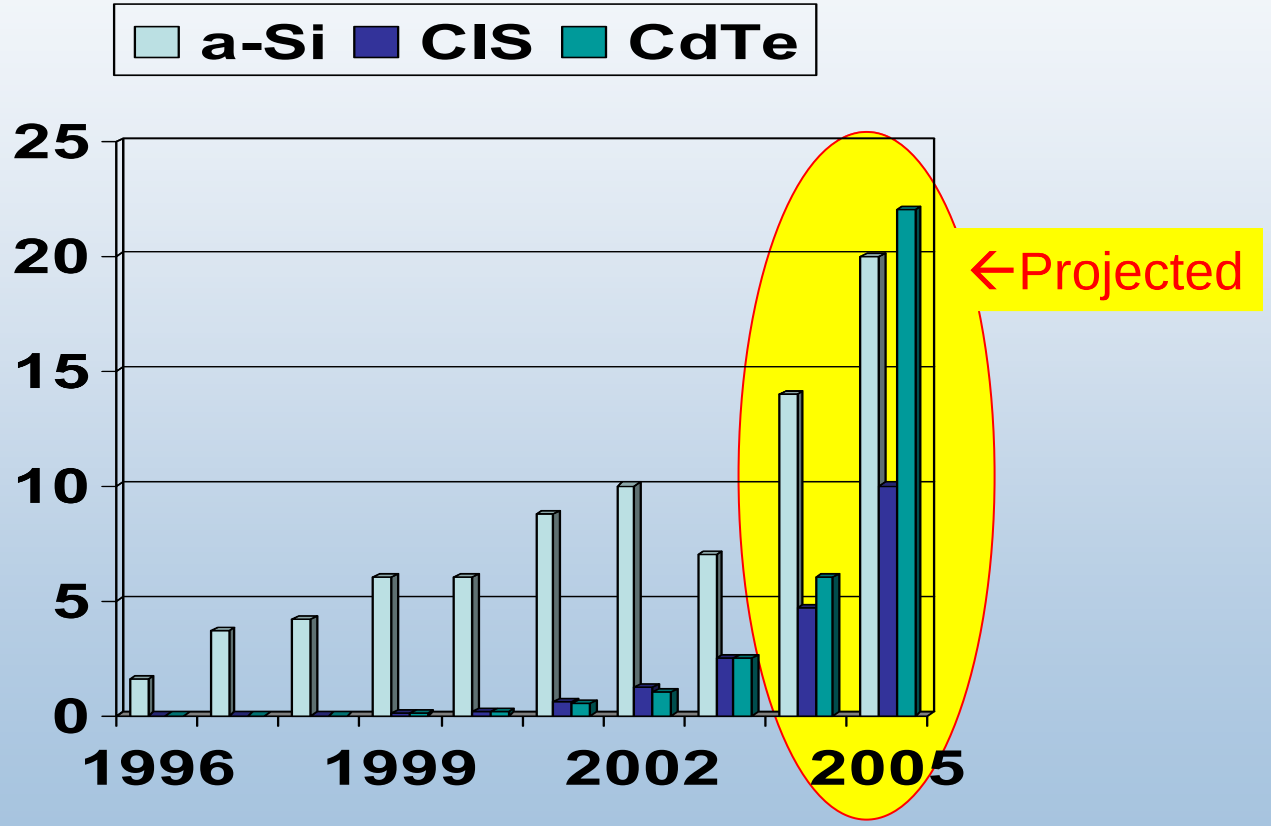
026587181

World PV Cell/Module Production (MW)

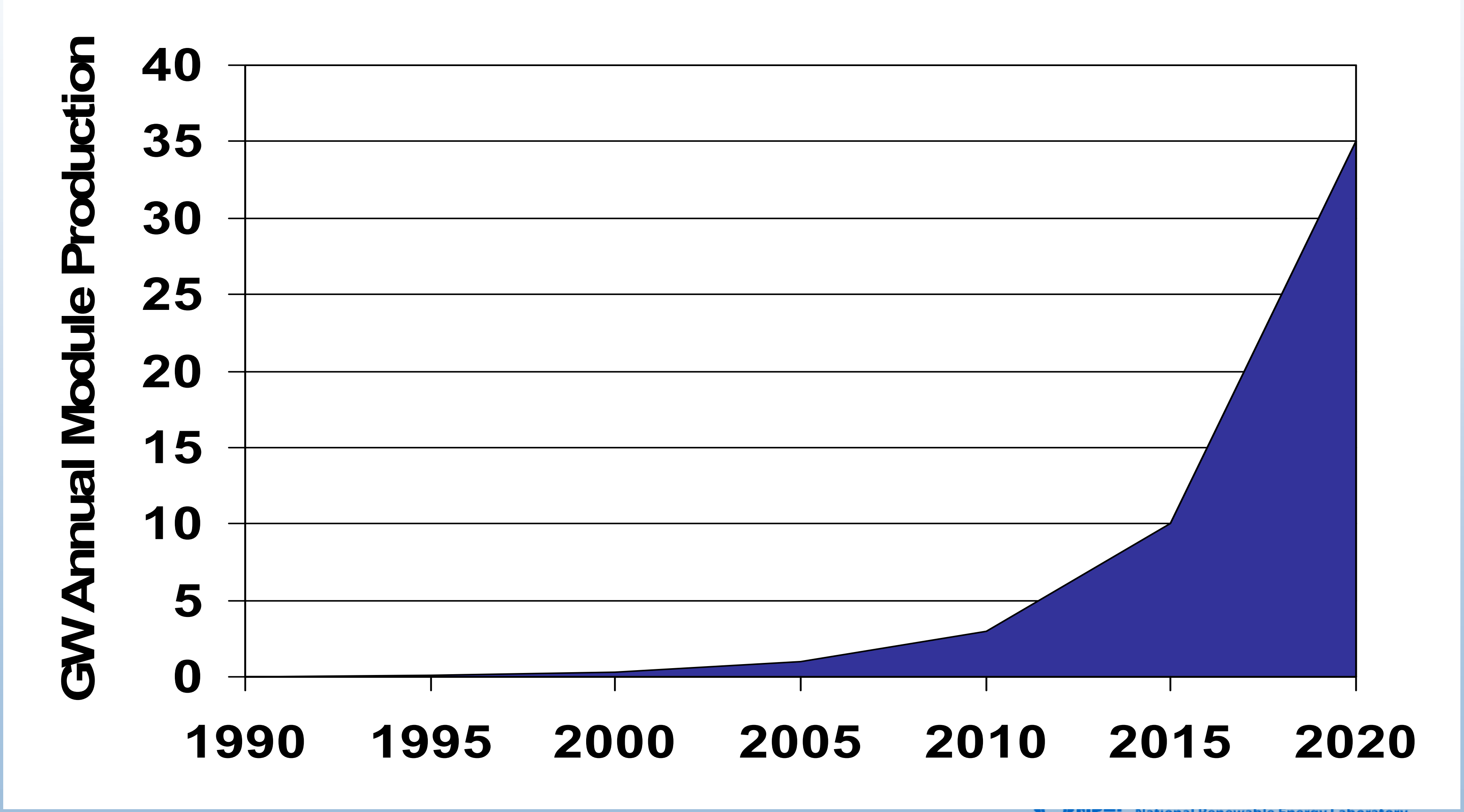


Source: *PV News*, March 2004

U.S. Thin-Film Manufacturing



Think Big -- Very Big
2-5 GW Factories



Ground Rules for GW Scale Factories

- Dedicated float glass line
  - 5x reduction in glass cost ~$4/m^2$ finished
- Redundant cluster production tools
  - 8x reduction in capital cost
  - ~100 20MW deposition clusters @ $2M each
- Recycled Effluents
  - 75% utilization
- Advanced Packaging Factory
- Aluminum Extruding and Fabrication

M. Keshner, et al, Hewlett Packard Final Rpt
NREL#ADJ-3-33631-01

Solar Factory Module

Cost Comparisons for Completed Solar Panels

Complete solar panel ready for simple attachment onto a roof

Cost Summary (all numbers are per sq. meter)	20 MW Plant	2 GW Plant	Net Gain
Coated Glass	\$ 23.62	\$ 4.62	5 x
Operating Expenses	\$ 4.00	\$ 1.50	2.5x
Materials and depreciation			
a - Si	\$ 2.33 + \$ 13.35	\$ 0.31 + \$ 2.67	5x
CdTe	\$ 3.46 + \$ 10.00	\$ 2.31 + \$ 2.00	7.5x
$CuInGaSe_2$	\$ 13.96 + \$ 13.35	\$ 9.31 + \$ 2.67	7.5x
Assembly, Packaging & Interconnect	\$ 41.71	\$ 10.50	4x
Overall process yield	60 %	93 %	1.55x

Total manufacturing cost per watt

		20 MW Plant	2 GW Plant
a - Si	(7%)	\$ 2.02	\$ 0.30
CdTe	(11%)	\$ 1.25	\$ 0.21
$CuInGaSe_2$	(12%)	\$ 1.34	\$ 0.26

Notes: If CdTe and CuInGaSe2 could use effective light trapping and be reduced in thickness to 0.4 um like a-Si, then their cost per Wp would be \$.19 and \$.19, respectively.
If a-Si could use a second junction of a-SiGe or uc Si, its efficiency would be circa 10% and its cost per Wp would be \$.21.

