Photovoltaics: Meeting the Terawatt Challenge

Harry Atwater
Thomas J. Watson Laboratories of Applied Physics
California Institute of Technology

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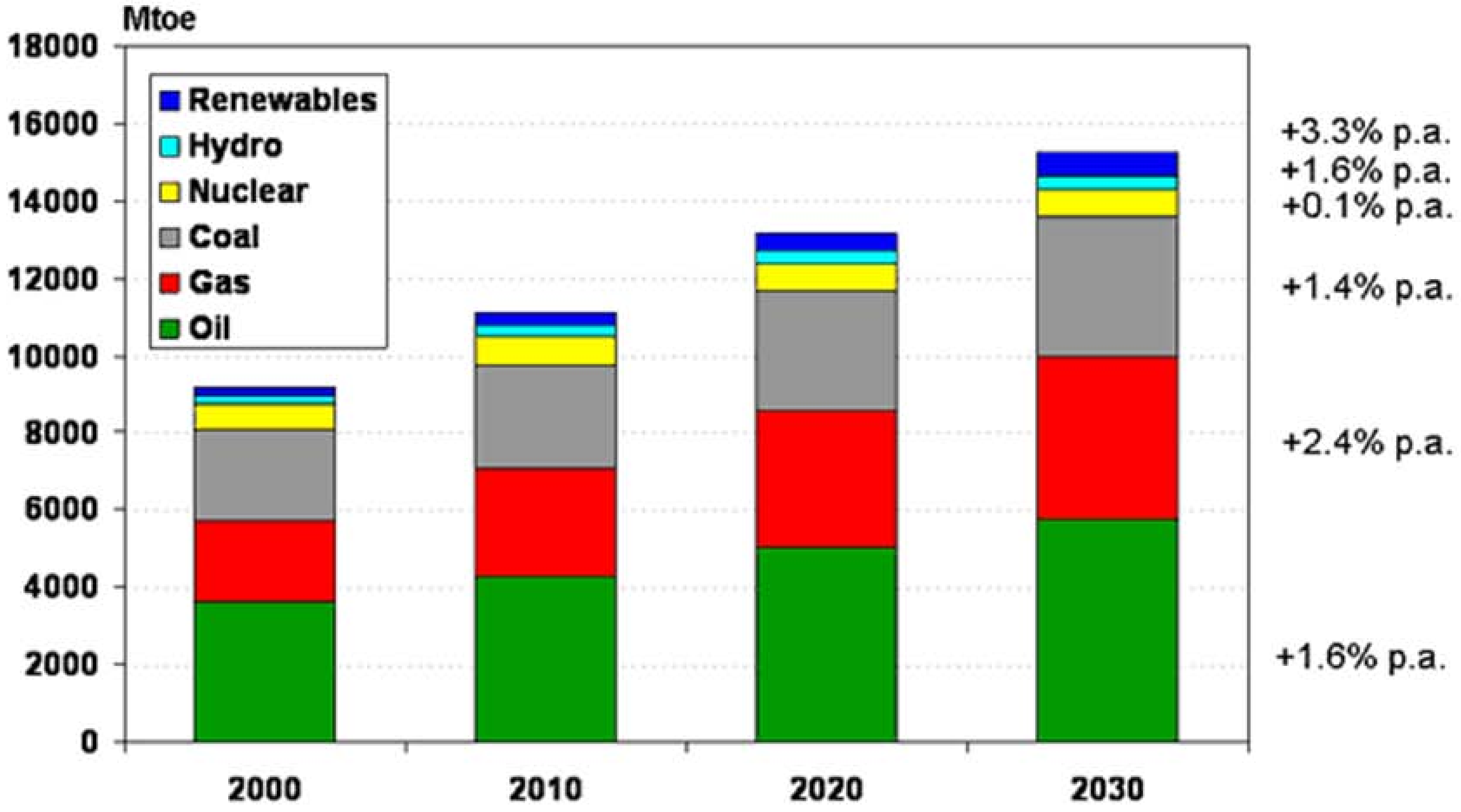
- *Photovoltaics in the Context of Energy Supply Need*
- *Limits to Photovoltaic Efficiency*
- *Silicon PV: the Incumbent Technology*
- *Multijunction PV: Path to Ultrahigh Efficiency*
- *3rd Generation PV: Beyond the Schockley-Queisser Limit*
- *Nanowire Photovoltaics*
- *Plasmonic Photovoltaics*

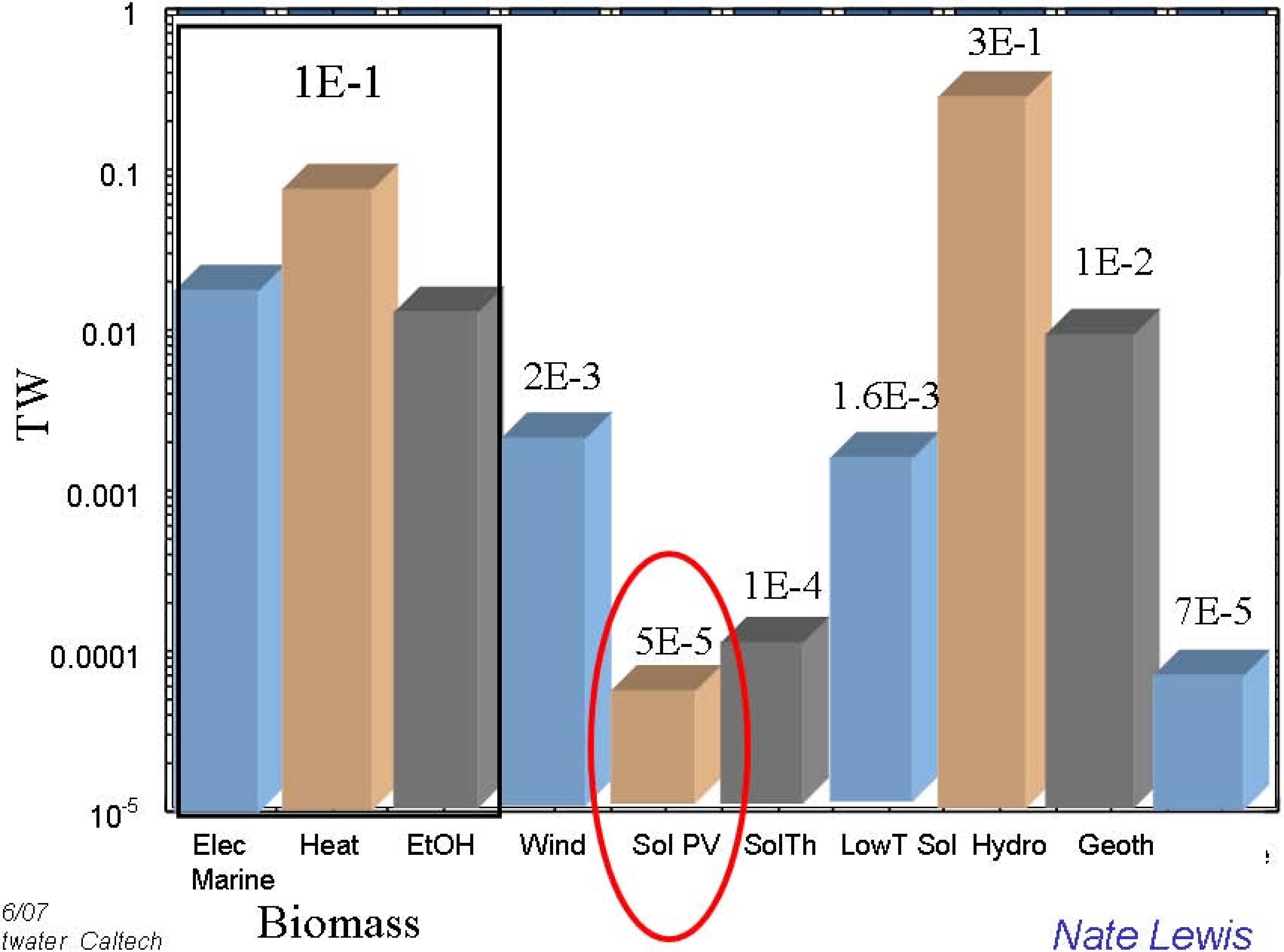
Energy Consumption by Source: 'Business as Usual' Scenario



Source: IEA WEO 2002

from: Steve Koonin; source: IEA WEO

Energy From Renewables, 1998



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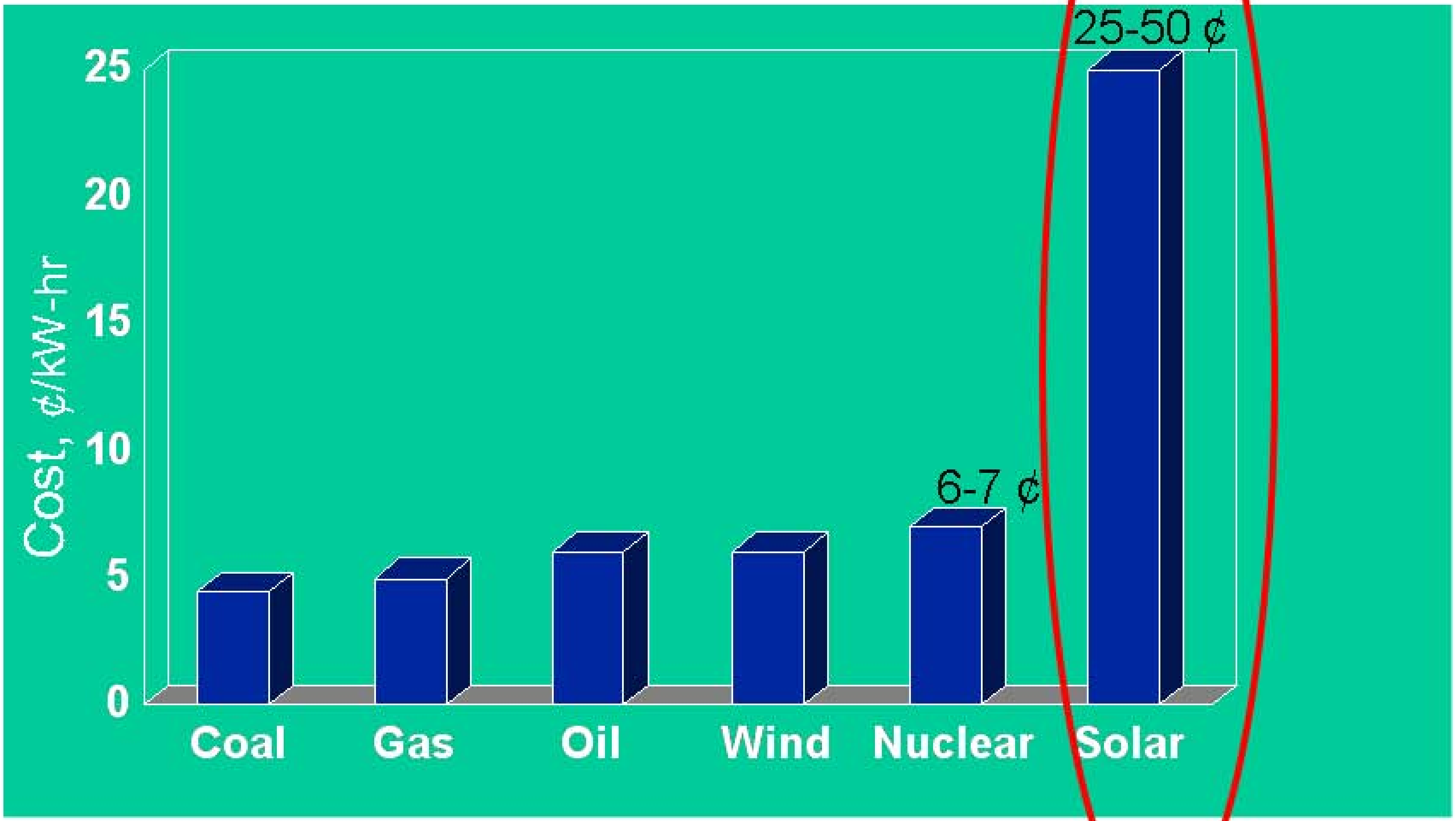
Nate Lewis

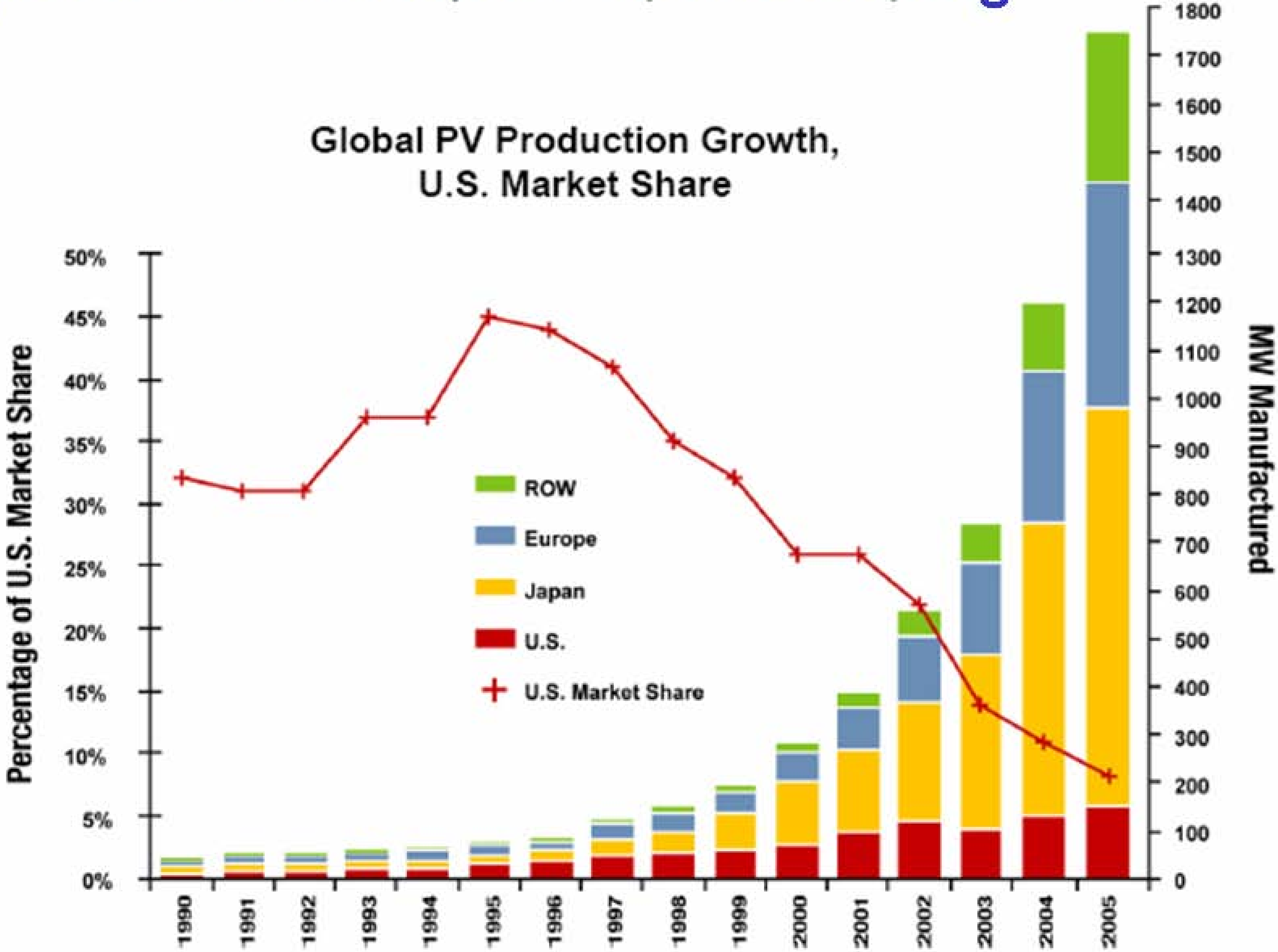
Production Cost of Electricity

(in the U.S. in 2002)

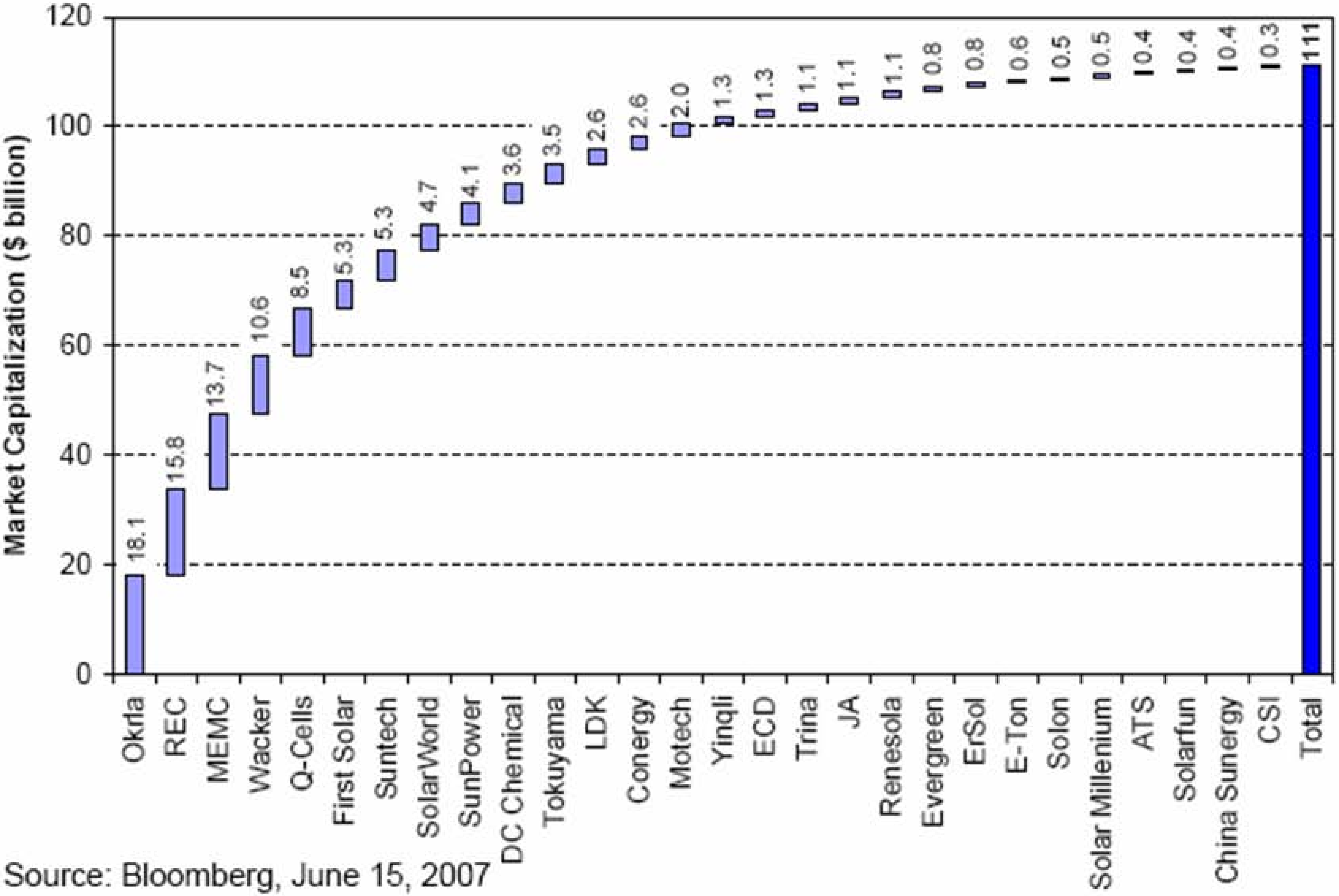


US DOE

Explosive Growth in PV Manufacturing



PV Company Market Capitalization



Source: Bloomberg, June 15, 2007

Plenty of fossil fuel energy…
… so why PV at (presently) higher cost?

Energy Security

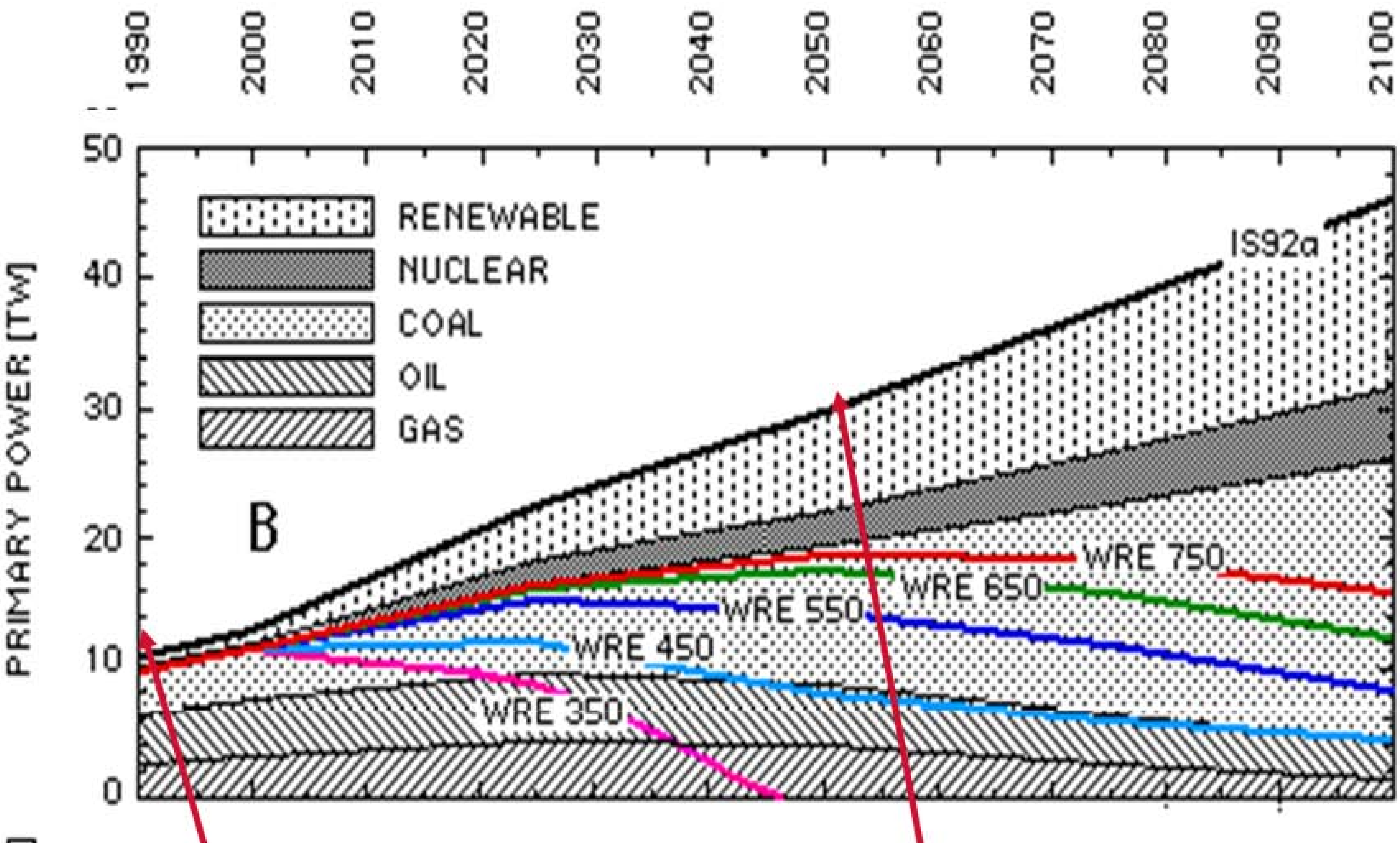
Photo : Javad Moghimi

OPEC Heads of State

Climate Change

Nobel Peace Prize Winner
Venture Capitalist

Total Primary Power vs Year



1990: 12 TW 2050: 28 TW

Marty Hoffert, NYU

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The New York Times

By FELICITY BARRINGER
Published: September 15, 2006

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AN INCENTIVE-DRIVEN VENTURE Dan Bolden installing solar panels in a subdivision in Rocklin, Calif. A new law requires the panels to be a standard option for buyers of new homes by 2012.

SACRAMENTO — In the Rocky Mountain States and the fast-growing desert Southwest, more than 20 power plants, designed to burn coal that is plentiful and cheap, are on the drawing boards. Much of the power, their owners expected, would be destined for the people of California. But such plants would also be among the country's most potent producers of carbon dioxide, the king of gases linked to global warming. So California has just delivered a new message to these energy suppliers: ***If you cannot produce power with the lowest possible emissions of these greenhouse gases, we are not interested.***

Office of the Governor

ARNOLD SCHWARZENEGGER
THE PEOPLE'S GOVERNOR

08/21/2006 GAAS:549:06 FOR IMMEDIATE RELEASE Print Version

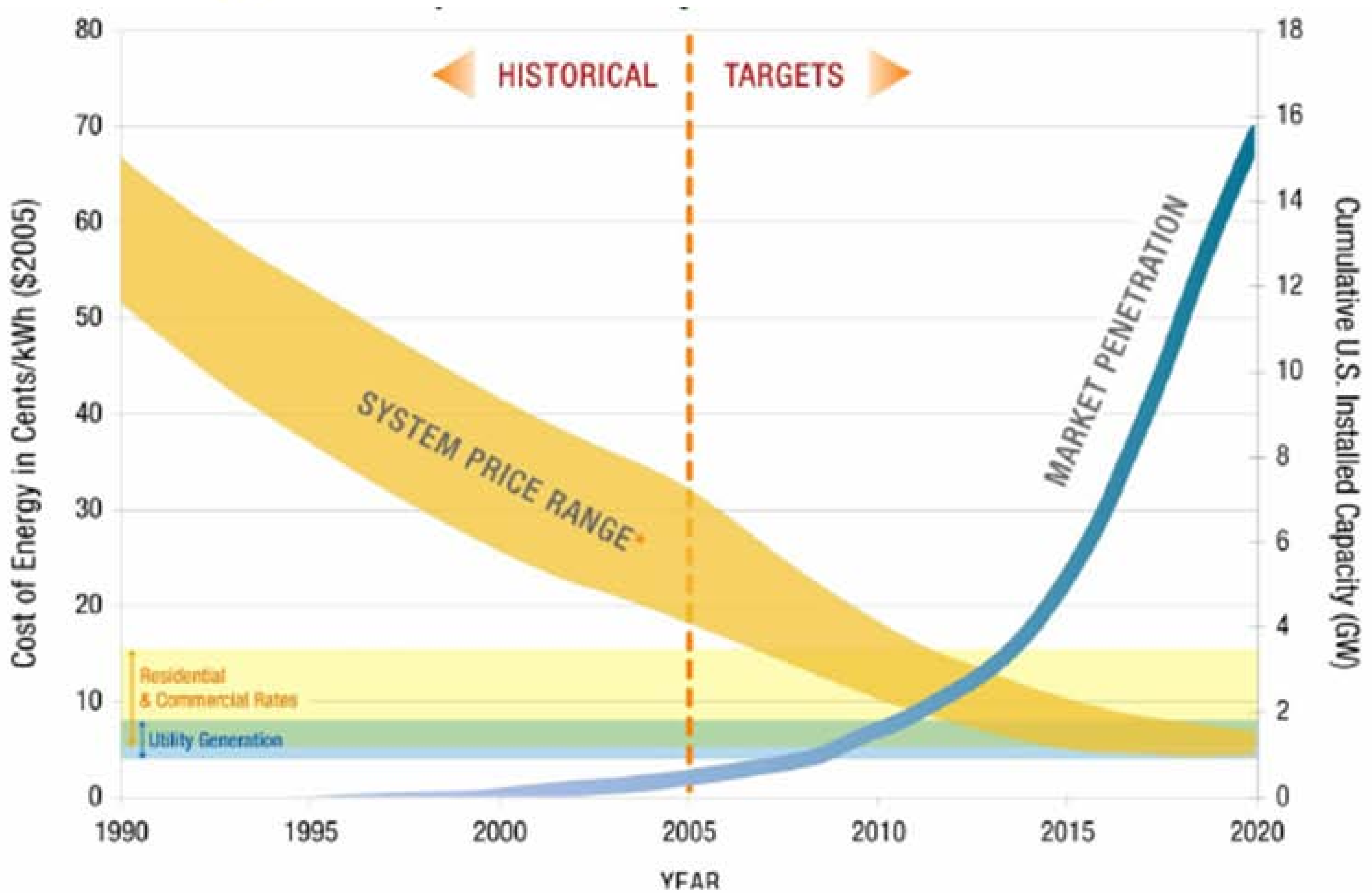
Schwarzenegger Signs Legislation to Complete Million Solar Roofs Plan

Governor Arnold Schwarzenegger delivers remarks before signing SB 1, a bill that completes his Million Solar Roofs plan.

Concluding a two-year effort to help make California the nation's leader in solar energy, Gov. Schwarzenegger signed SB 1 by Senator Kevin Murray (D-Los Angeles), putting the finishing touches on the Governor's Million Solar Roofs Plan.

"When I ran for governor, I vowed to make the environment the centerpiece of my administration and turn back the clock on pollution," said Gov. Schwarzenegger. "My Million Solar Roofs Plan will provide 3,000 megawatts of additional clean energy and reduce the output of greenhouse gasses by 3 million tons which is like taking one million cars off the road. I want to thank Sen. Kevin Murray for his hard work in helping me make California the leader on solar power again."

PV Nearing a Commercial Revolution



Market Sector	Current U.S. Market Price Range (¢/kWh)	Cost (¢/kWh) Benchmark 2005	Cost (¢/kWh) Target 2010	Cost (¢/kWh) Target 2015
Residential	5.8-16.7	23-32	13-18	8-10
Commercial	5.4-15.0	16-22	9-12	6-8
Utility	4.0-7.6	13-22	10-15	5-7

PV Today: Building Integrated Photovoltaics

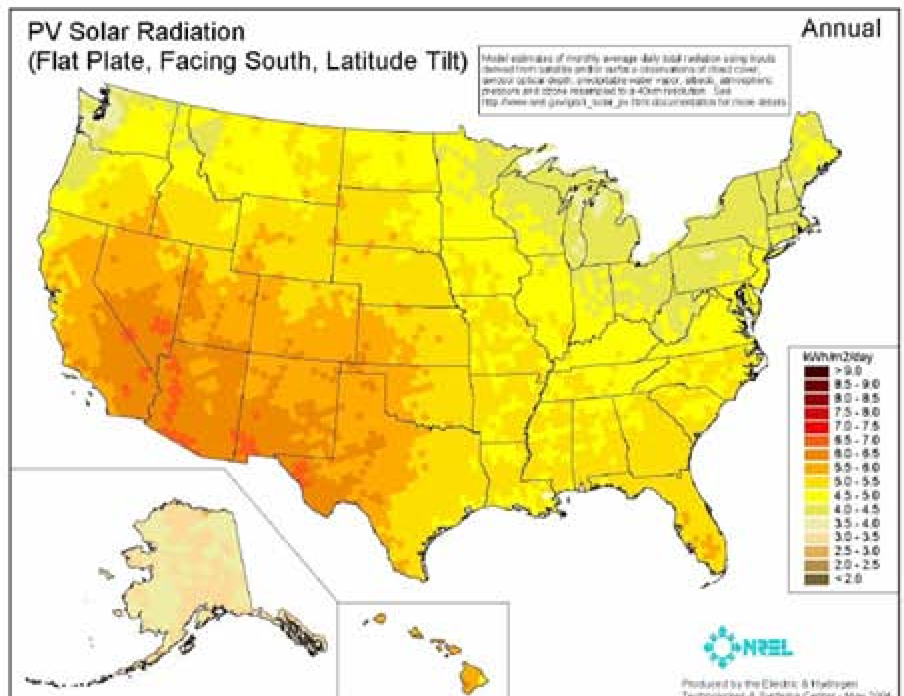
Solar Tract Homes, Steinfurt Germany

Scheidegger Building, Bern Switzerland

Industrial Rooftop Installation

BP Solar Headquarters, Frederick MD

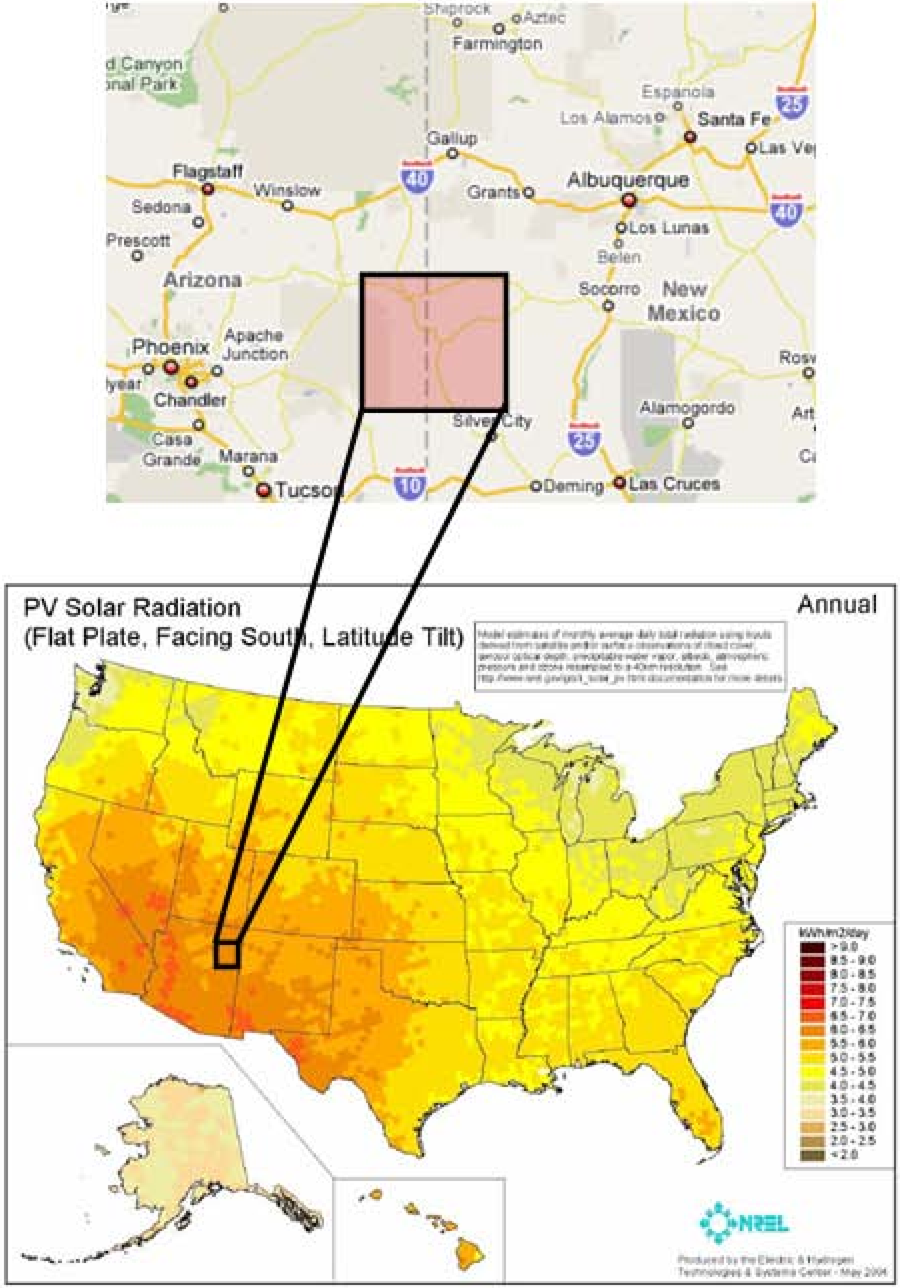
PV Land Area Requirements



PV Land Area Requirements

All US Electricity

800 Gigawatts w/ 10% modules



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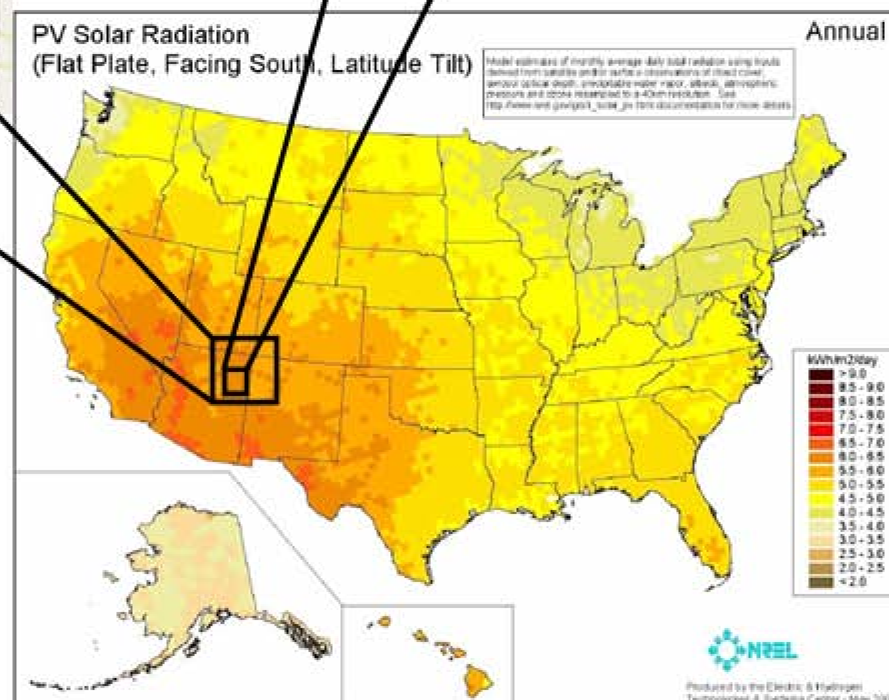
PV Land Area Requirements

