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United Nations
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"Current Progress in Future Opportunities for Thin Film Solar Cells"

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National Renewable Energy Laboratory
Innovation for Our Energy Future
A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Current Progress in Future Opportunities for Thin Film Solar Cells

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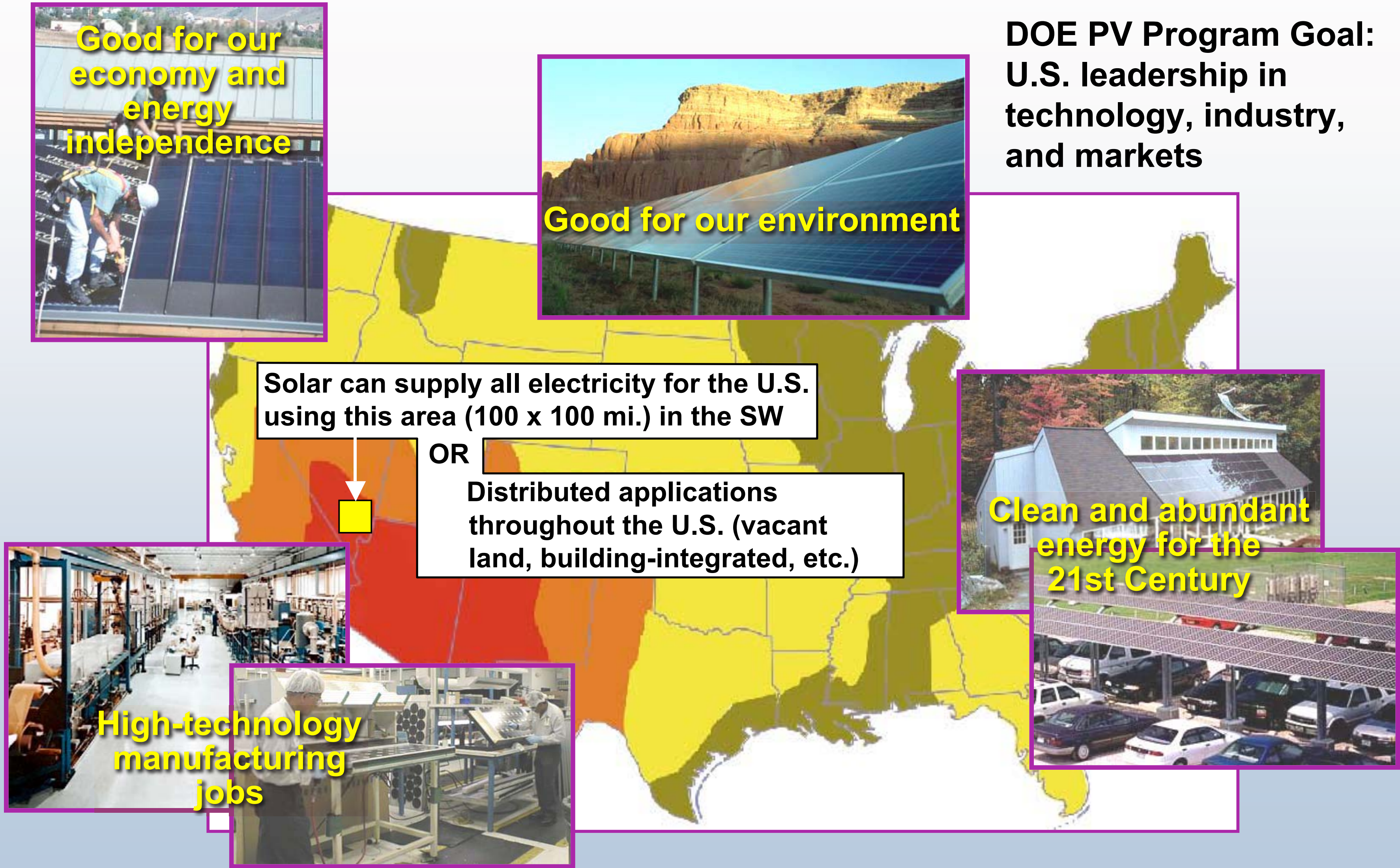
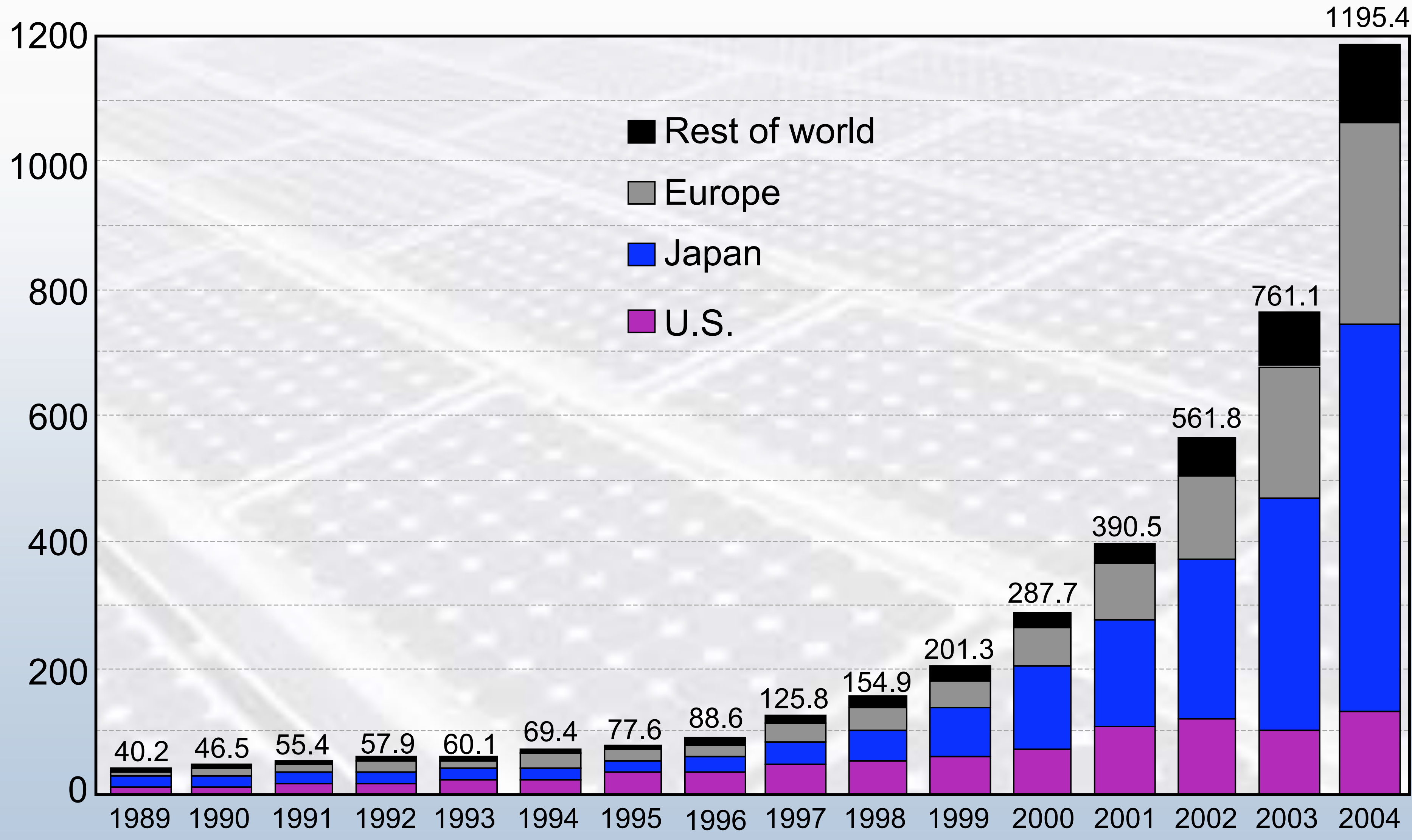
Presented at the Workshop on Physics for Energy Sources
International Center for Theoretical Physics (ICTP)
Trieste, Italy
October 17–29, 2005

Photovoltaics is Solar Electricity

DOE PV Program Goal:
U.S. leadership in technology, industry, and markets



World PV Cell/Module Production (MW)



Source: Paul Maycock, *PV News*, March 2005

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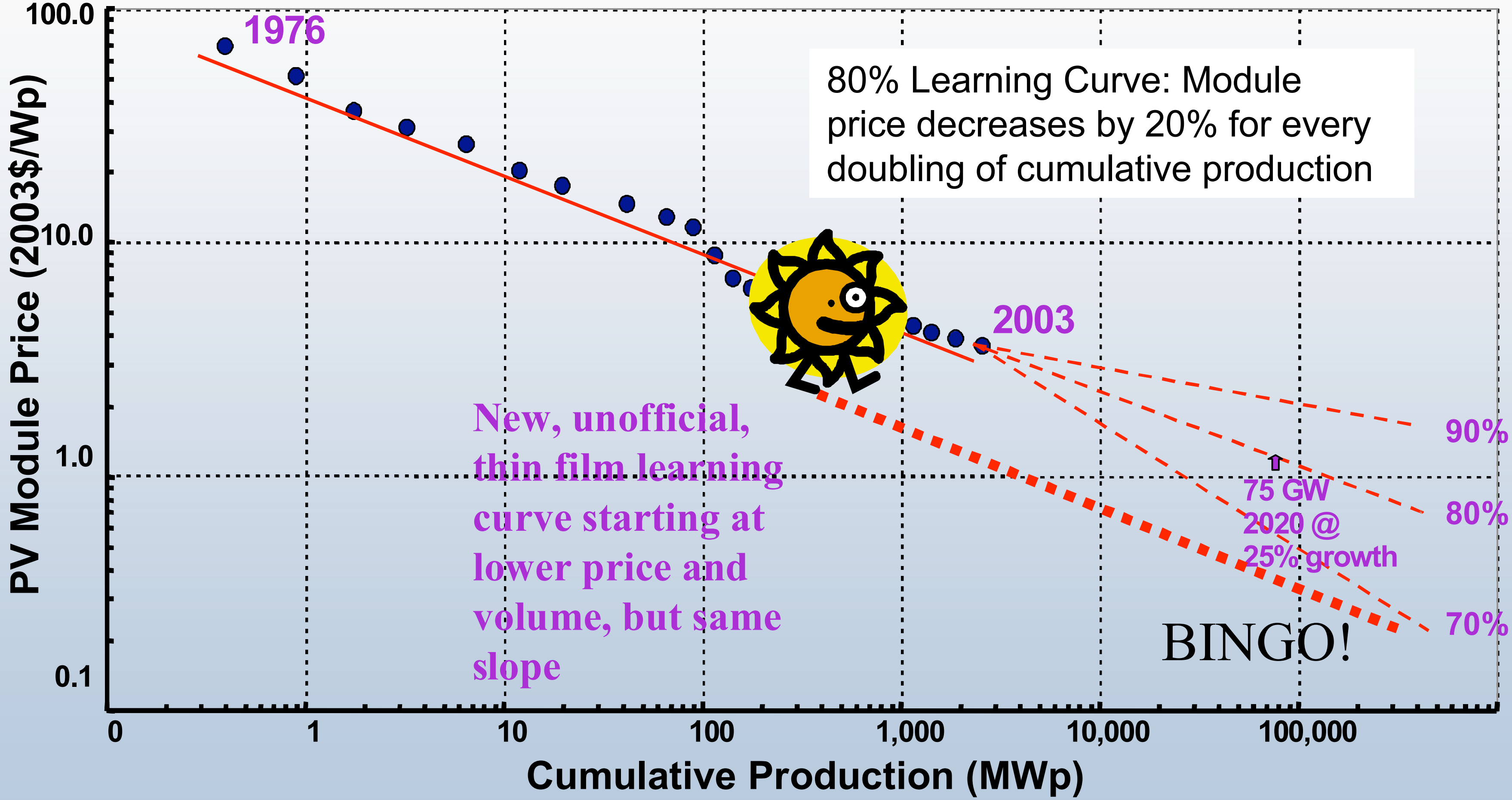
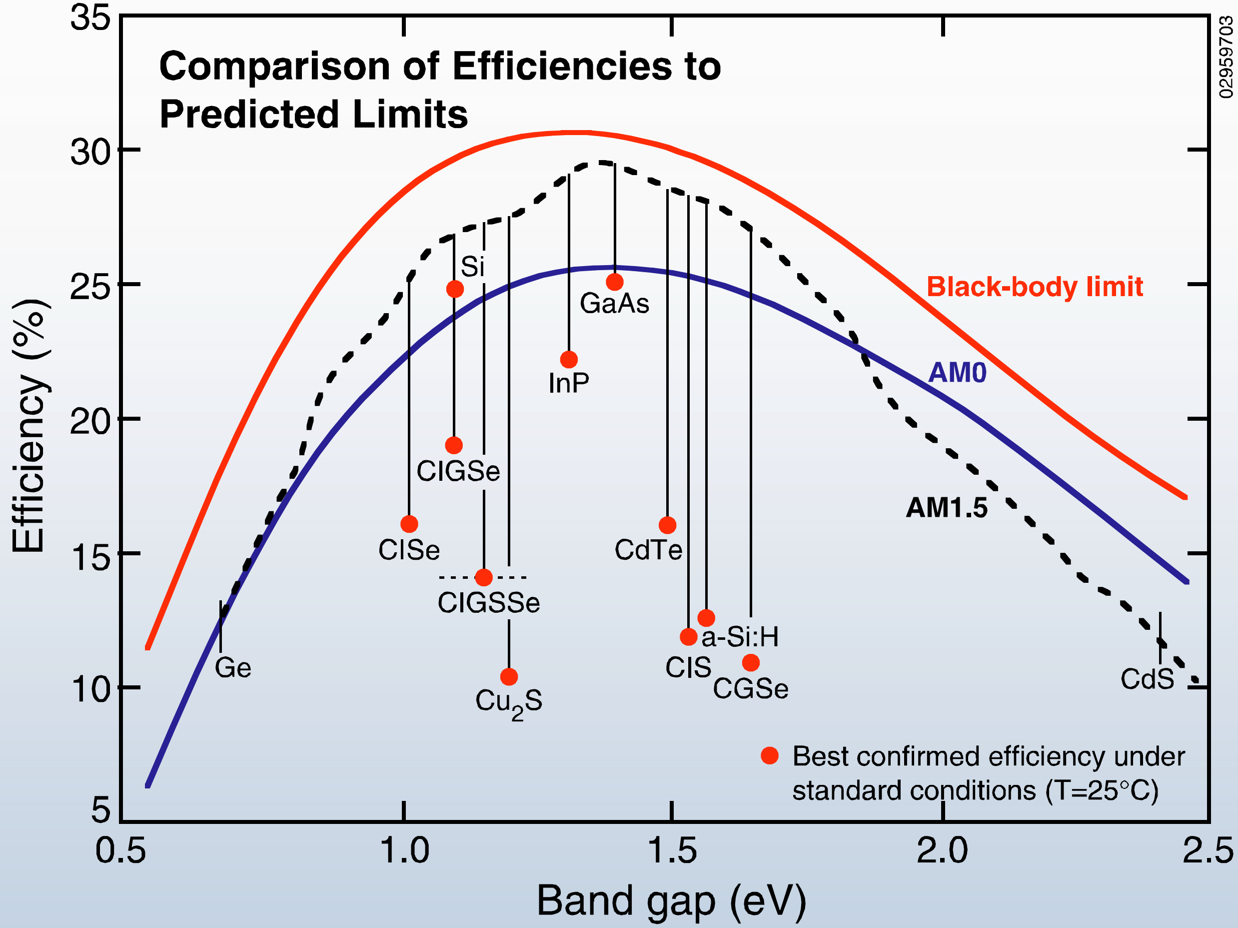
PV Module Production Experience (or Learning) Curve



Why Thin Films ?

- Substantial Cost Advantage
- Lower Consumption of Materials
- Ease of Manufacturing Large Area Devices
- Fewer Processing Steps
- Wider Selection of Materials
- Easier integration of Monolithic Devices
- Greater Tolerance on Materials Quality



Calculated AM1.5 efficiencies (dashed line) and AM0 efficiencies (solid line), comparing achieved cell efficiencies (laboratory-best, confirmed) for various technologies

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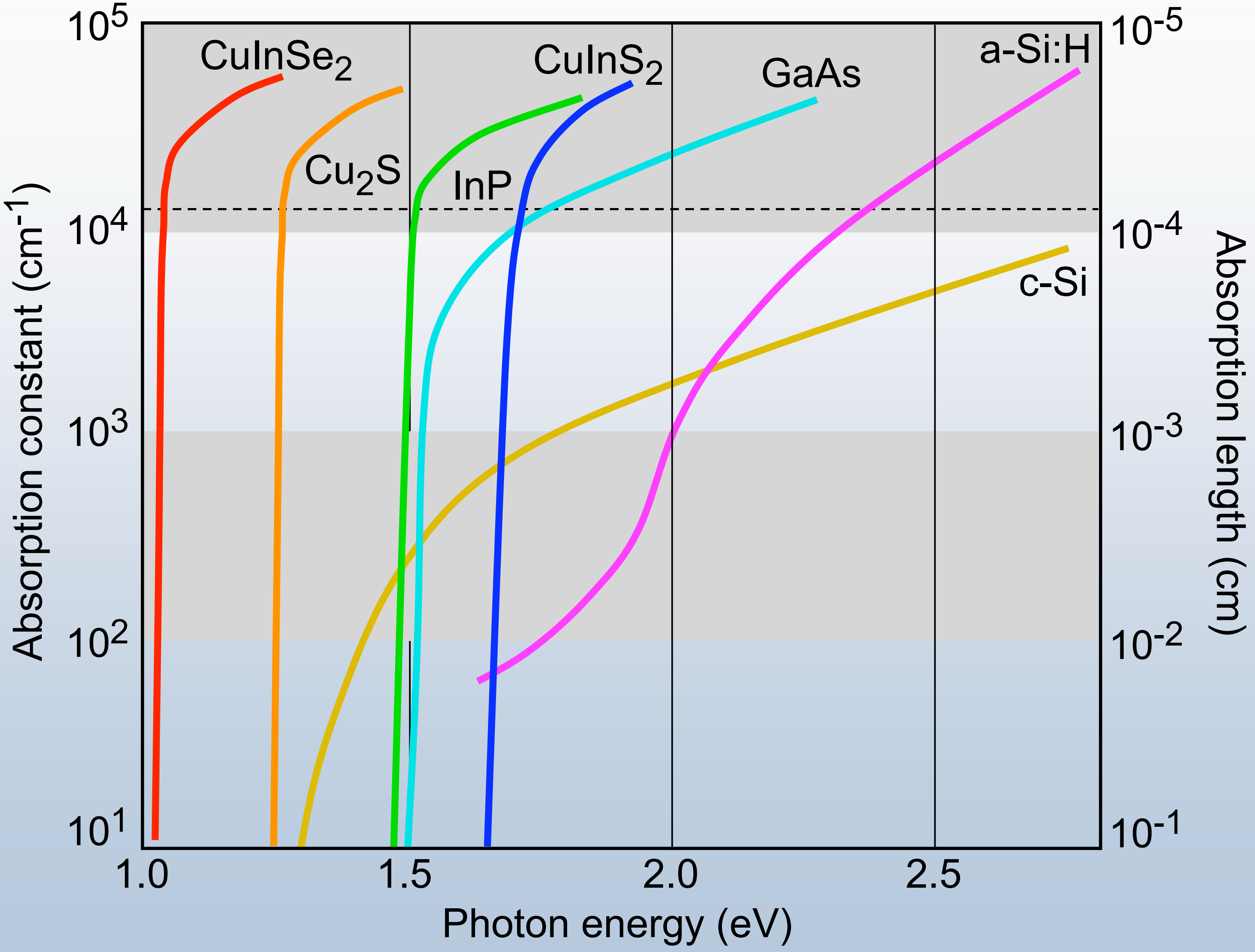
Absorption Coefficient of Chalcopyrite Compounds Together with Other Semiconductors Applied in PV



Thin-Film Solar Cells, Y. Hamakawa, Springer

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Thin Film Solar Cells - Present & Future

(1) First Generation Thin Film Solar Cells

- Amorphous Silicon Alloys
- CdS/CdTe Thin Films
- CIGS/CdS Thin Films

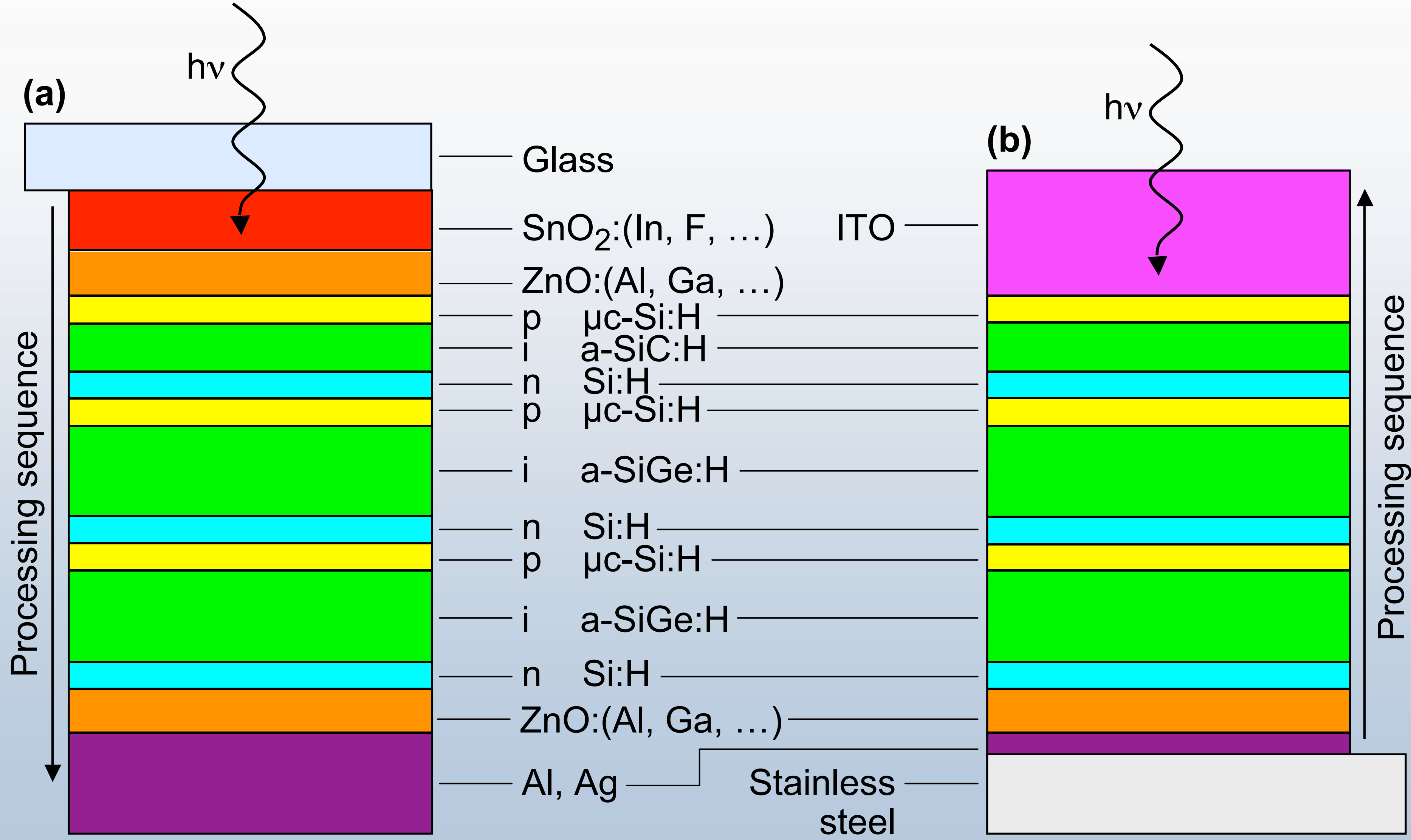
(2) Next Generation Thin Film Solar Cells