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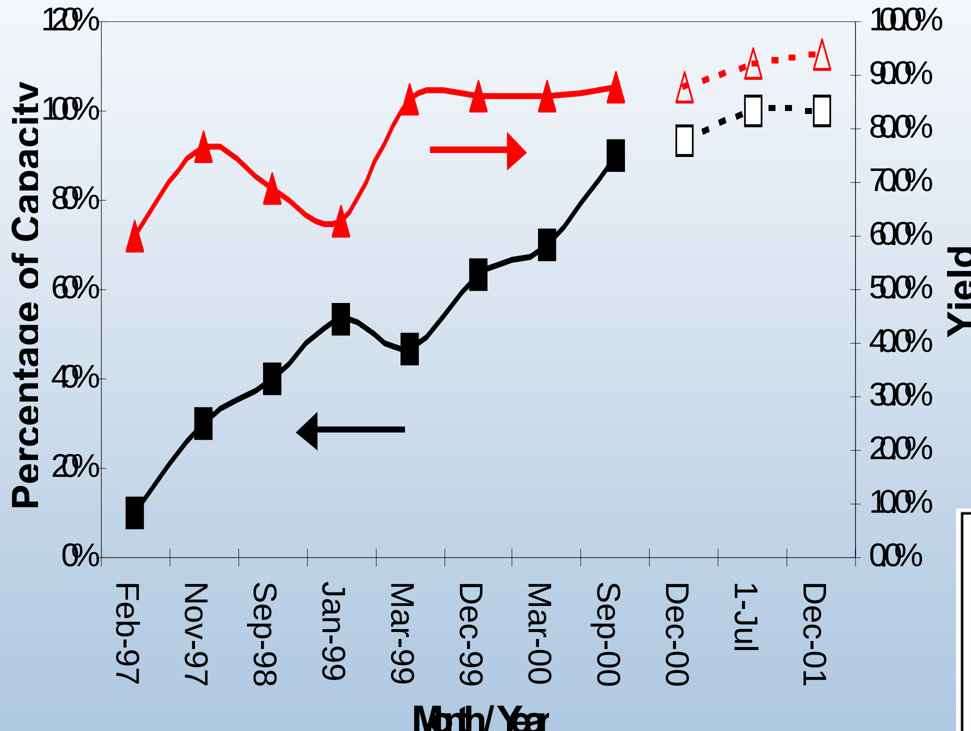
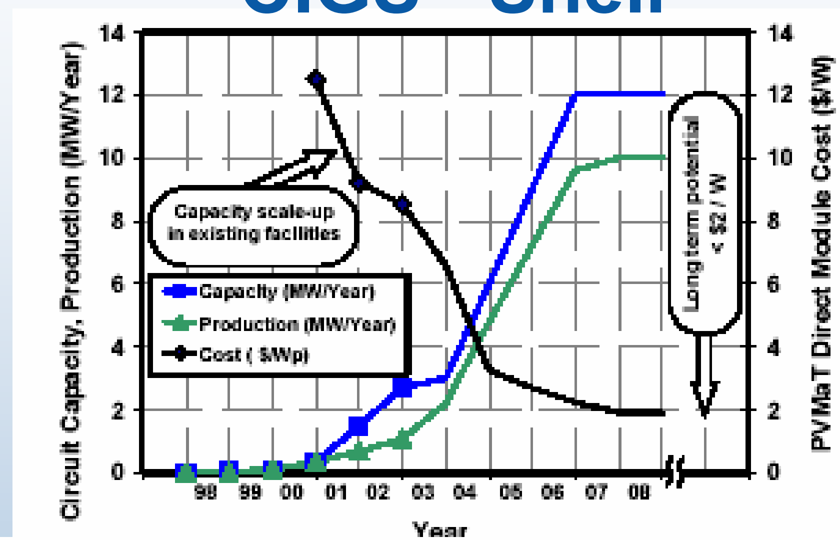
Time to Production: Processes must be better characterized