All US Primary Energy

4.1 Terawatts w/ 10% modules

All US Electricity

800 Gigawatts w/ 10% modules



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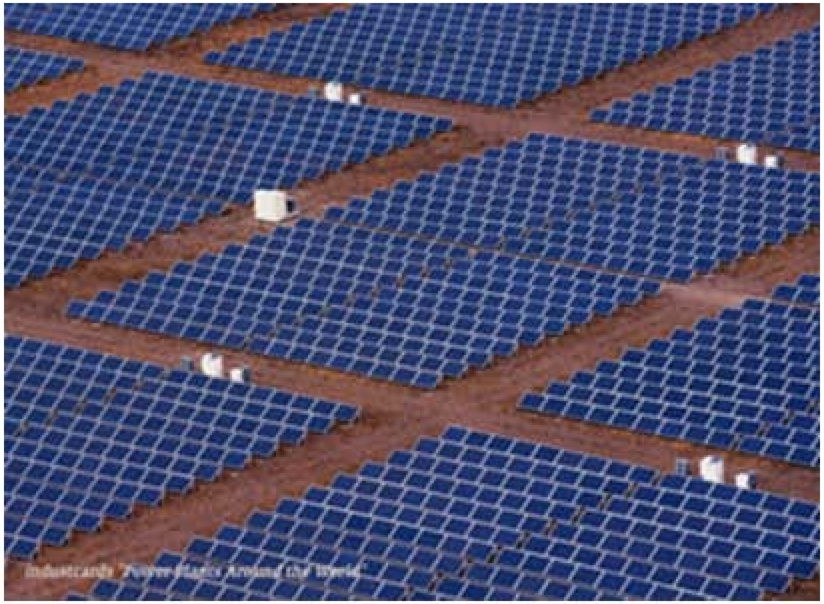
TeraWatt Scale PV : Utility Infrastructure

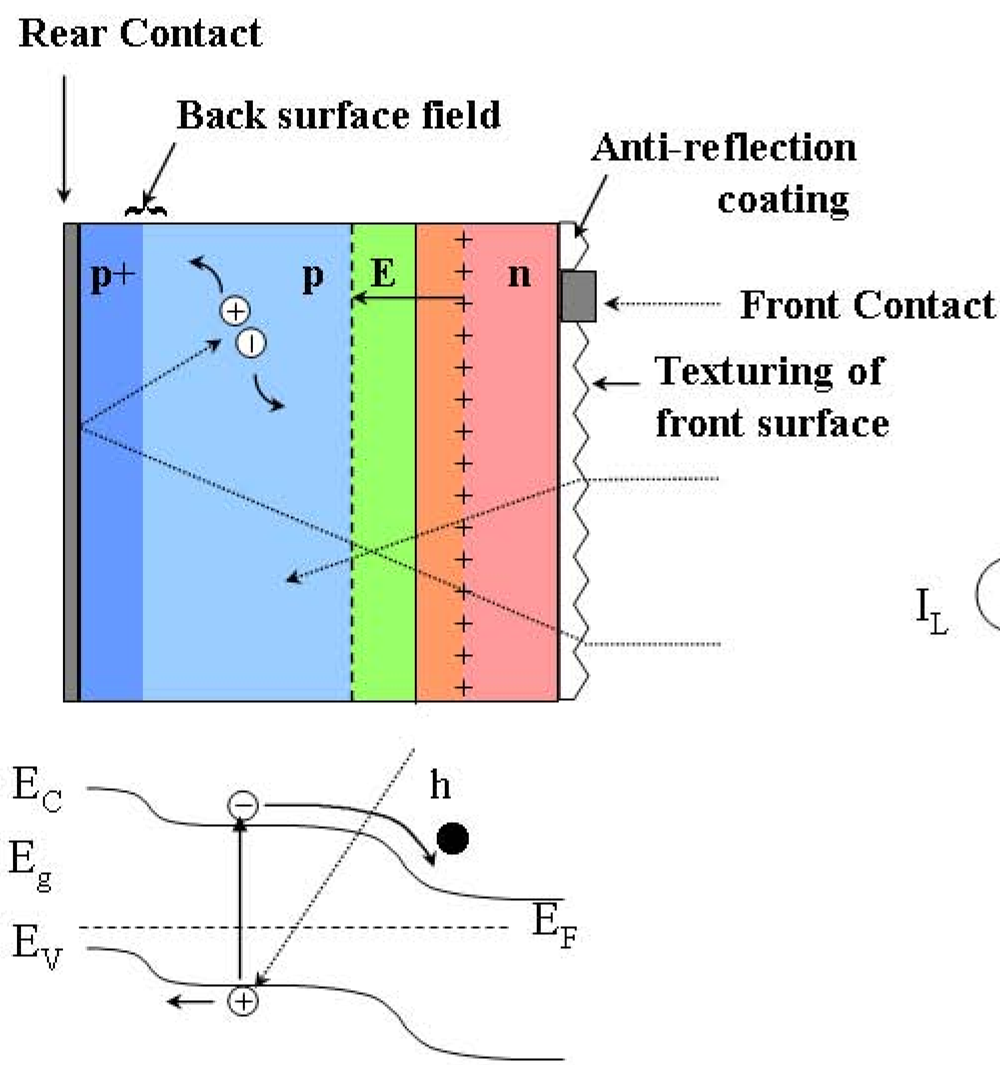
Hysperia California power station

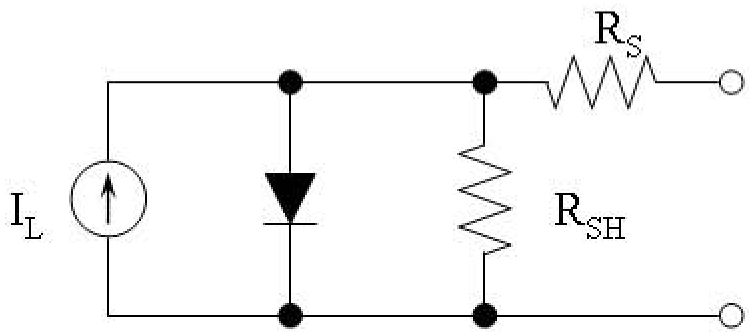


Tucson Electric Power, Tucson AZ

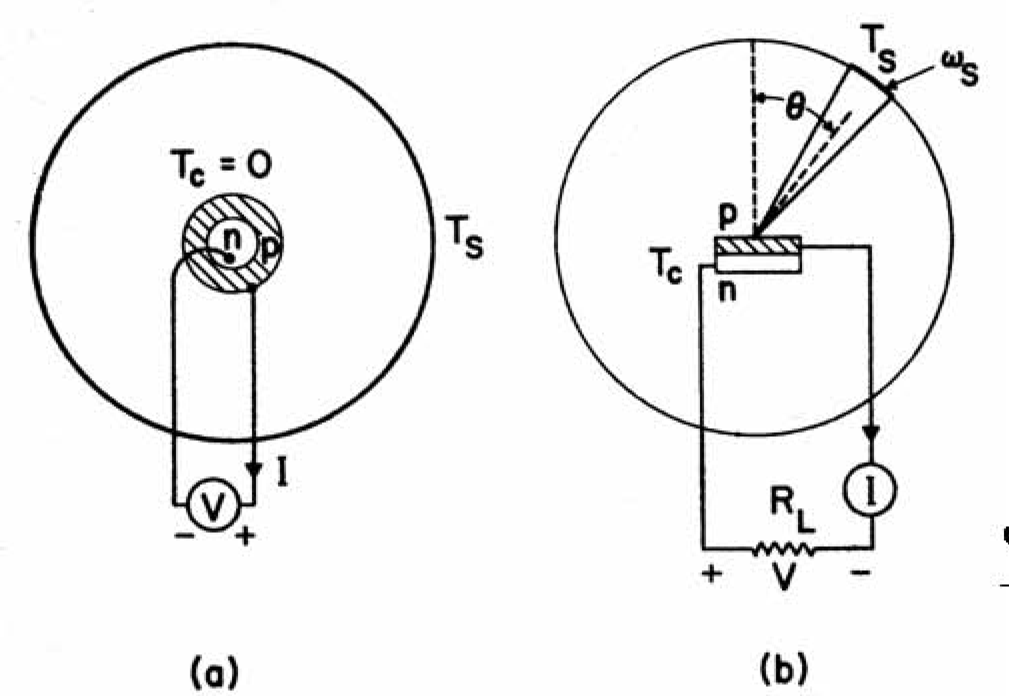
Arizona Public Service, Prescott AZ

Photovoltaic Solar Cell

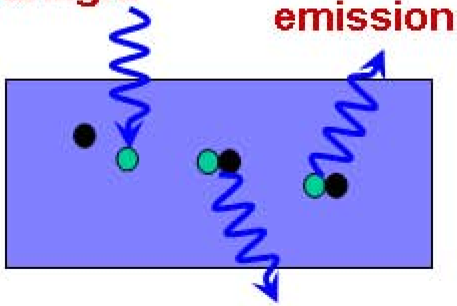




Detailed Balance Limit for Solar Cell Efficiency



Shockley and Queisser (1961)



$$\frac{J_1}{q} = {}^{AM1.5}N - {}^{rad}N_1$$

charge carrier flux

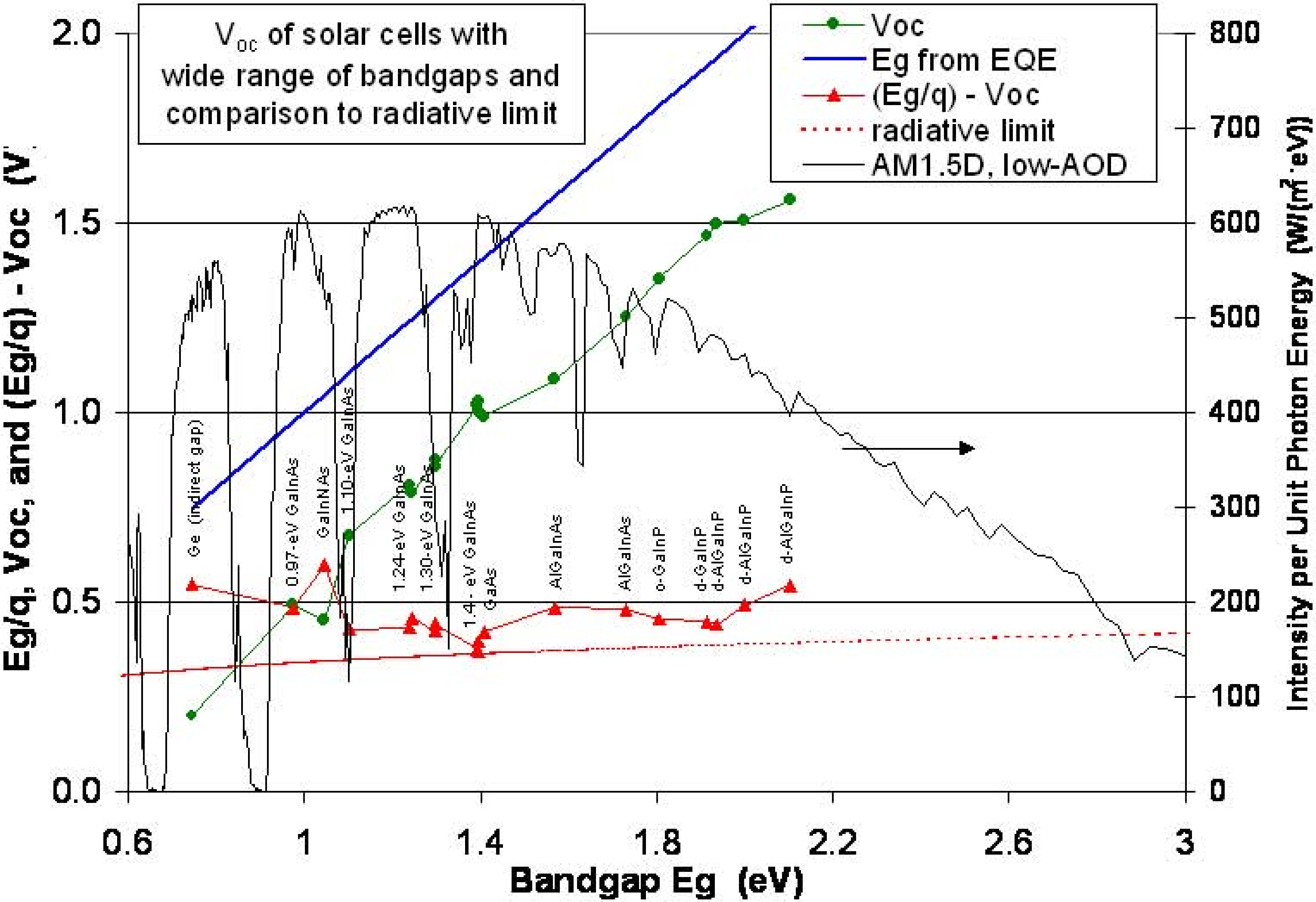
generation rate by sunlight absorption

radiative recombination rate

Open Circuit Voltage Offset from Bandgap: Photon Entropy

$$\Delta F = \Delta H - T\Delta S$$

$$qV_{oc} = E_g - T\,k\ln\Omega = E_g - kT\ln 46{,}200 = E - 10.7\,kT$$



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Maximum Solar Cell Efficiencies

Measured | Theoretical

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C. H. Henry, "Limiting efficiencies of ideal single and multiple energy gap terrestrial solar cells," *J. Appl. Phys.*, **51**, 4494 (1980).
W. Shockley and H. J. Queisser, "Detailed Balance Limit of Efficiency of *p–n* Junction Solar Cells," *J. Appl. Phys.*, **32**, 510 (1961).
J. H. Werner, S. Kolodinski, and H. J. Queisser, "Novel Optimization Principles and Efficiency Limits for Semiconductor Solar Cells," *Phys. Rev. Lett.*, **72**, 3851 (1994).
M. Green, K. Emery, D. L. King, Y. Hisikawa, W. Warta, "Solar Cell Efficiency Tables (Version 27)", *Progress in Photovoltaics*, **14**, 45 (2006)
R. R. King *et al.*, "Pathways to 40%-Efficient Concentrator Photovoltaics," *Proc. 20th European Photovoltaic Solar Energy Conf.*, Barcelona, Spain, 6-10 June 2005.
R. R. King *et al.*, "Lattice-Matched and Metamorphic GaInP / GaInAs/ Ge Concentrator Solar Cells," *Proc. 3rd World Conf. on Photovoltaic Energy Conversion*, May 11-18, 2003, Osaka, Japan, p 622.
A. Slade, V. Garboushian, "27.6%-Efficient Silicon Concentrator Cell for Mass Production," *Proc. 15th Int'l. Photovoltaic Science and Engineering Conf.*, Beijing, China, Oct. 2005.
R. P. Gale *et al.*, "High-Efficiency GaAs/CuInSe₂ and AlGaAs/CuInSe₂ Thin-Film Tandem Solar Cells," *Proc. 21st IEEE Photovoltaic Specialists Conf.*, Kissimmee, Florida, May 1990.
J. Zhao, A. Wang, M. A. Green, F. Ferrazza, "Novel 19.8%-efficient 'honeycomb' textured multicrystalline and 24.4% monocrystalline silicon solar cells," *Appl. Phys. Lett.*, **73**, 1991 (1998).

Measured

3-gap GaInP/GaAs/InGaAs cell @240suns (Spectrolab) **40.7 %**

3-gap GaInP/GaAs/Ge cell @ 1 sun (Spectrolab) **32.0%**

1-gap solar cell (Si, 1.12 eV) @92 suns (Amonix) **27.6%**

1-gap solar cell (GaAs, 1.424 eV) @1 sun (Kopin) **25.1%**

1-gap solar cell (silicon, 1.12 eV) @1 sun (UNSW) **24.7%**

Theoretical

95% Carnot eff. = $1 - T/T_{sun}$ $T = 300$ K, $T_{sun} \approx 5800$ K

93% Max. eff. of solar energy conversion $= 1 - TS/E = 1 - (4/3)T/T_{sun}$ (Henry)

72% Ideal 36-gap solar cell at 1000 suns (Henry)

56% Ideal 3-gap solar cell at 1000 suns (Henry)

50% Ideal 2-gap solar cell at 1000 suns (Henry)

44% Ultimate eff. of device with cutoff E_g: (Shockley, Queisser)

43% 1-gap cell at 1 sun with carrier multiplication (>1 e-h pair per photon) (Werner, Kolodinski, Queisser)

37% Ideal 1-gap solar cell at 1000 suns (Henry)

31% Ideal 1-gap solar cell at 1 sun (Henry)

30% Detailed balance limit of 1 gap solar cell at 1 sun (Shockley, Queisser)

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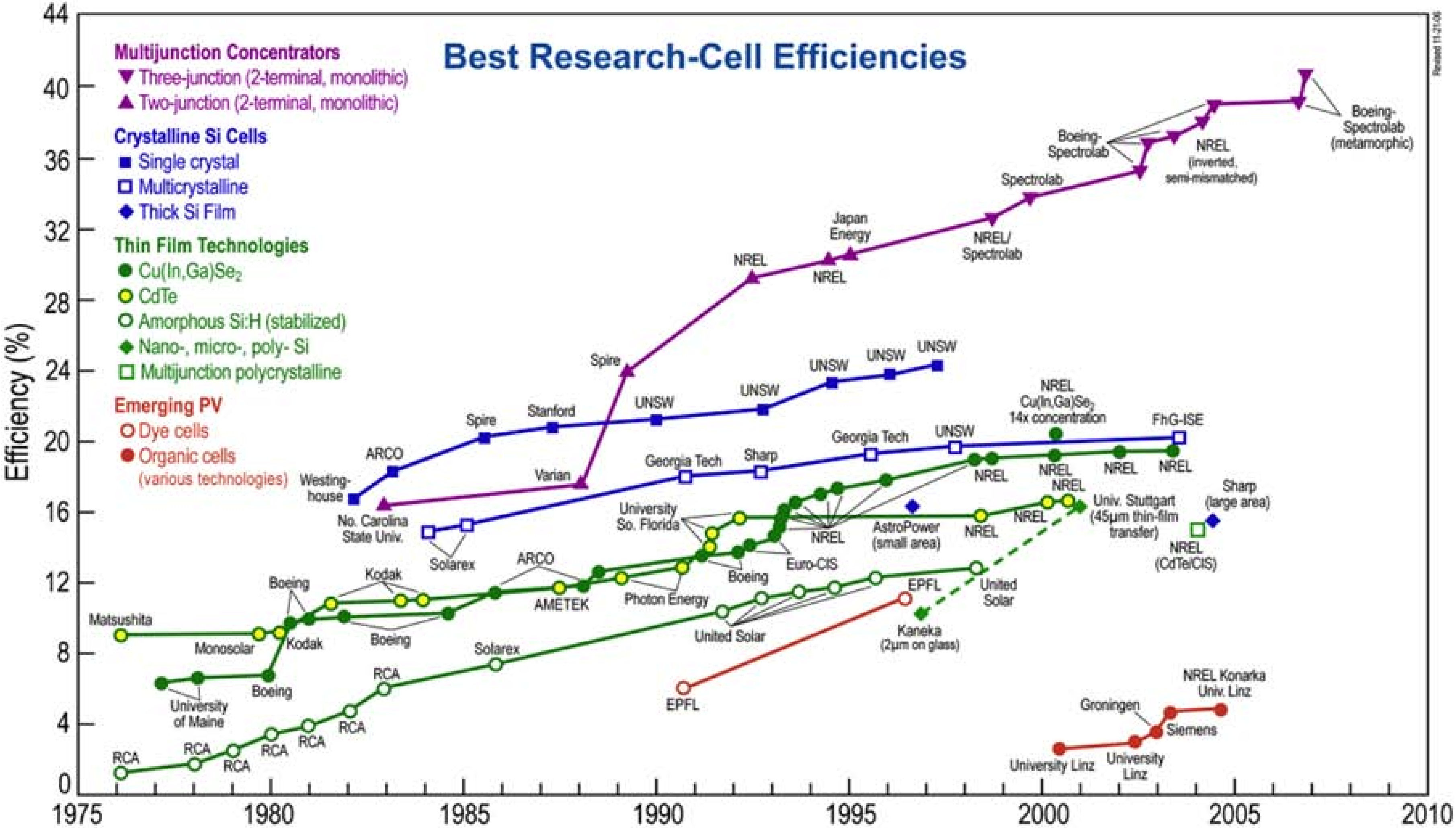
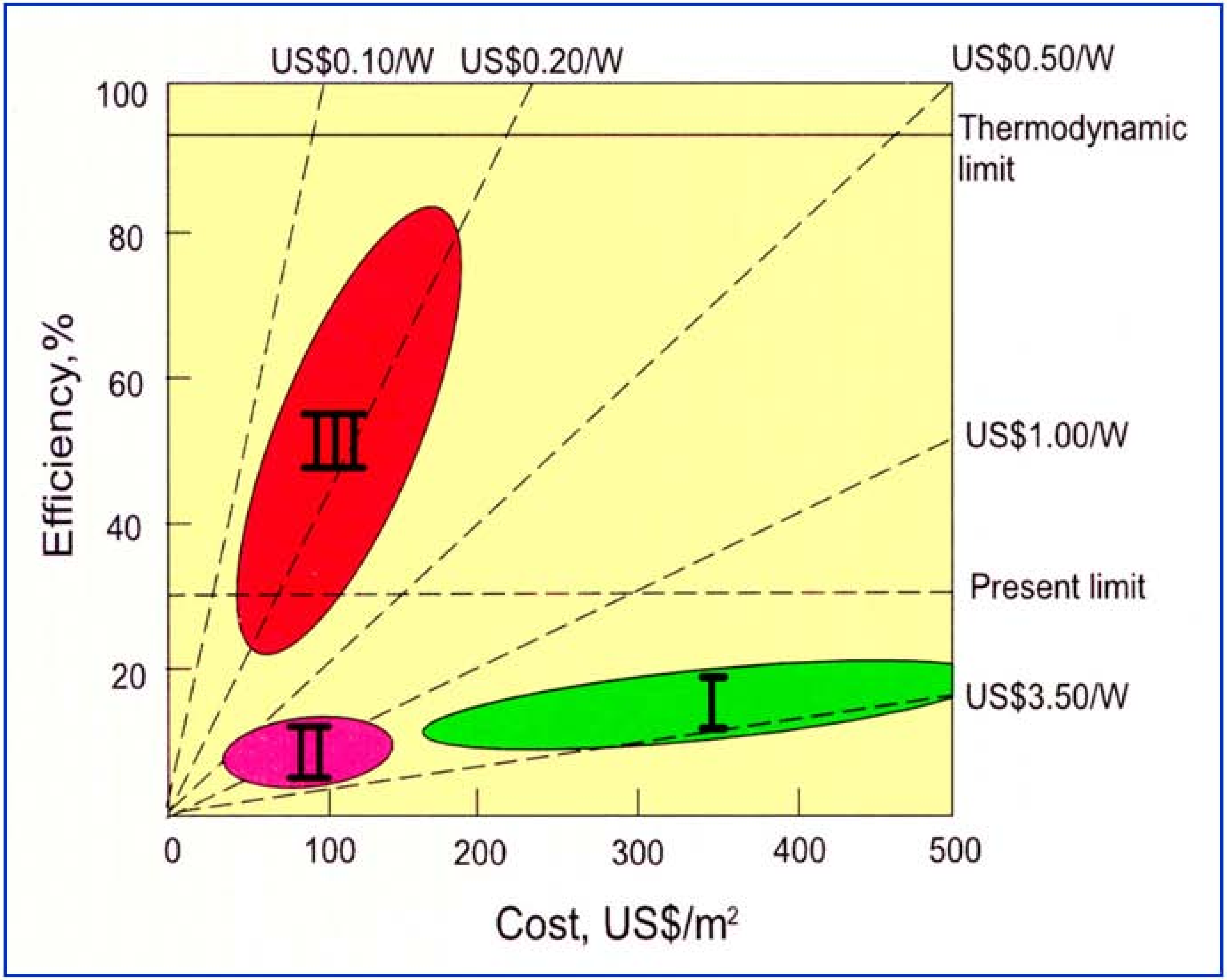
Improvements in Solar Cell Efficiencies



Cost/Efficiency of Photovoltaic Technology



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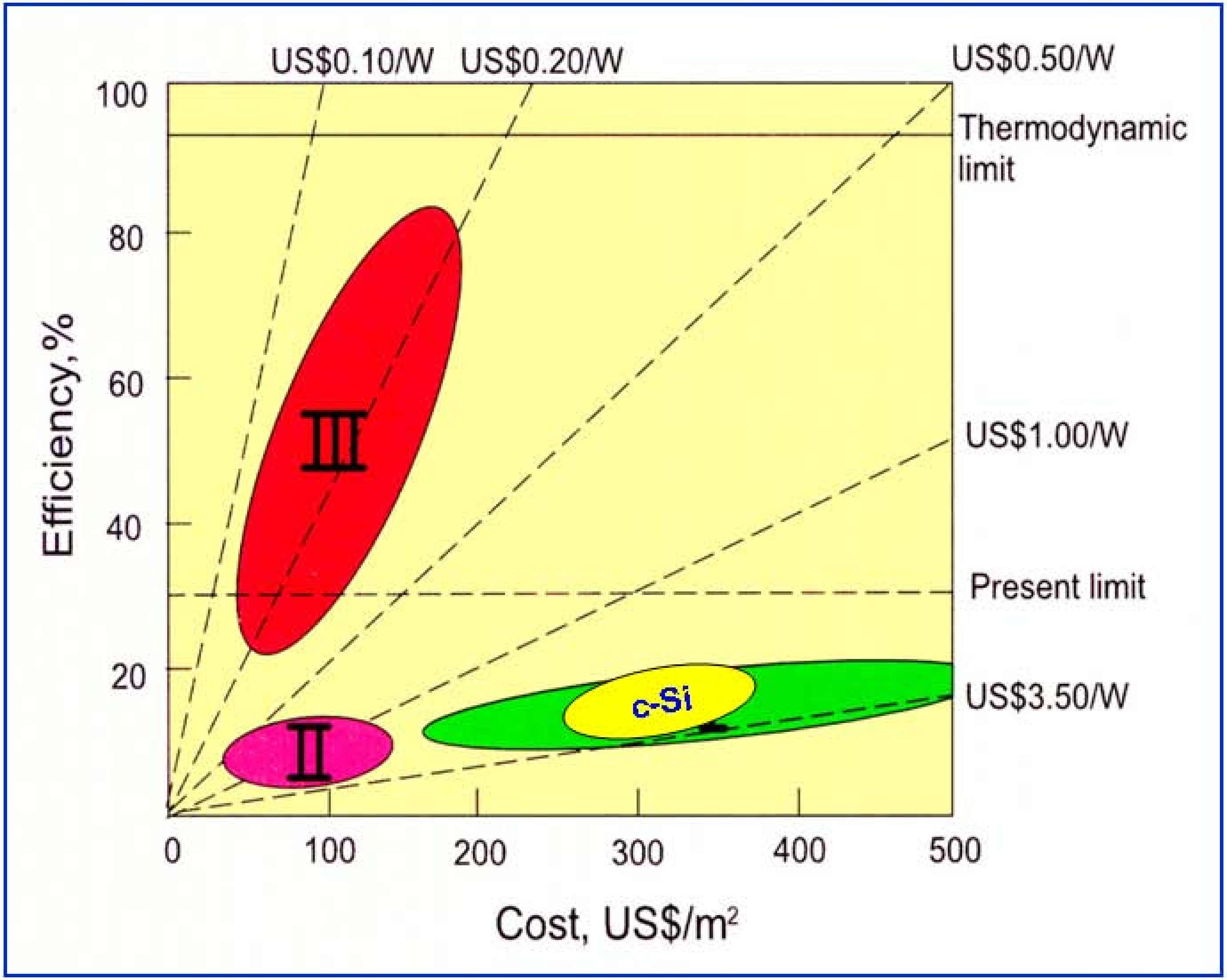

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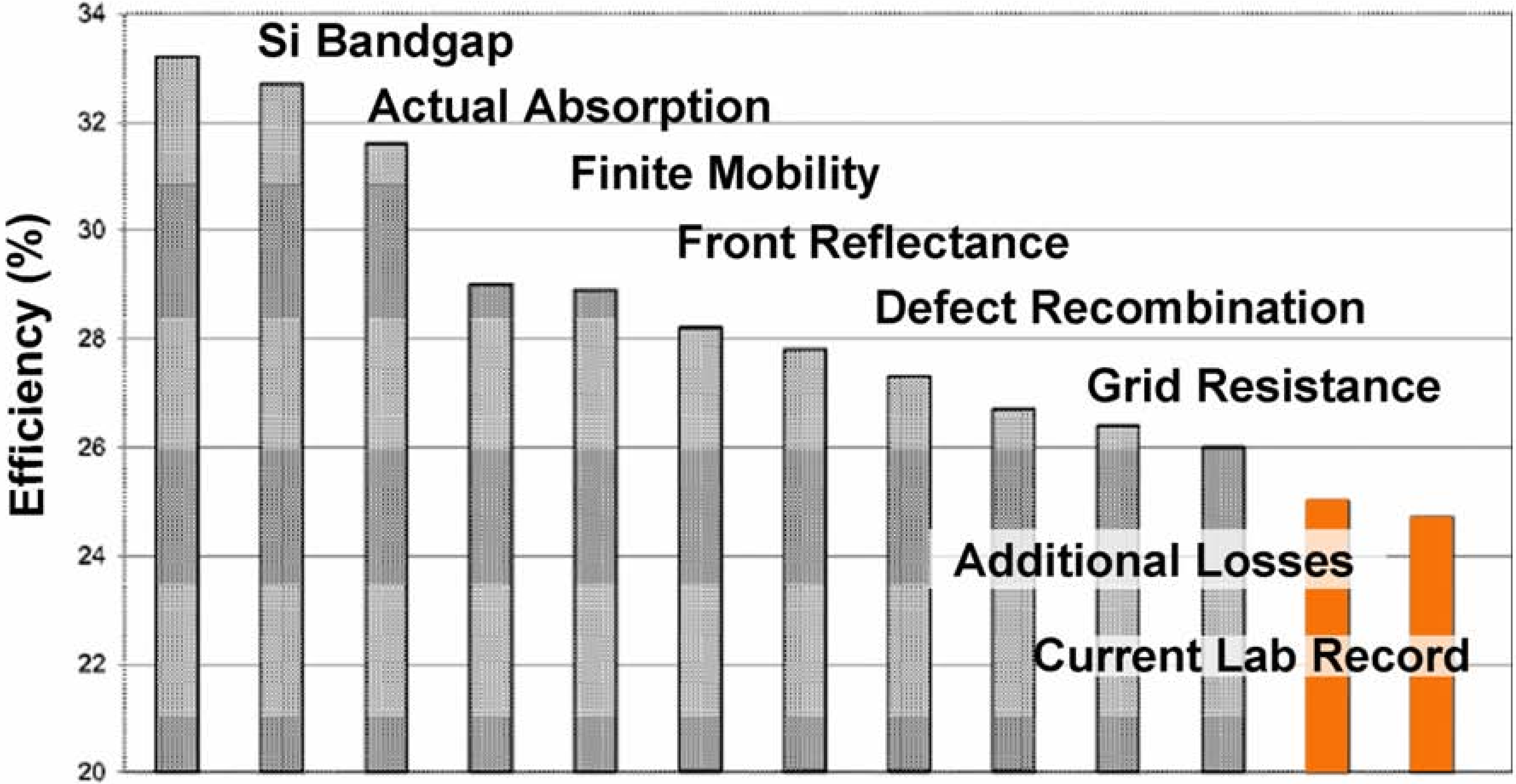
Factors Limiting Silicon Solar Cell Efficiency

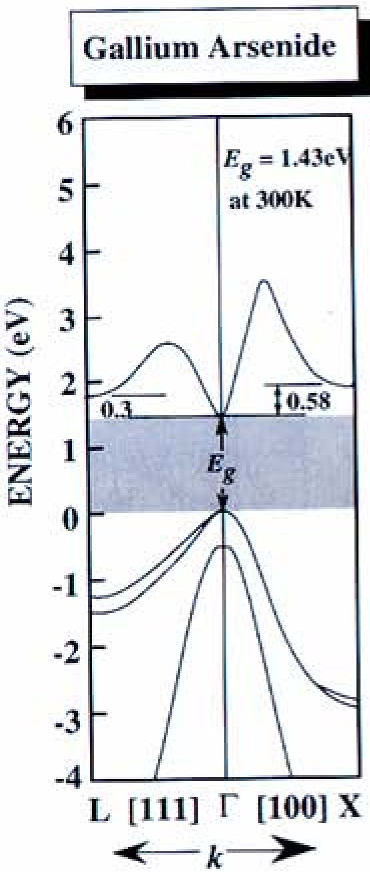


Must work towards lower cost!

Adapted from R.M. Swanson, *Proceedings of the 31st IEEE Meeting* (2005) p. 889.

Si an indirect bandgap semiconductor – wafer thicknesses for full light absorption

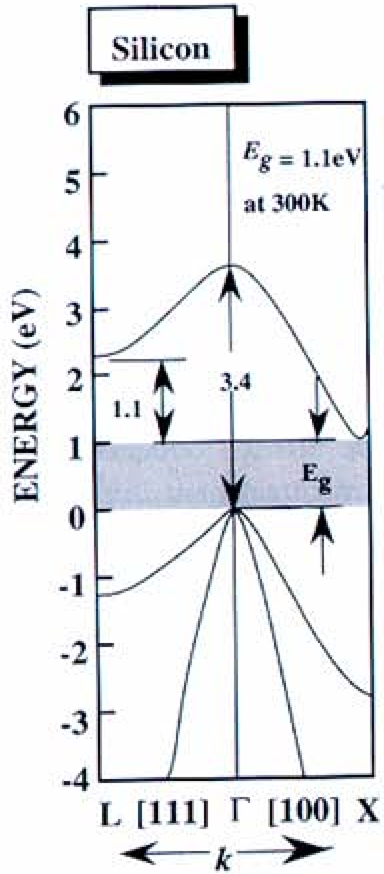
Si Shortage?!!



