Nanotechnology in Photovoltaics

ECSAC10 – Losinj, August 25th, 2009

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Our laboratory

Two lines of research on photovoltaic materials:

- Thin film PV (CdS/CdTe-based)
- Novel nanostructured materials – low-cost and high efficiency

Part of MEL, Laboratory for Energy Materials

research and services in the field of energy materials, including photovoltaic installations (e.g. 20 kW installation on DMRN's building roof, 20 kW installation on the City Hall's Roof in Trieste, …)

Our laboratory

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Facilties:

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Spectroscopy Lab DMRN

Contents

- Introduction – Why photovoltaics (PV)?
- Evolution of PV (economical – technical – social)
- Current PV technologies
  - Basic physics
  - Si-based technology
  - Thin films
- Emerging technologies
  - High efficiency approaches (Tandem)
  - Low-cost approaches (Biomimetics)
- Third generation technologies
  - Nanostructured materials – colloidal solids

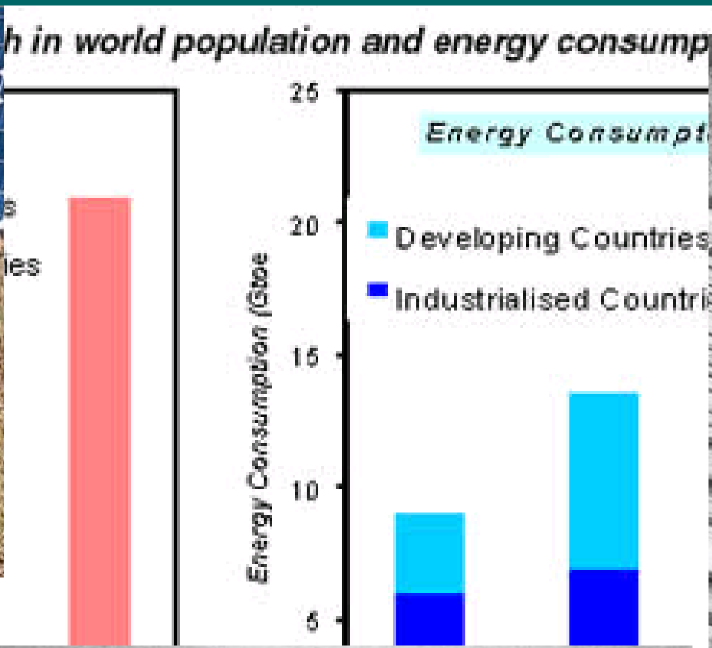
Photovoltaics

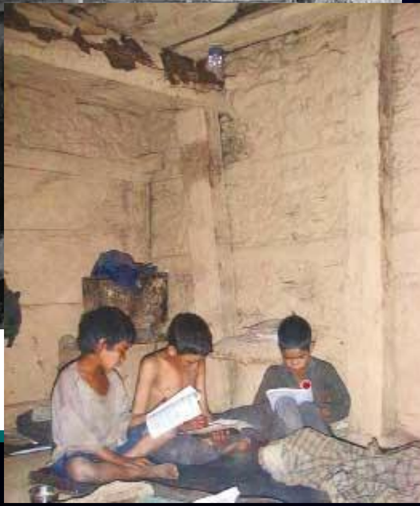
Direct conversion of solar energy to electrical energy (for free!)

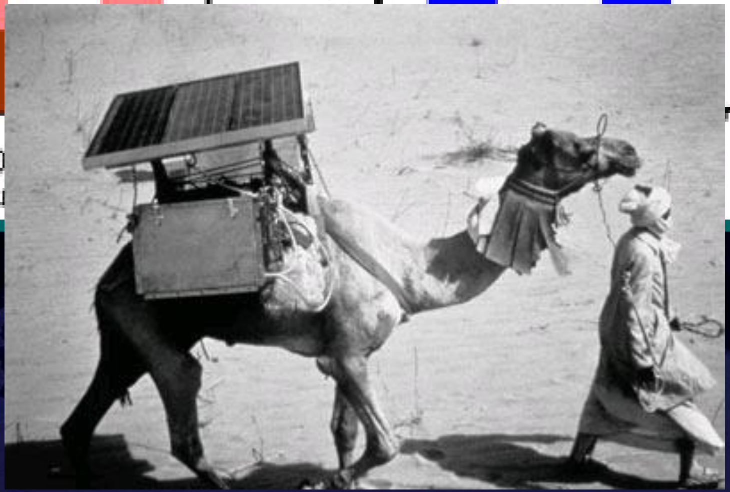
Why Photovoltaics?

Growth of the Energy Demand

- Particularly in the developing countries-







Growth of the Energy Demand

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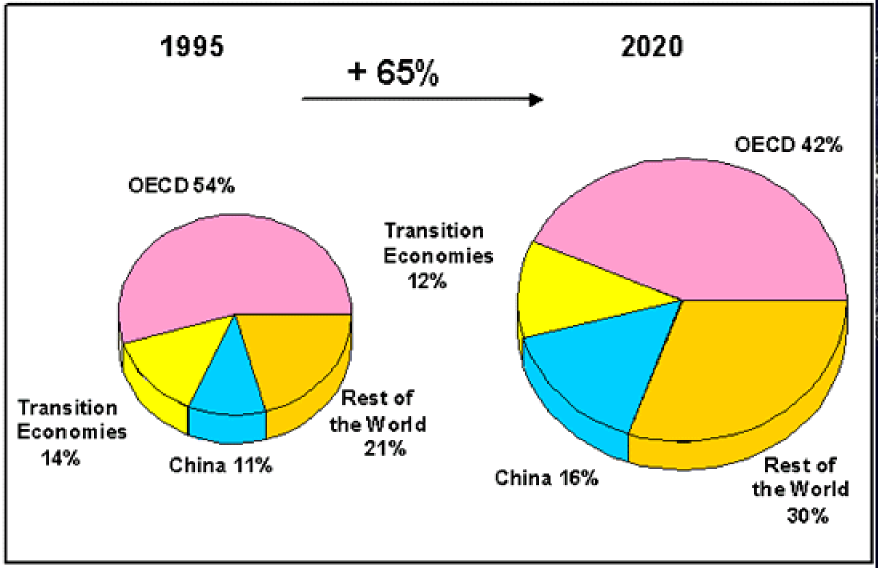
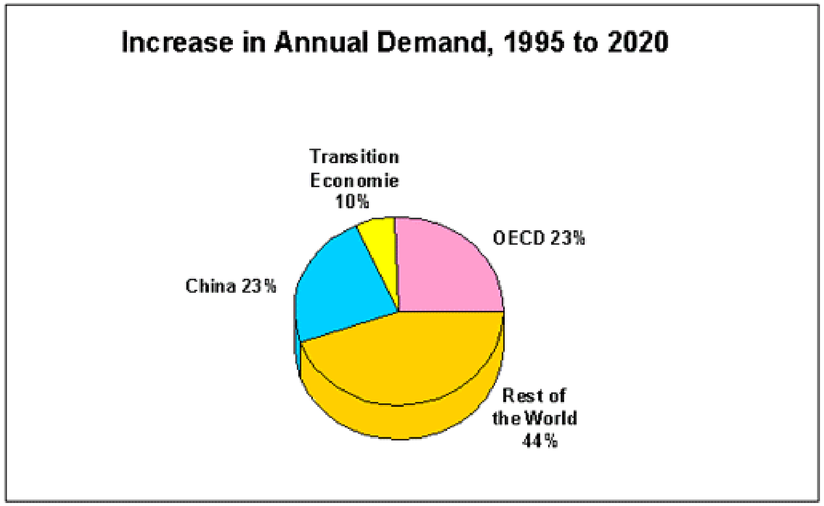
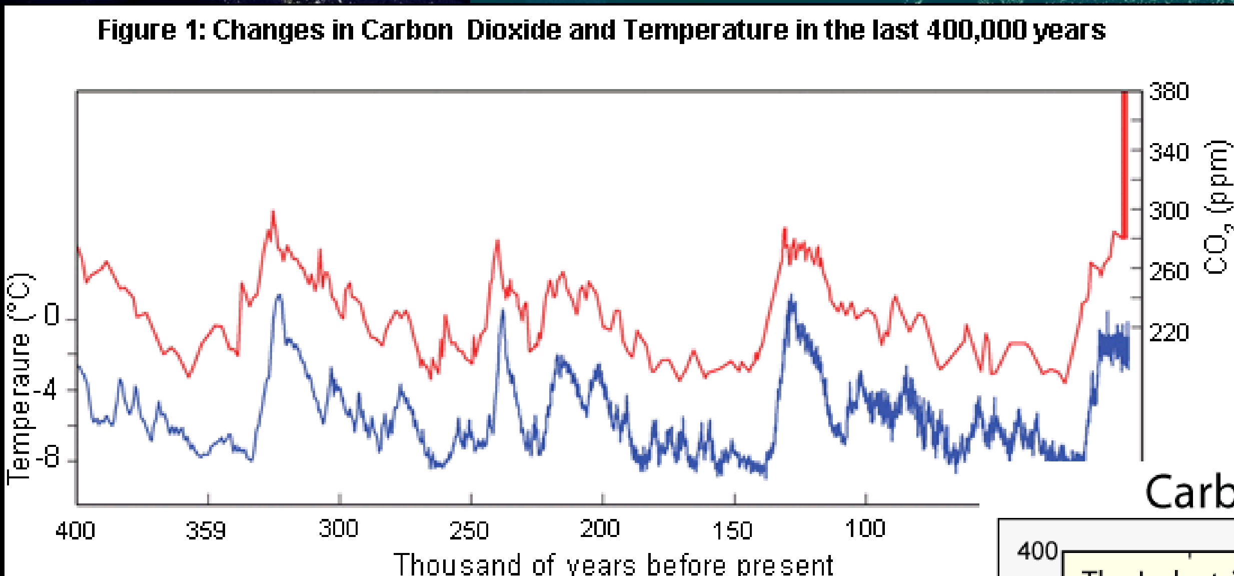




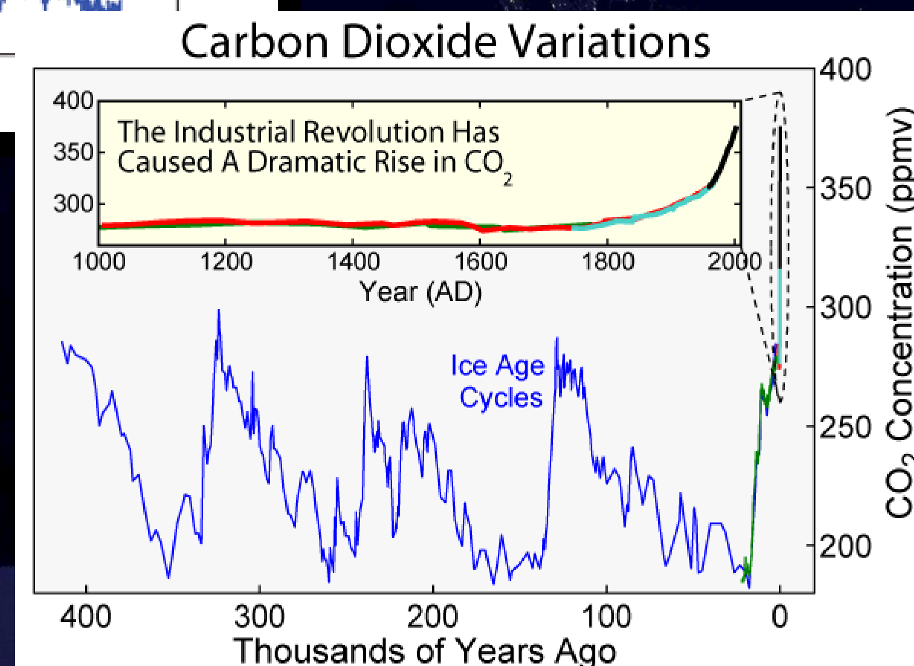
Earth at Night

Need for carbon-free energy sources

Temperature rising (?)



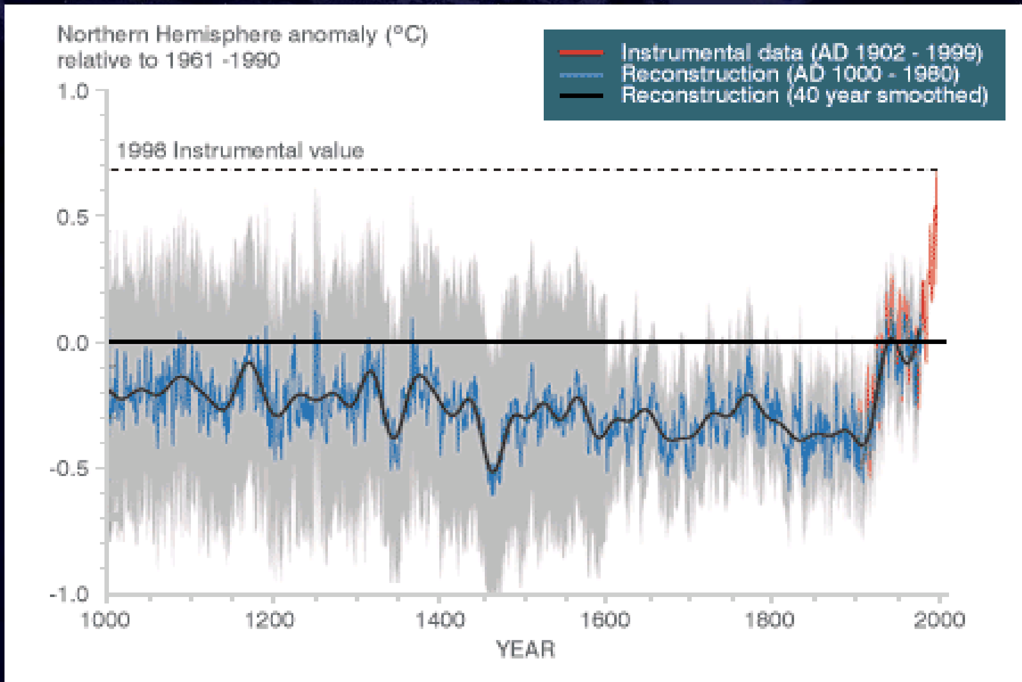
http://epa.gov/climatechange/science/images/co2-temp.gif



http://www.globalwarmingart.com/wiki/Image:Carbon_Dioxide_400kyr_Rev_png

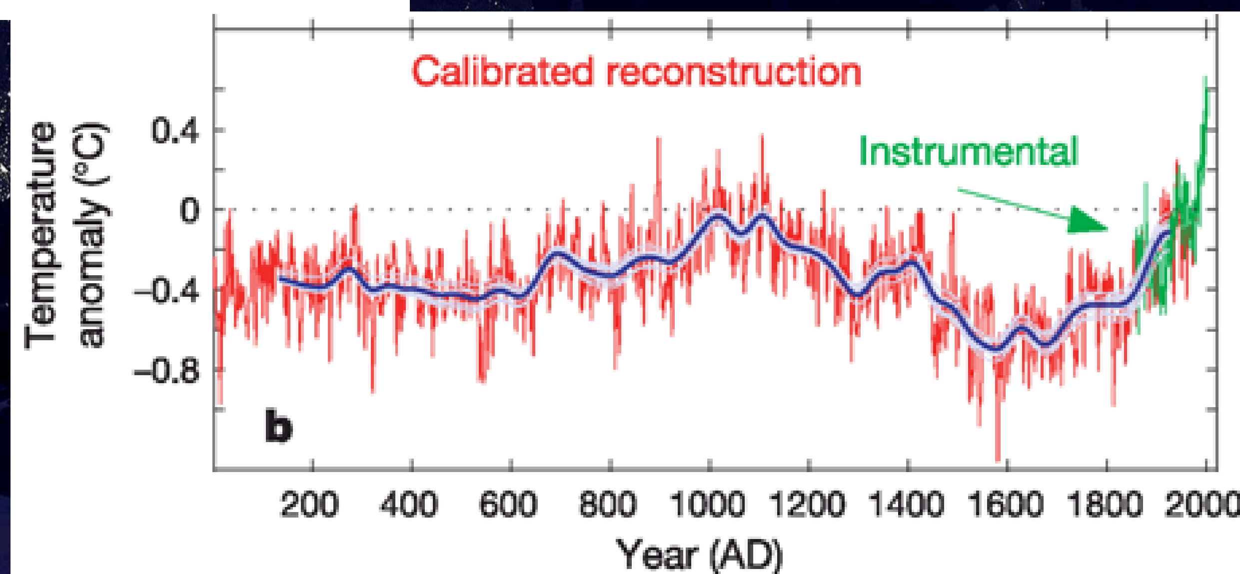
Need for carbon-free energy sources

Temperature rising (?)



Old Data

New Data



Earth at Night

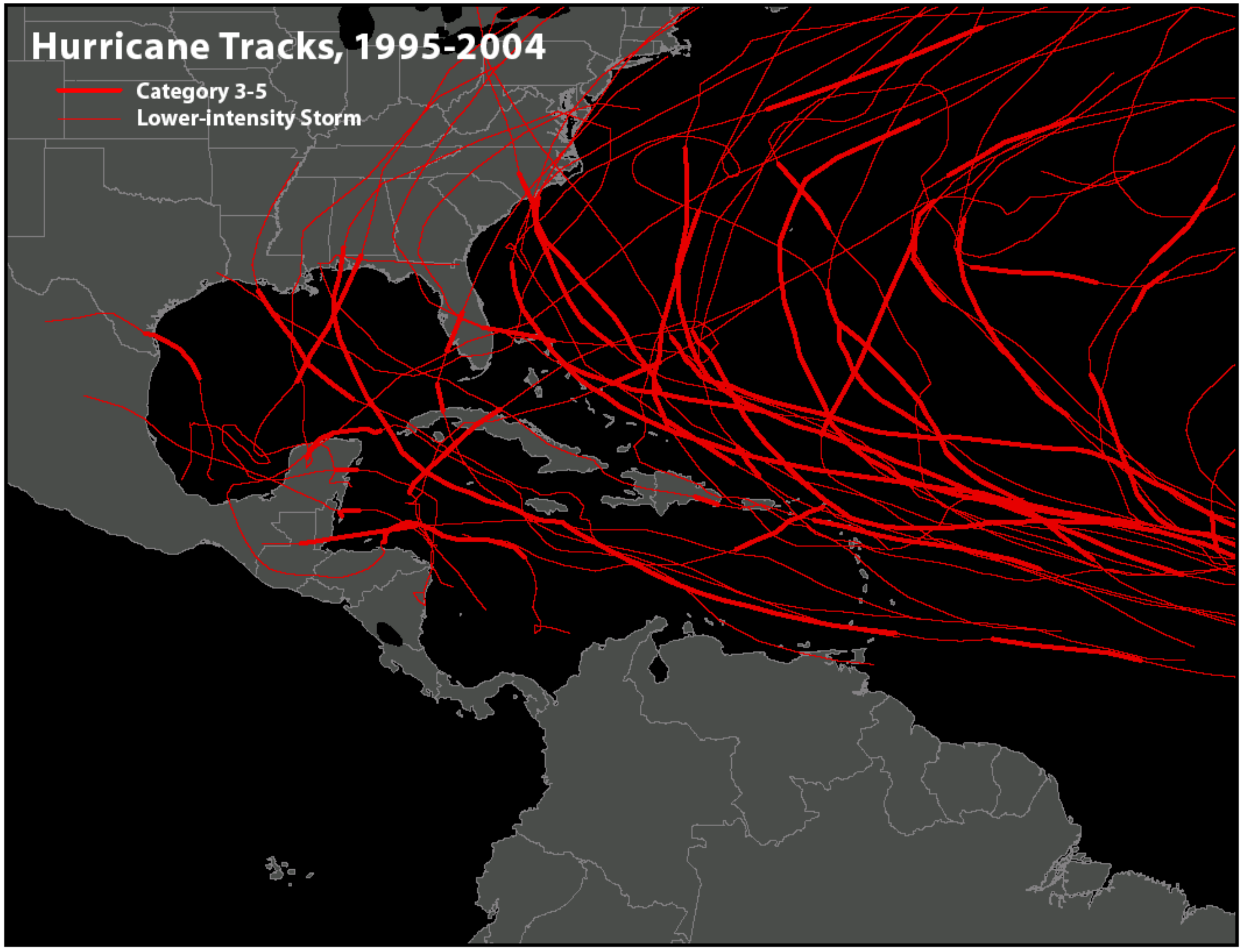
Need for carbon-free energy sources

Ice Melting

Pasterze Glacier, Austria
Change between 1875 and 2004
http://www.worldviewofglobalwarming.org/pages/glaciers.html

Need for carbon-free energy sources

Climate change



Earth at Night

Need for carbon-free energy sources

Economic sanctions

la Repubblica.it

Ultimo aggiornamento **lunedi 08.01.2007 ore 10.45**

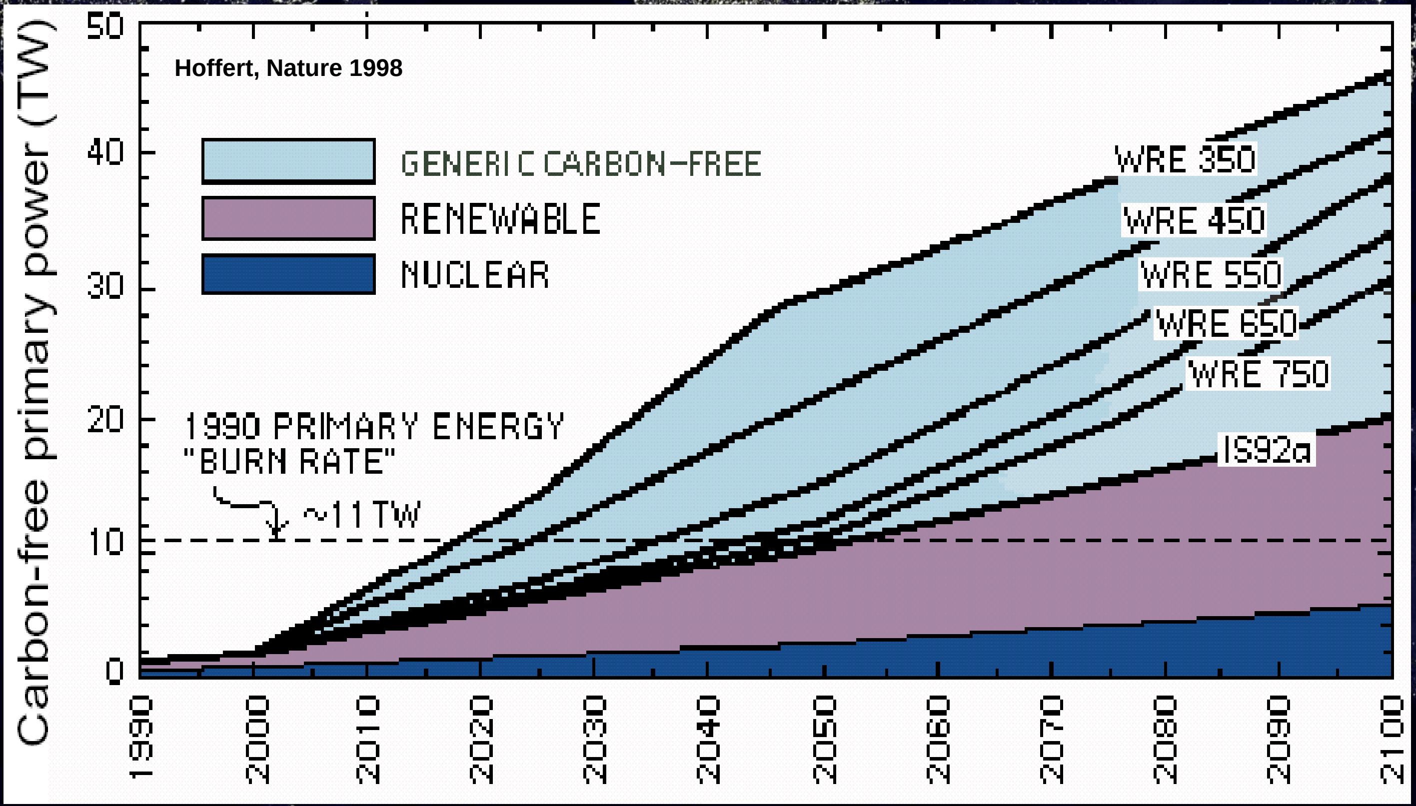
AMBIENTE

Entro gennaio convocati gli esperti che hanno preparato la ricerca per la Ue
Nel conto i danni a turismo e agricoltura e le sanzioni per le violazioni di Kyoto

Clima, minaccia per l'economia l'Italia rischia decine di miliardi

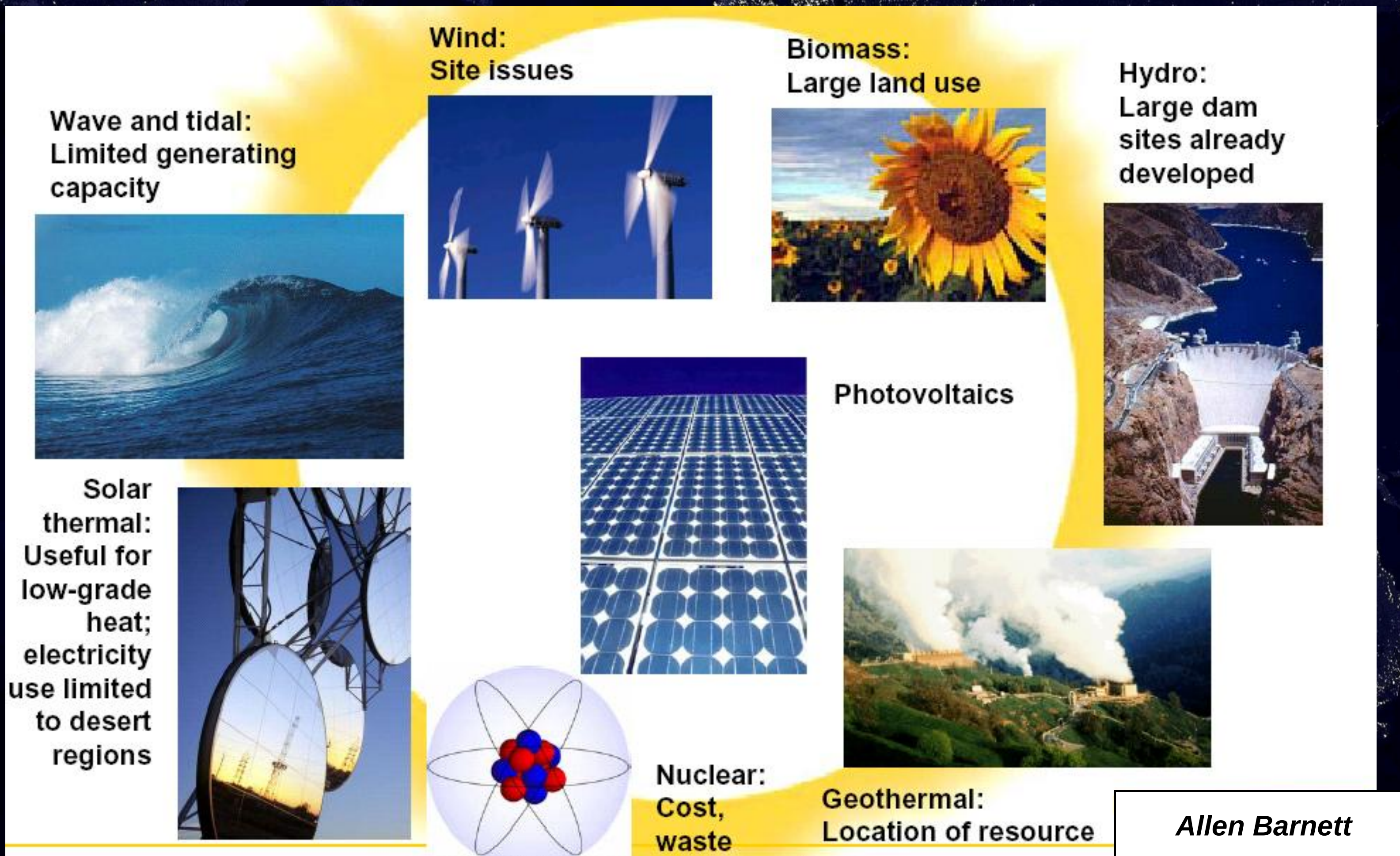
Earth at Night

Need for carbon-free energy sources



Earth at Night

Photovoltaics vs. other Renewable Resources



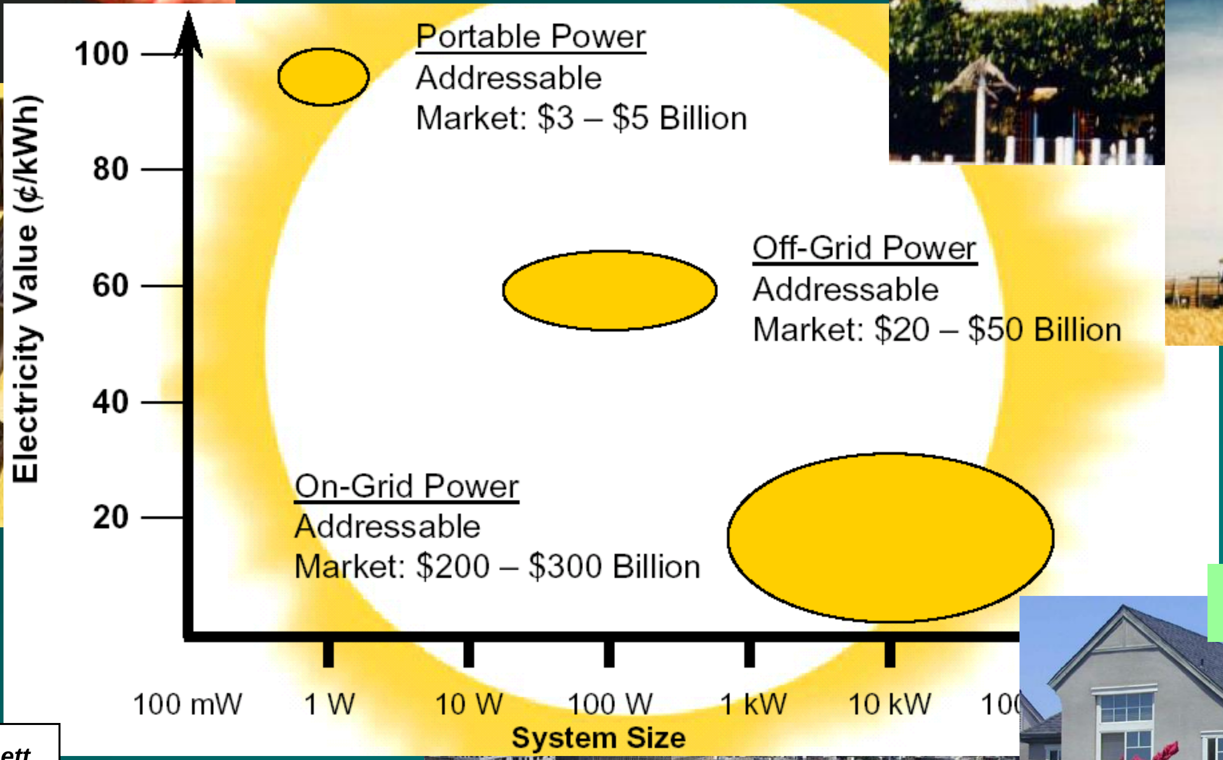
Earth at Night

Evolution of Photovoltaics

- Economical
- Technical
- “Social” – acceptance and integration

Economical Evolution: Photovoltaic Market

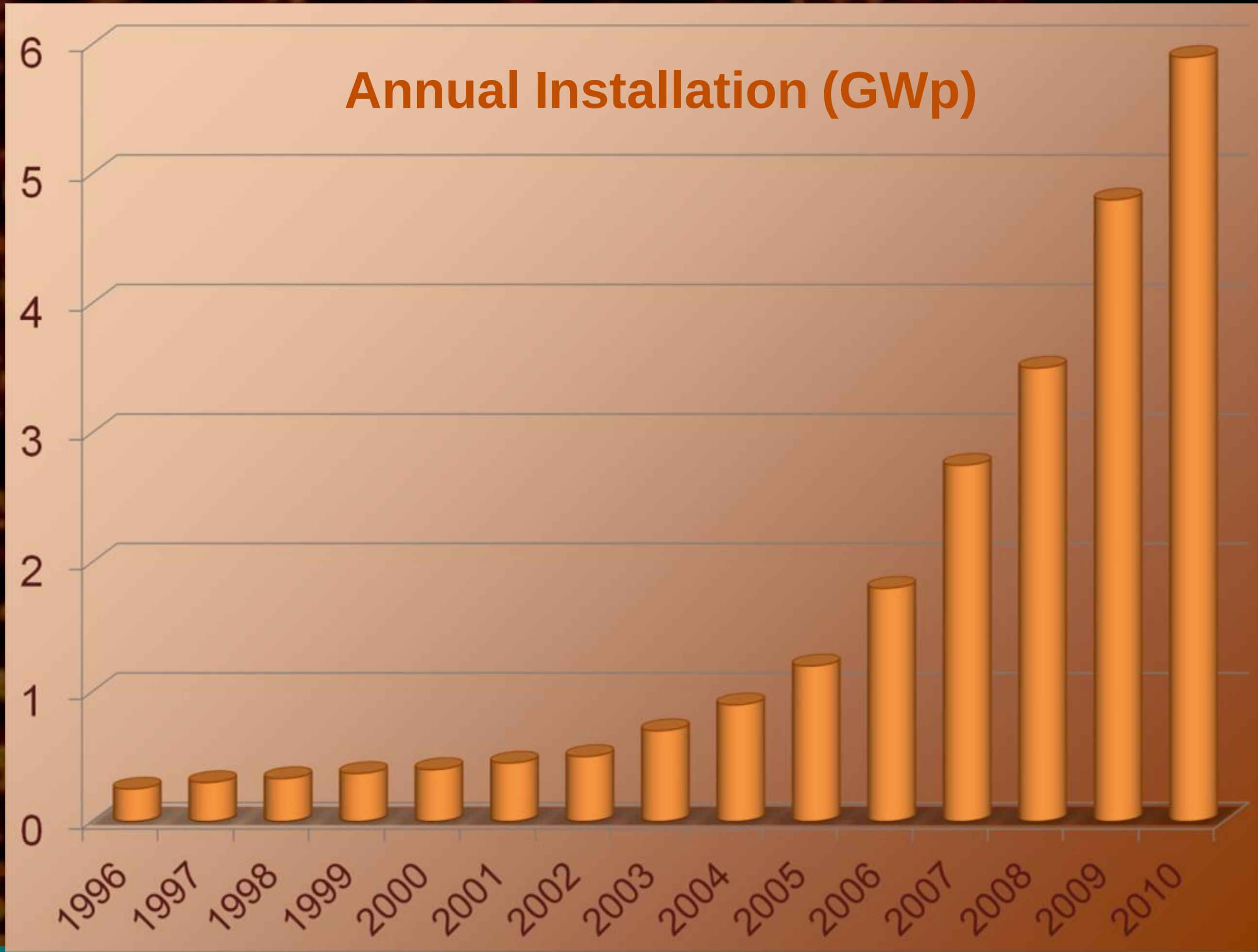
New Markets



Allen Barnett

Market size and growth

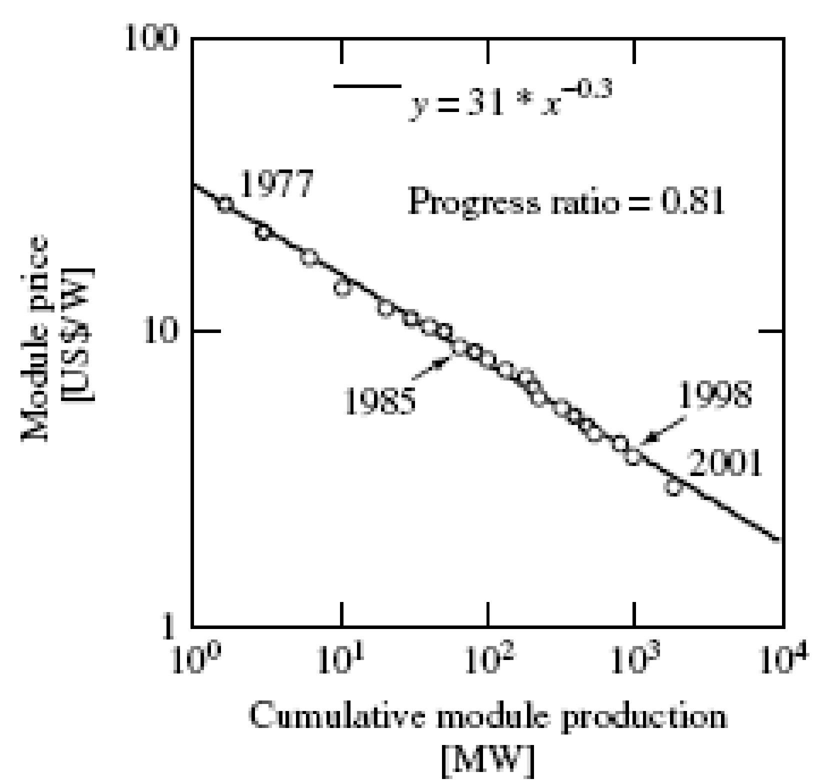
- World Market: € 15B
- Demand and supply growth: 35%/year
- Demand exceeds supply