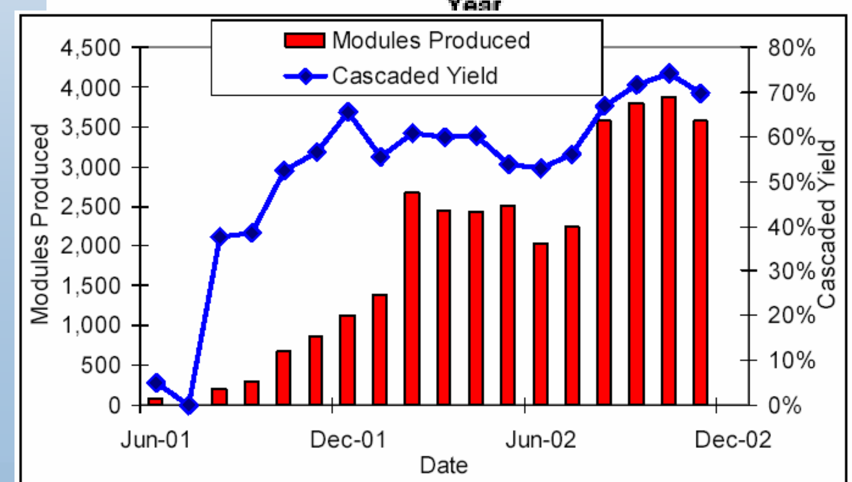
α-Si:H - BP



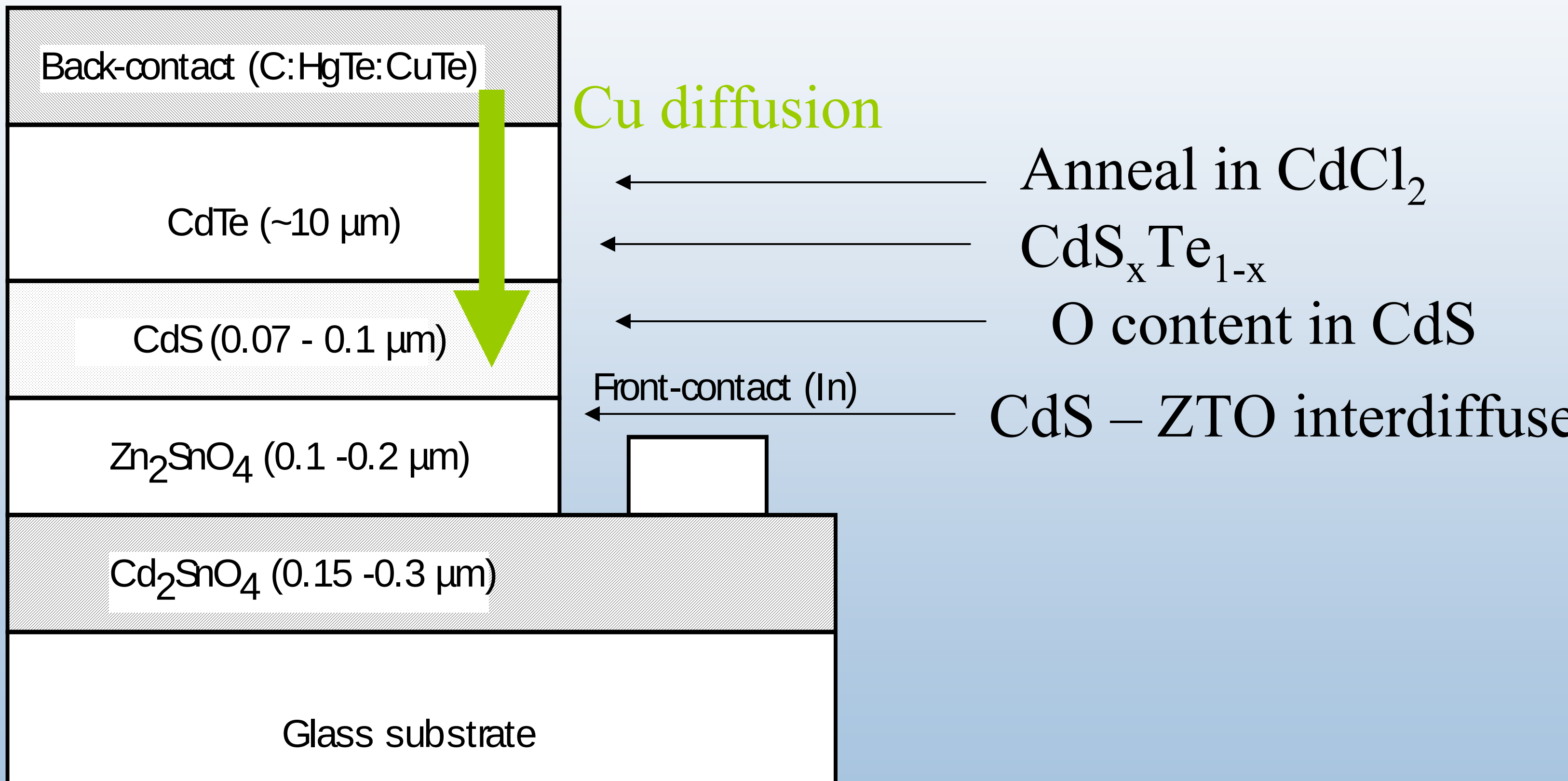
CIGS - Shell



CdTe – First Solar



16.5% Efficient CdTe Solar Cells



Thin Film Cells are.....Thin

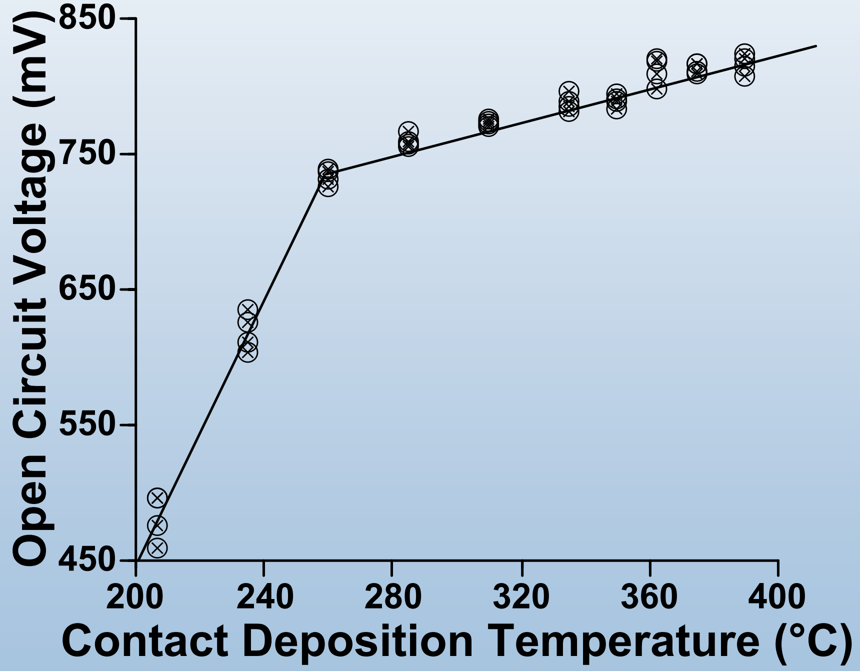
Advantages

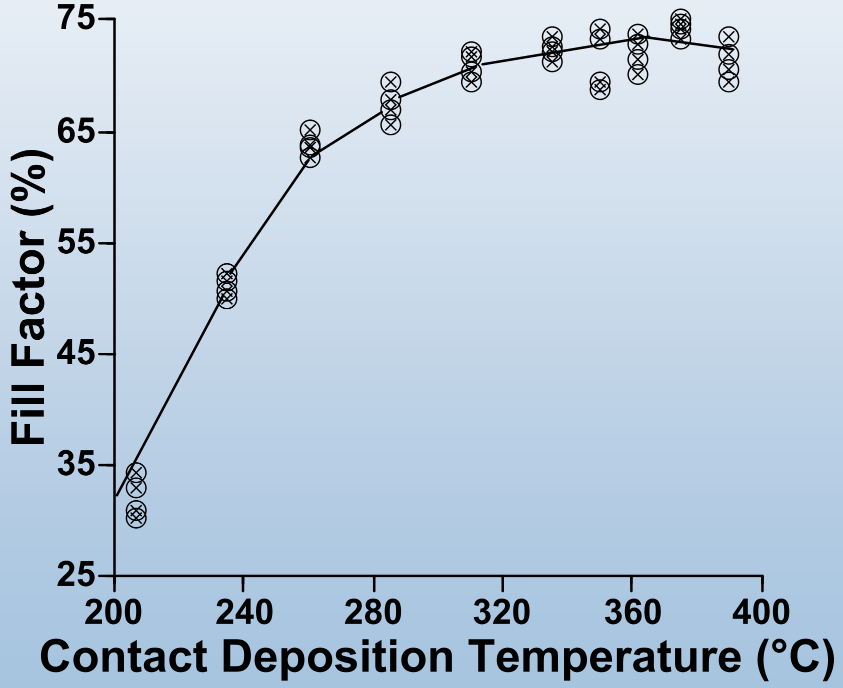
- Low material consumption
- High throughput potential
- Module patterning
- Improved carrier generation profile
- Drift collection
- Flexible
- Semi-transparent

Challenges

- Unique Materials
- Interdiffusion
- Grain size
- Low-lifetime
- Drift collection
- Characterization

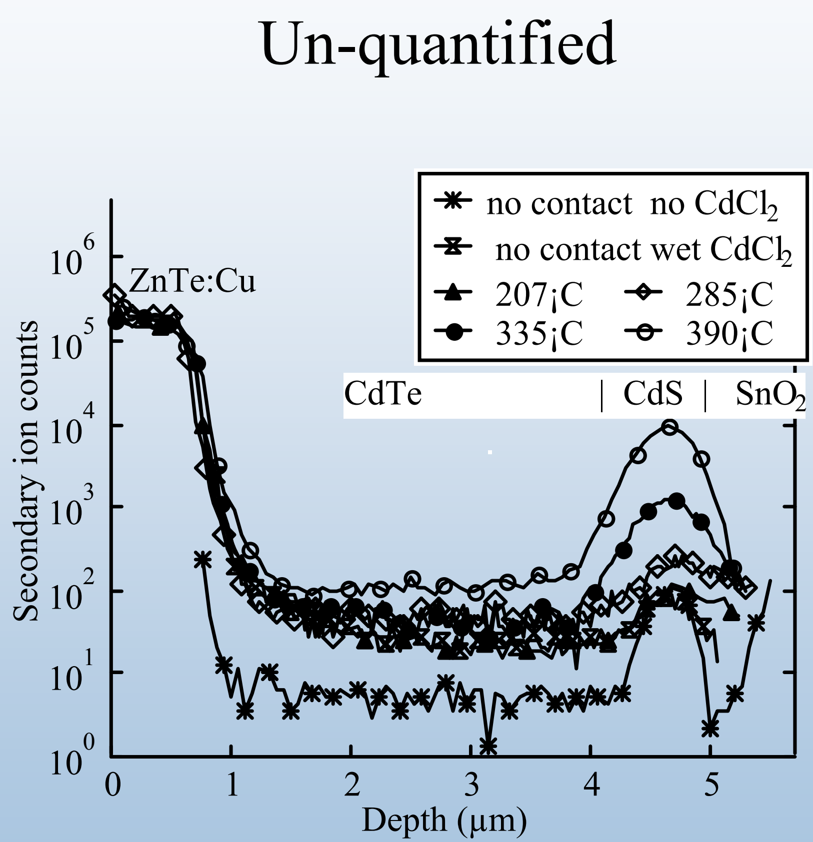
Effect of Back Contacts Deposition Temperature on Thin-Film CdTe Solar Cell Performance