Conduction Band:

Lowest Valley: Γ- vall

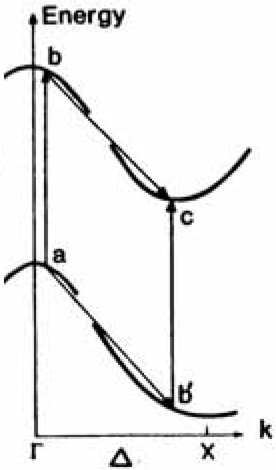
Upper Valley: L-valle

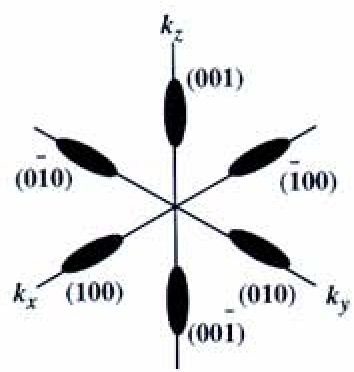


Γ point : $k = (0,0,0)$

X point : $k = \frac{2\pi}{a}(1,0,0)$

L point : $k = \frac{\pi}{a}(1,1,1)$



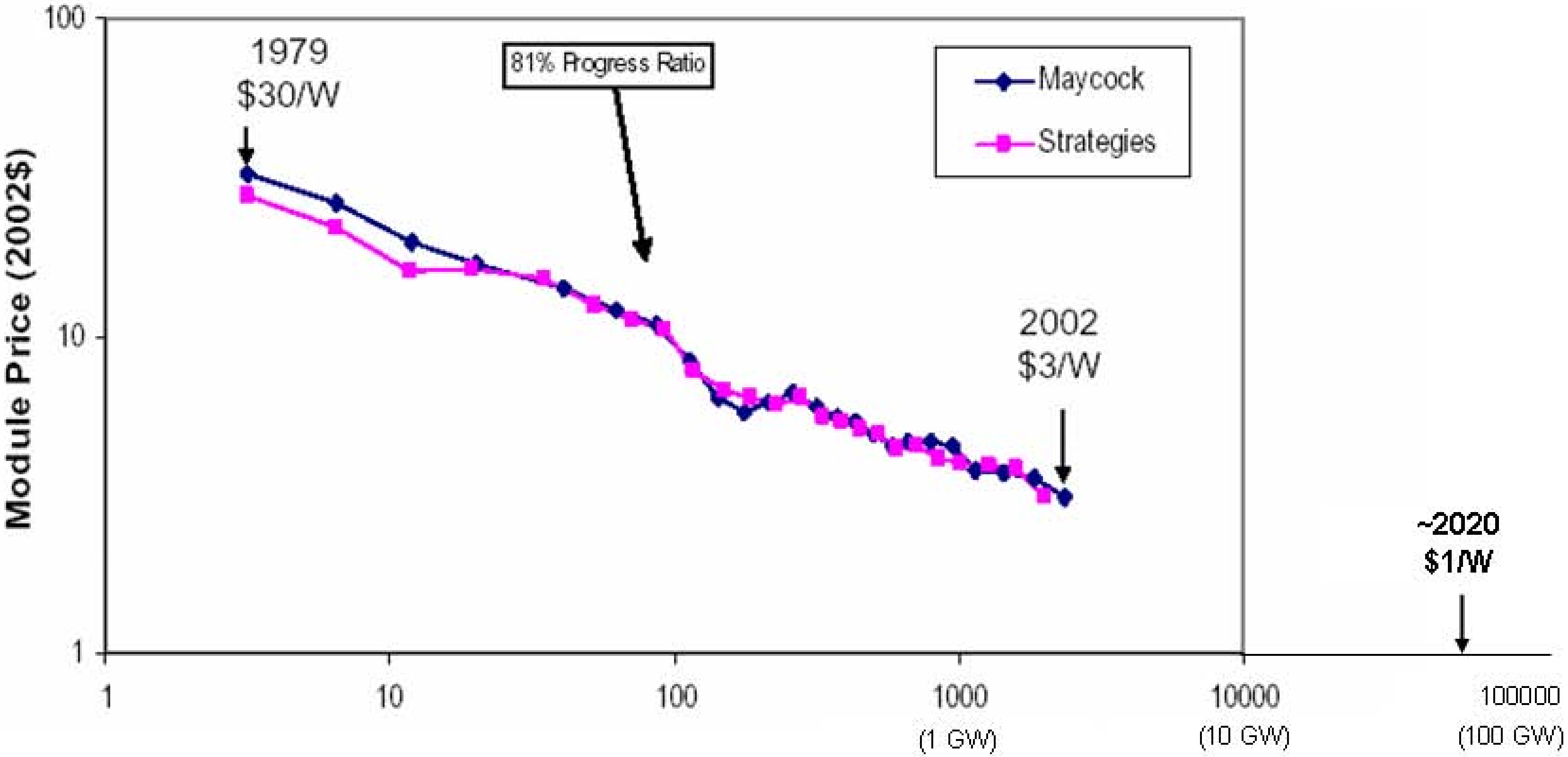


Six equivalent valleys at conduction bandedge

Silicon vs. "Nano-solar"

Philosophical and Technical Approach

- ***Disruptive Solar – seek to alter present PV landscape***
- ***Opportunity for TW Energy Supply (otherwise, why do it?)***
- ***10 Year Time Scale (not longer, because c-Si progress forbids it)***
- ***Ideally, solar technology suitable for electricity and fuel generation***



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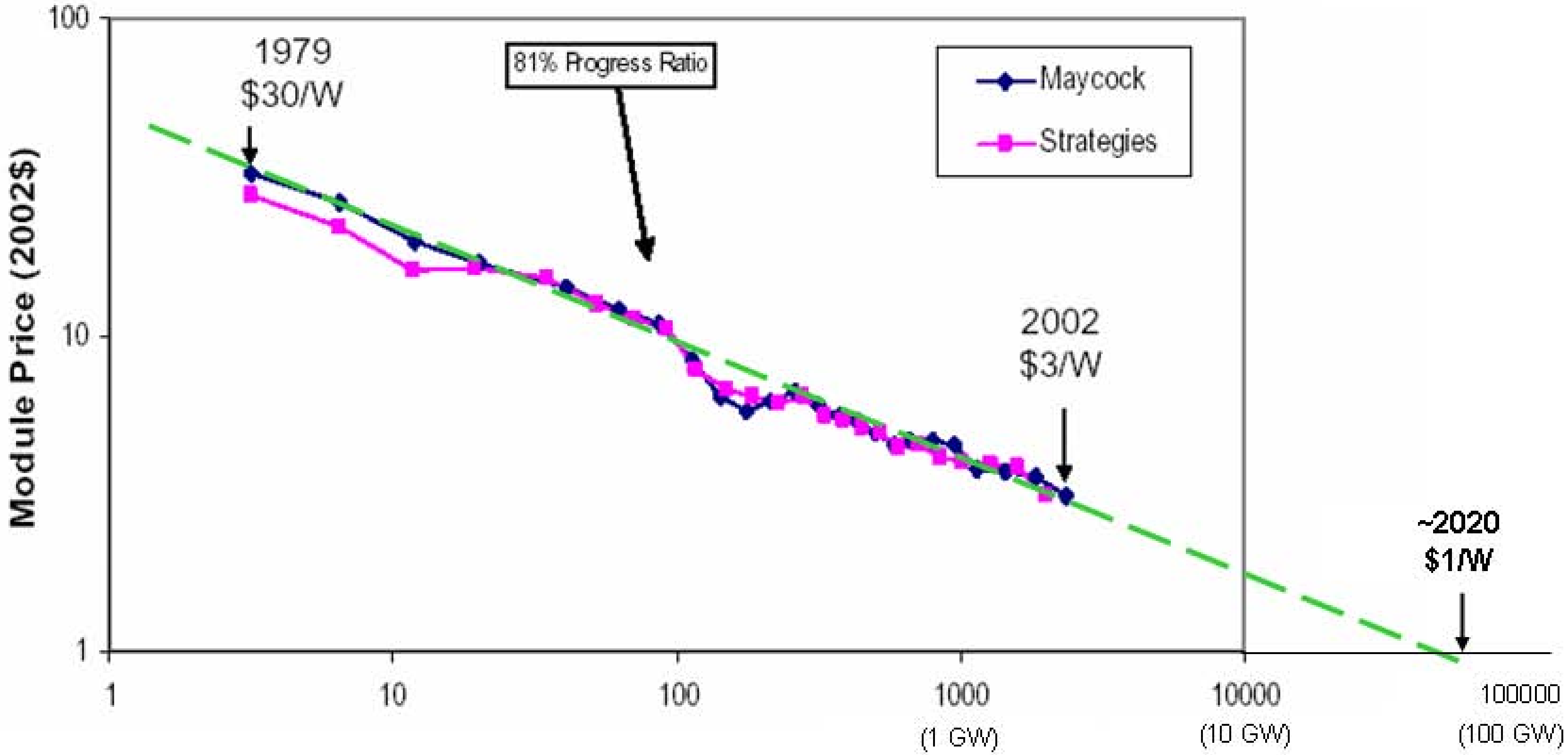

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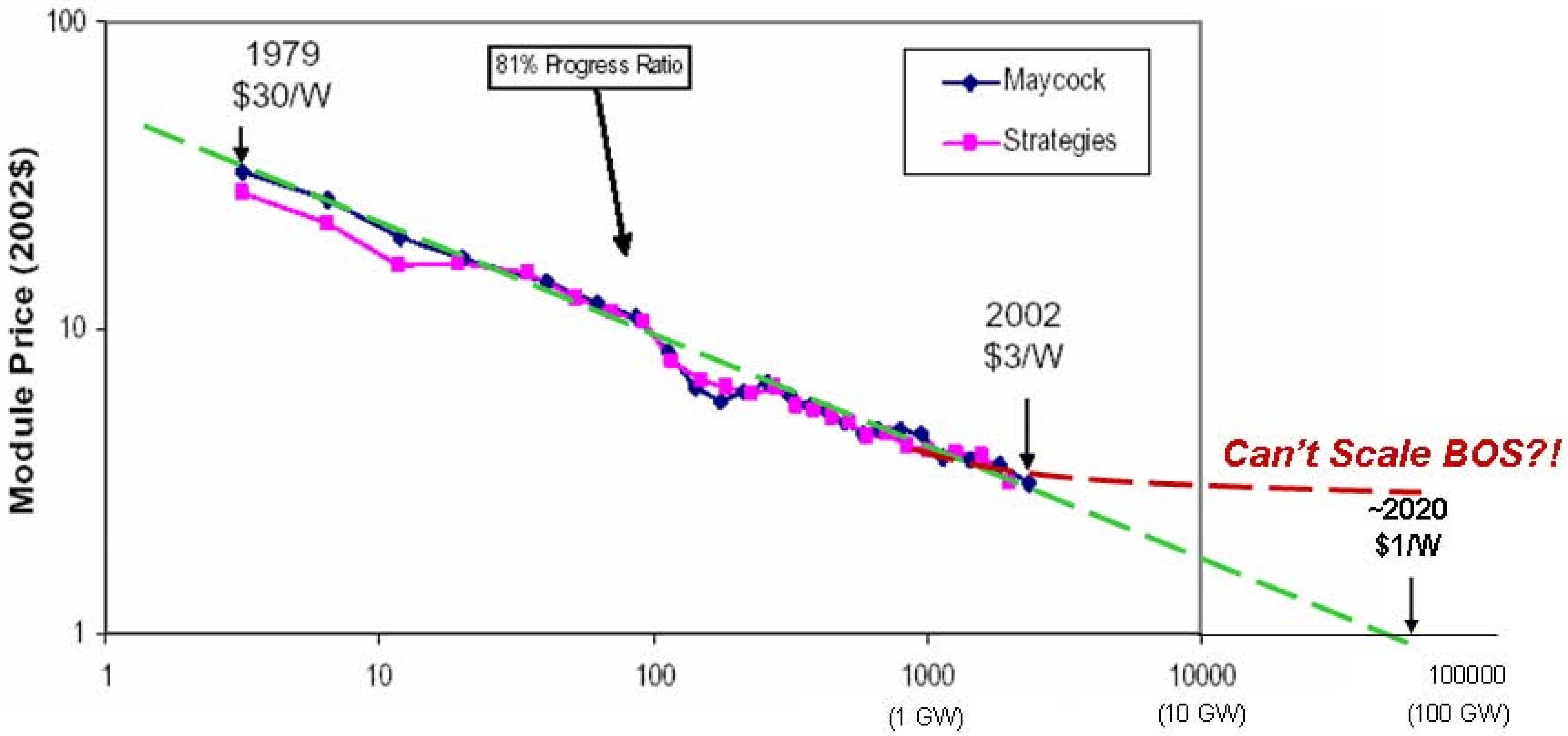

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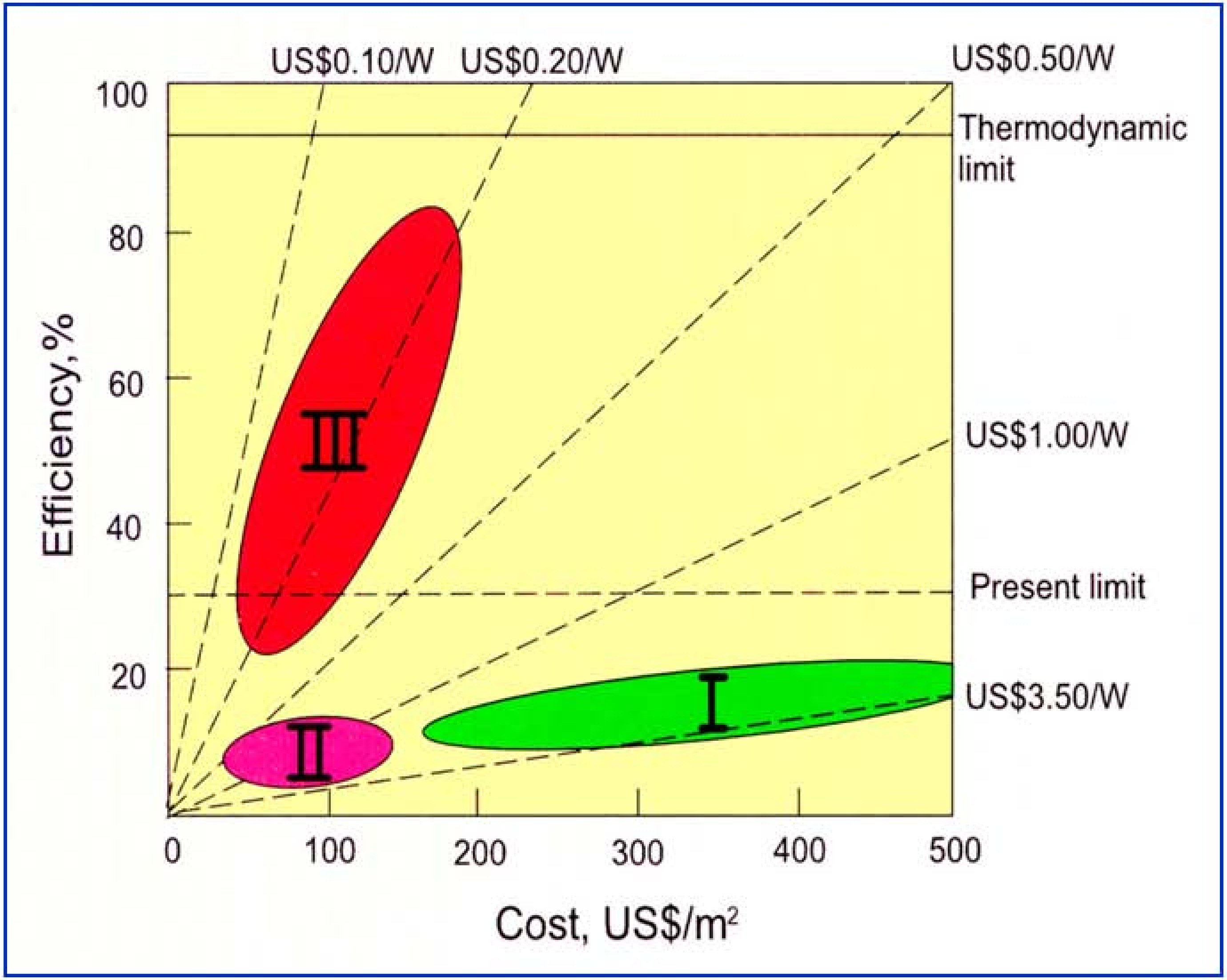
Cost/Efficiency of Photovoltaic Technology



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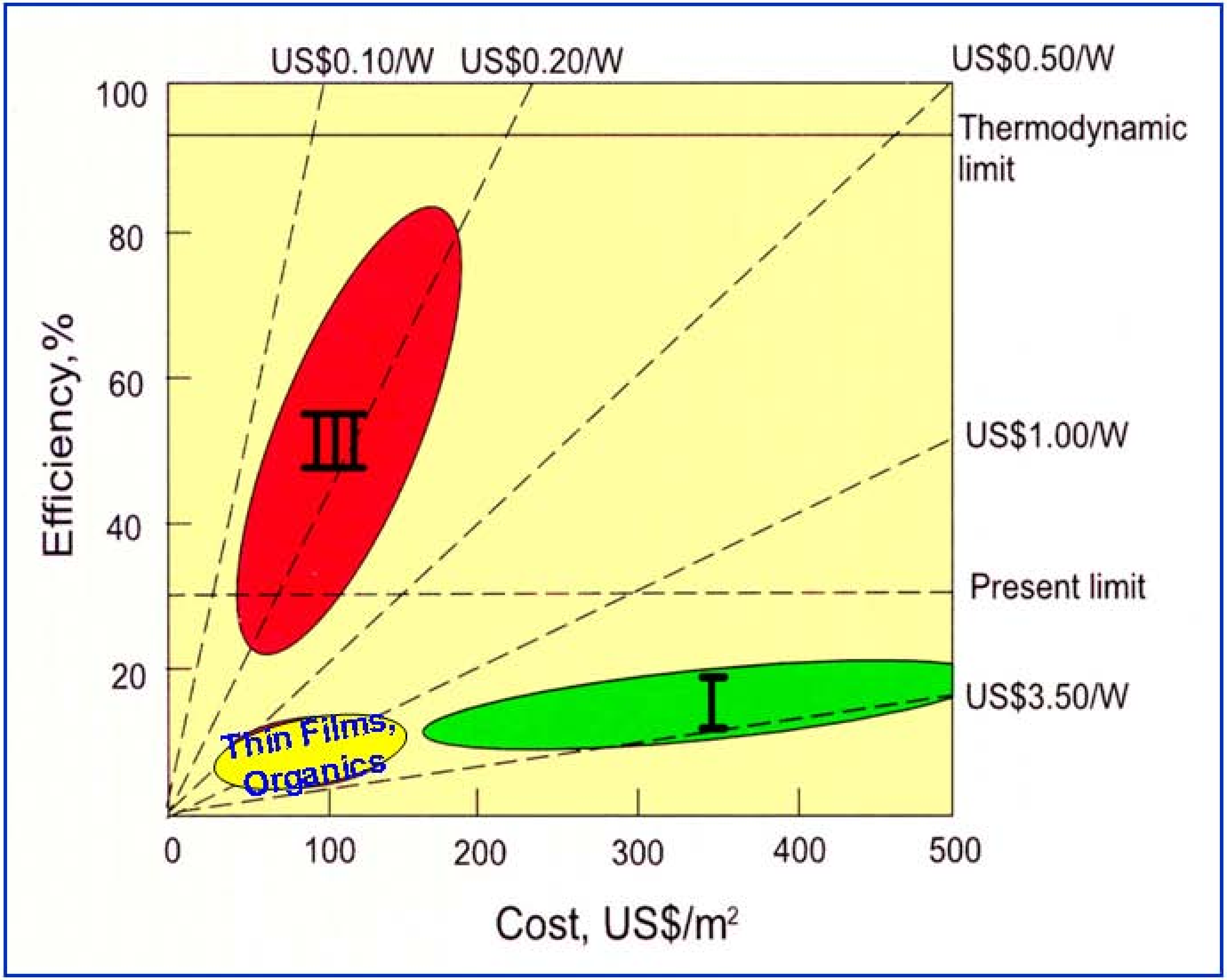

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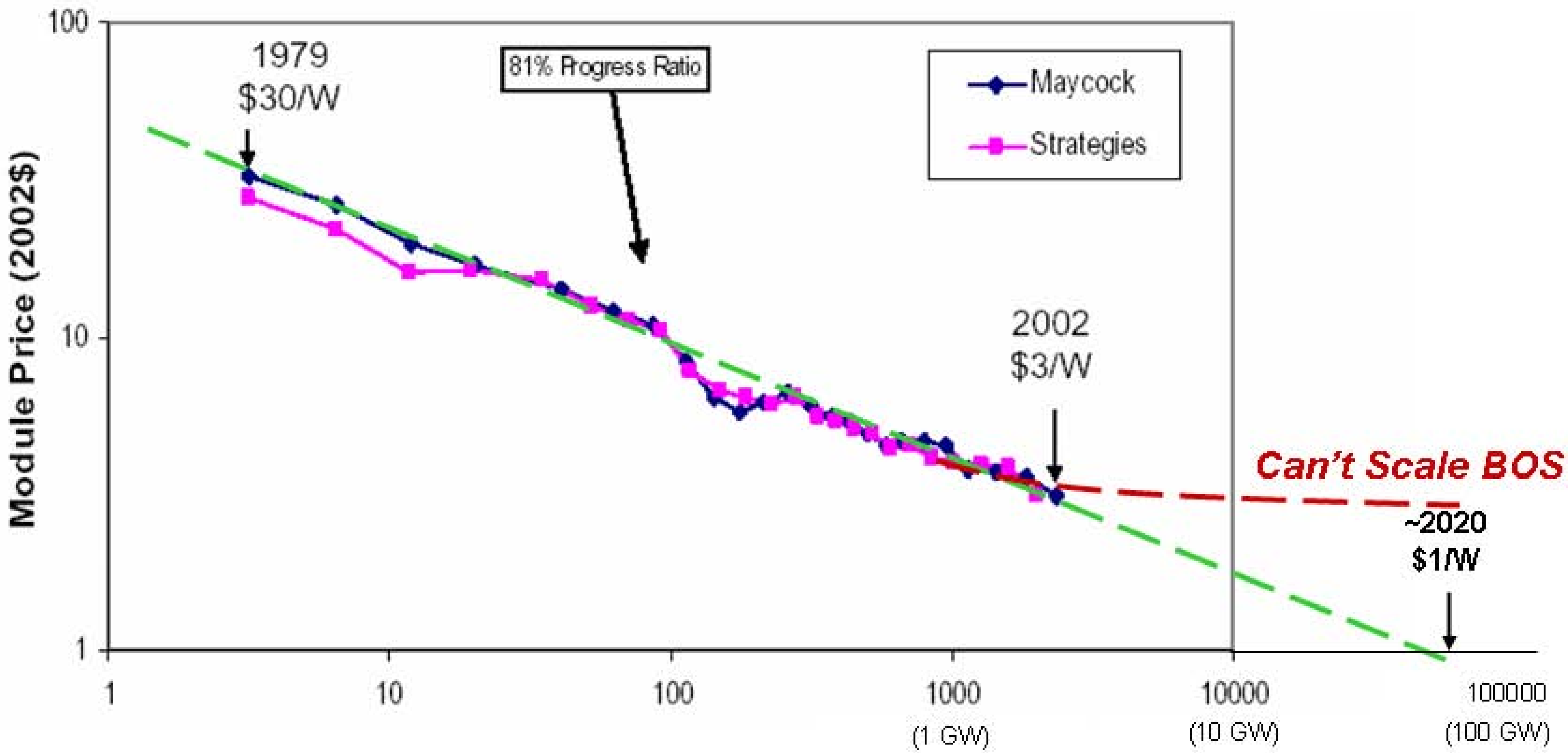

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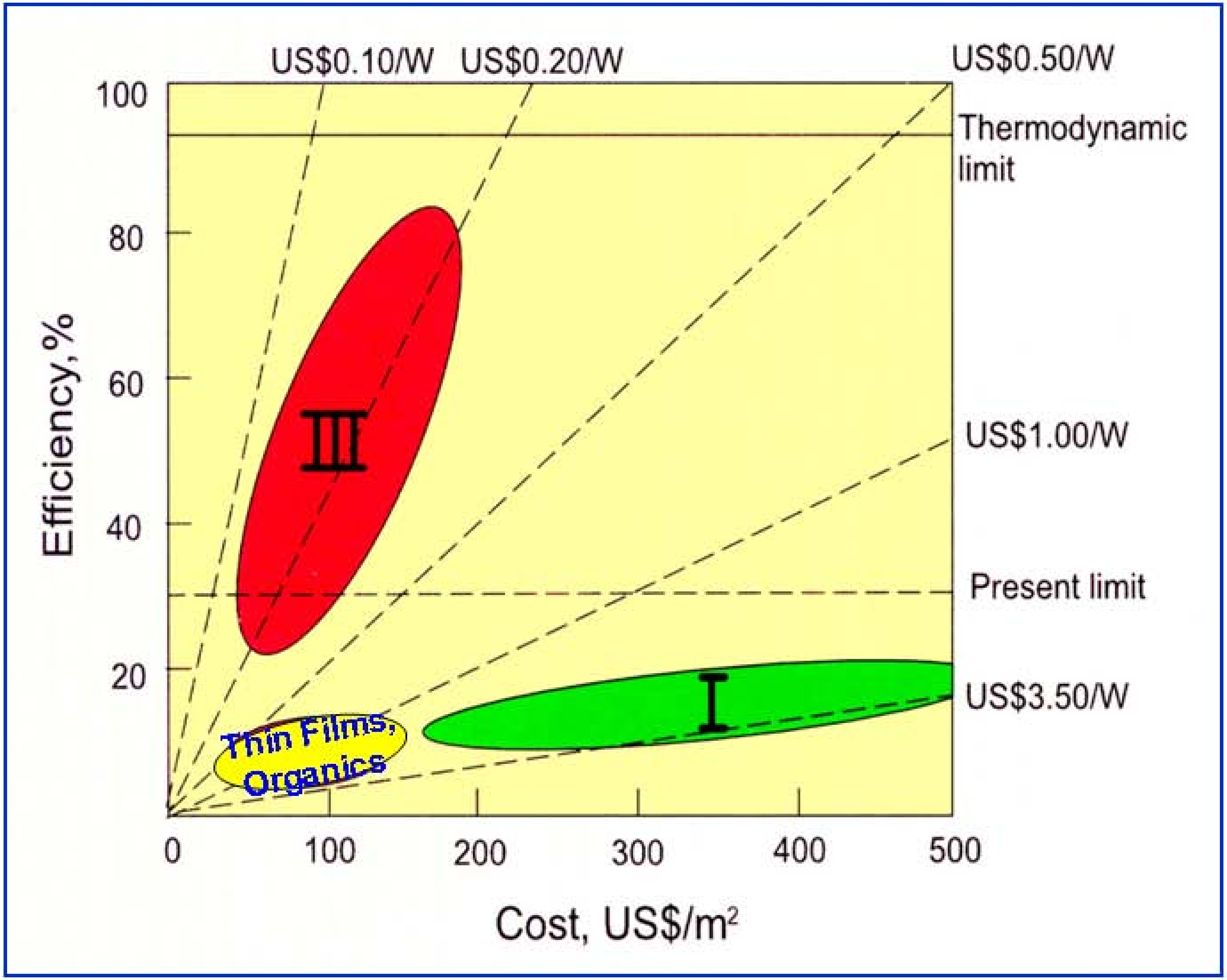
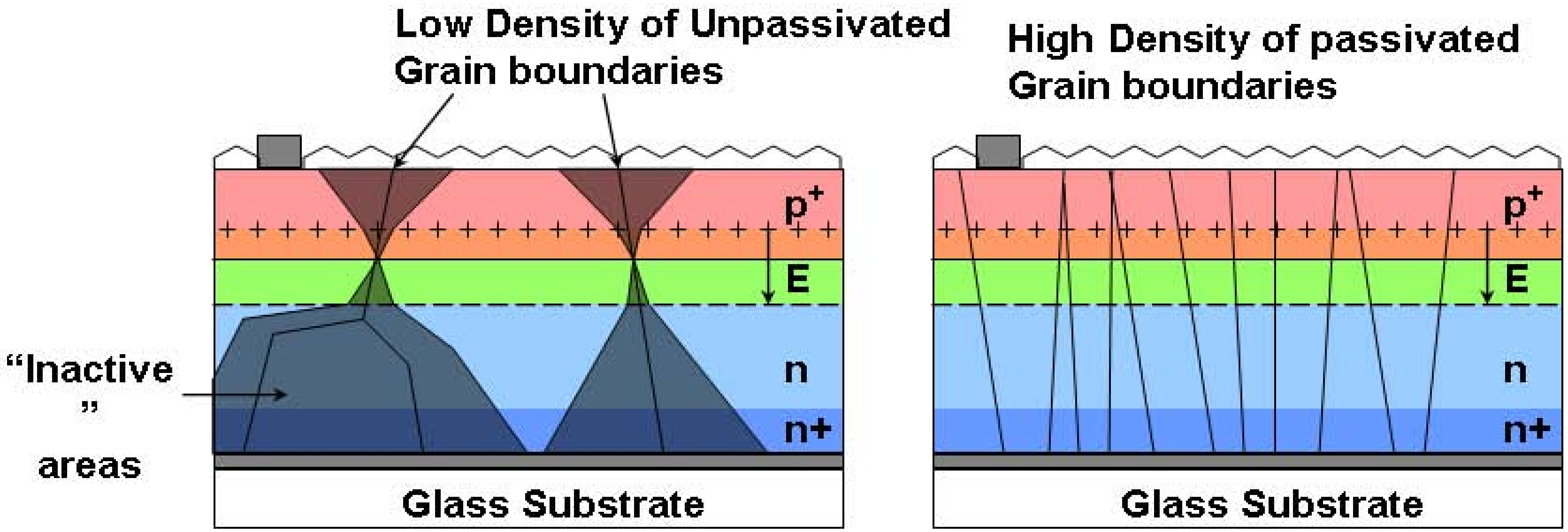
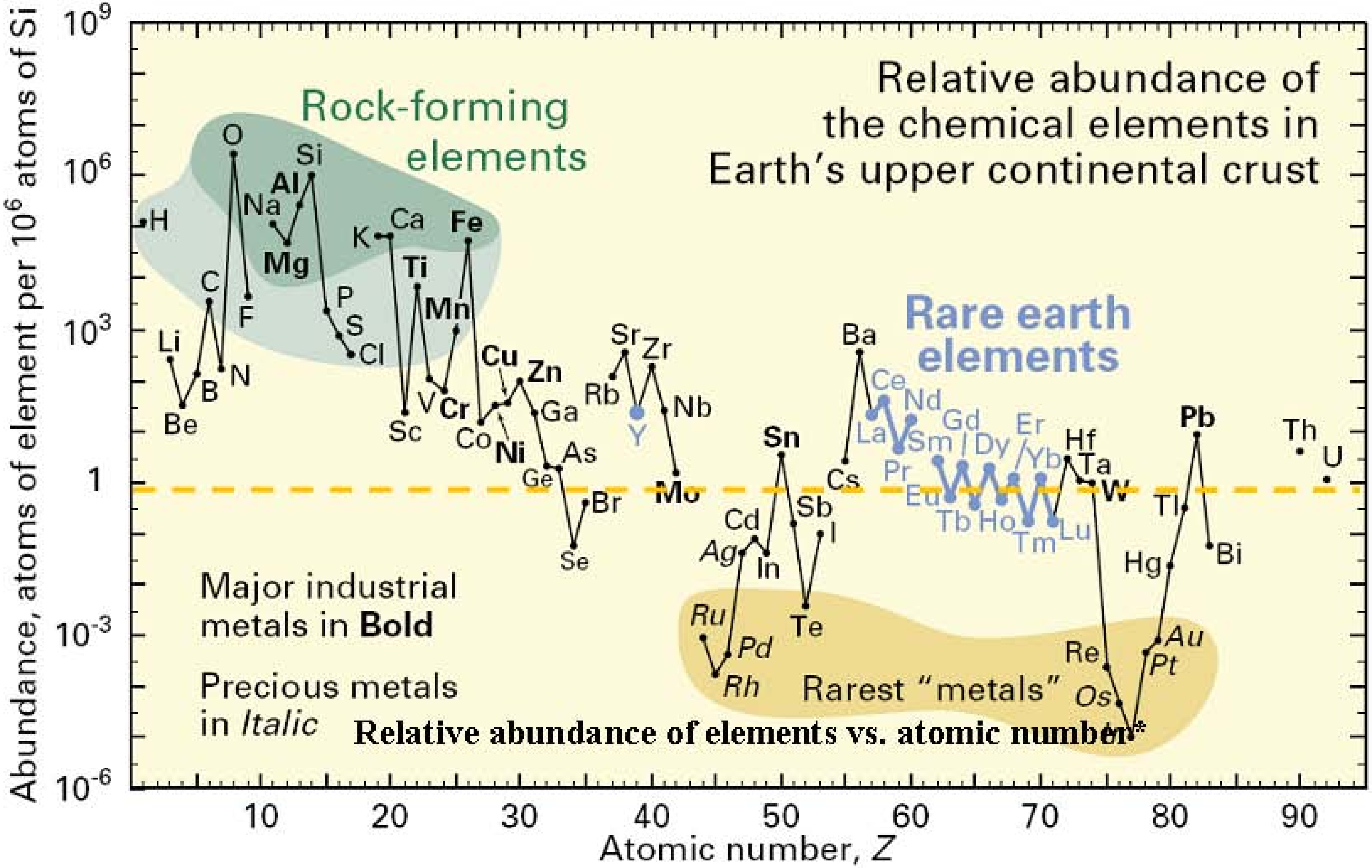


Thin Film Solar Cells

Materials: CdTe, $CuIn_xGa_{1-x}Se_2$, poly-Si, amorphous Si



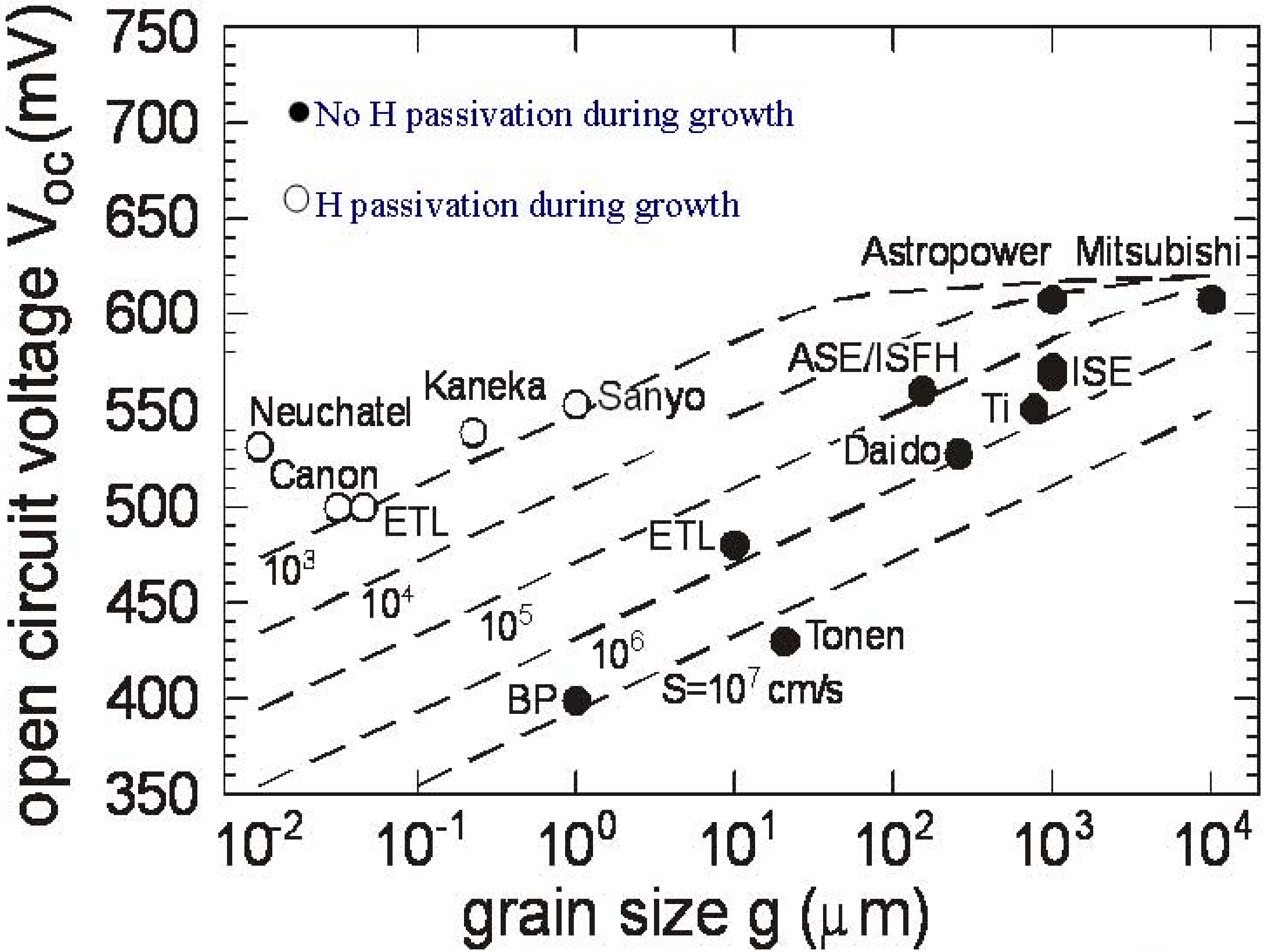
Among Conventional Thin Films ($CuIn_xGa_{1-x}Se_2$,, CdTe, Si) Only Si Abundant Enough



Relative abundance of elements vs. atomic number*

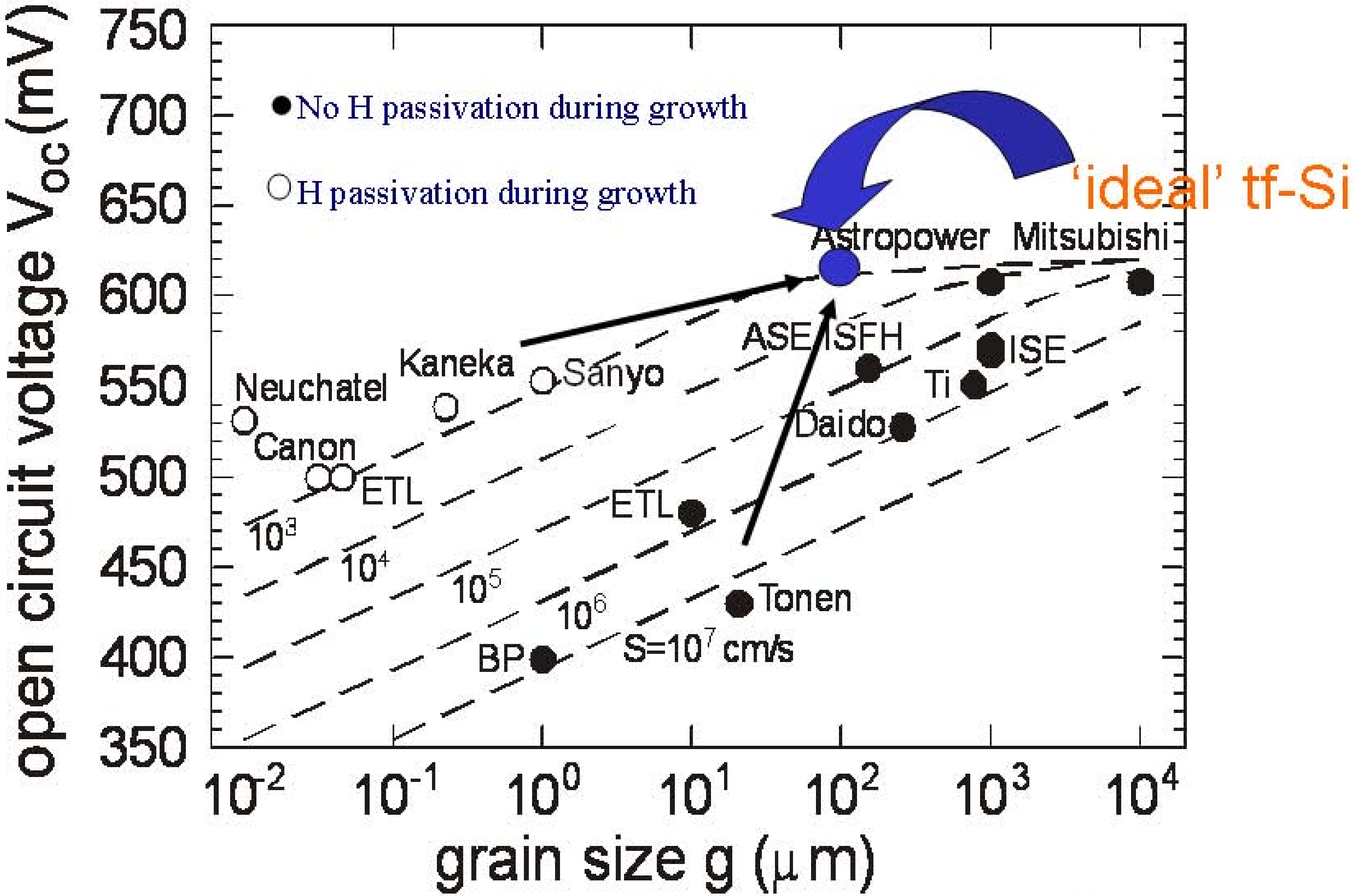
*from P.H. Stauffer et al, Rare Earth Elements - Critical Resources for High Technology, USGS (2002)