- Dye-sensitized TiO_2 Thin Film
- Crystalline Si Thin Films
- Microcrystalline Si
- GaAs Thin Film
- Organic Solar Cells
- Novel Ternary and Multinary Compound

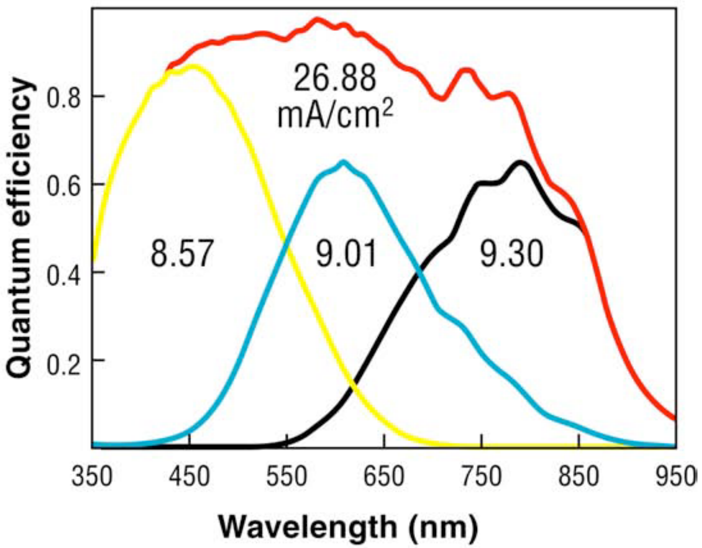
(3) Novel Concepts for High Efficiency Devices

Amorphous Si:H Solar Cell

Triple-Junction a-Si:H Solar Cell: (a) Substrate and (b) Superstrate Configuration



Triple-Junction Cell Structure



Device Performance

	Initial	Stable
V_{oc}	2.357V	2.294V
J_{sc}	8.57 mA/cm^2	8.27 mA/cm^2
FF	0.723	0.684
η	14.6%	13.0%

Deposition Recipes for MW-PCVD and RF-PCVD

Recipe for the low pressure MW-PCVD

MW power: 100~1000 W

Pressure: 0.1~30 mTorr

T_S: 200~400°C

Deposition rate: >4.0 nm/s

Source gases: SiH_4, GeH_4, and H_2

Recipe for the RF-PCVD

RF power: 0.1~10 Torr

Pressure: 0.1~30 mTorr

T_S: 100~400°C

Deposition rate: >0.1 nm/s

Source gases: SiH_4, H_2, PH_3, and BF_3

Thin-Film Solar Cells, Y. Hamakawa, Springer

Stabilized Efficiency of a Few Representative a-Si:H-Based Solar Cells and Modules

Device structure	Stabilized efficiency (%)	Area (cm^2)	Organization
Single-junction a-Si:H	9.3	0.25	United Solar
	9.0	1.0	Tokyo Inst. of Tech.
	8.9	1.0	Sanyo
Double-junction a-Si:Ge:H	12.4	0.25	United Solar
a-Si:H/a-SiGe:H	10.6	1.0	Sanyo
	9.1	842	BP Solar
	9.5	1200	Sanyo
	9.3	5000	Sanyo
Triple-junction	13.0	0.25	United Solar
	10.5	905	United Solar
	12.5 (initial)	922	United Solar

Thin-Film Amorphous Silicon PV—Progress and Status

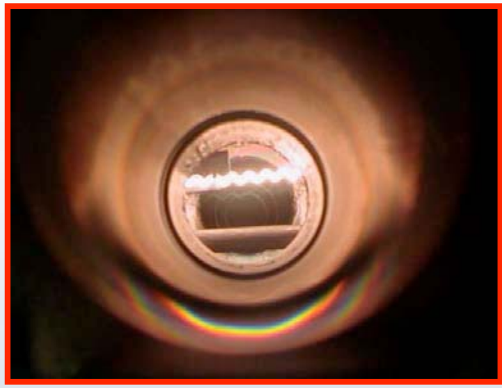
Key companies: BP Solar, United Solar/ ECD, EPV, Iowa Thin Films; Sanyo, Kaneka; Phototronics, DunaSolar

- Glass, stainless steel, plastic substrates
- Multi-MW/year in consumer products
- 5 and 10 MW factories for power products operational; many tens of MW in near term
- Unique products for building integration (e.g., roofing, cladding, semi-transparent canopies)

Efficiency status:	Cell	13.0
(stabilized)	Submodule	10.4
	Module	7–8
	Commercial	5–7

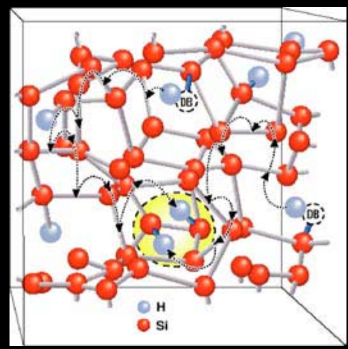
- Engineered "solution" for degradation: thin absorber layers and multijunctions
- Extensive fundamental research, leveraged by many other applications

Thin-Film Amorphous Silicon PV—Research Issues and Directions



Advantages of HW-CVD

- Extremely high deposition rates
- High gas utilization
- Better control of [H] in films
- More stable films
- Lower H_2:SiH_4 to get μc-Si inclusions
- Wide parameter window for quality films



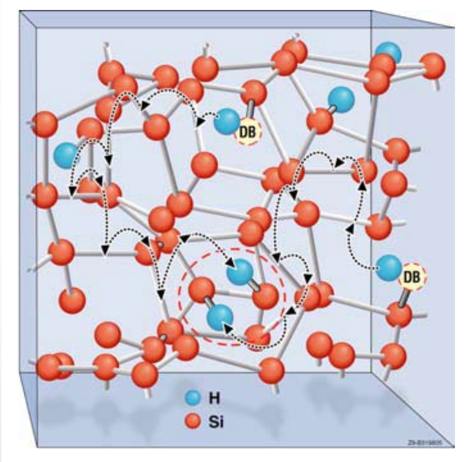
- Manufacturing throughput and yield — impact on equipment cost
- Novel growth techniques
  - e.g., hot-wire deposition, VHF plasma
  - Gas-phase chemistry and control
  - Nucleation and growth
  - High-rate deposition (10–100 vs. 1–3 Å/s)
  - Amorphous to microcrystalline structures
  - Low-bandgap (~1 eV) materials
- Improved fundamental understanding:
  - Metastability (e.g., *hydrogen collision* model and kinetics)
  - Role of hydrogen
  - Alloys with Ge, C, …
  - Characterization techniques
- Improved cell/module efficiencies; new device structures
- Long-term field performance

Key Issues for Efficiency Improvement of a-Si Solar Cells

Physical Process	Technical Solution
Efficient guidance of optical energy	• Antireflection coating (ARC) • Multi-energy-gap stacked juntion
Efficiently guided photon confinement	• Textured surface treatment • Use of back-surface-reflection (BSR) effect • Refractive index arrangement
Carrier confinement	• Minority carrier mirror effect by heterojunction • Increase of $\mu\tau$-product in the PV active layer
Reduction of photogenerated carrier recombination	• Film quality improvement by controlling the deposition condition such as RH, T_s, RF-frequency • Drift-type effect with p-i-n junction • Graded-gap PV active layer (bandgap profiling) • Graded impurity-doping involving back surface field (BSF) effect
Reduction of voltage factor losses	• Band profile control of the PV active layer • Insertion of proper buffer layer in the interface of the p-i and i-n junction
Reduction of series resistance losses	• Optimum design of electrode pattern • Decrease of transparent conductive oxide (TCO) resistance • Use of superlattice tunneling junction

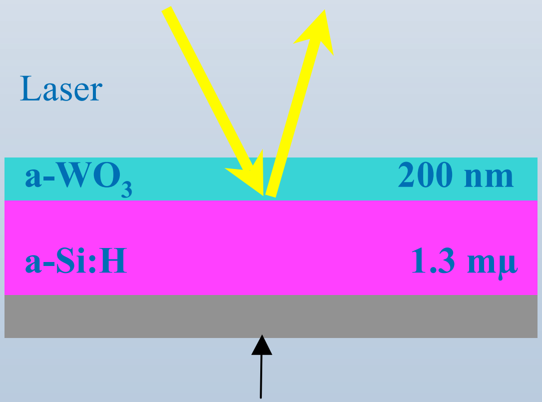
Thin-Film Solar Cells, Y. Hamakawa, Springer

Hydrogen Collision Model



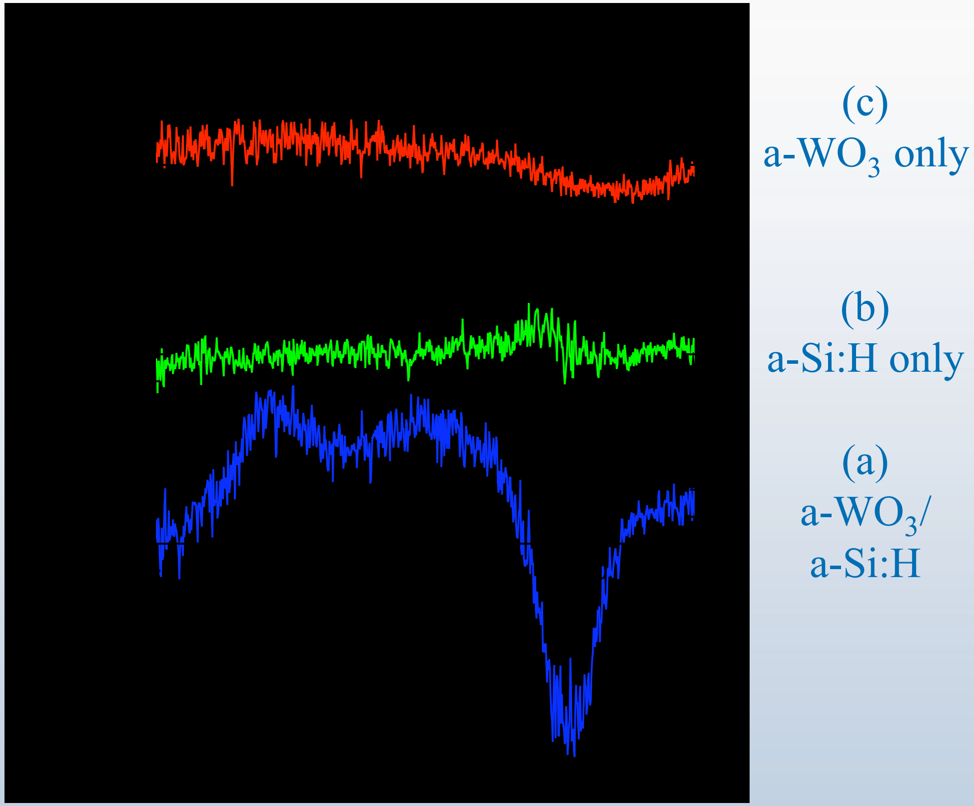
Problem: No experimental evidence for long-range hydrogen motion.

Solution



Stainless Steel Substrate

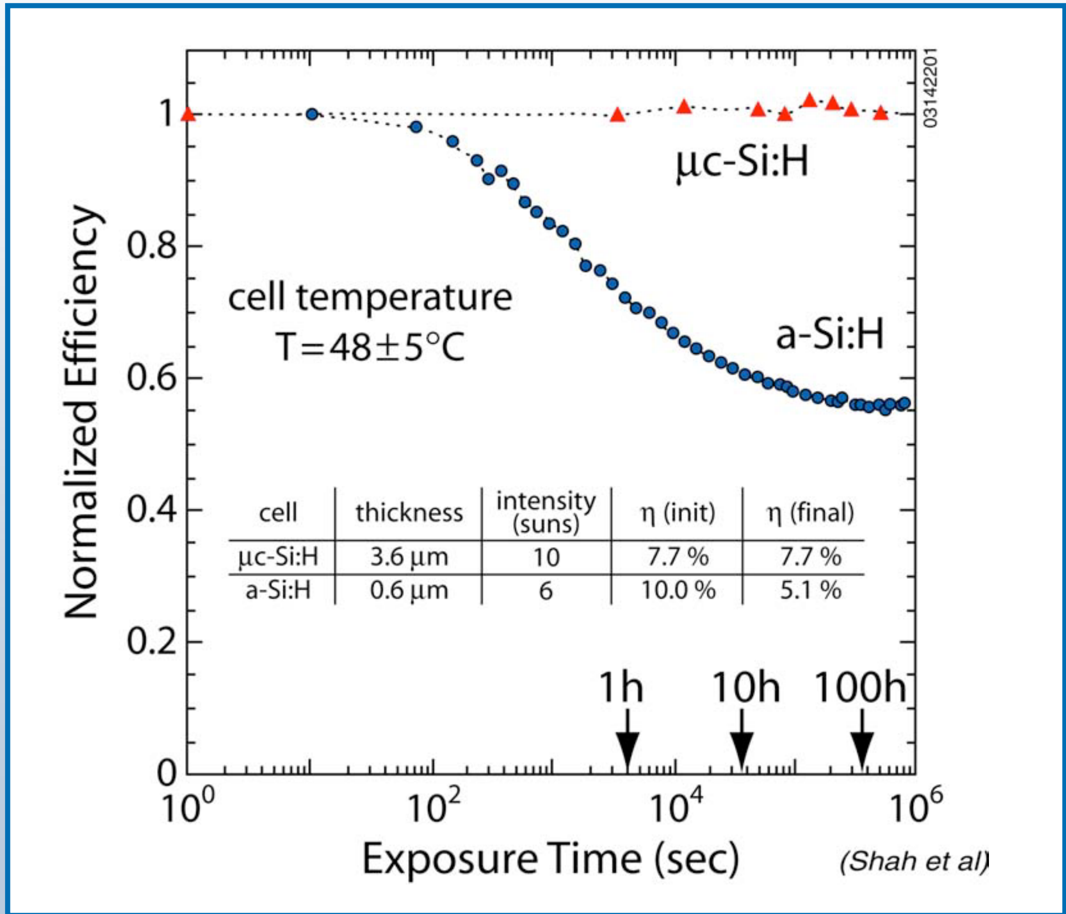
Difference Raman Spectra



Evidence for Hydrogen insertion from a-Si:H to a-WO_3

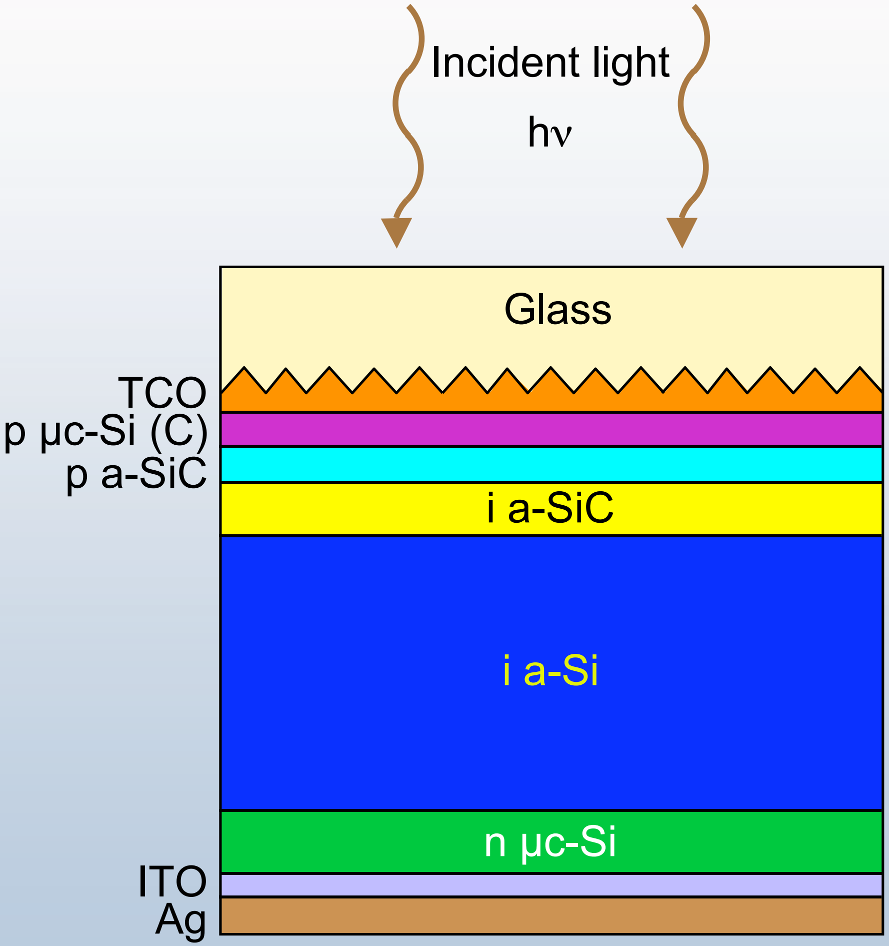
Deb et al. Appl. Phys. Lett. 77, 2686 (2000)

Comparative Stability of a-Si:H and μc-Si:H Solar Cells

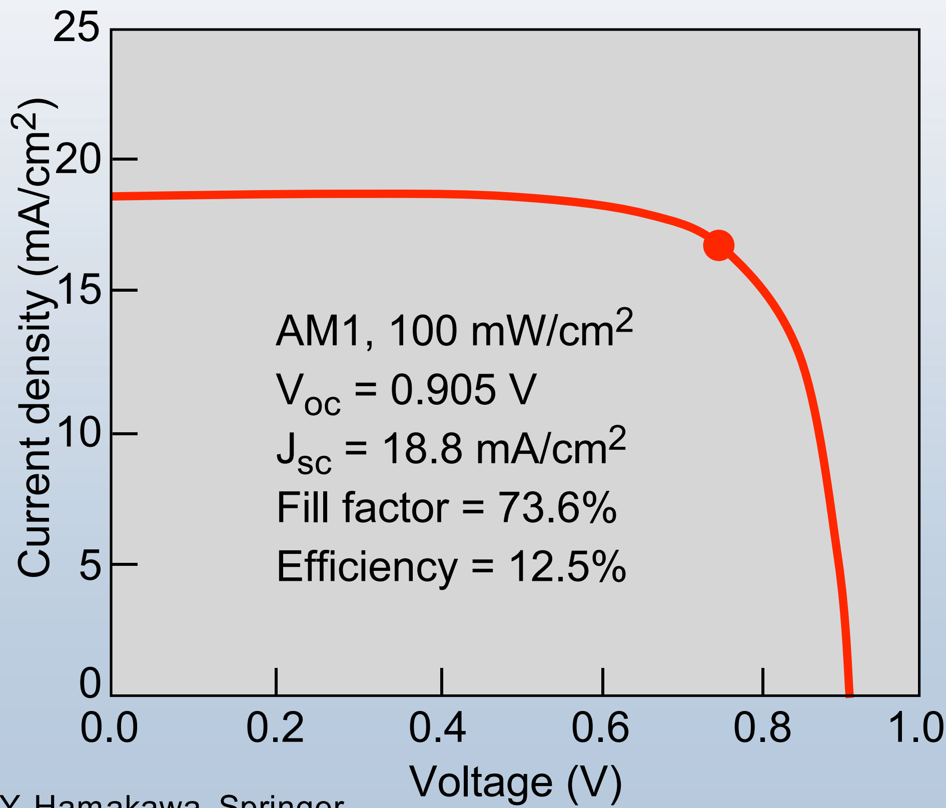


cell	thickness	intensity (suns)	η (init)	η (final)
μc-Si:H	3.6 μm	10	7.7 %	7.7 %
a-Si:H	0.6 μm	6	10.0 %	5.1 %

Structure and Performance of a-Si Double Heterojunction



Cell Performance Characteristics

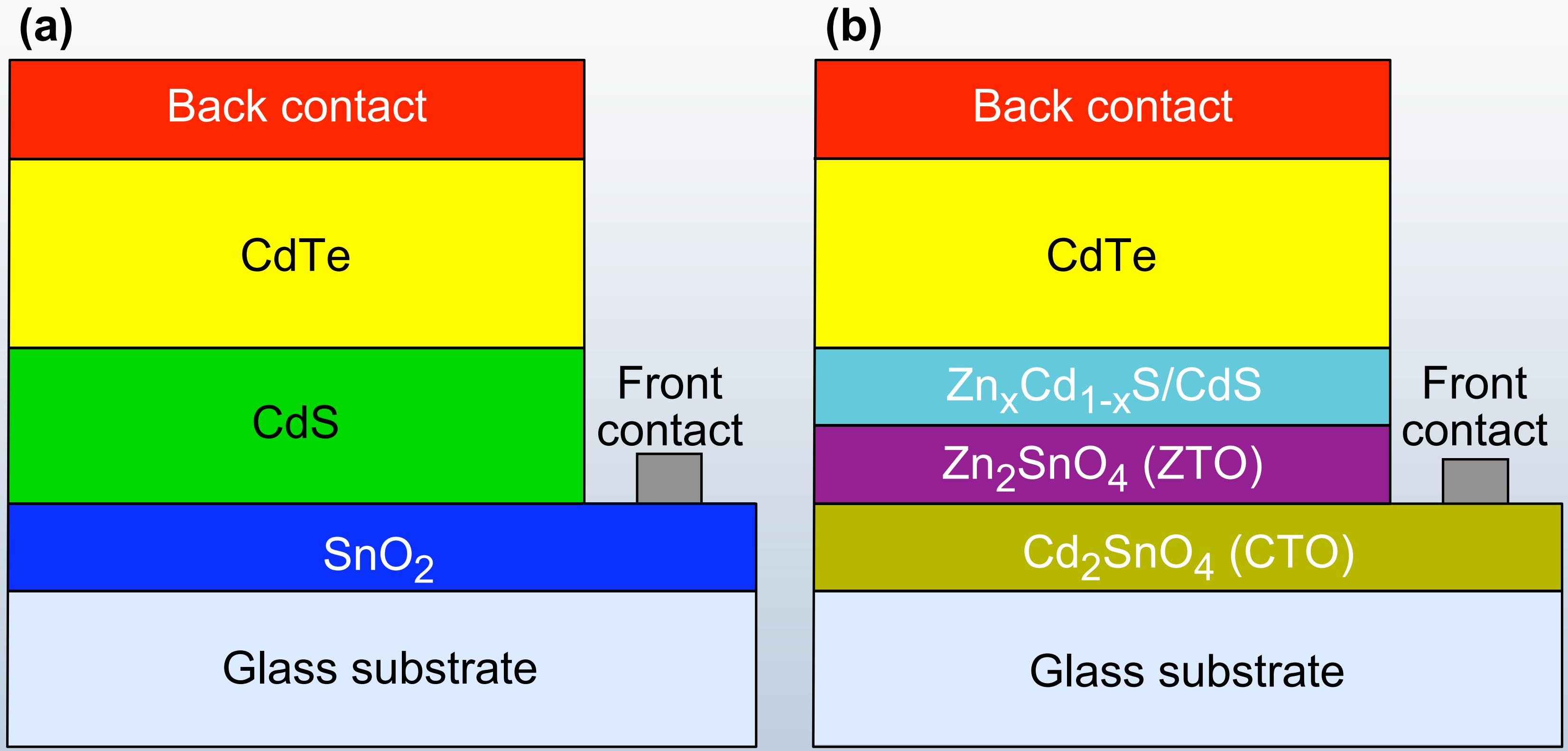


Thin-Film Solar Cells, Y. Hamakawa, Springer

UniSolar Roll-to-roll triple-junction a-Si deposition plant of 30 MW annual capacity