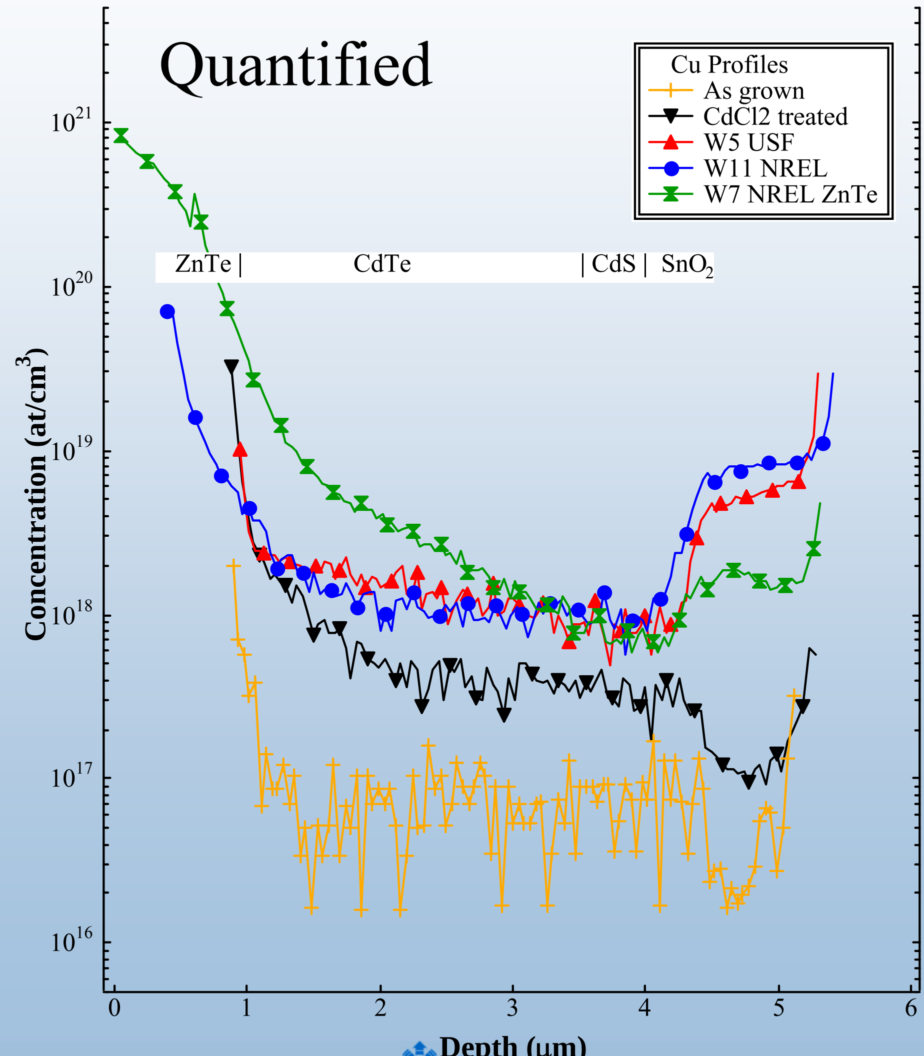




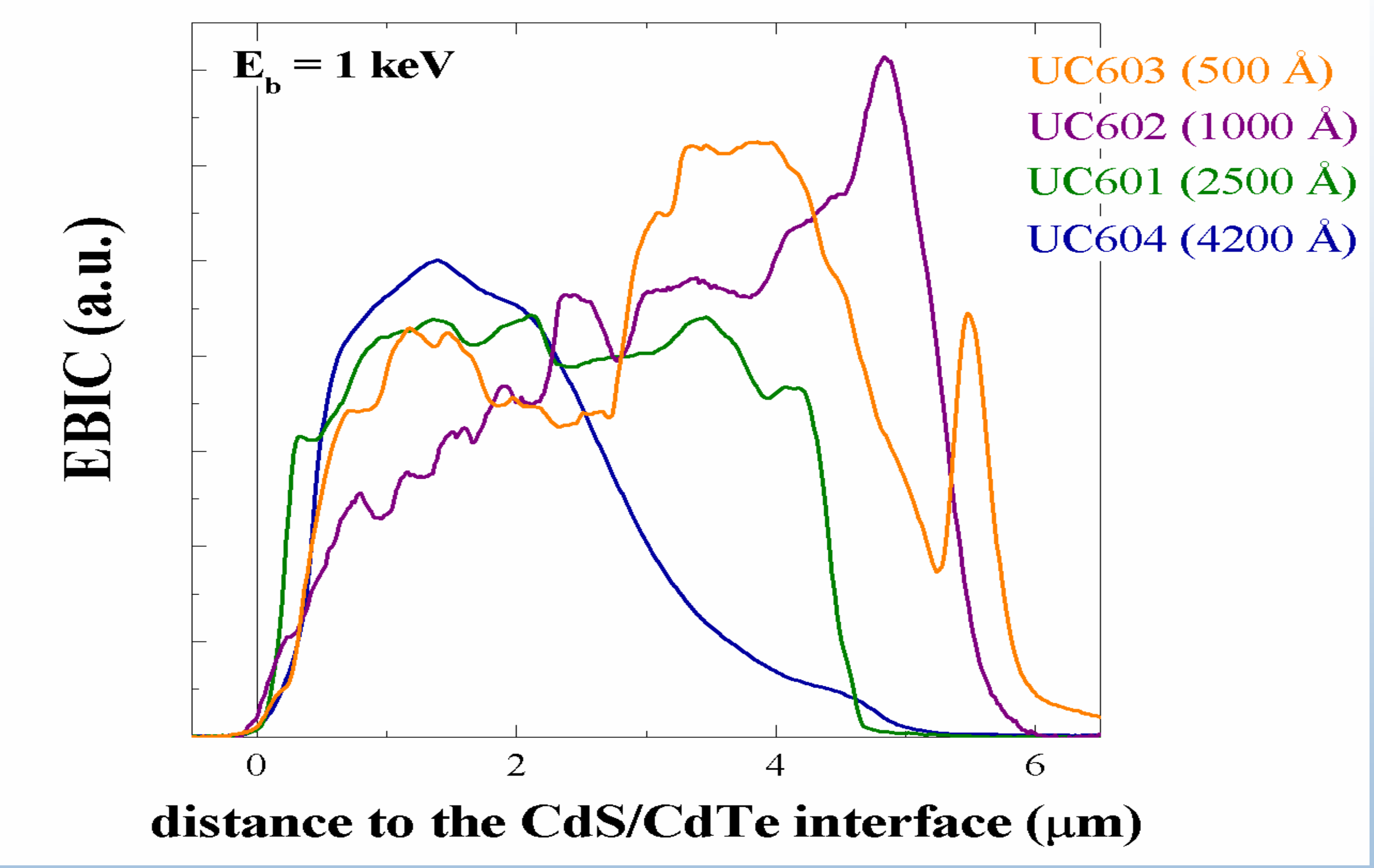
Cu Diffusion from $CdCl_2$ and Contact Processes

High-Resolution SIMS of Cu Concentration





Combined EBIC of ZnTe:Cu Contacted Devices

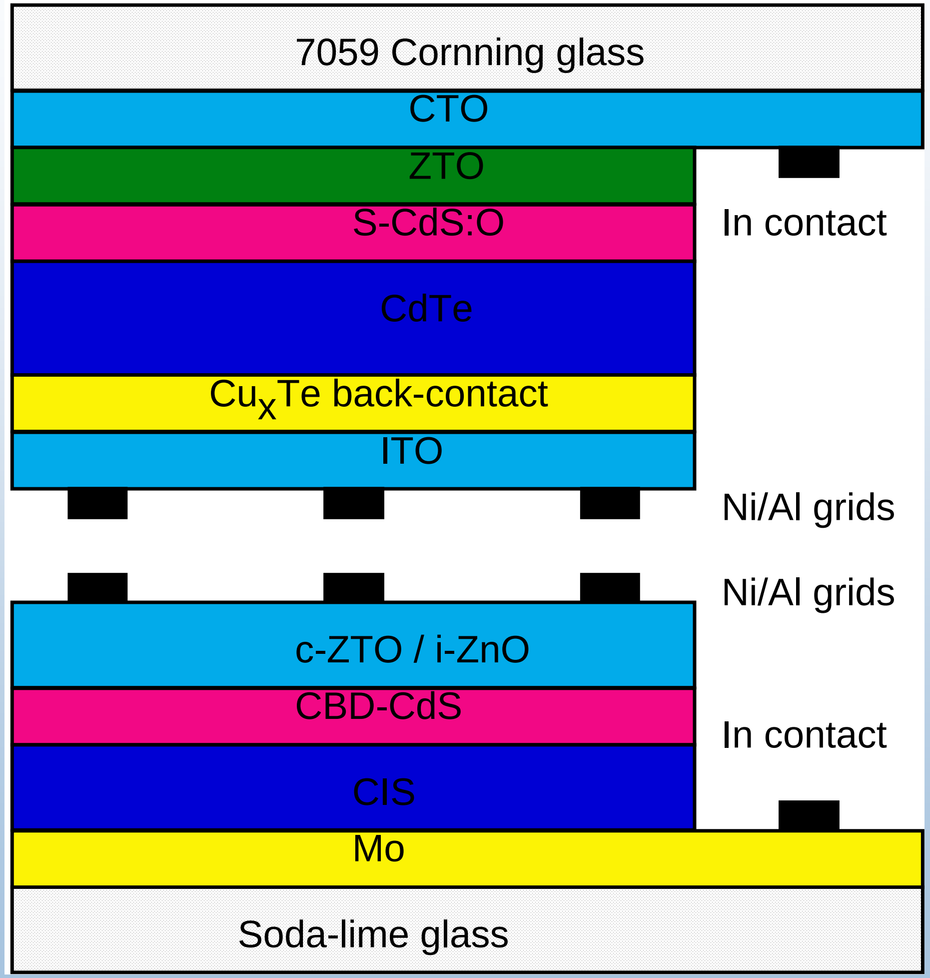


Think High

- High efficiency
  - Multi junction
  - Highly ordered, oriented films
  - Single crystal
- High rate deposition

Polycrystalline Thin Film Tandem Solar Cell

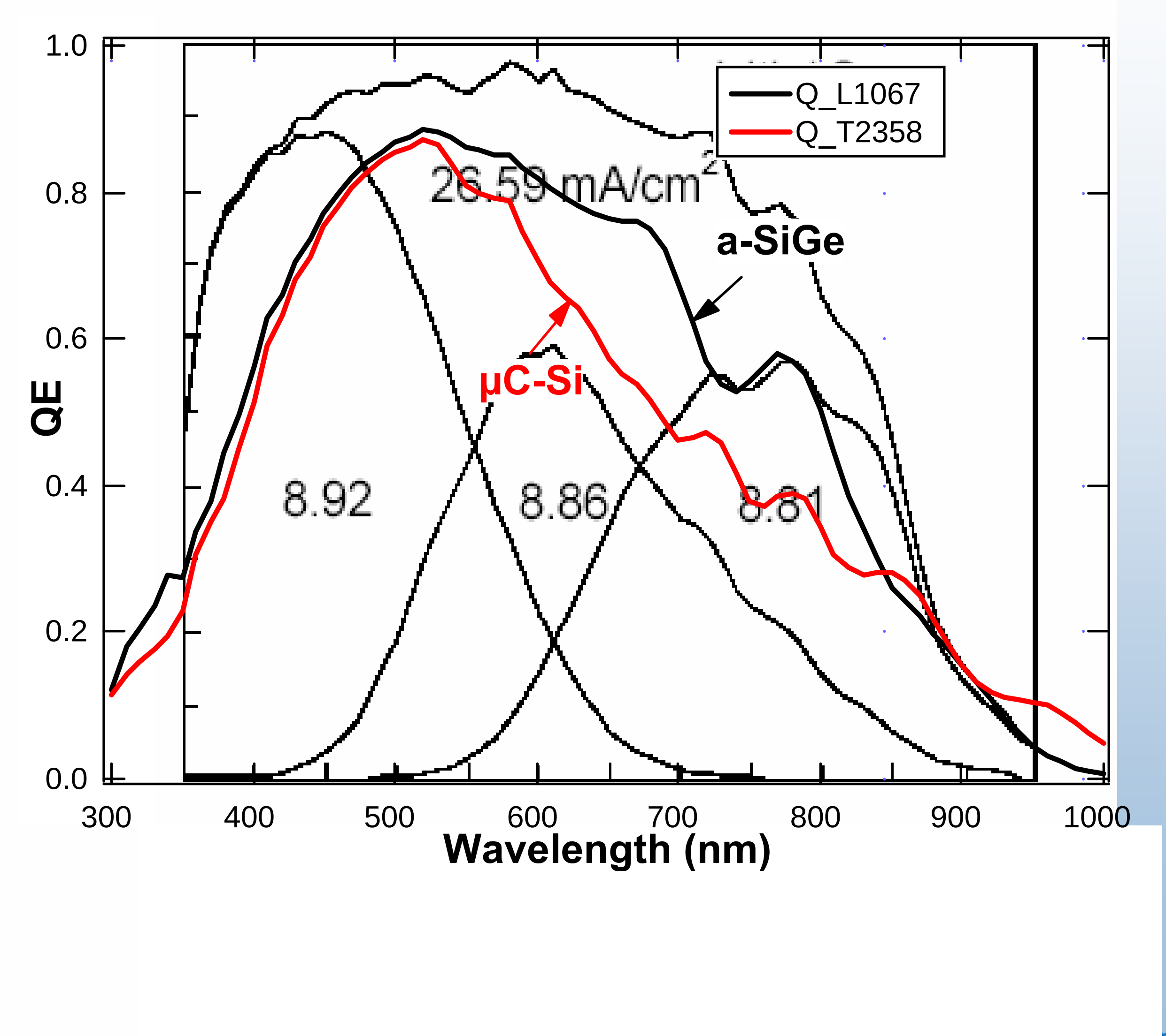
CdTe top cell
Achieved 50% transmission, 12.7% efficiency