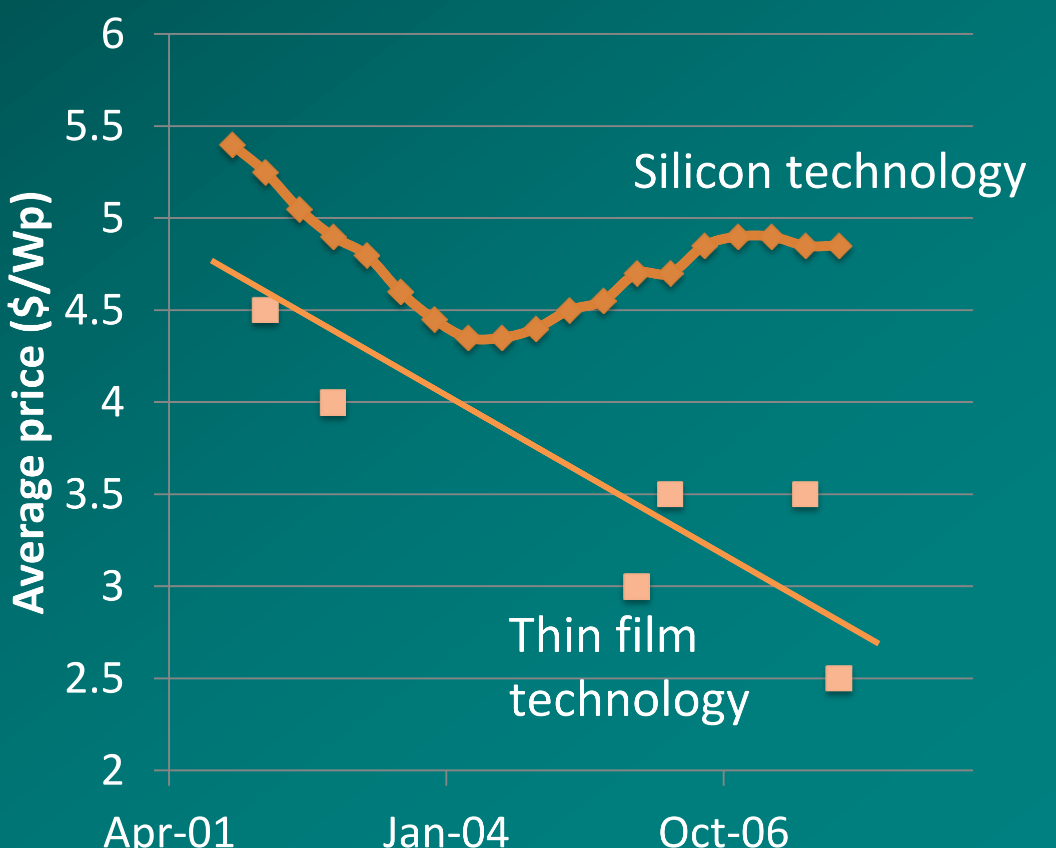
Trends in photovoltaic applications, Survey report of selected IEA countries between 1992 and 2005, report IEA-PVPS T1-15:2006

DOE Solar Energy Technologies Program, Multi-Year Program Plan 2007-2011, U.S. Department of Energy, Energy Efficiency and Renewable Energy

Price

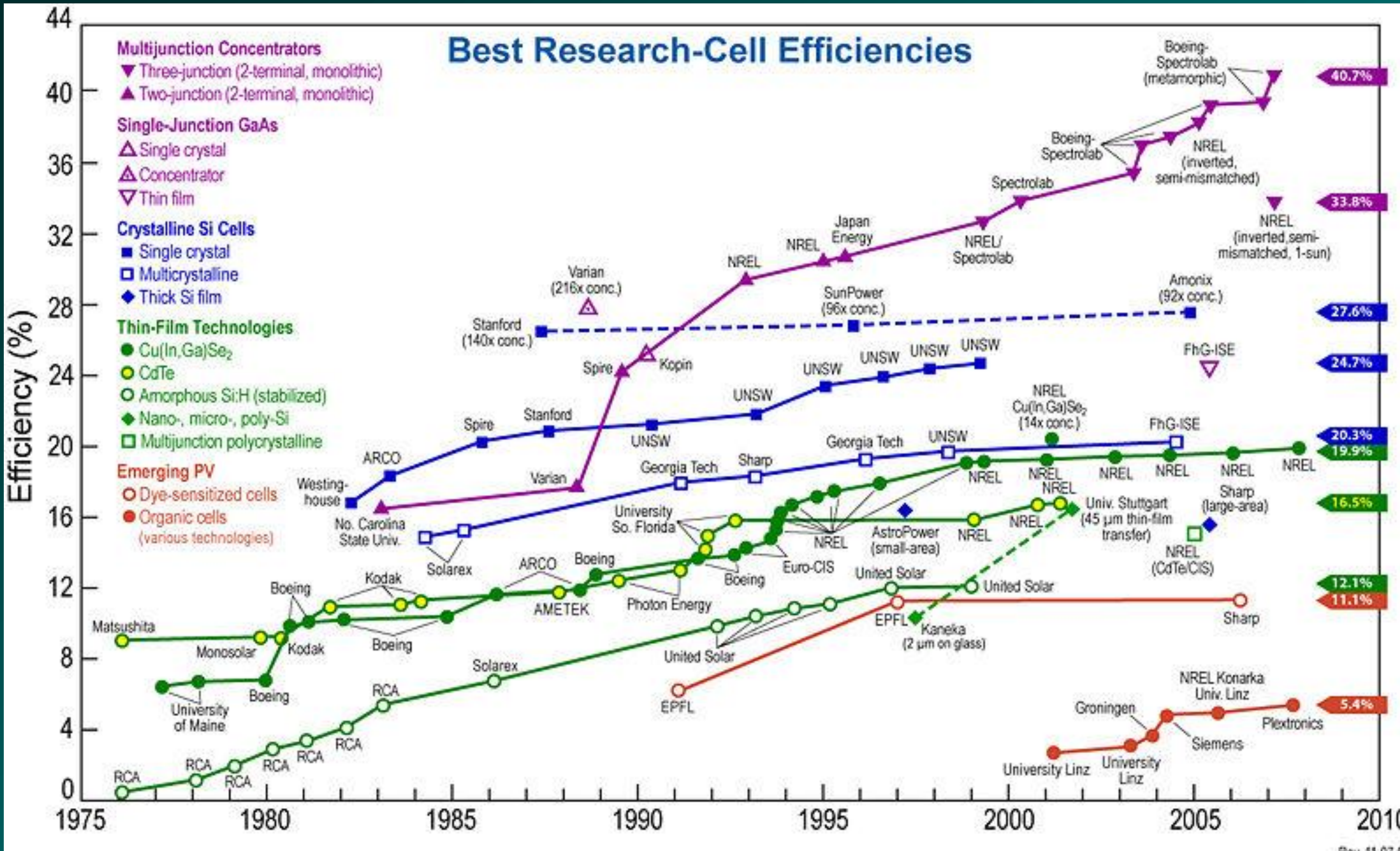


Learning curve: 80%



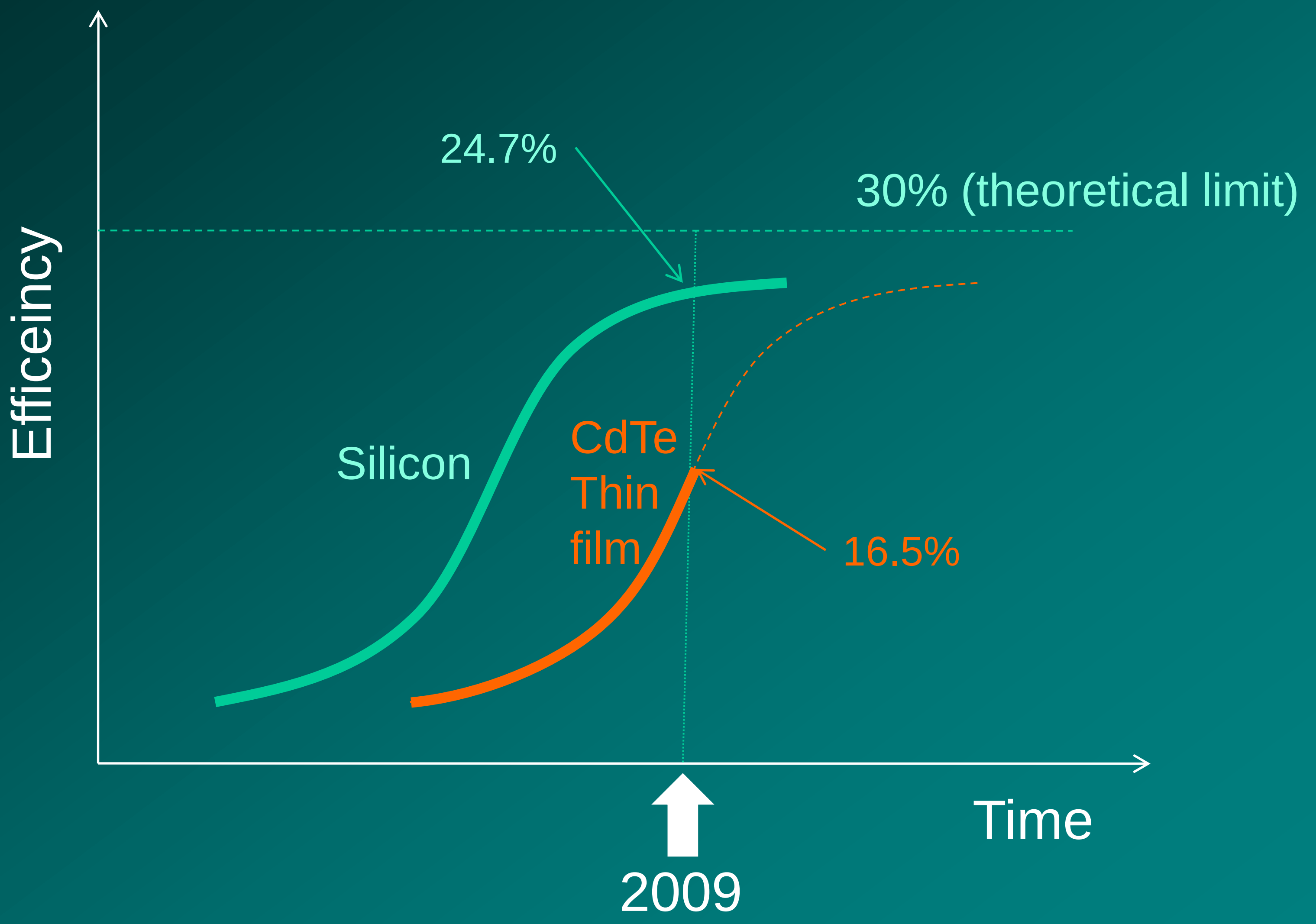
Technological evolution

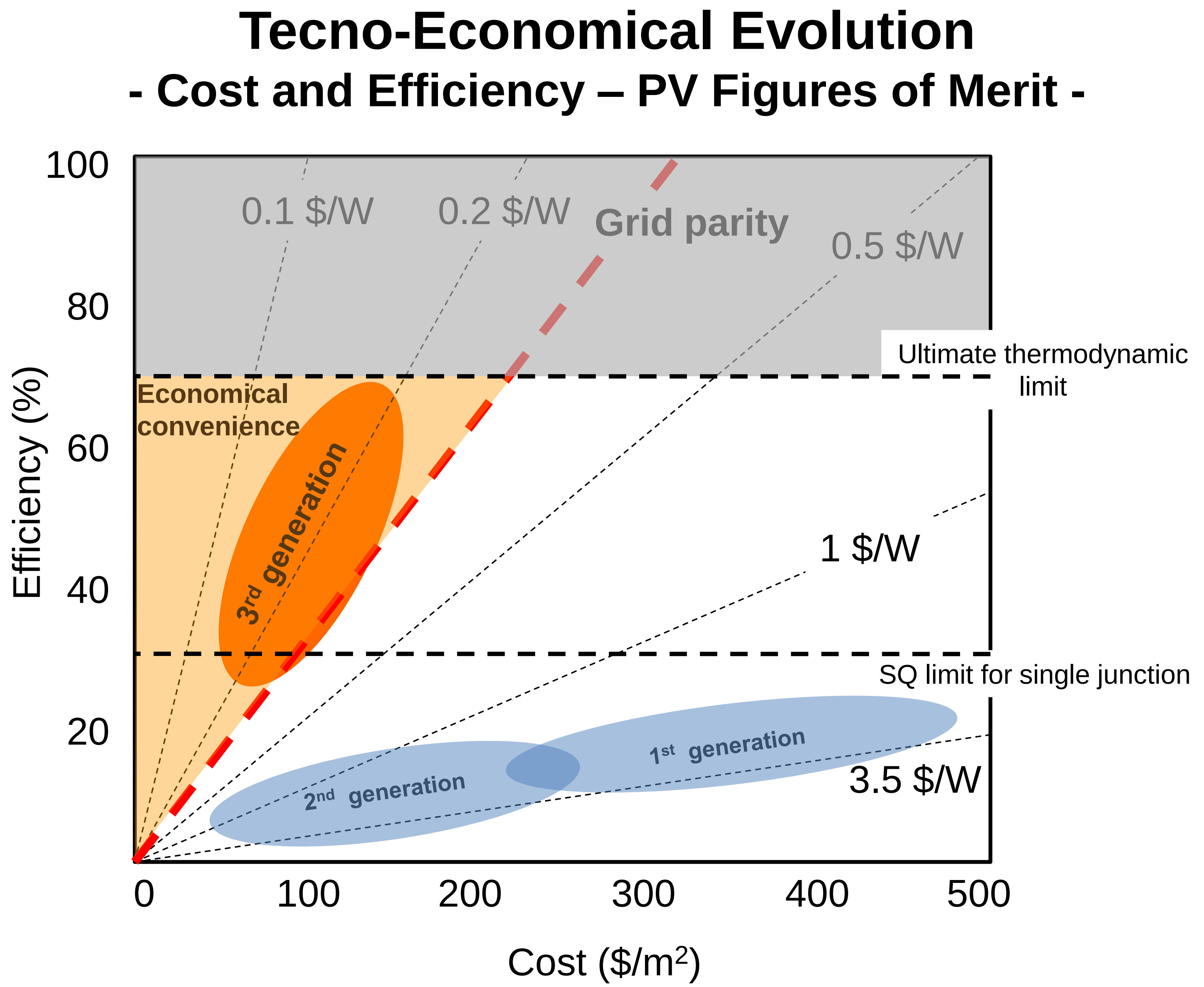
Technology evolution: Efficiency increase



NREL - US Dept.of Energy

Technology evolution: Efficiency increase




Tecno-Economical Evolution
- Cost and Efficiency – PV Figures of Merit -
100
80
60
40
20
0
100
200
300
400
500
Efficiency (%)
Cost ($/m2)
0.1 $/W
0.2 $/W
Grid parity
0.5 $/W
Ultimate thermodynamic limit
Economical convenience
3rd generation
1 $/W
SQ limit for single junction
1st generation
2nd generation
3.5 $/W

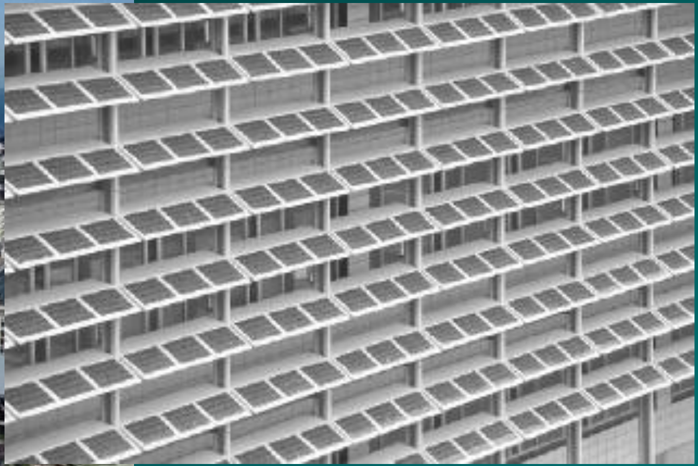
Integration of PV

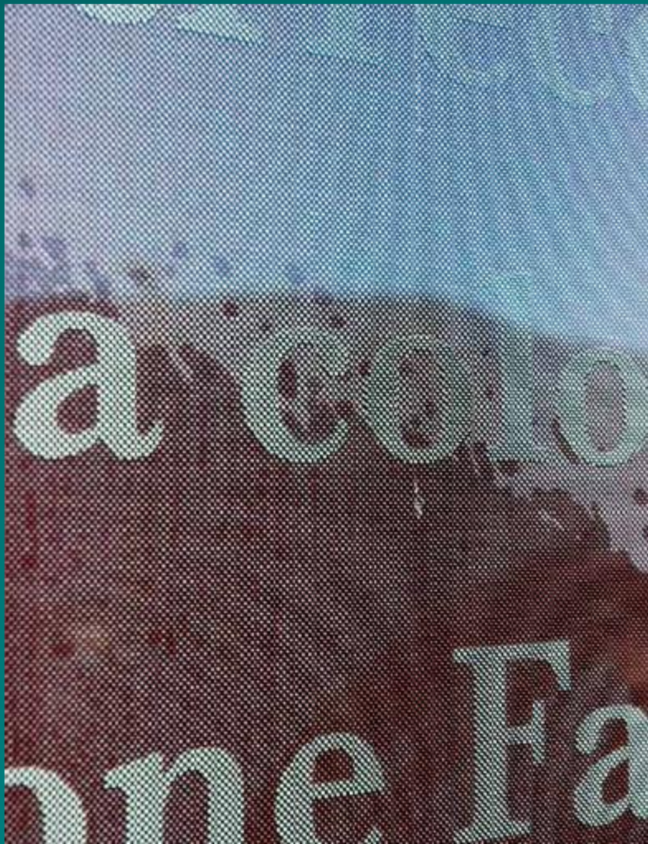
Traditional Photovoltaic Installations

Integration: Aesthetics

Integration: Aesthetics

Integration: Aesthetics & Function

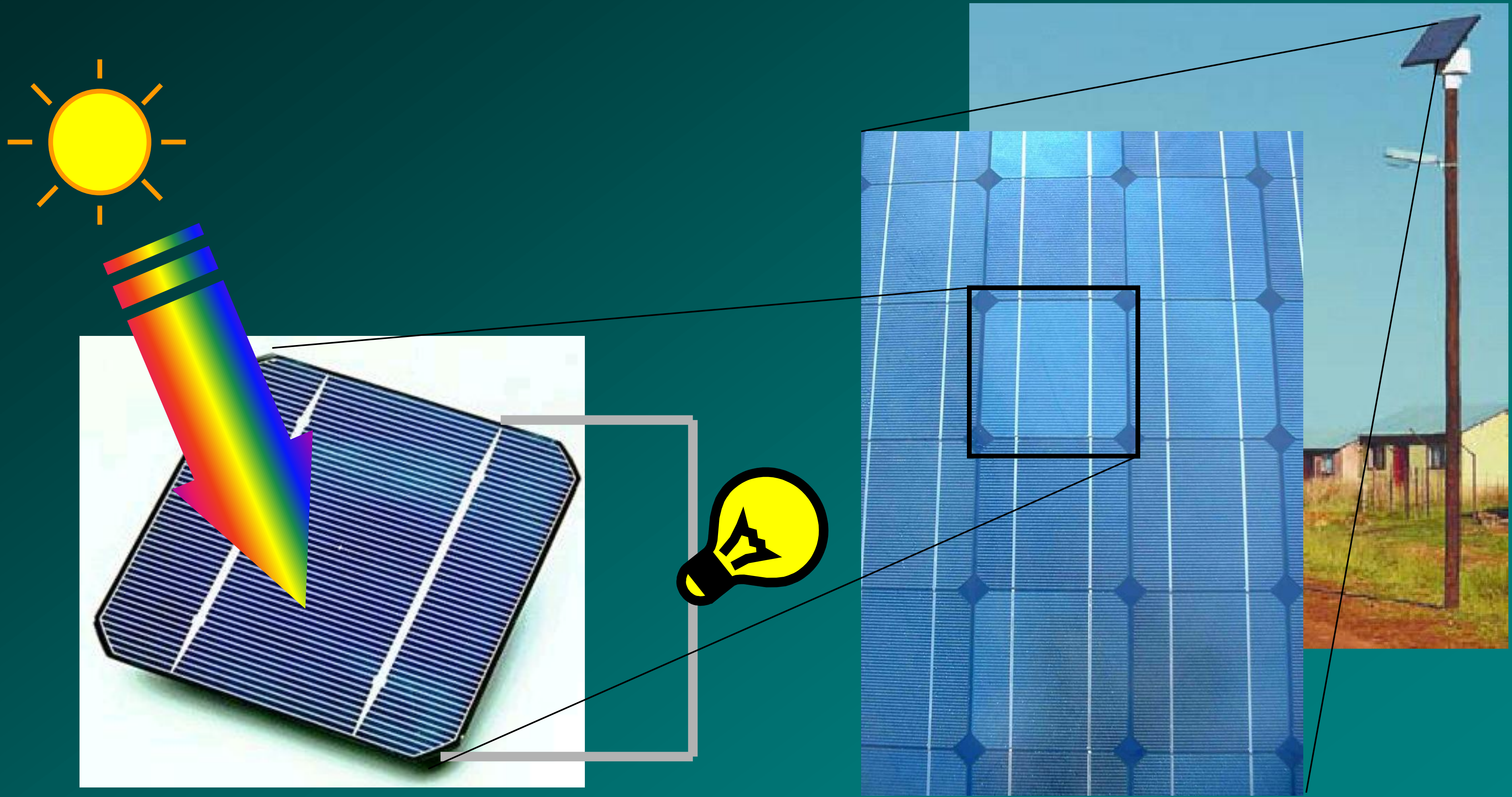




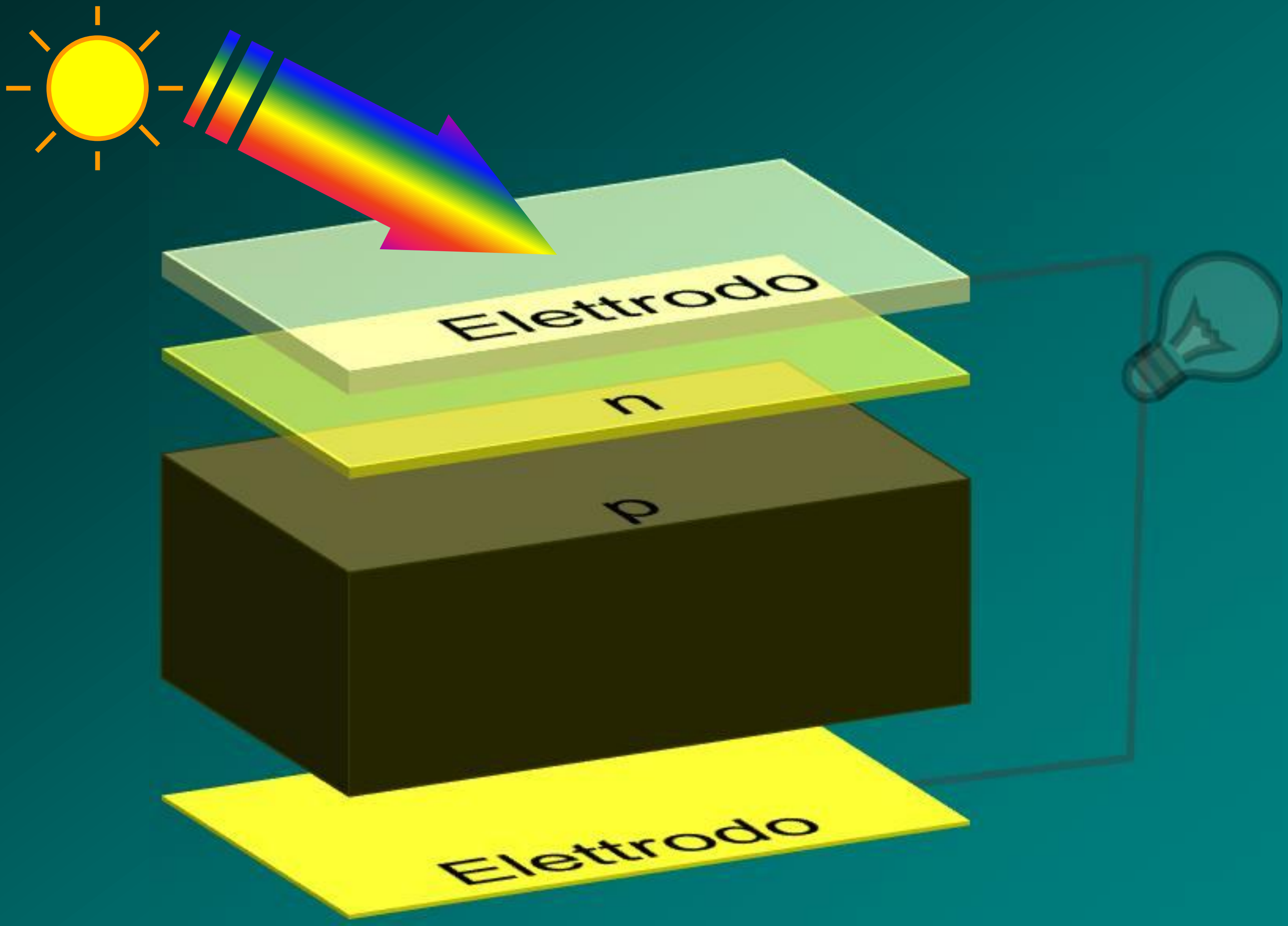
Integration: Aesthetics & Function

Current PV Technologies

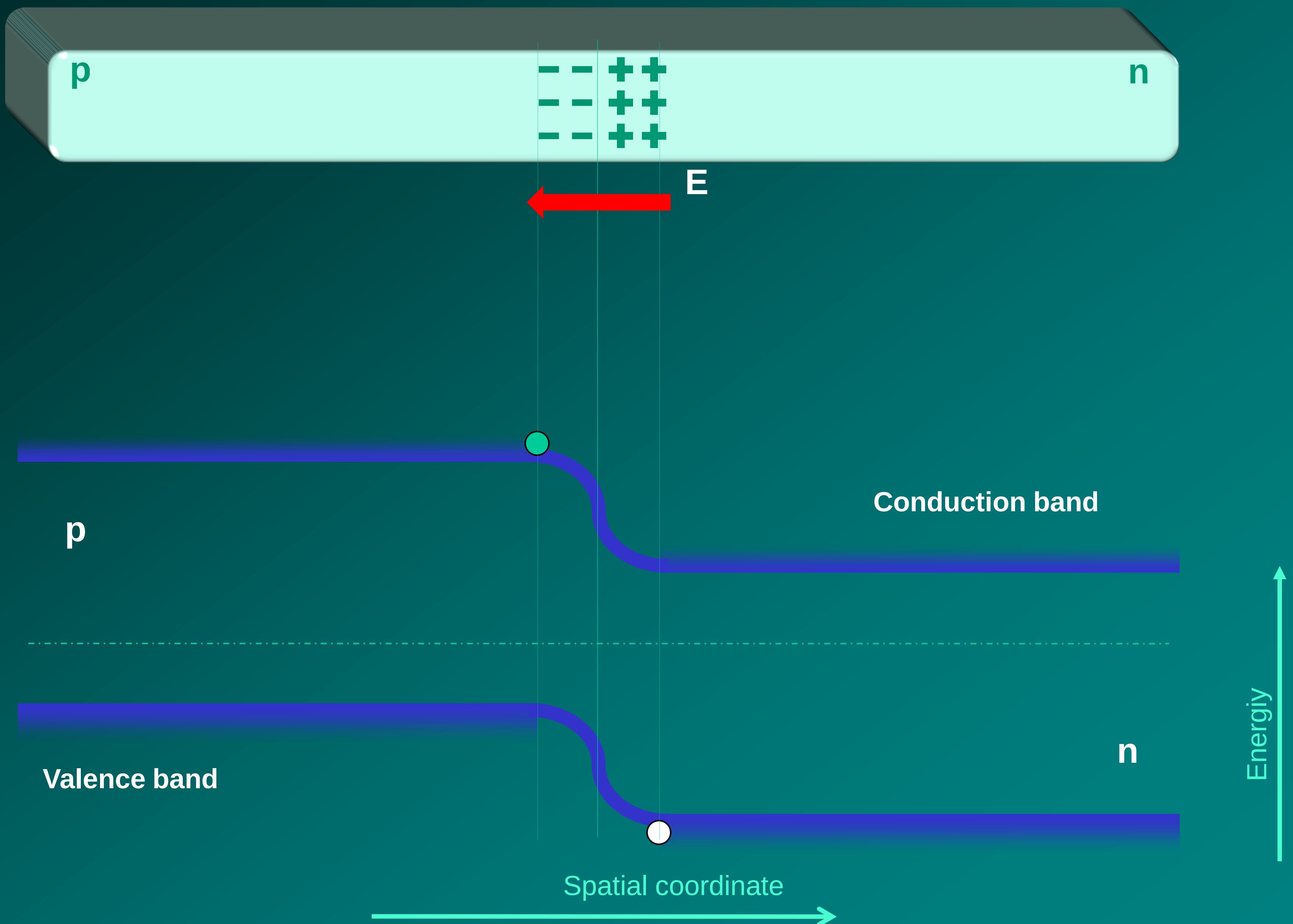
Photovoltaic Effect



Photovoltaic Effect



p-n junction



p
n
E
Conduction band
p
Valence band
n
Energiy
Spatial coordinate

Photovoltaic Effect

1.
Absorption of
solar radiation

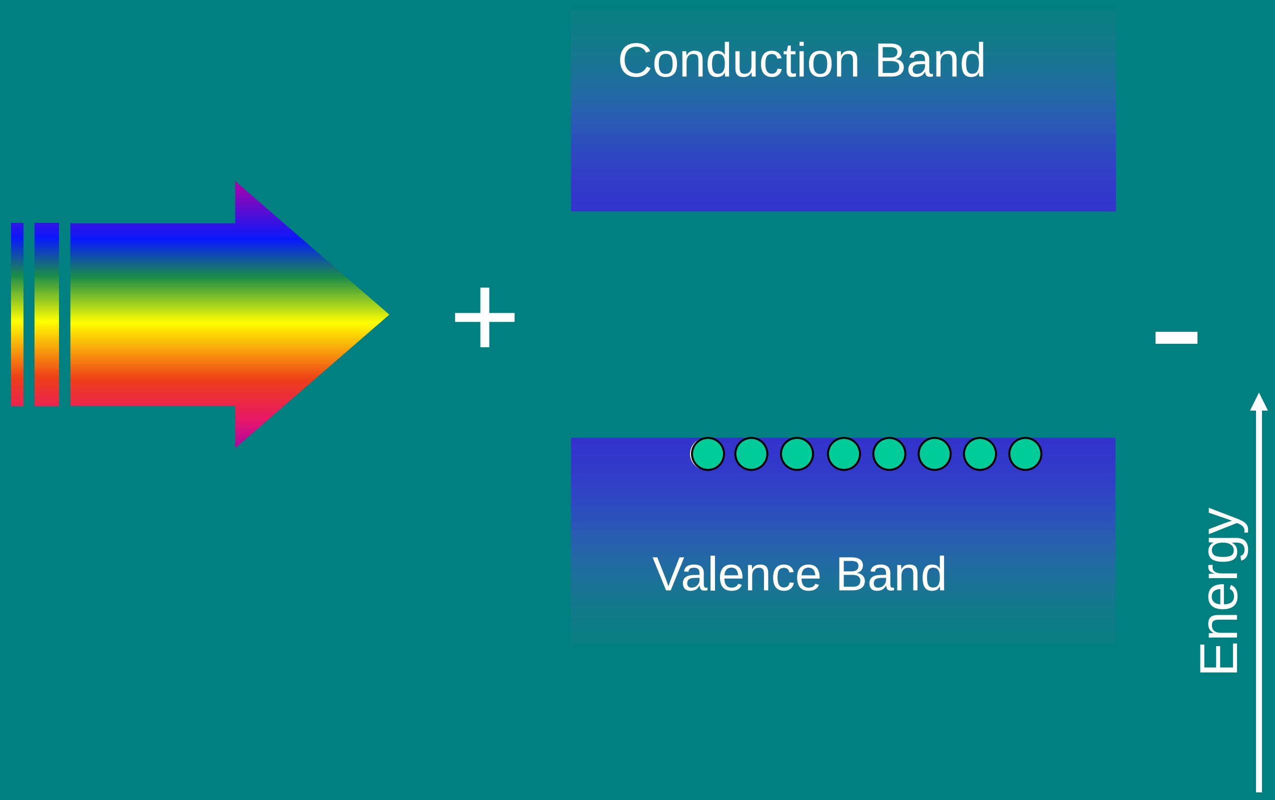
↓

Creation of
free carriers

2.
Free carrier
transport and extraction

↓

Electrical energy



Photovoltaic Effect ⇒ Choice of materials

1.
Absorption of solar radiation

↓

Creation of free carriers

⇒

- Materials with good absorption of the solar radiation

2.
Free carrier extraction

↓

Electrical energy

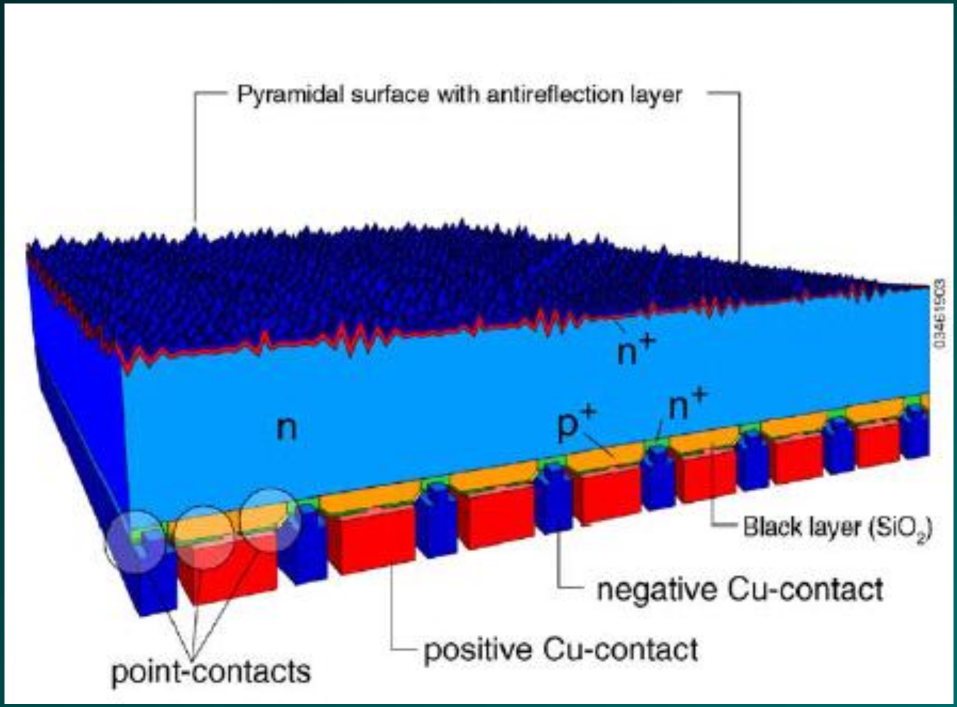
⇒

- “Perfect materials”
  (large mean free paths for the carriers)

- Short carrier paths

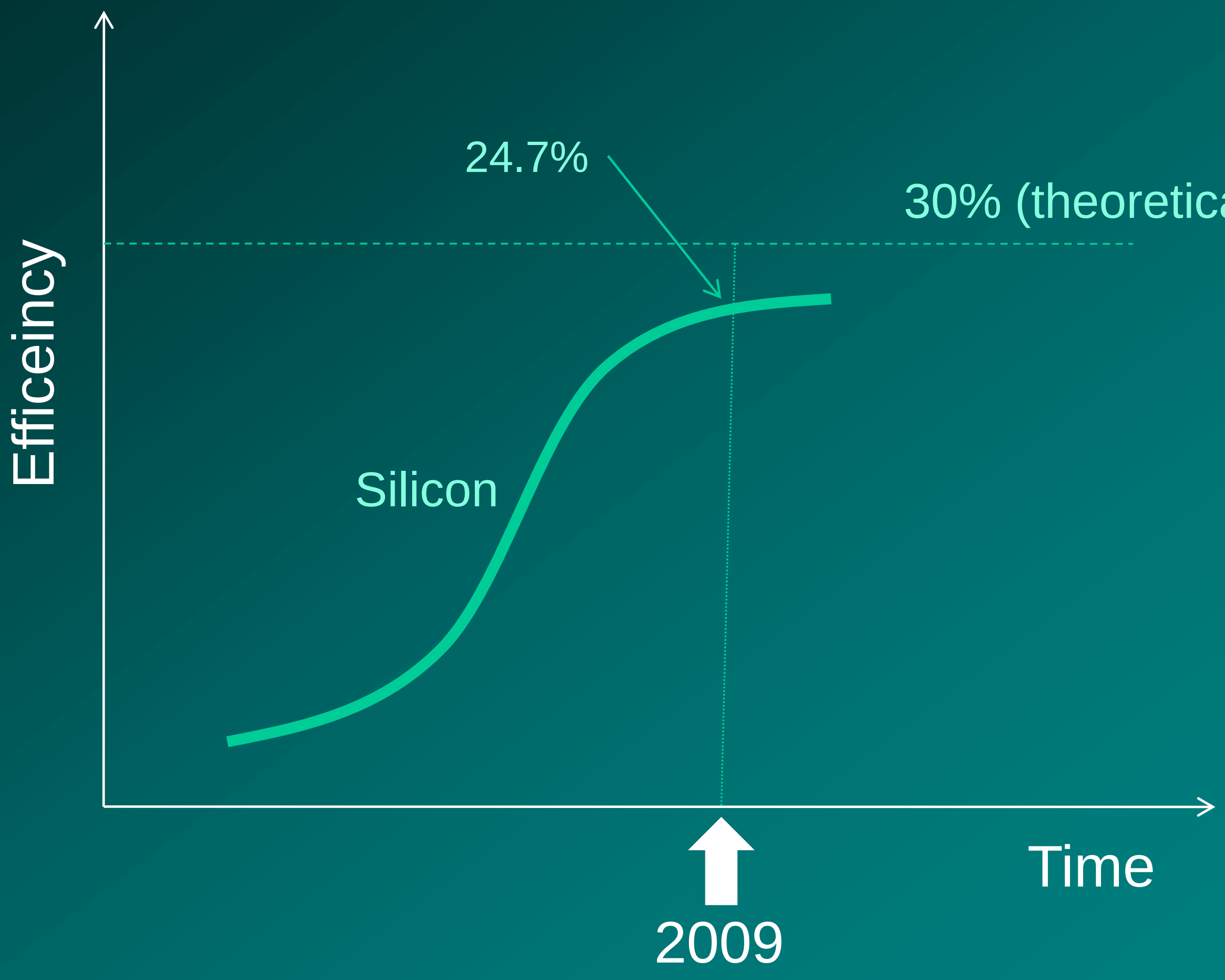
Silicon technology

Silicon technology – Record performance



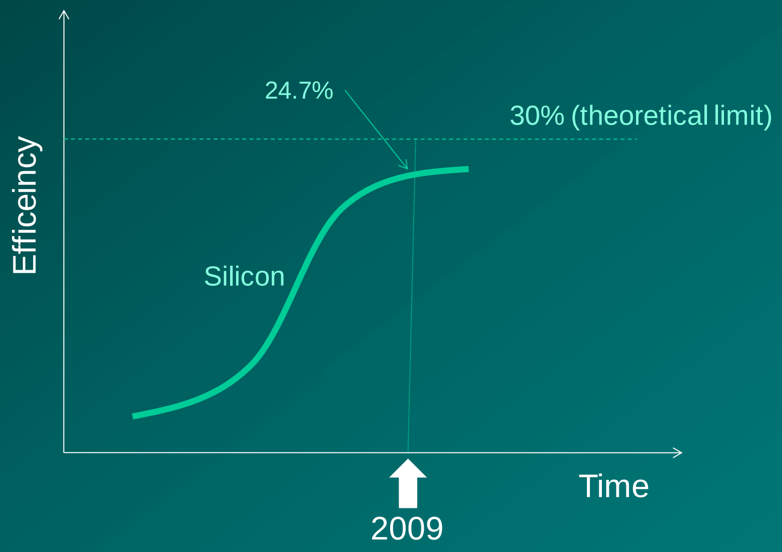
	Single crystal silicon	Polycrystalline
Cell Record	24.7%	20.3%
Module record	22.7%	15.3%
Commercial modules	15-18%	12-15