Poly-Si: Open Circuit Voltage vs. Grain Size



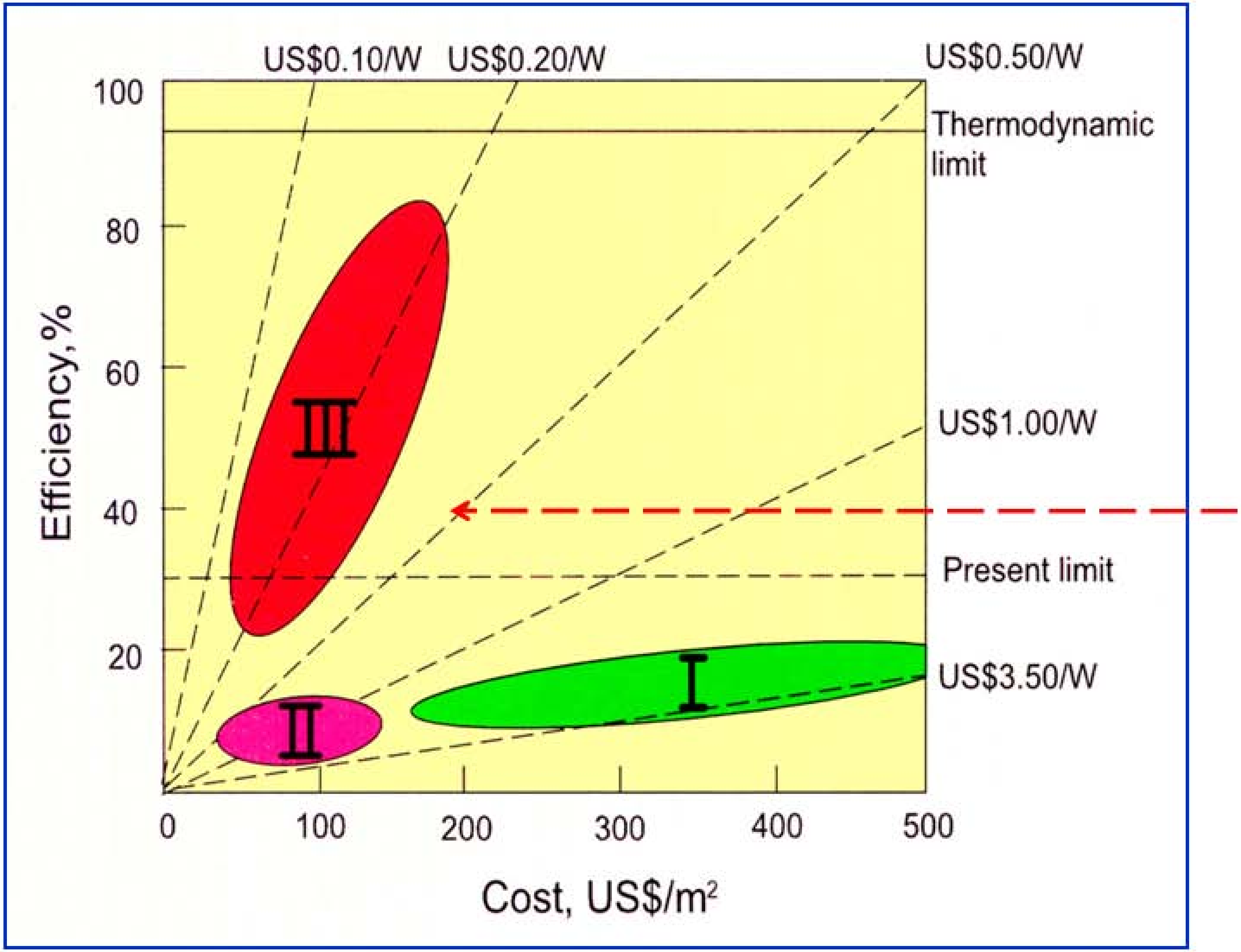
Jurgen Werner

Poly-Si: Open Circuit Voltage vs. Grain Size

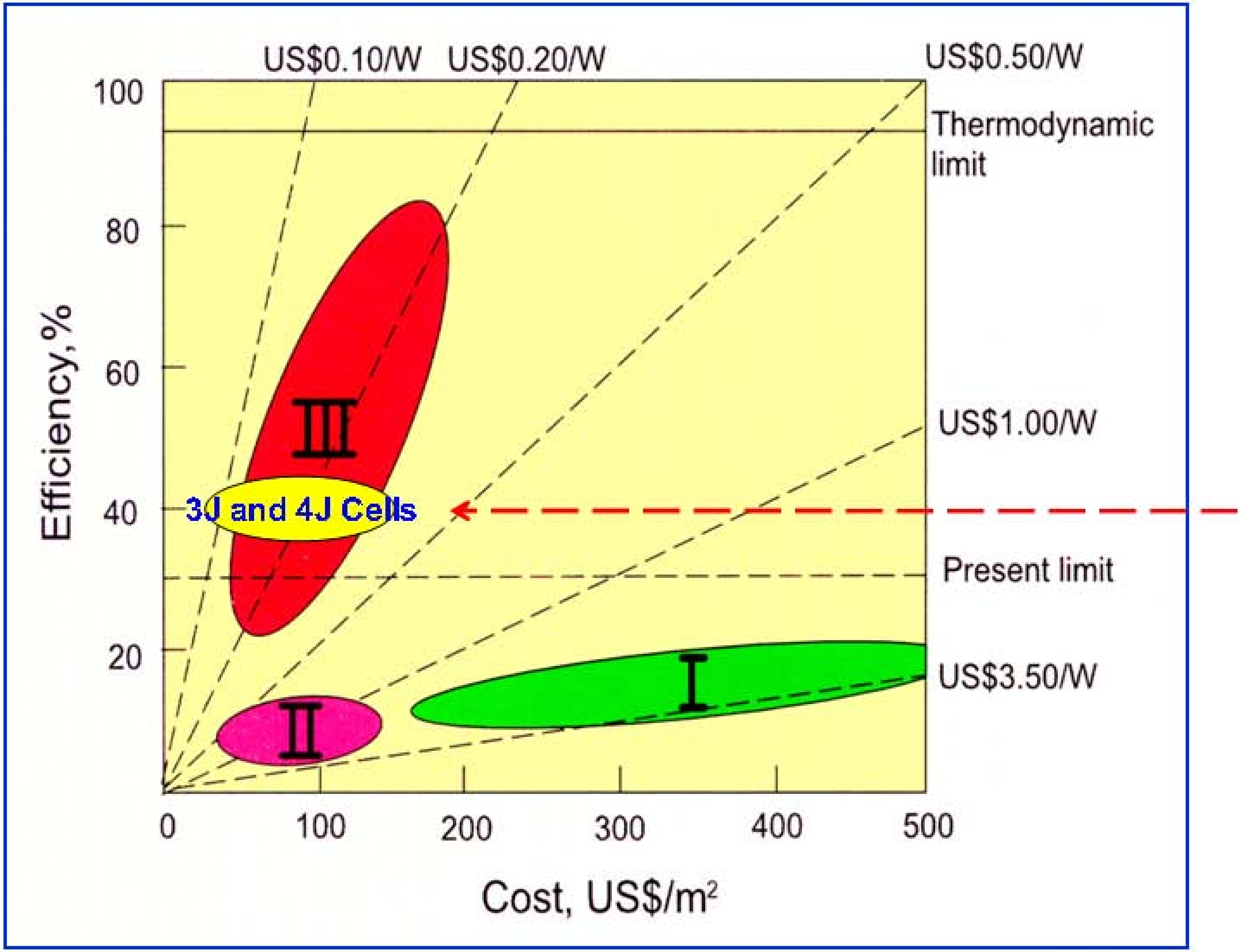


Jurgen Werner

Cost/Efficiency of Photovoltaic Technology



Cost/Efficiency of Photovoltaic Technology

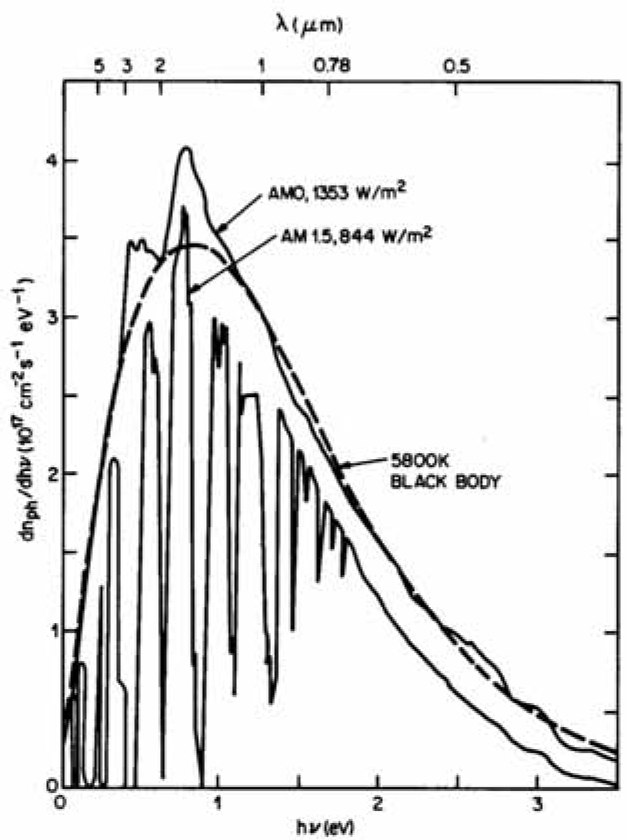


Concentrator Photovoltaics: An Approach to Reap Benefit from Expensive Ultrahigh Efficiency Cells

UMUWA SOLAR POWER STATION

SolarSystems

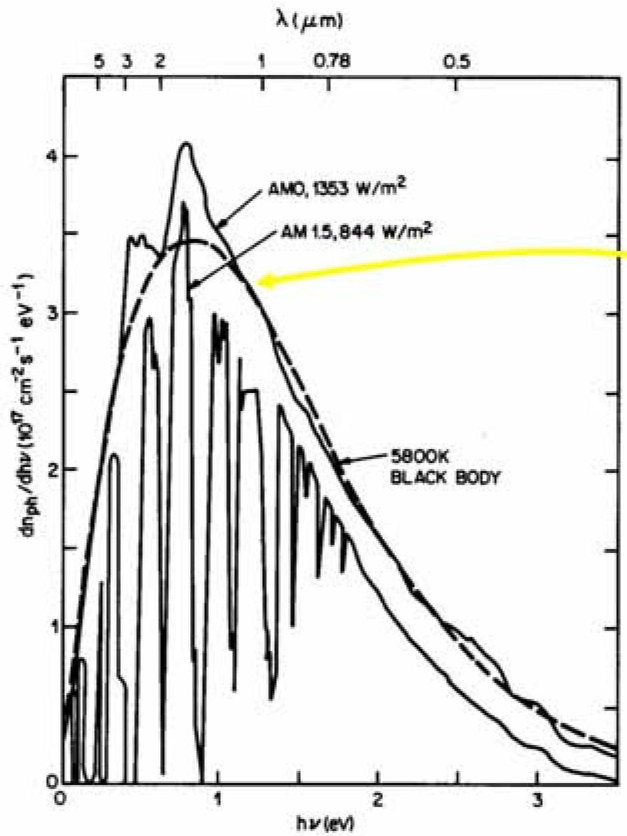
Limits to Efficiency: Spectral Absorption

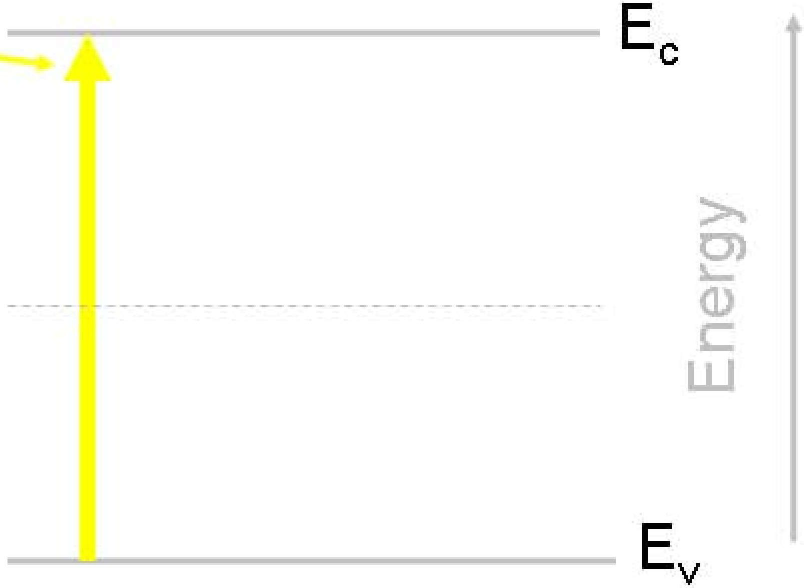


Band-to-Band Absorption **Hot Carrier Excitation** **Subgap Photon Energy**

S. M. Sze, *Physics of Semiconductor Devices*, (Wiley) 1981.

Limits to Efficiency: Spectral Absorption





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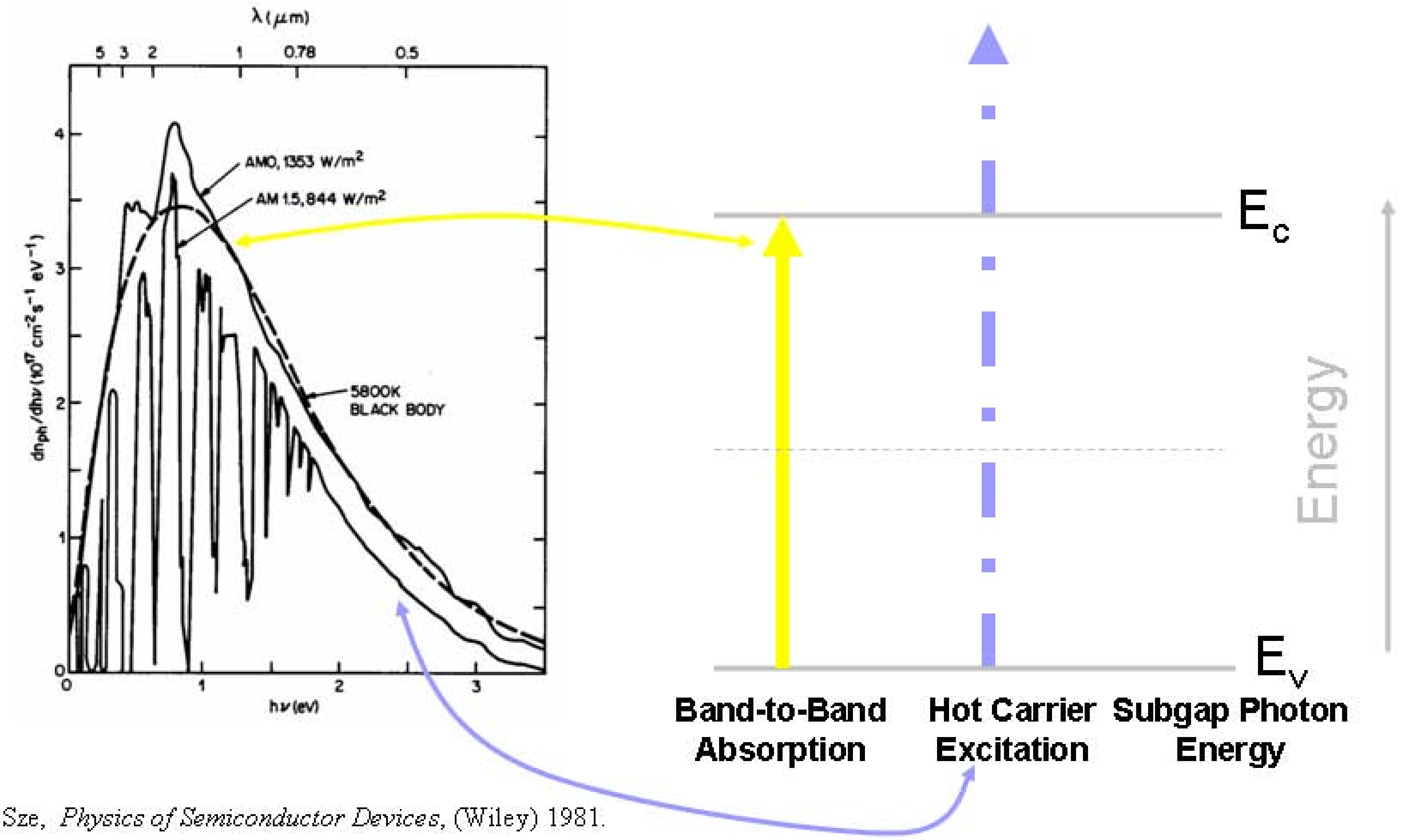

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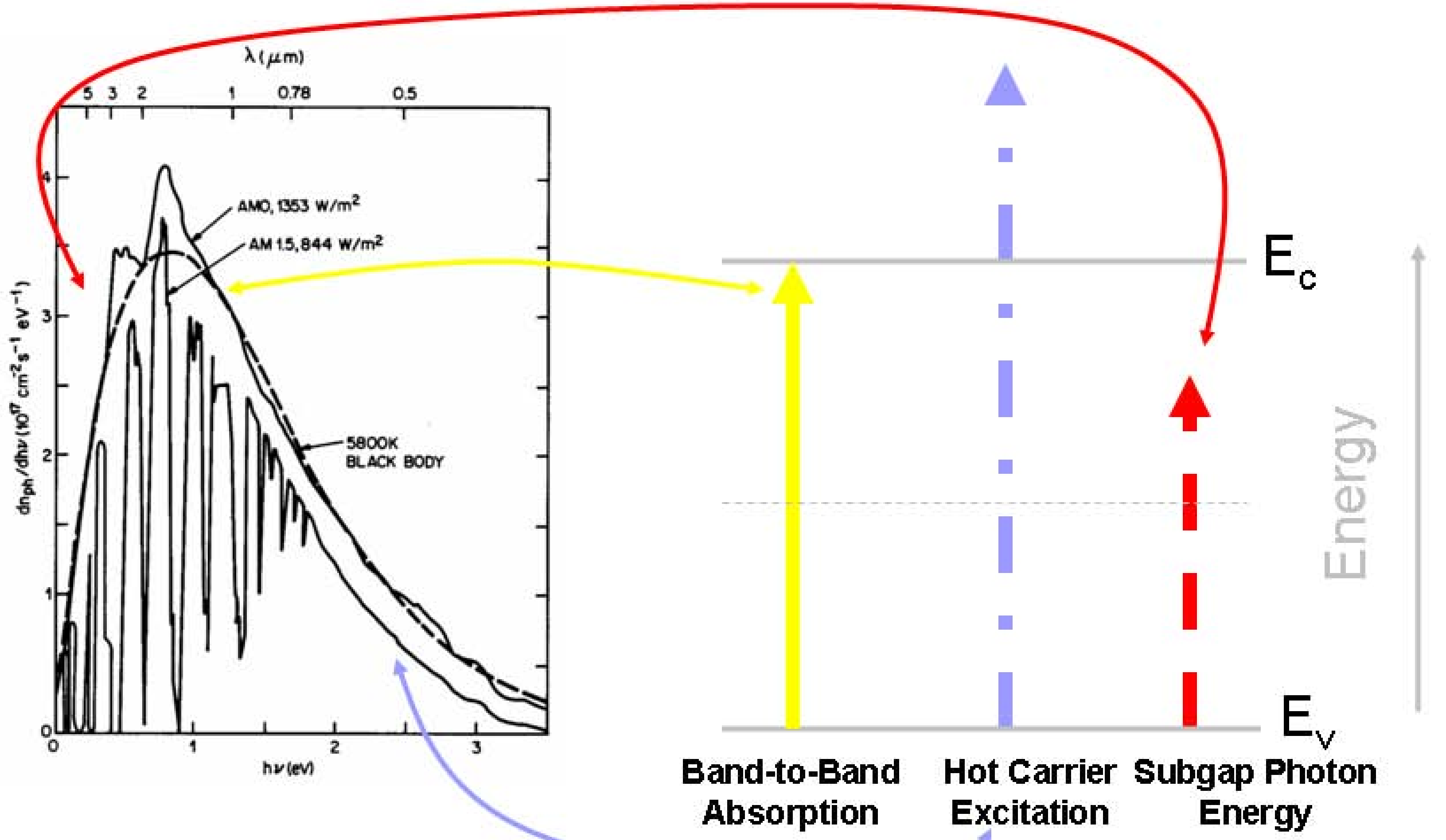
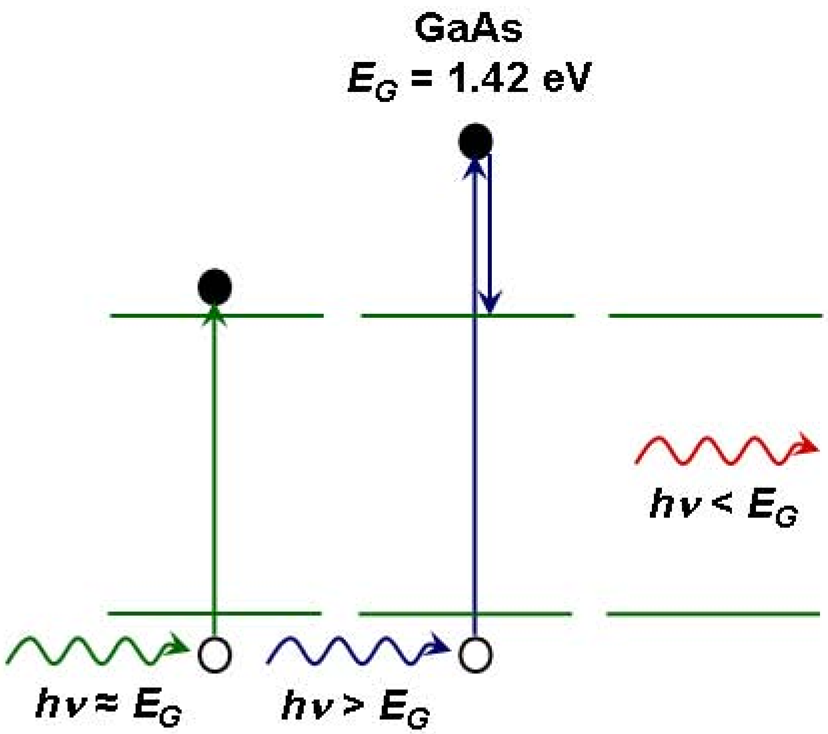
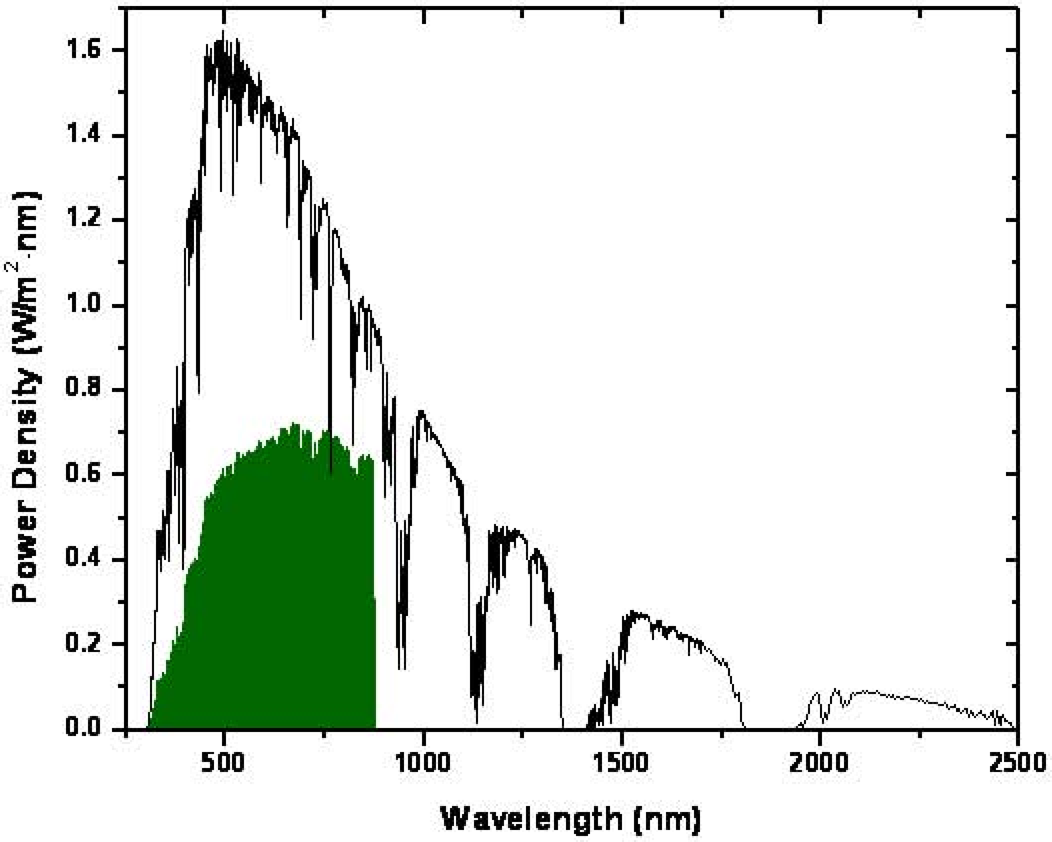


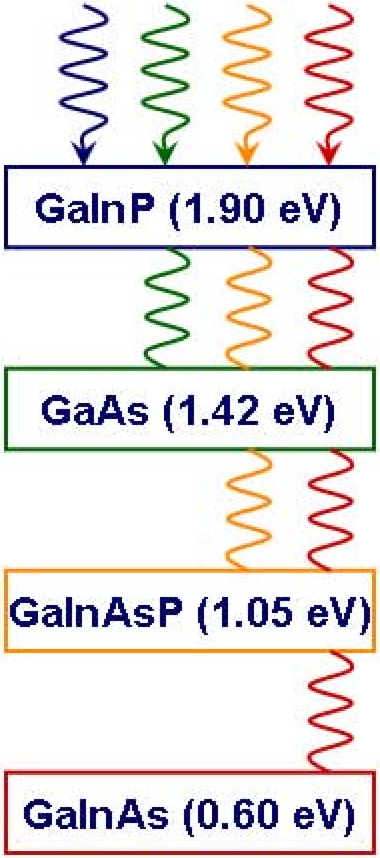
S. M. Sze, *Physics of Semiconductor Devices*, (Wiley) 1981.

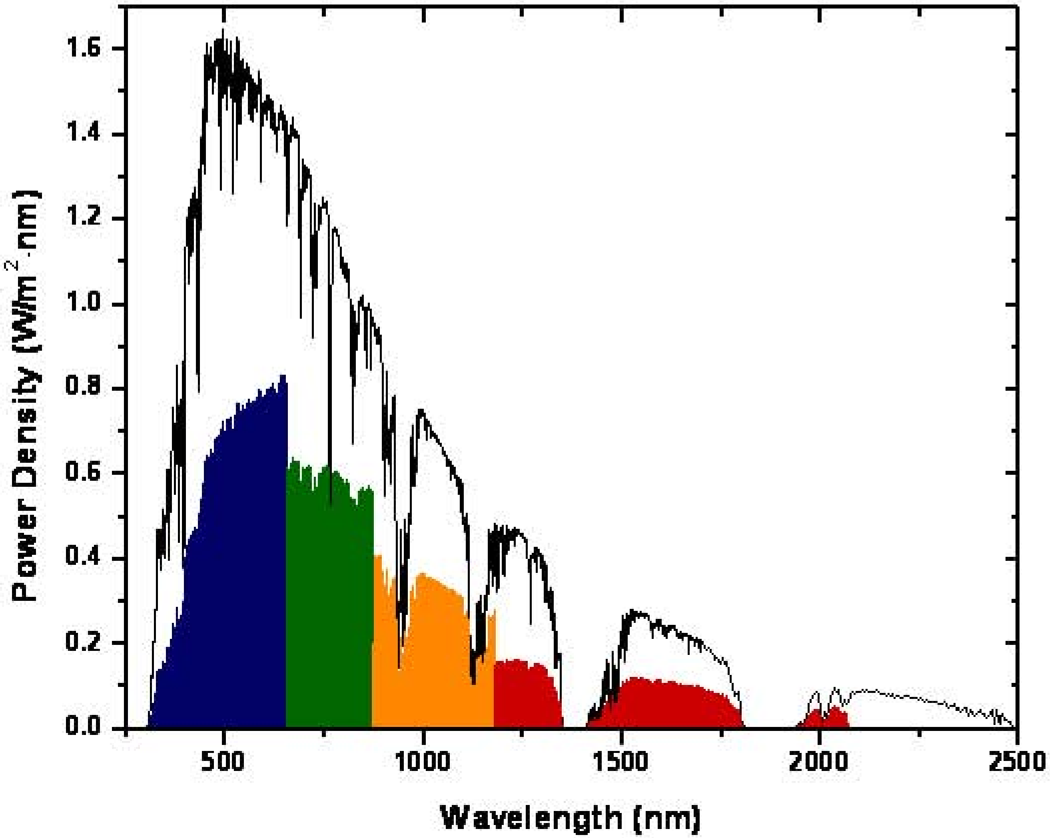
Single-junction GaAs Cell





Four Junction Solar Cell

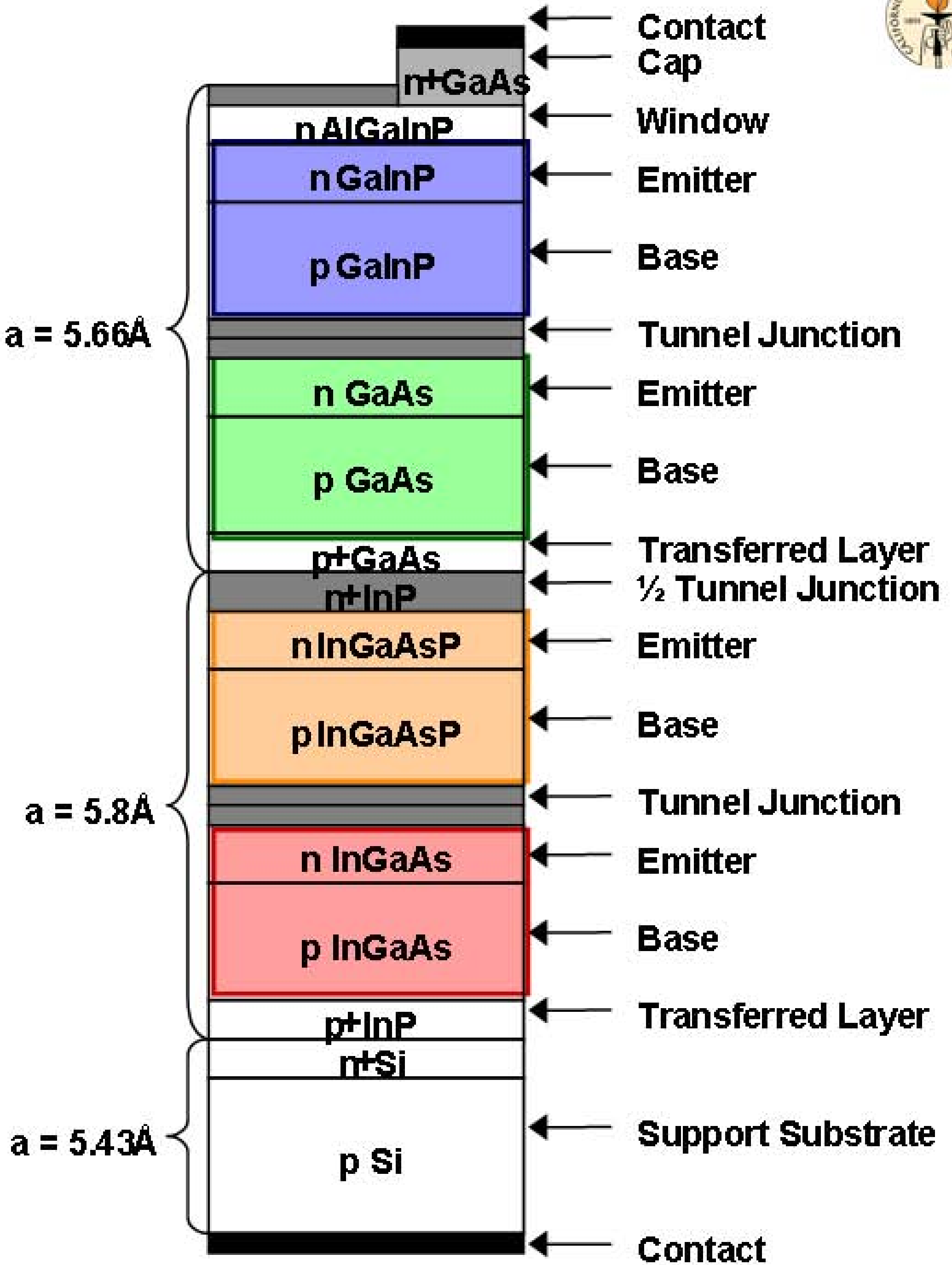




Four Junction Cell

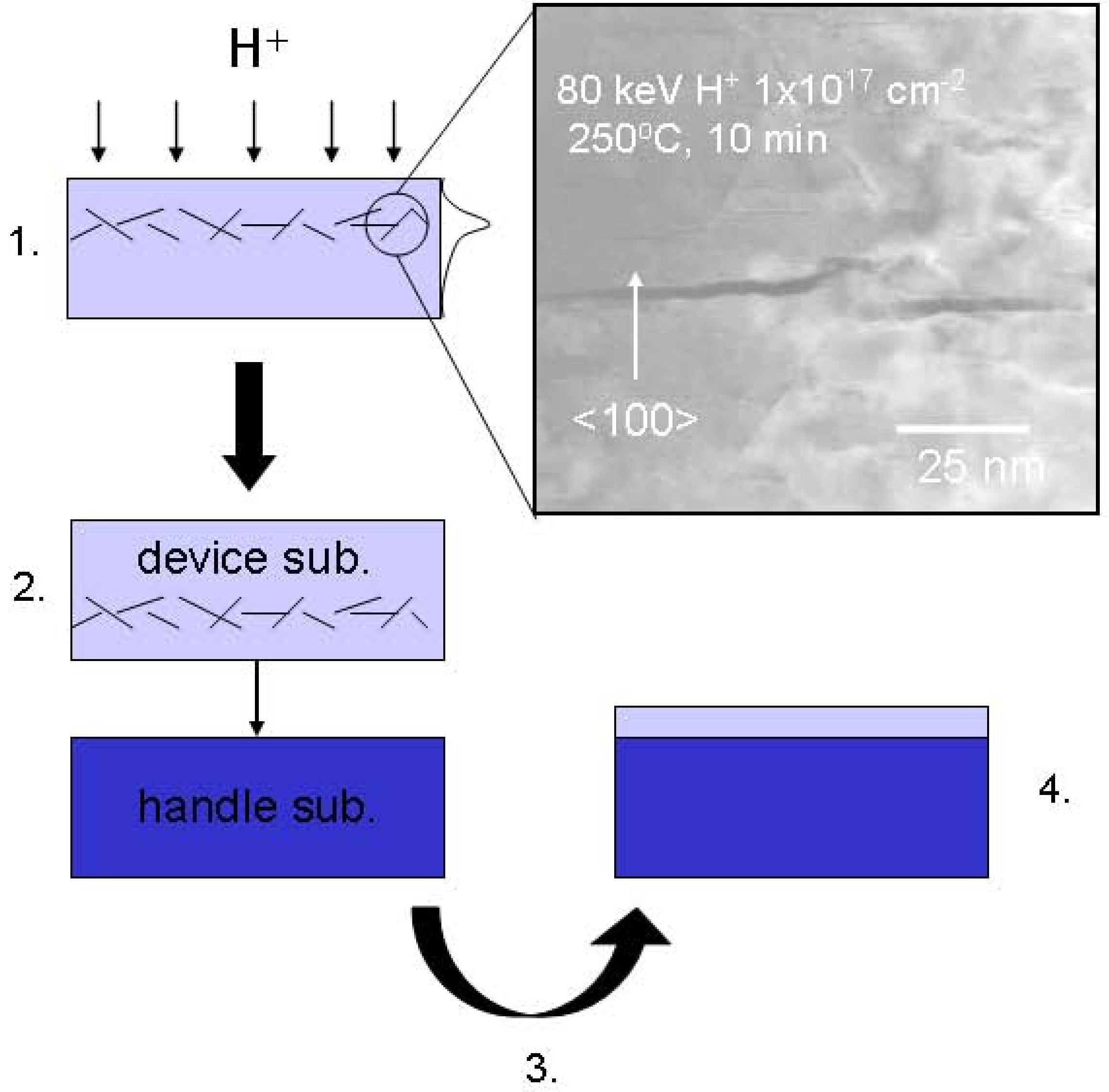
Features:

- Two bonded lattice mismatched interfaces
- Ohmic contacts at bonded interfaces
- low resistance tunnel junctions between subcells
- Si substrate
- InP and GaAs epitaxial templates
- Series/independent electrical connection options

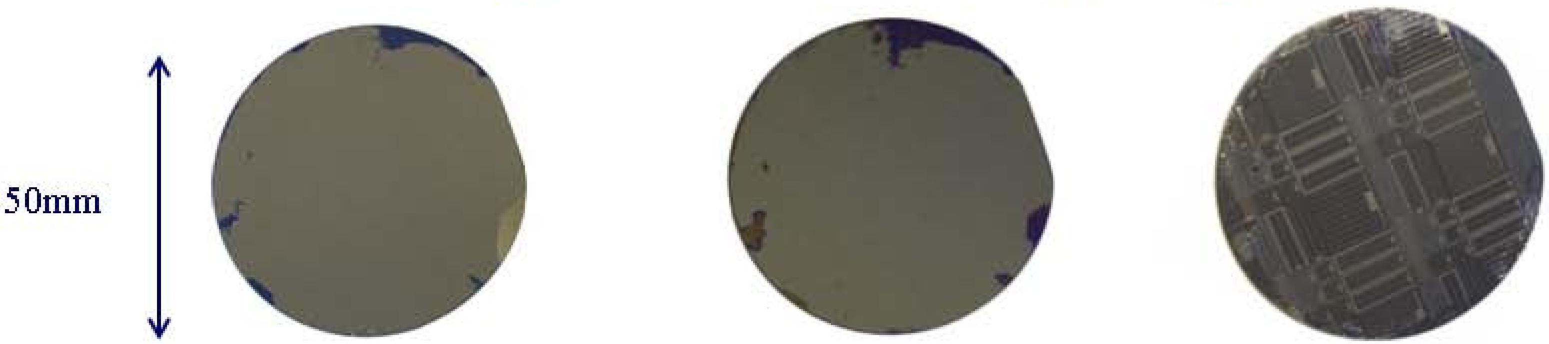


Wafer Bonding/Layer Transfer Process

1. Ion implantation:
   - Defects / Internal Surfaces
   - Pressure
2. Bond formation:
   - Smooth, particle-free surfaces
   - Surface activation
3. Thermal processing:
   - Bond strengthening
   - Exfoliation
4. Result:
   - Thin, uniform transferred film

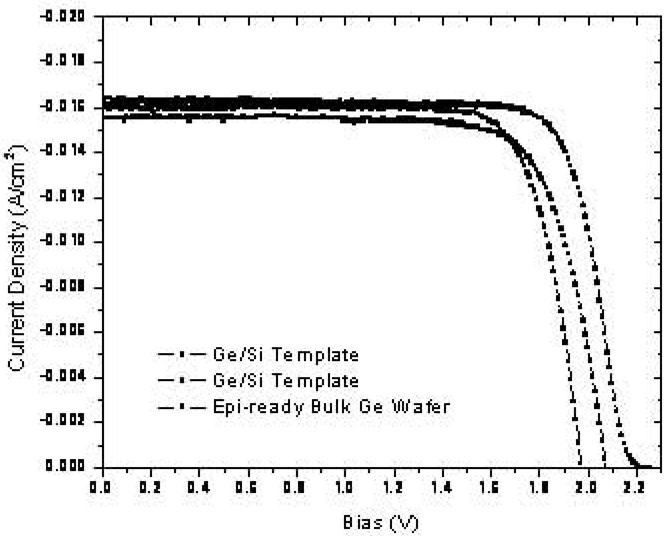


InGaP/GaAs/Ge/SiO_2/Si Two Junction Cells Fabricated by Wafer Bonding/Layer Transfer

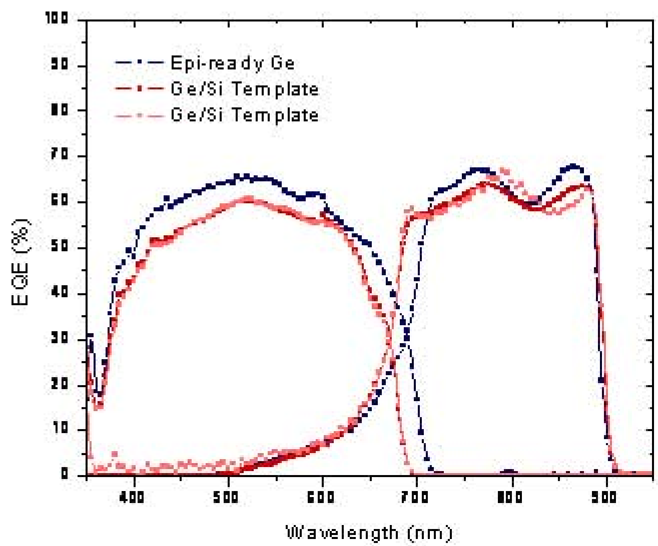


As-Transferred Ge/Si | **After Ge wet etch & CMP** | **After InGaP/GaAs Growth and Cell Processing**

AM 1.5D Light I-V



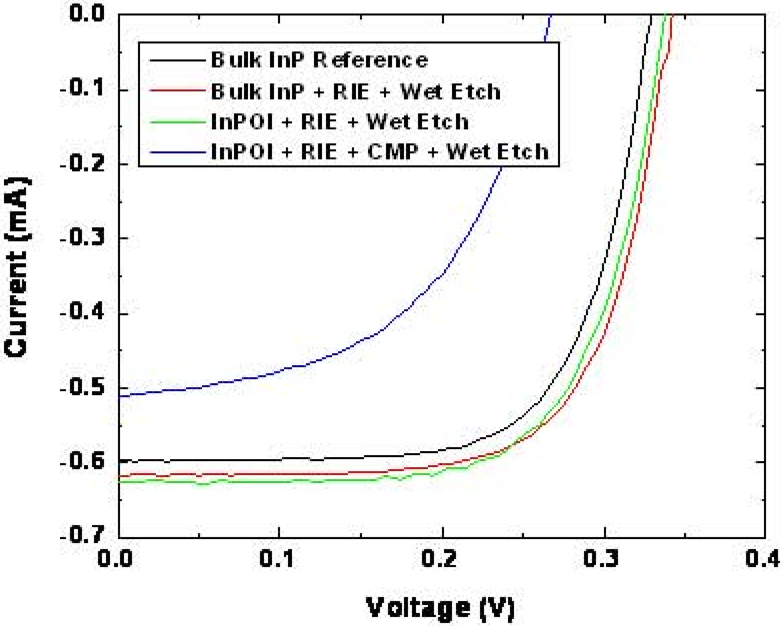
AM 1.5D Spectral Response

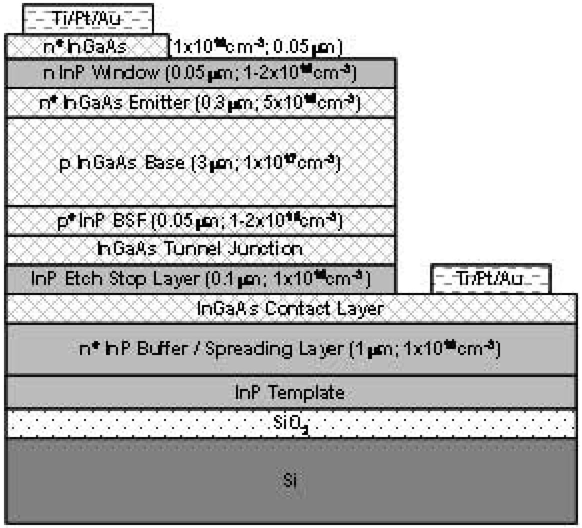


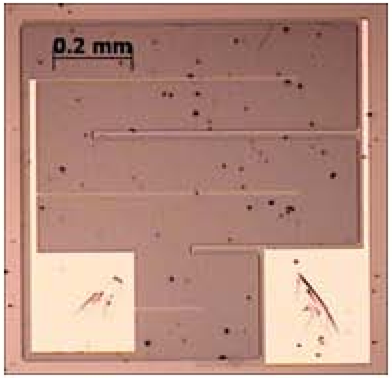
Cell Data

	Bulk Ge Control	Ge/Si Template
J_{sc}	0.016	0.016
V_{oc}	2.22	1.97
FF	0.77	0.79
Eff	~28%	~25%

InGaAs/InP/Si Low Bandgap Cell with Performance Equivalent to State-of-the-Art InGaAs/InP



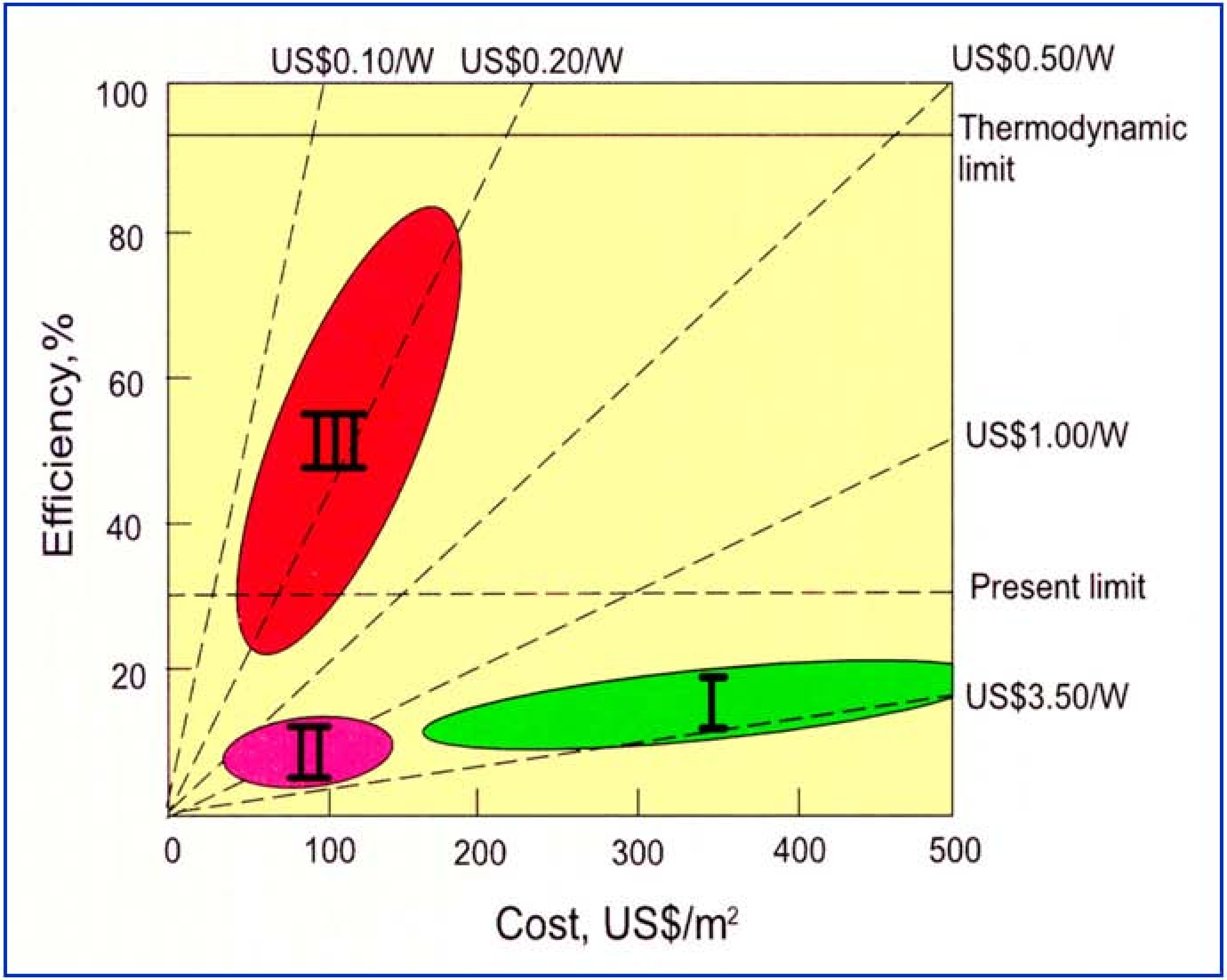




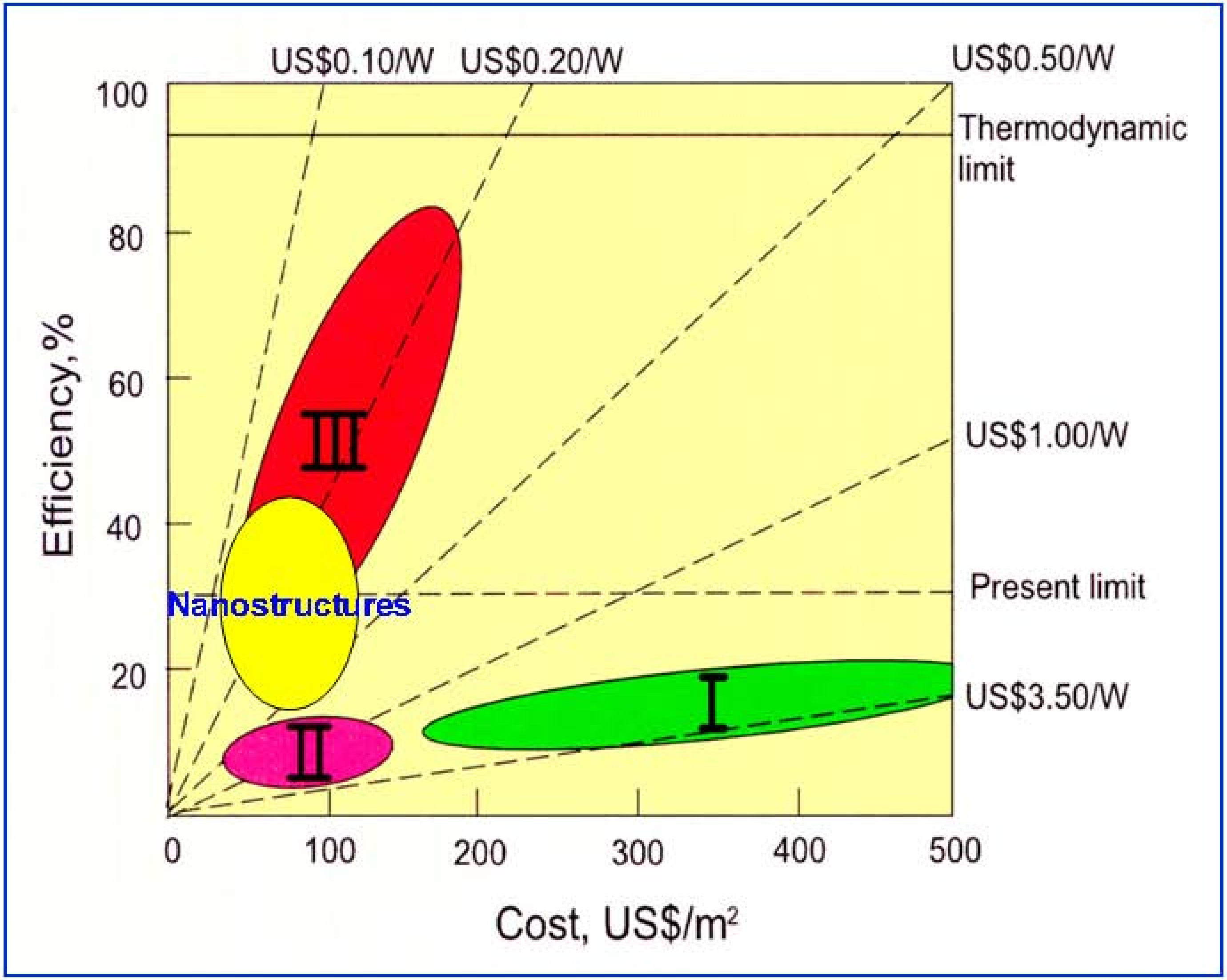
Cell Description	*Jsc*(mA/cm^2)	*Voc*(mV)	Fill Factor
Bulk InP Reference Cell	-59.7	329	0.686
Bulk InP + RIE + wet etch	-61.7	342	0.685
InPOI #1 (*InPOI + RIE + wet etch*)	-62.7	338	0.675

- ***Process <u>Eliminates</u> InP Substrate Cost***
- ***Template Fabrication Cost ~ Epi Cost***

Cost/Efficiency of Photovoltaic Technology



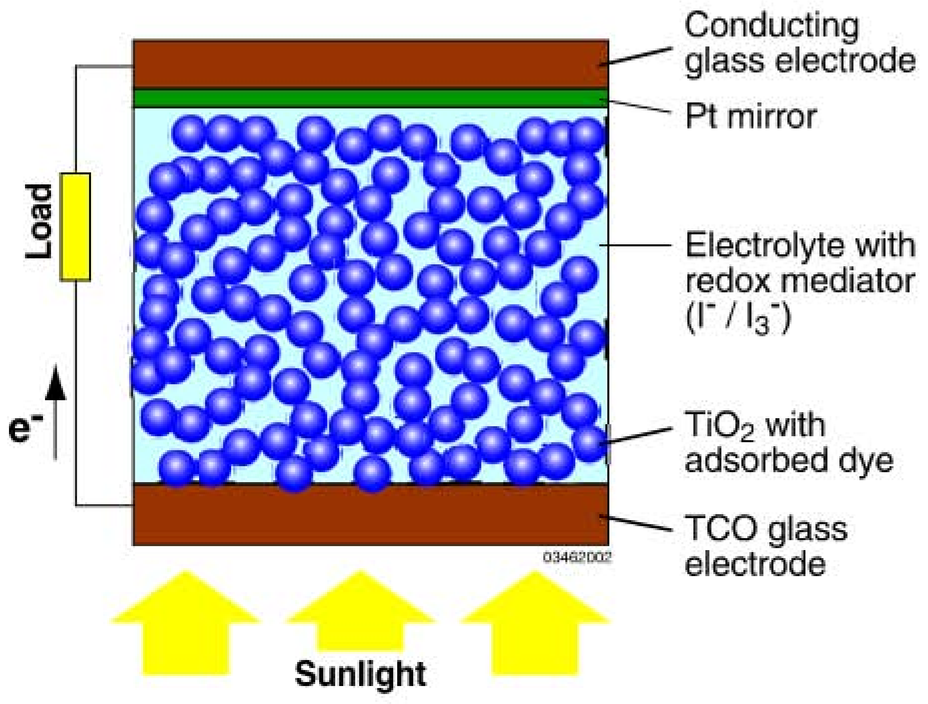
Cost/Efficiency of Photovoltaic Technology



Mesocopic Injection Dye-Senstized Solar Cells

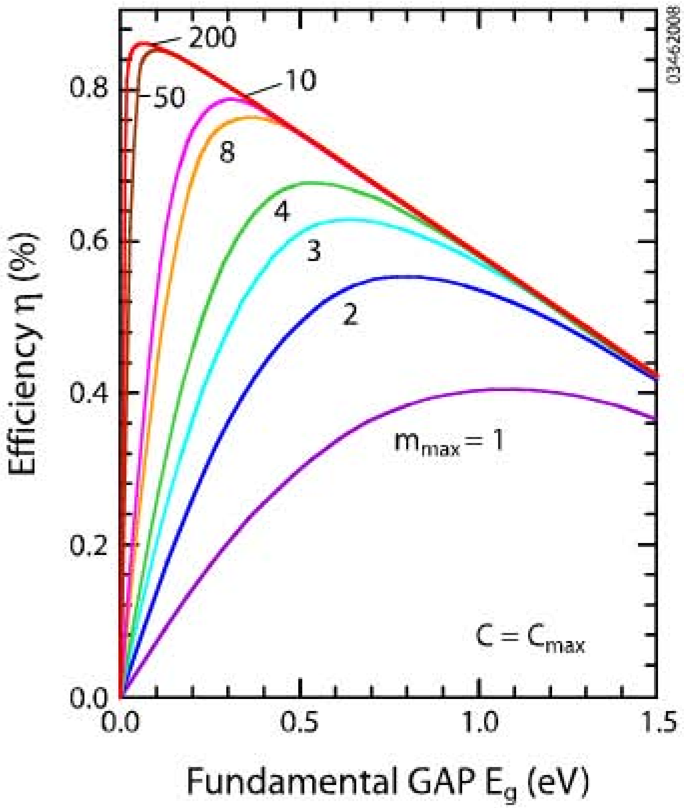
- Electron-hole pairs generated as excitons in a dye absorber (Ru-bpy)
- Excitons diffuse to TiO_2 interface
- Excitons dissociated into electrons and holes
- Electrons injected in TiO_2
- Holes injected into liquid electrolyte
- Potentially low costs for materials and processing

Dye Sensitized Solar Cell



Multiple Exciton Generation Solar Cells

- Electron and hole created simultaneously
- Hot electron and hole create multiple (m) electron-hole pairs through Auger emission and absorption instead of thermalizing
- Need materials (e.g., quantum dots) susceptible to creation of multiple Auger electron-hole pairs
- Recently report by NREL and Los Alamos …3 carriers for 1 photon in PbSe

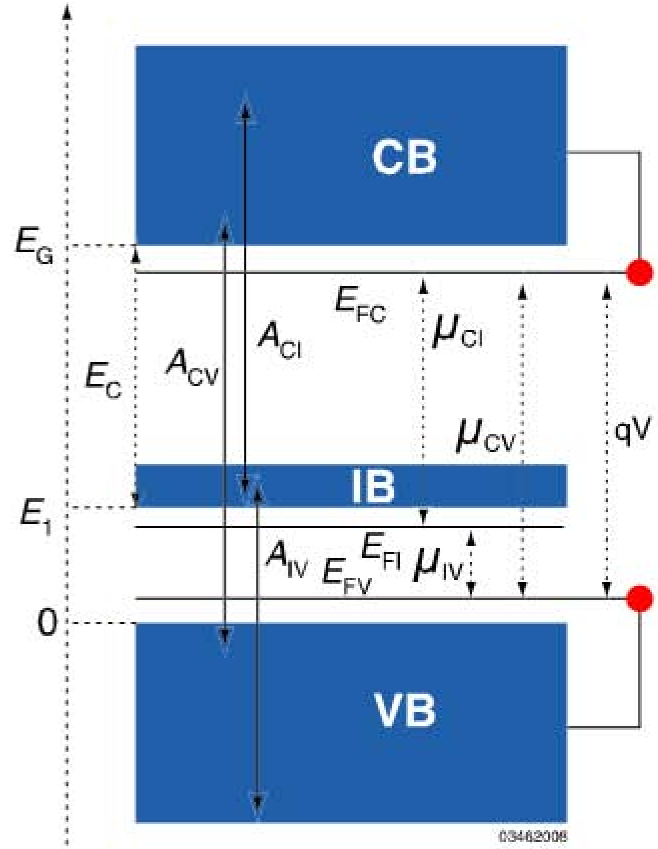


H. Queisser et al., Max Planck Inst.,
Solar Energy Materials and Solar Cells, 41/42, 1996

Intermediate-Band Solar Cells

- Multiple transition paths via intermediate band
- Theoretical efficiency advantages over equivalent multijunction cells
- Can simplify and augment multijunction solar cell efficiencies

A. Luque et al., U. Politecnica de Madrid
Phys. Rev. Lett., 78, No. 26, 1997

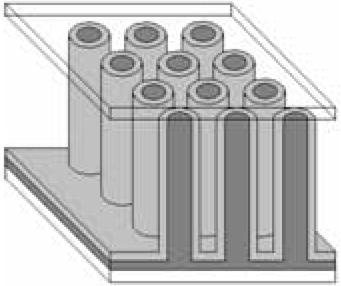


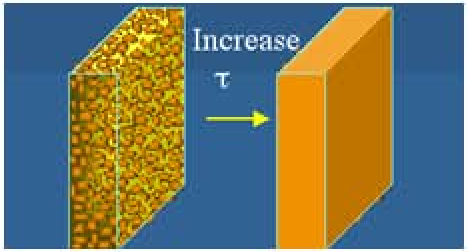
Band diagram of a solar cell with an intermediate band.

Nanowire Photovoltaic Cells

Emergent Concepts for Photovoltaic Nanostructures:

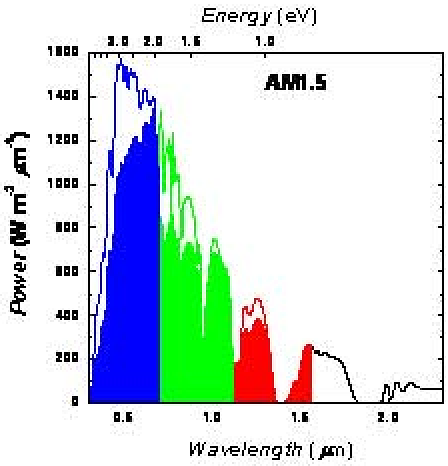
1. **Nanowires** are a significant opportunity: carrier collection at low diffusion length – 'improve' poor quality materials

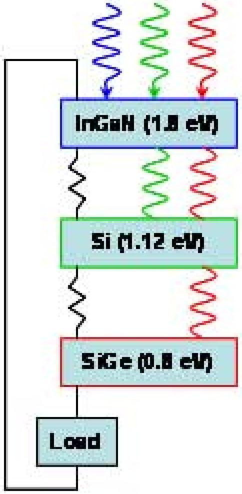




2. **Passivation** is essential in nanostructures

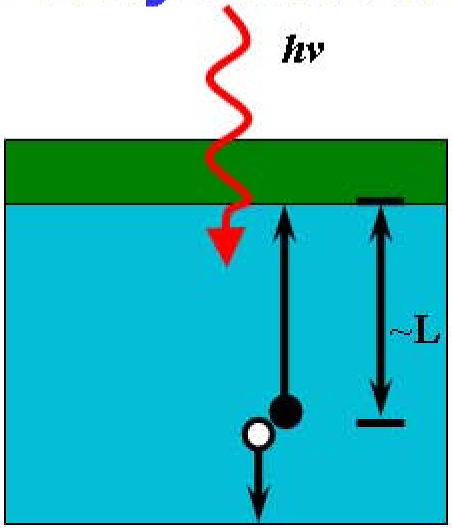
3. **Multijunction** architecture highly desirable for efficiency





4. **Sheet Processing**: Large-area low-cost reliable processing

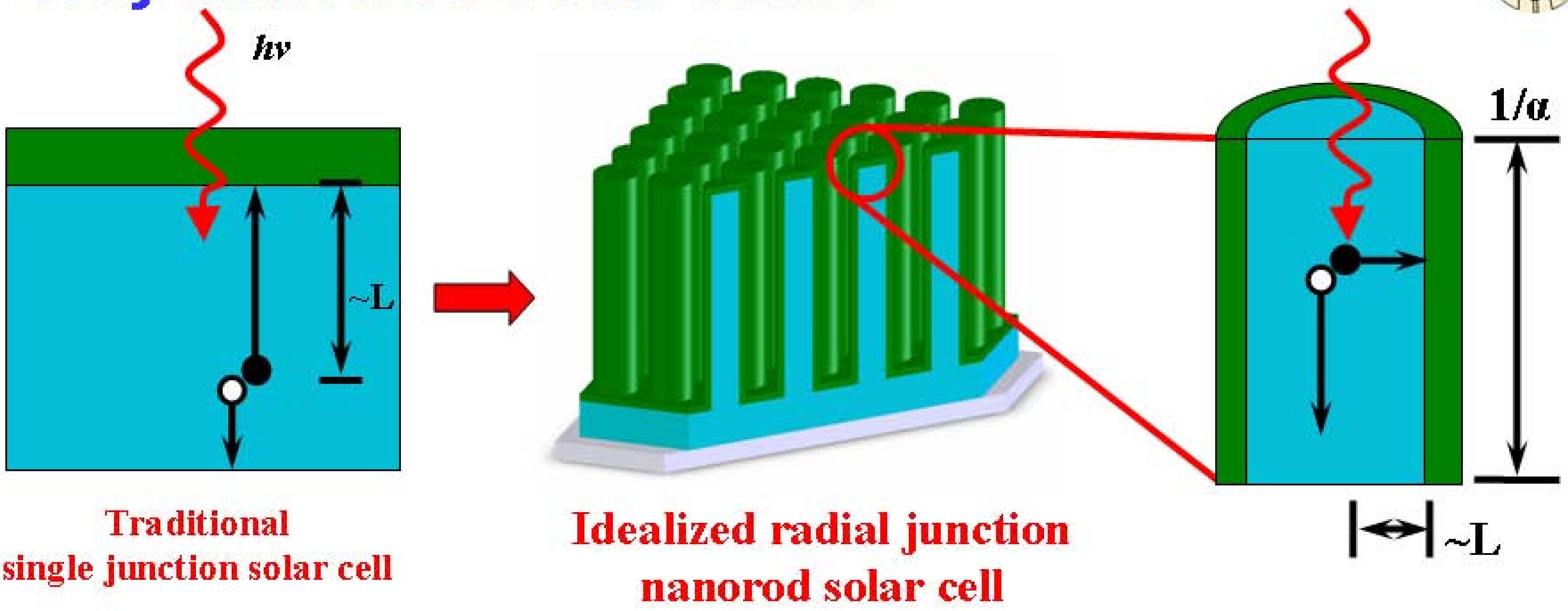
Why Nanowire Solar Cells?



Traditional single junction solar cell

- Traditional device design requires expensive, long diffusion length materials

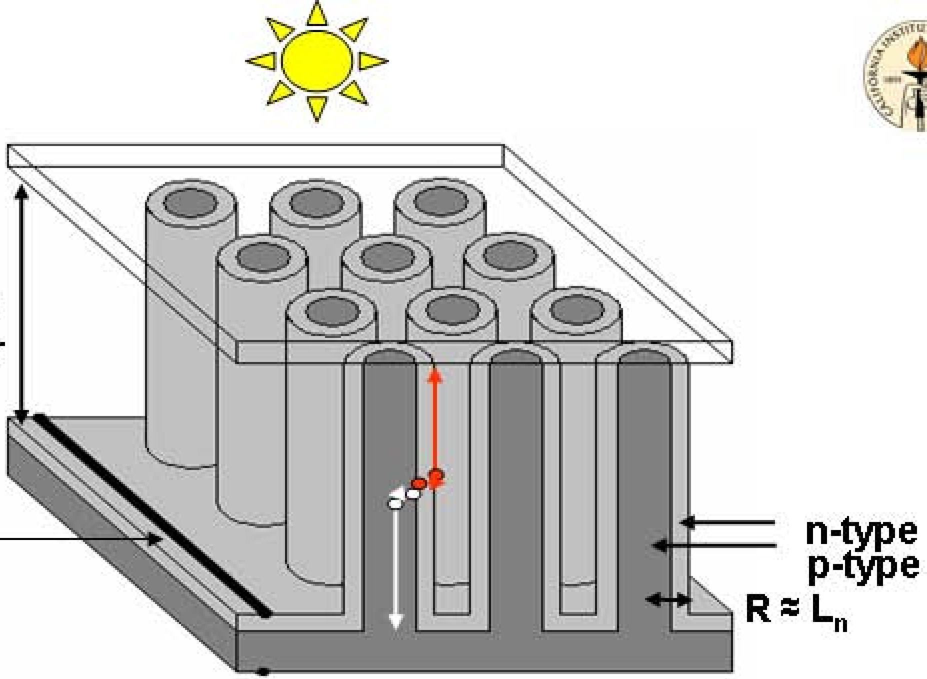
Why Nanowire Solar Cells?