Cadmium Telluride

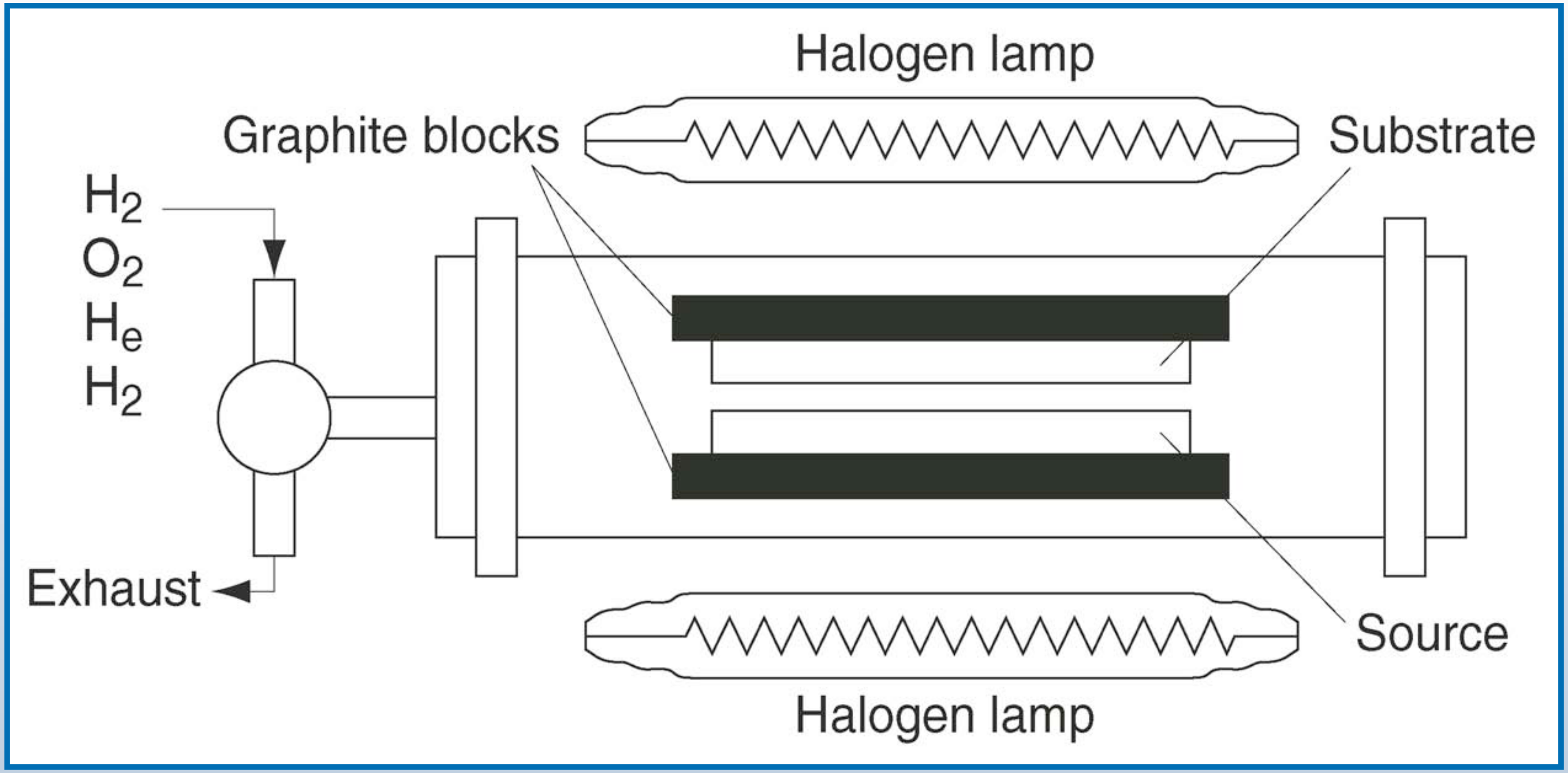
Typical CdTe Device Structure: (a) Conventional and (b) Modified Version



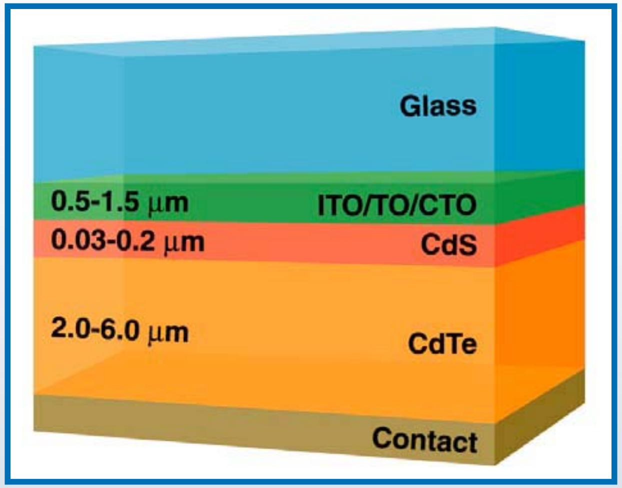
CdTe Thin Film Deposition Technologies

- Sublimation-condensation
- Close-spaced sublimation (CSS)
- Chemical spraying
- Electrodeposition
- Screen printing
- Chemical vapor deposition
- Atomic layer epitaxy
- Sputtering

Apparatus Used for the Deposition of CdTe by the CSS Technique



Thin-Film Cadmium Telluride PV—Progress and Status



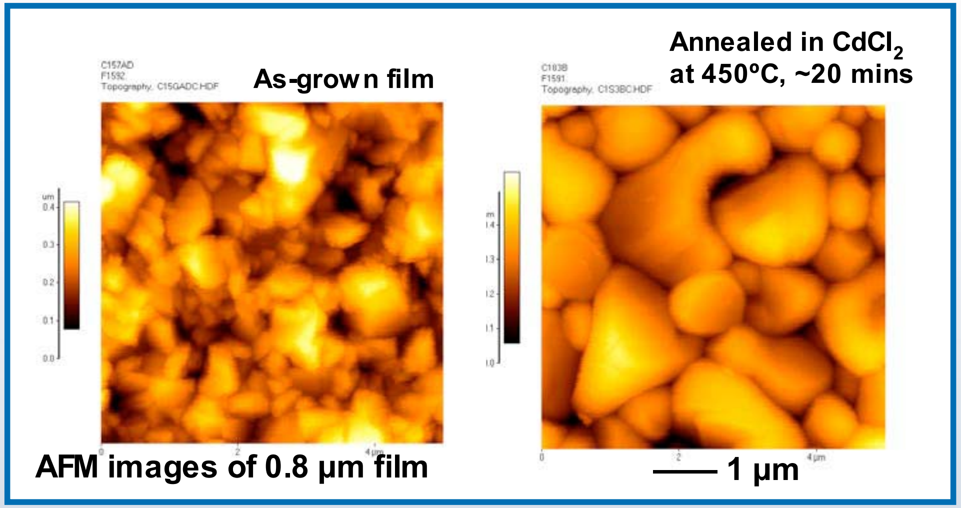
- **Key companies:** BP Solar, First Solar; Matsushita; Antec Solar
- ~1 MW/year in consumer products for years
- Successful first-time manufacturing underway:
  - High-rate vapor transport (vacuum)
  - Electrodeposition (non-vacuum)
  - Few tens of MW in near term
- Field testing of large power modules (50–90 W) shows promise

- **Efficiency status:**

Cell	16.5
Module	11.0
Commercial	7–9

- Many deposition approaches for >10% efficiency
- Early fundamental scientific and engineering base for materials and devices
- ES&H issues studied and under control (e.g., recycling)—Cd perception issue?

Thin-Film Cadmium Telluride PV— Research Issues and Directions



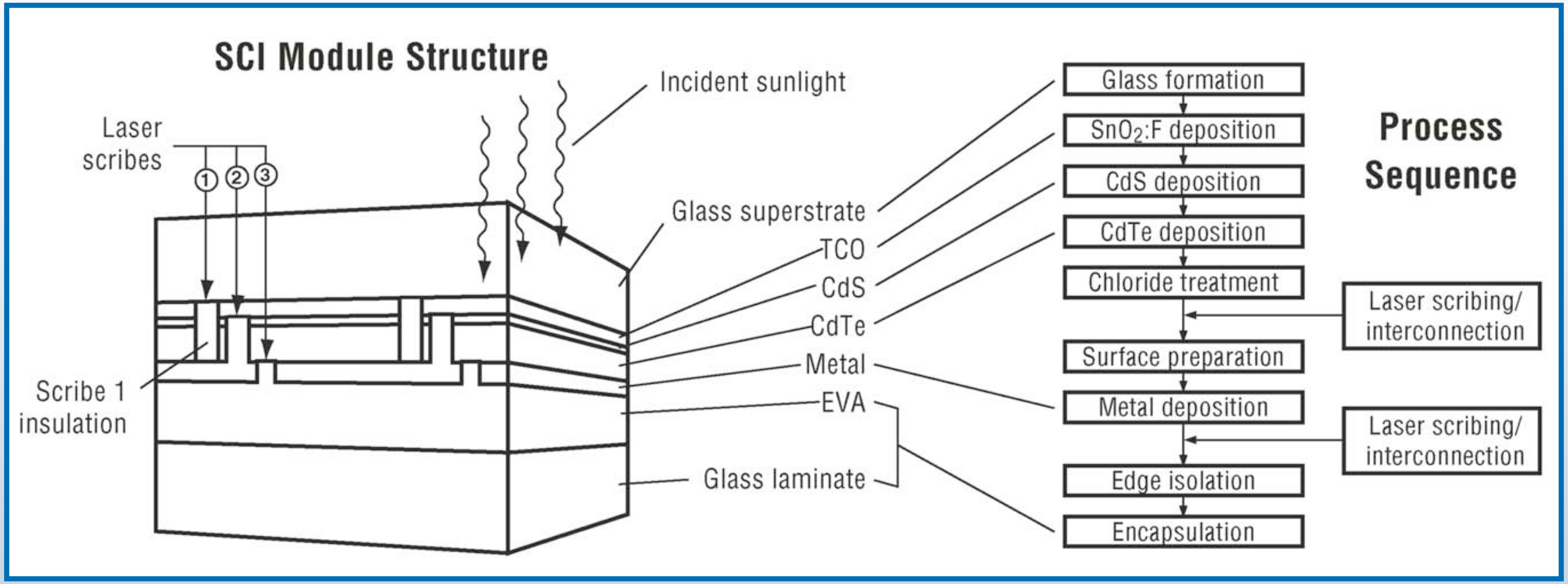
- Film deposition development:
  - Nucleation and growth
  - Gas-phase and surface chemistries
  - Annealing and heat treatment ($CdCl_2$)
  - Grain growth, native defects, dopants
  - CdS/CdTe interdiffusion
  - Alternate transparent conductors and impacts film growth

- Front and back contacts
  - Alternate transparent conductors
  - Low resistance, stable back contacts
  - Role of Cu; Cu-free contact strategies?
- Close efficiency gap (cell to module)
- Compatibility of manufacturing process steps
- Low-cost module packaging for long-term reliability (>20 years); edge sealants and moisture ingress
- Accelerated module test procedures

CdTe Research Issues

- Improved contacts to p-CdTe
- Effective p-type doping of CdTe to improve Voc
- CdTe-alloys that allow device design gradients
- Investigation of materials and device properties allowing ultra-thin CdTe layers (to 0.25 micron) while maintaining high efficiencies
- Reducing tellurium usage by replacement of tellurium with other elements while maintaining performance
- Materials Availability, Safety,and Environmental Issues
- Closing Gap Between Small and Large Area Devices

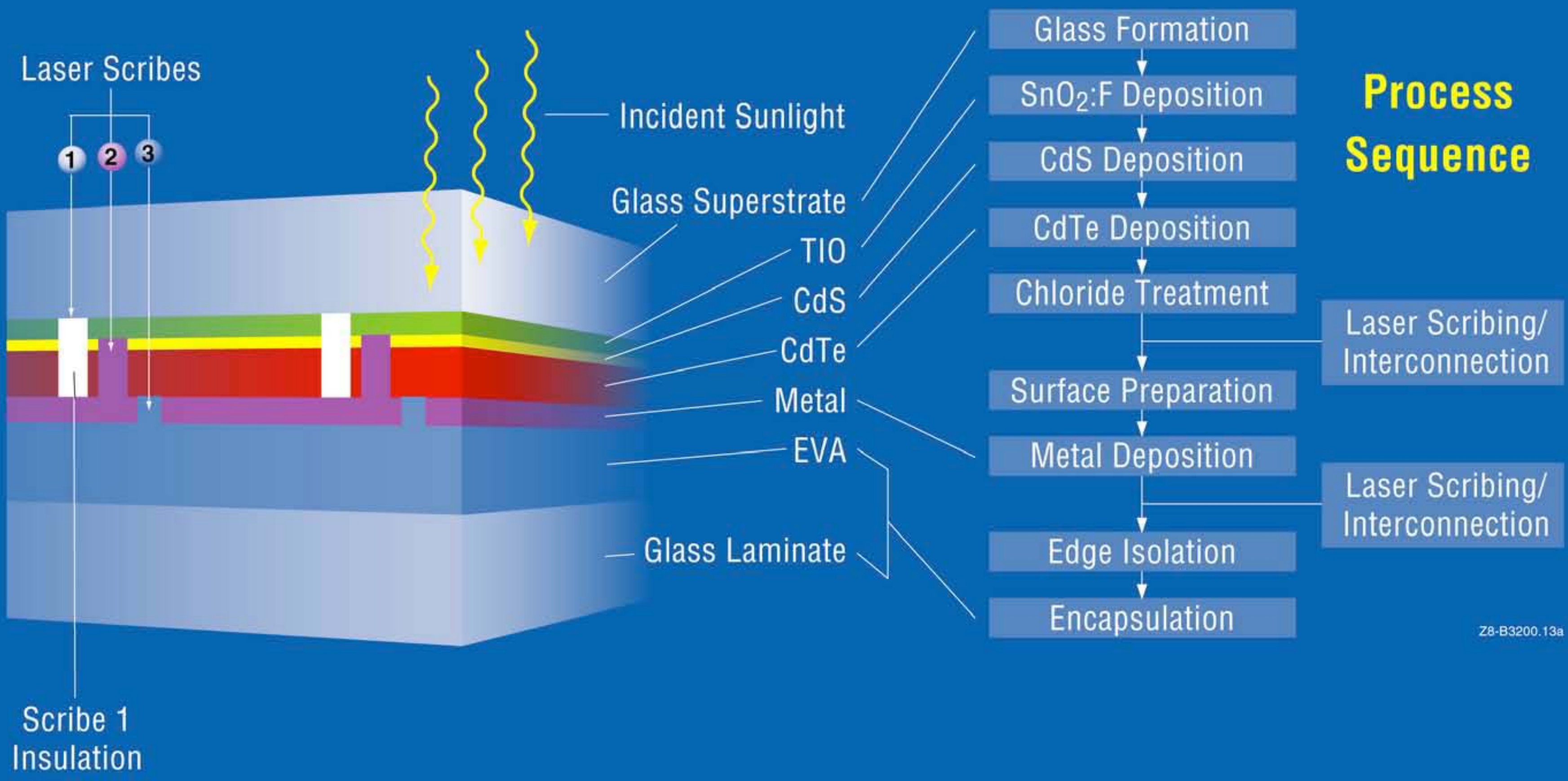
Module Structure and Processing Sequence Used by Solar Cells, Inc.



Thin Film CdTe Solar Cell Back Contacts

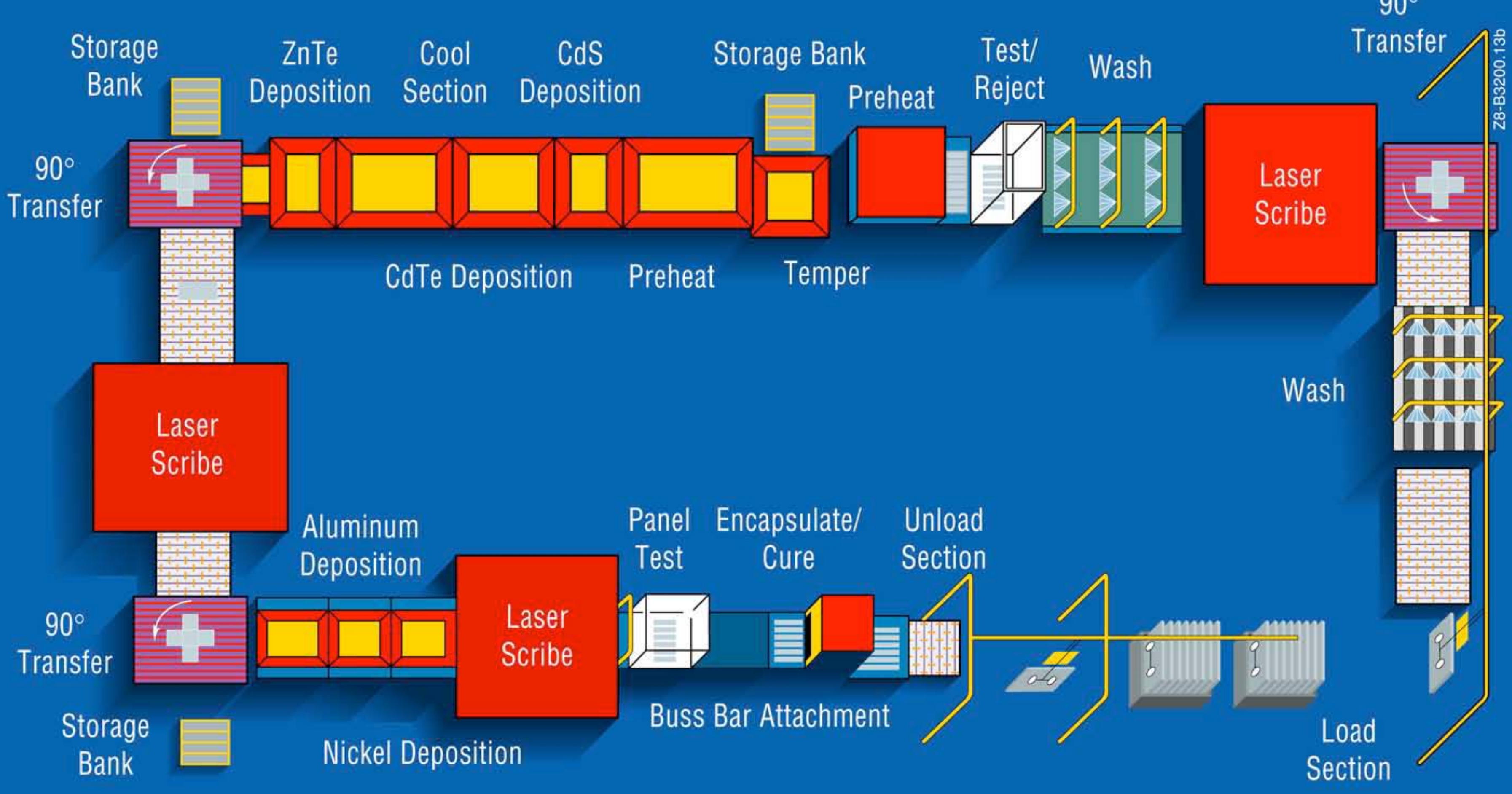
Metals	Others	
– Cu	– Graphite	– Sb_2Te_3/Metal
– Au	– Graphite (Cu, HgTe, Ni_2P)	– ZnTe: Cu/Metal
– Cu/Au	– As_2Te_3/Metal	– ZnTe: N/Metal
– Ni	– Cu_2Te/Metal	
– Ni/Al	– Ni_2P/Metal	
– Sb/Al	– $NiTe_2$/Metal	
– Sb/Au	– Te/As_2Te_3/Metal	

SCI Module Structure



Z8-B3200.13a

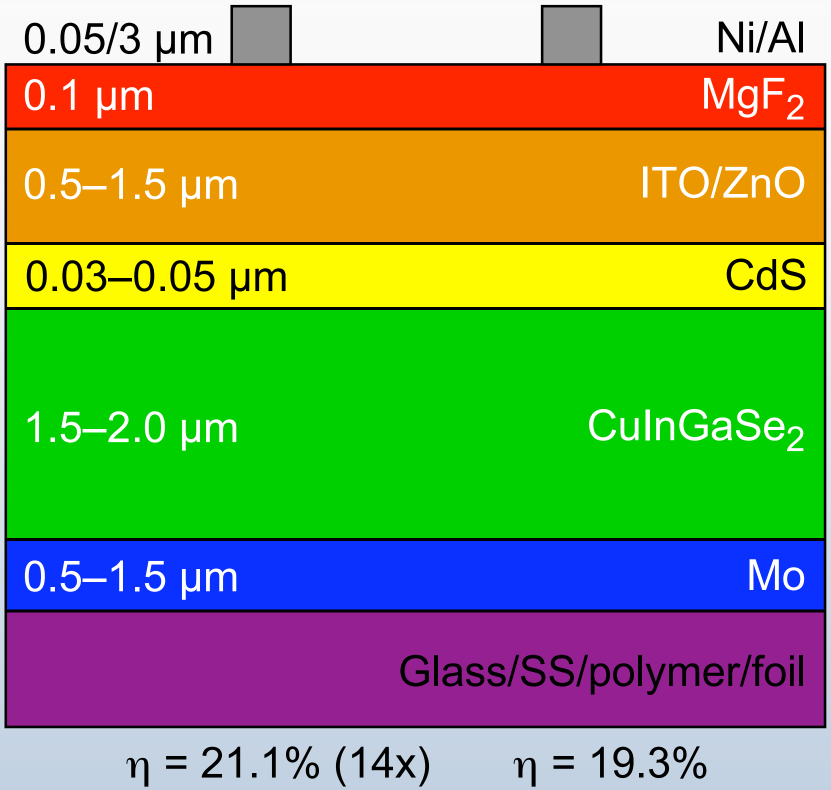
In-line Manufacturing of Thin-Film CdTe Photovoltaic Modules