Silicon Technology

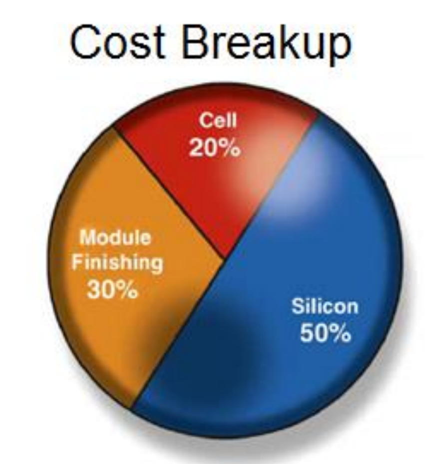


Silicon Technology - Summary

- Mature Technology
  (max efficiency > 80% thermodynamic limit)



- Large quantities of pure silicon are needed
  ⇒ high cost of raw material

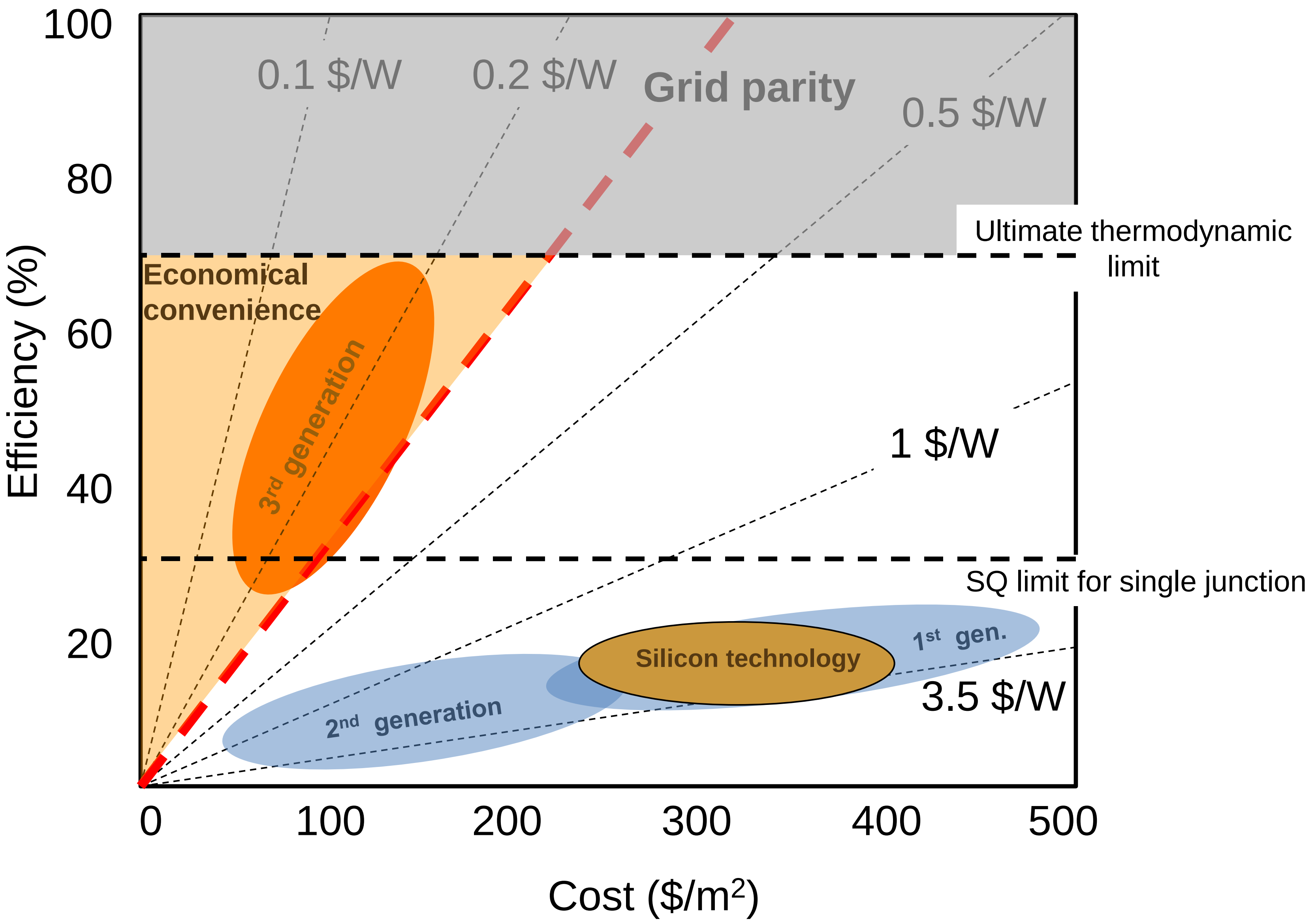


Kazmersky, 2006

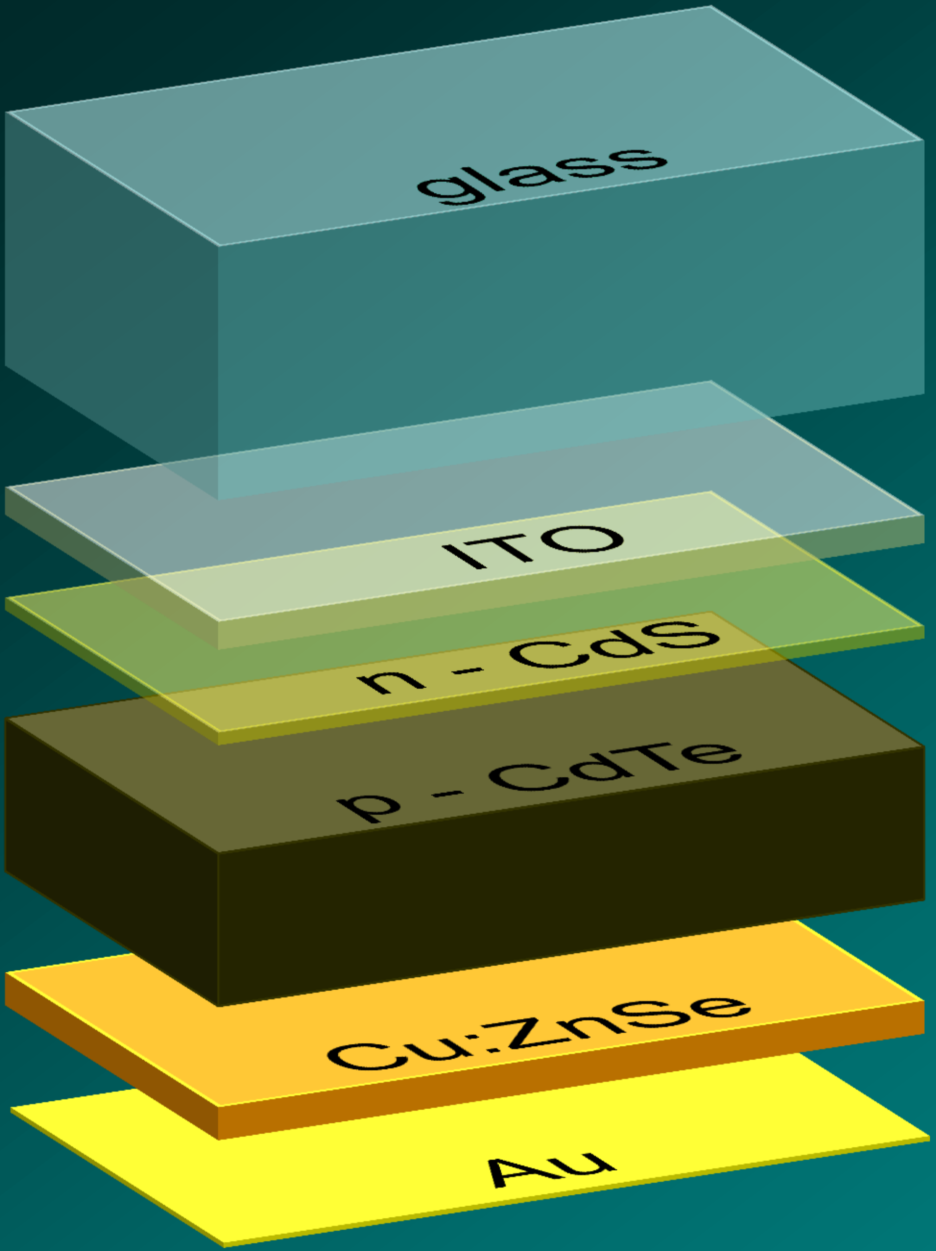
- Limitation in raw material supply

Tecno-Economical Evolution

- Cost and Efficiency – PV Figures of Merit -

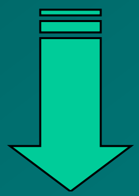


Thin Film Solar Cells



Materials with:

- high absorption coefficient
- good match with the solar spectrum (1.5 eV)



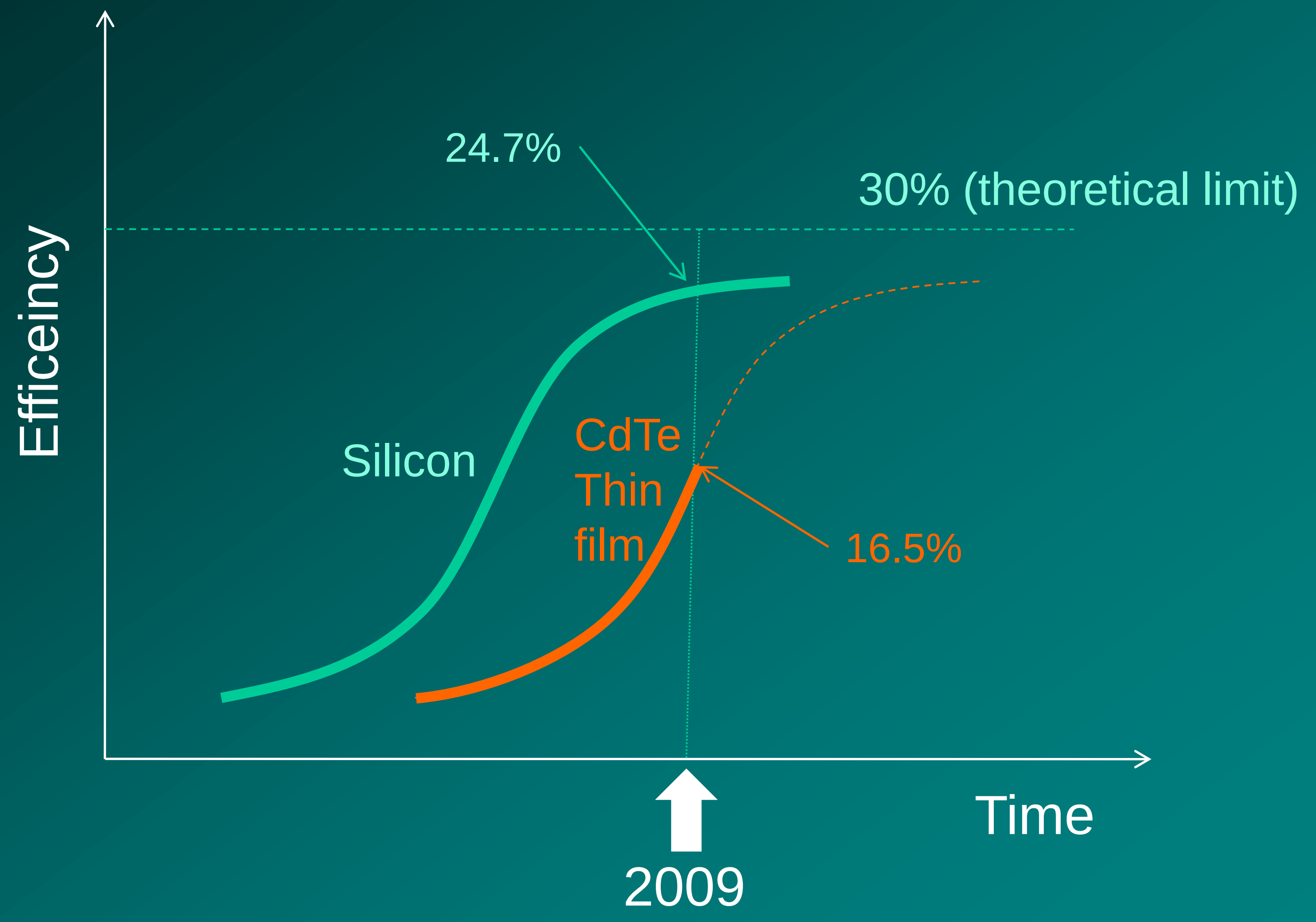
- Less active material is needed (thin films: 0.1 – 10 um)
- Lower cost
- Less problems with supply of raw materials
- Short carrier paths (perfection requirements are relaxed)

Thin Film Solar Cells

Medium efficiency – Low Cost

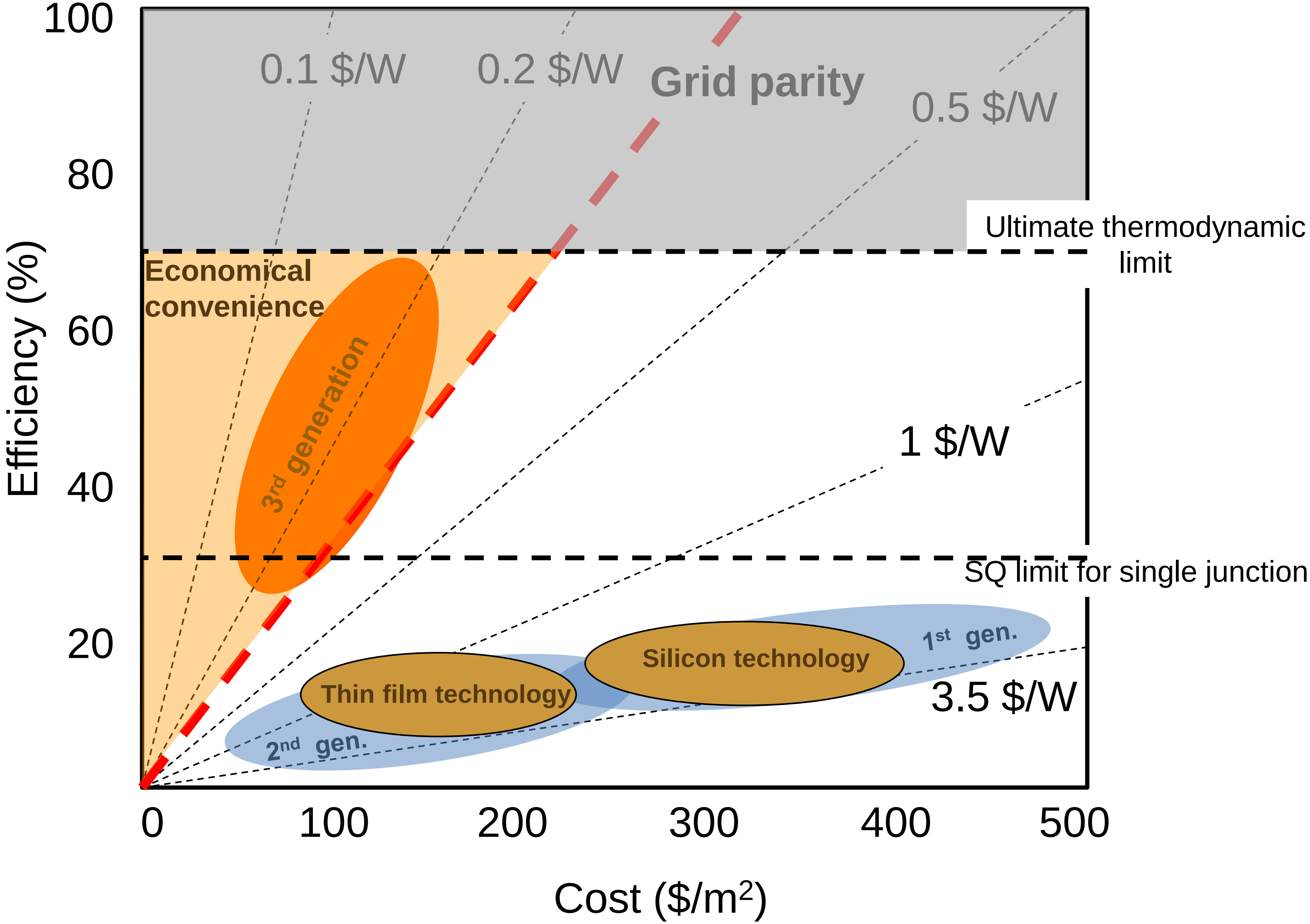
	CdTe	CIGSS	Amorphous Si
Cell Record	16.5%	19.5%	9.5%
Module record	10.7%	13.4%	--
Commercial modules	8-10%	--	4-7%

Technology evolution: Efficiency increase



Tecno-Economical Evolution

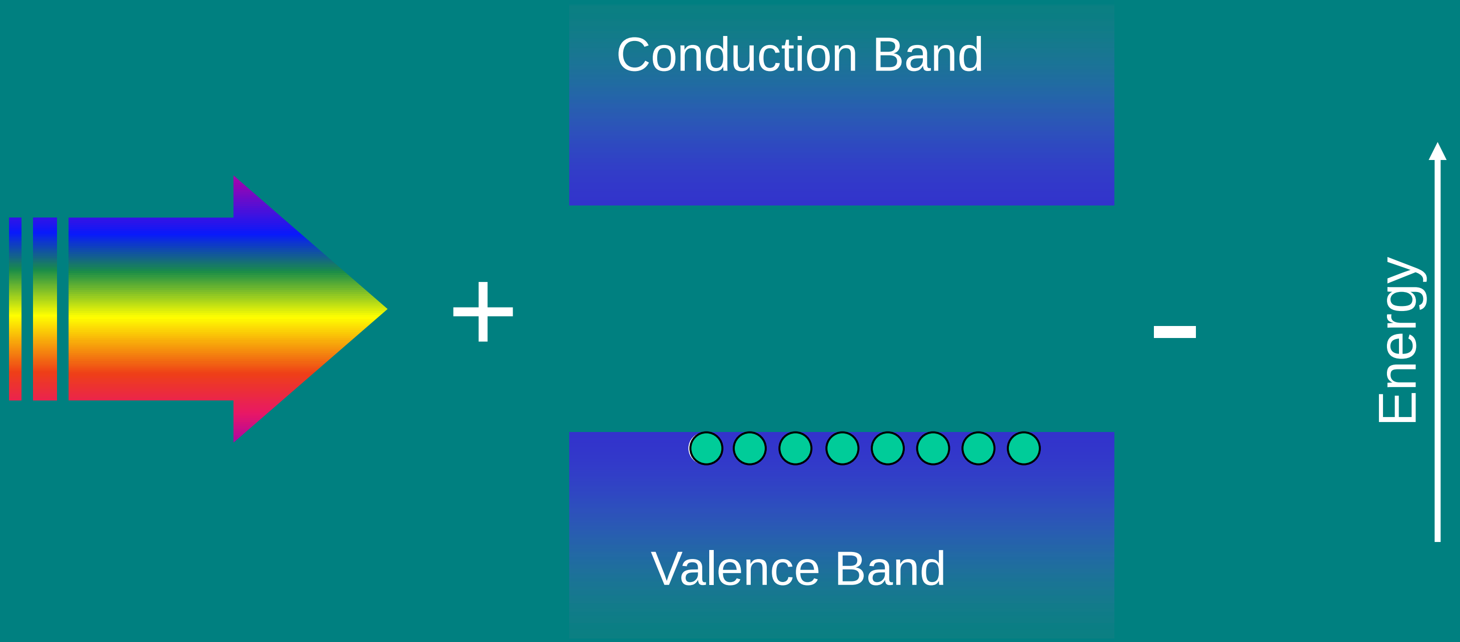
- Cost and Efficiency – PV Figures of Merit -



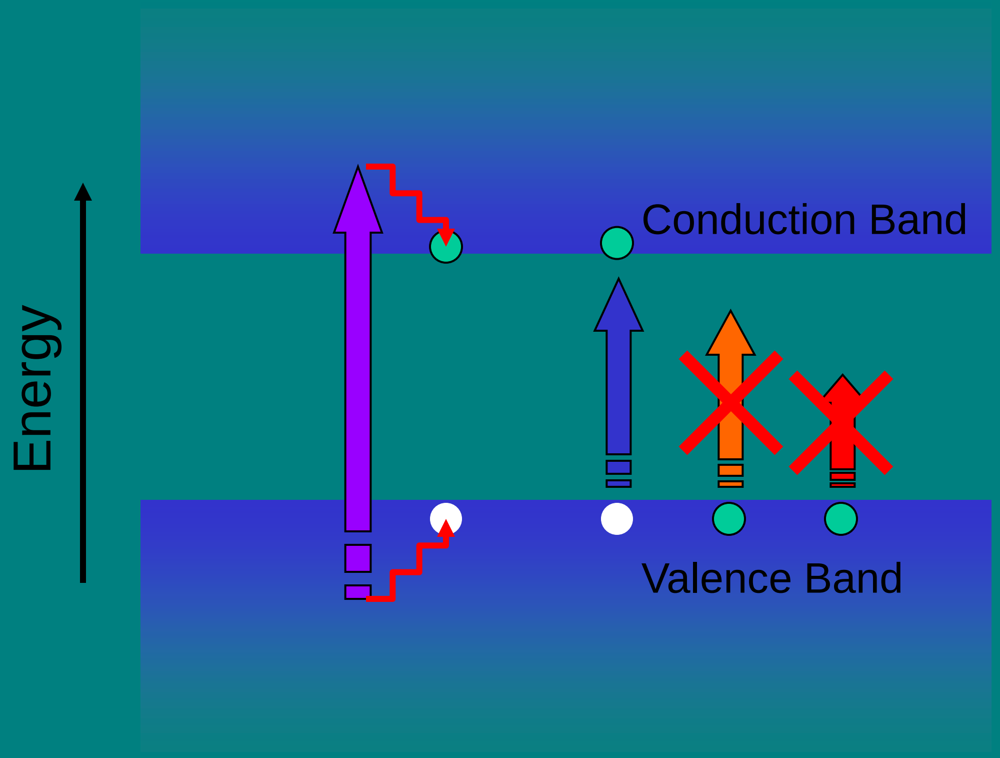
Thin Film Solar Cells

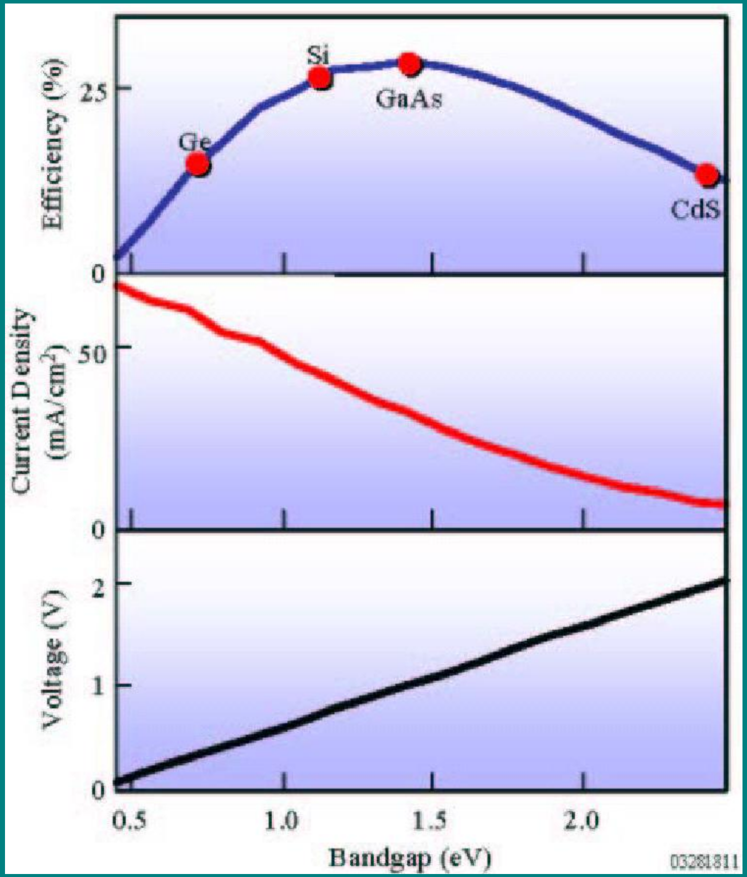
- **Young Technology(max efficiency is 30-40% of thermodynamic limit)**
- **Films can be deposited on various substrates** (flexible, architectural elements for building integration, etc.)
- **Low Cost**
- **Thermodynamic limit is still 30%**
- **Nanotechnology-based films are currently reaching the market**

PV efficiency: Thermodynamic limit



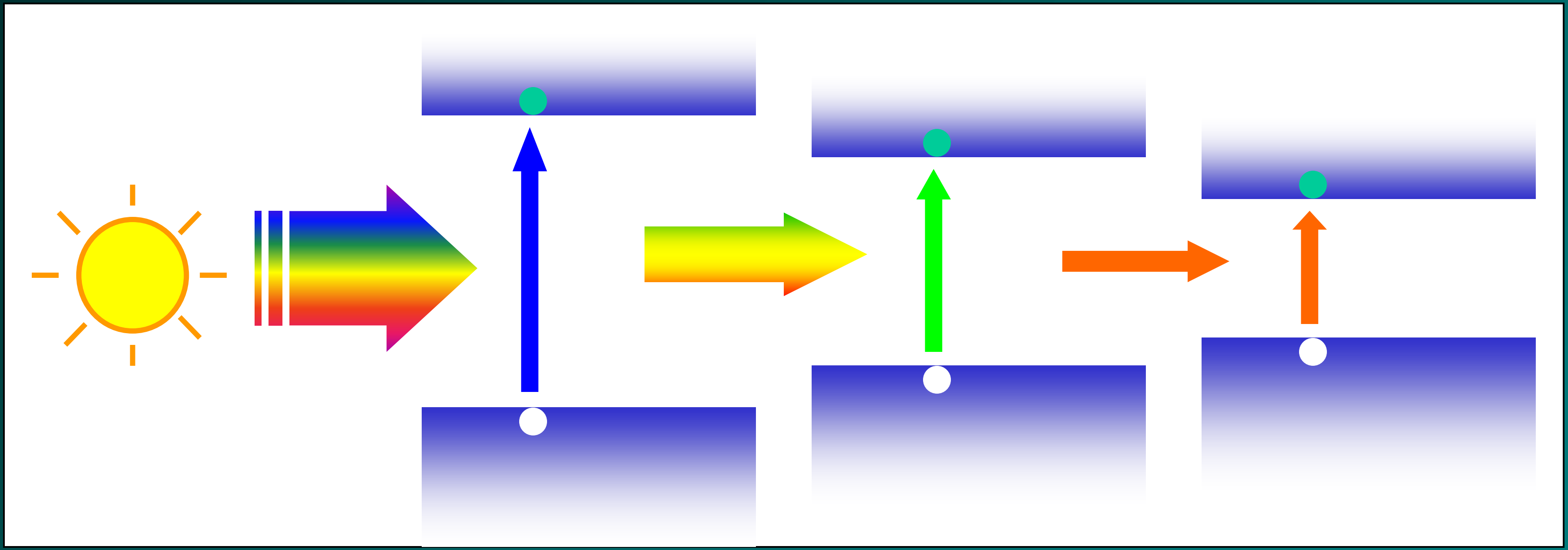
PV efficiency: Thermodynamic limit





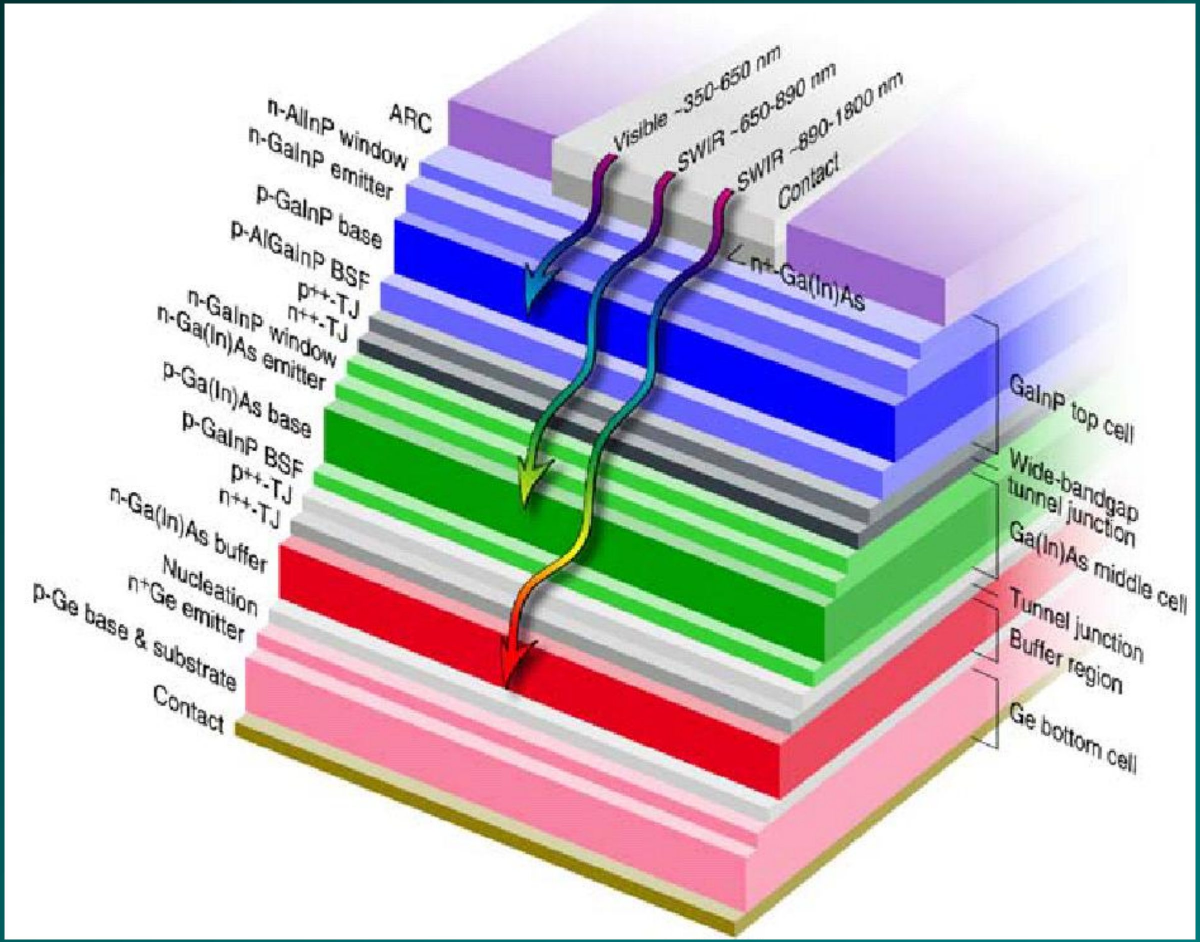
Max efficiency: 30%

Beyond The Single Junction Limit: Tandem cells



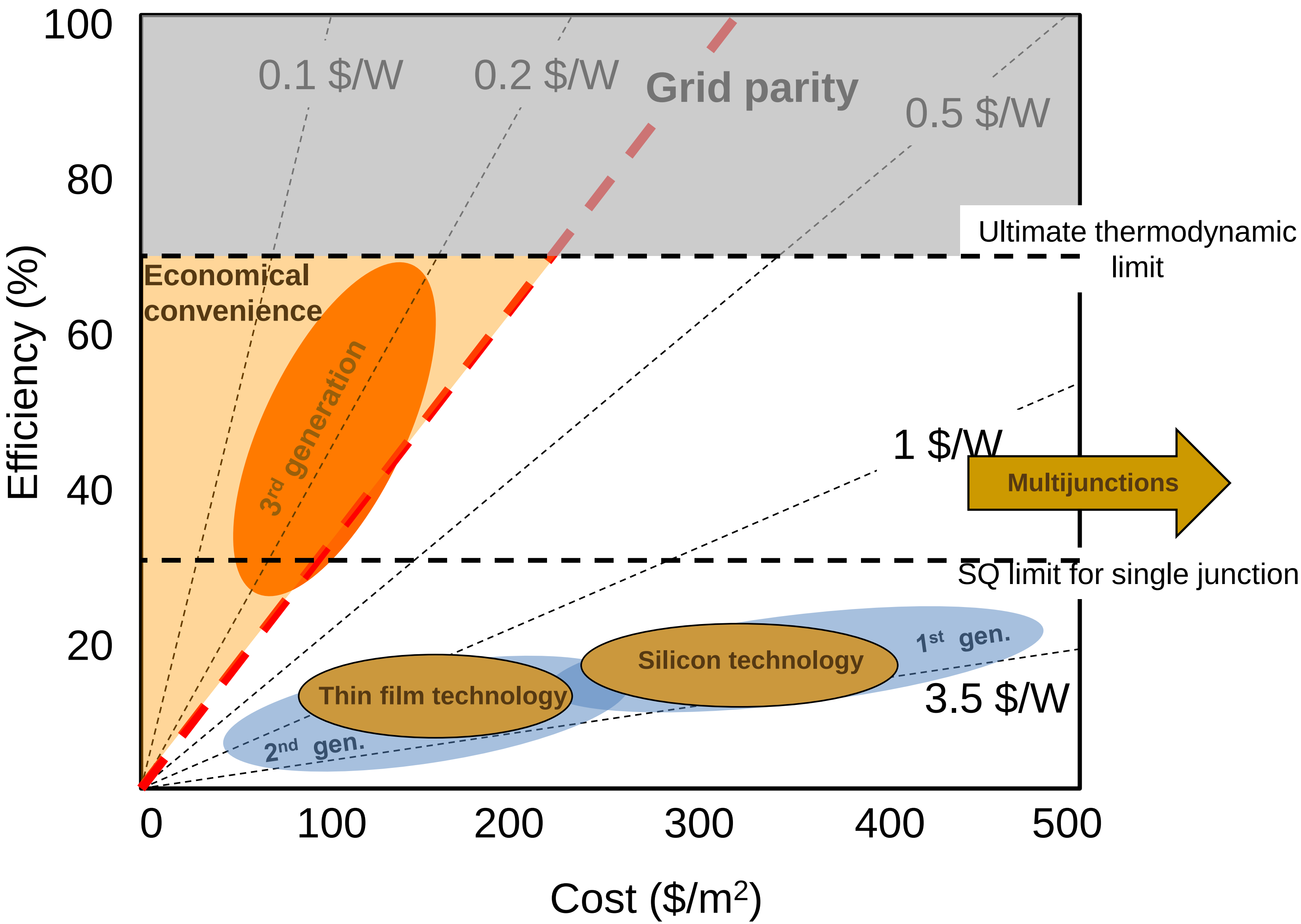
More efficient use of the solar spectrum

Tandem Cells



- Current efficiency record > 40%
- Multijunction cells – very expensive
- Aerospace applications or terrestrial concentration

Tecno-Economical Evolution
- Cost and Efficiency – PV Figures of Merit -

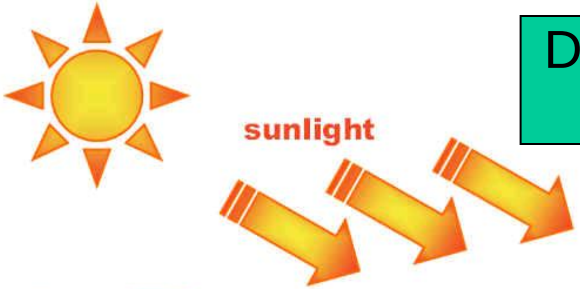


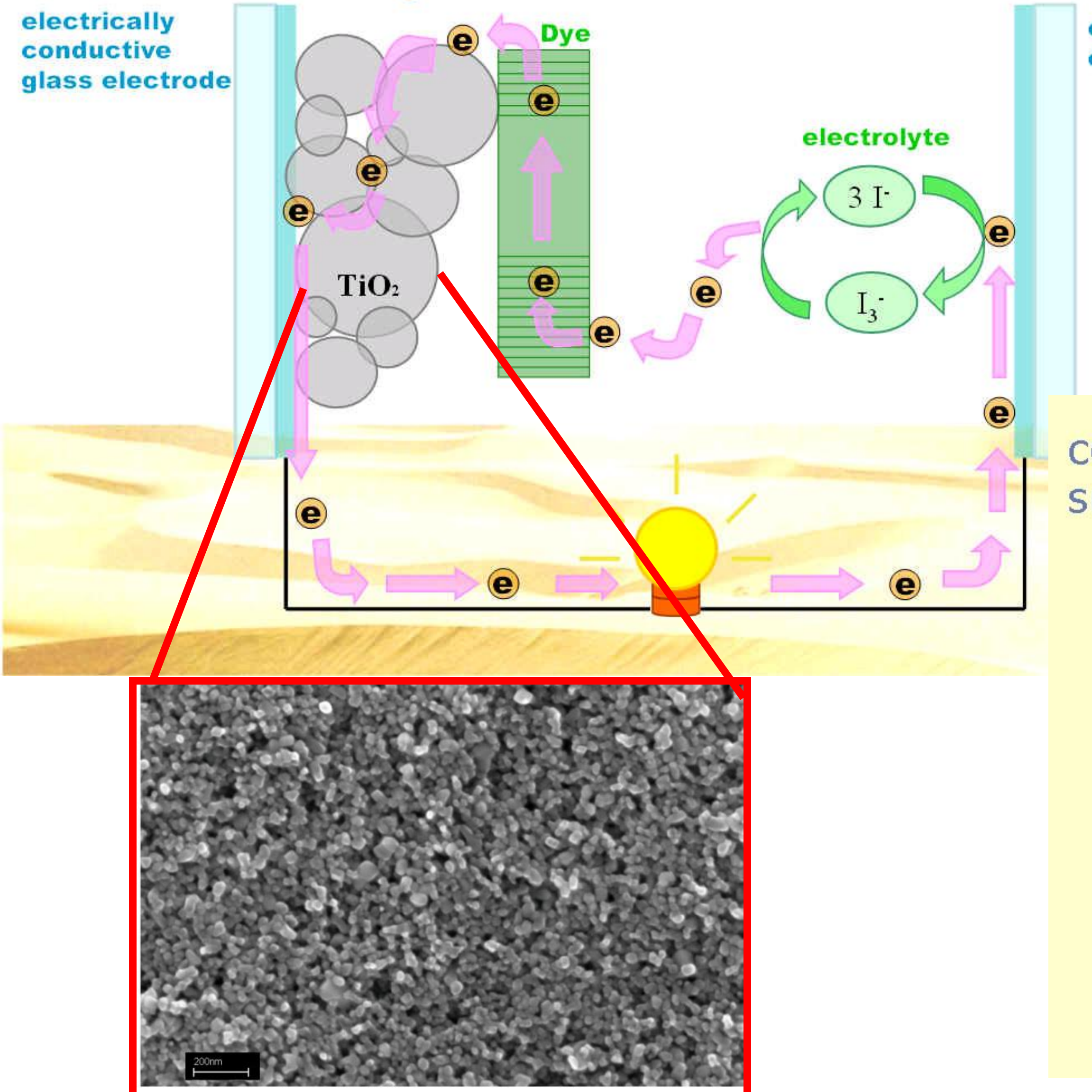
Why nanotechnology?