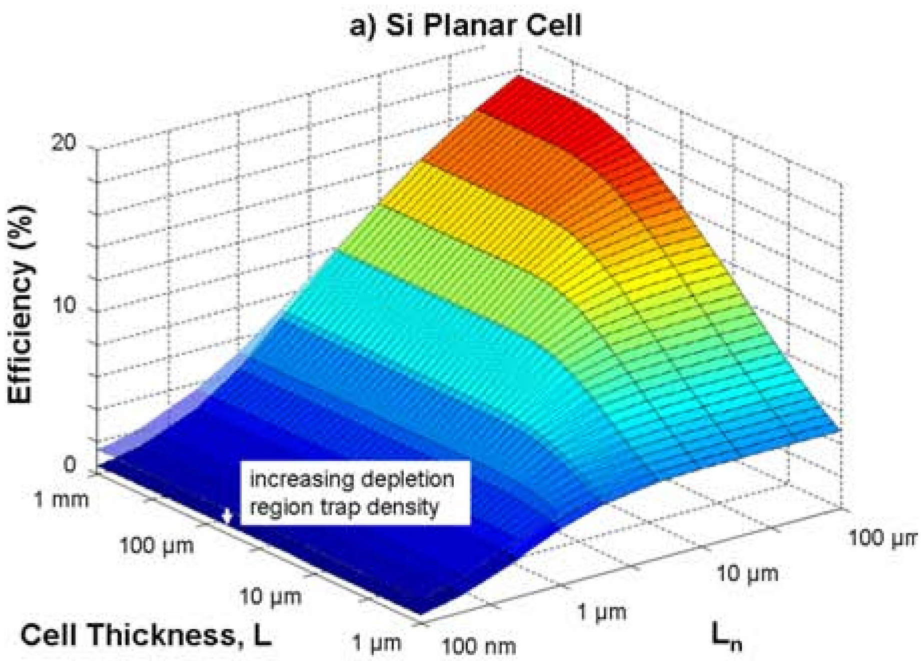


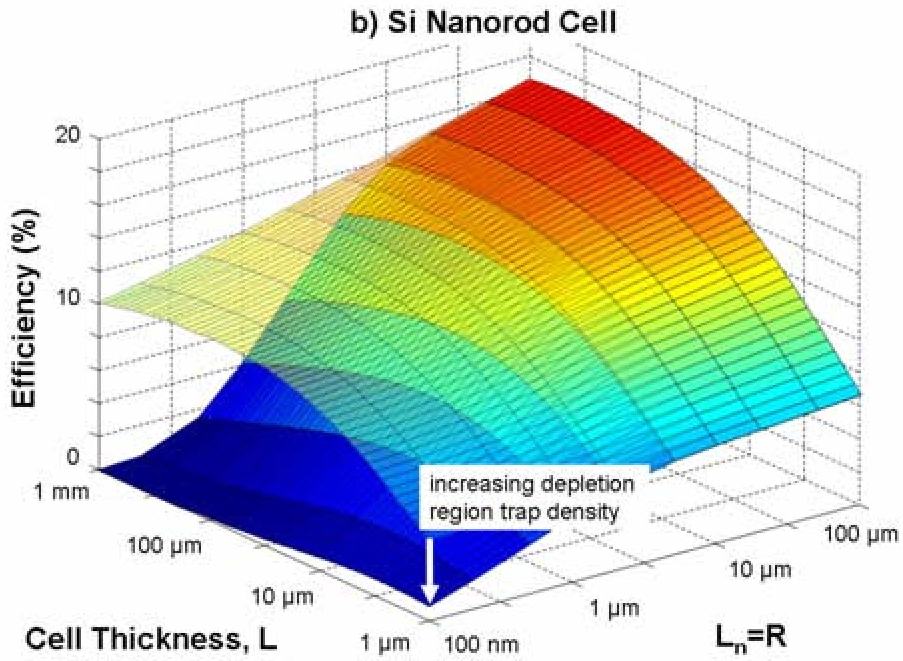
- Traditional device design requires expensive, long diffusion length materials
- Nanowire device decouples light absorption and carrier extraction into orthogonal spatial directions
- Radial geometry allows for high quantum efficiency with short minority carrier diffusion lengths (i.e. inexpensive materials and processes)
- Radial or axial pn junction geometries envisioned
- Hetero- and multi-junction devices possible

Radial p-n junction nanowire solar cell

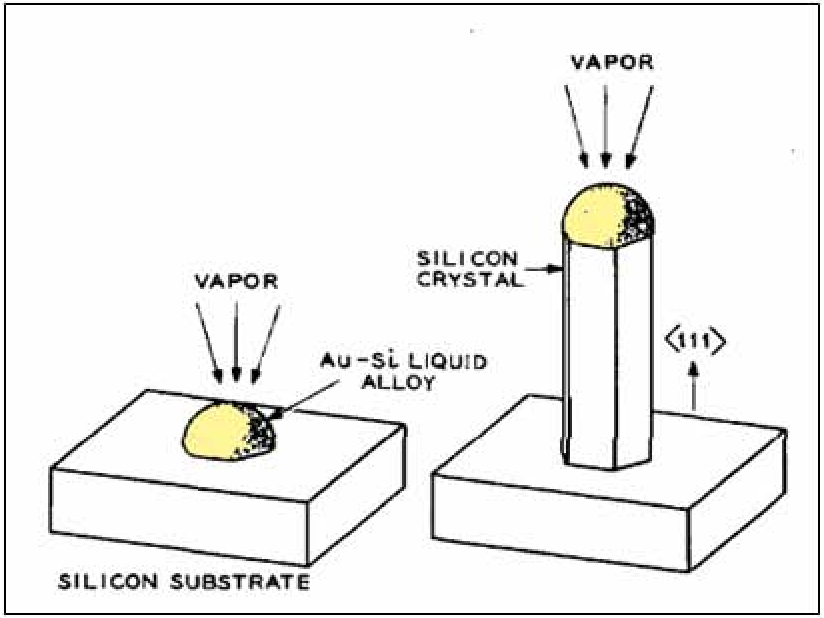
B.M. Kayes, et.al.,
J. Appl. Phys. 2005

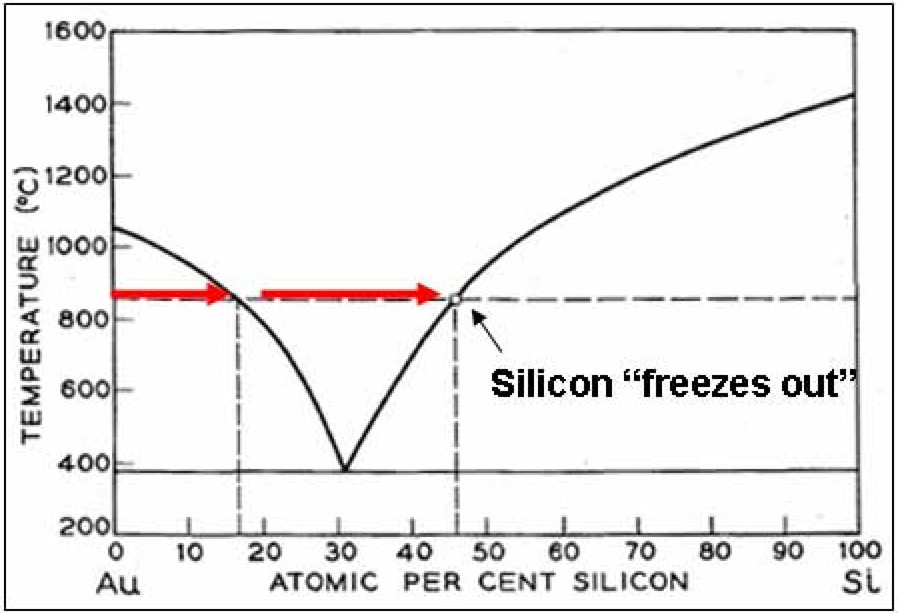




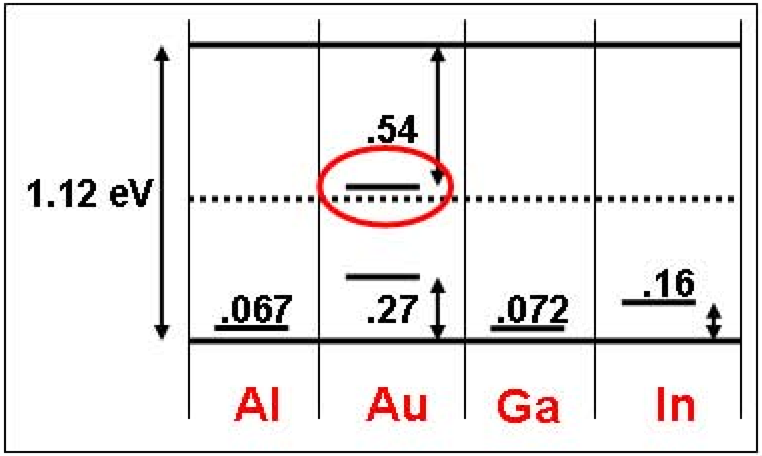


Vapor-Liquid-Solid (VLS) Growth



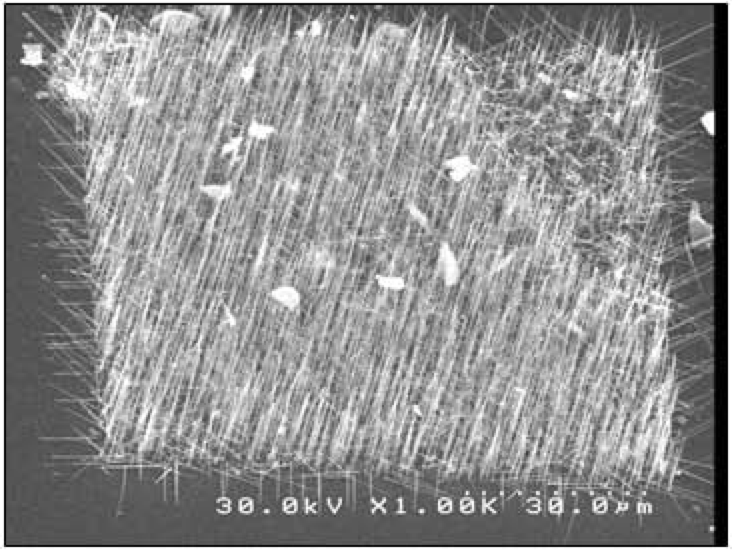


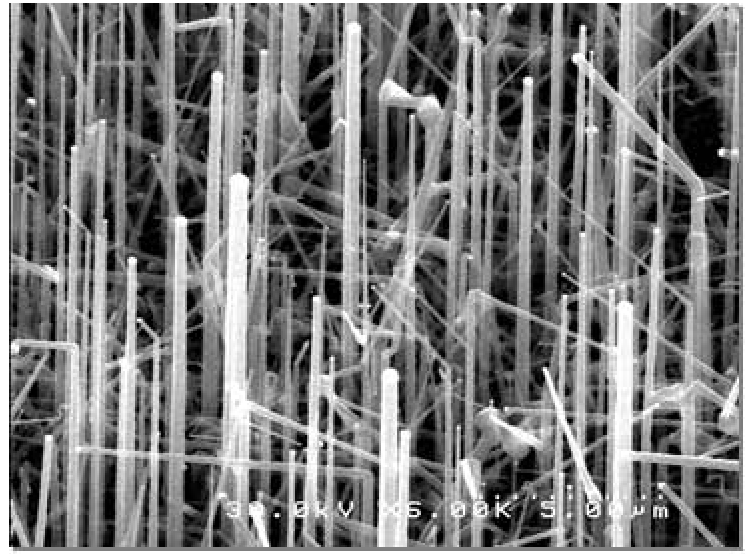
Photovoltaics may require use of alternative VLS catalysts

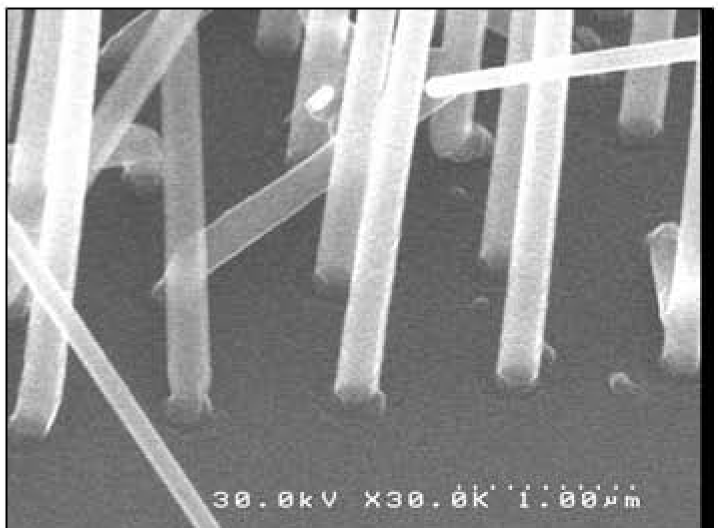


R.S. Wagner and W.C. Ellis, Appl. Phys. Lett. 4, 89-90 (1964)
R.S. Wagner and W.C. Ellis, Trans. Metall. Soc. AIME 233, 1053-1064 (1965)
S.M. Sze *Physics of semiconductor devices* (New York, Wiley-Interscience, 1969)

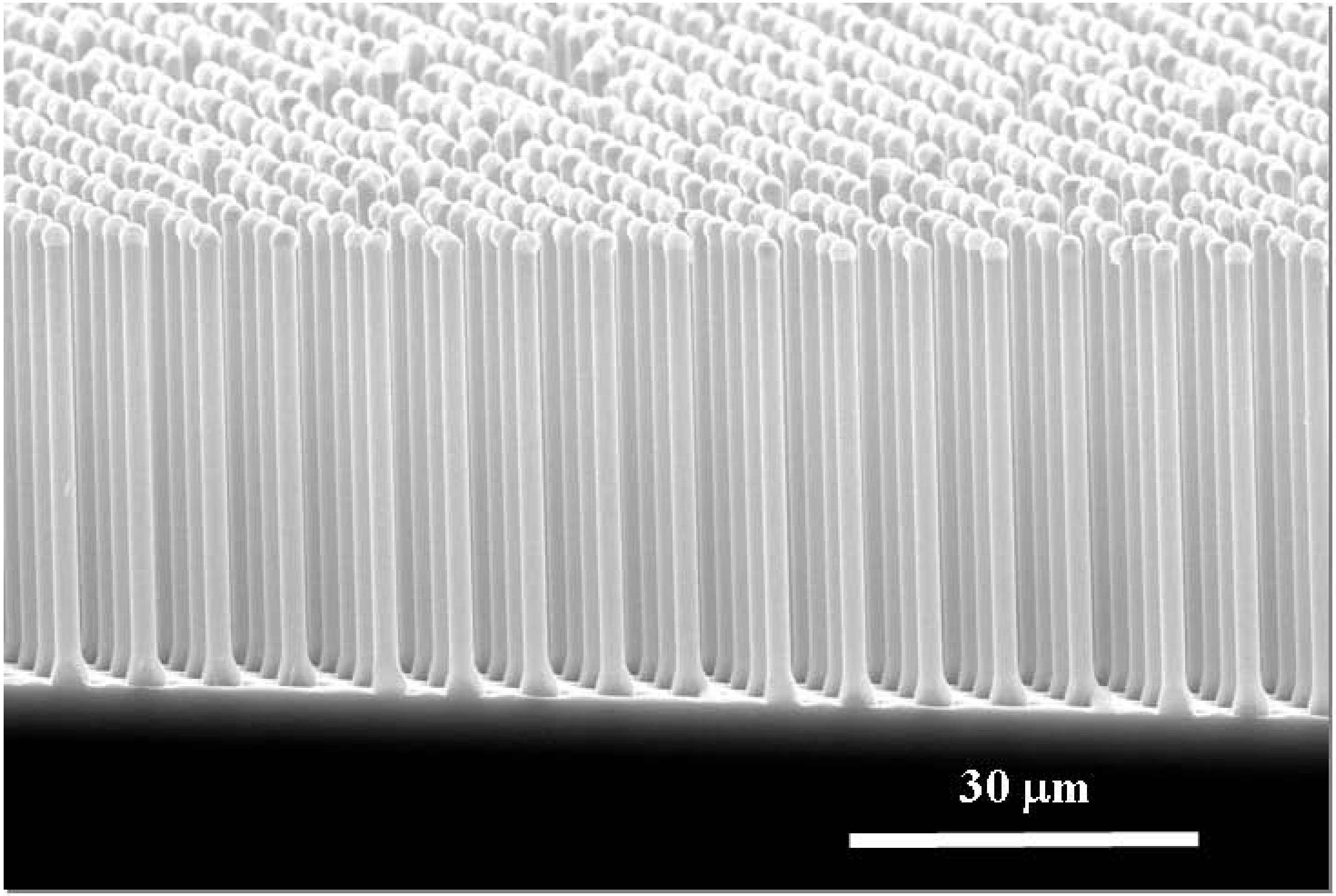
Vapor-Liquid Solid Synthesis of Si nanowire arrays







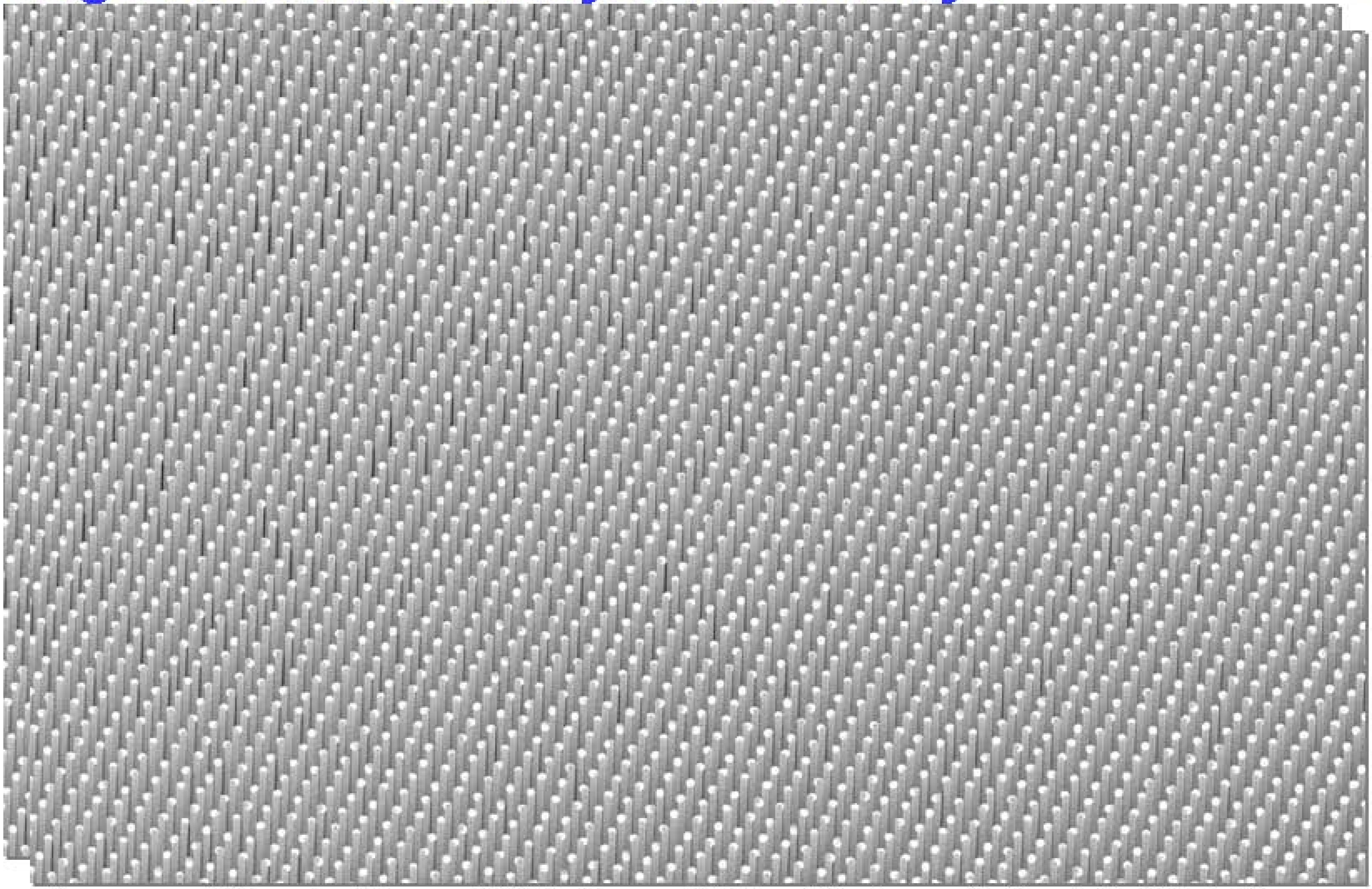
Large Area Au-Catalyzed Si Arrays



3 μm array, 500 nm Au, T_{growth} = 1000°C, P_{growth} = 760 Torr, 30 min growth, 2 mole % $SiCl_4$ in H_2

Nearly 100% vertically aligned, 75 μm length microwire arrays over areas > 1 cm^2.

Large Area Au-Catalyzed Si Arrays



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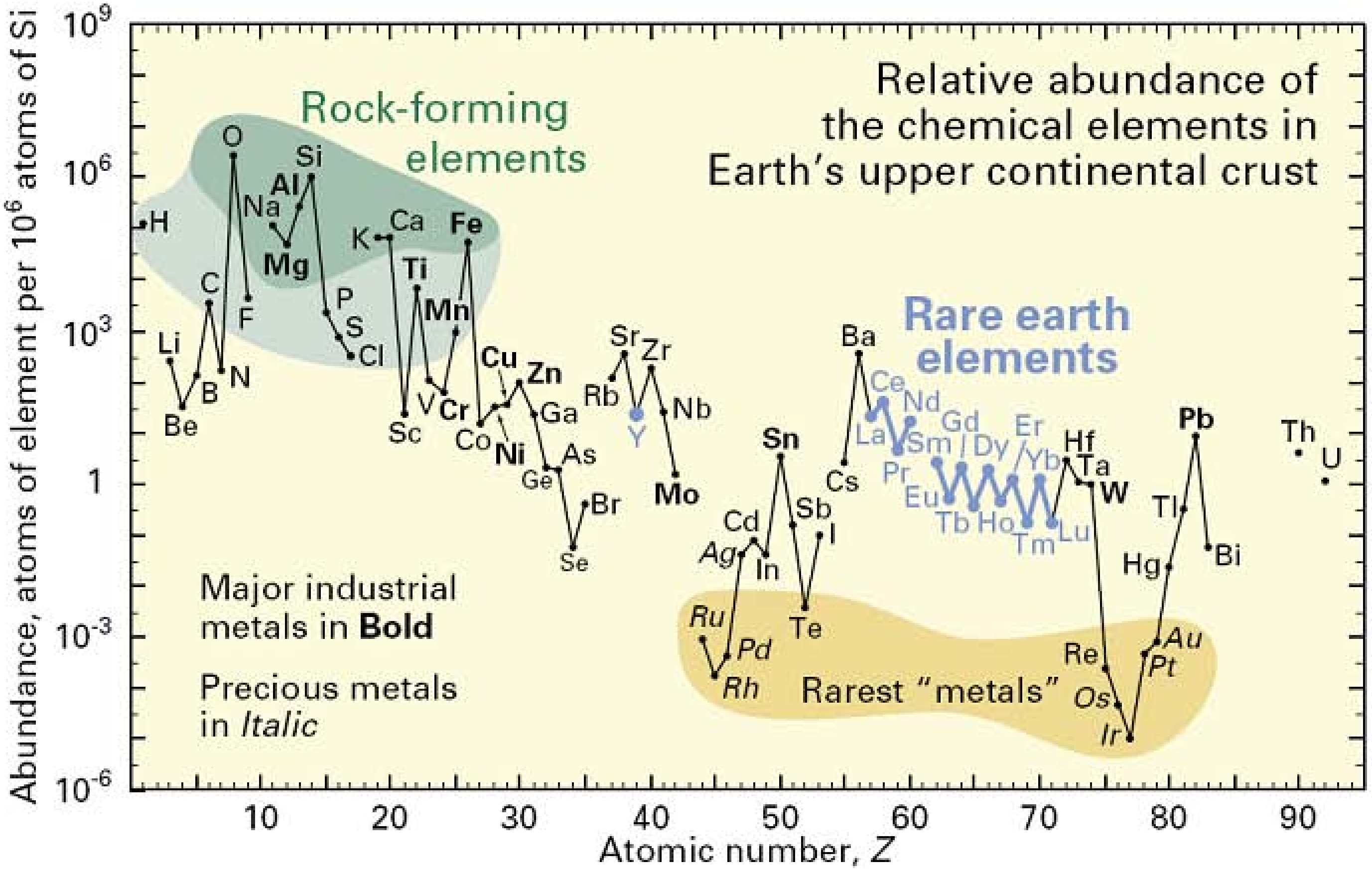
VLS Catalysts - Cost/Abundance

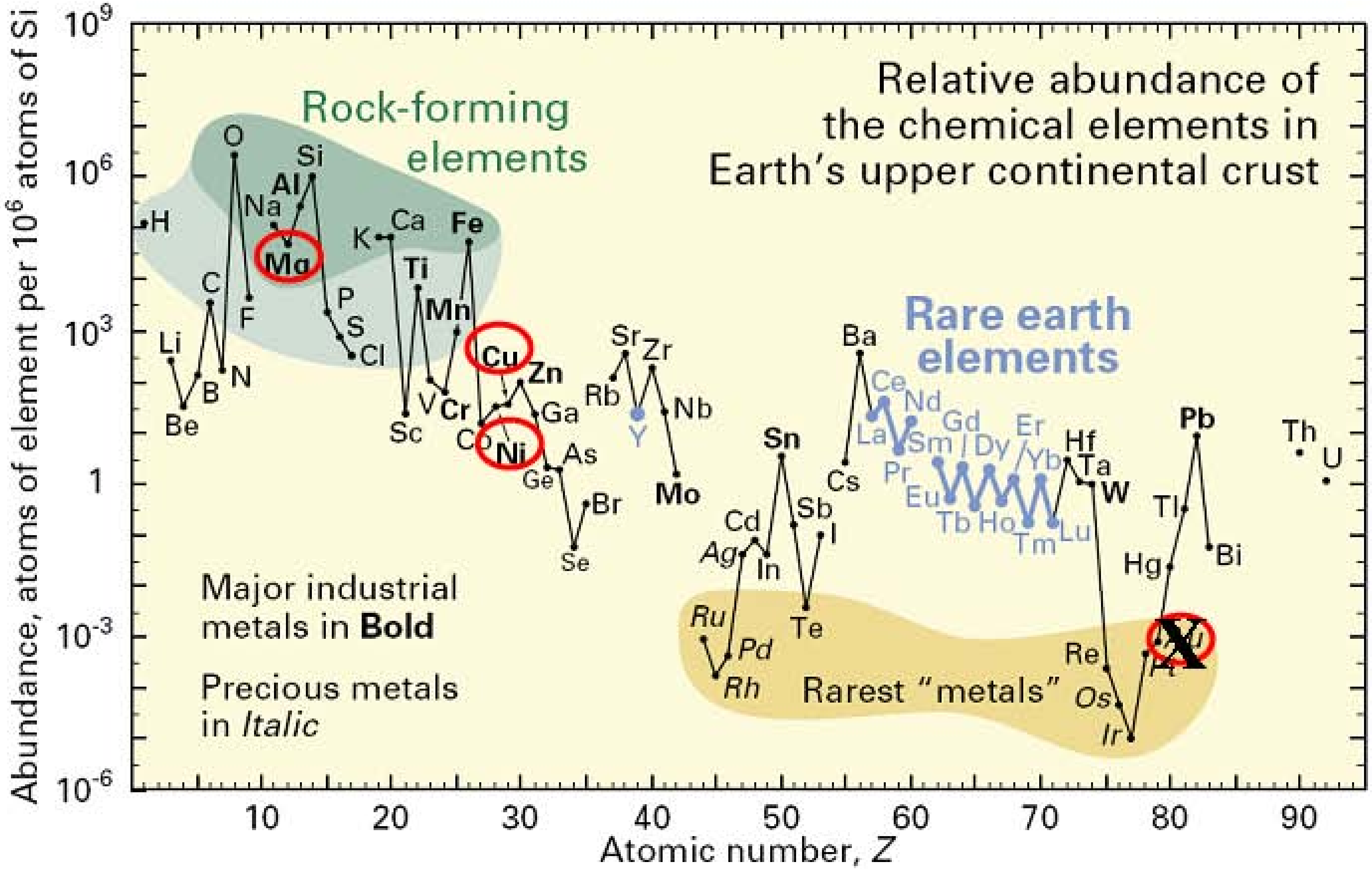


Relative abundance of elements vs. atomic number*

Implementation of more inexpensive and earth-abundant catalysts will be important for large scale technology deployment.

*from P.H. Stauffer et al, Rare Earth Elements - Critical Resources for High Technology, USGS (2002)

VLS Catalysts - Cost/Abundance



Relative abundance of elements vs. atomic number*

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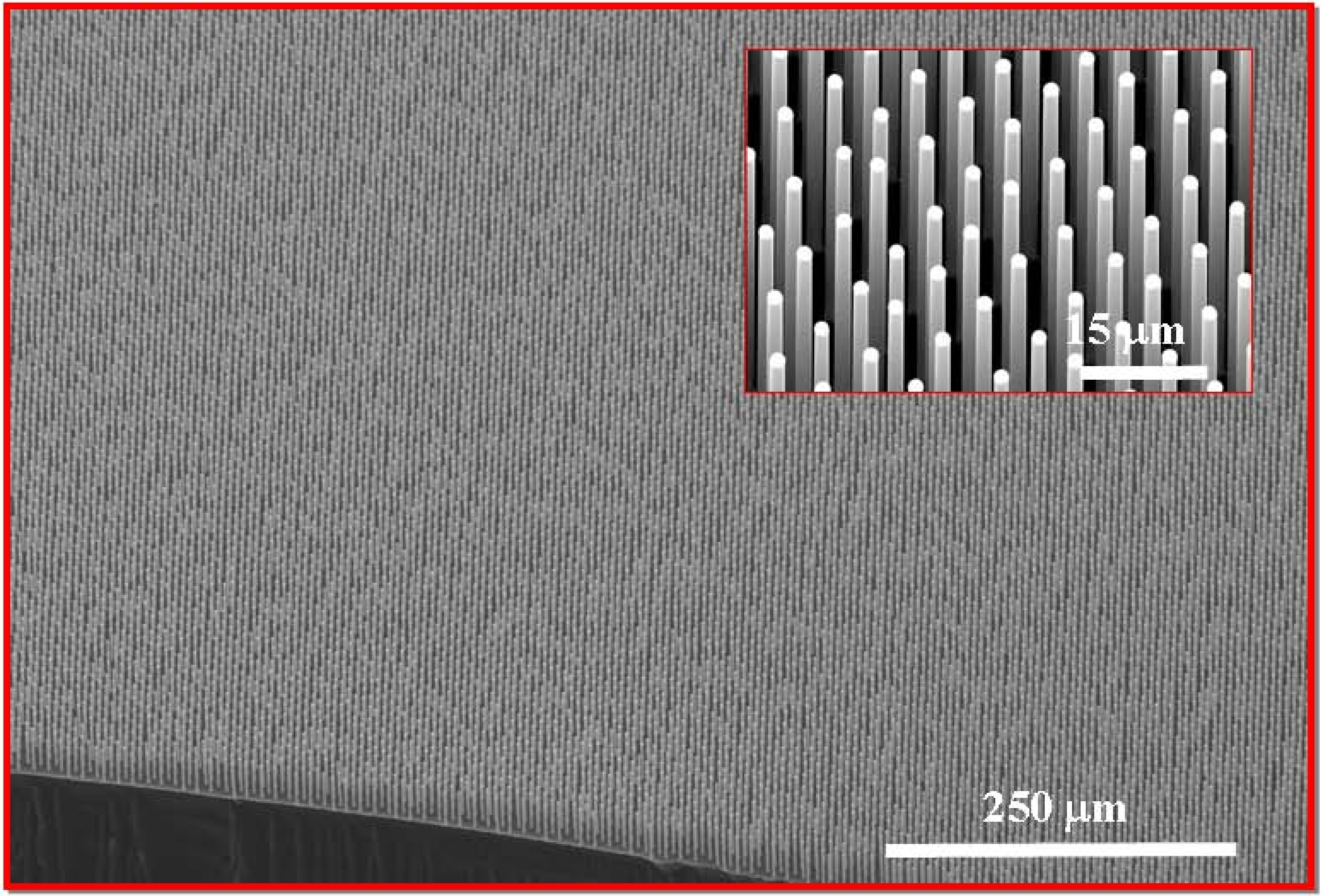
Copper-Catalyzed Si Wire Arrays



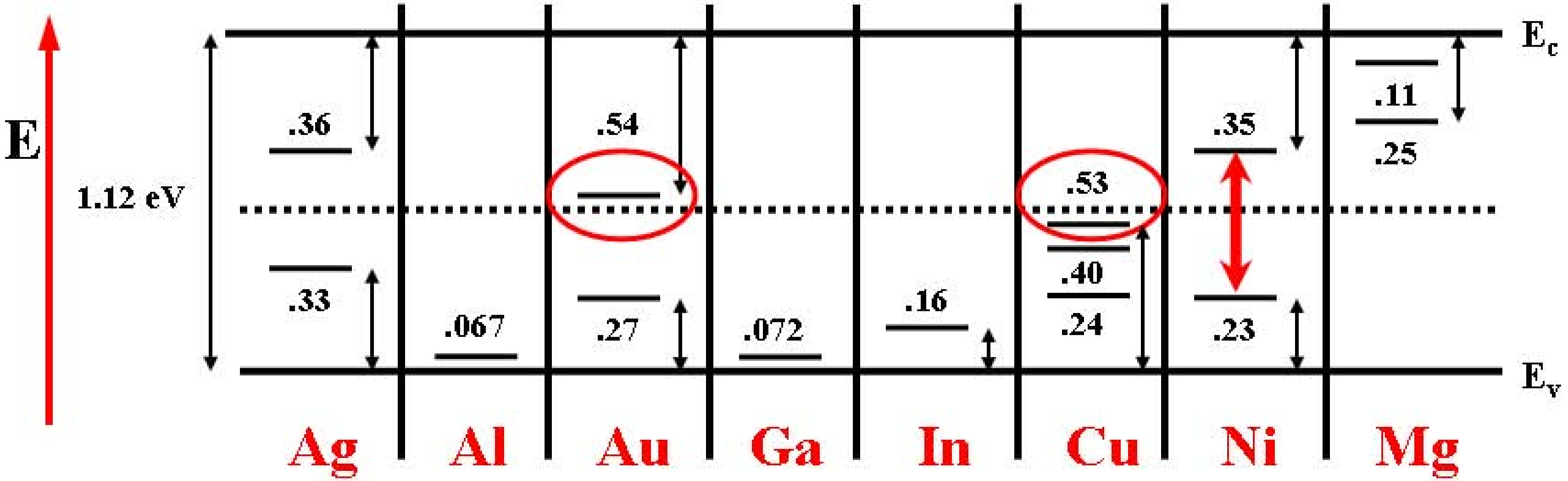
3 μm array, 500 nm Cu, T_{growth} = 1000°C, P_{growth} = 760 Torr, 10 min growth, 2 mole % $SiCl_4$ in H_2

Copper produces wire arrays that are structurally equivalent to gold.

VLS Catalysts - Trap Levels

- Solubility of gold in silicon ~ 1×10^{16} cm^{-3} at 1000°C.[1]
- Using $\sigma = 1 \times 10^{-15}$ cm^2, $v_{th} = 1 \times 10^7$ cm/s:

$$\tau = \frac{1}{\sigma N_r v_{th}} \approx 10\ ns \qquad L_D = \sqrt{D\tau} = \sqrt{\frac{k_B T}{q}\mu\tau} \approx 1-5\ \mu m$$



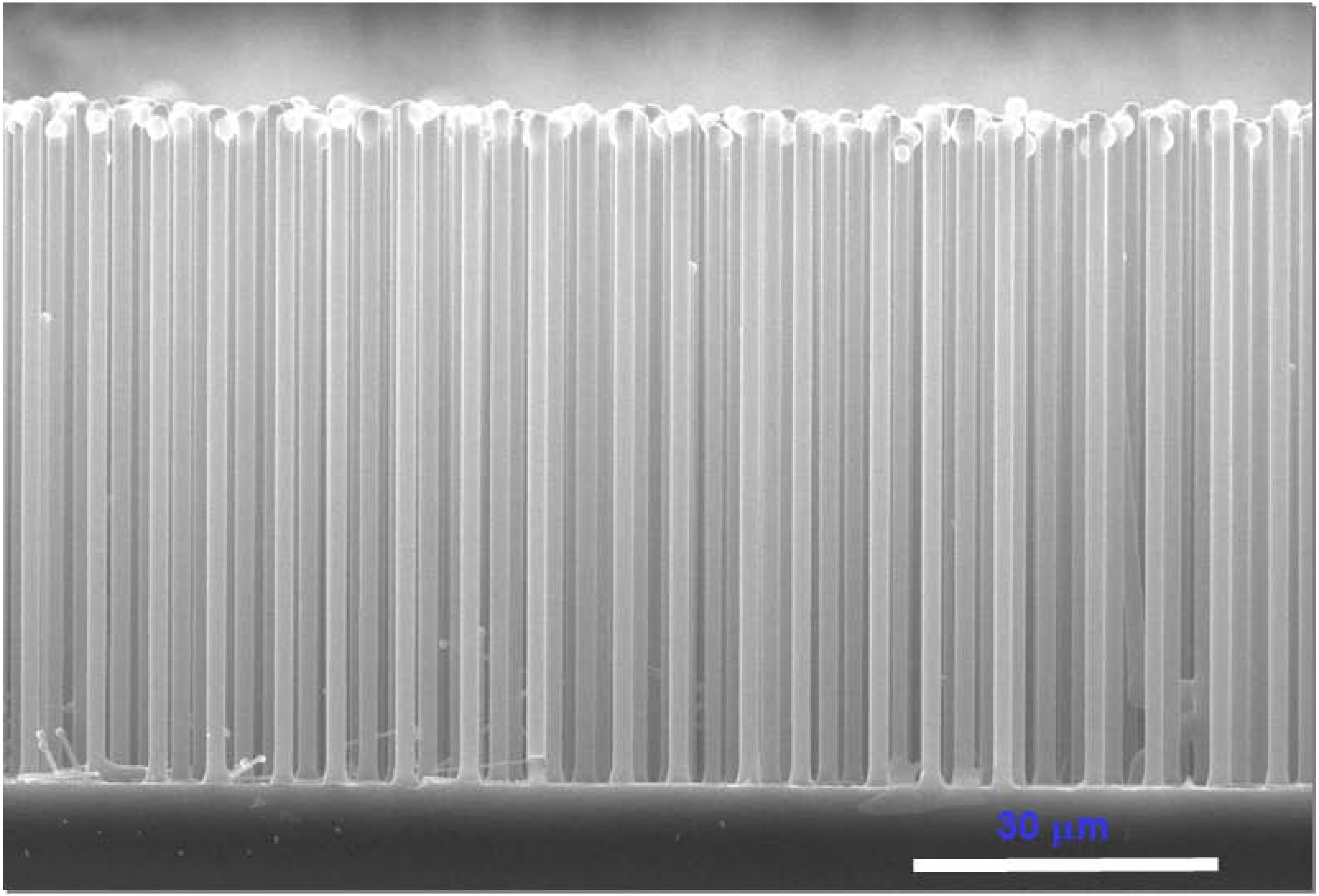
Mid-gap energy levels for selected catalyst materials[2]

While Au-catalyzed Si wires have sufficient lifetimes for a wire-based PV device, other metals (e.g. Ni) may provide significant improvements.

[1] J.D. Struthers, *J. Appl. Phys*. **27** 1560 (1956)

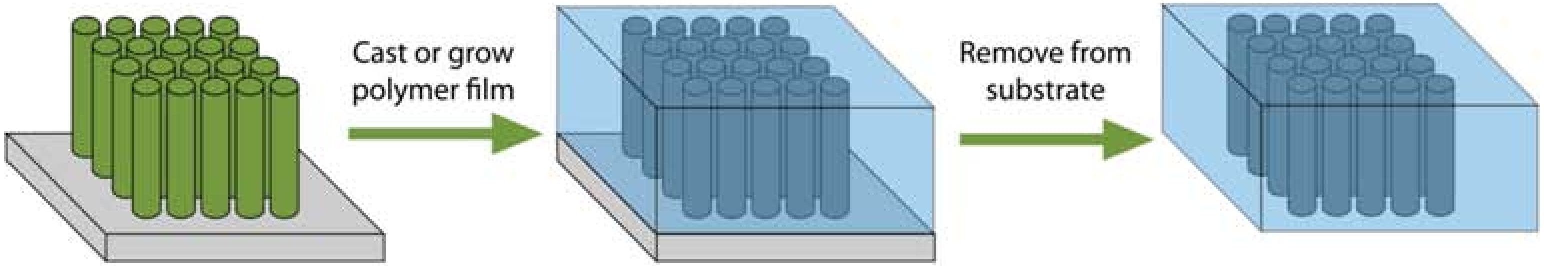
[2] data from S.M. Sze, *Physics of Semiconductor Devices, 2nd ed*. (1981)

Nickel-Catalyzed Si Wire Arrays



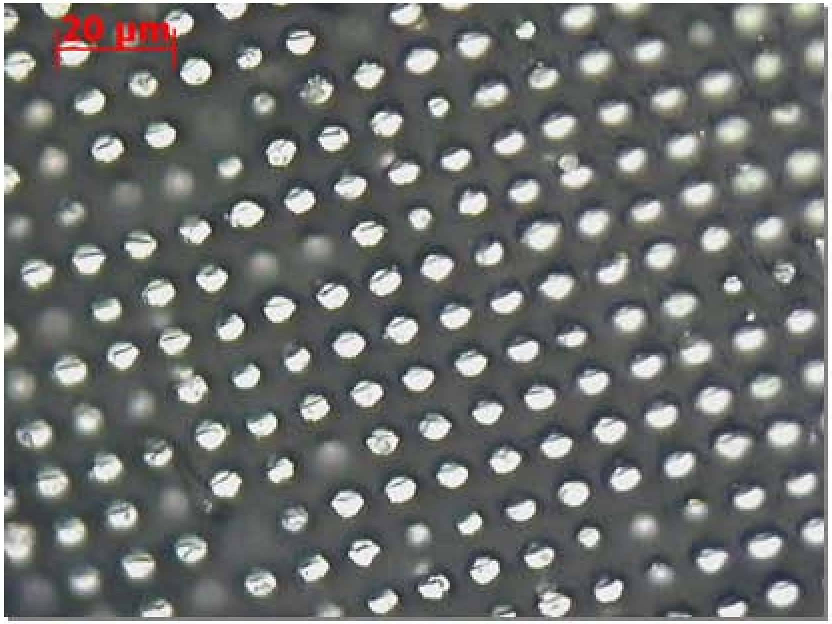
3 μm array, 300 nm Ni, T_{growth} = 1000°C, P_{growth} = 760 Torr, 20 min growth, 2 mole % $SiCl_4$ in H_2

Polymer-Supported Si Wire Membranes



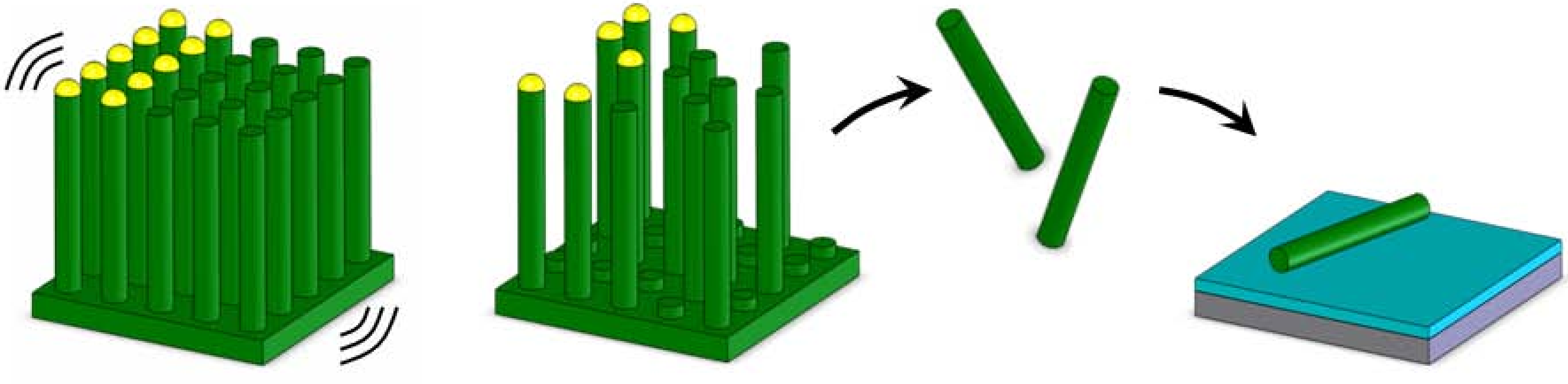
Drop cast Slygard 184 PDMS (10:1 w/w base to curing agent) in CH_2Cl_2 (1g / 2mL)
Cure at 120°C for 1.5-2 hr

1. Nanowire array in peeled polymer film
2. Re-use Si(111) substrates



K.E. Plass and M.A. Filler et al, *in preparation*.