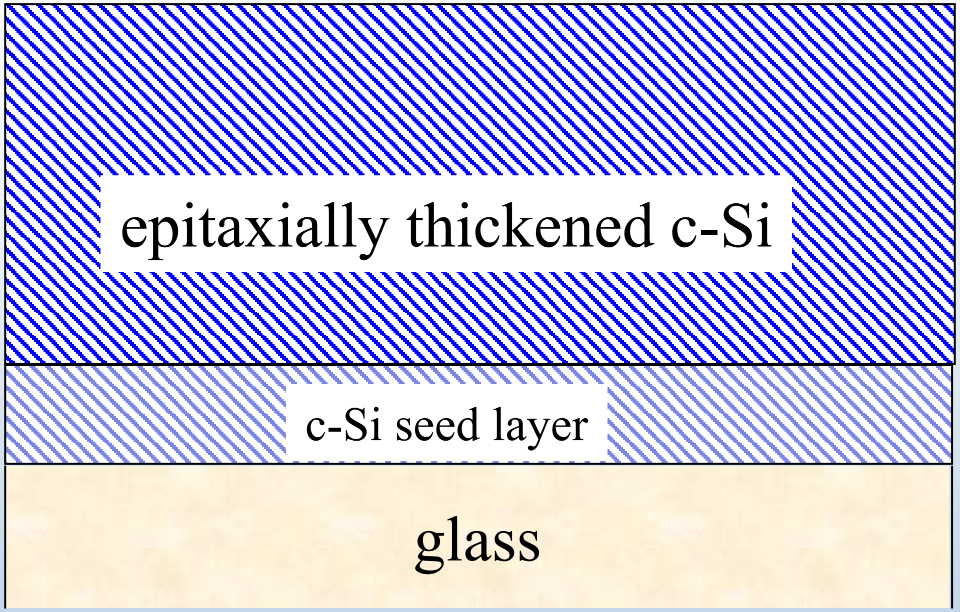
CIS bottom cell
Achieved 14.5% efficiency

FY06 milestone: 15% efficient 4-terminal device will be met one year early

Red QE equals USSC bottom cell



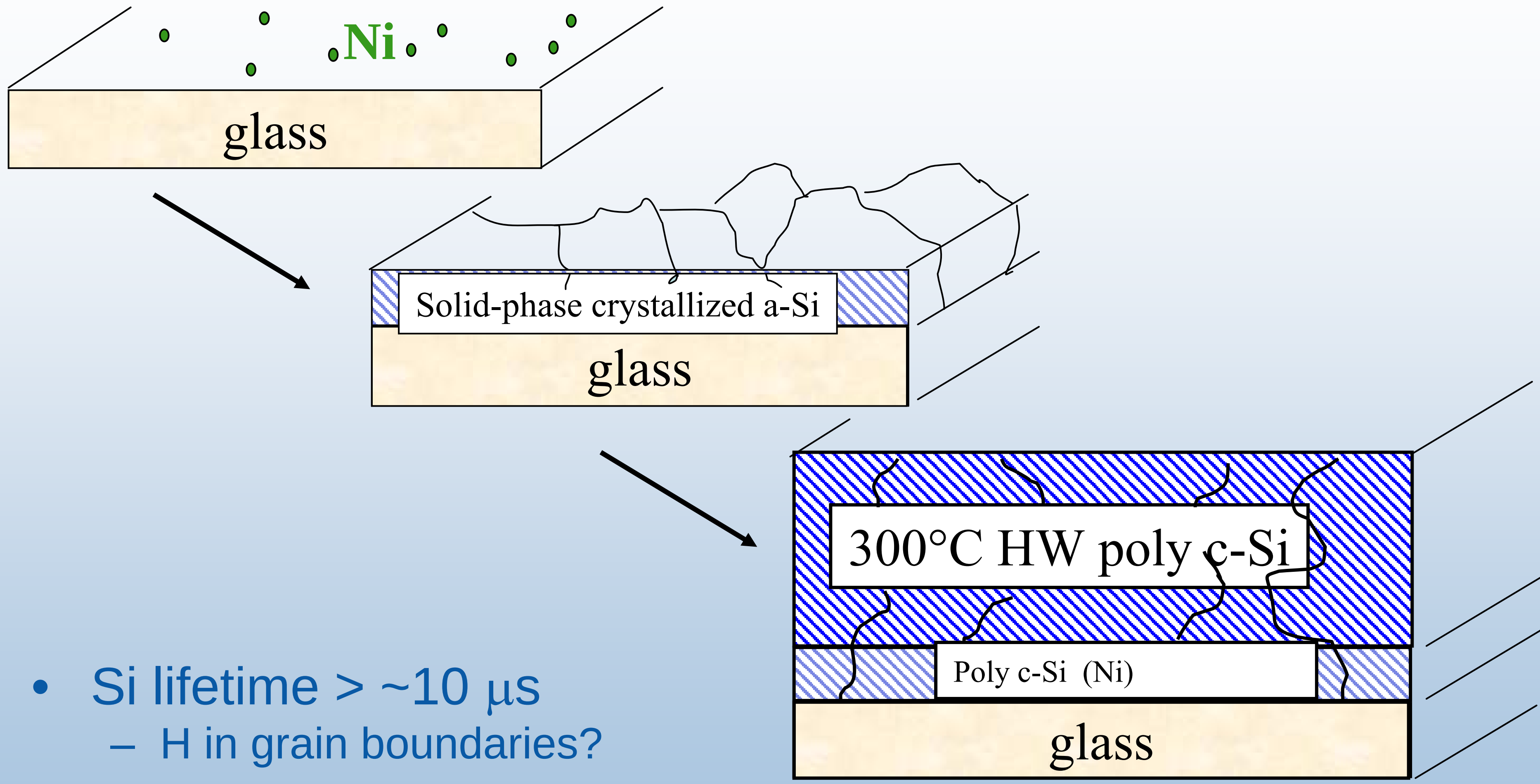
Film c-Si on glass concept



- Many approaches to both seed and epitaxy under study

See, review by Bergmann & Werner, Thin Sol Films 2002

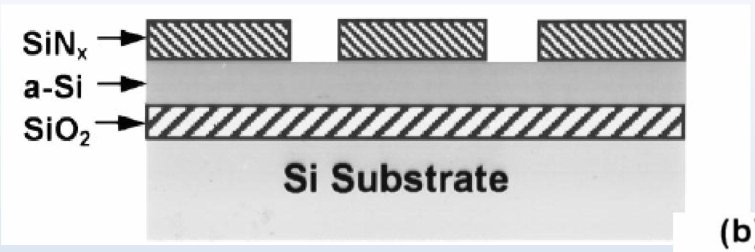
Ni-seeded c-Si template / HWCVD c-Si

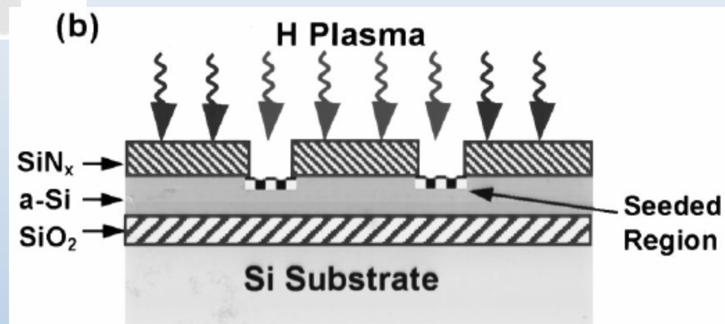


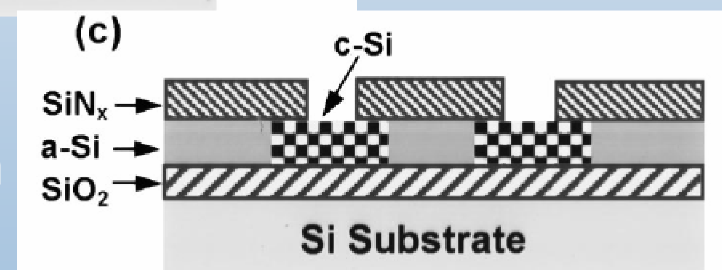
- Si lifetime > ~10 μs
  - H in grain boundaries?
- Poly-Si growth rate 1 Å/s --> slow at ~3 hr per μm
  - heavy H_2 dilution