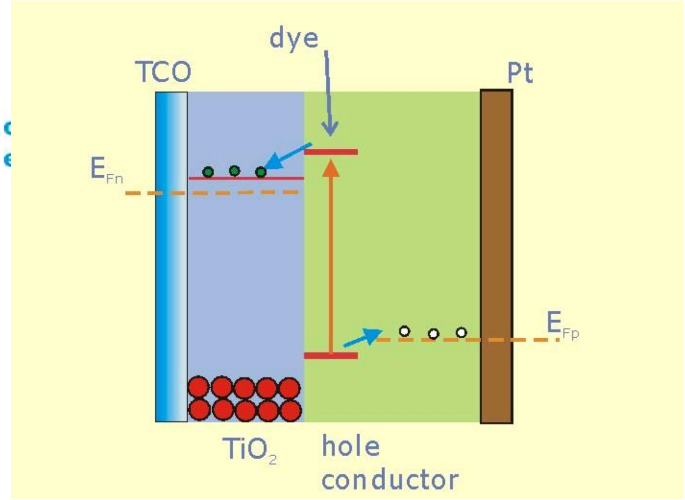
- Morphological advantages (surface area)
- Phenomena that govern optoelectronic properties of materials **occur at the nanoscale**
- Phenomena at the nanoscale are governed by the laws of quantum mechanics

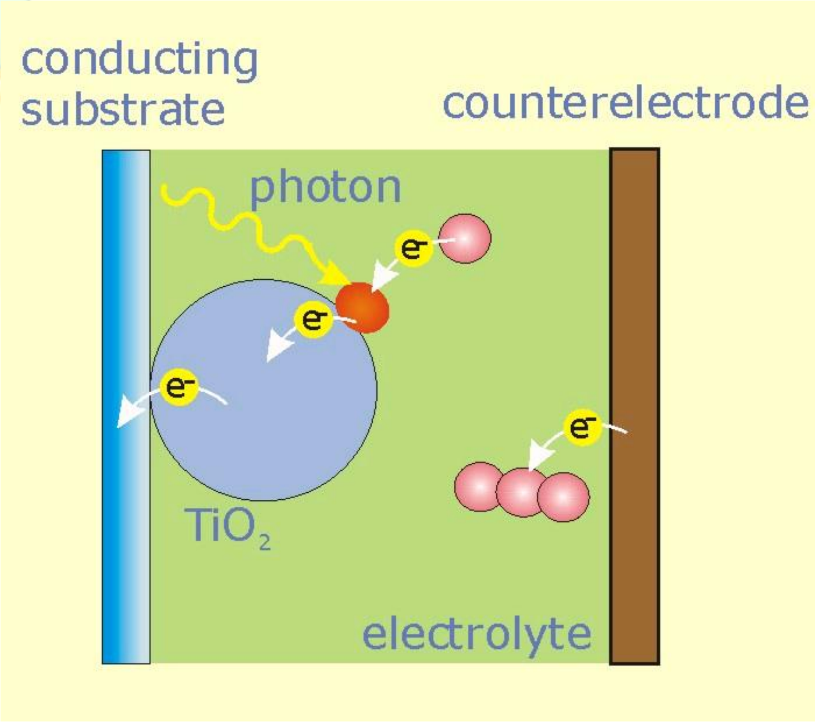
→ new opportunities for controlling material properties

Dye Sensitized Solar Cell (DSSC)
Graetzel Cell

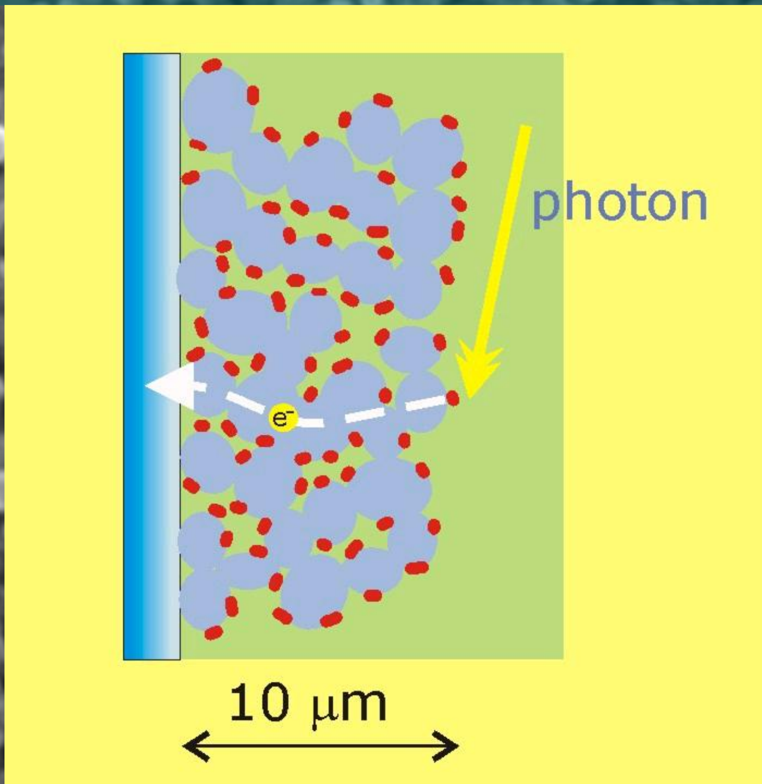


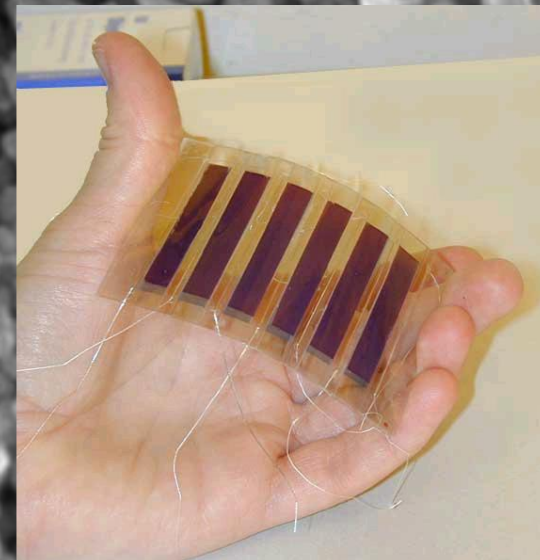


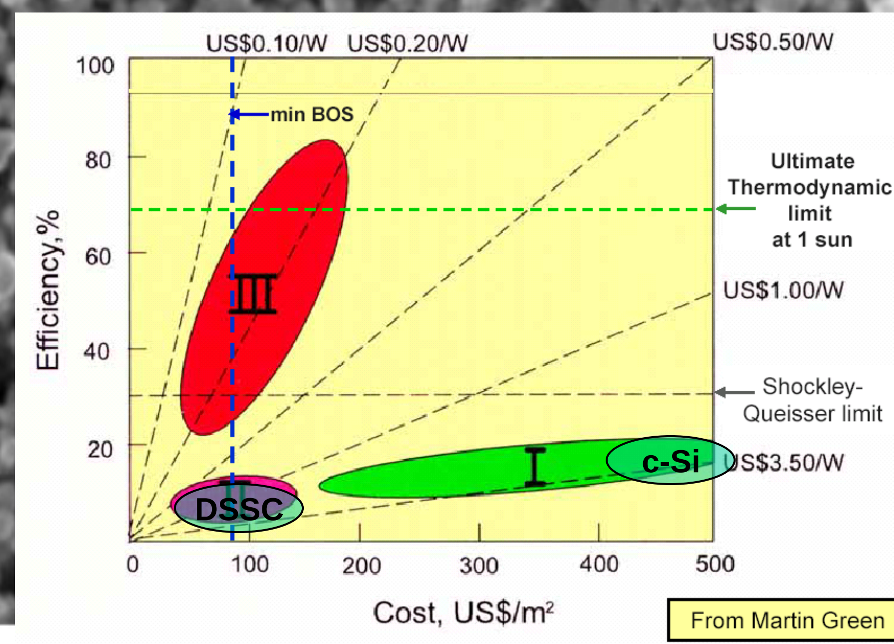




Dye-sensitized solar cell (DSSC) – Grätzel cell

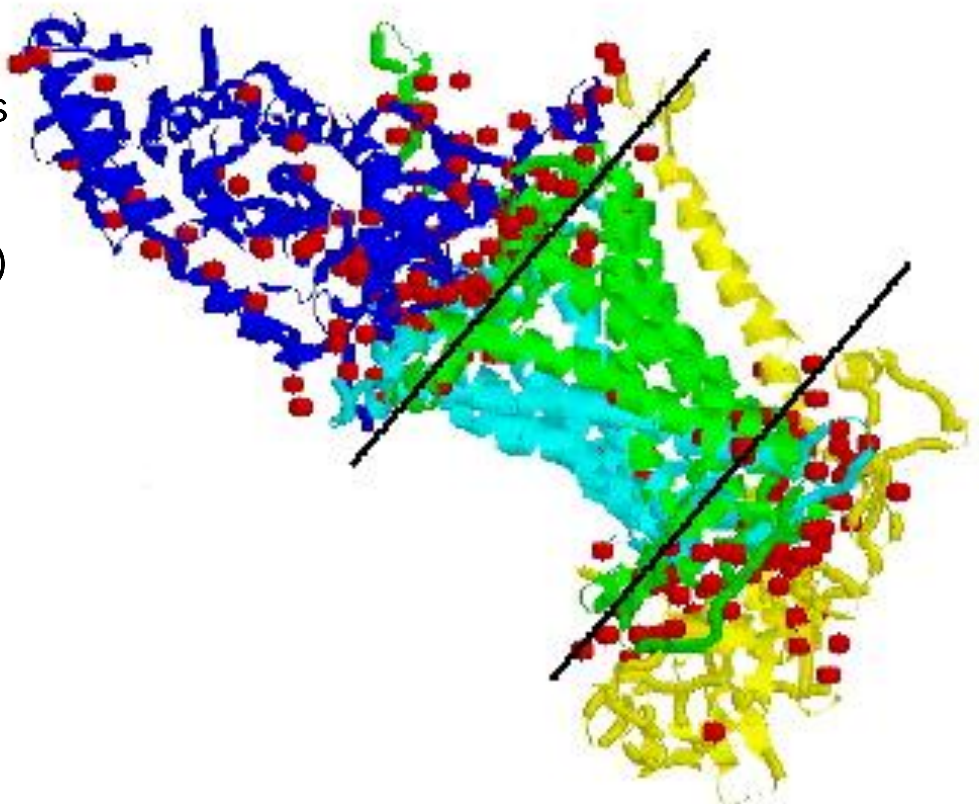




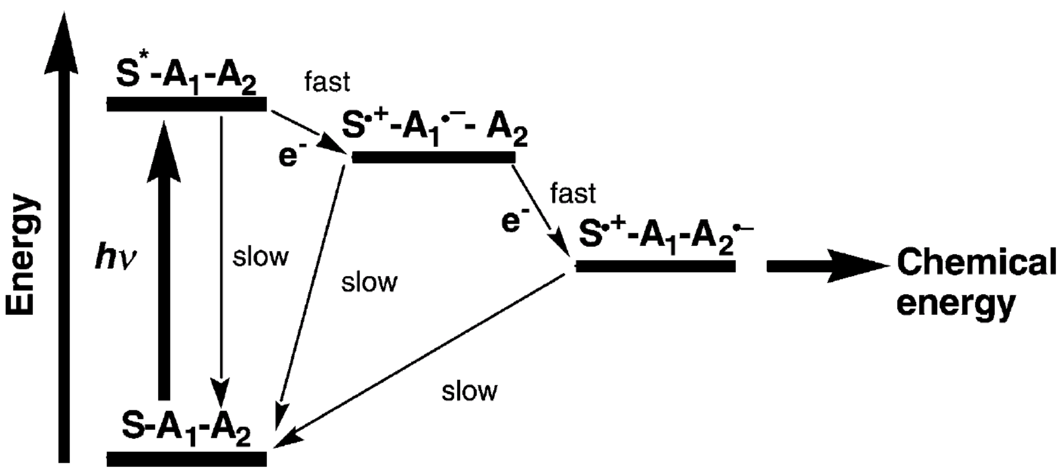


- Efficiency ~ 5 - 10%
- Liquid electrolyte

Photosynthesis



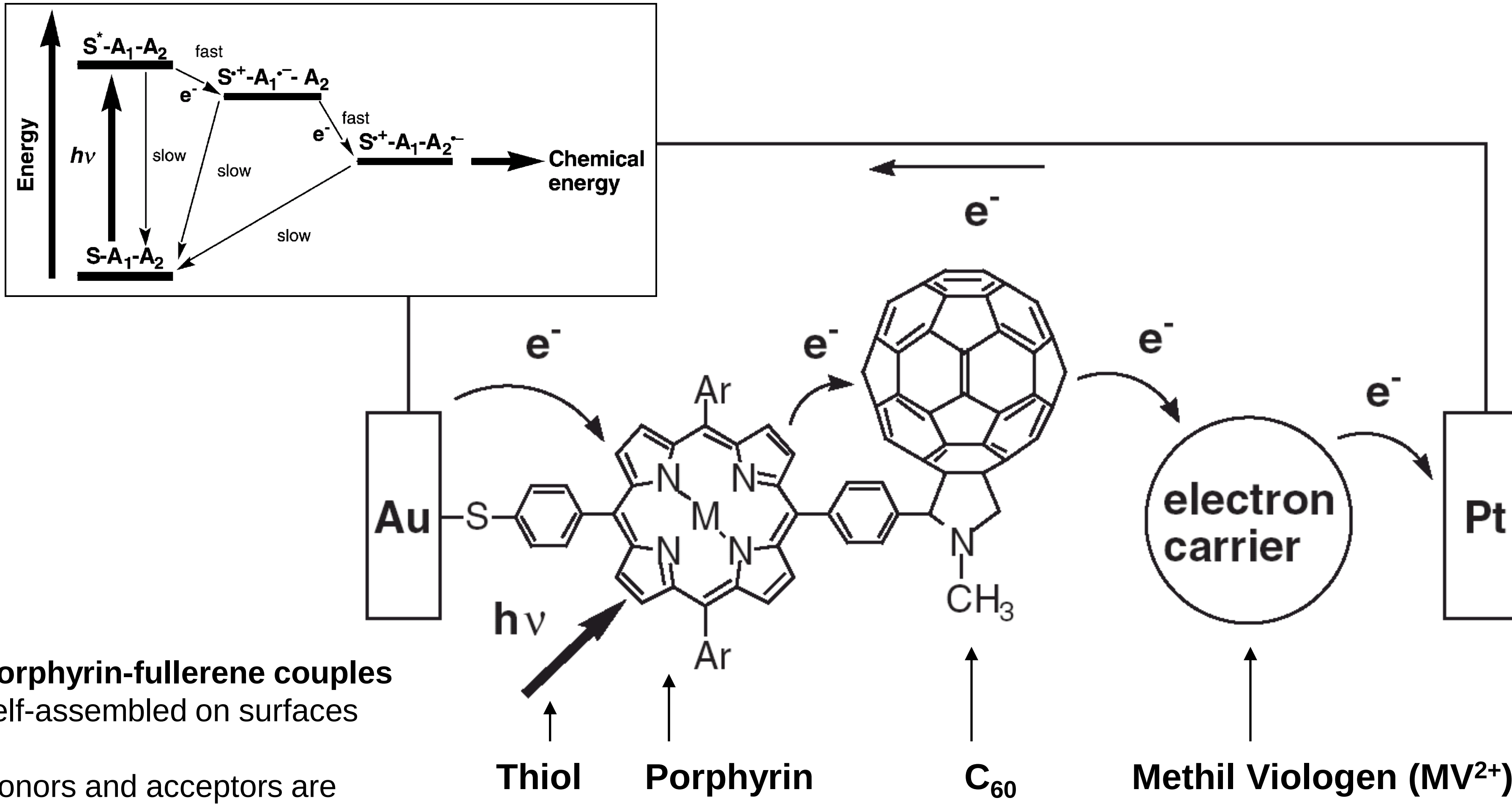
- Energy is absorbed by the *antenna* complexes
- Cascade of **energy** transfer between donors and acceptors embedded in antennas (FRET)
- Energy is funneled to the reaction center
- Subsequent multistep **electron** transfer
- This creates a charge-separated state which lasts for 10s of μs or more, with a ~100% QE



Limitations

- Absorption is only efficient at specific wavelenghts
- To reach the charge-separated state the electron needs to spend energy
- Energy converted in chemical energy ~ 9%

Artificial Photosynthesis: Basic Example



- **Porphyrin-fullerene couples** self-assembled on surfaces
- Donors and acceptors are bonded covalently

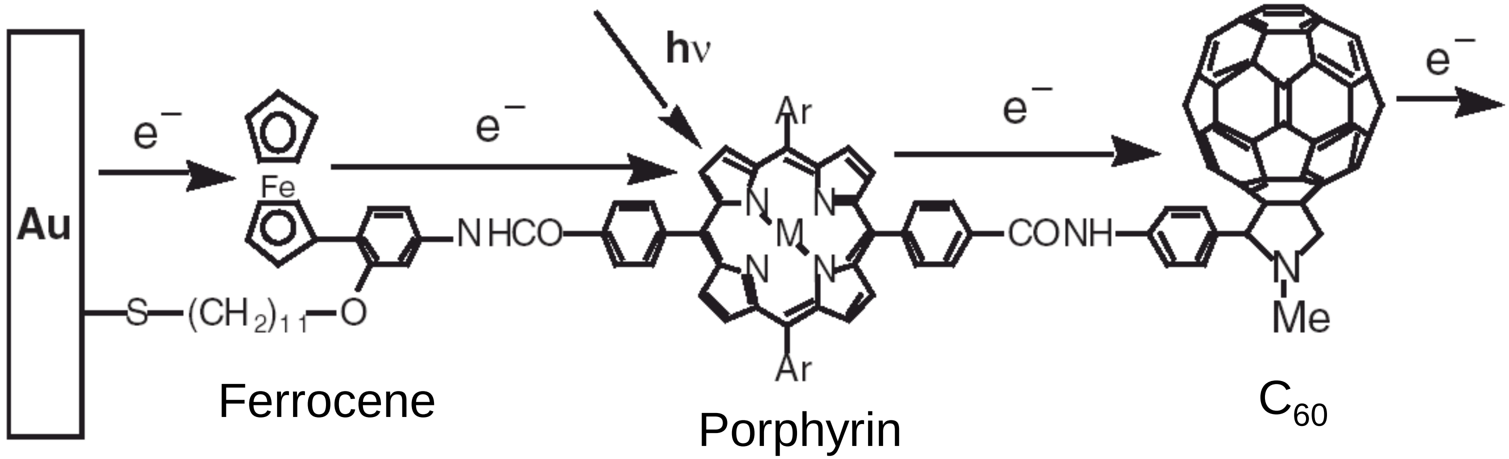
- **Quantum yield: 0.5%**
- **Lifetime 0.77 μs**
- **Loose packing on the surface**

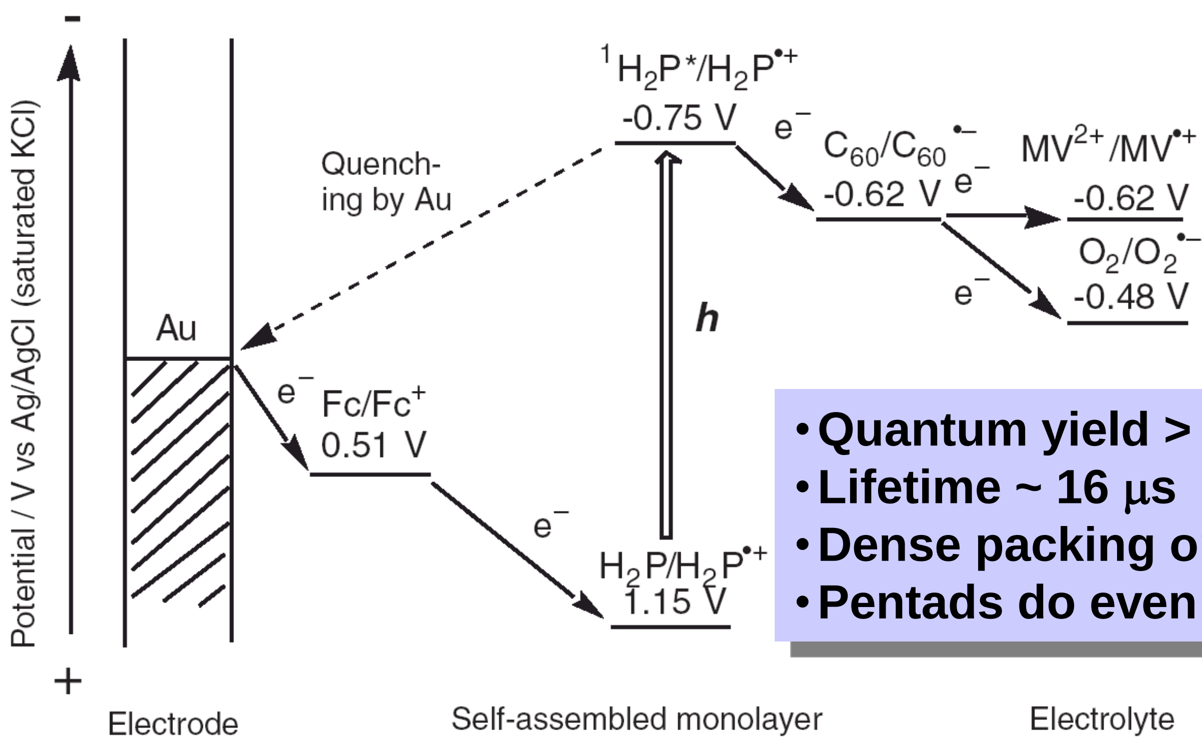
Artificial Photosynthesis Requirements

- Appropriate redox potentials and excitation energy for donors and acceptors (*quantum yield*)

- Small reorganization energy λ ($-\Delta G_{cs} \sim \lambda$ and $-\Delta G_{CR} >> \lambda$) to favor forward electron transfer (*charge separation time*)
    - Distance between donors and acceptors
    - Solvent characteristics
    - Vibrational modes of the molecules

Artificial Photosynthesis: A more efficient scheme

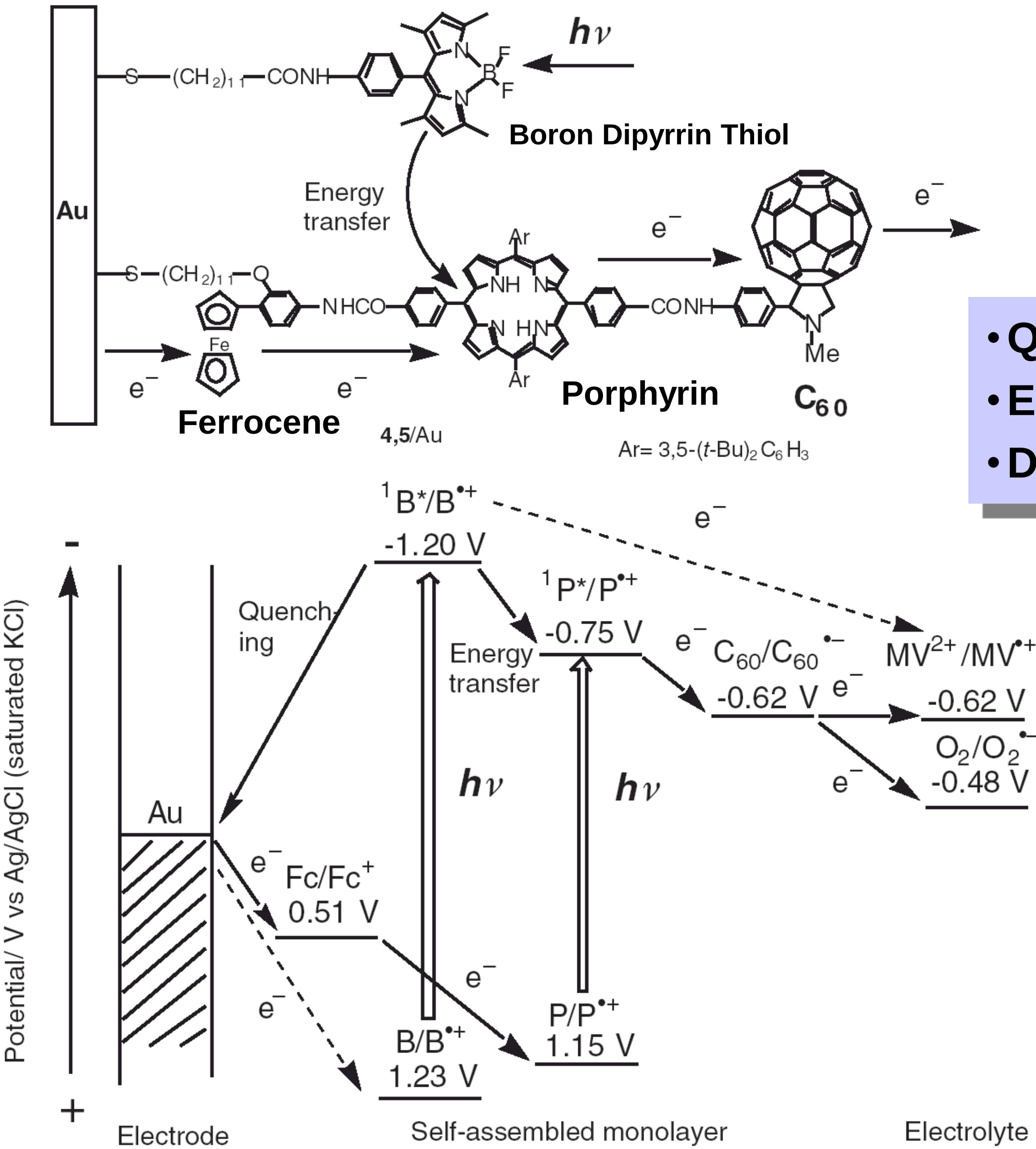




- **Quantum yield > 25%**
- **Lifetime ~ 16 μs**
- **Dense packing on the surface**
- **Pentads do even better**

H. Imahori et al., Adv. Func. Materials 14, 525 (2004)

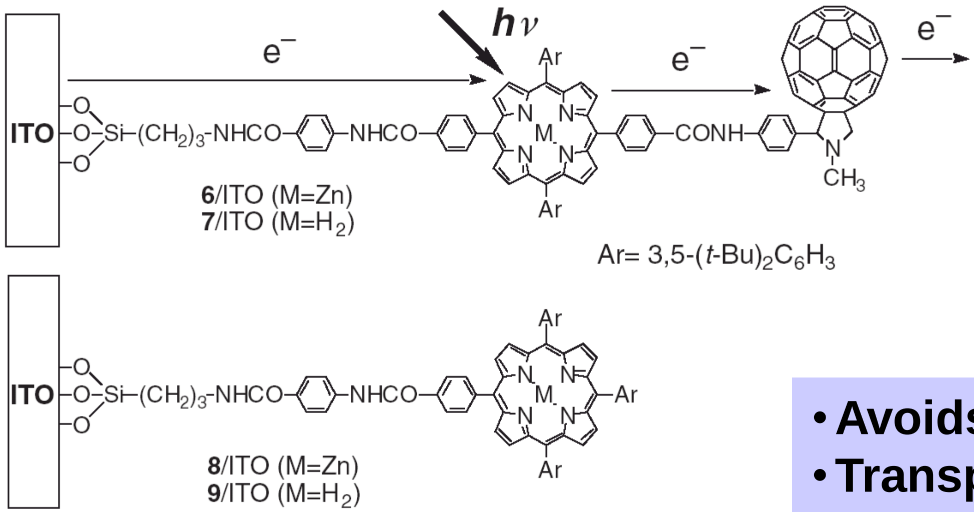
Artificial Photosynthesis: Mimicking energy transfer



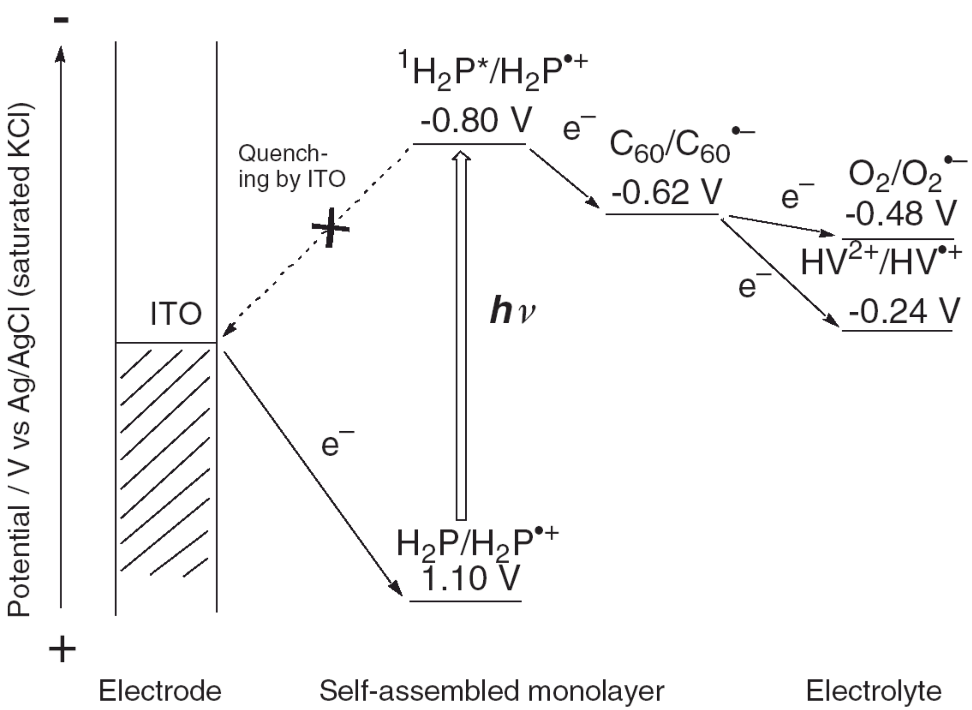
- **Quantum yield: up to 50%**
- **Enhanced spectral absorption**
- **Dense packing on the surface**

H. Imahori et al., Adv. Func. Materials 14, 525 (2004)

Artificial Photosynthesis on Transparent Conductive Oxide (ITO)

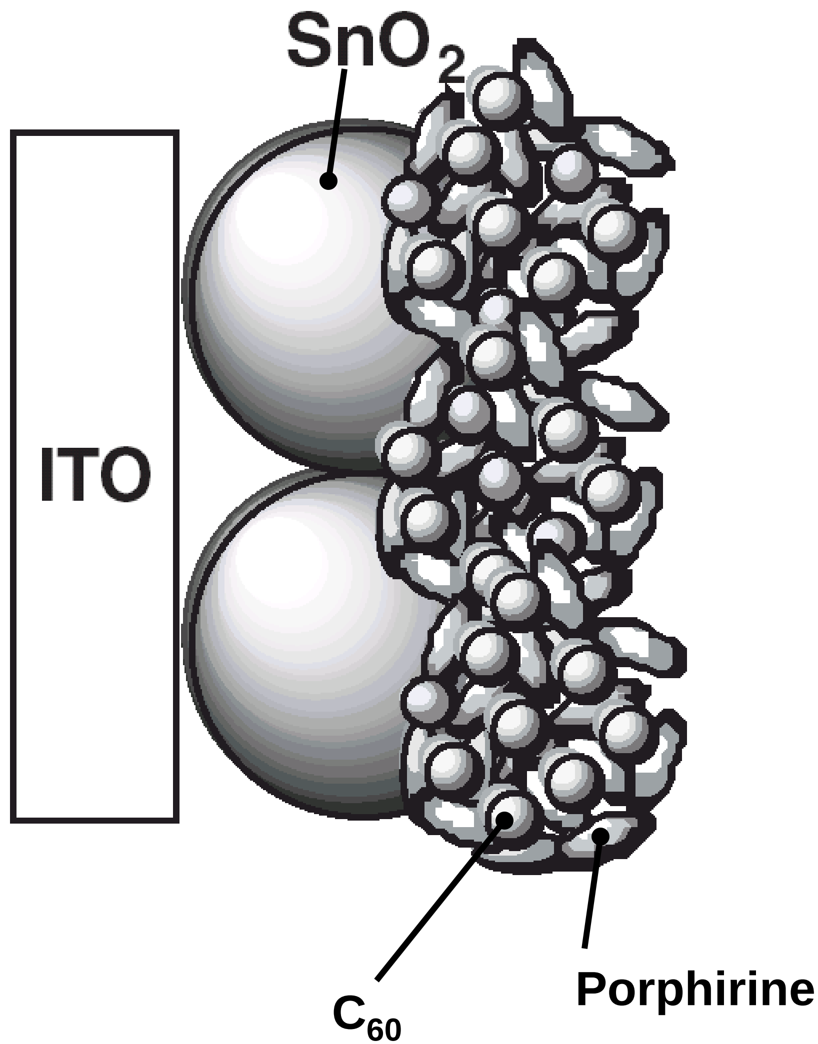


- **Avoids quenching by electrode**
- **Transparent substrate**



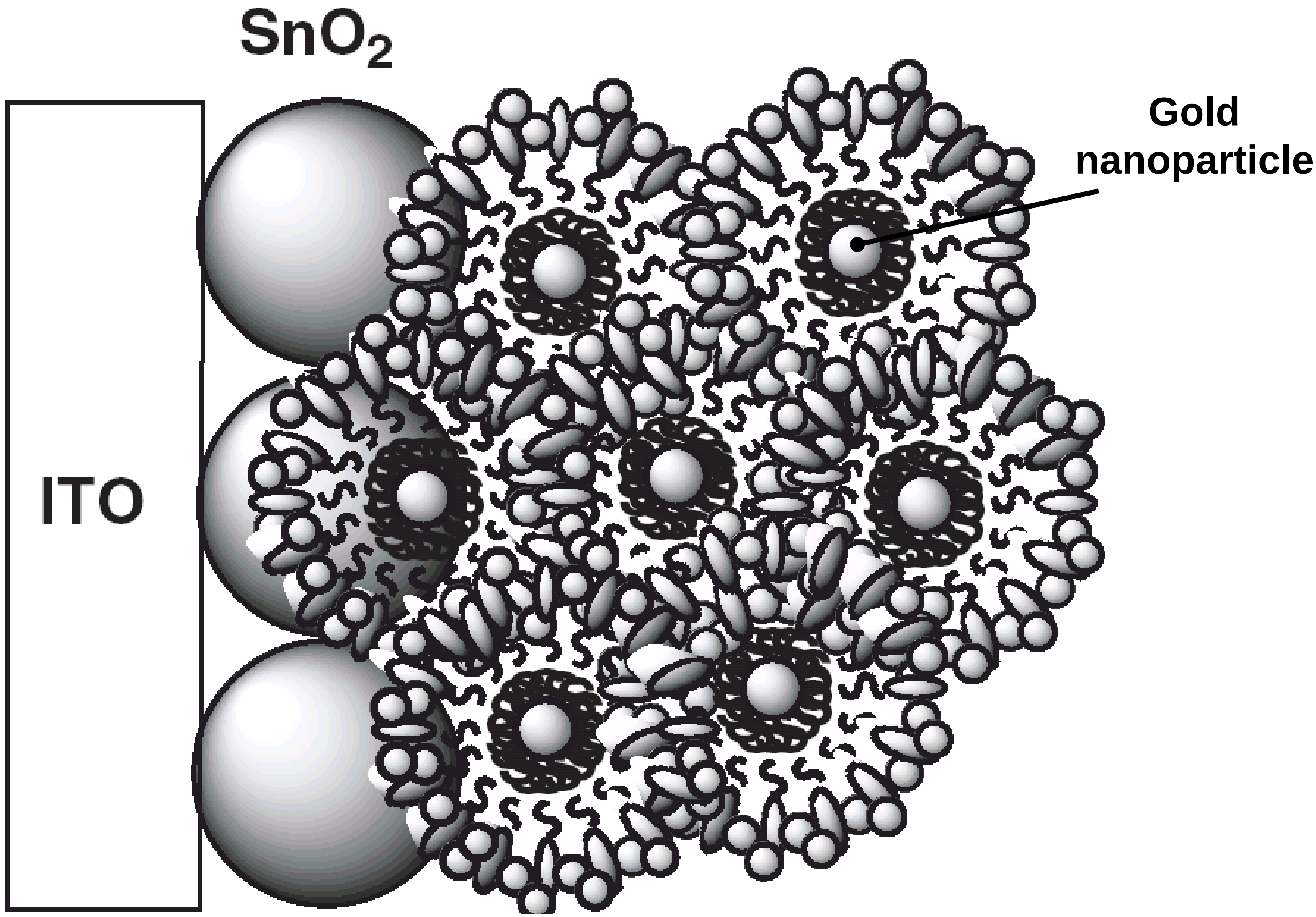
H. Imahori et al., Adv. Func. Materials 14, 525 (2004)