First Solar CdTe 25 MWp Vapor Transport Manufacturing Line

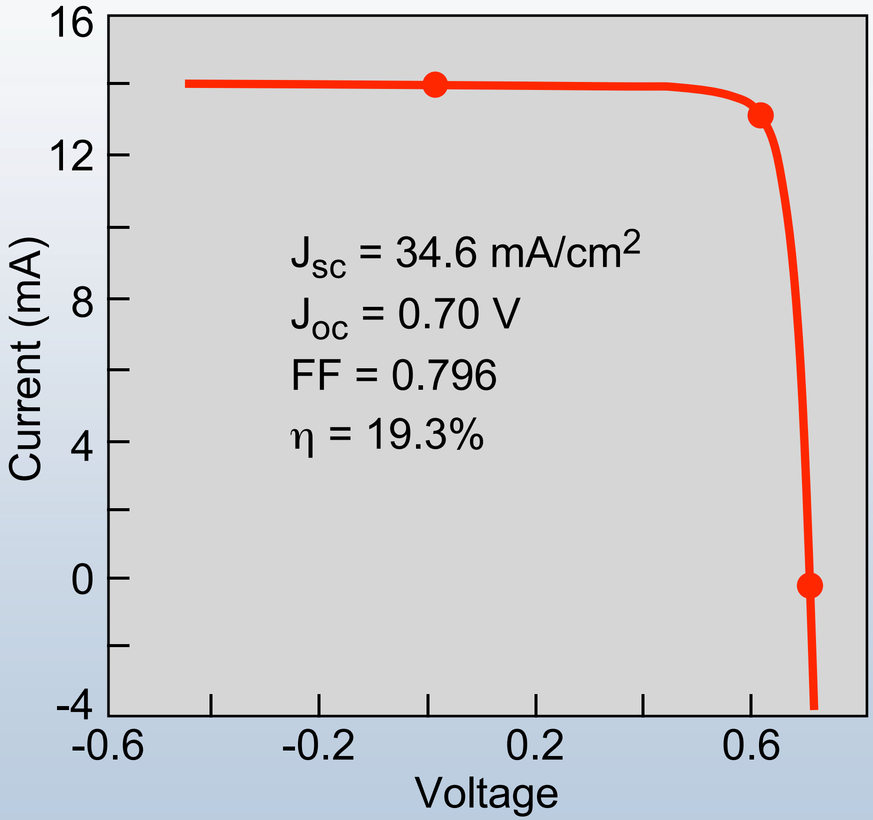
CIGS Solar Cell

Thin Film CIS Solar Cell Structure

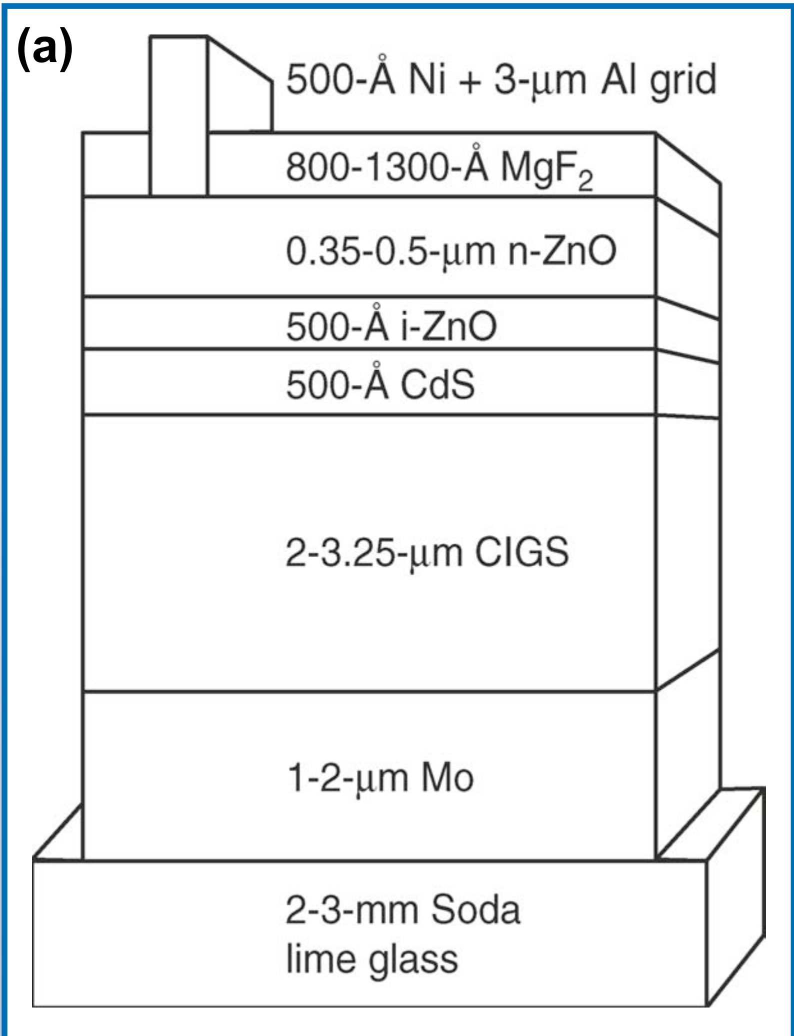


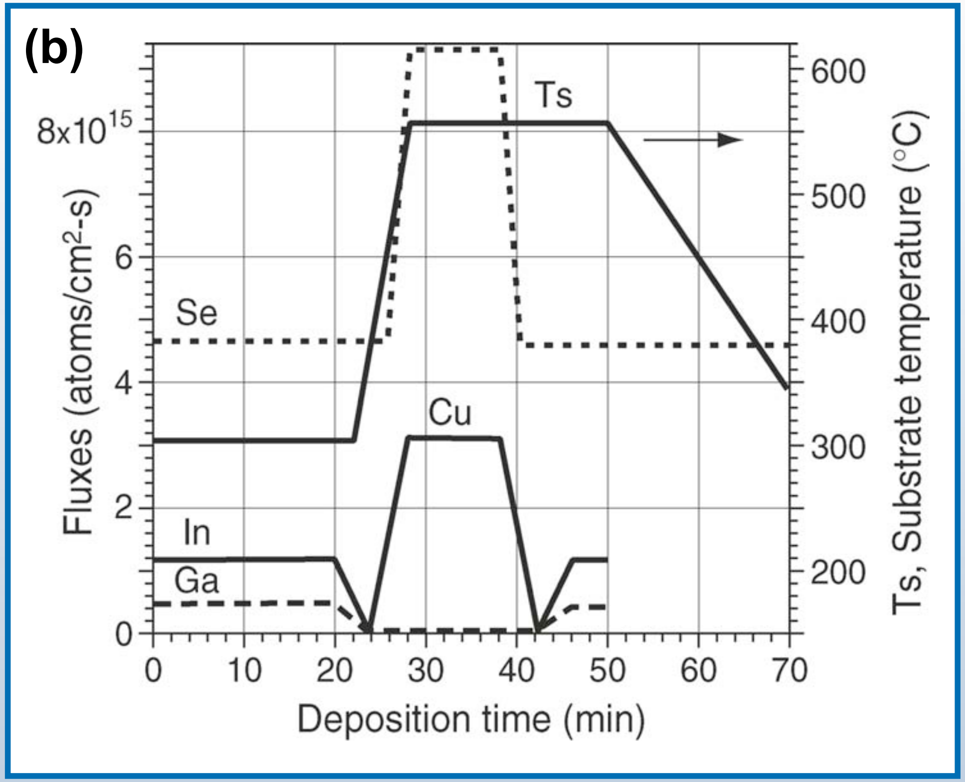
I-V Curve for a 19.3% Thin Film CIGS Solar Cell

MgF_2/ZnO/CdS/CIGS/Mo/glass

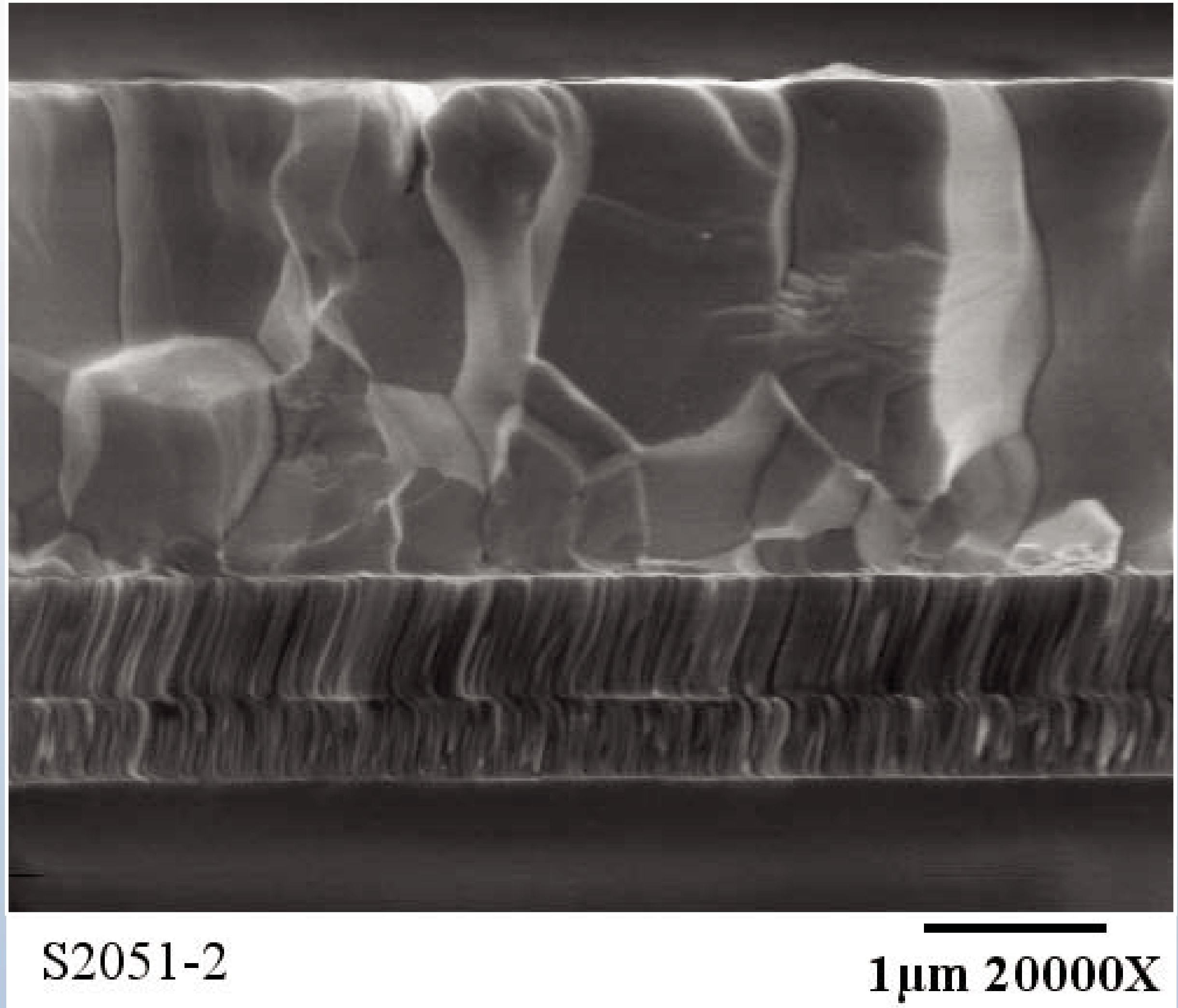


18.8%-Efficient CIGS/CdS/ZnO Solar Cell: (a) Device Structure and (b) Elemental Fluxes and Substrate Temperature vs Deposition Time

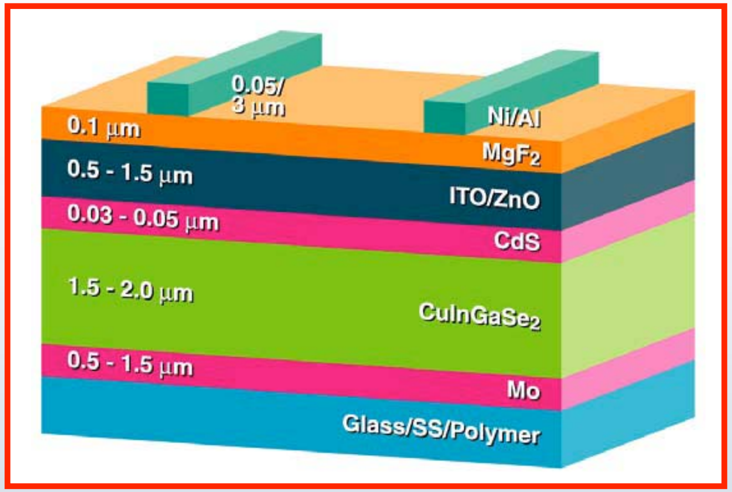




SEM-Thin Film CIGS Solar Cell



Thin-Film Copper Indium Diselenide (CIS) PV—Progress and Status



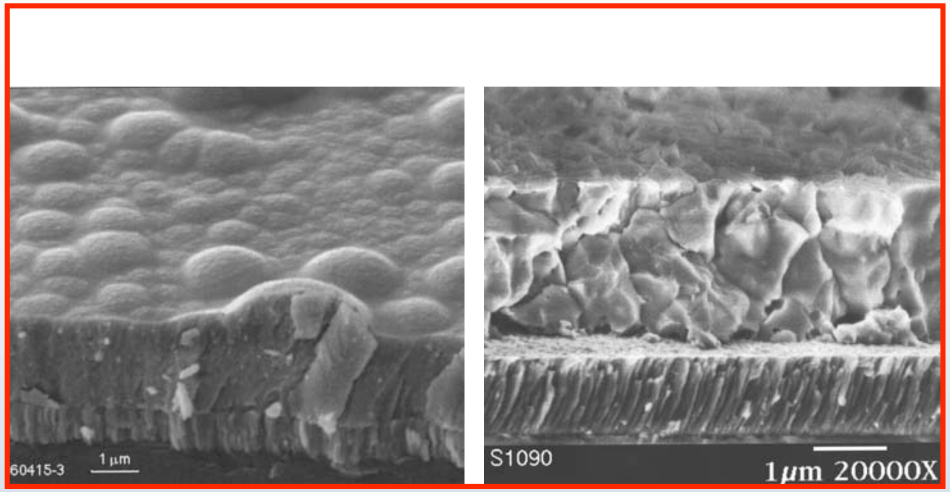
Key companies: Siemens/Shell Solar, Global Solar/ITN, ISET, EPV; Wurth Solar; Showa/Shell

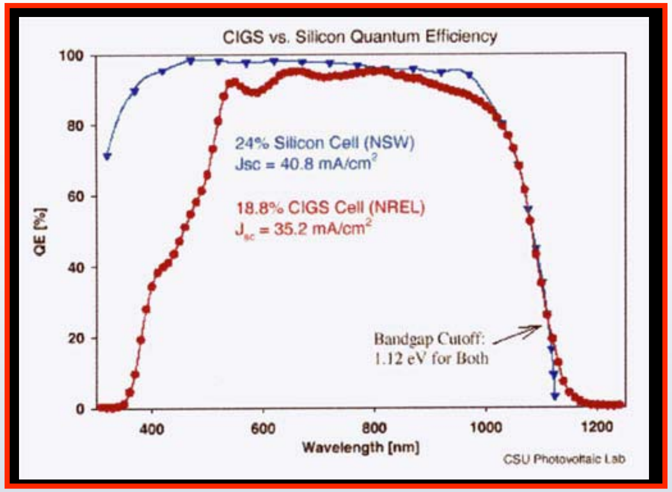
- Prototype production started in 1998:
  - First commercial products (5–40 W)
  - Efficient, large modules (>12%)
  - Expansion to multi-MW in near term
- Field testing of modules shows promise; >10 years outdoors, no degradation

Efficiency status:	Cell	19.3
	Module	12.1
	Commercial	>10
Others:	Stainless steel substrate	17.5
	Electrodeposition	15.4
	With ZnO (no CdS buffer)	15.7
	Concentrator (14X)	21.5

- Understanding of film growth, microstructures, defects, and device physics
- Reproducible high-efficiency processes

Thin-Film Copper Indium Diselenide (CIS) PV—Research Issues and Directions





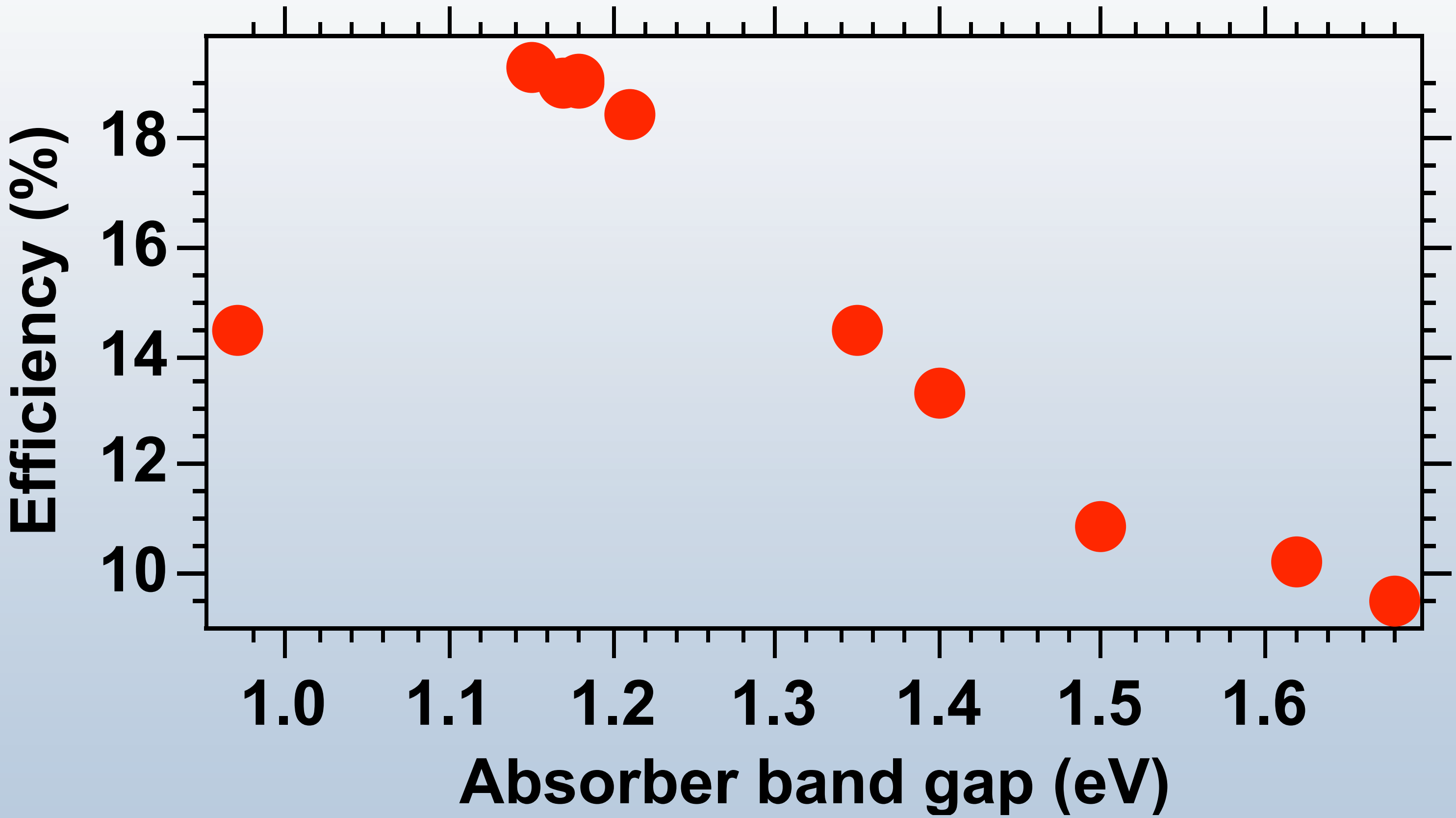
- Scalability of current processes
  - Predictive models of materials growth, devices, and processes
  - Real-time process controls
  - Yield and throughput
- New techniques and materials
  - Non-vacuum approaches
  - Low-temperature depositions

- Device research and development
  - Heterojunction vs. homojunction
  - Role of window materials; improvements in blue response
  - Alternate front and back contacts
  - Higher bandgaps and multijunctions
  - Device models and characterization
- Theory: Band structures, optoelectronic properties, defect physics, doping