Richardson et al, MRS Spring A, 2004

Single Grain Si Films Induced by Hydrogen Plasma Seeding





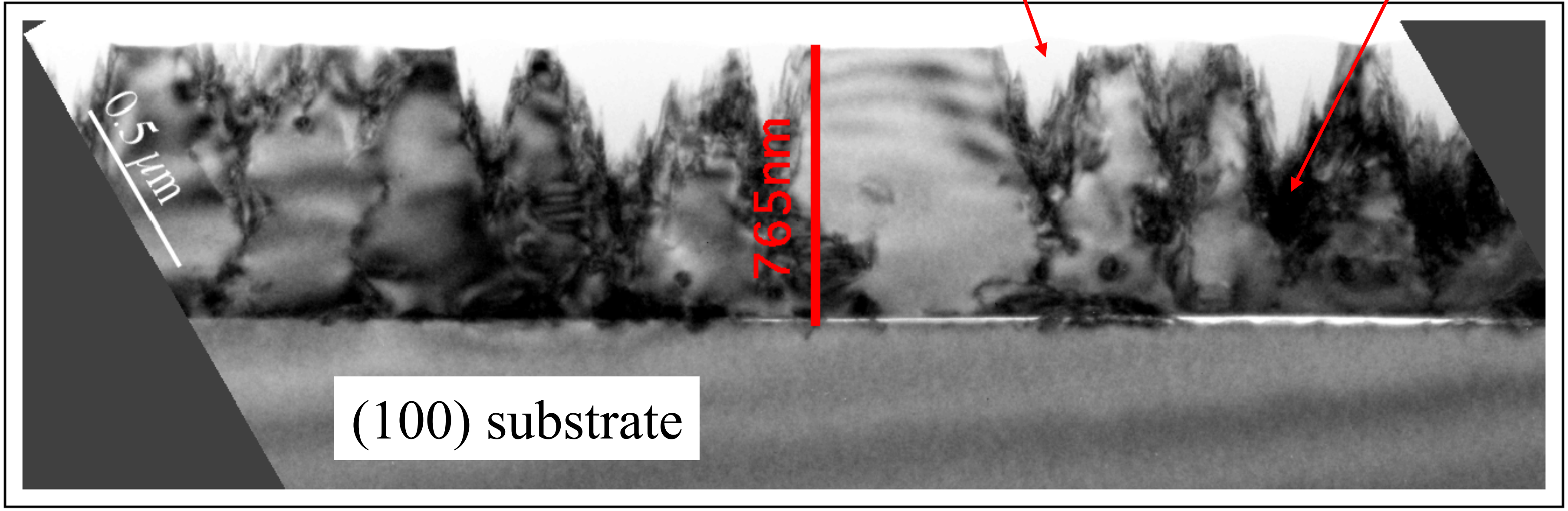


Single nucleus achieved for holes <0.6 μm

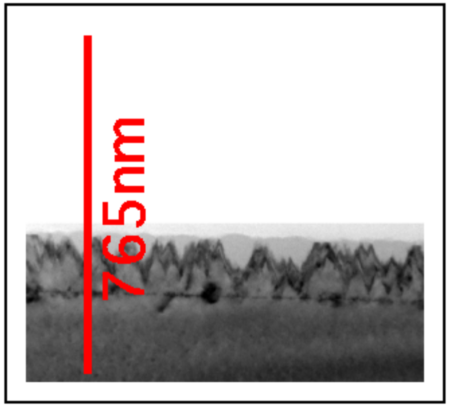
Bo et al, JVST B. May 2002

Ta wire improves epitaxy

- ~ 3Å/s at 270°C



- Ta filament: about 350 nm epitaxy



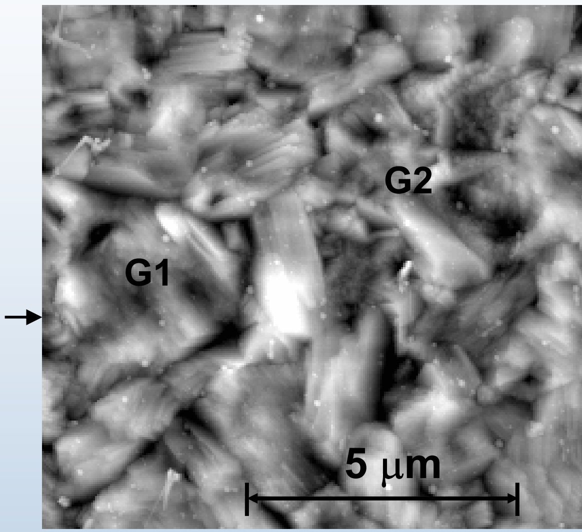
- W filament: 50 to 100 nm epitaxy

Think Small

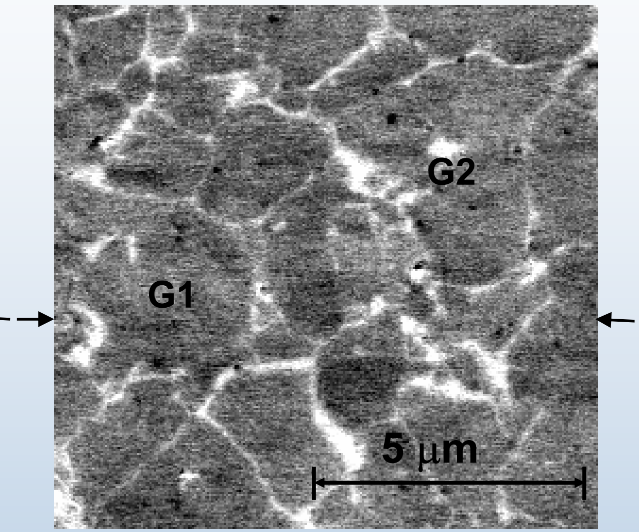
- Defects and nanostructure
- Thinner Devices