Artificial Photosynthesis:
Hierarchical assembly for enhancing absorption



H. Imahori et al., Adv. Func. Materials 14, 525 (2004)

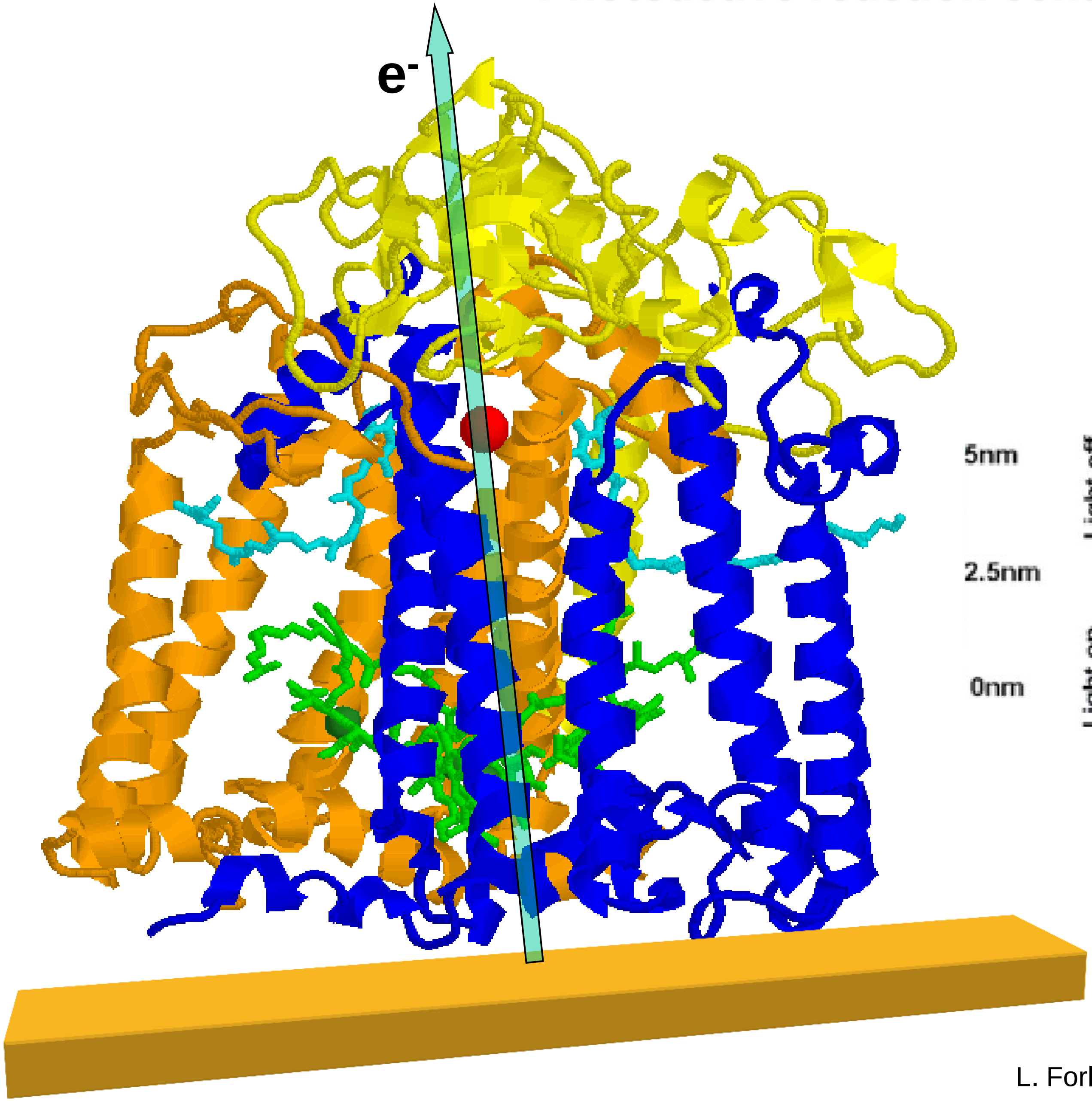
Artificial Photosynthesis:
Hierarchical assembly for enhancing absorption

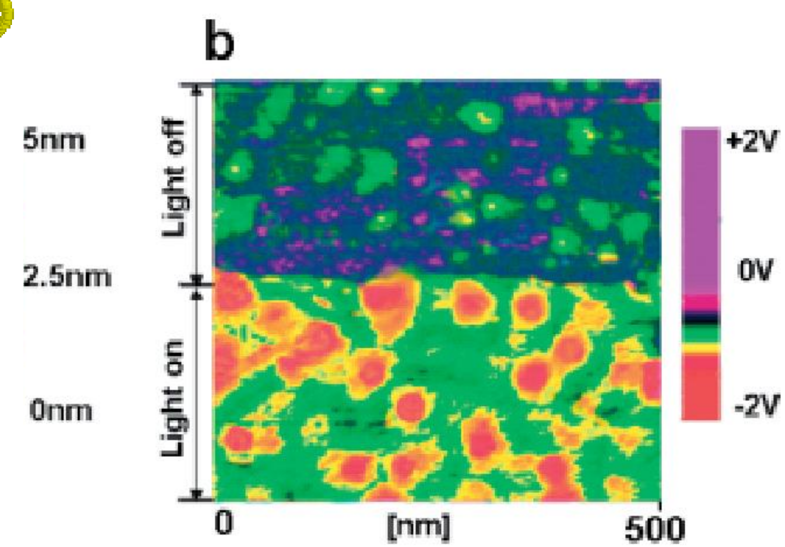


H. Imahori et al., Adv. Func. Materials 14, 525 (2004)

“Stealing” from Nature

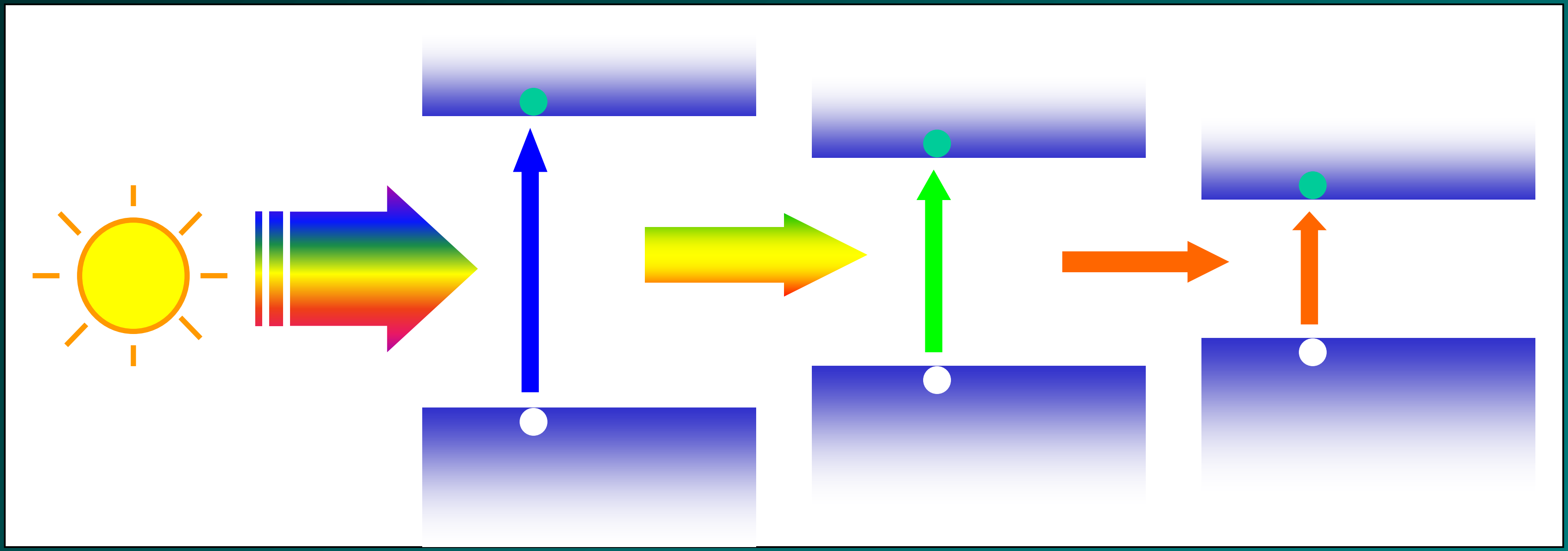
Photoactive reaction centers on metal substrates





L. Forlov et al., Adv. Materials 17, 2434 (2005)

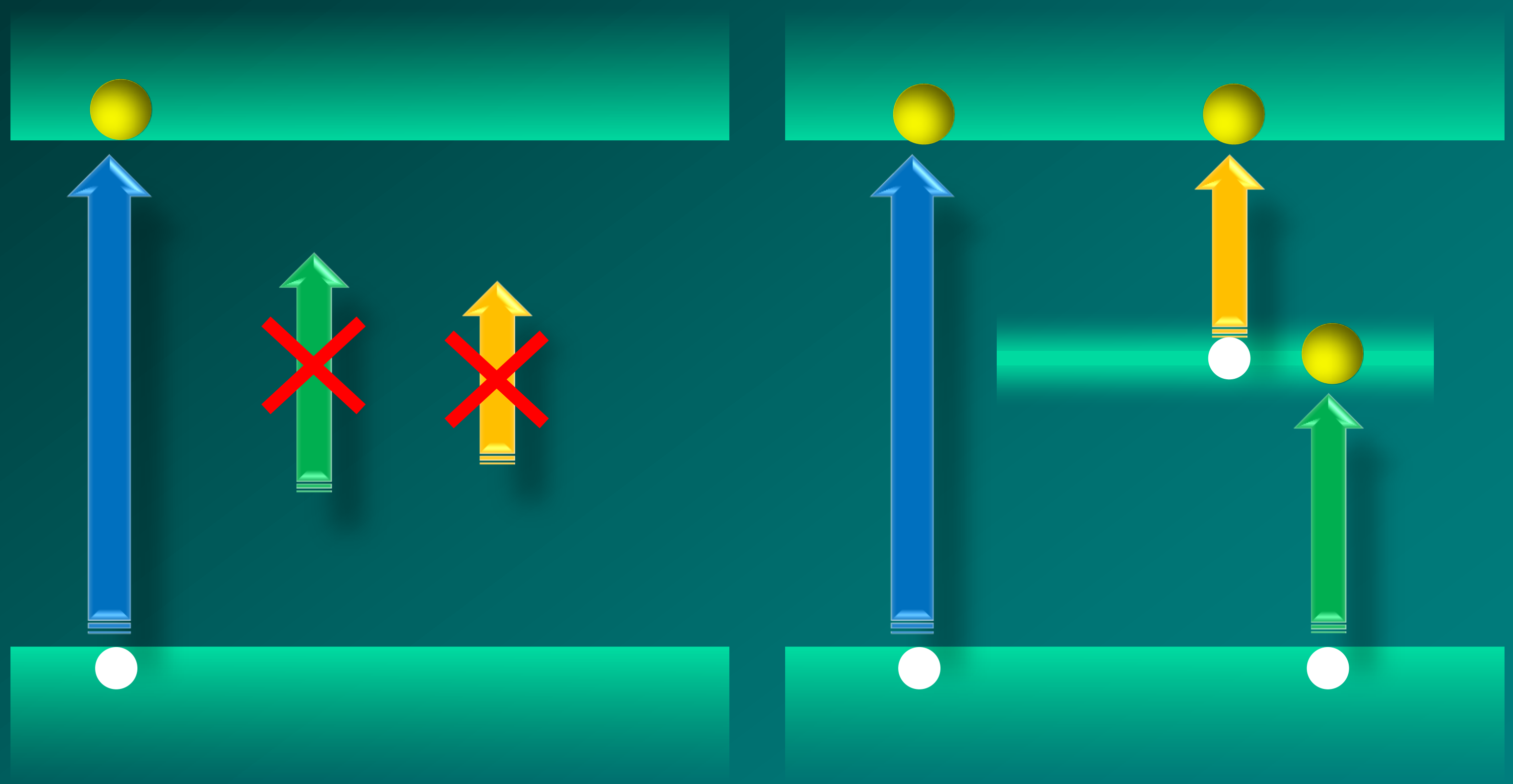
Beyond The Single Junction Limit: Tandem cells



More efficient use of the solar spectrum

Intermediate Band Materials

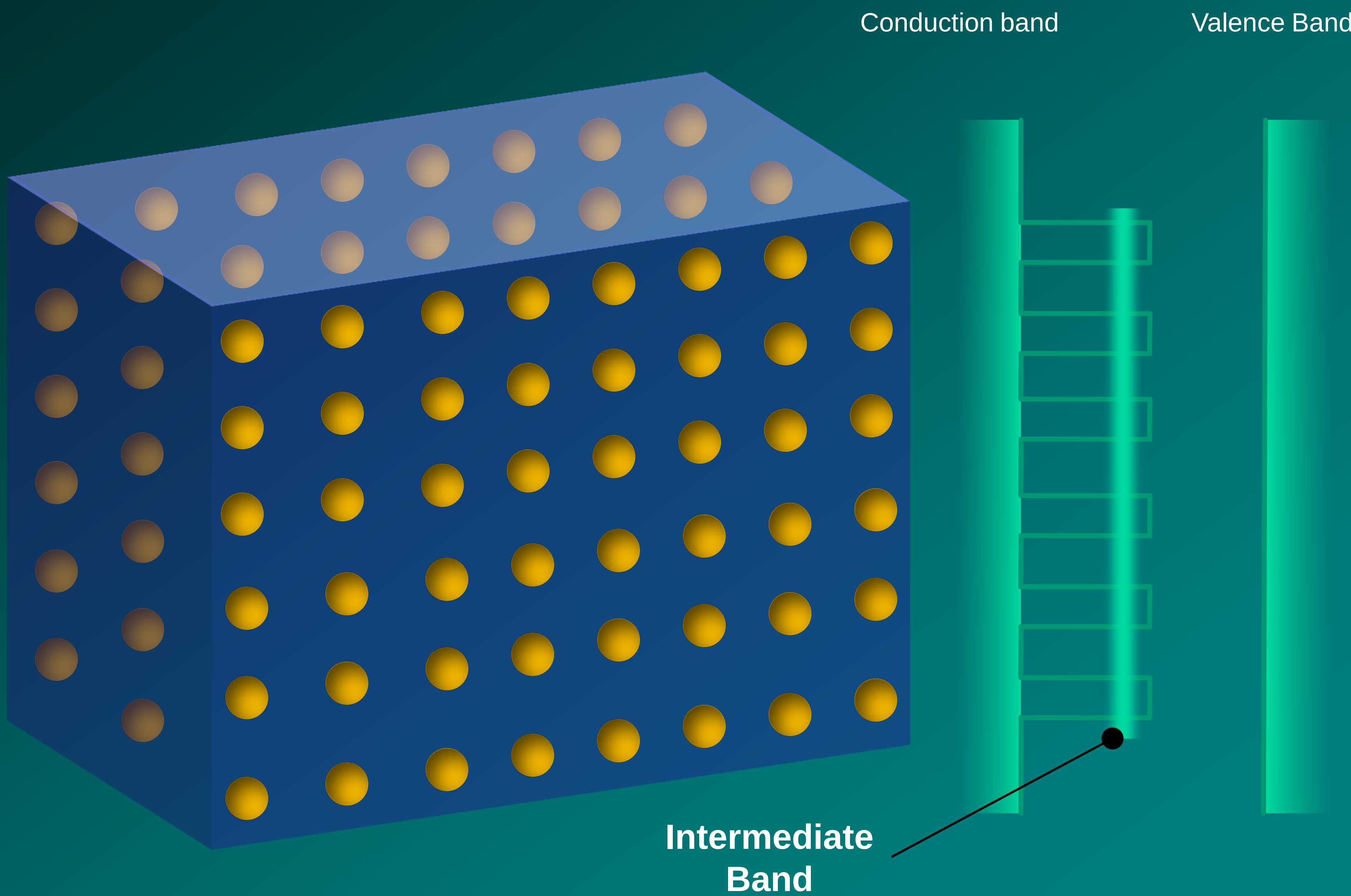
Beyond single junction limits (at low cost!)



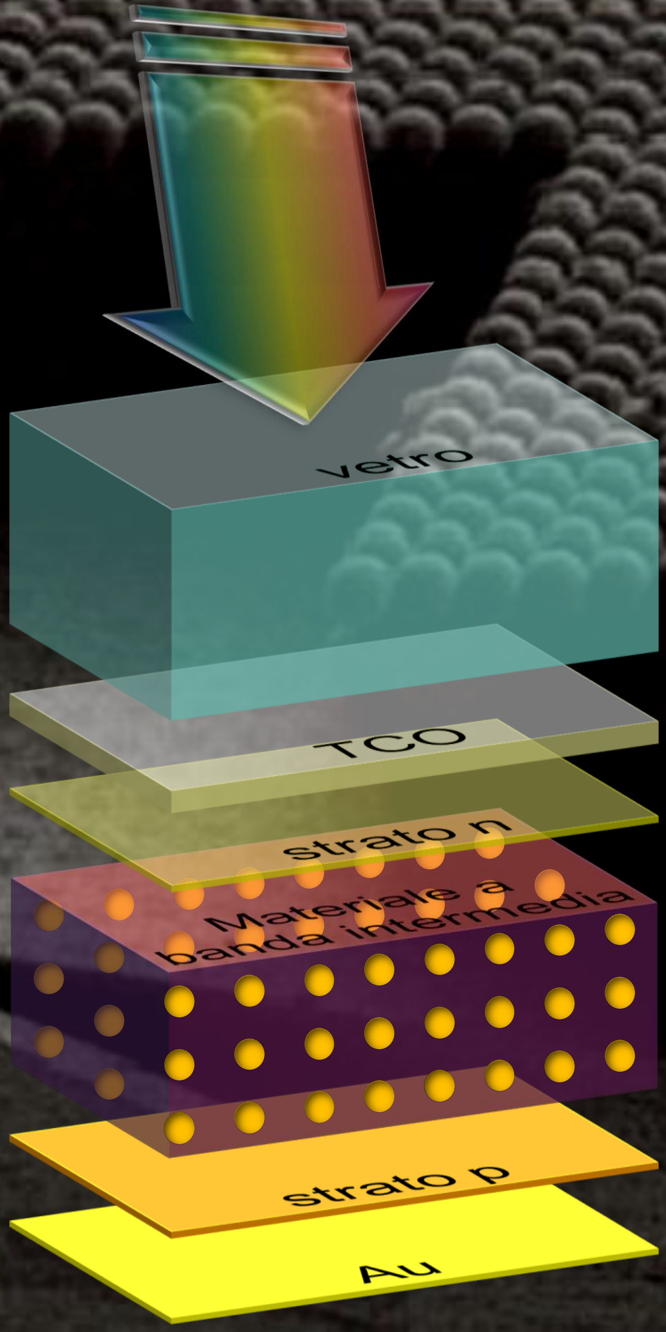
Making an Intermediate Band Material

Quantum dots embedded in a semiconductor

Nanotechnology at the service of PV



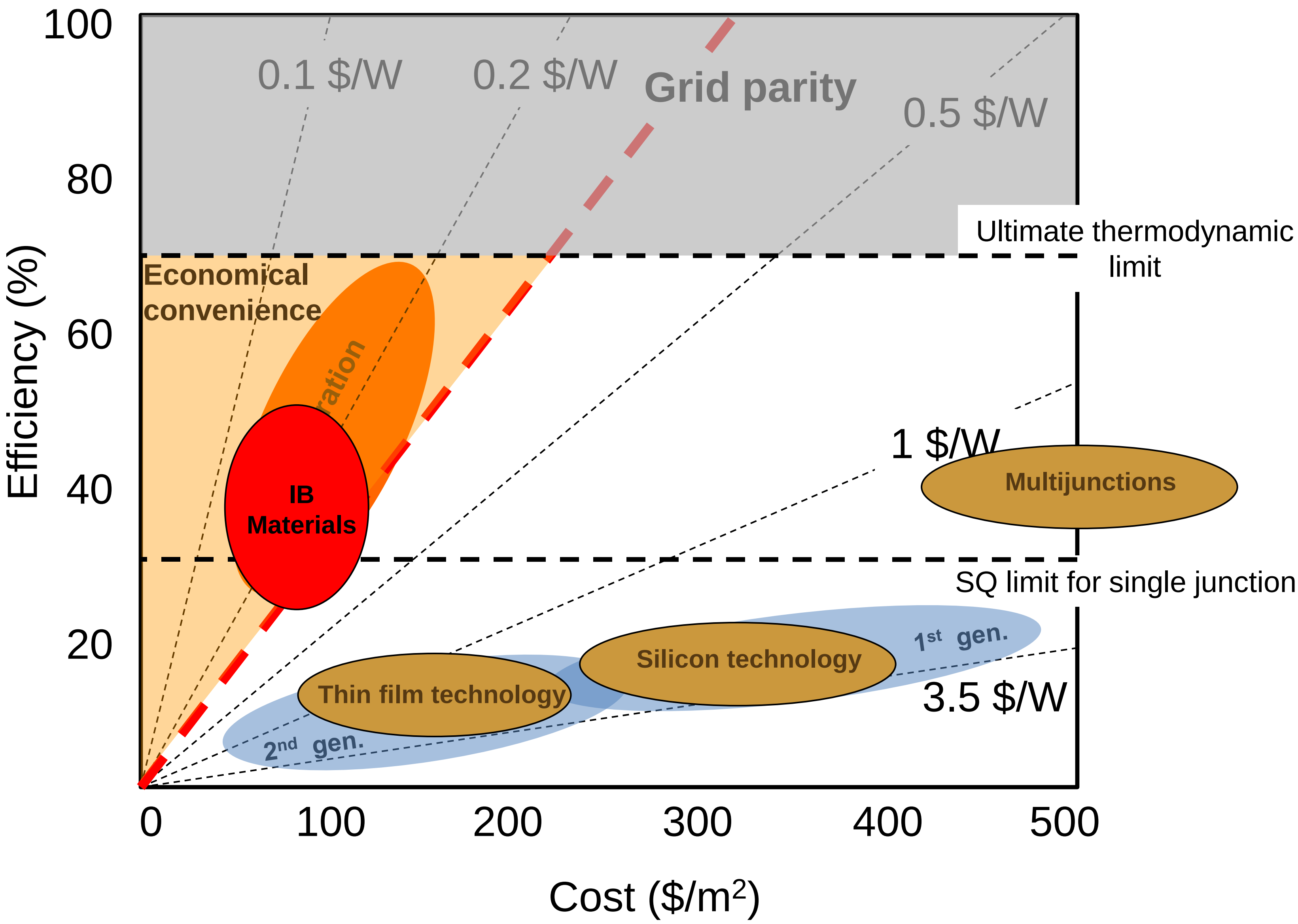
Photovoltaic Devices Based on Intermediate Band Materials

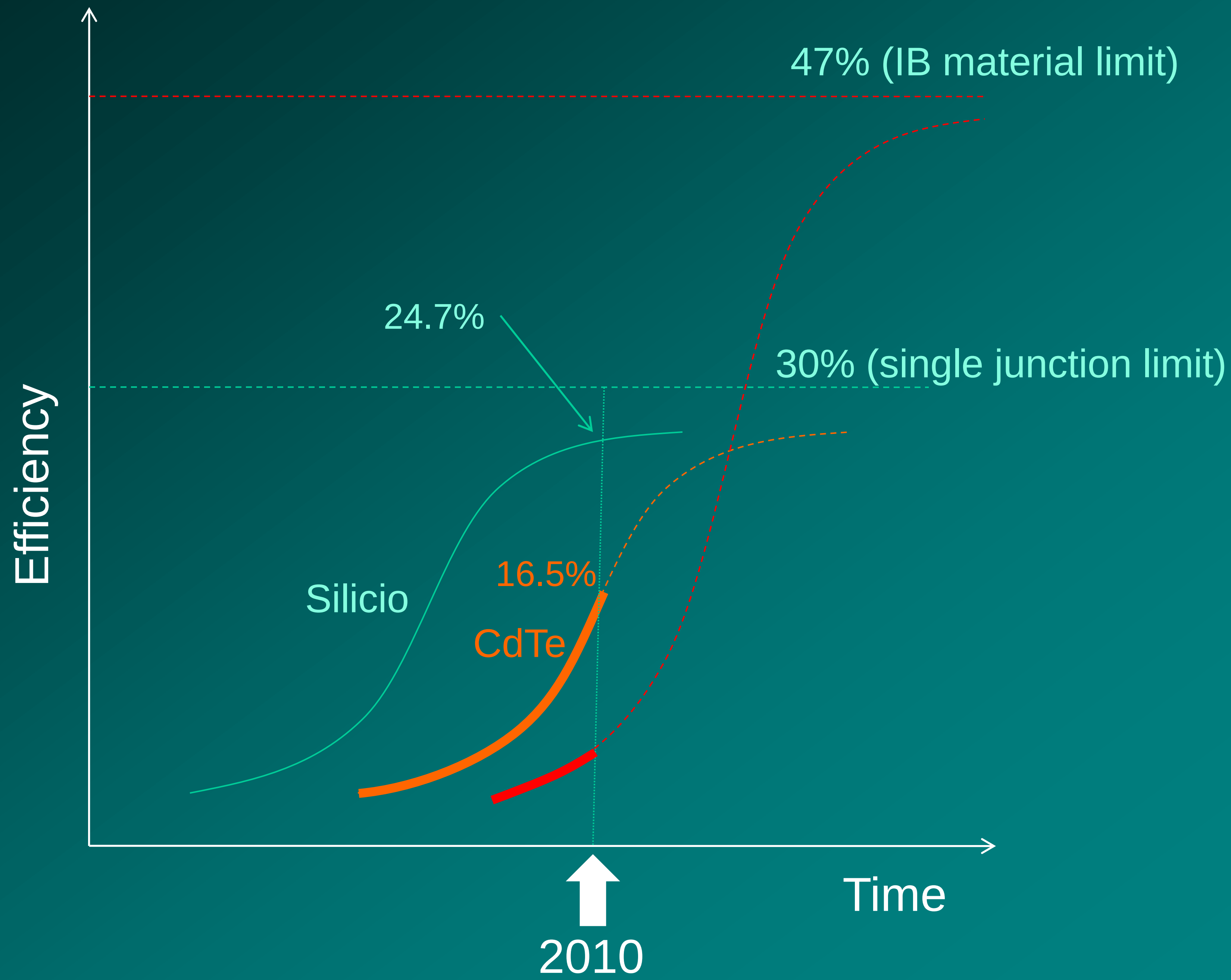


- Max efficiency 47%
- Current record for single-junction cell: 28.3%
- Scalable, low-cost production approaches
- Diversity of substrates – excellent integration (nanoinks and photovoltaic “paints”)

Tecno-Economical Evolution

- Cost and Efficiency – PV Figures of Merit -




47% (IB material limit)
24.7%
30% (single junction limit)
Efficiency
16.5%
Silicio
CdTe
Time
2010

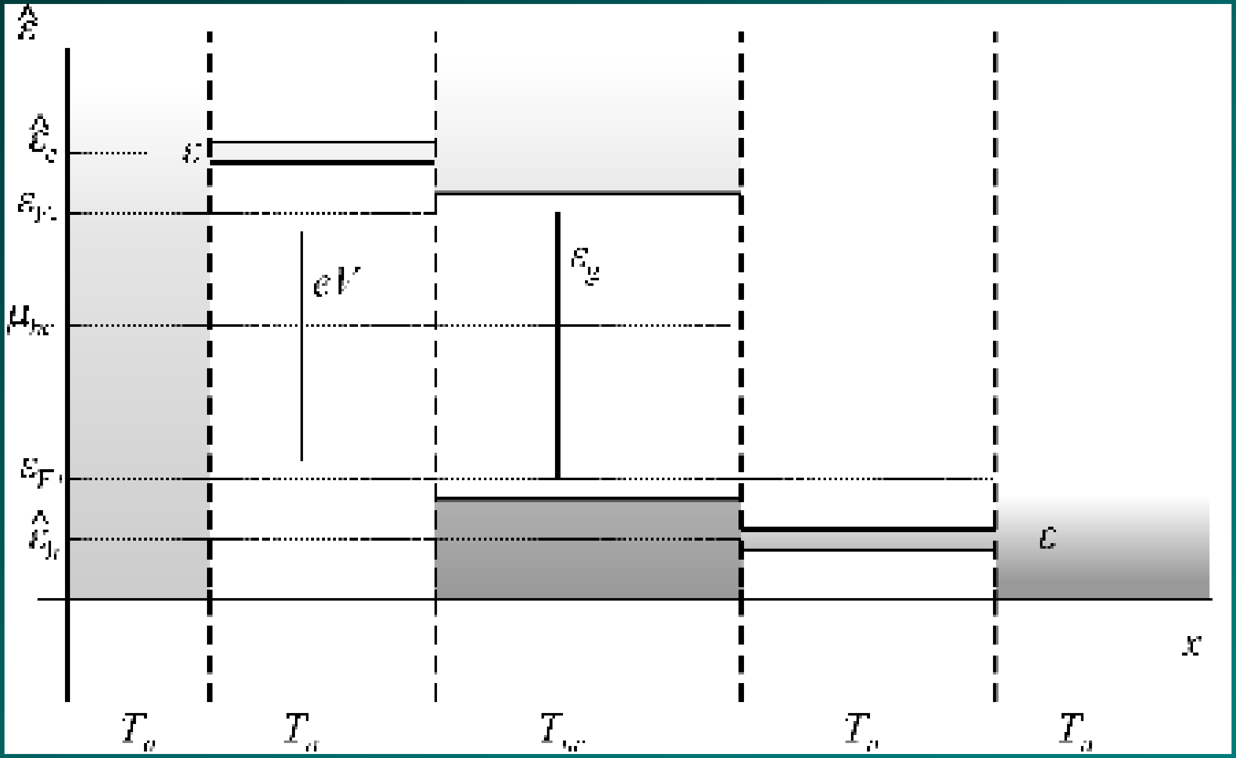
Beyond The Single Junction Limit: Other approaches

- Multiple carrier generation

  using high energy photons to extract more than one electron per photon

- Hot electron extraction

  extracting high energy photogenerated electrons before they thermalize



Thermodynamic limiting efficiency (both cases): 86.8%

Properties of nanomaterials

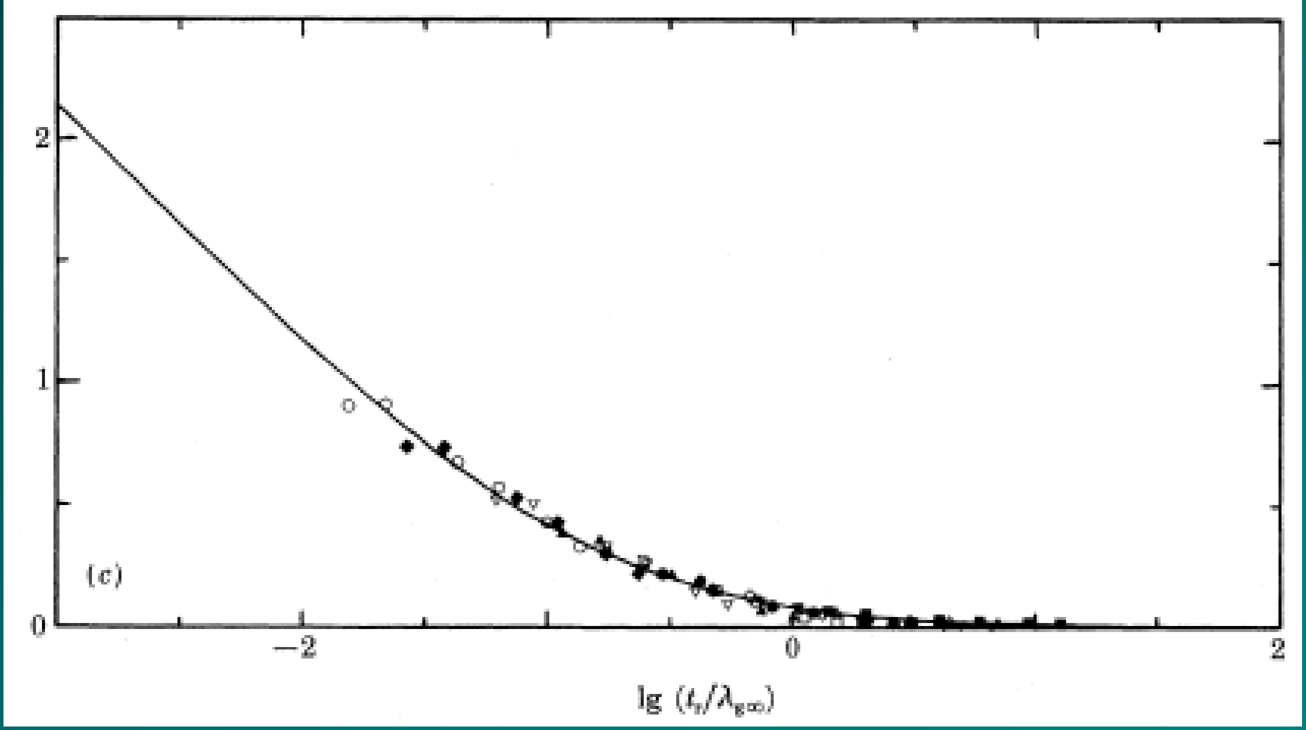
Phenomena at the nanoscale
are governed by the laws of quantum mechanics.

→ new opportunities for controlling material properties

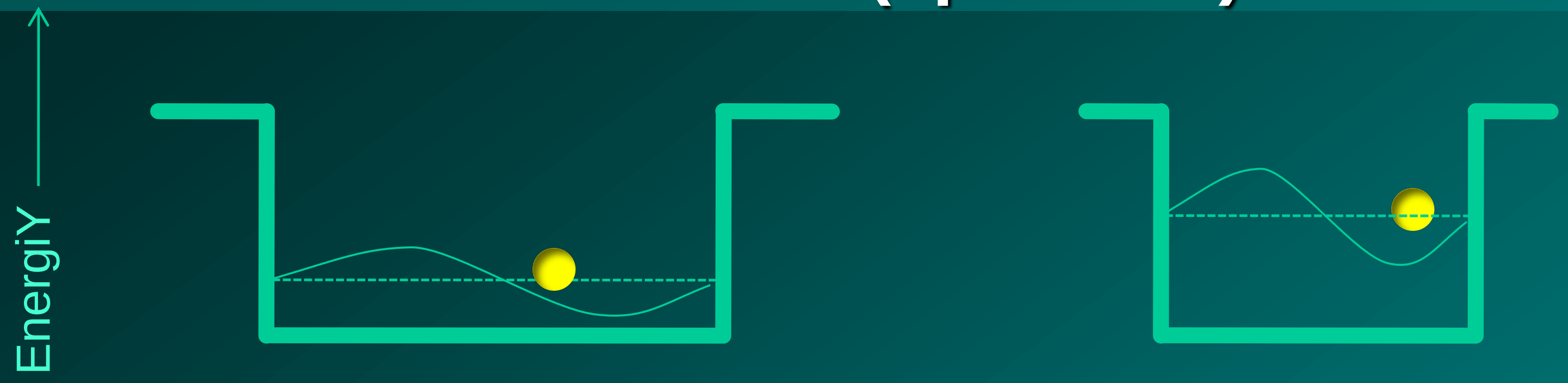
Phenomena that govern optoelectronic properties of materials
occur at the nanoscale

Properties of nanomaterials
What does "nano" mean?