$CuInSe_2$-alloys Research Issues

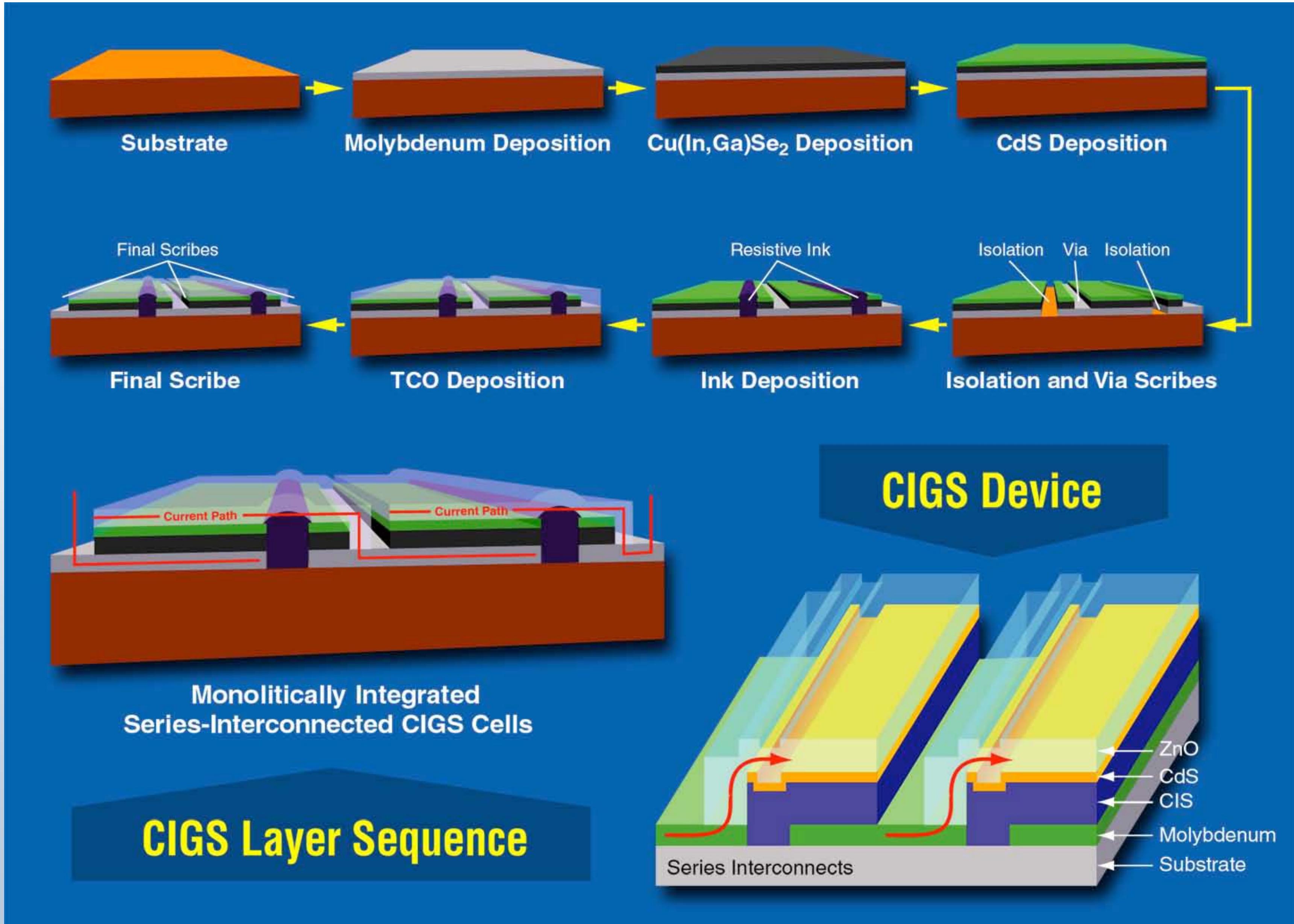
- Understanding materials science of complex compositions, alloys and gradients
- Understanding the complex properties and interactions of key interfaces
- Investigation of materials and device properties allowing ultra-thin CIS layers (to 0.25 micron) while maintaining high efficiencies
- Reducing indium usage by replacement of indium with other elements while maintaining performance
- Investigating low-cost processes, and the science of such processes to establish the control and flexibility needed to reach high performance and high yield

Efficiency vs. CIGS Bandgap

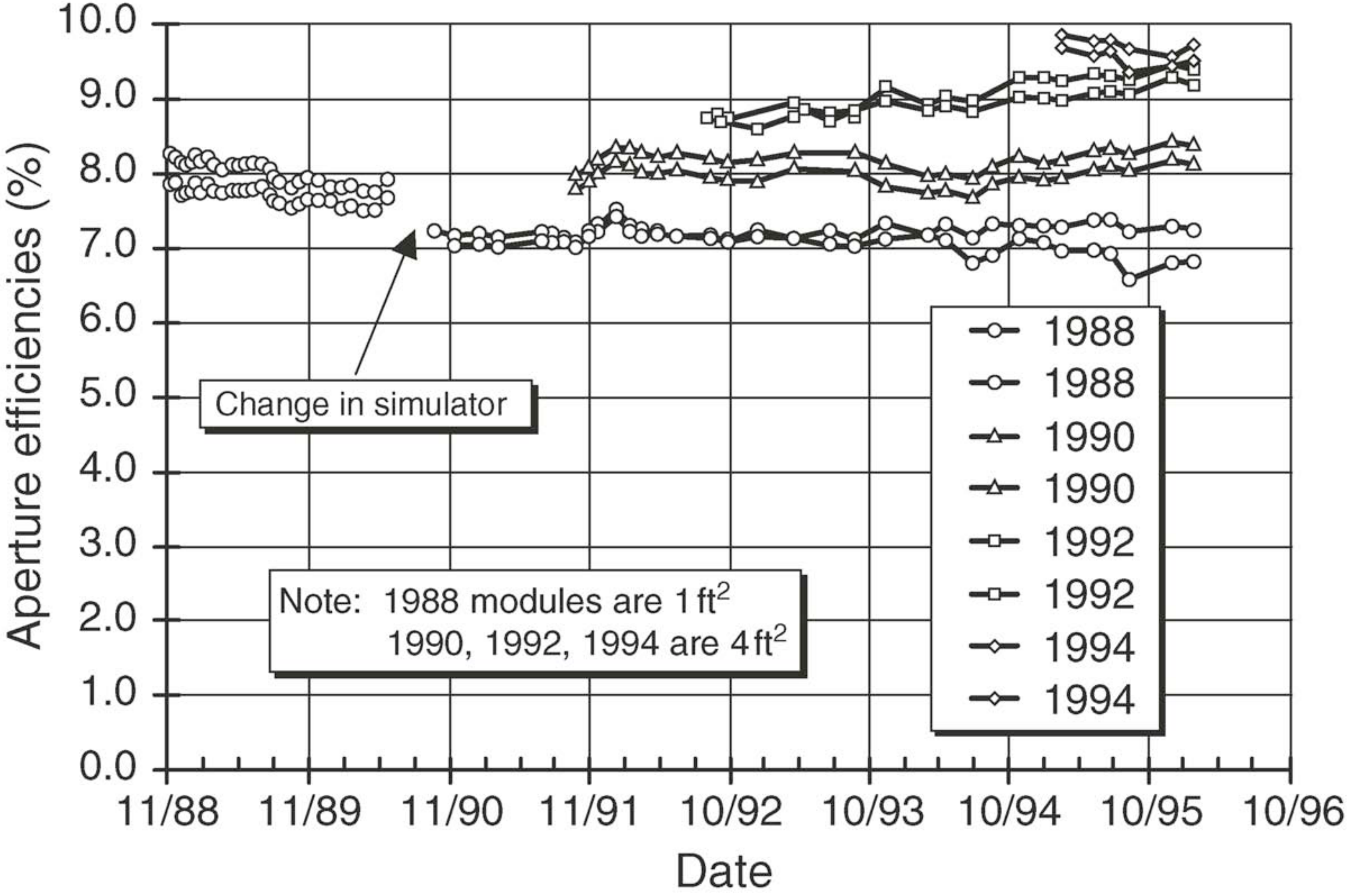


Efficiencies of Cd-Free Buffer Layers in CIGS Solar Cells

Structure	Efficiency	V_{oc} mV	Organization	Process
CIGS/In(OH,S)/ZnO	15.4	594	Uppsala/Stuttgart	CBD
DIGS/Zn(OH,S)/ZnO	14.0	560	Showa Shell	CBD
CIGS/Zn(S,OH)/ZnO	15.1	632	Aoya Univ.	CBD
CIS/In(O,OH)/ZnO	9.7	420	Showa Shell	CBD
CIGS/In_xSe_y/ZnO	11.4	735	Stuttgart	CBD
CIGS/In_xSe_y/ZnO	13.0	595	Tokyo Inst. Tech.	Coevaporation
CIGS/$ZnIn_xSe_y$/ZnO	12.7	579	Tokyo Inst. Tech.	Coevaporation
CIGS/ZnSe/ZnO	11.6	502	Tokyo Inst. Tech	ALD
CIGS Se/Zn(Se,OH)/ZnO	13.7	535	HMI/GSI	
CIS/ZnSe/Ar	14.1	506	Wash. St. Univ.	
CIGS/ZnO	15.1		NREL	


Substrate
Molybdenum Deposition
Cu(In,Ga)Se$_2$ Deposition
CdS Deposition
Final Scribes
Resistive Ink
Isolation Via Isolation
Final Scribe
TCO Deposition
Ink Deposition
Isolation and Via Scribes
Current Path
Current Path
Monolitically Integrated
Series-Interconnected CIGS Cells
CIGS Layer Sequence
CIGS Device
ZnO
CdS
CIS
Molybdenum
Substrate
Series Interconnects

Stability of Thin Film CIS-Based Modules Fabricated by Siemens Solar, Inc.



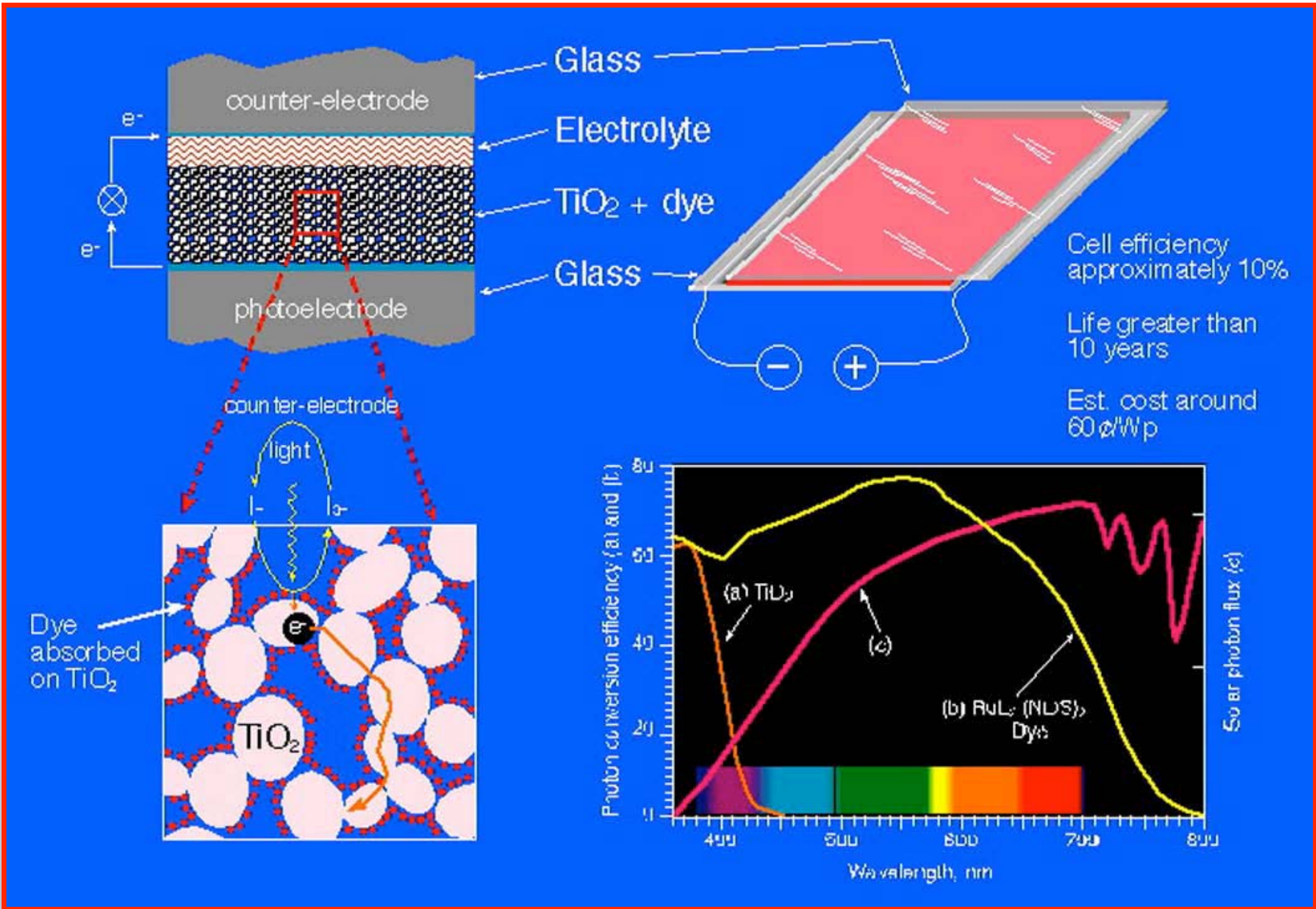
Polycrystalline Thin Film Photovoltaic Modules

Organization	Material	Area (cm^2)	Eff (%)	Power (W)	Date
BP Solar	CdTe	8390	11.0*	92.5*	09/01
Wurth Solar	CIGS	6507	12.2	79.2	05/02
First Solar	CdTe	6612	10.1*	67.1*	12/01
Shell Solar - GmbH	CIGSS	4938	13.1	64.8	05/03
Matsushita Battery	CdTe	5413	11.0	59.0	05/00
Global Solar	CIGS	7714	7.3*	56.8*	03/02
Antec Solar	CdTe	6633	7.0	46.7	11/01
Shell Solar	CIGSS	3626	12.8*	46.5*	03/03
Showa Shell	CIGS	3600	12.8	44.15	05/03

* NREL Confirmed; All aperture-area efficiency

Dye-Sensitized TiO2 Solar Cell

Dye Sensitized TiO_2 Solar Cell



Dye-sensitized Nano-structure TiO_2 Solar Cells

Advantages

- Relatively simple and inexpensive fabrication processes with production cost potential of ~50¢/Wp
- Demonstrated cell efficiency (h≥10%) comparable to conventional amorphous silicon solar cell
- Device constituents (TiO_2, dye,electrolyte) are abundant and environmentally benign
- Optional color and device transparency leads to multiplicity of products and applications

Disadvantages

- Use of liquid electrolyte is not an optimum solution
- Very long-term stability of dyes questionable
- Significantly higher efficiency difficult to achieve

The First U.S. Patents on Dye-Sentised TiO_2 Solar Cells Issued to Deb etal in 1978

United States Patent [19] — [11] 4,080,488

Chen et al. — [45] Mar. 21, 1978

[54] DYE-TITANIUM DIOXIDE PHOTOGALVANIC CELL

[75] Inventors: Schoen-Nan Chen, North Brunswick; Satyendra K. Deb, East Brunswick; Horst Witzke, Princeton, all of N.J.

[73] Assignees: Optel Corporation, Princeton, N.J.; Grumman Aerospace Corporation, Bethpage, N.Y. ; part interest to each

[21] Appl. No.: 740,876

[22] Filed: Nov. 11, 1976

[51] Int. Cl.[2] H01M 6/30; H01M 6/36
[52] U.S. Cl. 429/111
[58] Field of Search .... 136/89 NB; 429/111

[56] References Cited

U.S. PATENT DOCUMENTS

3,989,542	11/1976	Clark	136/89 NB
4,037,029	7/1977	Anderson	429/111

OTHER PUBLICATIONS

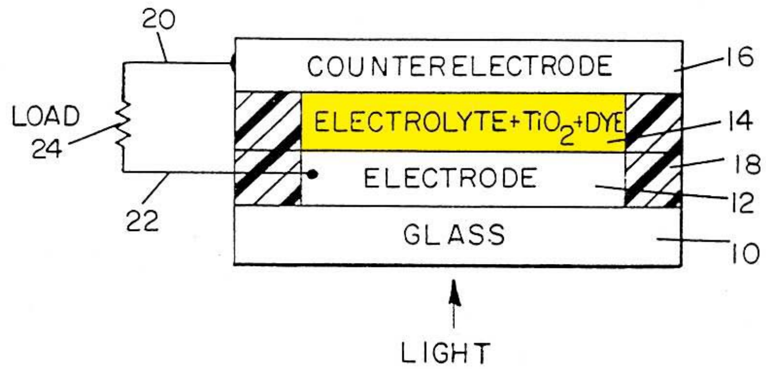
H. Gerischer et al. "Photoelektrochemische Prozesse und Photokatalyse an Zinkoxid-Suspensionen und Zinkoxid-Deckschichten" *Ber. Bunsen Gesell,* vol. 76, pp. 385-388 (1972).
J. R. Bolton, "Photochemical Storage of Solar Energy by the Dye Sensitized Photolysis of Water", Proc. VIII Int'l Conf. on Photochem, Edmonton, Canada, Aug 1975.
A. J. Nozik "Photoelectrolysis of Water Using Semiconducting TiO_2 Crystals", Nature, vol. 257, p. 383-386, Oct. 1975.
R. Gomer, "Photogalvanic Cells", *Electrochimica Acta vol. 20, pp. 13-20, (1975).*

Primary Examiner—John H. Mack
Assistant Examiner—Aaron Weisstuch
Attorney, Agent, or Firm—Morris Liss

[57] ABSTRACT

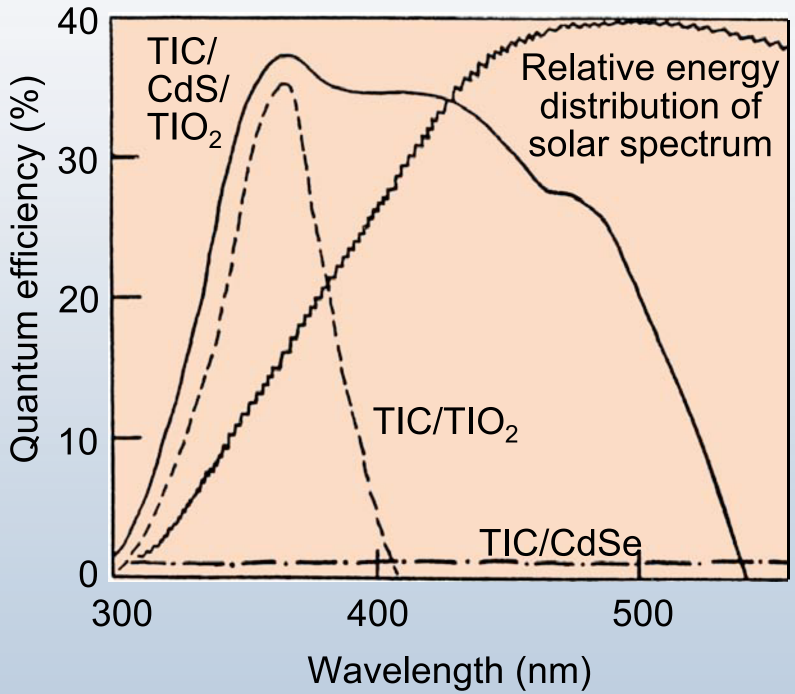
A photogalvanic cell has a glass substrate through which irradiating light passes. A light transparent conductive thin film serves as an electrode, the film being deposited upon the glass substrate. Another layer is an electrolyte and includes an aqueous medium having TiO_2 suspended therein, the TiO_2 forming photoactive sites with the remaining ingredients of the electrolyte. The electrolyte layer further includes N-methylphenazine methosulfate dye which has photoconversion and electrical storage properties. During irradiation the cell may drive a load, or stored energy resulting from irradiation may drive a load after the source of irradiation is removed.

6 Claims, 2 Drawing Figures

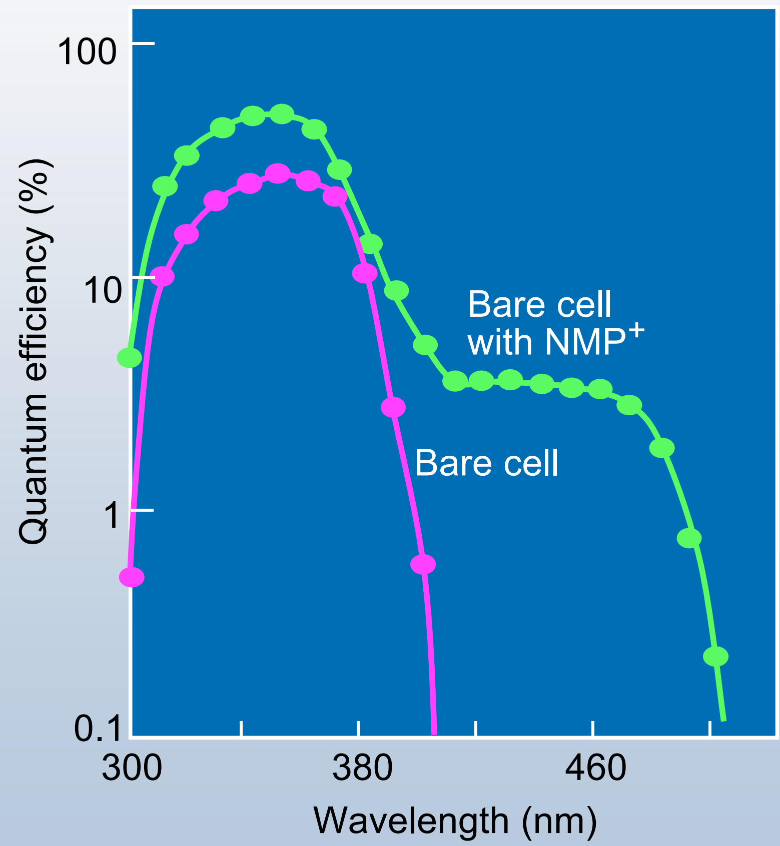


Other related US Patents issued to Deb etal in 1978:
4117510; 4,080,488; 4,084,043; 4,118,246; 4,118,247.