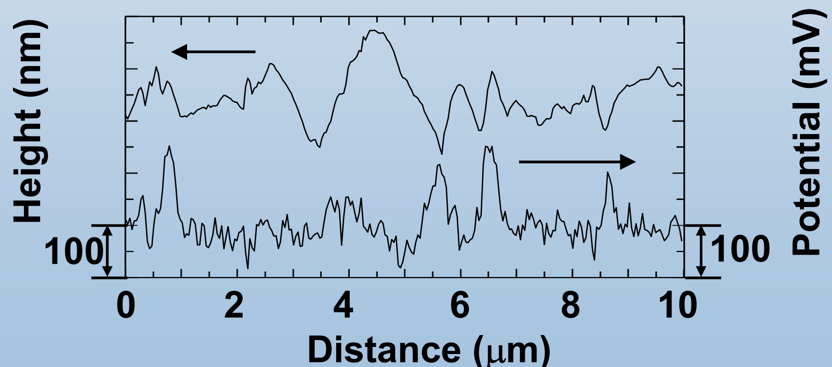
CIGS, Ga/(In+Ga)=28.5%

AFM



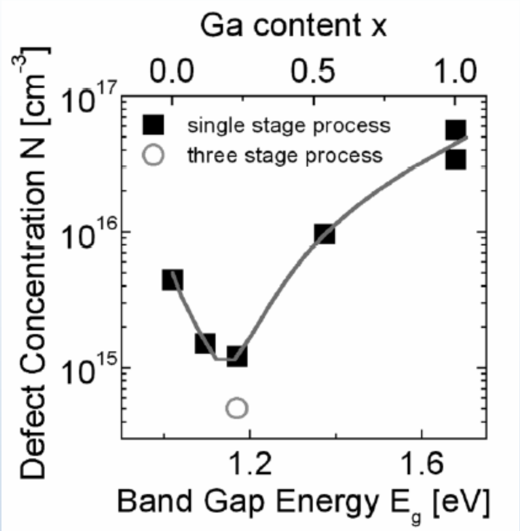
SKPM

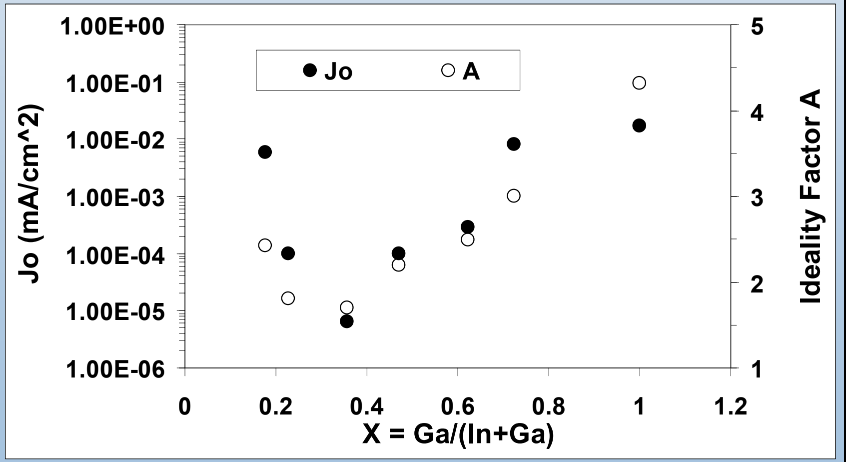


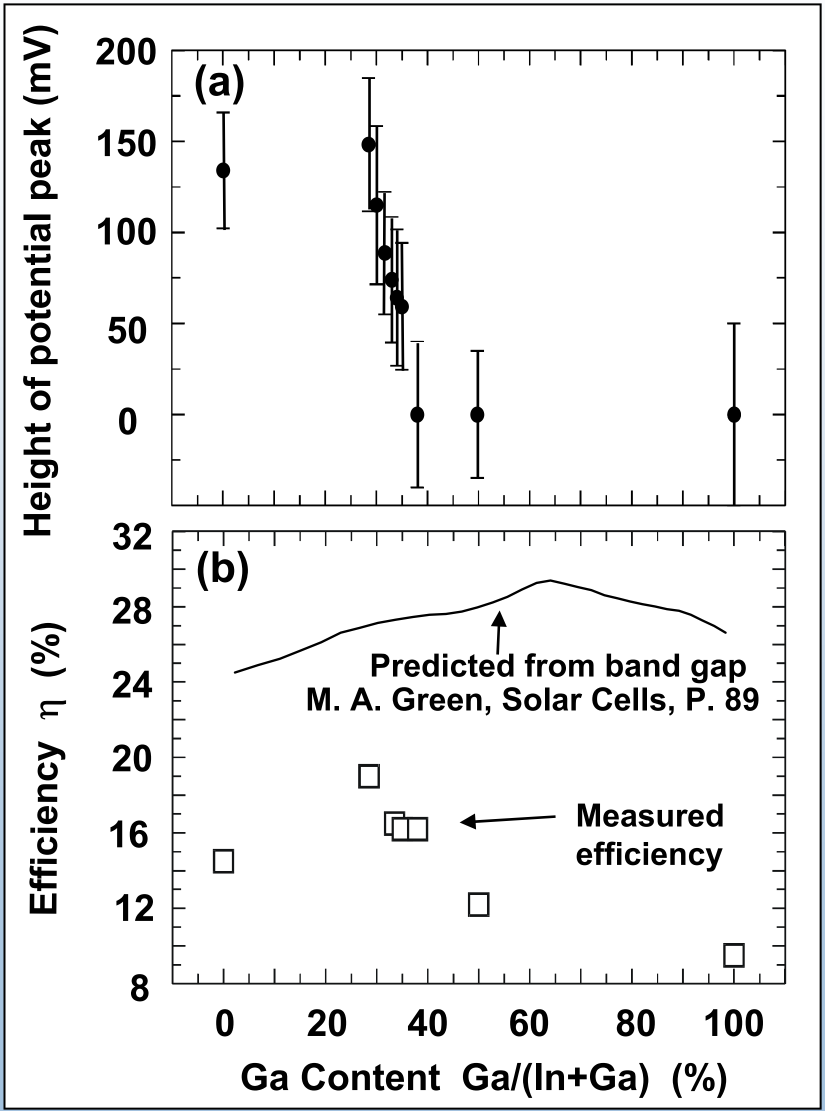


- Potential height: ~150 mV
- Depletion width: 150~400 nm.