Single wire solar cells -fabrication



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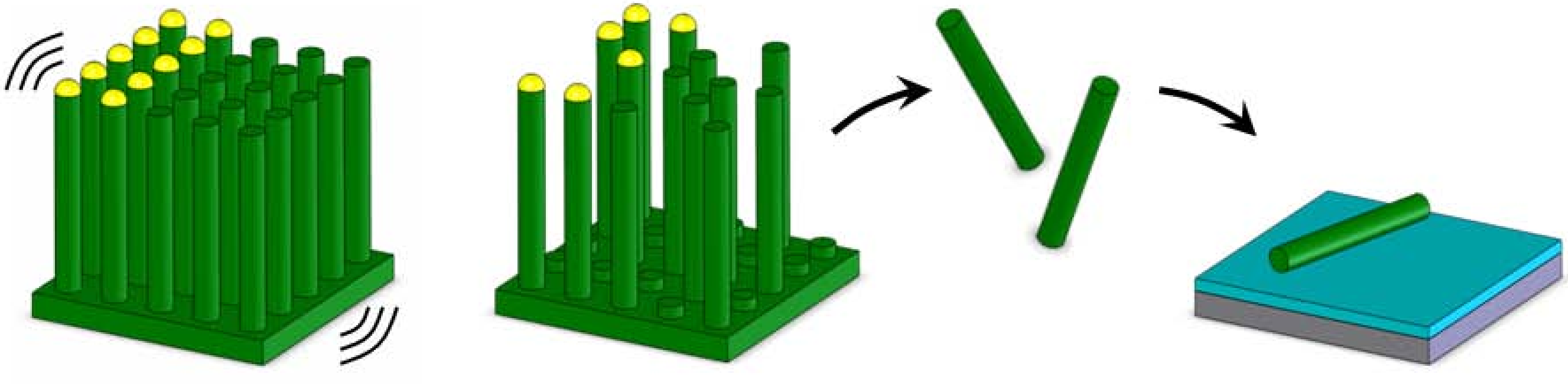

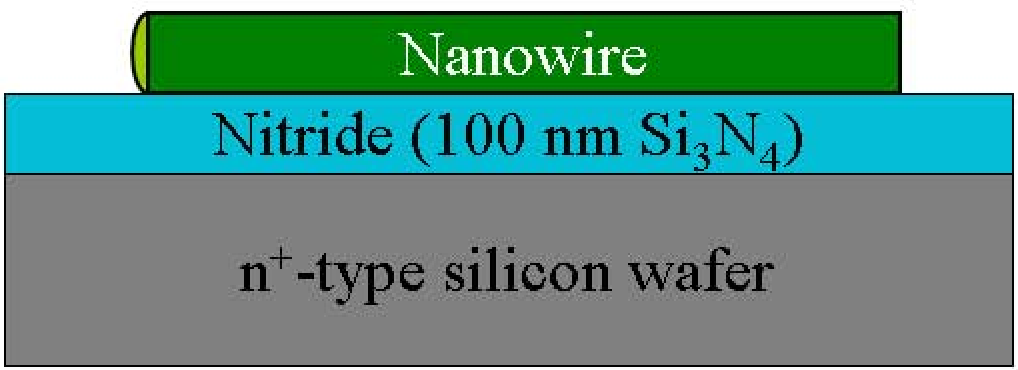

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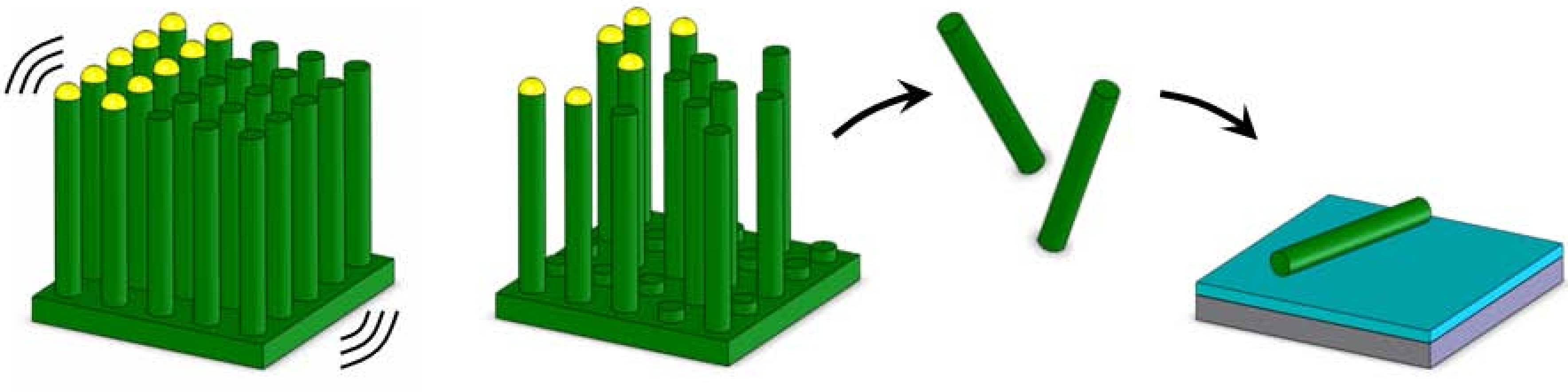

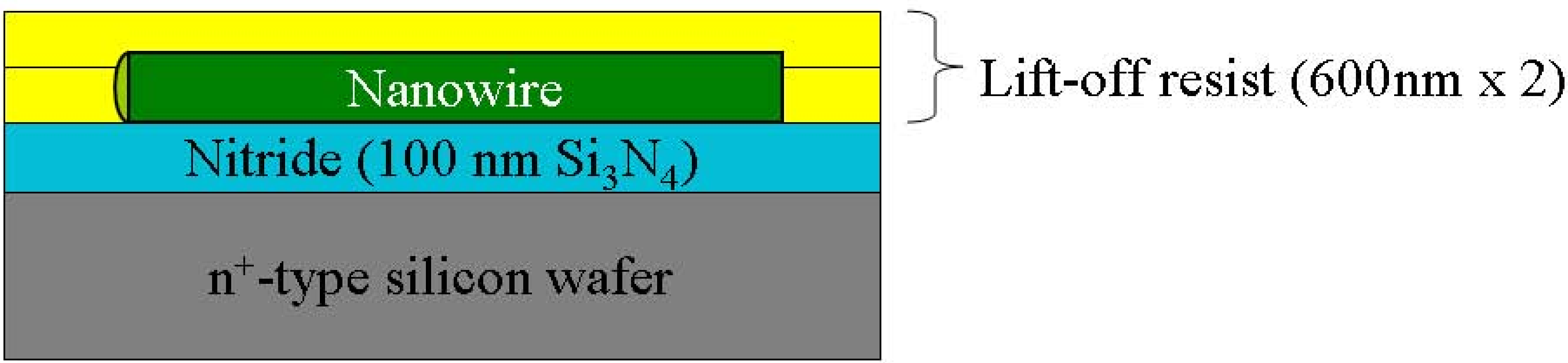

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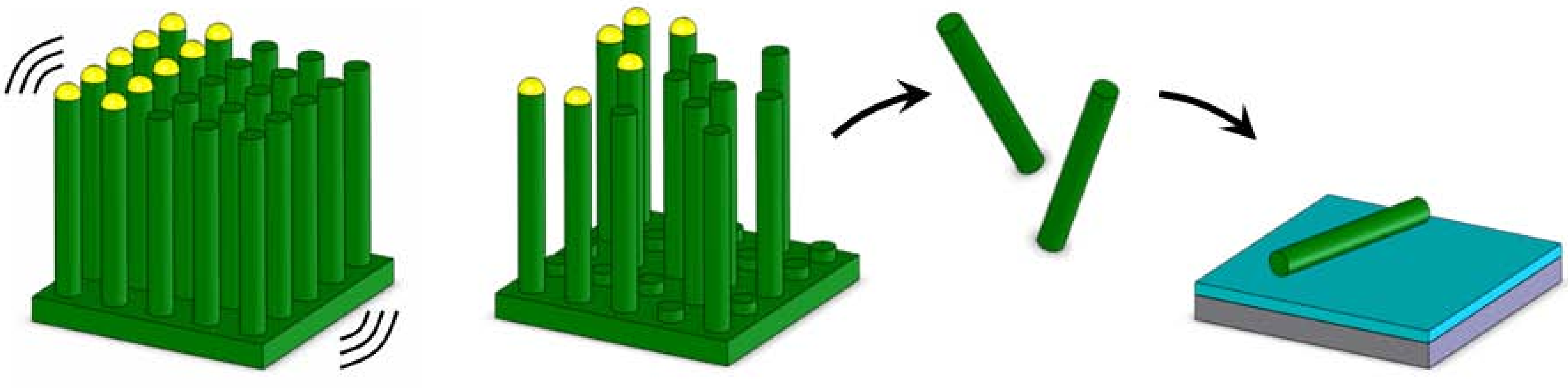

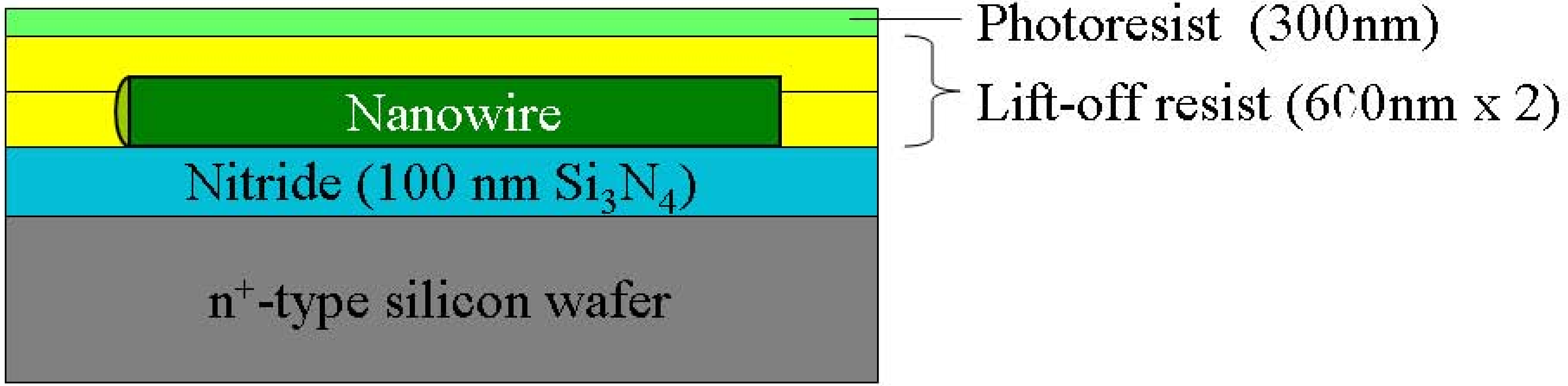

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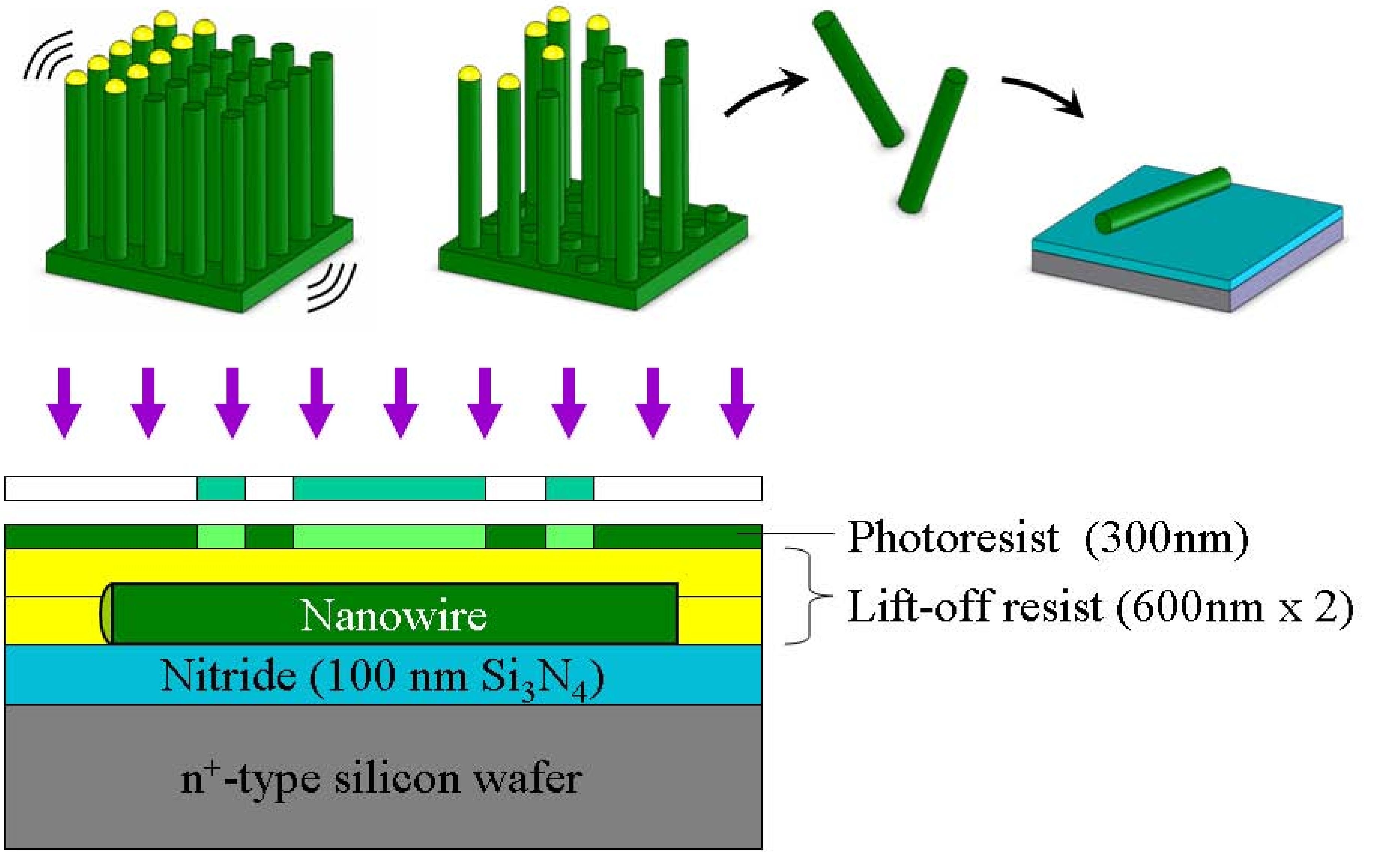

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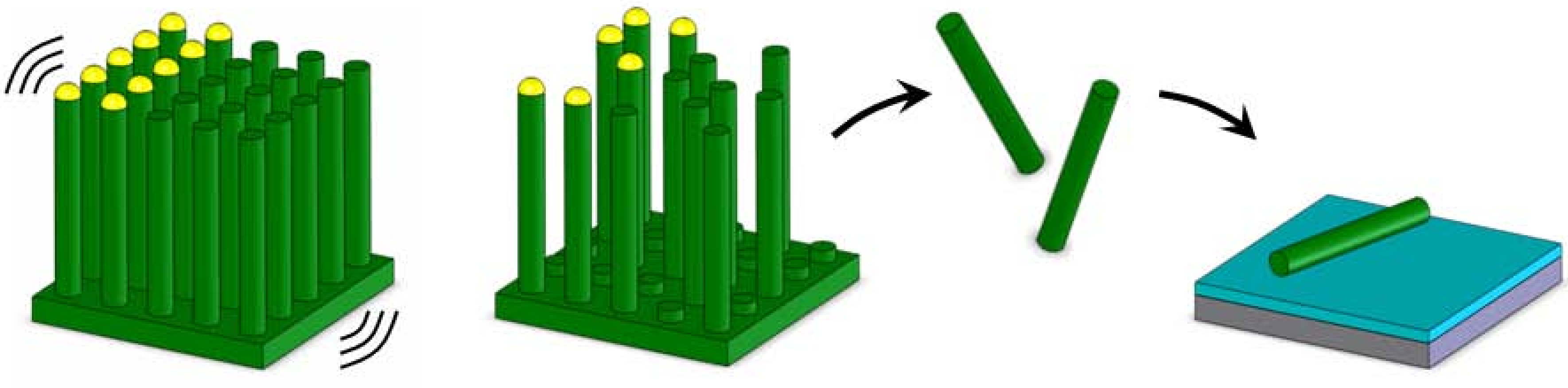

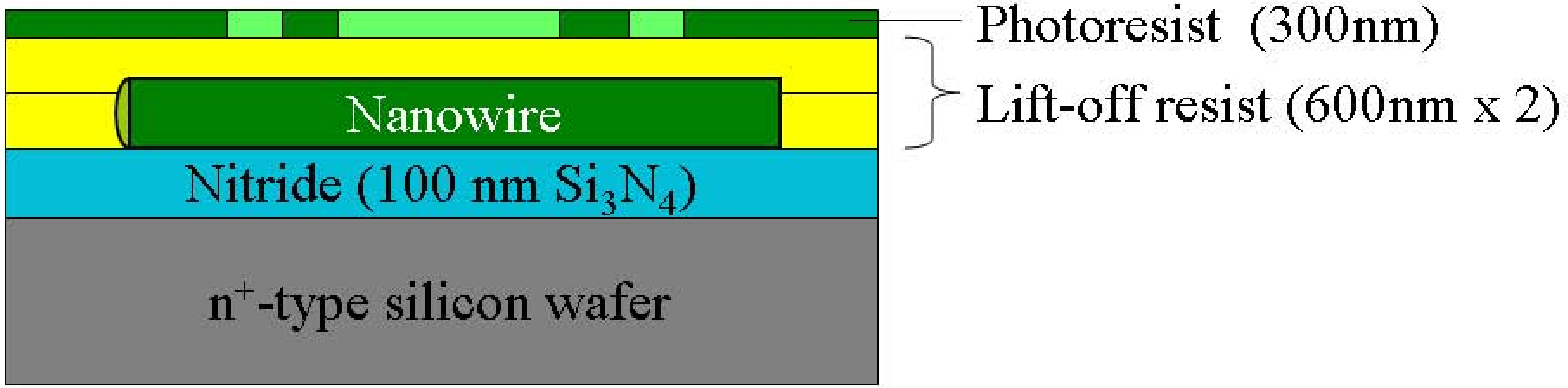

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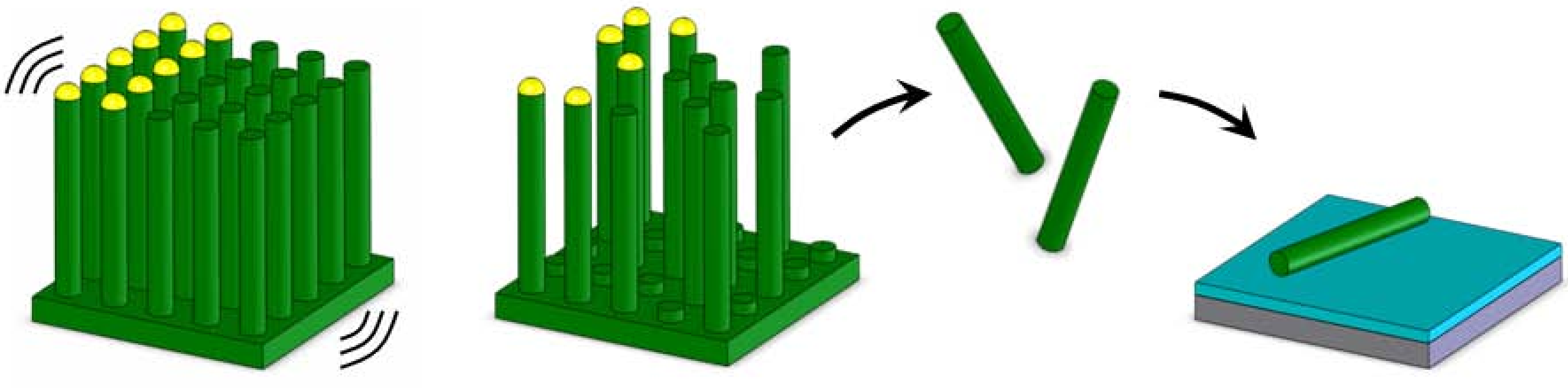

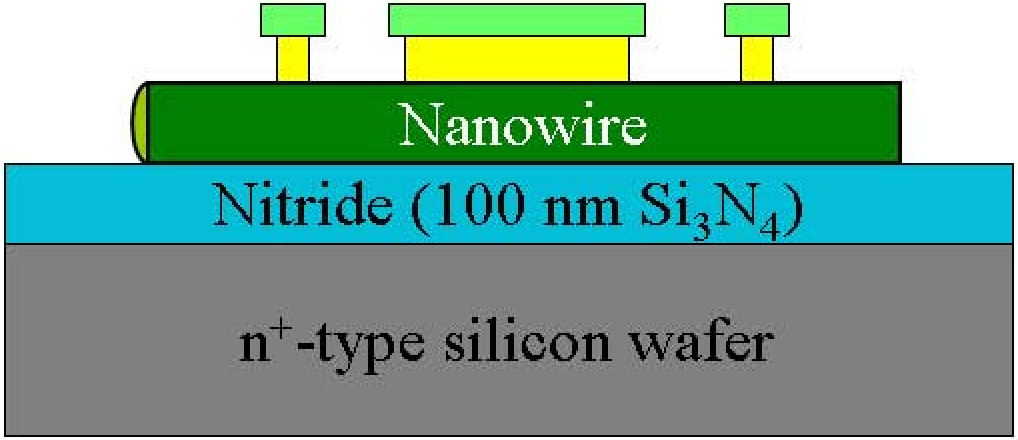

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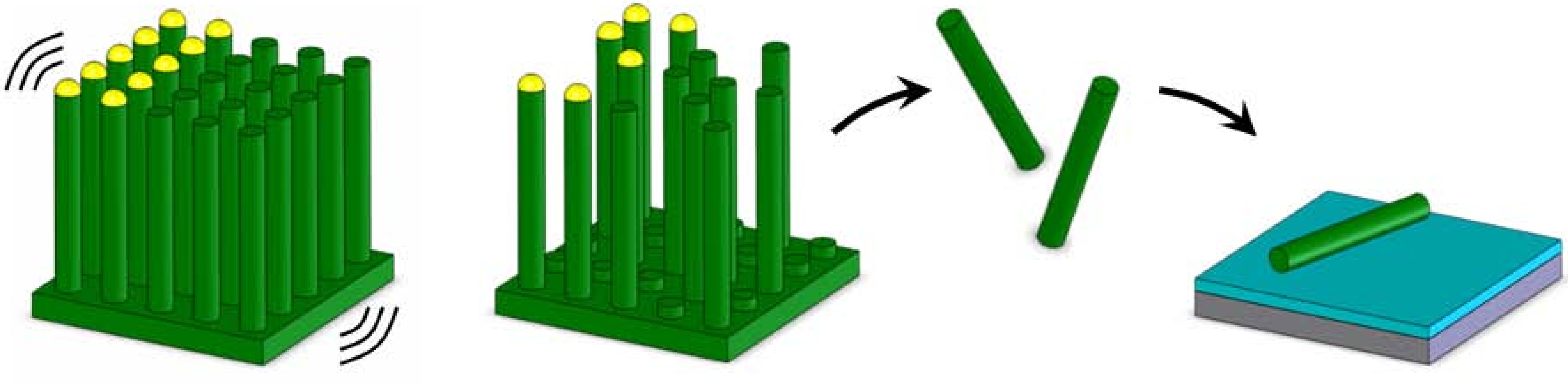

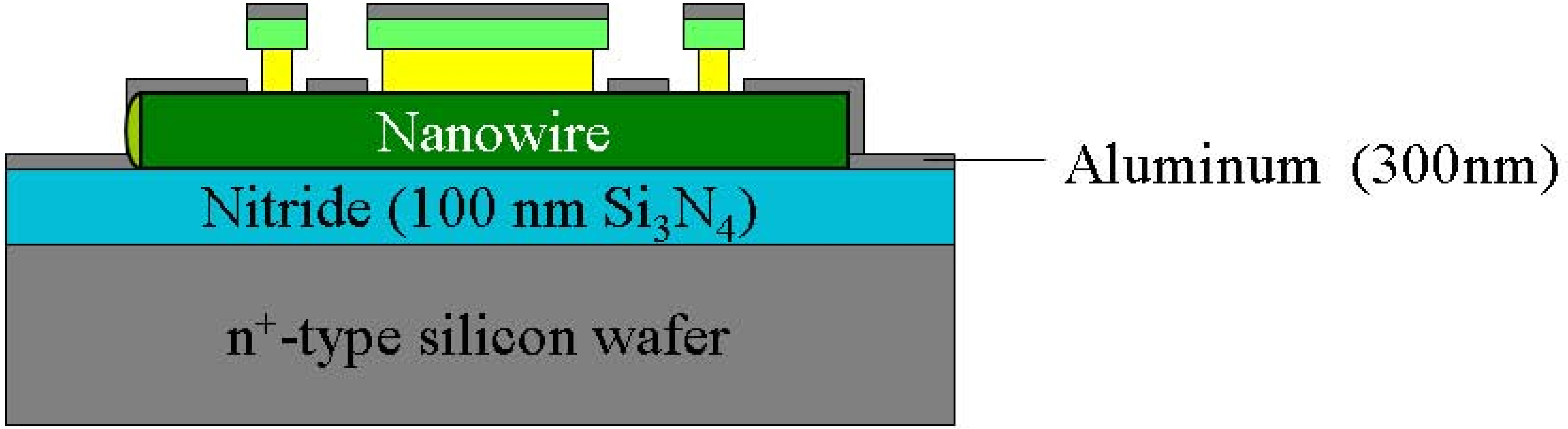

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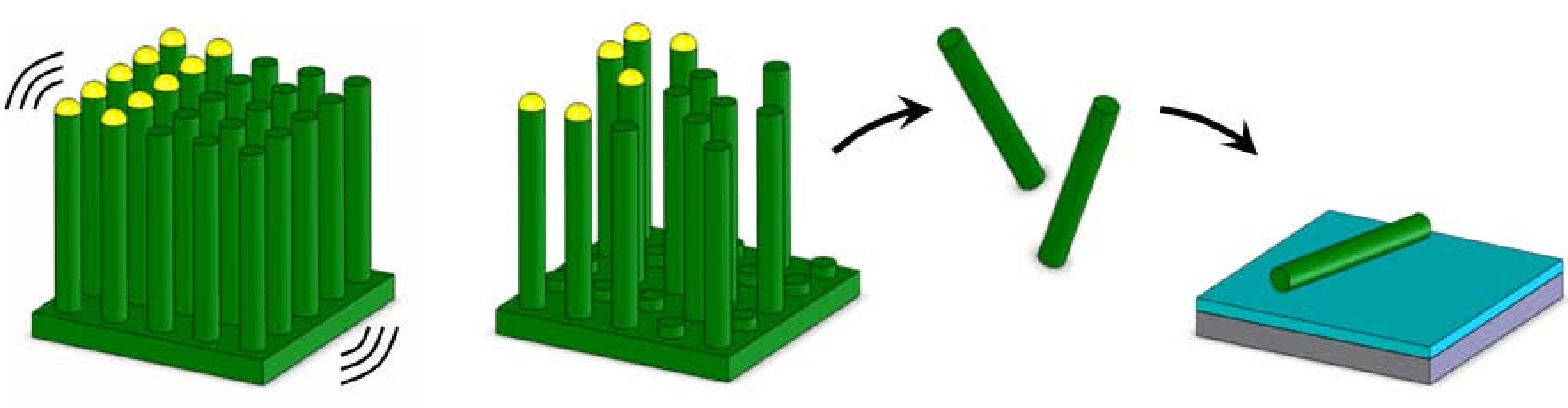

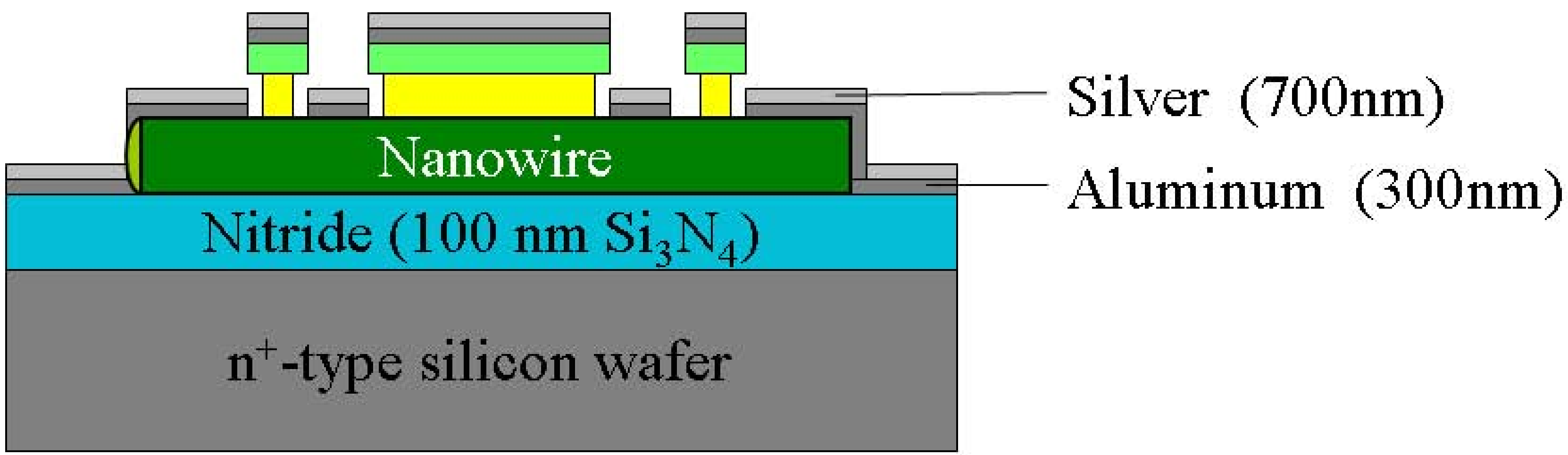

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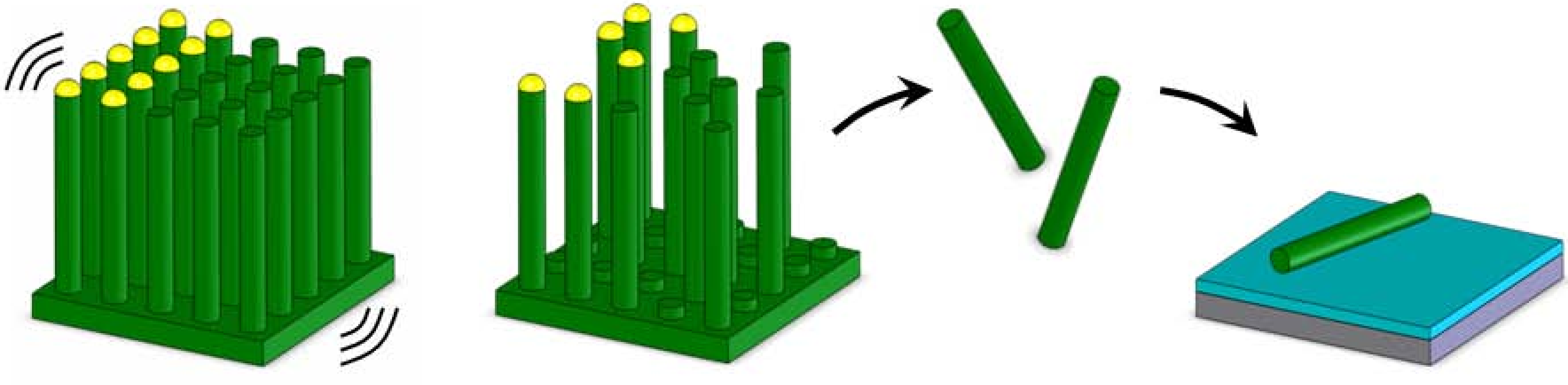