A material is "nano" when
a selected property starts to differ from its bulk behavior



Electrons in a (spherical) box



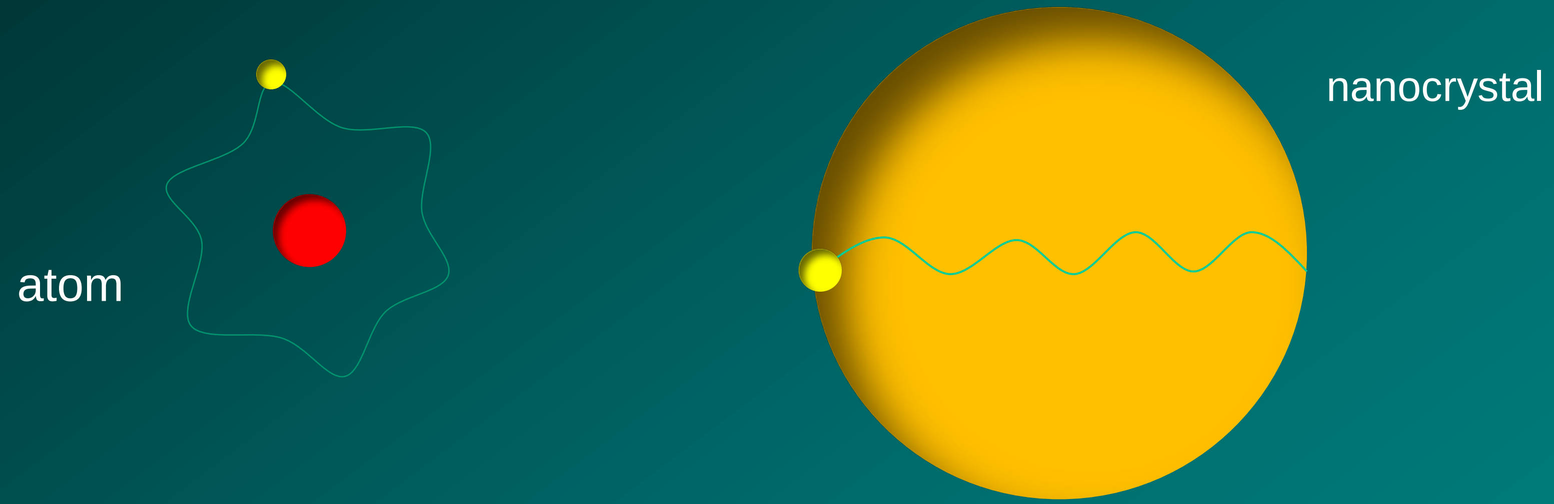
$$E = \frac{\hbar^2 \pi^2}{2 m_e R^2} n^2 \qquad n = 1, 2, 3, \ldots$$

- Electrons can be described by waves
- Confined waves can only have a discrete set of wavelengths

⇨ In confined systems, electrons can only assume discrete values of energy

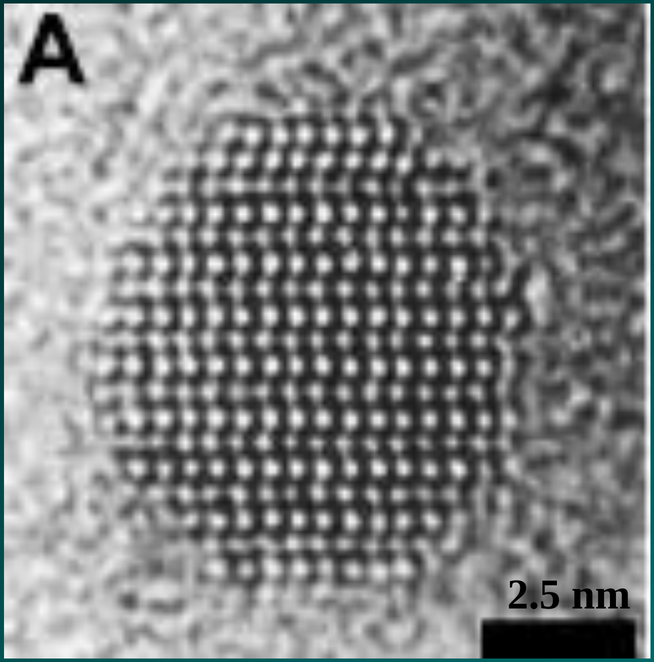
Position of energy levels depends upon confinement (size of the box)

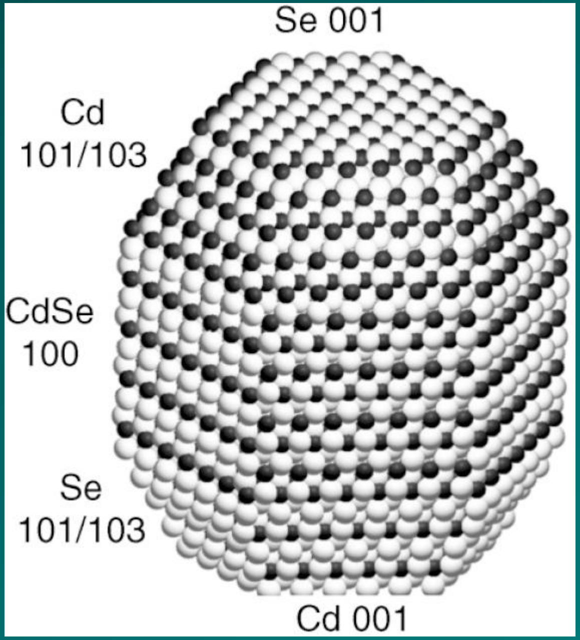
Quantum Dots
"Artificial atoms"



As for atoms, quantum dots have discrete electron energy levels

Nanocrystals





Typical size: 1 – 100 nm (10^2 - 10^5 atoms)
Most atoms are at the surface (75% for 1 nm nanocrystals)
Essentially free of lattice defects

Nanocrystals

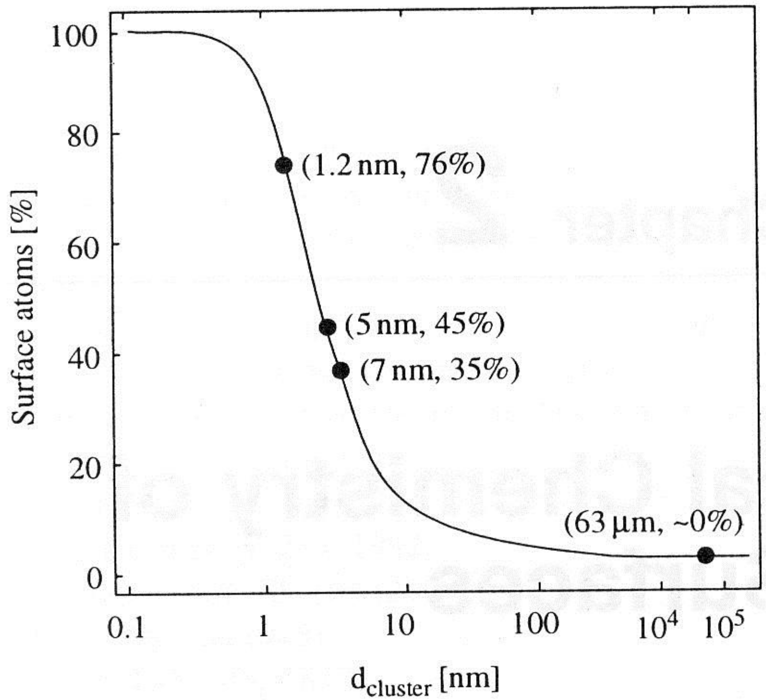
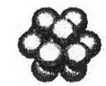
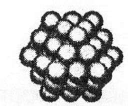
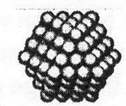
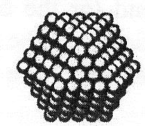
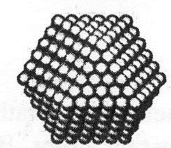
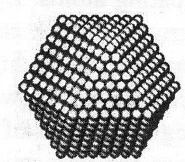
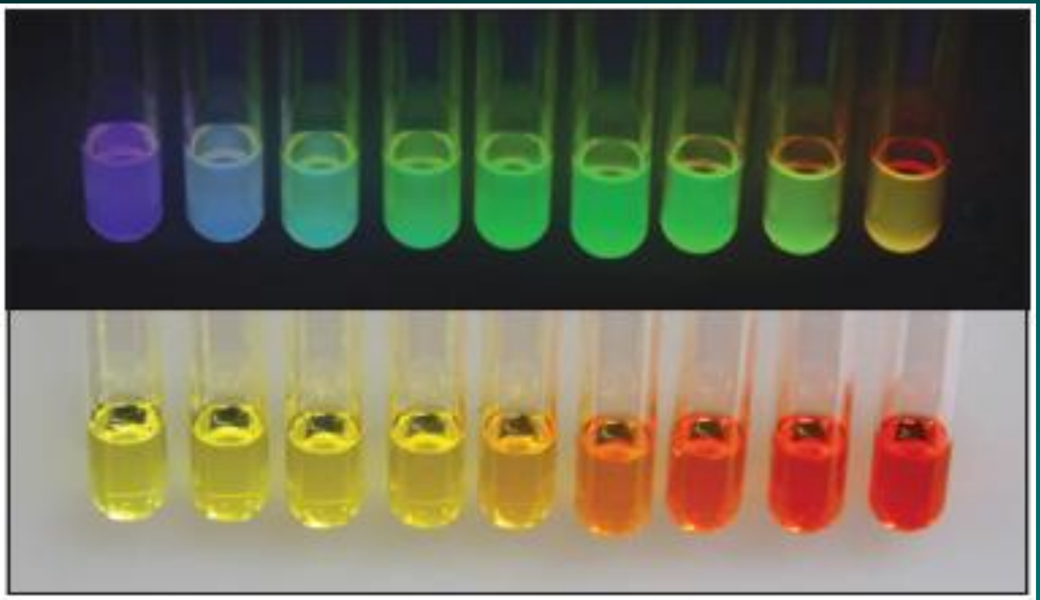


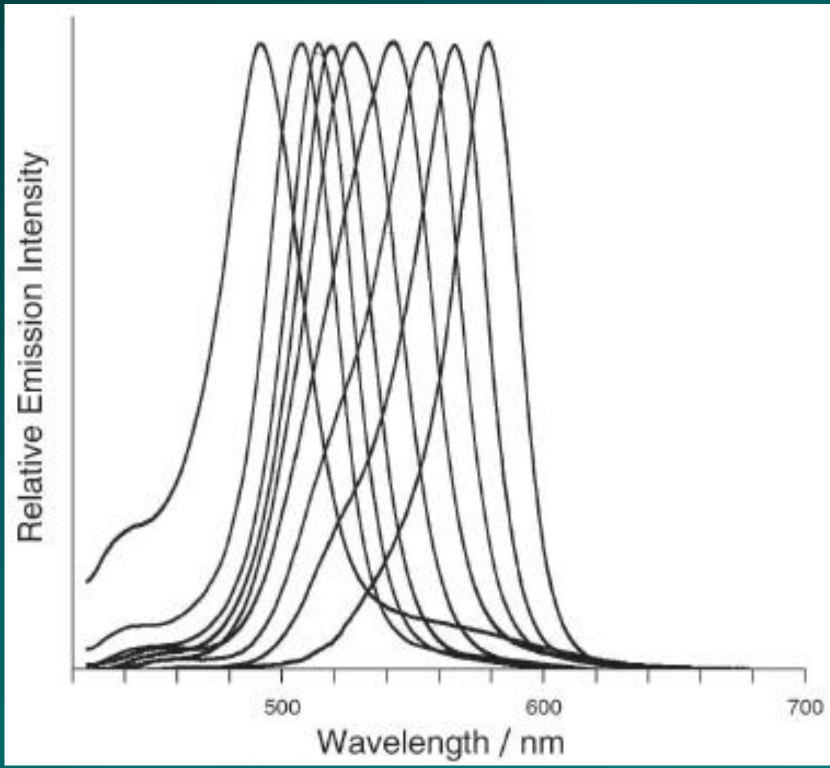
Fig. 2.1. The percentage of surface atoms changes with the palladium cluster
[C. Nützenadel, A. Züttel, D. Chartouni, G. Schmid, and L. Schlapbach, *Eur. Pi*
245 (2000).]

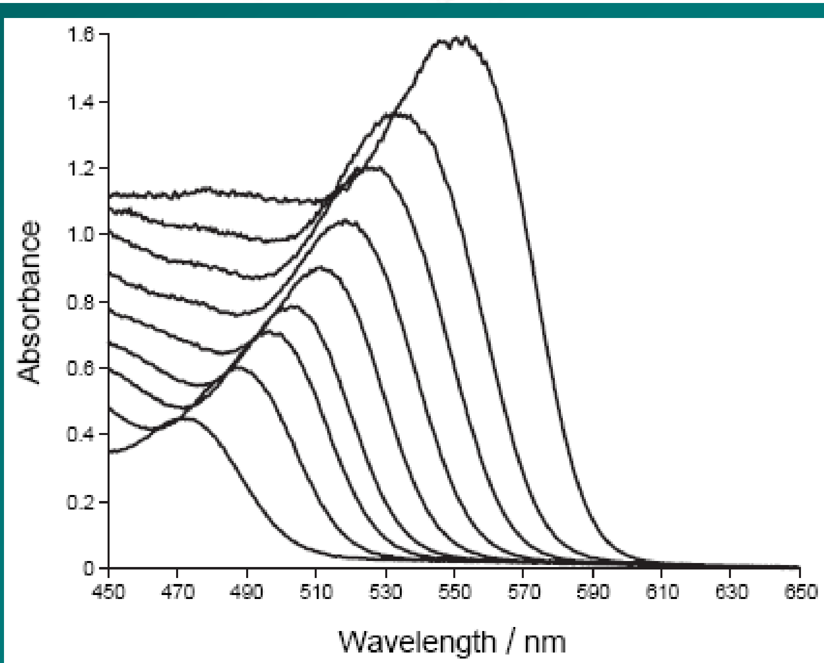
TABLE 2.1 The relation between the total number of atoms in fu shell clusters and the percentage of surface atoms

Full-shell Clusters		Total Number of Atoms	Surface Ator (%)
1 Shell		13	92
2 Shells		55	76
3 Shells		147	63
4 Shells		309	52
5 Shells		561	45
7 Shells		1415	35

Semiconductor nanocrystals (quantum dots): Optical properties



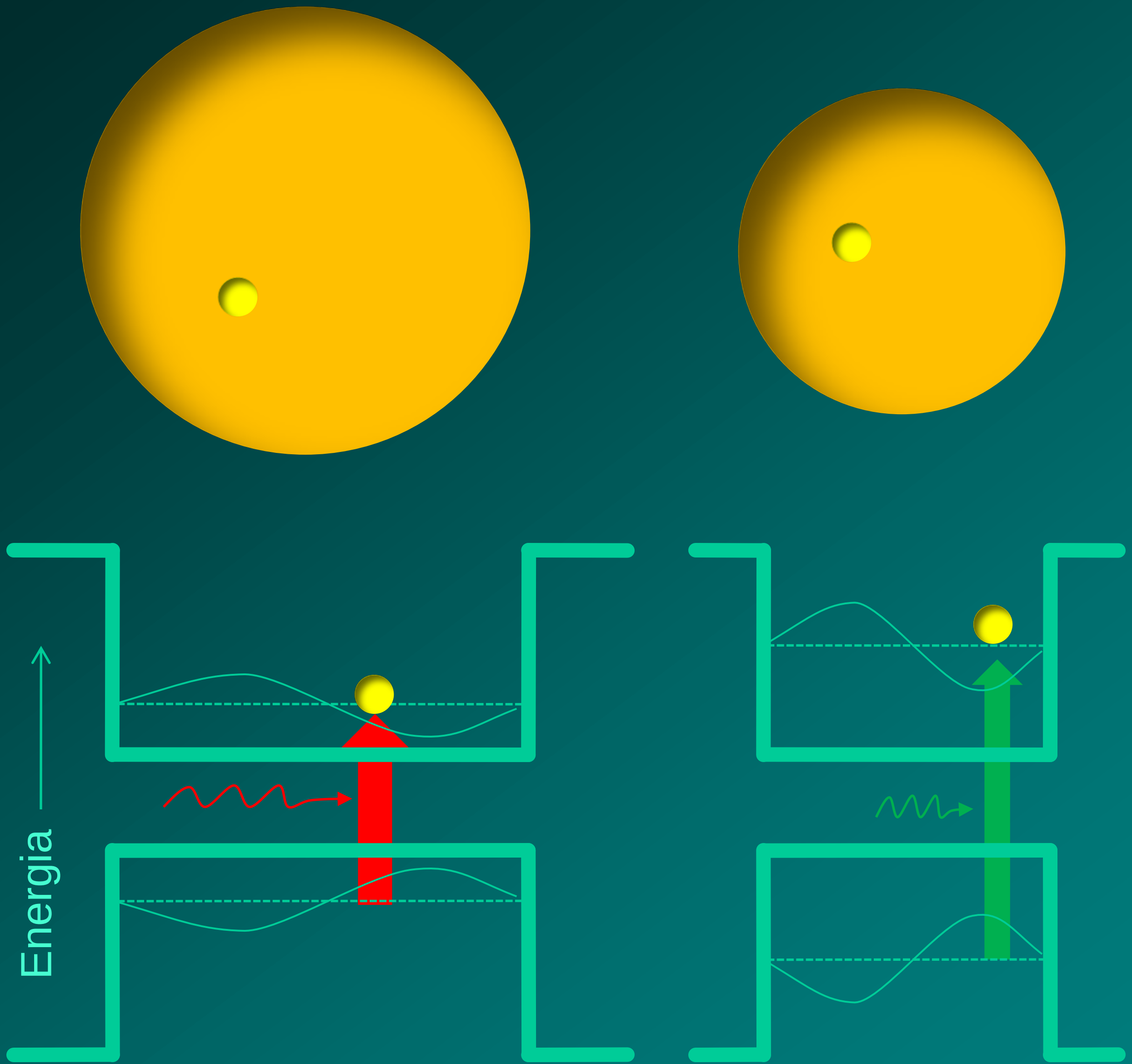


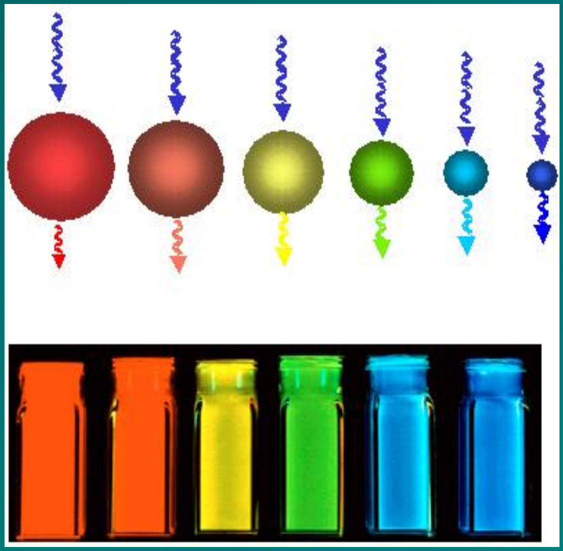


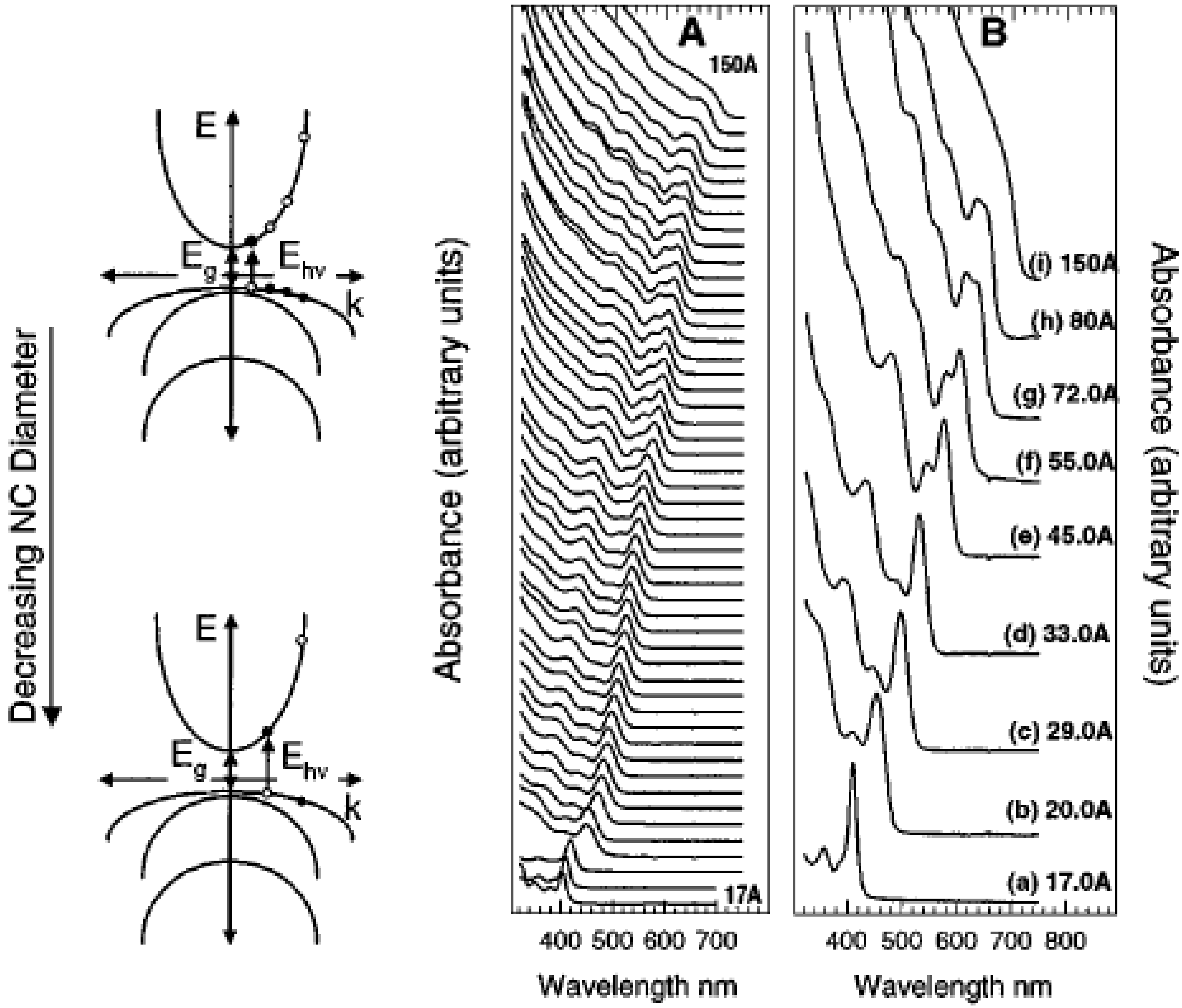
Quantum dot absorption and emission

Dependence on size

$$E_g(Q.D.) = E_{g0} + \frac{\hbar^2 \pi^2}{2 m_{eh} R^2}$$

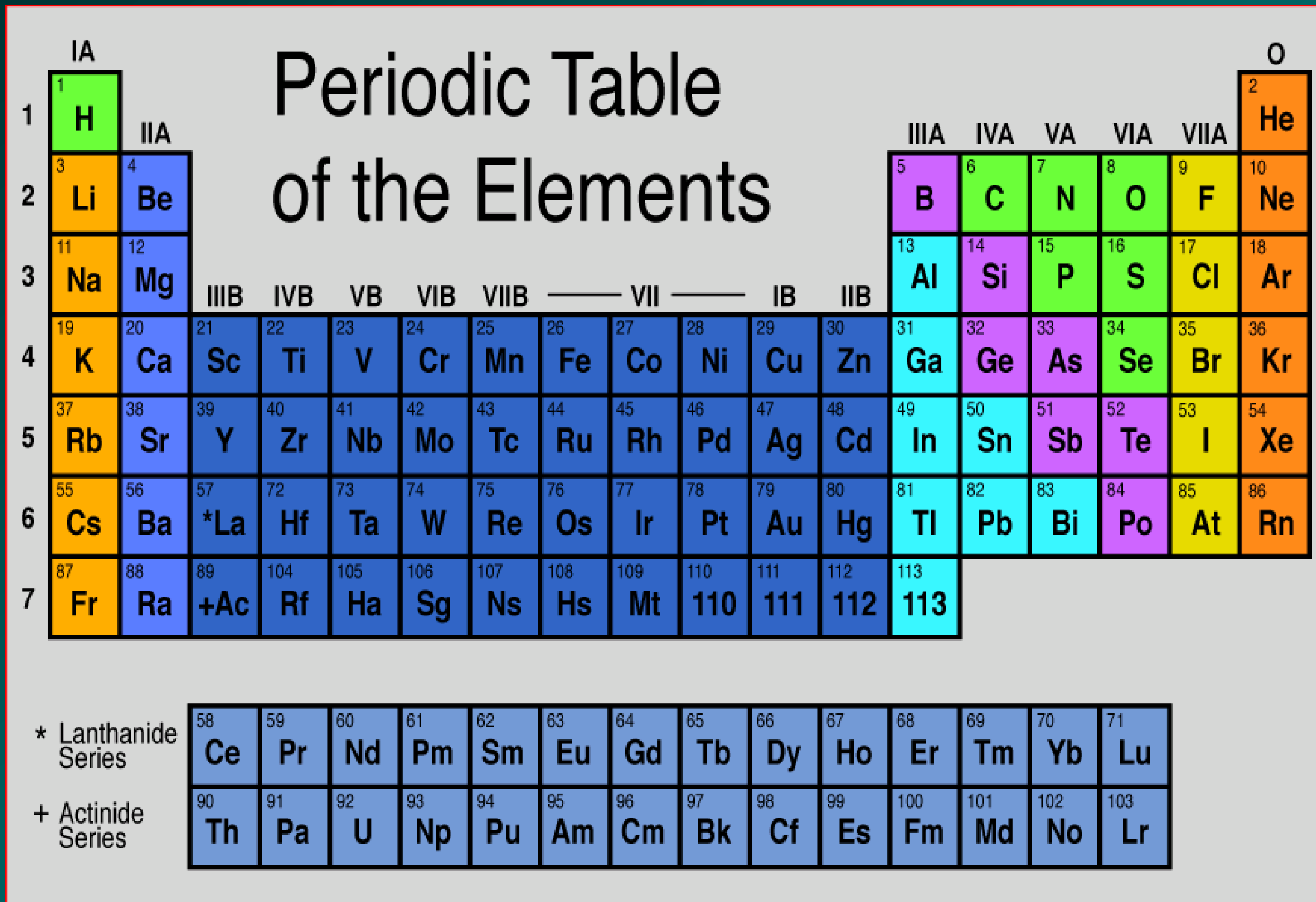






Decreasing NC Diameter
E
E_g
E_{hv}
k
E
E_g
E_{hv}
k
Absorbance (arbitrary units)
A
150A
17A
400 500 600 700
Wavelength nm
B
(i) 150A
(h) 80A
(g) 72.0A
(f) 55.0A
(e) 45.0A
(d) 33.0A
(c) 29.0A
(b) 20.0A
(a) 17.0A
400 500 600 700 800
Wavelength nm
Absorbance (arbitrary units)

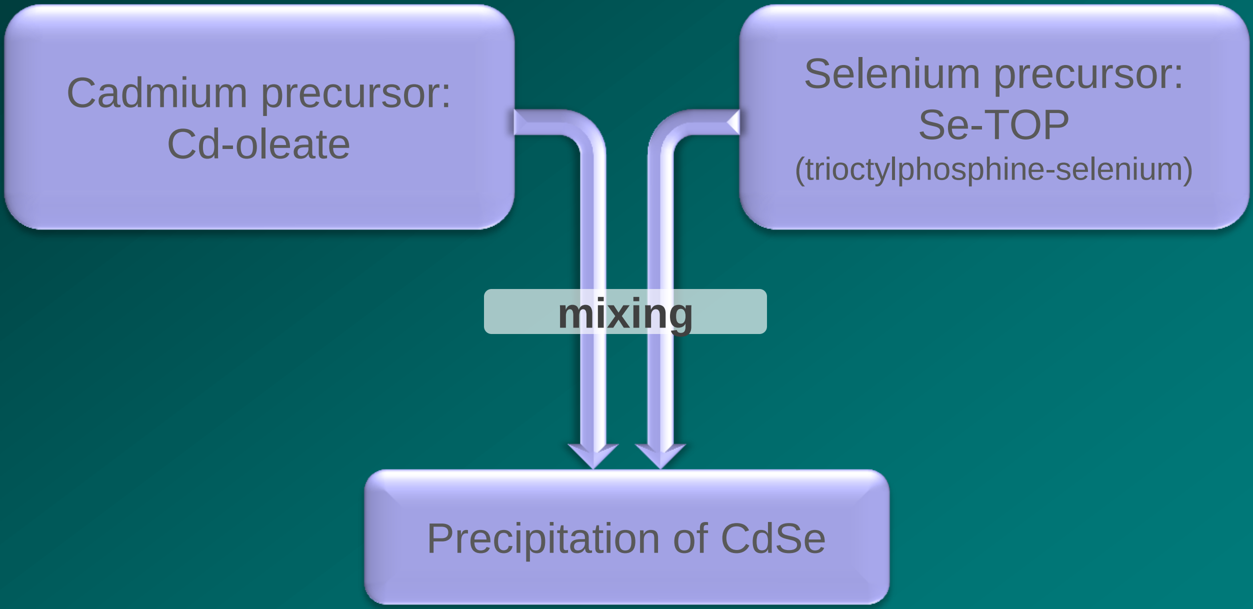
Semiconductor Nanocrystals: Synthesis

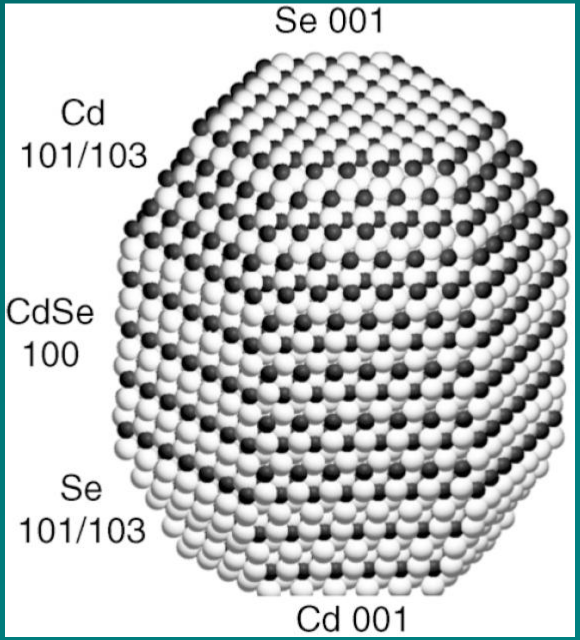


Semiconductor Nanocrystals: Synthesis

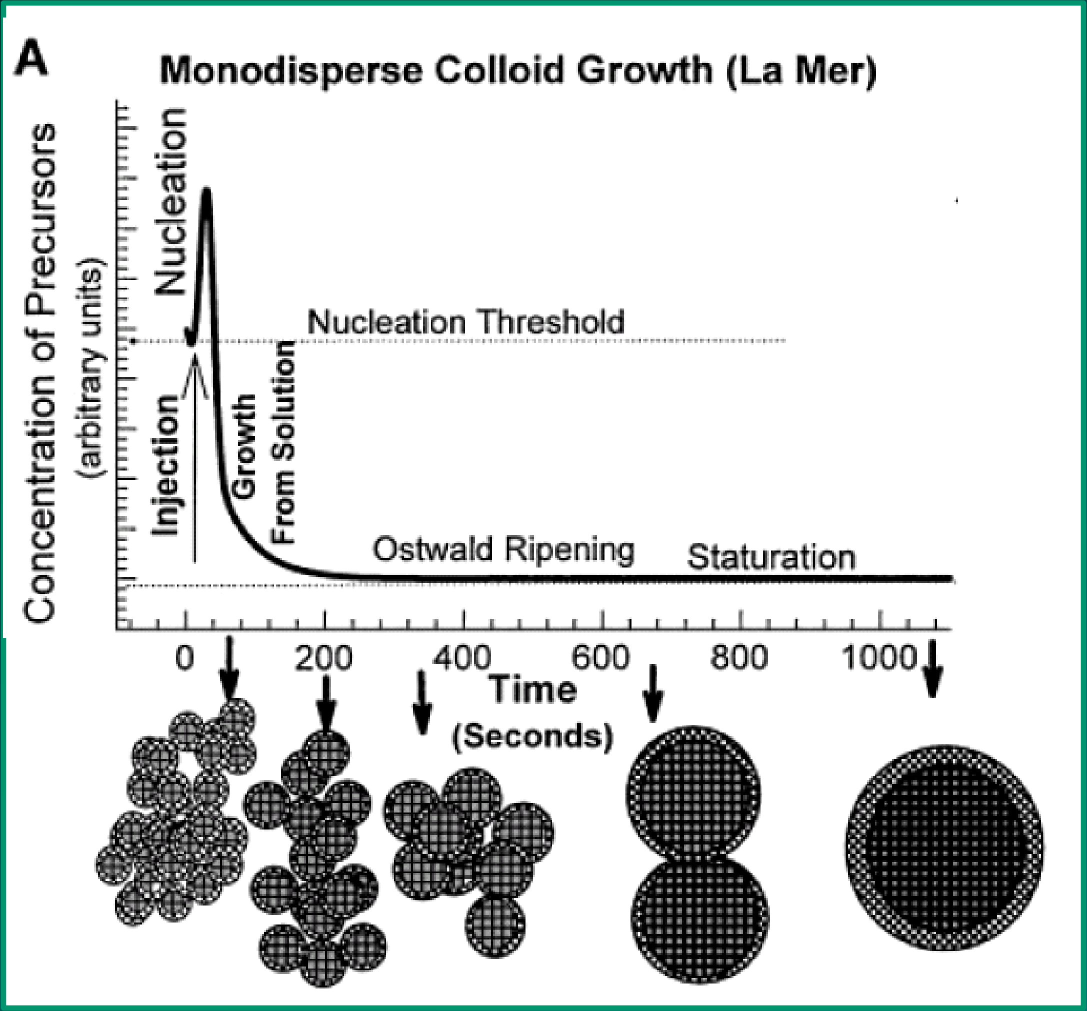
Colloidal synthesis of cadmium selenide

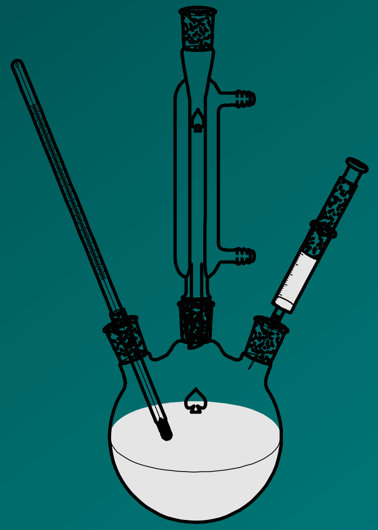
Cd-oleate + Se-TOP ⟶ **CdSe** + products





Semiconductor Nanocrystals: Colloidal Synthesis



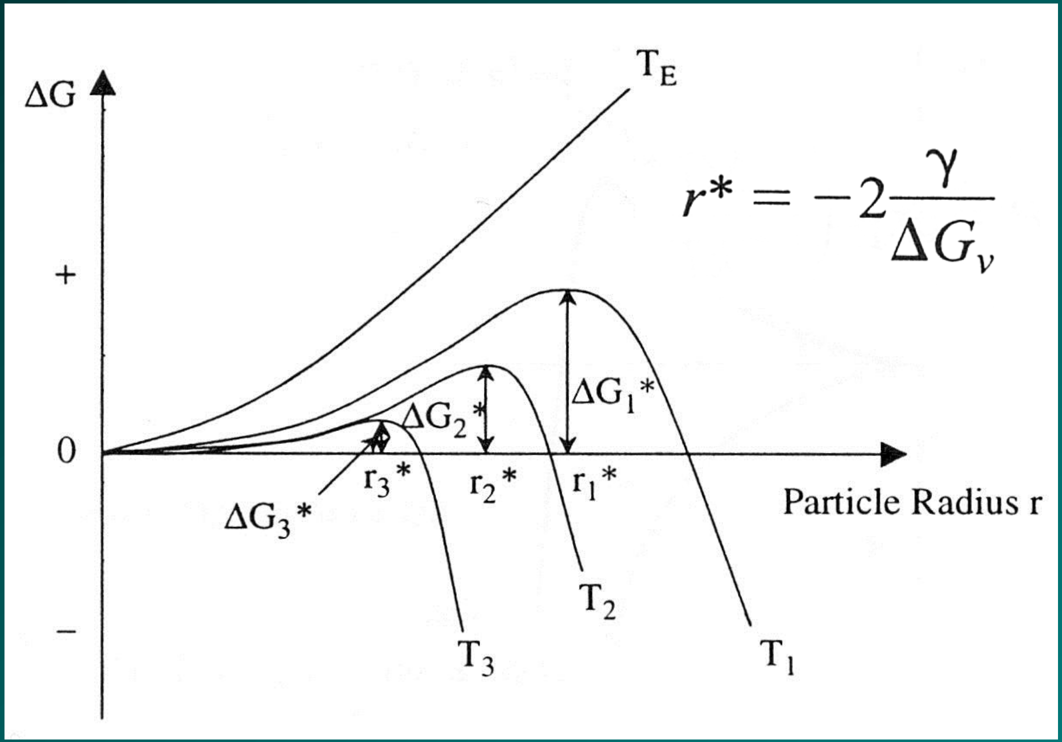


Key role of

NUCLEATION
and
GROWTH

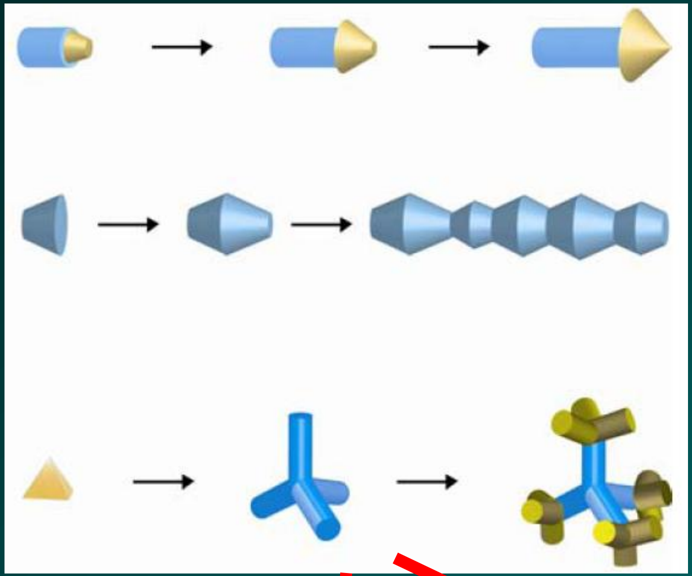
TIME, TEMPERATURE and CONCENTRATION control reaction kinetics
Surfactant are needed to avoid cluster formation

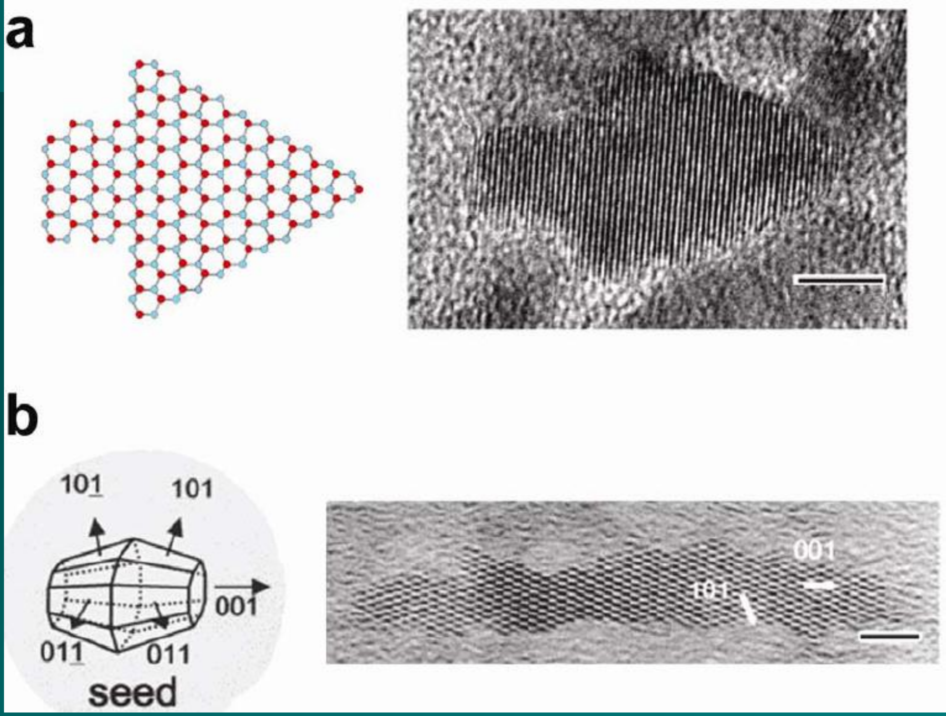
Nucleation

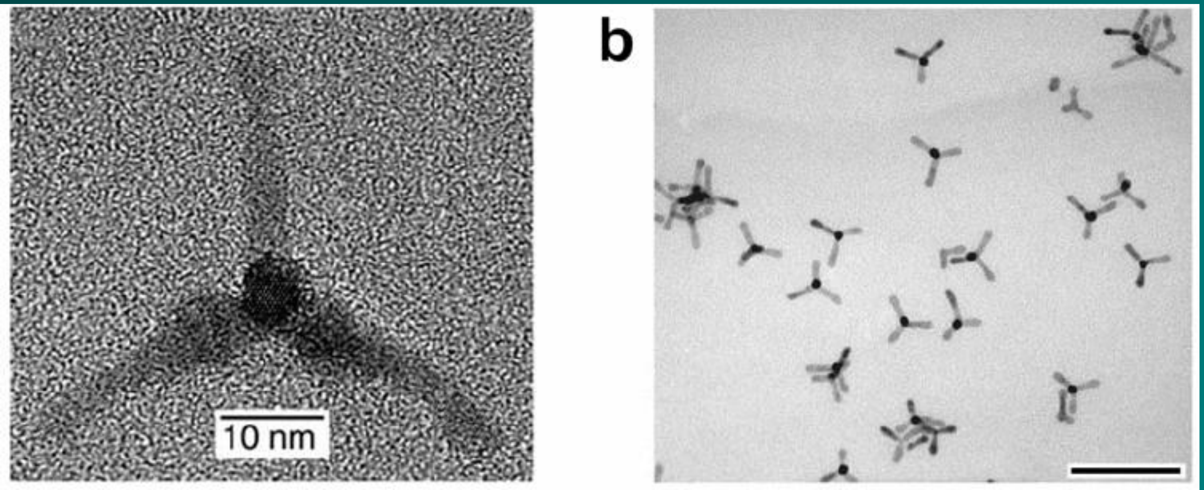


$$R_N = nP\Gamma = \left\{\frac{C_o kT}{3\pi\lambda^3\eta}\right\} \exp\left(-\frac{\Delta G^*}{kT}\right)$$