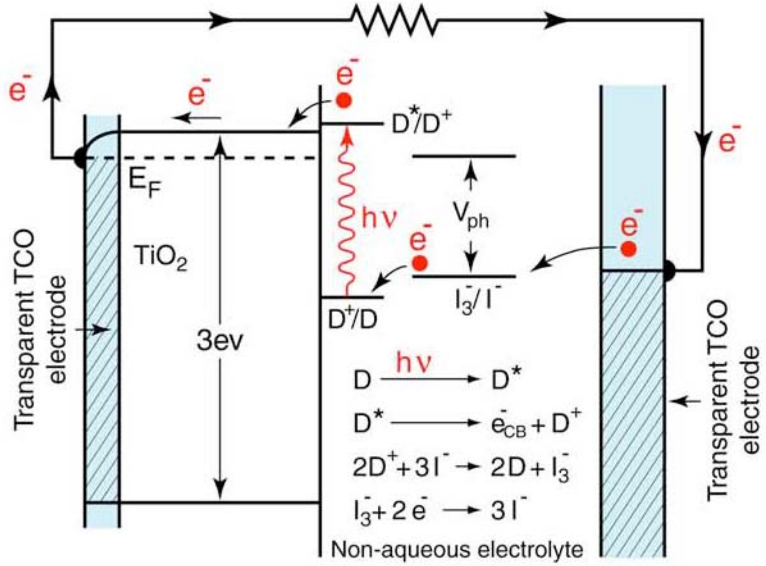
Spectral Sensitization of TiO_2 PEC Cell



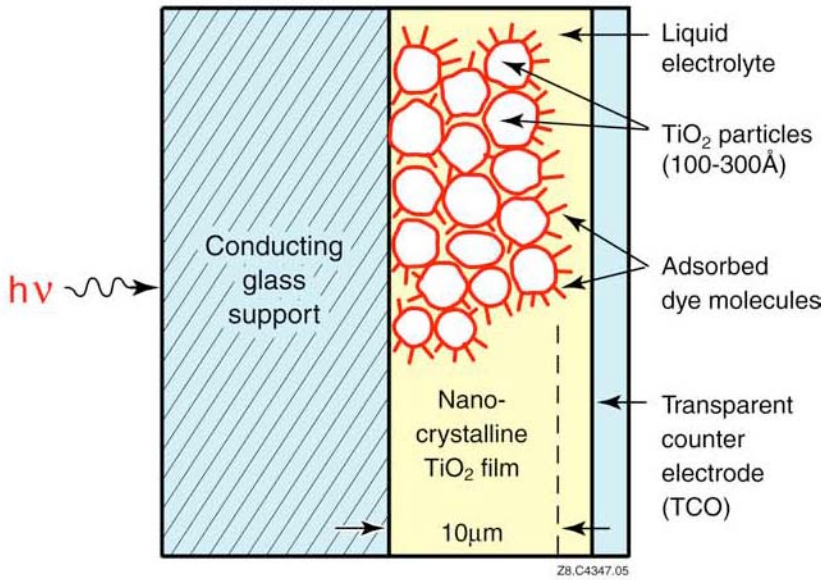
Action Spectra of a Bare Cell and the Same Cell with NMP^+



Band Diagram



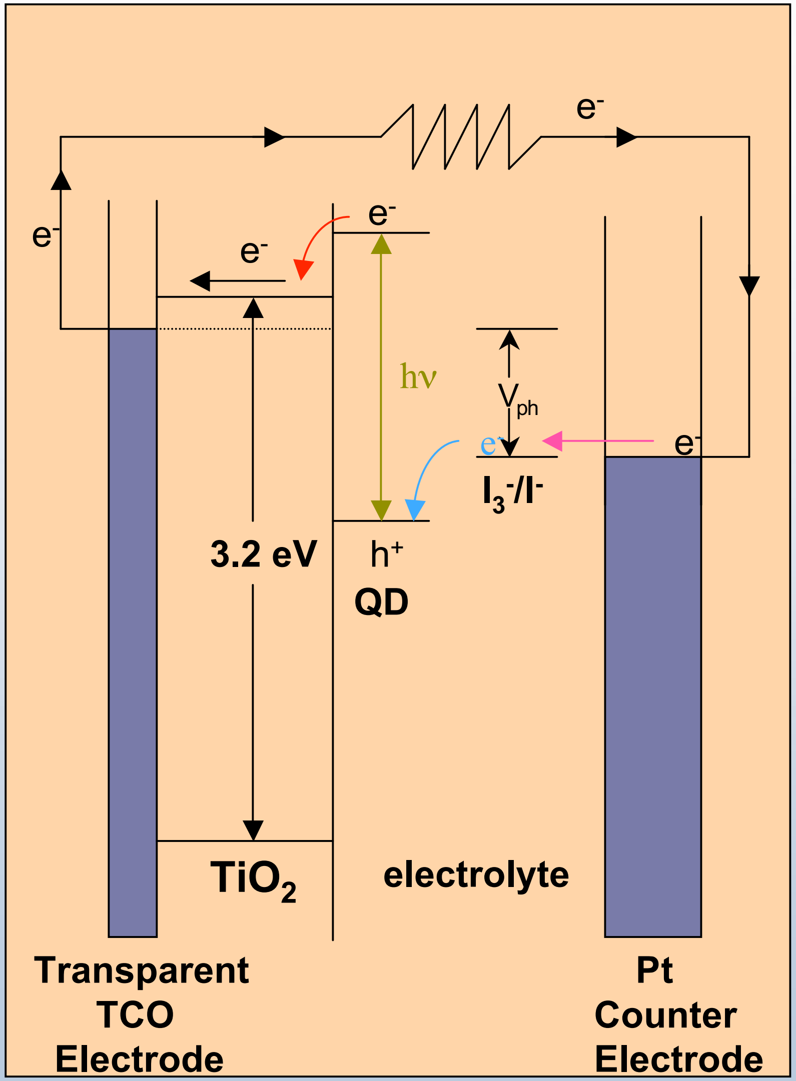
Dye-Sensitized Nanocrystalline TiO_2 Photochemical Solar Cell

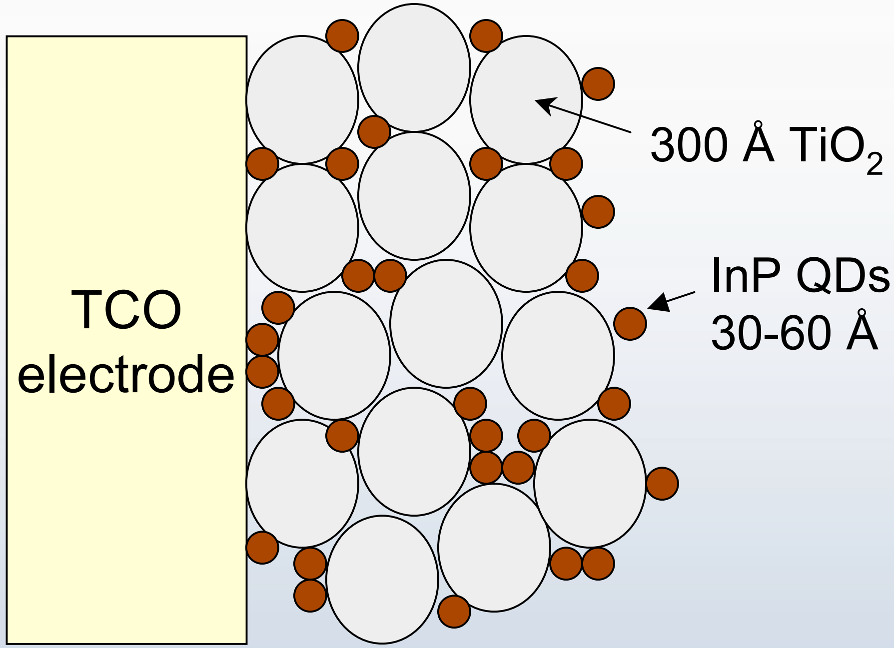


Research Issues and Directions for Dye-TiO_2 Solar Cells

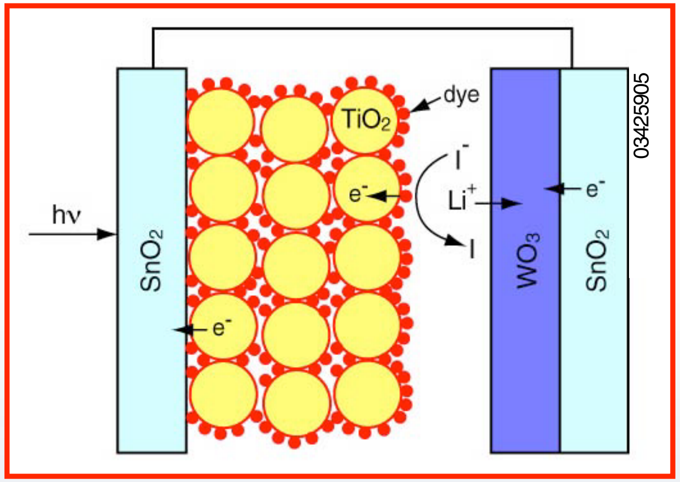
- Dynamics of electron transfer processes
- Surface and interface properties
- Charge transport in TiO_2 film and electrolytes
- Role of crystal structure and film morphology
- Electrolyte properties and solid electrolytes
- New Dyes and novel approaches to sensitization
- Efficiency enhancement- multi-junction devices
- Degradation mechanisms

Quantum Dot Sensitized TiO_2 Solar Cell



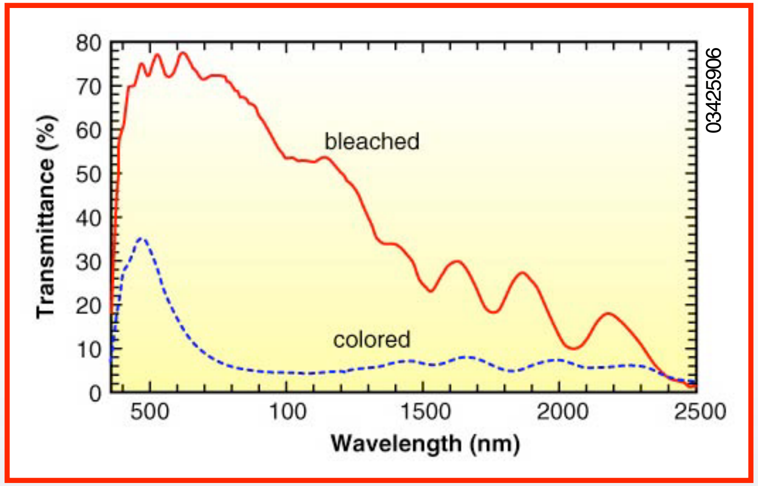


- -Analogous to dye-sensitized TiO_2 solar cells
  - -10 to 20 μm film of NC TiO_2 (10-30 nm)
  - -Ru dyes ⇒ Efficiency ~ 11%
- -Advantages of QD's as sensitizers:
  - -possibility of slowed hot e^- cooling
  - -possibility of impact ionization
  - -tunable absorption

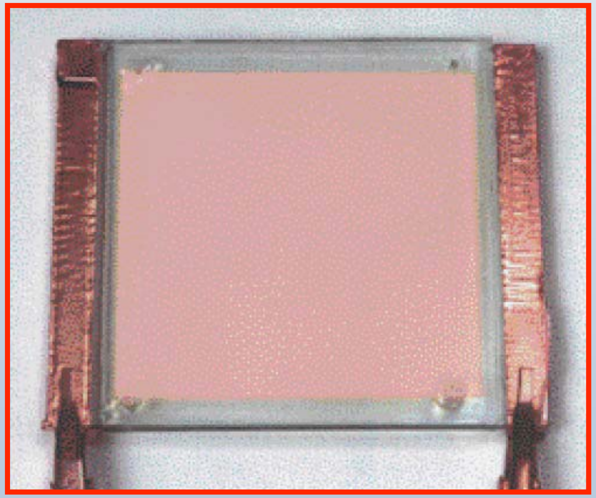


Schematic diagrams of a dye-sensitized electrochromic smart window.

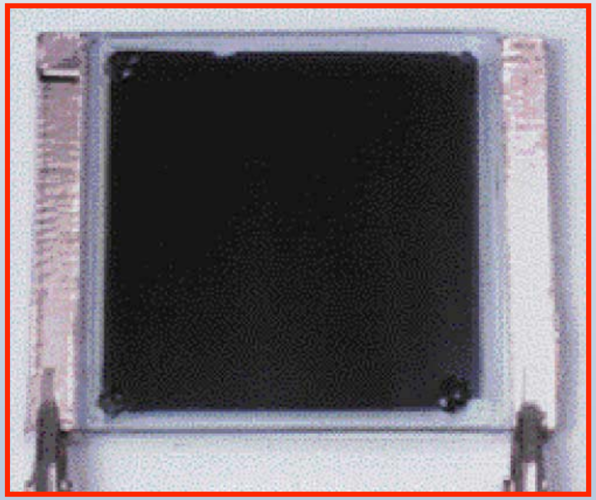
B.A. Gregg, Endeavour Vol. 21(2) 1997.



Transmittance spectra of an experimental solid-state electrochromic cell in both the bleached and colored states.

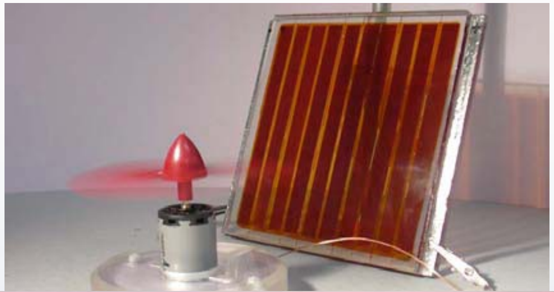


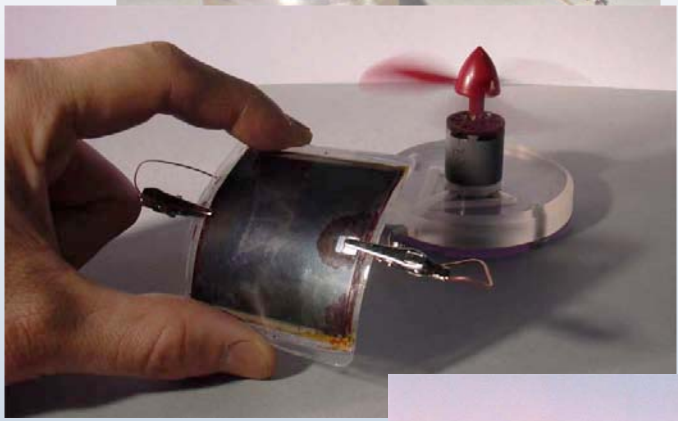
Bleached



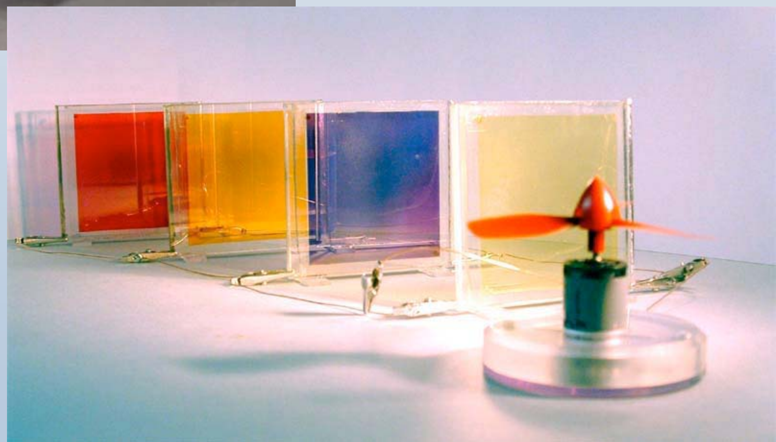
Colored

Dye-sensitized Solar Cells (DSC)





- attractive application
- light weight
- colorful
- sharp cut in production cost
- environmentally benign points

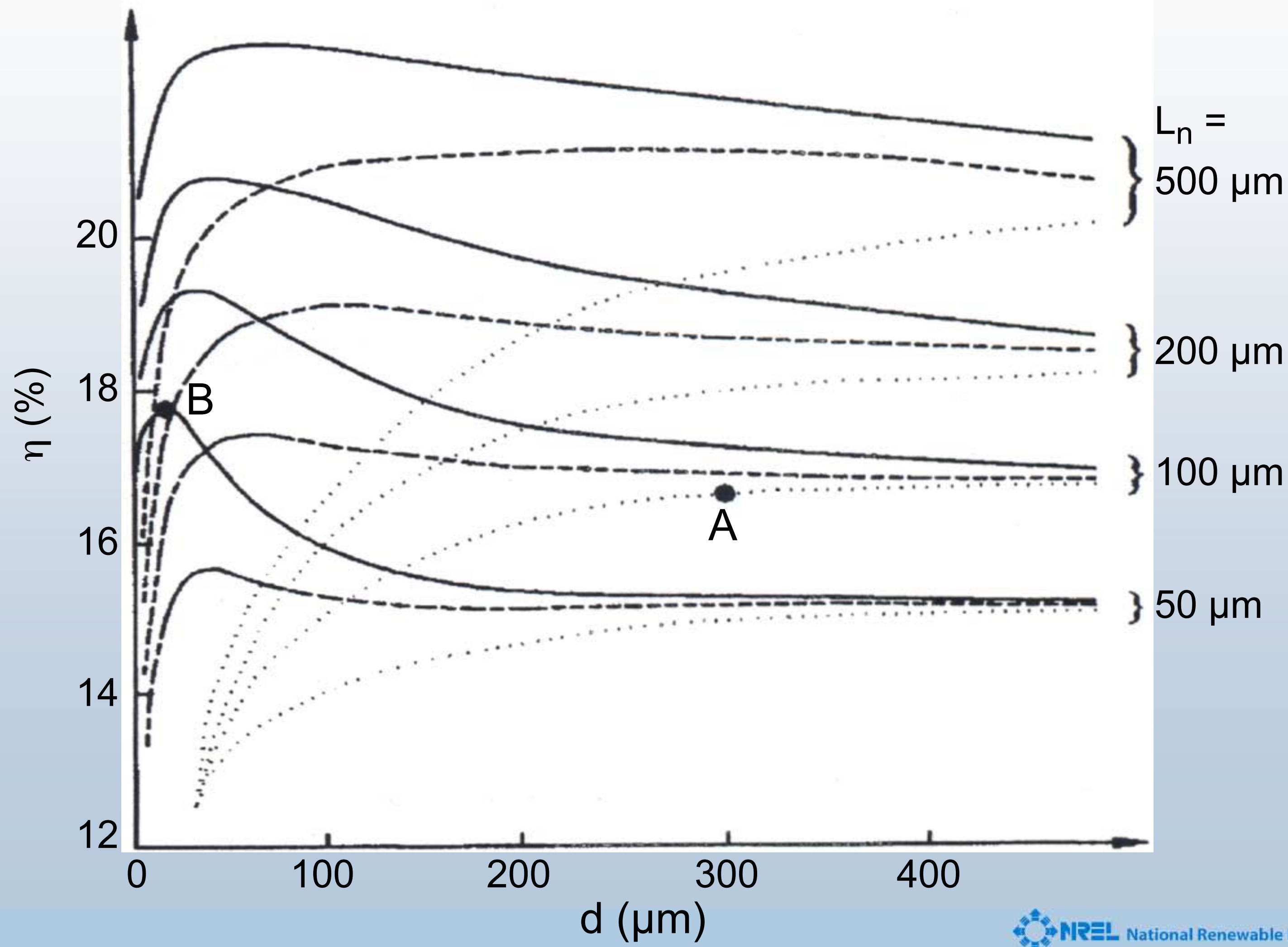


NIKKEI 2003.3

Thin Film Si Solar Cell

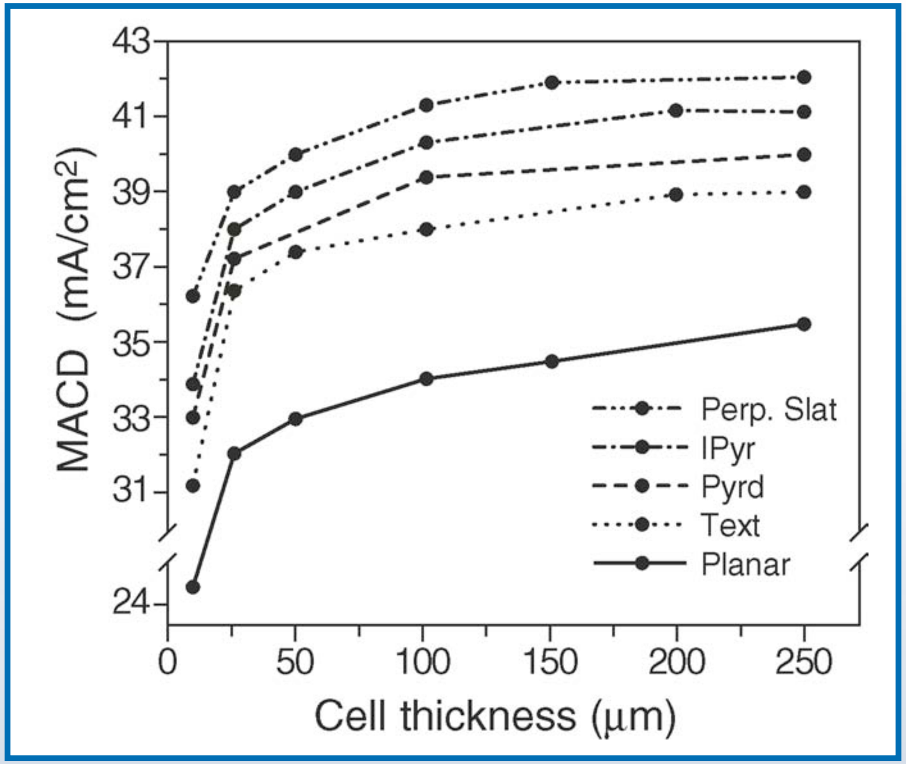
Calculated Efficiency of Solar Cells with Base Diffusion Length, L_n, and Base Thickness d, Having Very Good Emitters

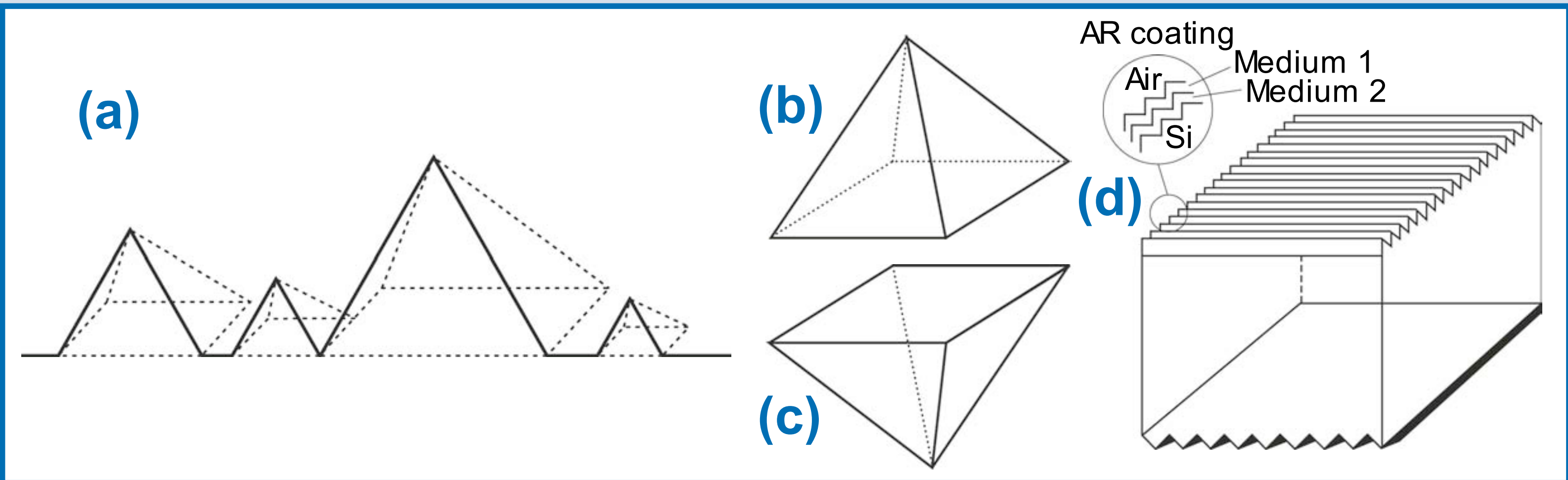
(Cell B [thin, with back surface field BSF and optical confinement OC] is better than cell A [thick, no BSF, no OC], though its diffusion length is lower.)



Calculated MACD for Si Solar Cells with Different Texture Shapes

Various Surface Structures (a) Random Pyramids (b) Textured Pyramids (c) Inverted Pyramids (d) Perpendicular Slats





Approaches to Thin-Film Polycrystalline Si Solar Cells on Different Substrates

Objective: To fabricate 10-20 μ Si film of sufficient electronic quality with high throughput (>1μ/min) on low-cost substrates at relatively low processing temperature.