$Cu_{0.9}(In_{1-x}Ga_{0.30})_{1.1}Se_2$

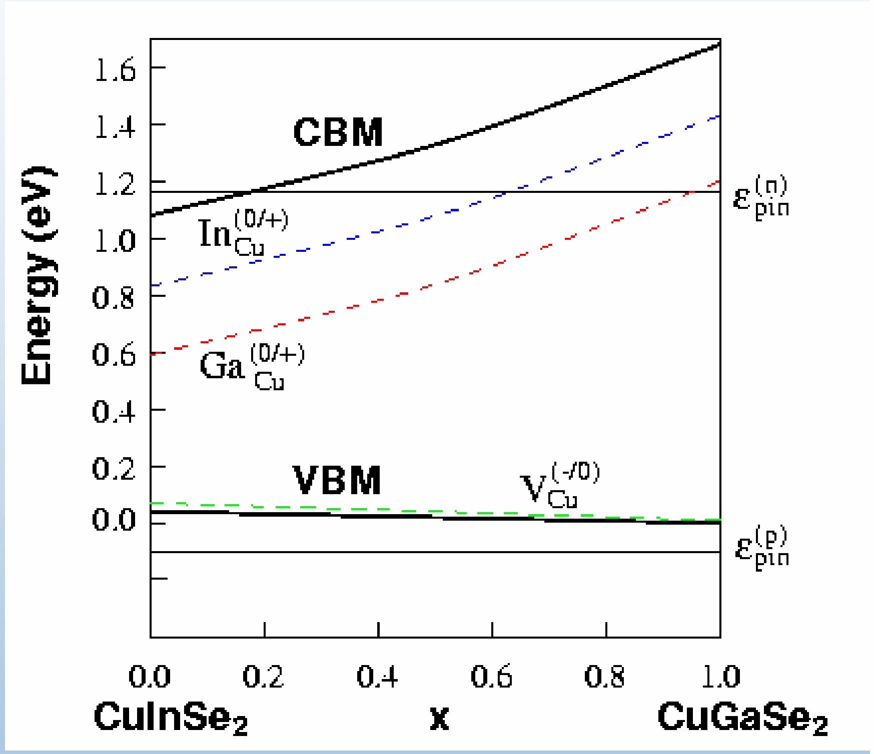


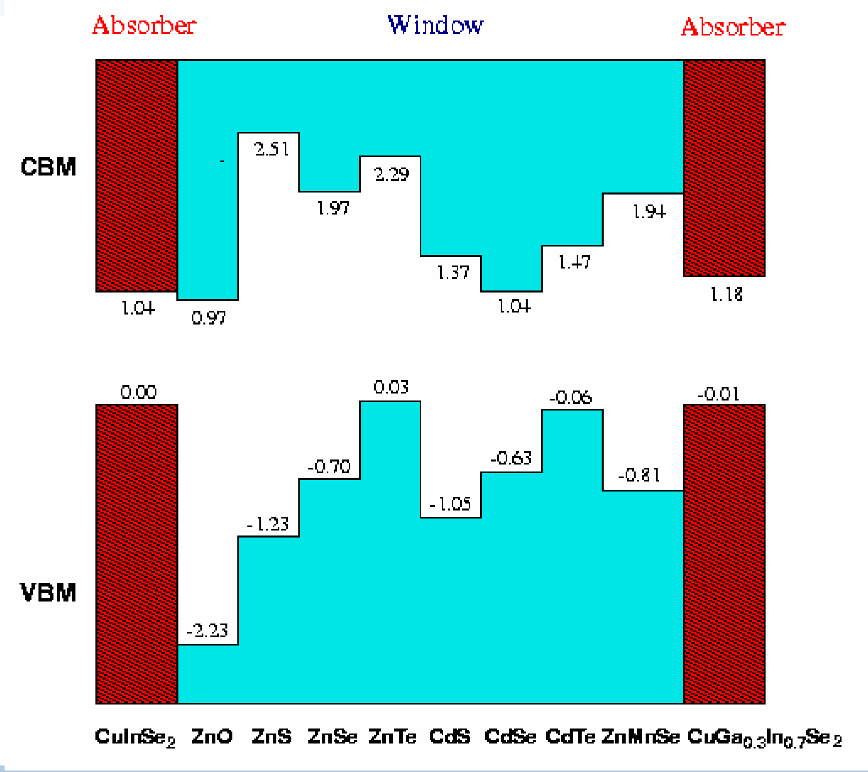




National Renewable Energy Laboratory

Difficulty for Ga>30%

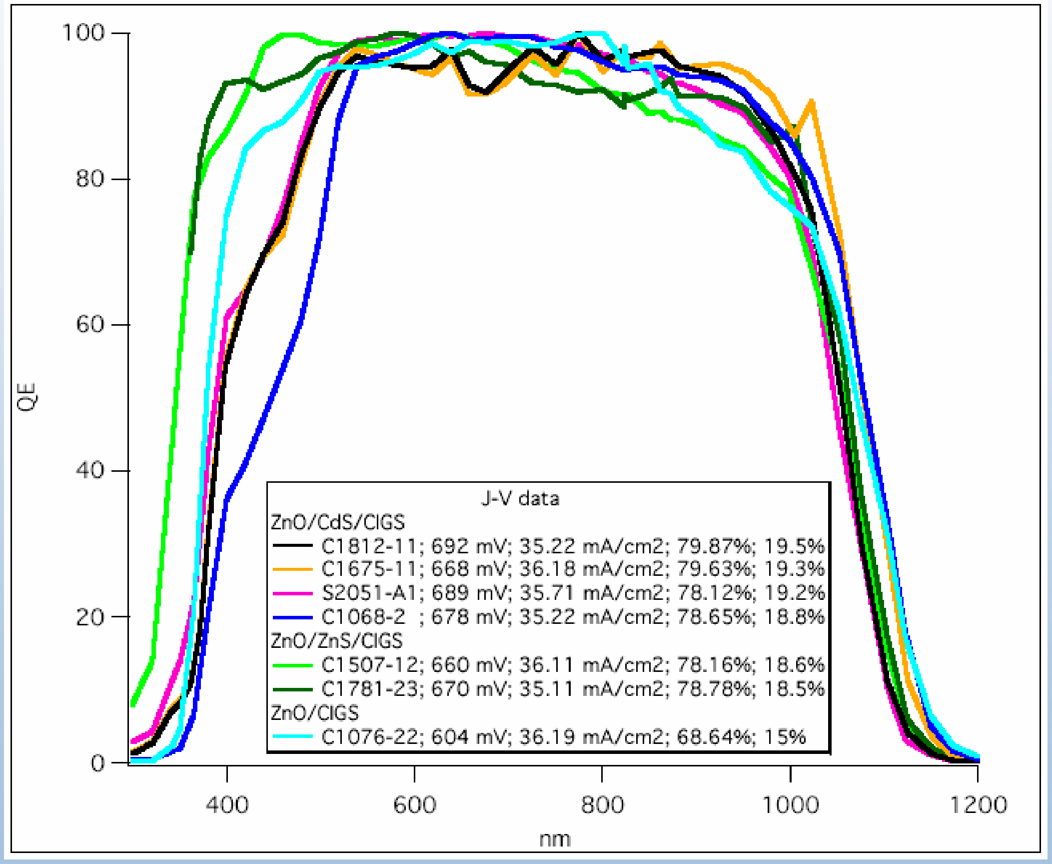




- Difficult to dope n-type
- Difficult to form n-type Cu-poor layers

S.-H. Wei et al APL 1998

Quantum Efficiency of CIGS Solar Cells



How is a Crystal 10% Cu Poor?

Cu_2Se

$CuInSe_2$

$CuIn_3Se_5$

$Cu_2In_4Se_7$

$CuIn_5Se_8$

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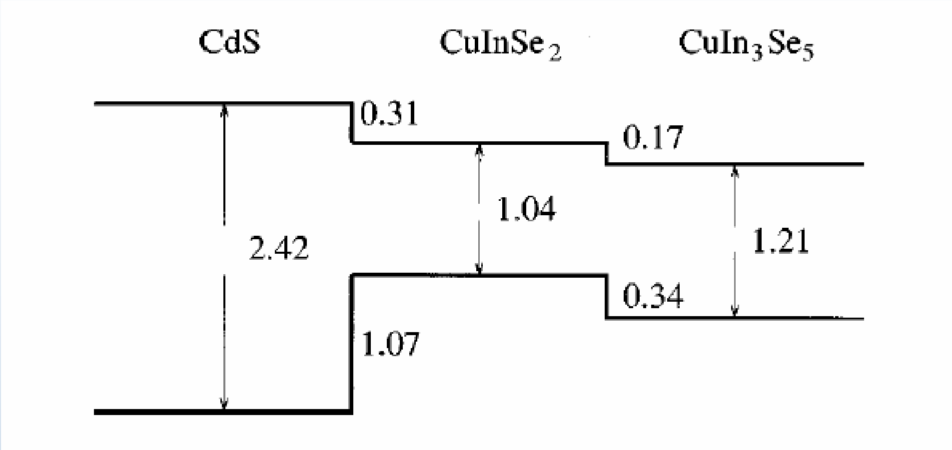
Neutral Defect Complex

$(2V_{Cu}^{-} + In_{Cu}^{2+})$



Zhang et al Phys Rev B 1998

Phase Segregation

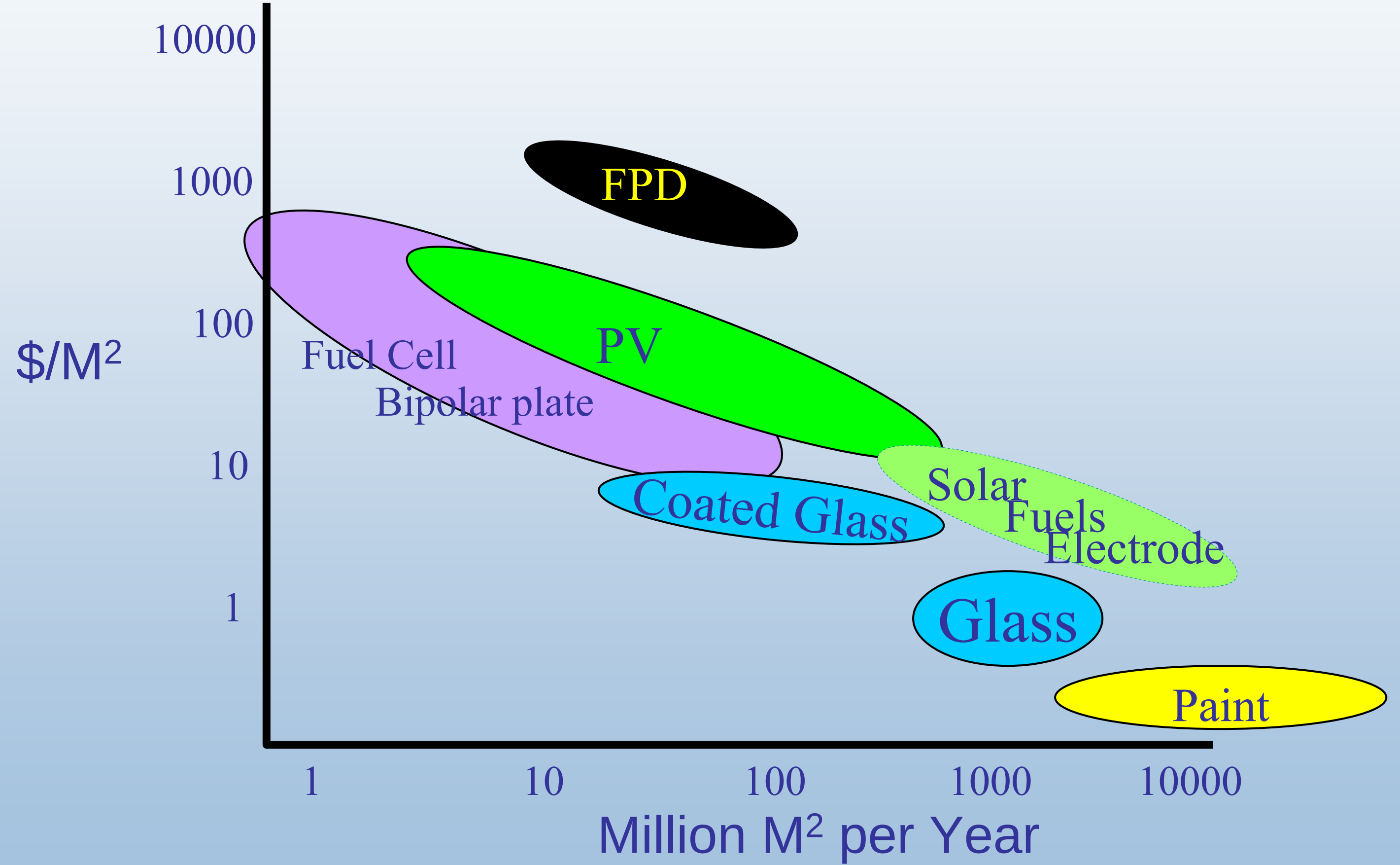
Material immediately surrounding dislocations and grain boundaries in device-quality CI(G)S will have higher bandgap

The α/β hole mirror disappears at [Ga]/[Ga+In] ≅ 35%

Stanbery TBP

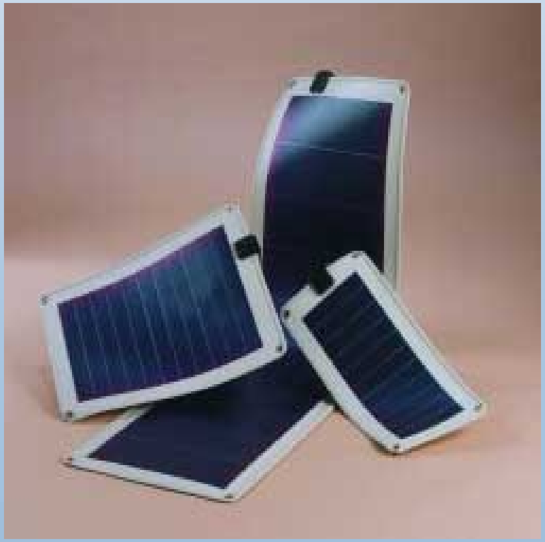
Low Cost Processes

Large-Area Optical and Electronic Materials



Advances in PV System Design Achieve Cost Advantages

Uni-Solar Amorphous Silicon Field Applied Roofing Products in units to 128W (18’x16”, 17 lbs, 33V & 3.88 A)



United Solar Shingles

Summary

- Inorganic Thin-Film PV is on the threshold of increasing market presence.
- Potential for further improvement
    - 10x reduction in $/m2
    - 2-3x increase in module efficiency
- Current fundamental understanding in all material systems contains large gaps
- Large entry investments will demand improved understanding and predictive capability.
- Shared production infrastructure simplifies start-up and growth

Presented with Great Appreciation for the original work, contributions, discussions and figures from my colleagues:

- Mowafak Al-Jassim
- Sally Asher
- Howard Branz
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- Tim Coutts
- Tim Gessert
- Falah Hasoon
- Chun-Sheng Jiang
- Rommel Noufi
- K. Ramanathan
- Manuel Romero
- Su-Huai Wei
- Xuanzhi Wu
- Yanfa Yan
- Alex Zunger
- Ken Zweibel
- Marvin Keshner (HP)
- B. Stanbery (HelioVolt)