Nanocrystal shapes



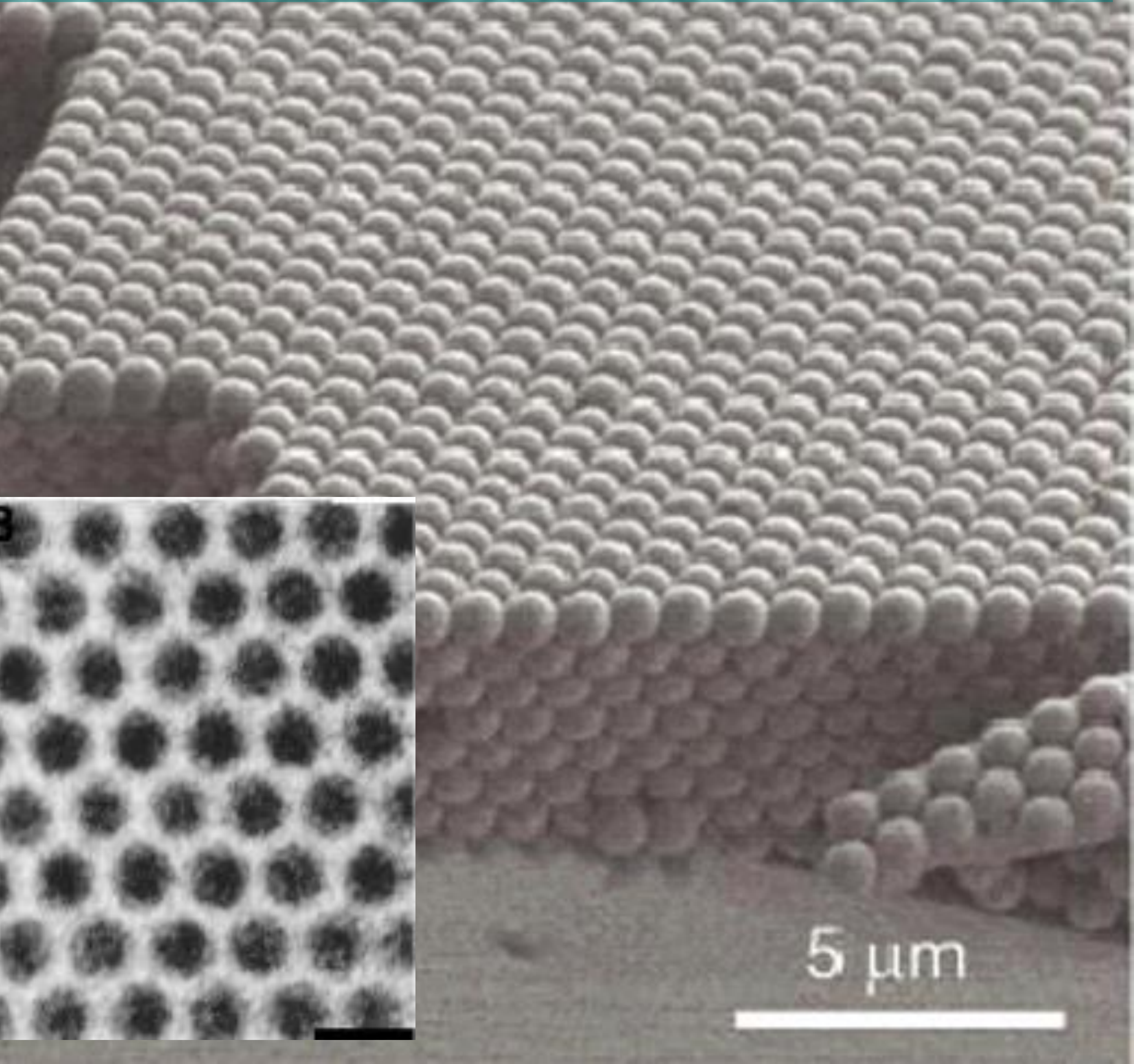


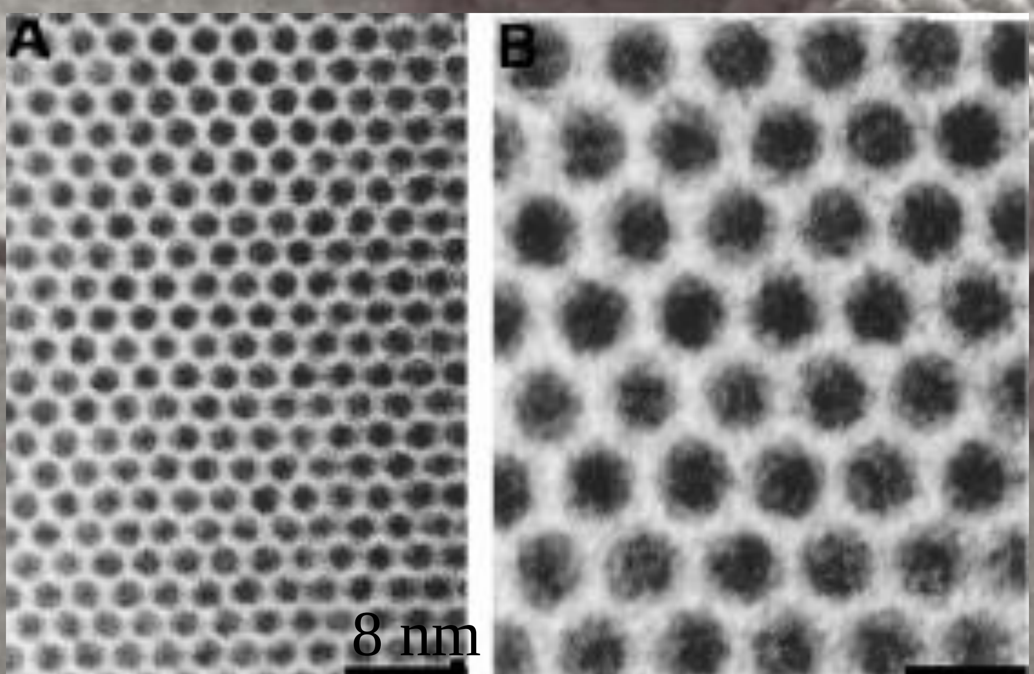


Paul Alivisatos, UC Berkeley

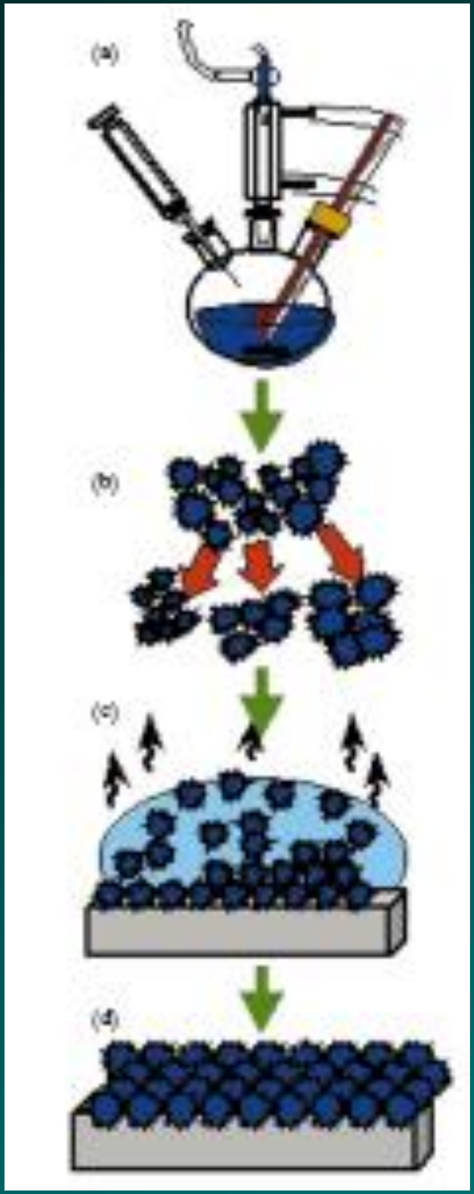
Nanostructured materials – Colloidal solids

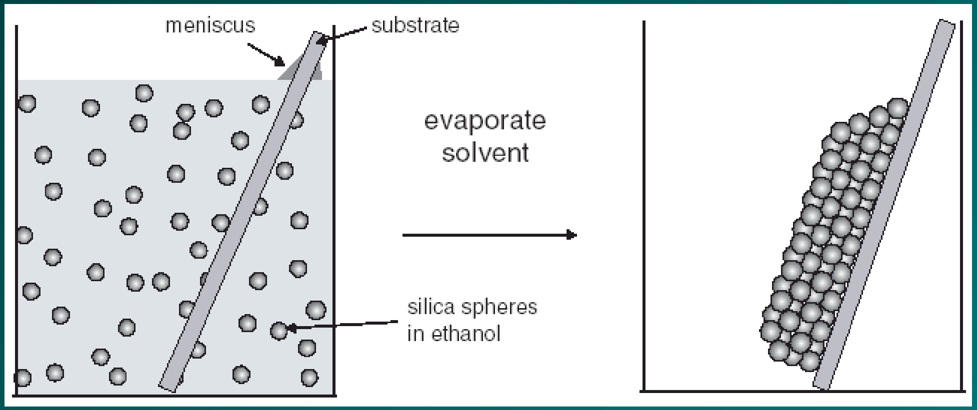
A chance to design novel materials with entirely new properties

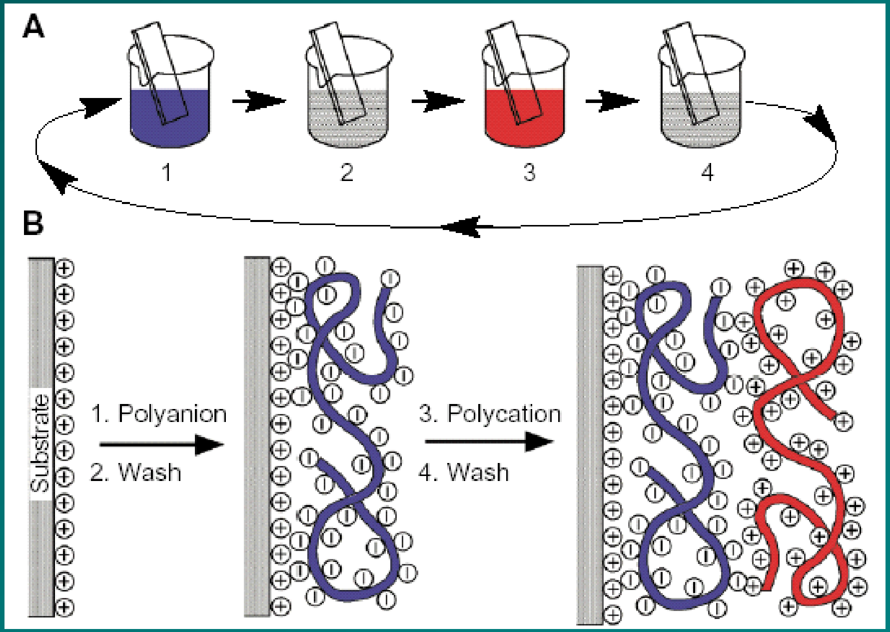




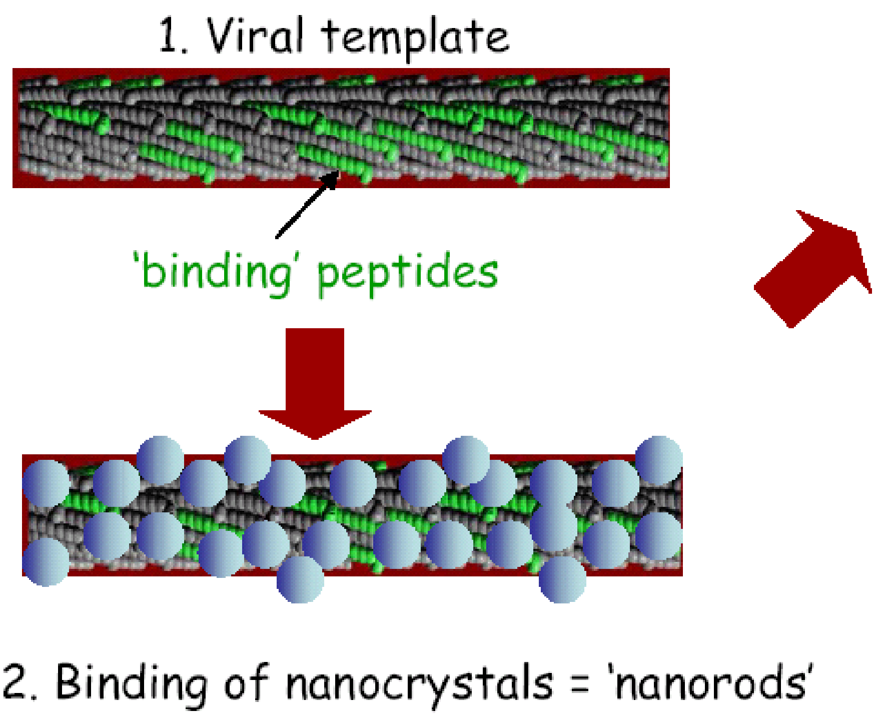
Methods for assembling colloidal solids







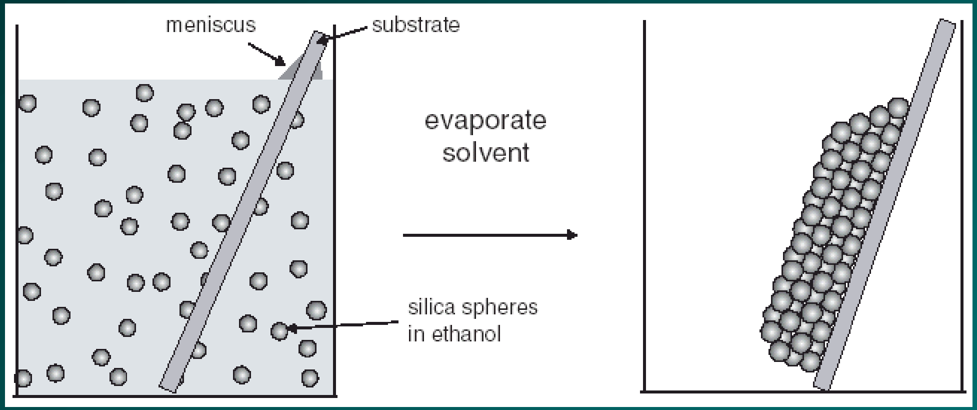
Bio-templated nanomaterials



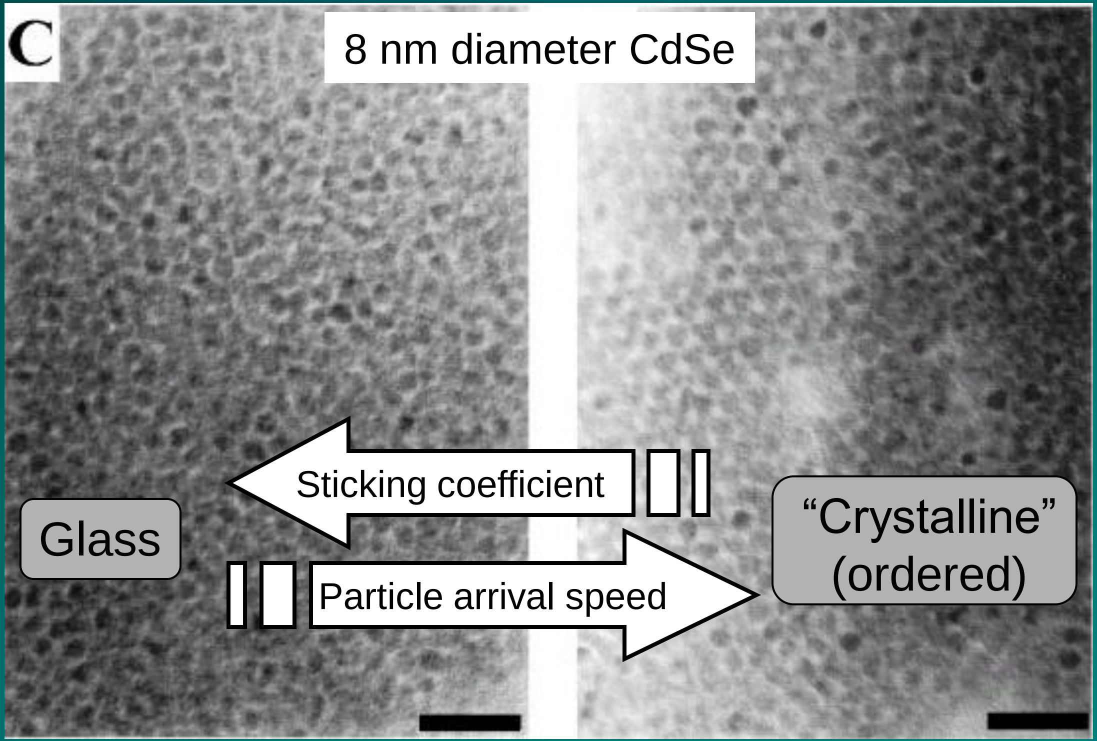
- Single crystal nanorods possible (optimize nucleation, annealing)
- Can bind 2 nanocrystals for additional compositional control (e.g. $In_xGa_{1-x}N$)

E. Hu, UCSB
A. Belcher, MIT

Assembly and structural control

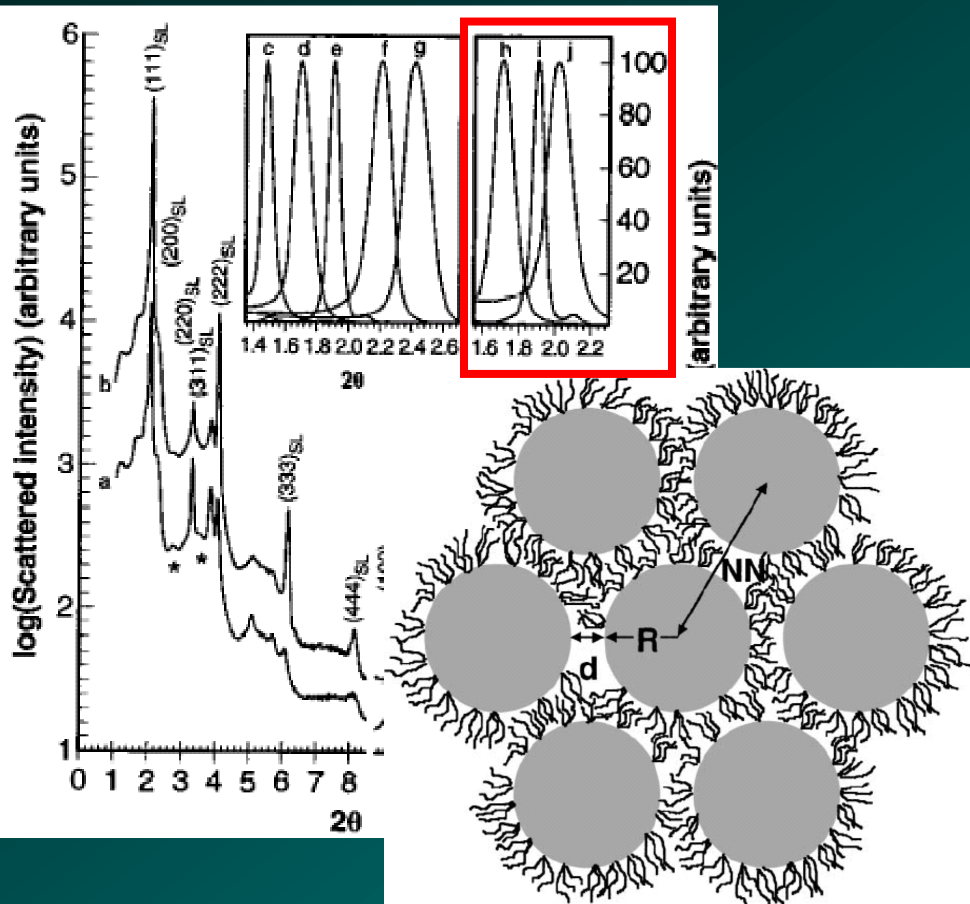


D.J. Norris, Adv. Mater. **16**, 1394 (2004)



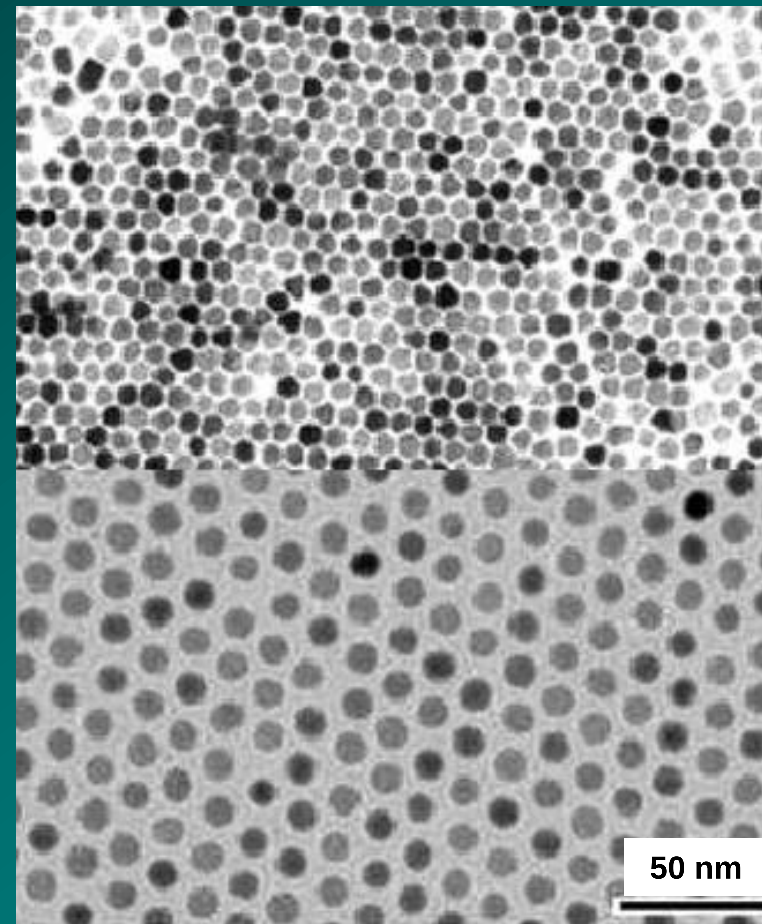
C.B. Murray et al., Annu. Rev. Mater. Sci **30**, 545 (2000)

QD-solid assembly: QD Distance Engineering



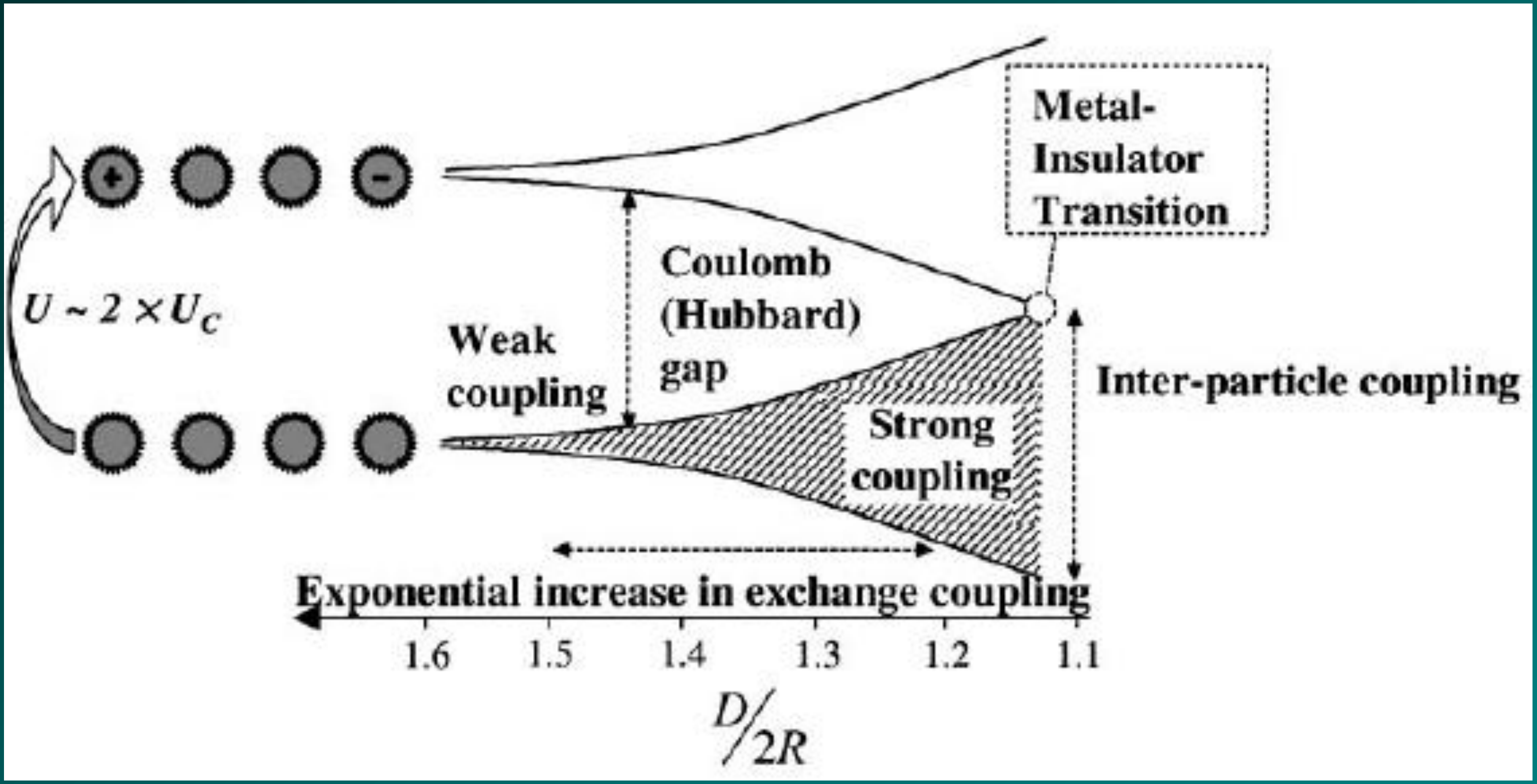
Curve	Capping agent	Atoms per chain	Interparticle distance (Å)
h	Trihexadecylphosphate	16	17
i	Trioctylphosphine calchogenide	8	11
j	Tributylphosphine oxide	4	7

C.B. Murray et al., Science **270**, 1335 (1995)

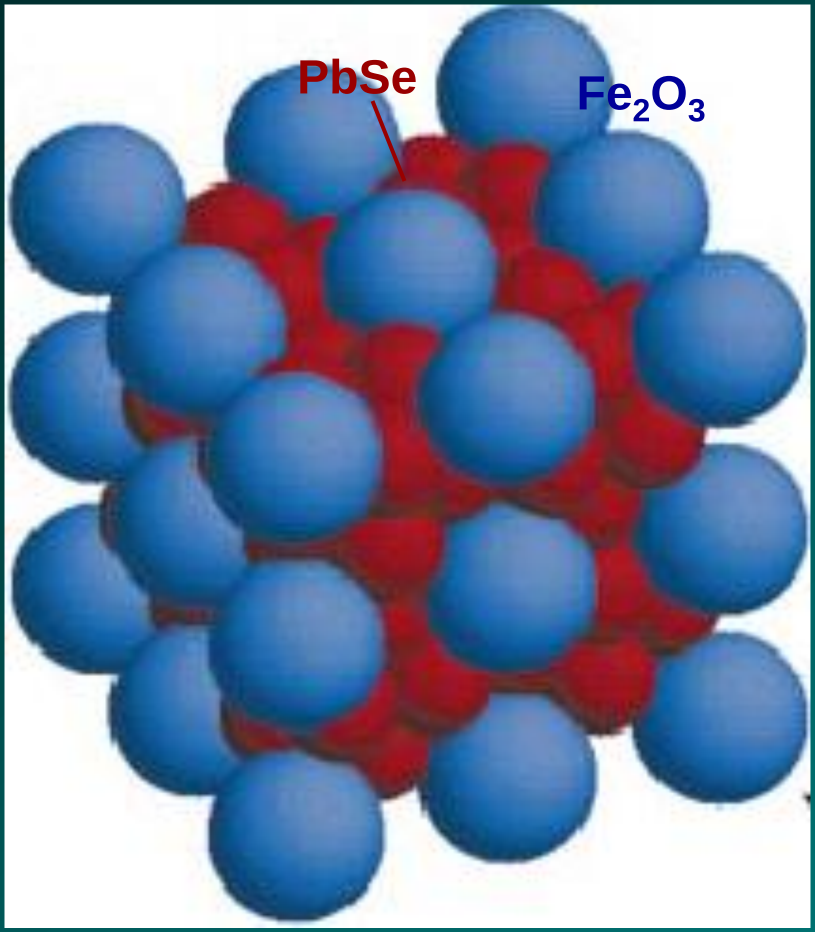


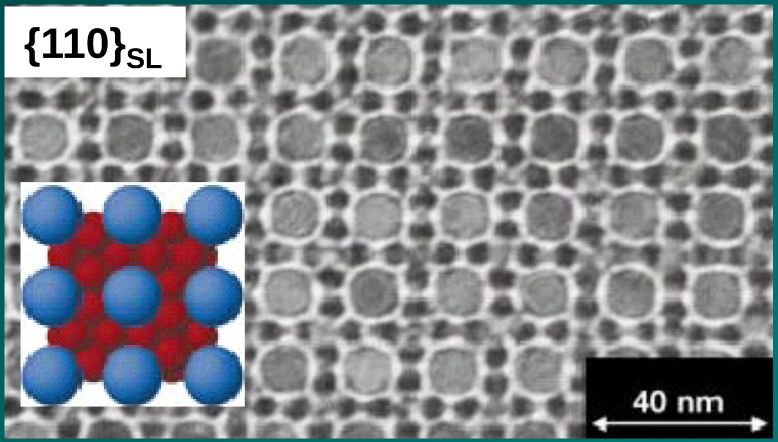
Y. Yin, A.P. Alivisatos, Nature **437**, 664 (2005)

Electronic properties of colloidal solids



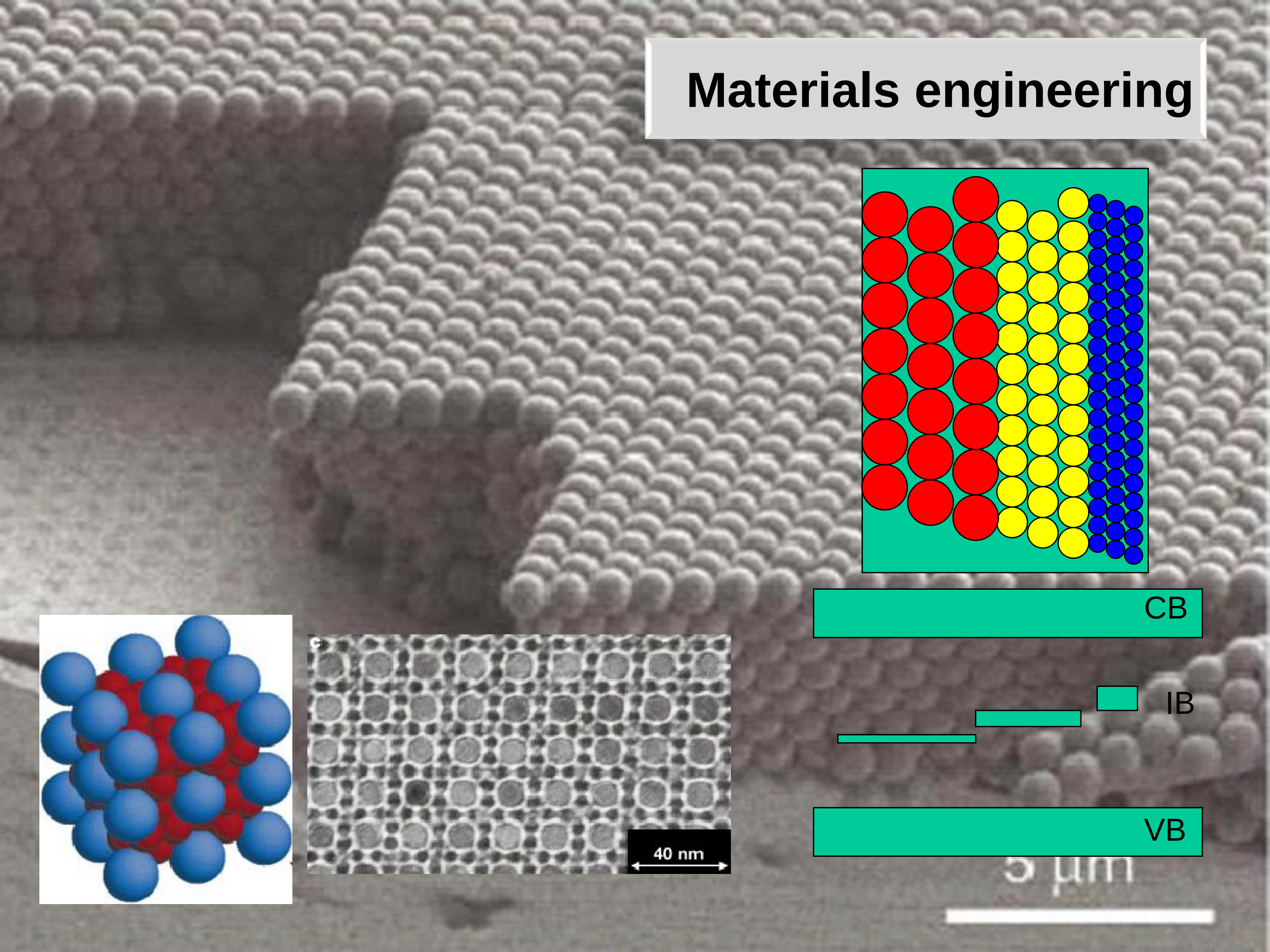
QD-solid assembly: Bi-component QD-Solid





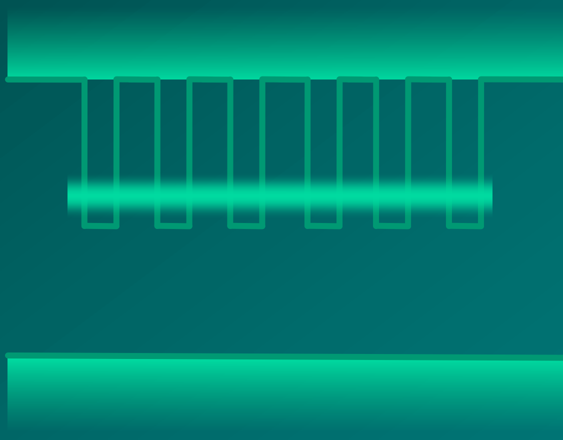
F.X. Redl et al., Nature 423, 968 (2003)