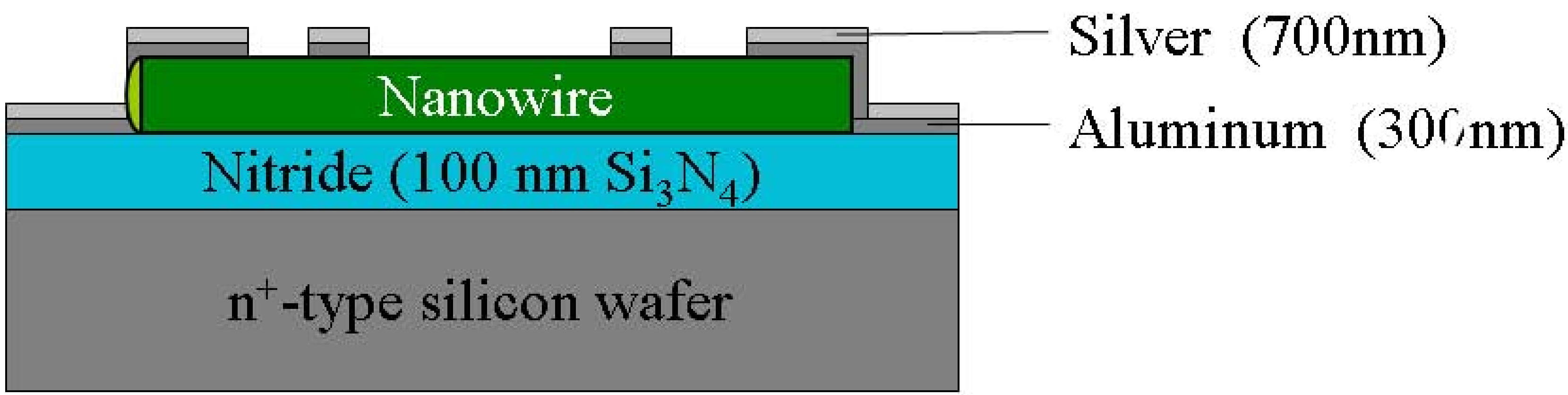

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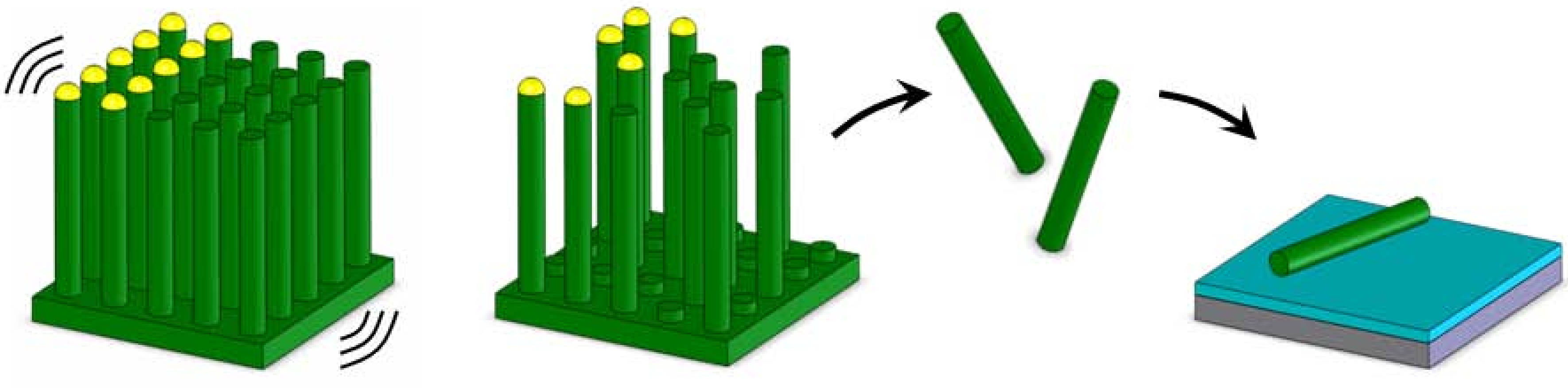
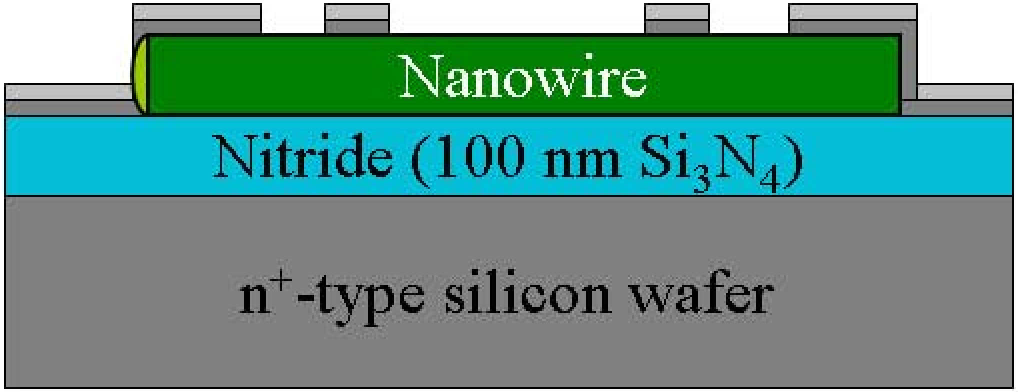
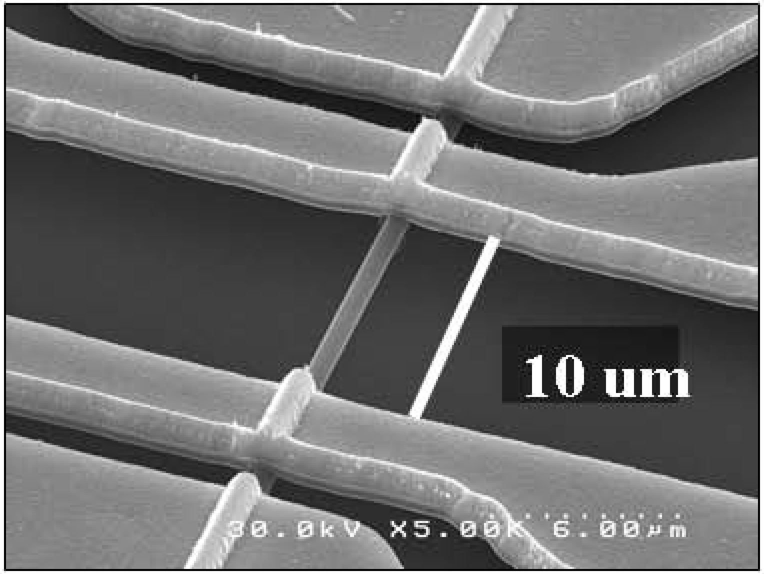
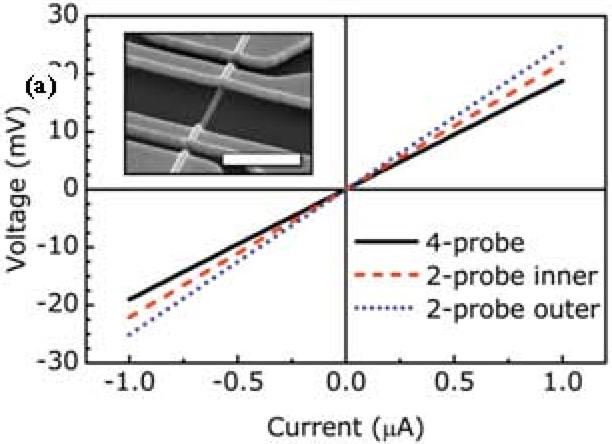
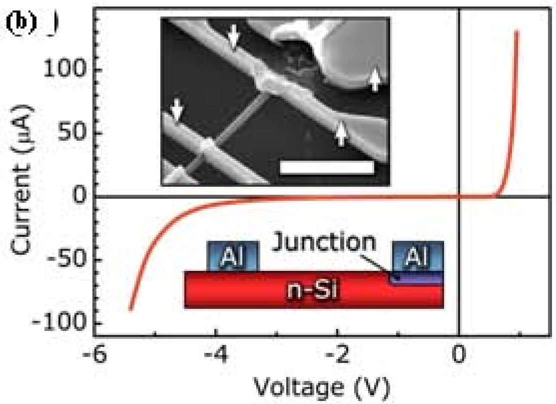


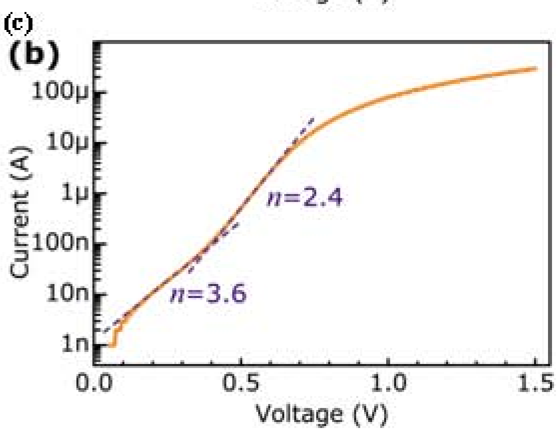




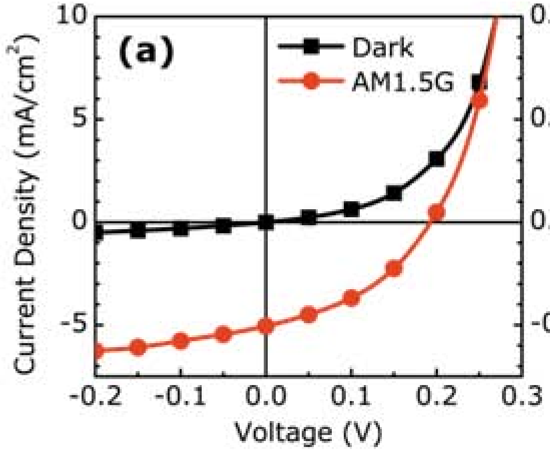
Single wire solar cells -characterization

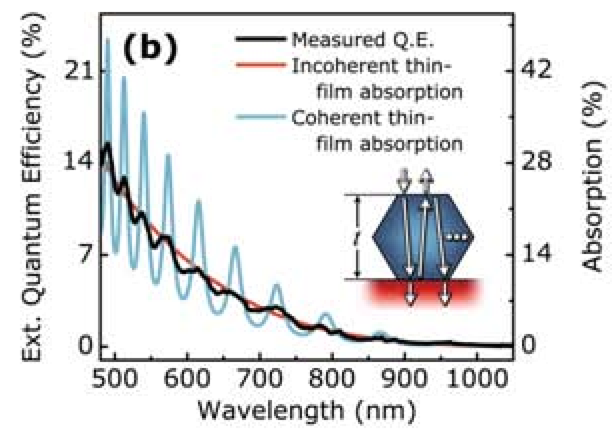






- $SiCl_4$/Au-catl. VLS-grown wires (800nm nom. dia.)
- Individually contacted with Al contacts
- Heated ("splat") to produce rectifying junction



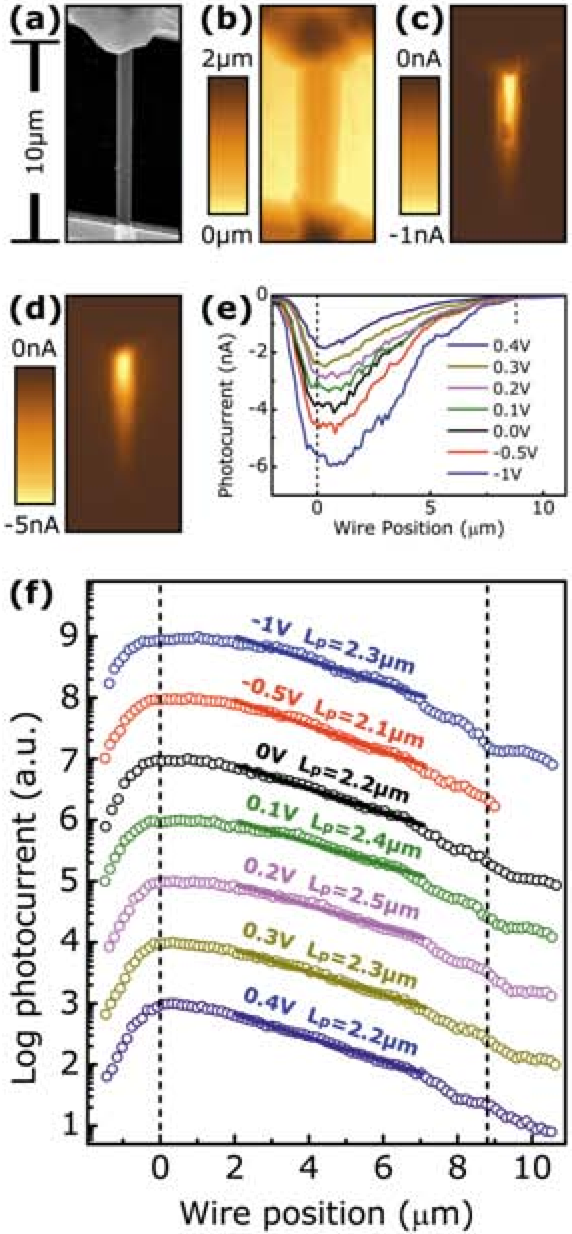


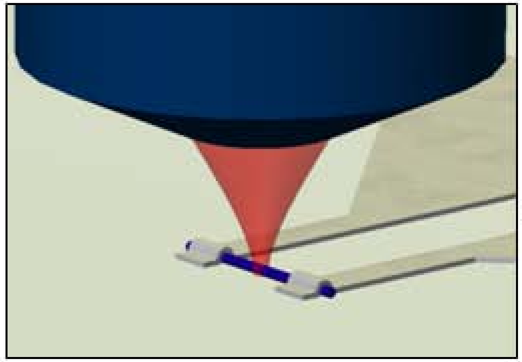
V_{OC} = 193 mV I_{SC} = 0.31 nA (5 mA/cm^2)

FF = 0.40 η = 0.46 % (AM 1.5G)

- Spectral response indicates interference effects with qualitatively uniform internal Q.E.

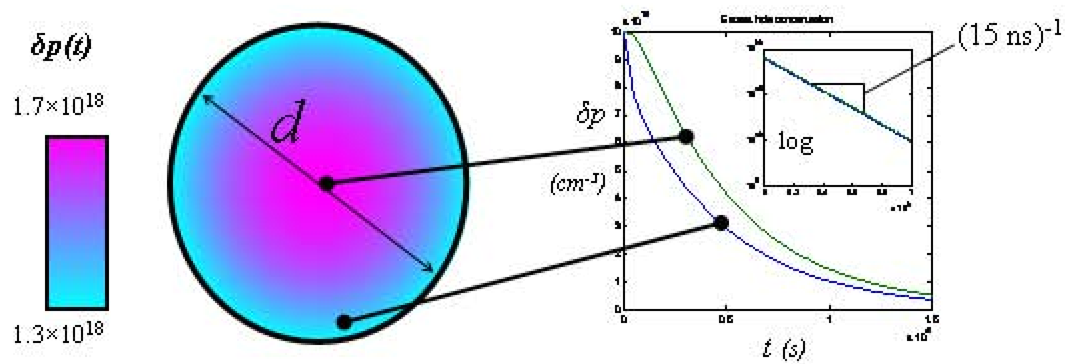
Single wire solar cells -characterization





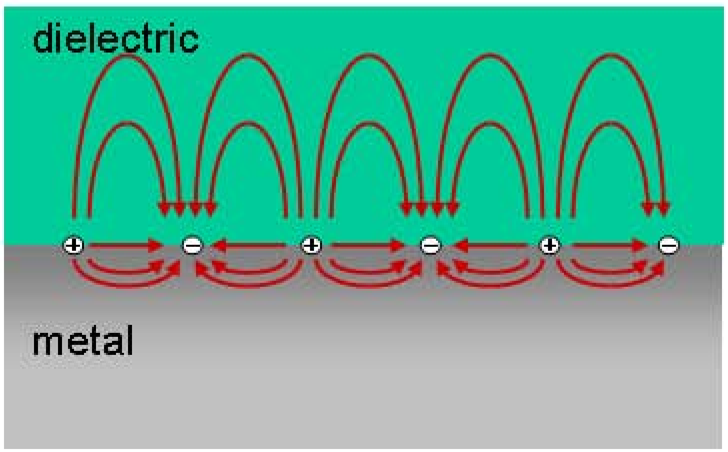
Scanning Photocurrent Microscopy (SPCM) - *Records photocurrent as function of confocal (or nearfield probe) optical excitation point*

- Indicates ~2μm hole diffusion length
  - Corresponds to τ_h ~ 15 ns ($\tau_p = \frac{L_p^2}{D_p}$)
  - Corresponds to S ~ 1350 cm/sec

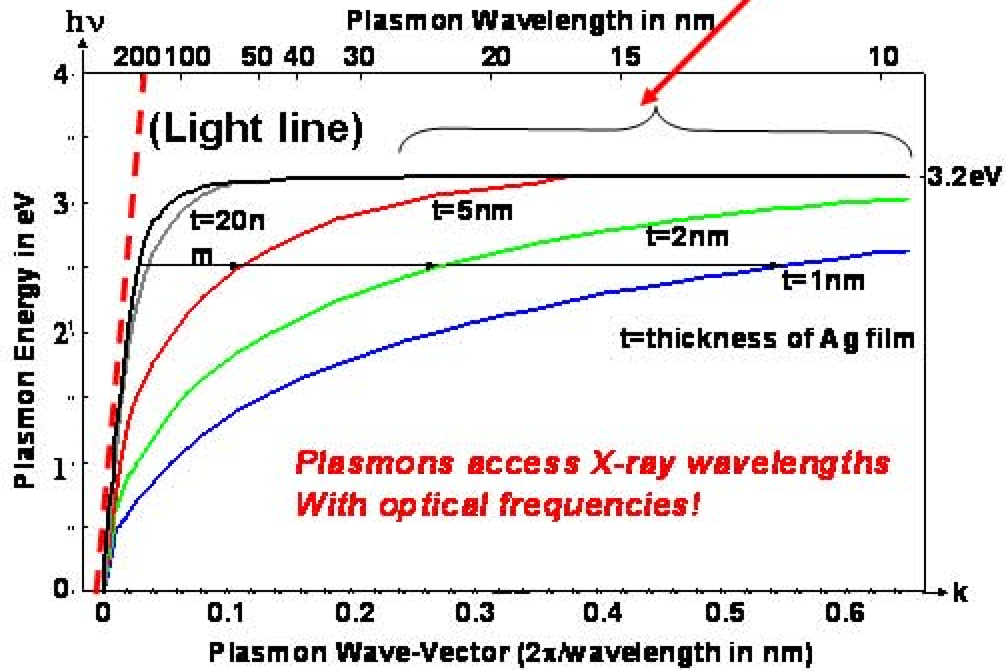


Plasmons at planar metal surfaces and interfaces

surface plasmons are longitudinal charge density fluctuations on the surface of a conductor



Can form an optical signal with these spatial frequencies on the Ag surface



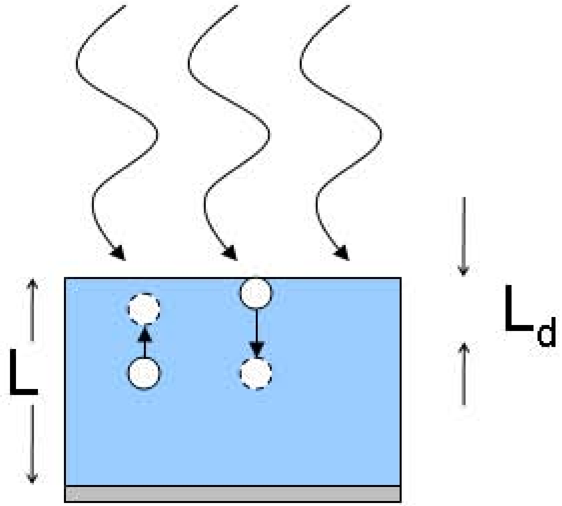
Surface Plasmon dispersion relation for Ag/SiO_2

SPP dispersion relation:

$$k_x = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}}$$

c.f.HAA Scientific American April 2007

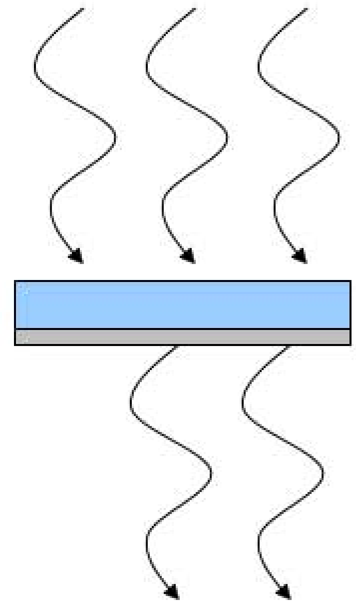
Carrier Collection for Low Diffusion Lengths



Optically Thick, but
Collection-Limited

$L_d << L$

$1/\alpha << L$



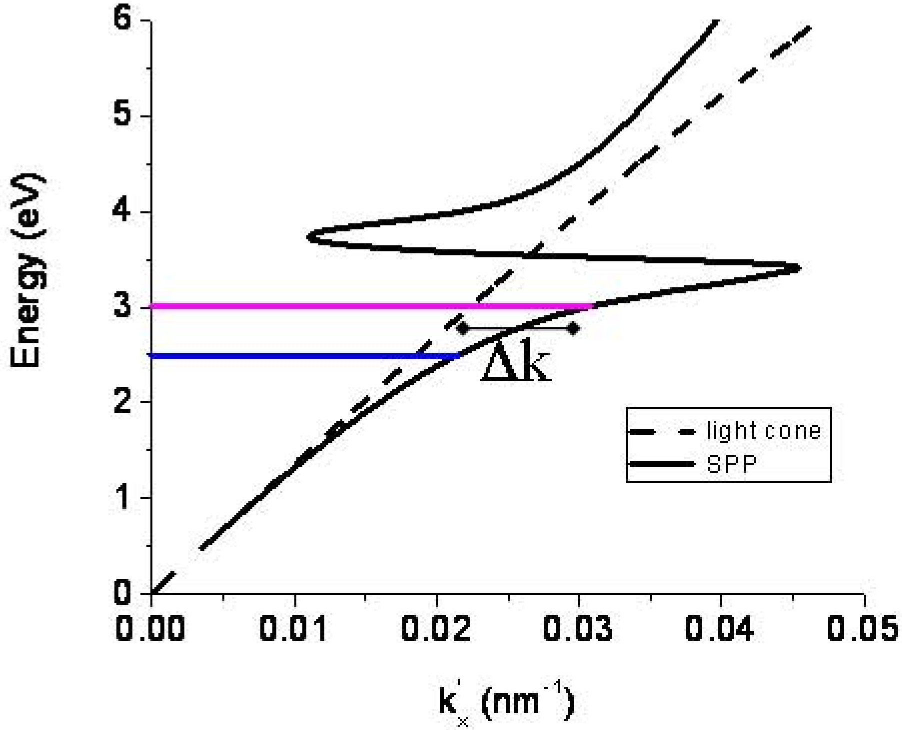
Collection across base,
but Optically Thin

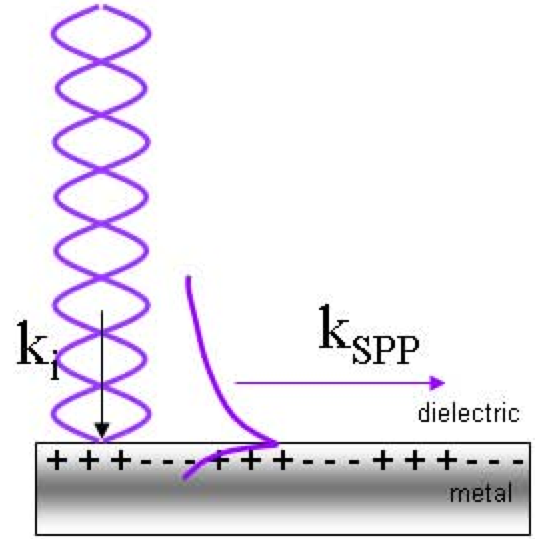
$L_d >> L$

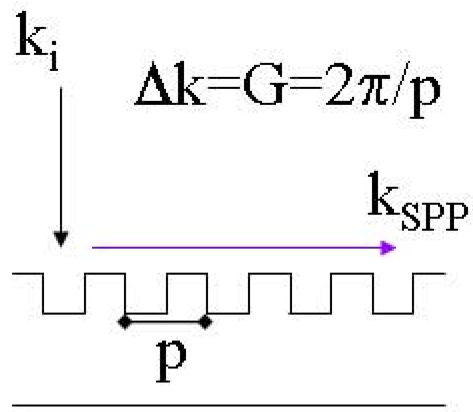
$1/\alpha >> L$

Surface Plasmon Excitation in Thin Films

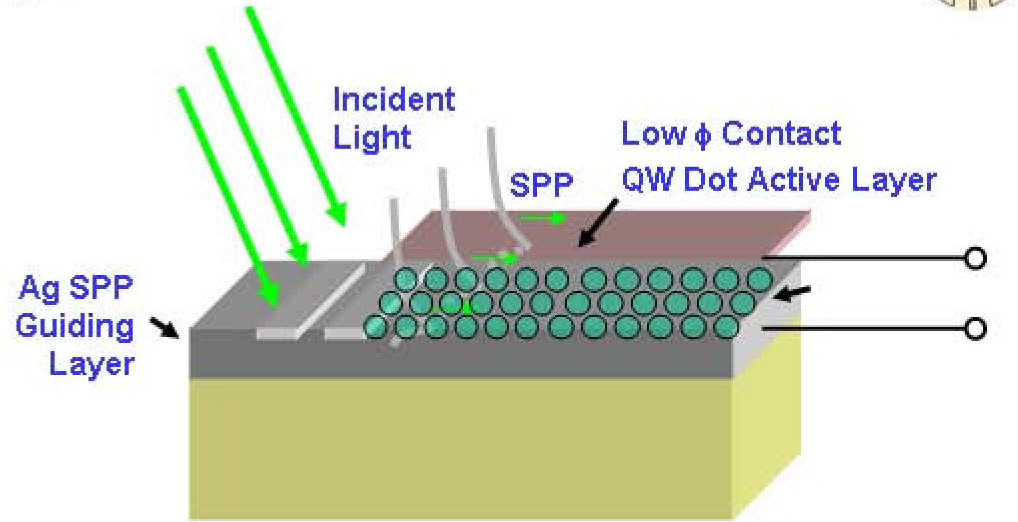
Surface plasmon polaritons (SPPs):
1. guided EM waves at a metal dielectric interface
2. high field confinement at the interface.

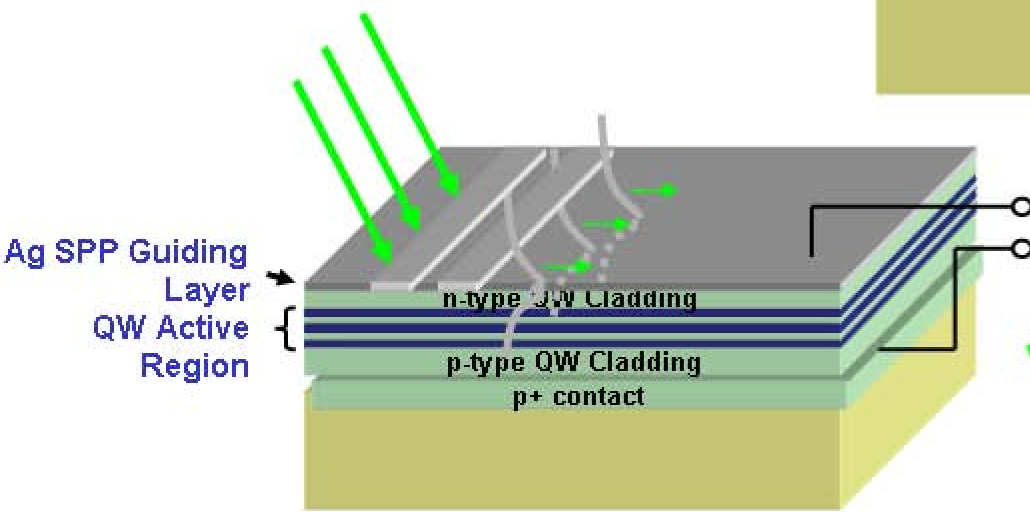


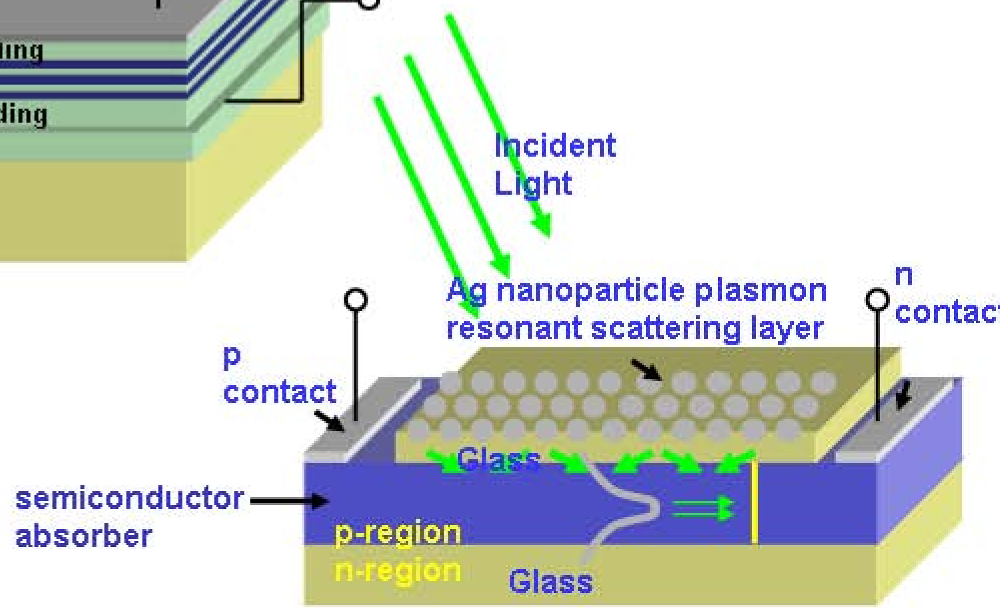




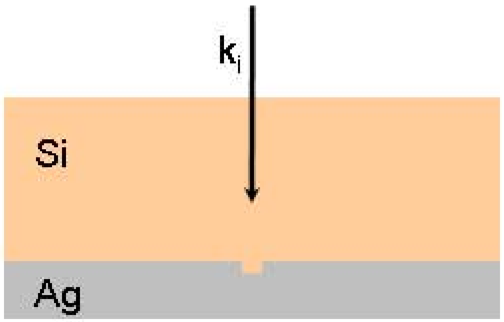
Plasmonic Solar Cells

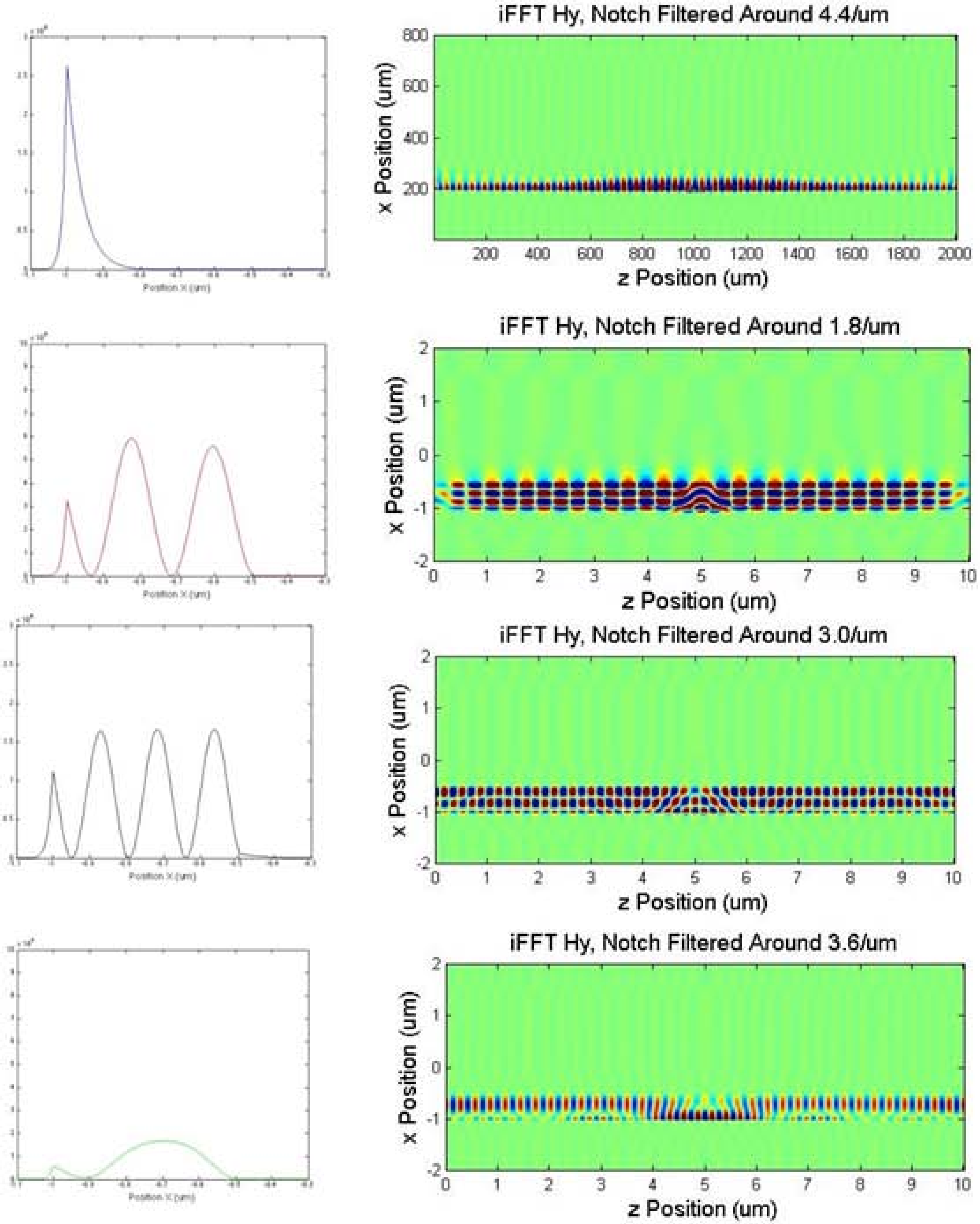






Plasmonic Thin Si Solar Cell

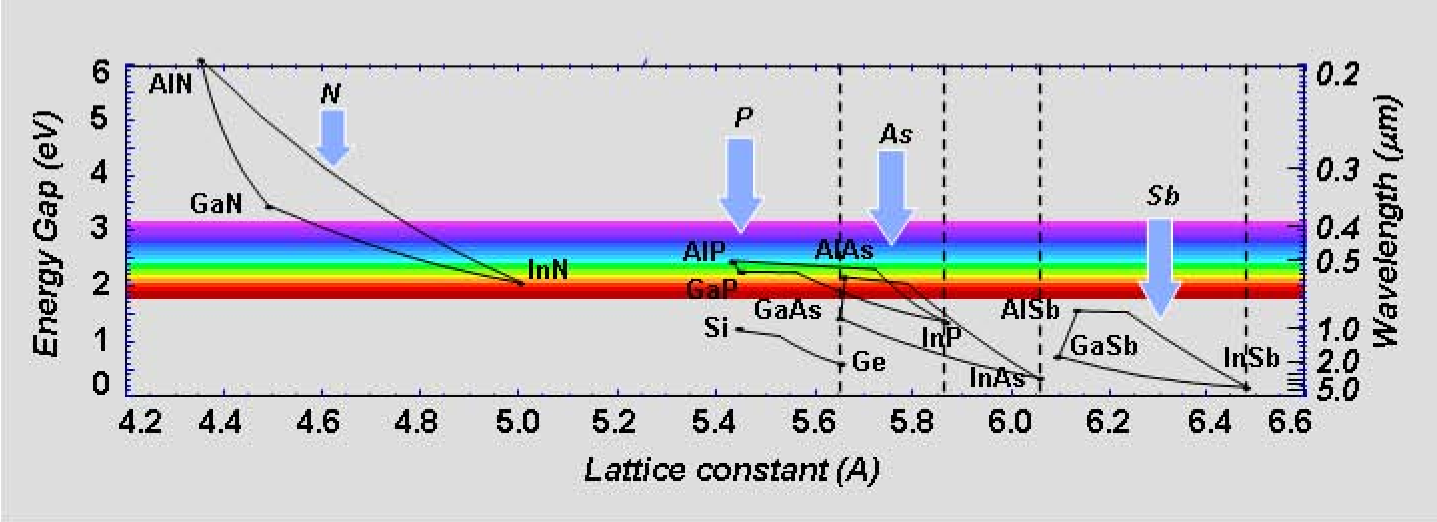




Earth-Abundant Semiconductors

TW scale energy supply need motivates a rethinking of semiconductor materials

Typical "Optoelectronic Semiconductors"



"Earth-Abundant Semiconductors"

Si

FeS_2

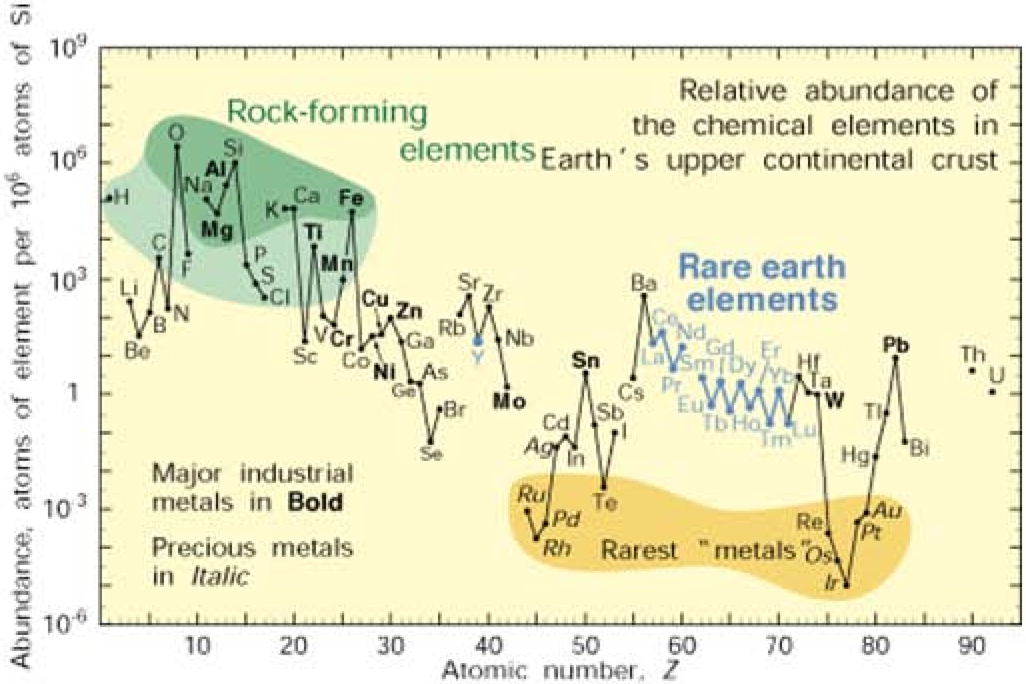
β $FeSi_2$

Cu_2O

TiO_2

AlN

$CaSi_2$



11/16/07
H. Atwater Caltech

Summary

- Photovoltaics Resource is TW-capable
- Close to Limiting PV Efficiency for Single Junction Cells
- Silicon PV is the Incumbent Technology: will it remain so?
- Any alternaive must outperform c-Si by cost/Watt
- Multijunction PV a viable path to >50%
- 3rd Generation PV: Beyond the Schockley-Queisser Limit
- Nanowire PV – scaleable large area technology
- Reduce Material Thickness – plasmonics
- Earth-Abundant Materials!