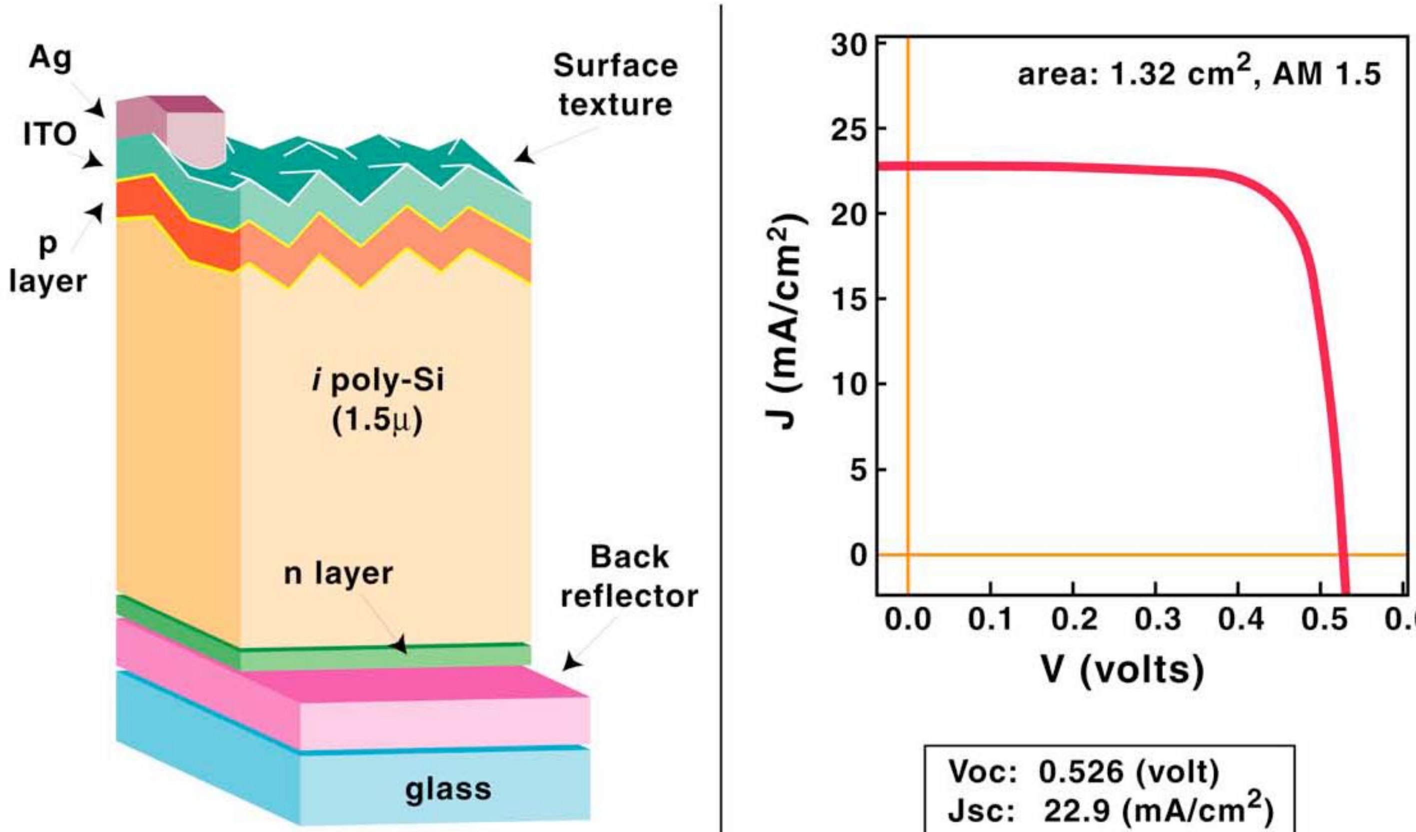
Approaches

(1) Single-crystal substrates (Cz or Fz growth)
- Epitaxial growth on porous silicon followed by separation by chemical etching
- Hydrogen implantation in subsurface Si-wafer followed by separation (demonstrated for 1μ Si layer)
- "Epilift" process consisting of deposition of epilayer on patterned single-crystal substrate

(2) Multicrystalline Si-substrate — metallurgical-grade Si-substrate

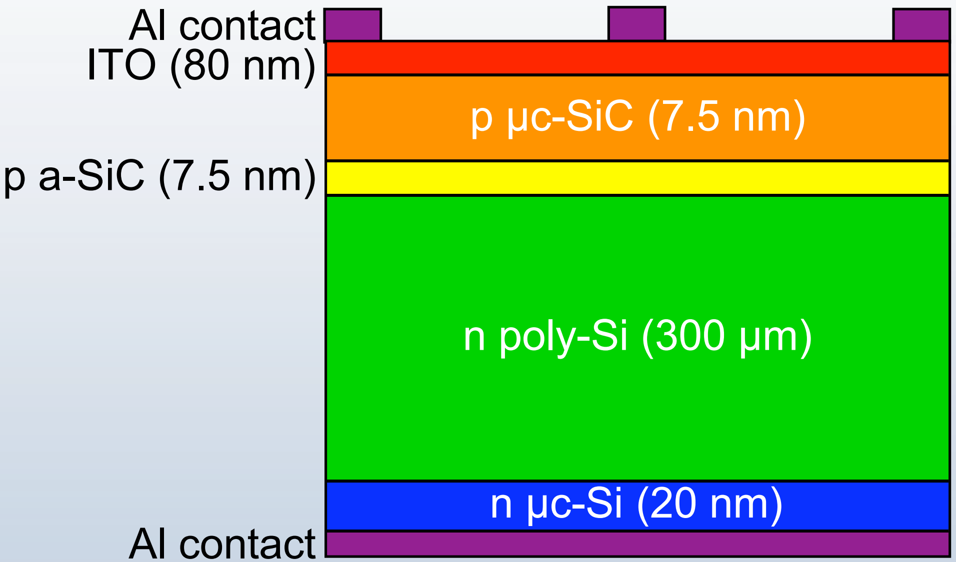
(3) Low-cost, non-silicon substrates — glass, ceramic, metals

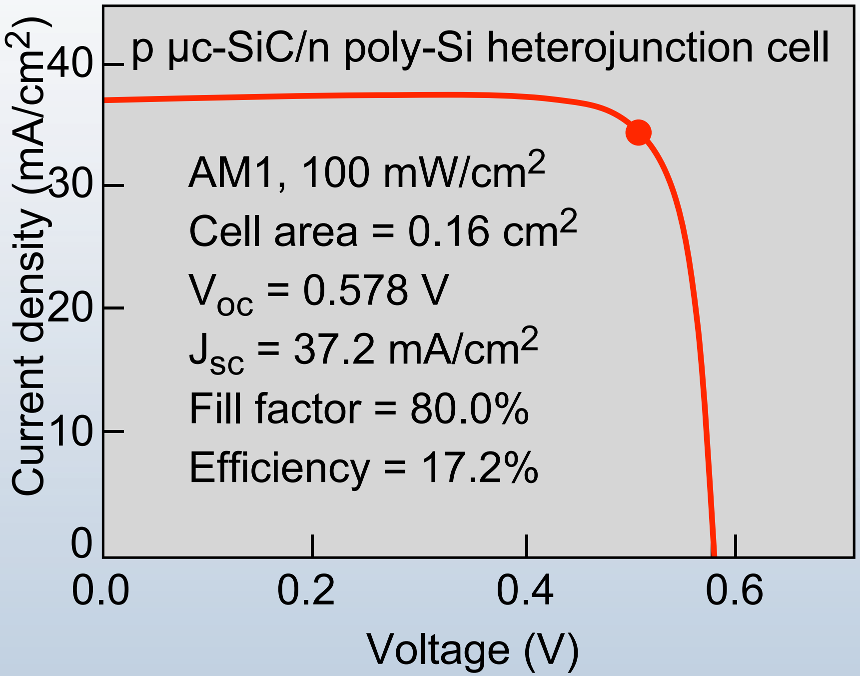
STAR Structure



Voc:	0.526 (volt)
Jsc:	22.9 (mA/cm^2)
F.F.:	77.2 (%)
Eff.:	9.3 (%)

μc-SiC/Poly-Si Heterojunction Solar Cell and Its Output Characteristics
(Presented by Osaka Univ.)





Thin-Film Solar Cells, Y. Hamakawa, Springer

Current Status of Thin-Film Si Solar Cell Efficiency*

Substrates	Efficiency (%)	Thickness range (μ)
(1) Single-crystal substrates processing temperature 300° - 1000°C	6 - 21.5	6 - 50
(2) Metallurgical-grade Si zone melt recrystallization at > 1300°C	14 - 16	50 - 60
(3) Glass, ceramics gas-phase growth techniques 100° - 600°C	8 - 13	2 - 50

* **Ref.** S.K. Deb and B. Sopori, Recent Advances in Thin Film Solar Cells - Handbook of Thin Film Devices, Vol. 2, ed. by M.H. Francombe, 311-362, Academic Press, 2000.

Summary of Various TF-Si Solar Cells

Technique	Institution	Temperature °C	Substrate	Processing	Efficiency	Remarks
Chemical Vapor Deposition (CVD)	Univ. de Neuchatel	200	Textured TCO/glass	3.6-μm, μc-Si by PECVD at 100 MHz (SiH_4), doping by PH_3 and B_2H_6, ZnO/Ag backcontact	8.5%, 1 cm^2 (1999) 13.1% a-Si:H/μc-Si 10.7% (1999)	Deposition rate < 2 A/s, unstabilized, Stabilized (other substrates possible)
	IMEC	>1000	P+ SILSO	20-μm film by thermal CVD, DARC, no texture, SiN passivation, evaporated contacts	13.7%, 4 cm^2 (1997)	No H passivation 11.6%, 7.6% on SSP, 10.3% on RGS, 13.2% on EFG
	FhG-ISE	>1000	Silicon Sheets from Powder (SSP)	First deposition BSF, 30 micron by thermal CVD, no texture, no H passivation, SiN coating	8.00%, 4cm^2 (1997)	Dep. Rate > 10 μm/min., 11.1%on SiLSO, 17.4% on FZ (inverted pyramids, local emitter, thermal oxide)
	Ecole Polytechnique	150	Textured TCO/glass	Polymorphous standard P-I-N, 0.4-0.8 micron I-layer.	9.30%, 0. 1 cm^2	Mixed a-Si:H/ μc-Si matrix
	Canon Co	200-400	Unknown	Standard N-I-P structures, Ag/ZnO back-contact, > 1 micron thick I-layer, VHF used.	7.4%, 0.25 cm^2 (1999) 11.5% a-Si:H/μc-Si	Stabilized results
Excimer laser crystallization	Kaneka Co.	600	Glass	Laser crystallization of 100-nm a-Si by PECVD (B_2H_6/SiH_4), followed by N- and P-type μc-Si and 6 micron intrinsic poly-Si (all PECVD), ITO front contact and Ag fingers.	10.1% 0.25 cm^2 (JQA 1997) 12.8% a-Si:H/μc-Si (1997)	Efficiency >14% expected

Summary of Various TF-Si Solar Cells

Technique	Institution	Temperature °C	Substrate	Processing	Efficiency	Remarks
Zone Melt Recrystallisation (ZMR)	Mitsubishi Electric Co.	>1300	SiO_2 on MG-Si	LPCVD 50-60 micron active layer, alkaline wet etching, P indiffusion, H passivation by ion implantation, DARC, backside etching for rear electrode	4.2%, 100 cm^2 (JQA 1993) 16.4 %, 4 cm^2	Recrystallization speed = 1 mm/s
	FhG-ISE	>1300	Perforated SiO_2 on Si	No seeding, no texture, no defect passivation, interdigitated grid, 30 micron by thermal CVD	6.1%, 4 cm^2 (1996)	9.3% by Large-Area Recrystallisation (LAR)
		>1300	Graphite	Interdigitated grid, reactive ion etching	11.0% , 4 cm^2 (1997)	9.3% on ceramic, >17% expected for screenprinting
Solid Phase Crystallization (SPC)	Sanyo Electric Co.	600	Metal	PECVD p-type a-Si:H (SiH_4), ITO sputtering, evaporation of Ag finger contacts	9.2%, 1 cm^2 (1994)	10-um a-Si, 10-600 min annealing
Liquid-Phase Epitaxy (LPE)	Astropower Inc.	~1000	Graphite cloth	Gas phase P indiffusion, PECVD H passivation, photolithographic contacts, DARC	13.4%, 1 cm^2 (NREL 1994)	Si directly deposited on substrate, active layer =80 μm
			Unknown	$POCl_3$, Al gettering, H passivation, PECVD SiO_2 as ARC	14.6%, 1 cm^2 (NREL 1996)	Film thickness unknown
			Unknown	Unknown	16.6%, 1 cm^2 (NREL 1997)	Record thin film Si on foreign substrate, no vacuum process

Future Developments of Thin-Film Si (polycrystalline) Solar Cells

- New approaches to improvements in materials quality (grain size, electron transport, grain-boundary passivation, etc.) on low-cost substrates
- Breakthroughs in high-throughput growth rates
- Surface morphology and roughness control to achieve optimum light-trapping
- Novel approaches to converting indirect-bandgap Si to direct bandgap (co-doping, quantum confinement, Si:Ge superlattice structure, etc.)

GaAs Thin-Film Solar Cells

Current Status and Potential Advantages

- Material with optimum energy gap and light absorption characteristics
- High efficienty (~25%) achieved on epitaxially grown GaAs on Ge-coated

  GaAs single crystal substrate
- High efficiency GaAs thin solar cells fabricated on reusabel substrate

  (CLEFT Process)
- Polycrystalline thin film GaAs solar cells (h = 11%) fabricated in early

  1980s using low-cost w-coated graphite substrate

Current-Voltage Characteristics of $p^+/n/n^+$ Polycrystalline GaAs Thin Film Homojunction Solar Cells*

(1) Cell fabricated on substrate with graphite (2-3μ GaAs), 1 cm^2

V_{OC} = 0.57 V I_{SC} = 24.5 mA/cm^2 FF = 63% η = 8.8%

(2) On large-grain Ge-substrate (6-7μ GaAs), 1 cm^2

V_{OC} = 0.69 V I_{SC} = 18.8 mA/cm^2 FF = 0.72 η = 9.3%

(3) On large-grain Ge-slices, 1 cm^2

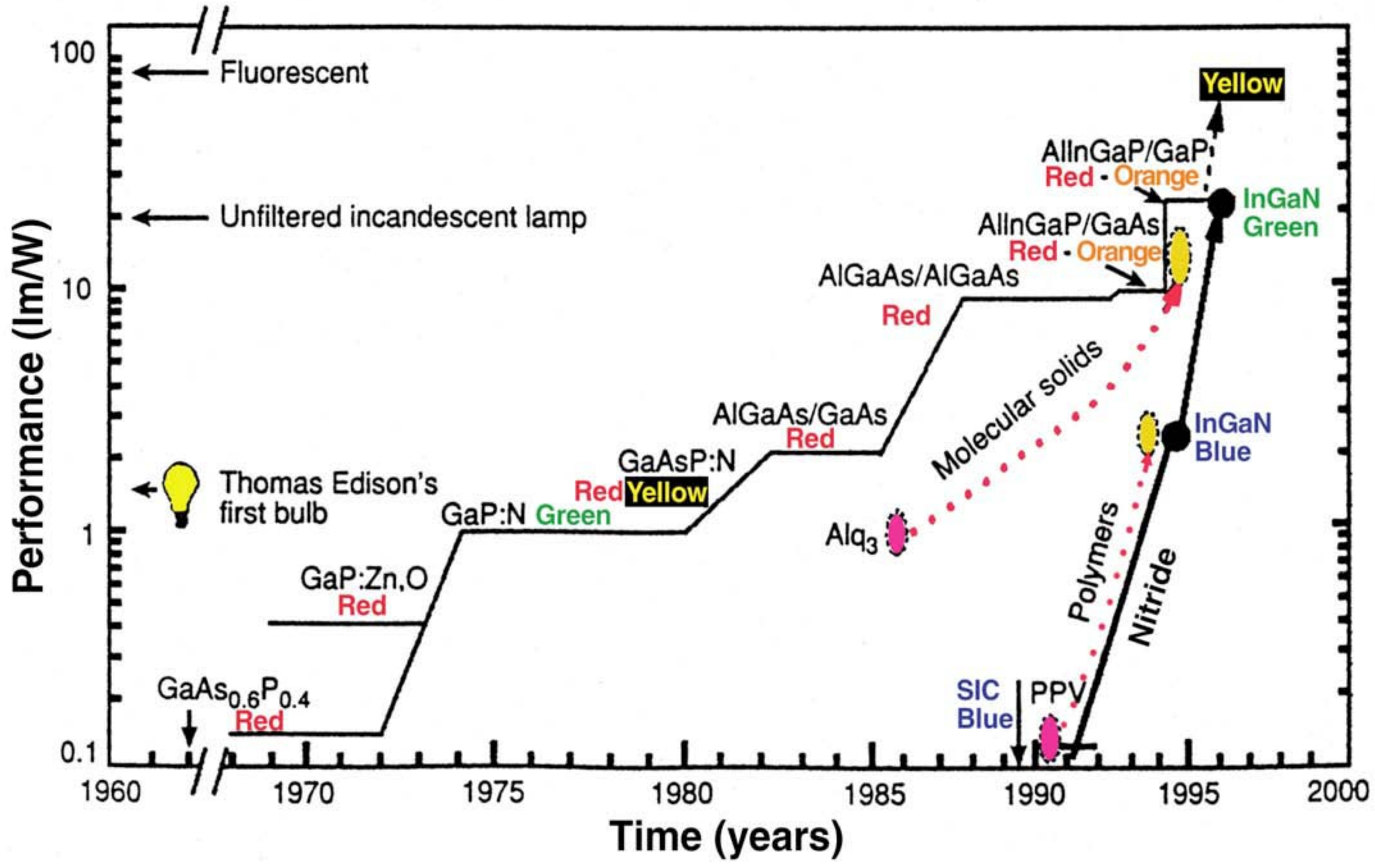
V_{OC} = 0.84 V I_{SC} = 17.7 mA/cm^2 FF = 0.69 η = 10.3%

(4) On Ge-coated single-crystal Si substrate, 25 mm^2

V_{OC} = 0.8 V I_{SC} = 21.0 mA/cm^2 FF = 0.708 η = 11.9%

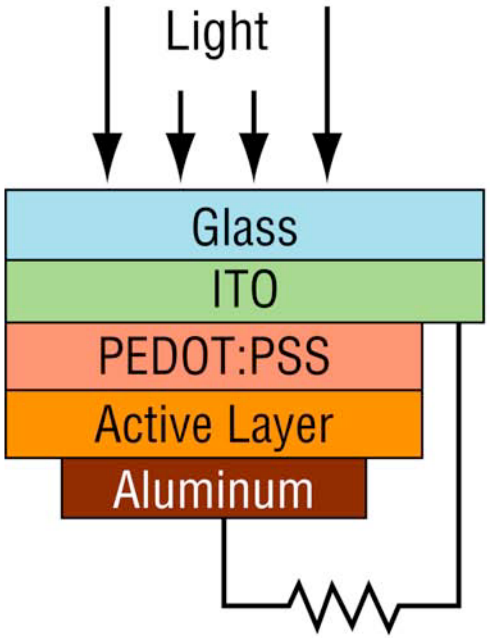
* SERI subcontract # XL-4-04018 and SERI/STR 211-2471, S. Chu et al. 1983-1985.

Organic Thin Film Solar Cell

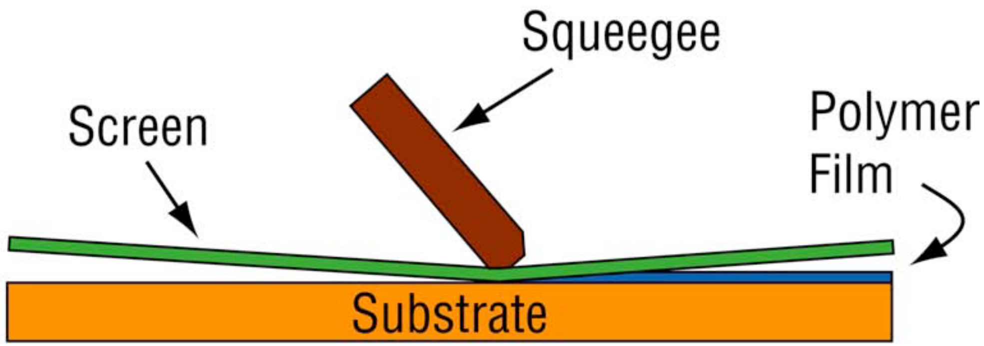


Progress in LED efficiencies.

Sheats *et al.,* H.P. Lab, Science 273, 884 (1996).

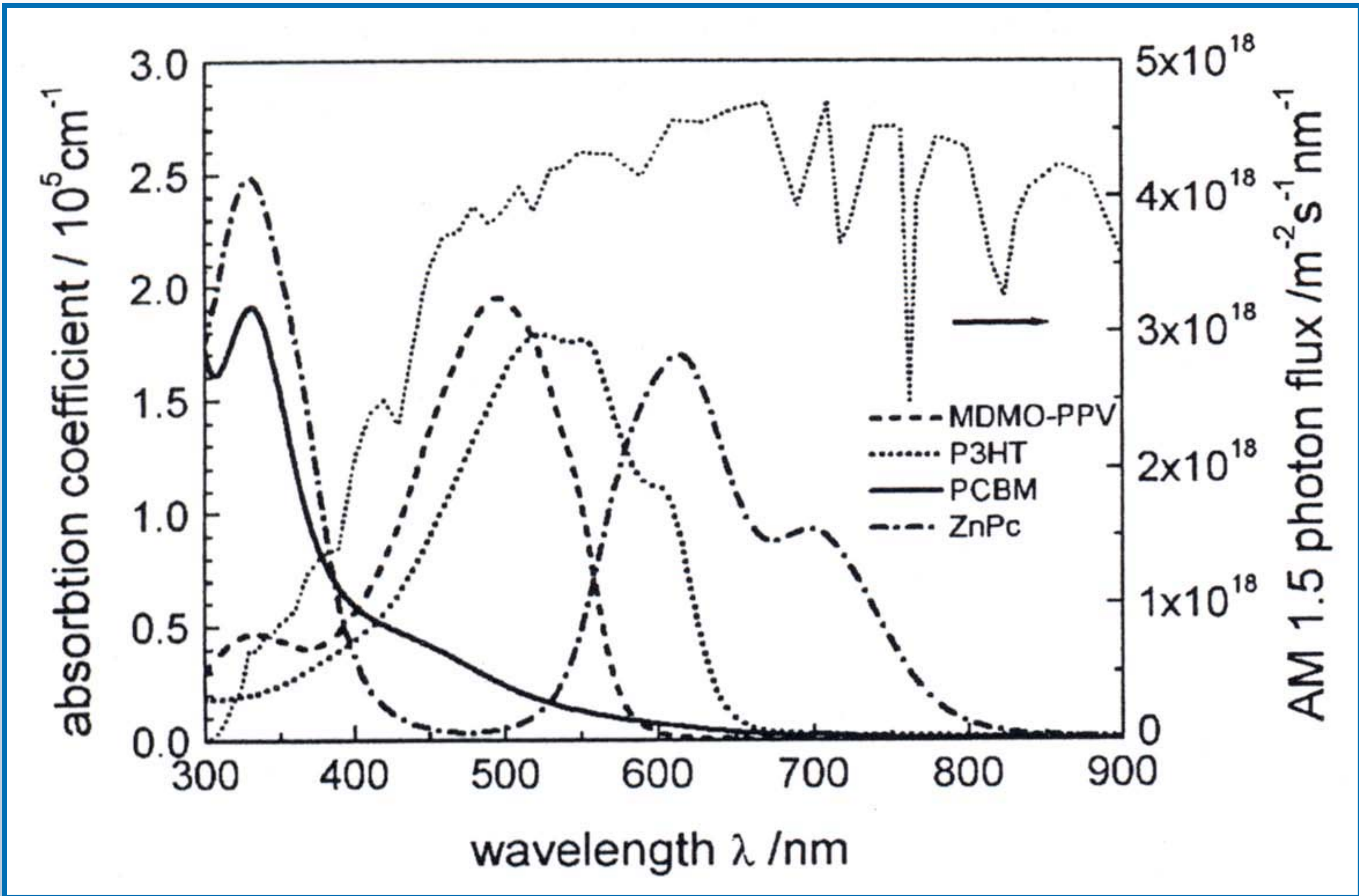


Bulk Heterojunction Solar Cell Connected To An External Resistive Load & Screen Printing Technique

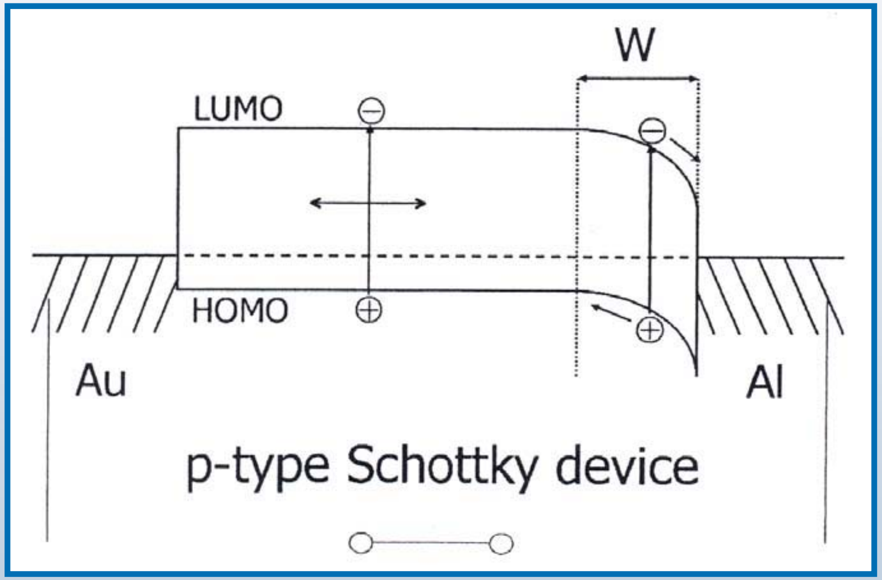


Absorption Coefficients of Films of Commonly Used Materials are Depicted in Comparison with the Standard AM 1.5 Terrestrial Solar Spectrum

(the overlap is generally small)

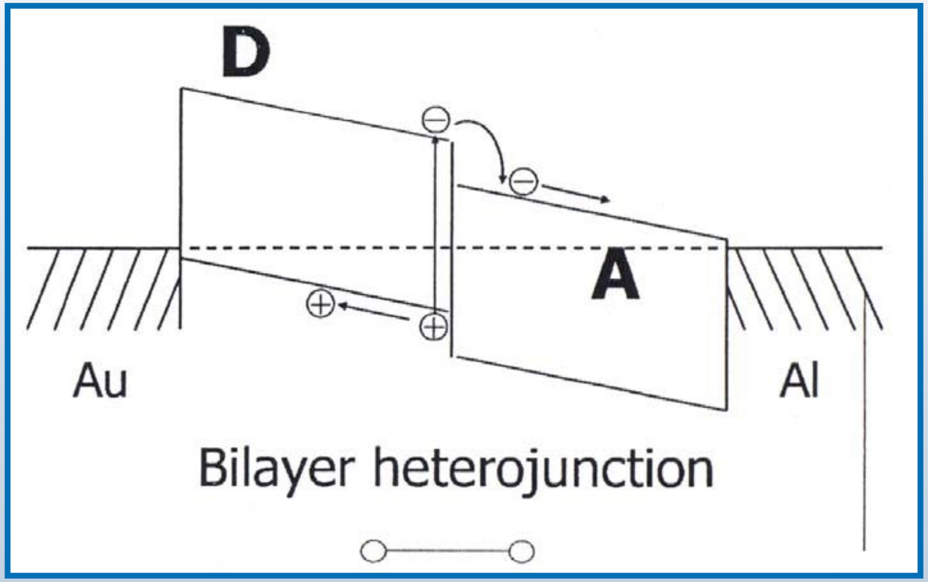


Single Layer Device with a Schottky Contact at the Aluminum Contact



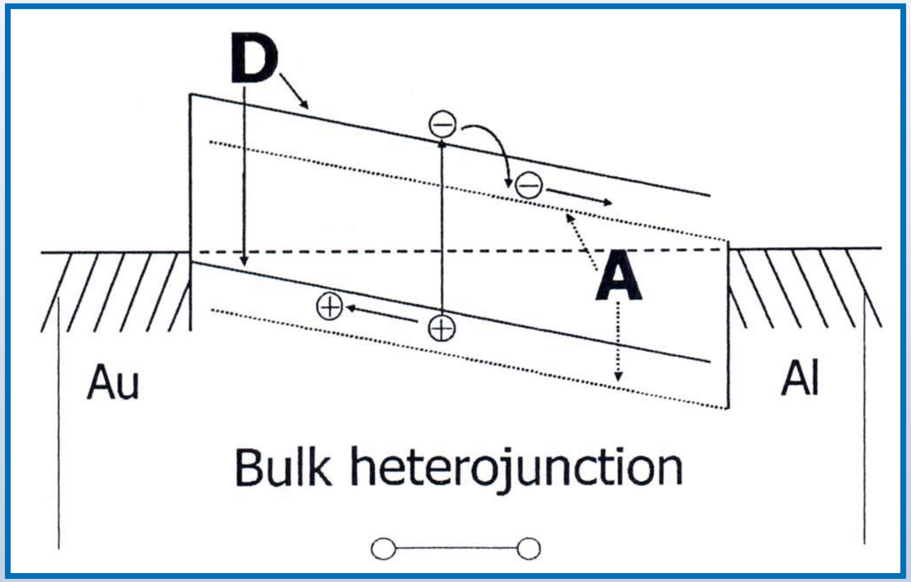
Bilayer Heterojunction Device

(The donor [D] contacts the higher and the acceptor [A] the lower work function metal, to achieve good hole and electron, respectively.)

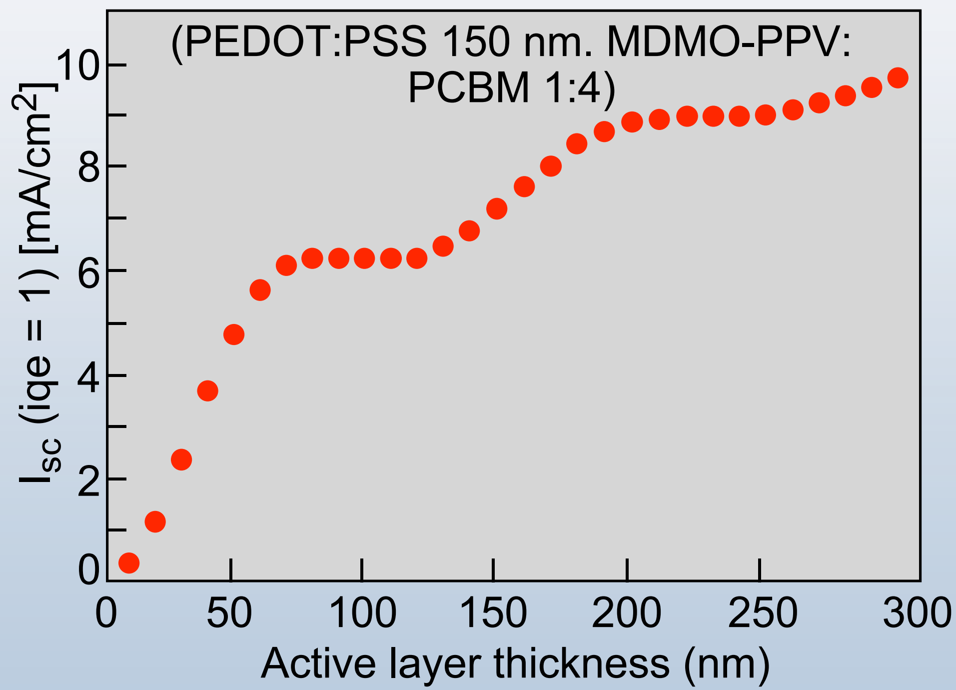


Bulk Heterojunction Device

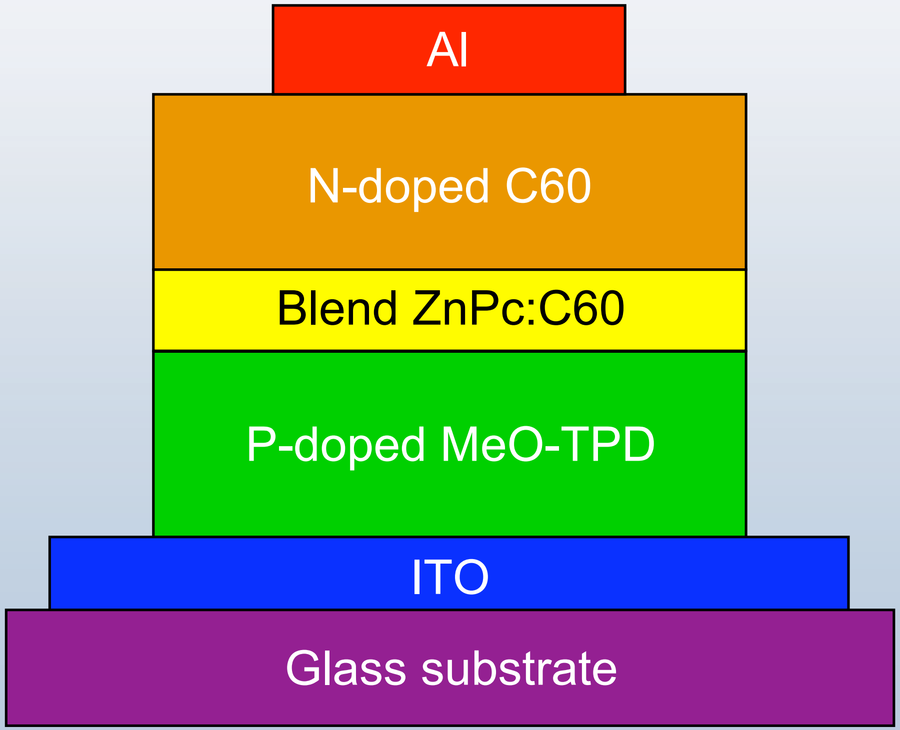
(The donor [D] is blended with the acceptor [A] throughout the whole film.)

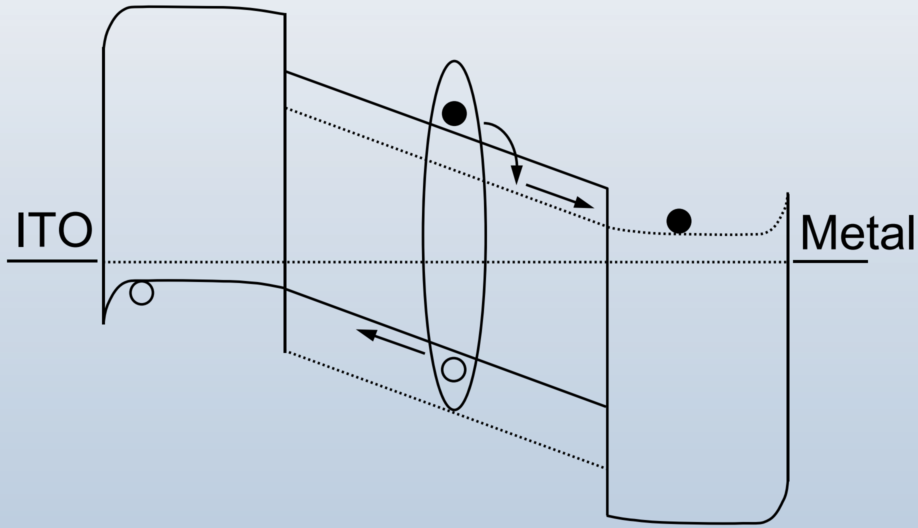


Calculated Photocurrent of a MDMO-PPV:PCBM-Based Solar Cell under the Ideal Assumption of an Internal Quantum Efficiency of Unity



Structure (left) and the Energetic Description at Closed Circuit Conditions (right) of an Organic p-i-n Solar Cell





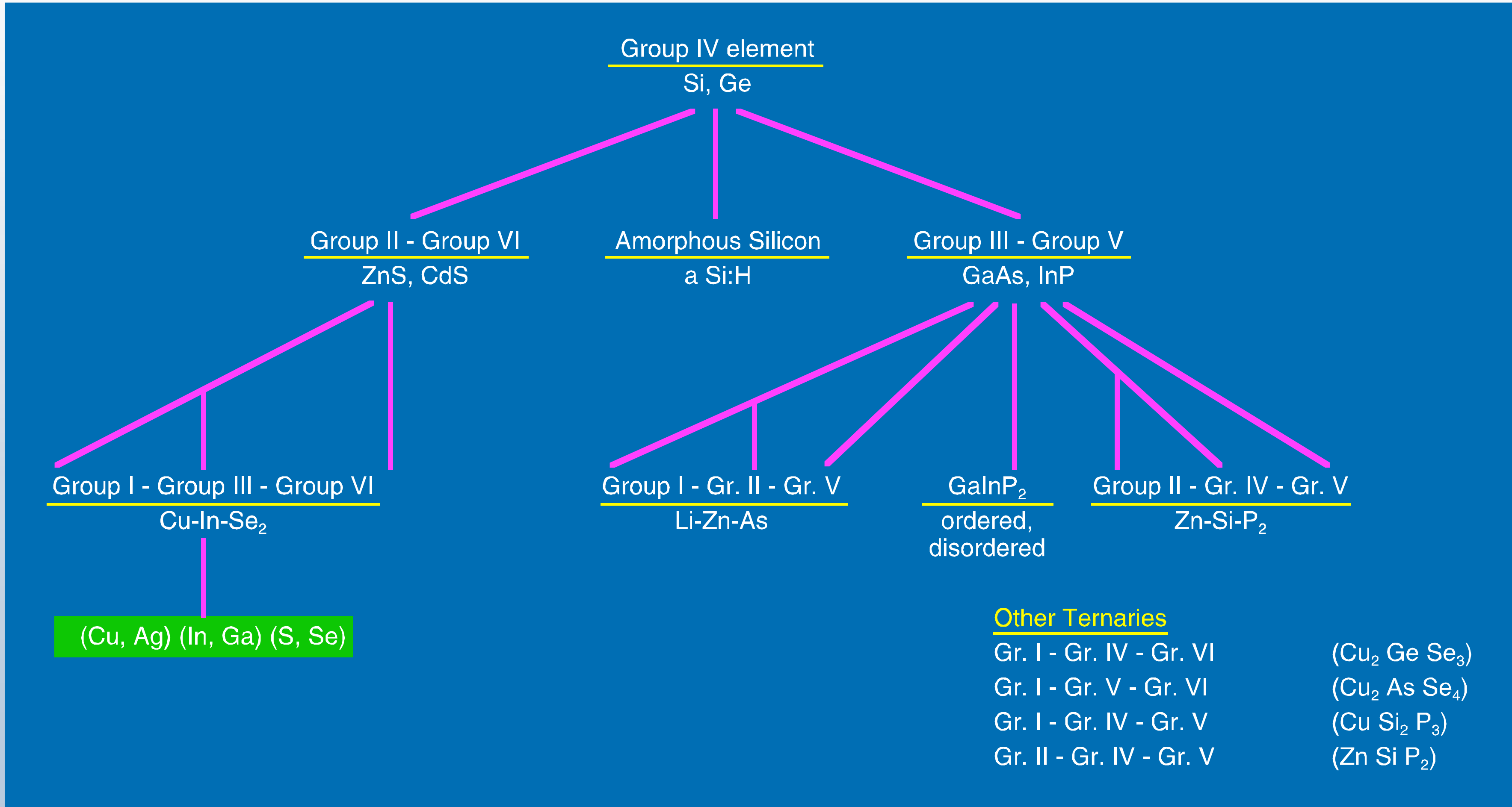
Reported Efficiencies of Some Recent Organic Solar Cells at AM1.5

Device Structure	η(%)	Ref.
ITO/CuP$_c$/PV/Ag	1.0	59
ITO/MEH-PPV-C_{60}/Al or Ca	2.9	60
ITO/POPT + MEH - CN - PPV (5%)/top layer MEH-CN-PPV + POPT) 5%/Al or Ca/bottom layer	1.9	61
Ag/ITO/Pentacene/Al or Mg	2.4	62
ITO/CuPc/PTCBI/BDP:PTCBI/Ag	2.4	63
ITO/PEDOT/MDMO-PPV: PCBM/LiF/Al	2.5	64
ITO/PEDOT: PSS/CuP$_c$/C_{60}/BCP/Al	3.6	65
ITO/PEDOT:PSS/MDMO-PPV: PCBM/Al	4.3	66

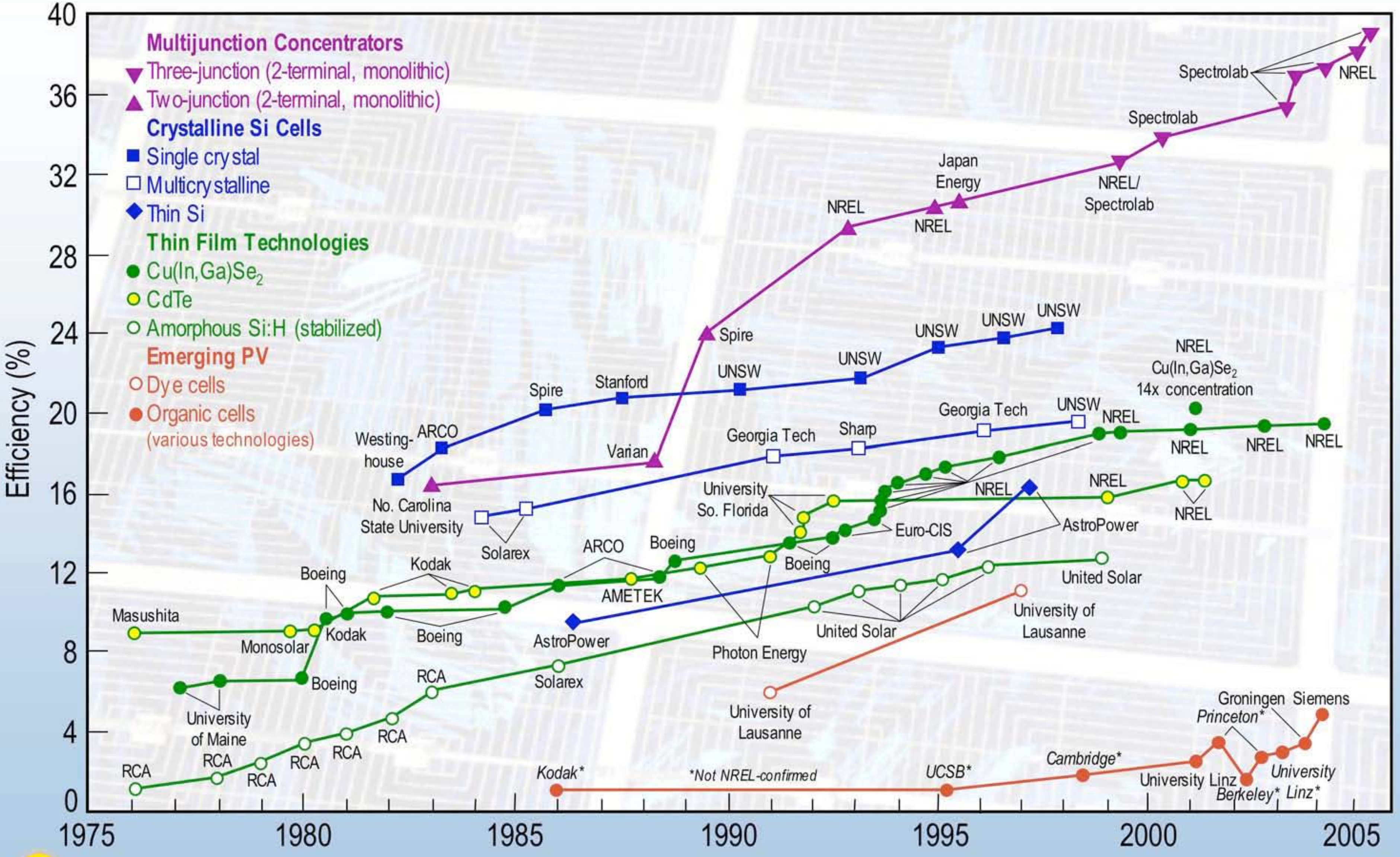
CuP$_c$: Copper Phthalocyanine; PEDOT: Polyethylenedioxythiophene; PSS: Polystyrenesulfonate;C_{60}: Fullerene; BCP: Bathocuproine; PTCBI: Perylenetetracarboxylic-bis-benzimidazole; MEH: Methoxyethoxyhexyloxy; PPV: Polyphenylenevinylene; POPT: derivative of Polythiophene

Global Views of Semiconductor Materials for PV Applications

Elemental, Binary, and Ternary Semiconductors



Best Research-Cell Efficiencies



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NREL National Renewable Energy Laboratory

Science Topics Needed by All Thin Films

- Science Base
- Degradation and Metastable Mechanisms
- Device Characterization and Modeling
- In situ process diagnostics and controls
- Device protection from water vapor
- Innovative module design, including cell interconnects, device protections, lower-cost substrate, less-costly replacement packaging

Conclusions

- Future of thin-film solar cells looks very promising
- Major improvements in efficiency, stability, and reduction in cost are being made continuously
- Multiple options are available
- Industries are gearing-up for large-scale production
- Performance gap between laboratory scale devices and commercial modules needs to be narrowed
- Opportunities are enormous for new innovation in terms of materials and device technologies