Materials engineering

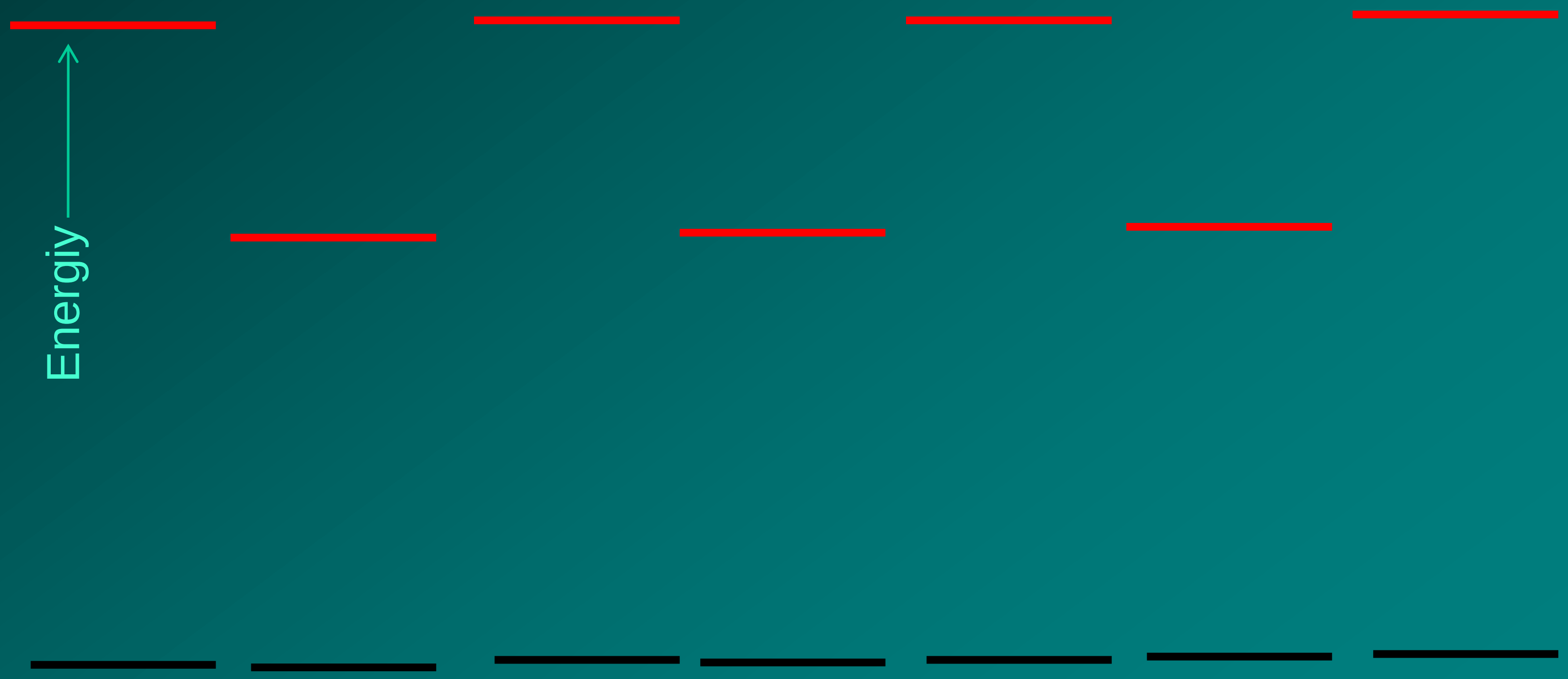


Our approach for sinthesizing an IB material

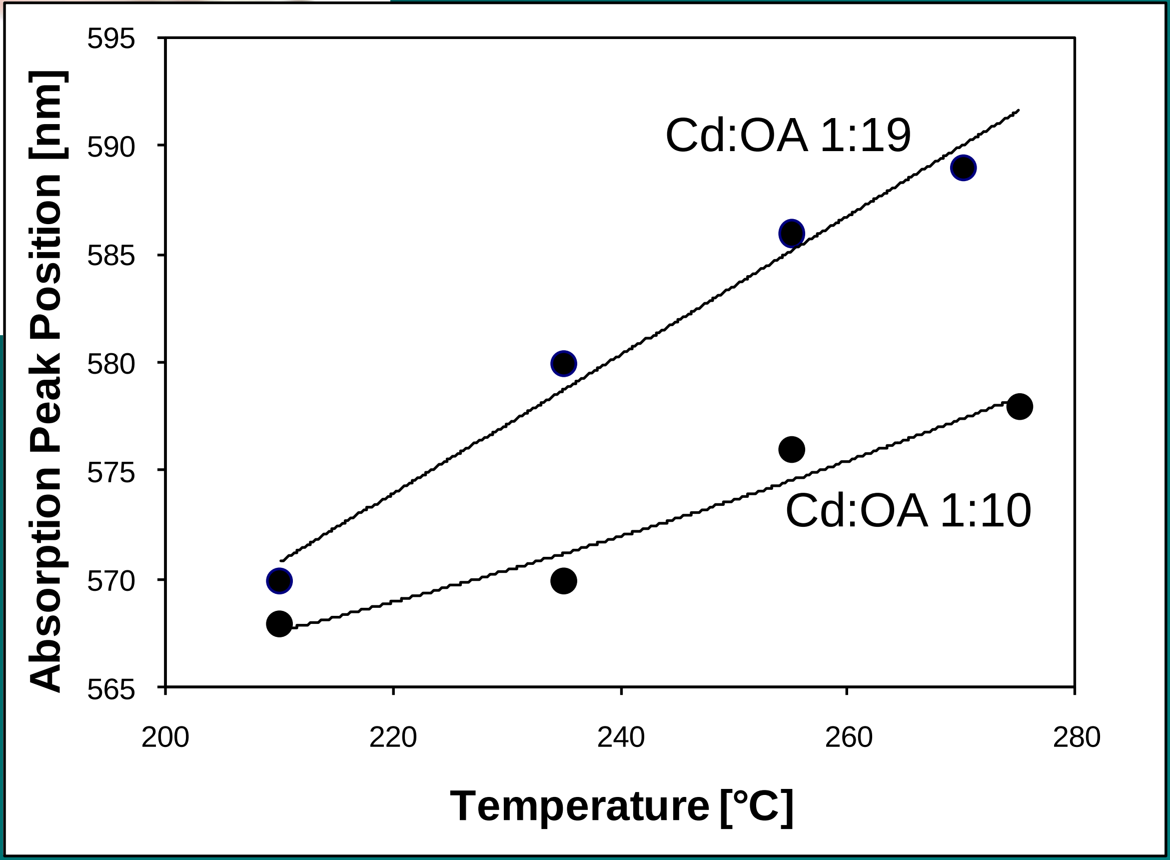
Matrice di ZnSe matrix – CdSe QDs



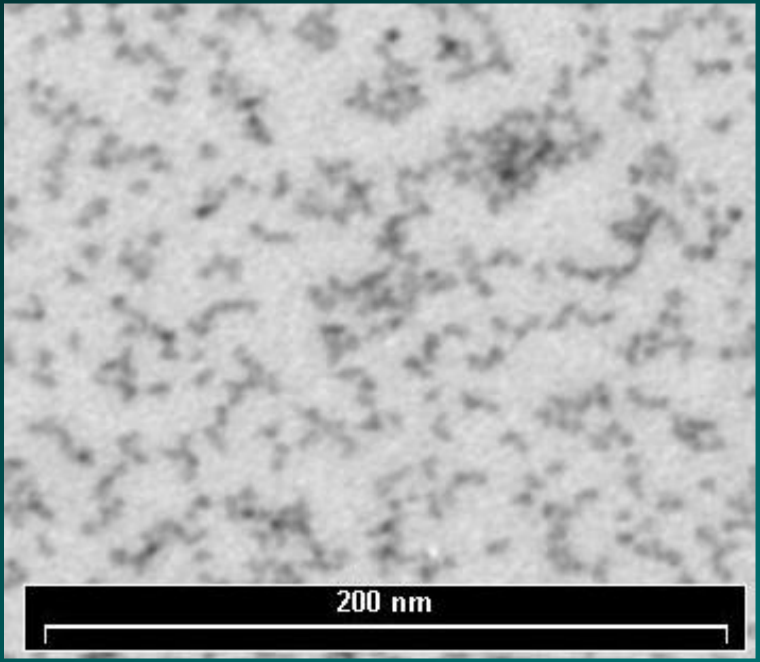
	ZnSe	CdSe	ZnSe
Electron affinity	4.09	4.95	4.09
Bandgap	2.58	1.74	2.58

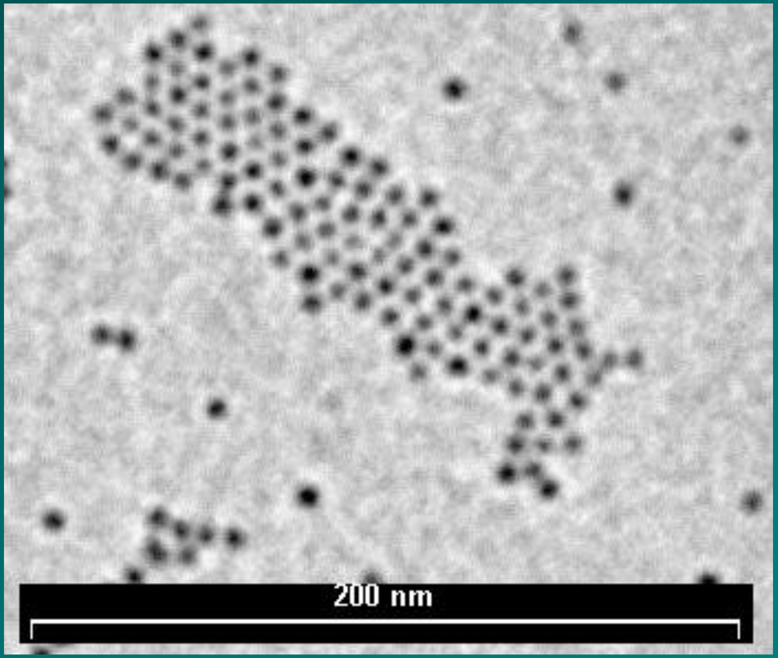


NCs Growth Kinetics – Control of Size

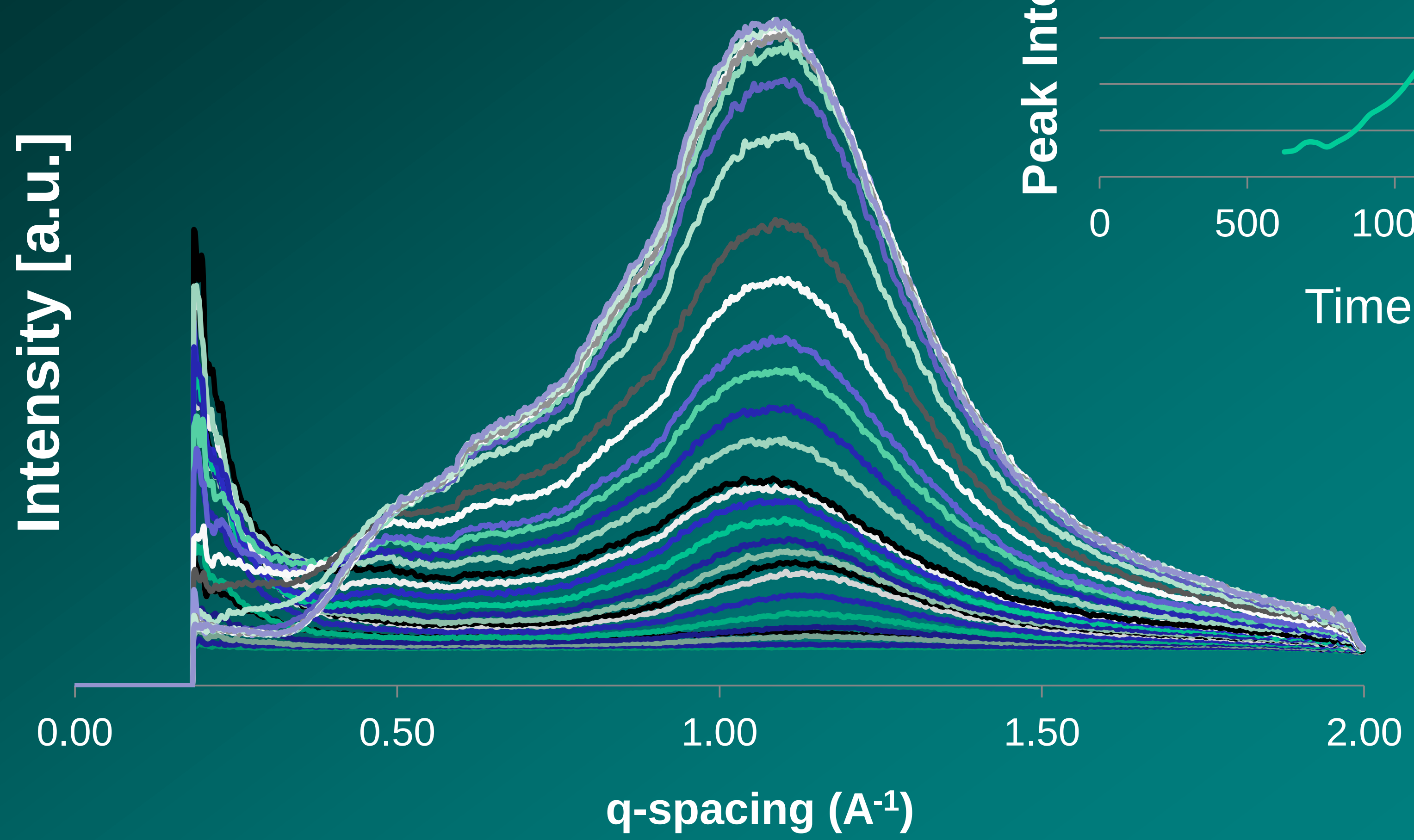


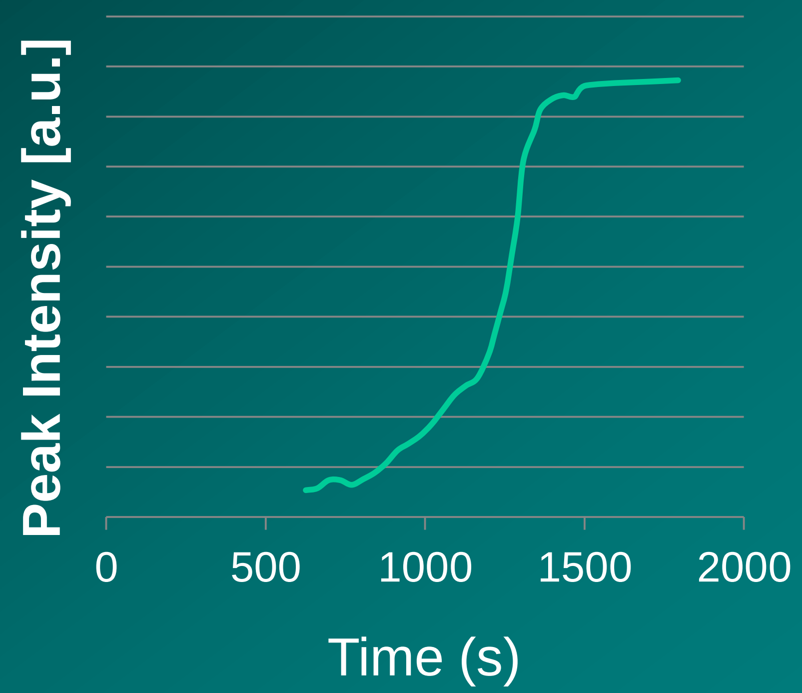
Assembly: Control of interparticle forces



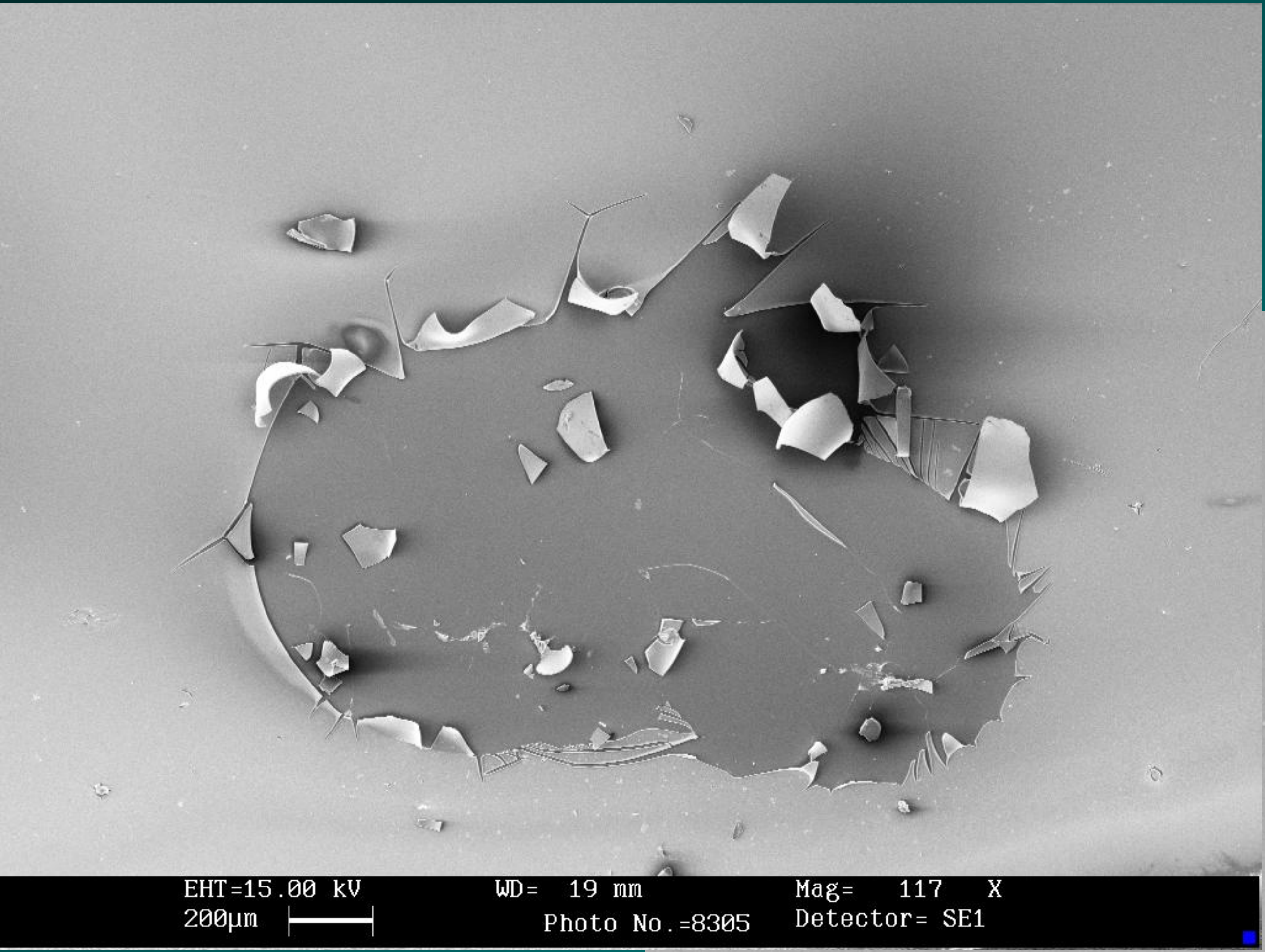


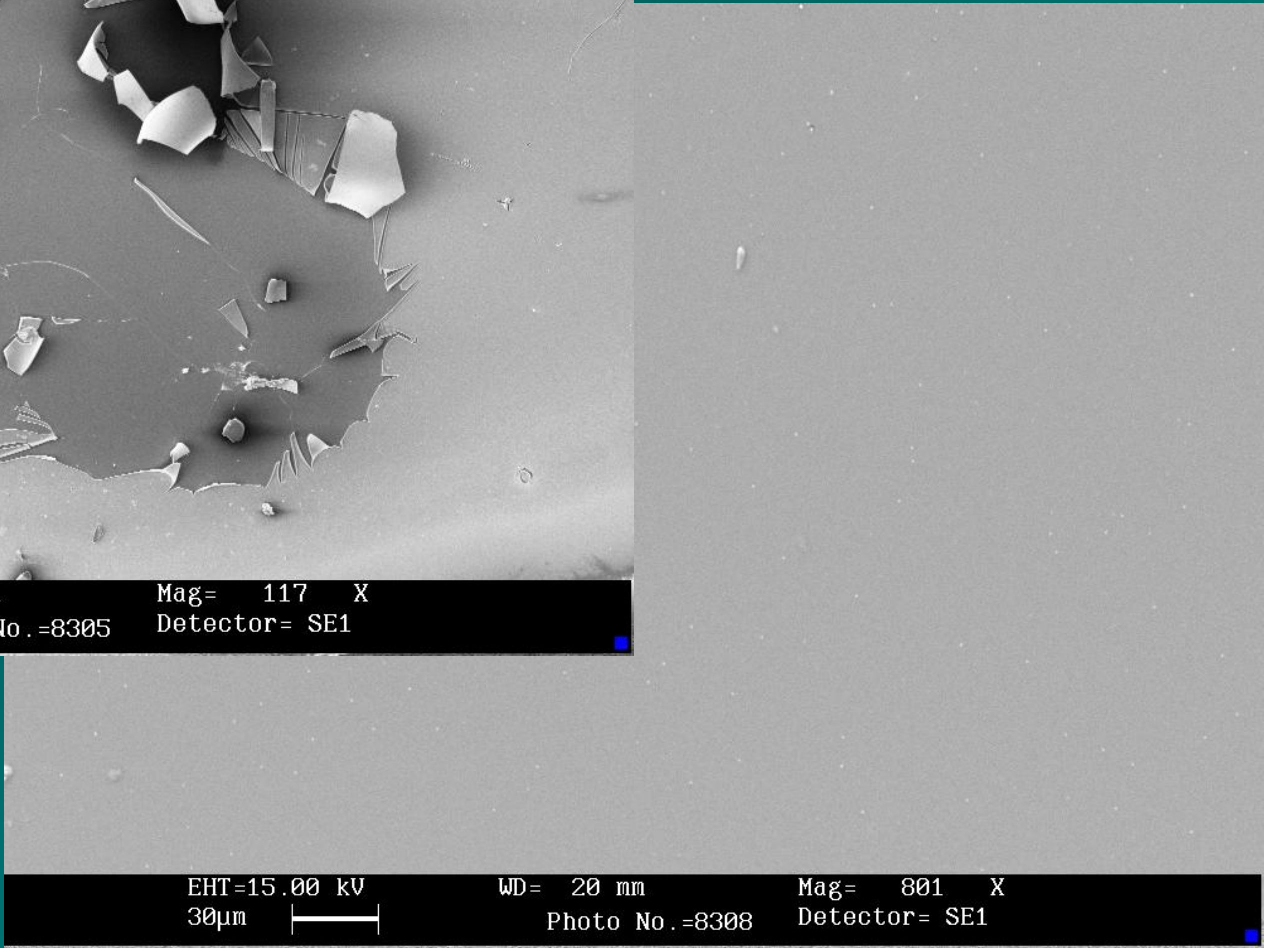
Assembly: Ordering



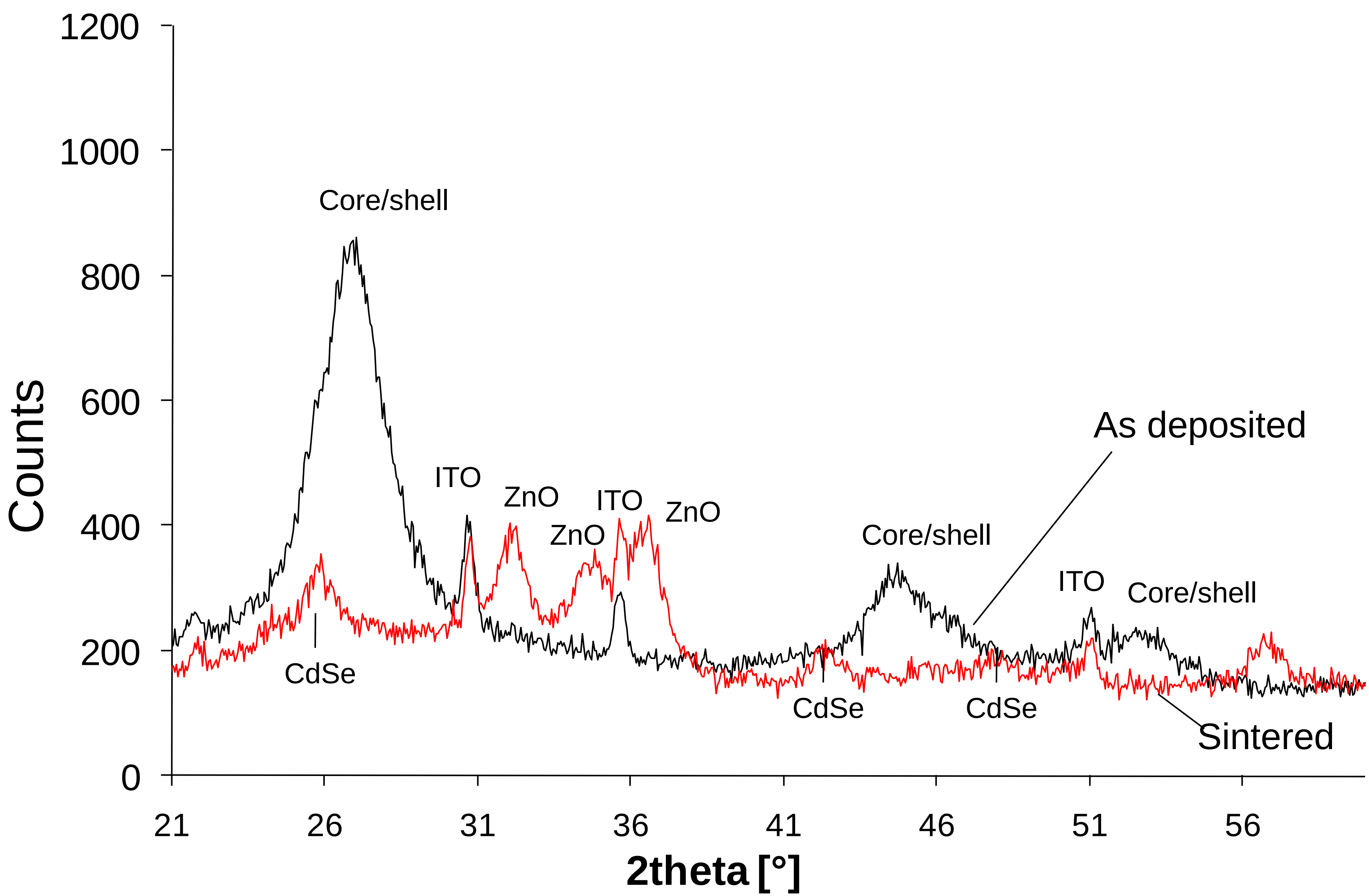


Uniform Thin Films of NC assemblies

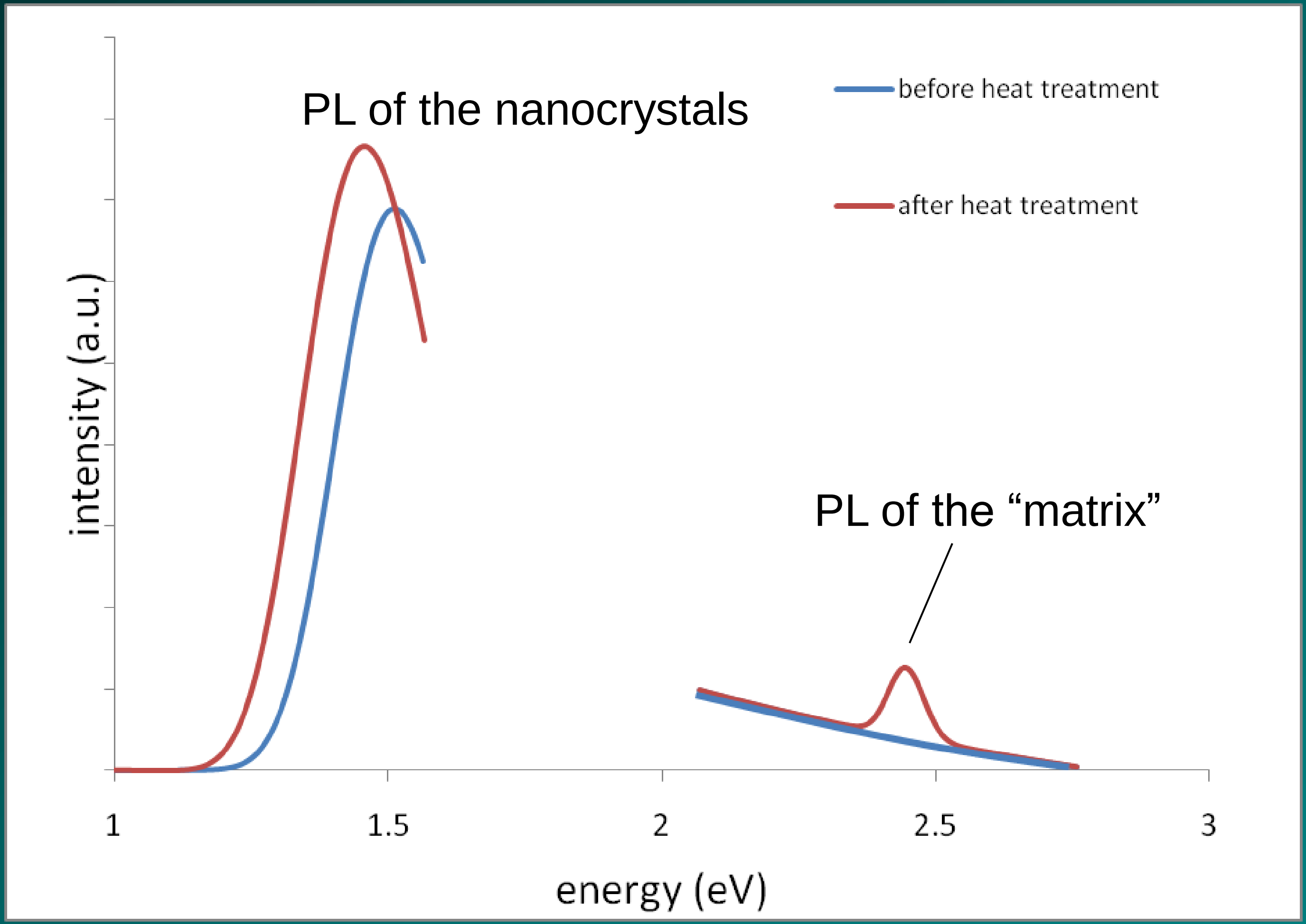




Densification of NC assemblies



Optical properties of NC assemblies



Concluding Remarks

- PV is at a "tipping point" – breakthrough technology is just around the corner
- Bio- and Nanotechnology will likely be the key to high performance, low cost PV devices
- Colloidal routes to fabricate PV materials are extremely promising:
  - The structure can be finely engineered at the nanoscale
  - Cost can be reduced (ambient process conditions)

Aknowledgements

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State of the art

Table I. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1·5 spectrum (1000 Wm^{-2}) at 25°C

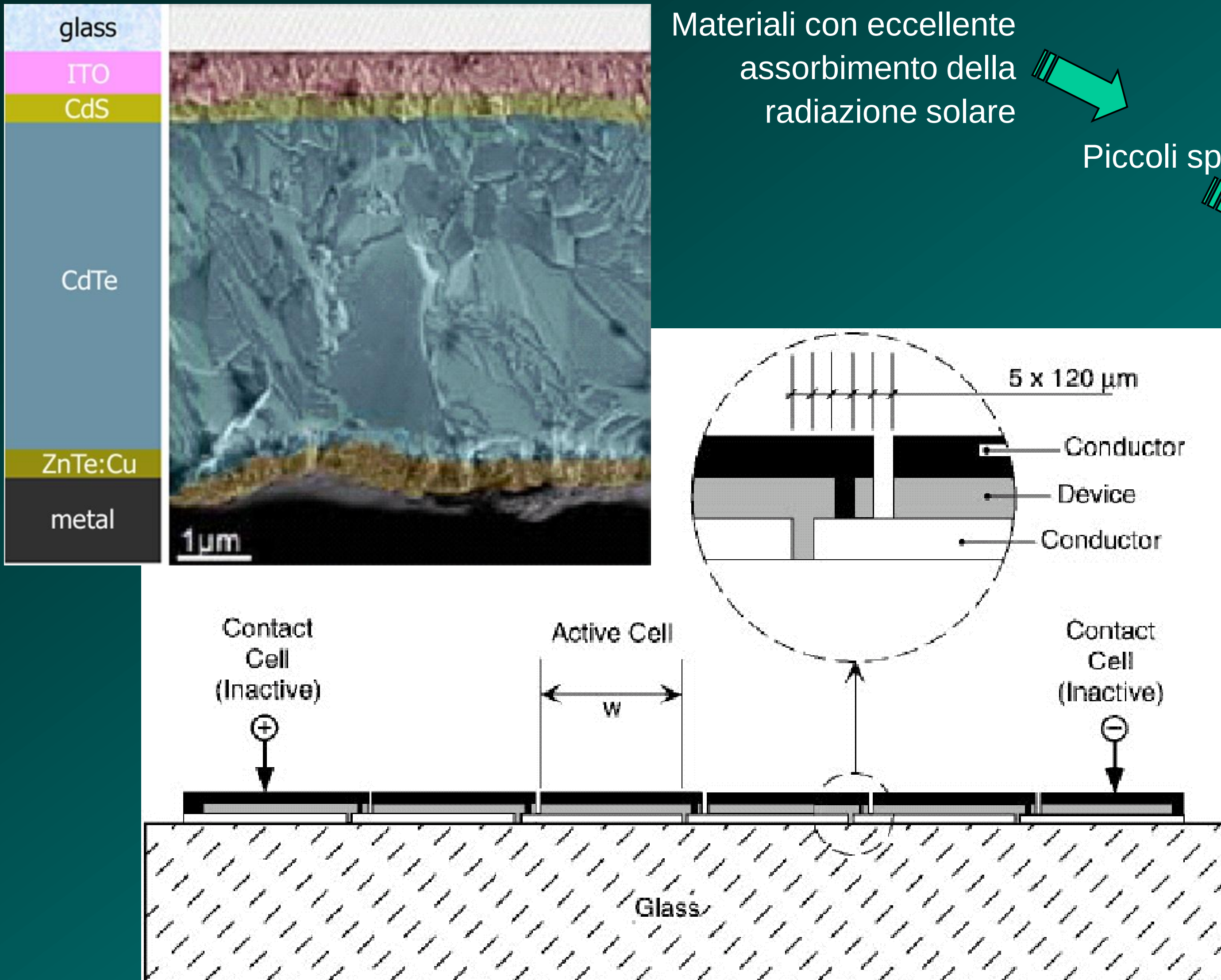
Classification*	Effic.† (%)	Area‡ (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF§ (%)	Test centre‖ (and Date)	Description
Silicon							
Si (crystalline)	24·7 ± 0·5	4·00 (da)	0·706	42·2	82·8	Sandia (3/99)	UNSW PERL[9]
Si (multicrystalline)	20·3 ± 0·5	1·002 (ap)	0·664	37·7	80·9	NREL (5/04)	FhG-ISE[10]
Si (thin-film transfer)	16·6 ± 0·4	4·017 (ap)	0·645	32·8	78·2	FhG-ISE (7/01)	U. Stuttgart (45 μm thick)[11]
Si (thin-film submodule)	**9·8 ± 0·3**	**96·3 (ap)**	**0·487¶**	**27·0¶**	**74·5**	**Sandia (8/06)**	**CSG Solar (1–2 μm on glass; 20 cells)[5]**
III–V Cells							
GaAs (crystalline)	25·1 ± 0·8	3·91 (t)	1·022	28·2	87·1	NREL (3/90)	Kopin, AlGaAs window[12]
GaAs (thin-film)	24·5 ± 0·5	1·002 (t)	1·029	28·8	82·5	FhG-ISE (5/05)	Radboud U., NL[13]
GaAs (multicrystalline)	18·2 ± 0·5	4·011 (t)	0·994	23·0	79·7	NREL (11/95)	RTI, Ge substrate[14]
InP (crystalline)	21·9 ± 0·7	4·02 (t)	0·878	29·3	85·4	NREL (4/90)	Spire, epitaxial[15]
Thin-film chalcogenide							
CIGS (cell)	**18·8 ± 0·5#**	**0·998 (ap)**	**0·699**	**33·8**	**79·4**	**NREL (2/06)**	**NREL, CIGS on glass[16]**
CIGS (submodule)	16·6 ± 0·4	16·0 (ap)	0·661¶	33·4¶	75·1	FhG-ISE (3/00)	U. Uppsala, 4 serial cells[17]
CdTe (cell)	16·5 ± 0·5#	1·032 (ap)	0·845	25·9	75·5	NREL (9/01)	NREL, mesa on glass[18]
Amorphous/nanocrystalline Si							
Si (amorphous)**	9·5 ± 0·3	1·070 (ap)	0·859	17·5	63·0	NREL (4/03)	U. Neuchatel[19]
Si (nanocrystalline)	10·1 ± 0·2	1·199 (ap)	0·539	24·4	76·6	JQA (12/97)	Kaneka (2 μm on glass)[20]
Photochemical							
Dye sensitised	10·4 ± 0·3	1·004 (ap)	0·729	21·8	65·2	AIST (8/05)	Sharp[21]
Dye sensitised (submodule)	6·3 ± 0·2	26·5 (ap)	6·145	1·70	60·4	AIST (8/05)	Sharp[22]
Organic							
Organic polymer††	3·0 ± 0·1	1·001 (ap)	0·538	9·68	52·4	AIST (3/06)	Sharp, fullerene derivative[23]
Multijunction devices							
GaInP/GaAs/Ge	32·0 ± 1·5	3·989 (t)	2·622	14·37	85·0	NREL (1/03)	Spectrolab (monolithic)
GaInP/GaAs	30·3	4·0 (t)	2·488	14·22	85·6	JQA (4/96)	Japan Energy (monolithic)[24]
GaAs/CIS (thin-film)	25·8 ± 1·3	4·00 (t)	-	-	-	NREL (11/89)	Kopin/Boeing (4 terminal)[25]
a-Si/μc-Si (thin submodule)‡‡	11·7 ± 0·4	14·23 (ap)	5·462	2·99	71·3	AIST (9/04)	Kaneka (thin-film)[26]

Stato dell'arte

Table II. Confirmed terrestrial module efficiencies measured under the global AM1·5 spectrum (1000 W/m^2) at a cell temperature of 25°C

Classification*	Effic.† (%)	Area‡ (cm^2)	V_{oc} (V)	Isc (A)	FF§ (%)	Test centre (and Date)	Description
Si (crystalline)	22·7 ± 0·6	778 (da)	5·60	3·93	80·3	Sandia (9/96)	UNSW/Gochermann[27]
Si (multicrystalline)	15·3 ± 0·4‖	1017 (ap)	14·6	1·36	78·6	Sandia (10/94)	Sandia/HEM[28]
Si (thin-film polycrystalline)	8·2 ± 0·2	661 (ap)	25·0	0·318	68·0	Sandia (7/02)	Pacific Solar (1–2 μm on glass)[29]
CIGSS	13·4 ± 0·7	3459 (ap)	31·2	2·16	68·9	NREL (8/02)	Showa Shell (Cd free)[30]
CdTe	10·7 ± 0·5	4874 (ap)	26·21	3·205	62·3	NREL (4/00)	BP Solarex[31]
a-Si/a-SiGe/a-SiGe (tandem)¶	10·4 ± 0·5	905 (ap)	4·353	3·285	66·0	NREL (10/98)	USSC (a-Si/a-Si/a-Si:Ge)[32]

Moduli basati su film sottile



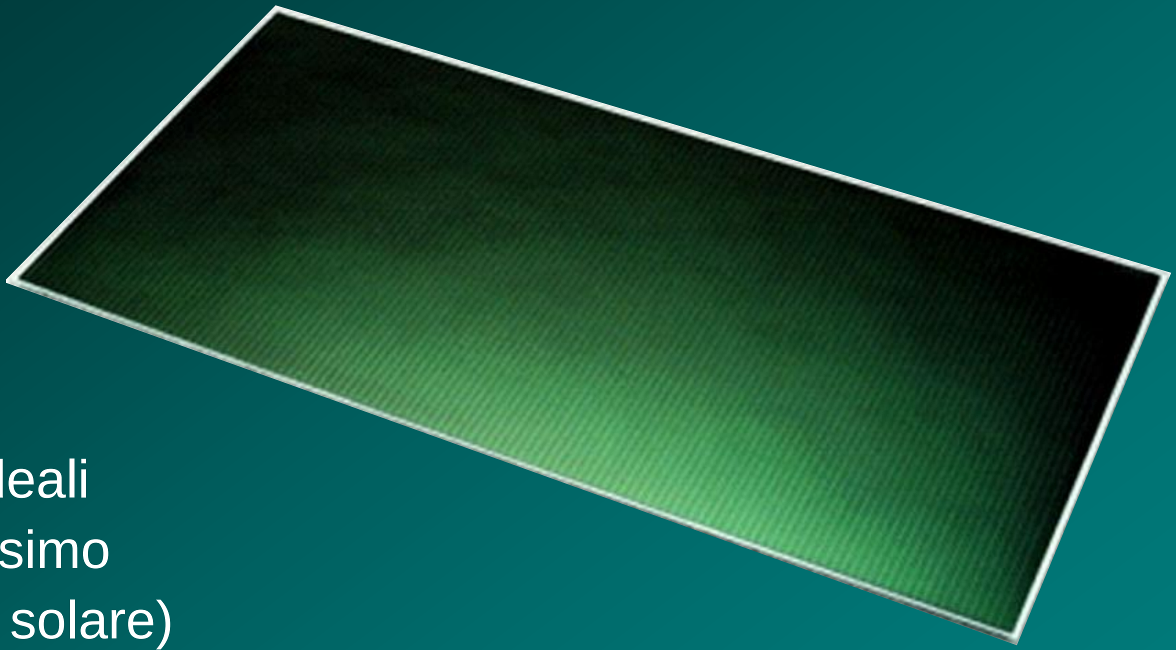
Materiali con eccellente assorbimento della radiazione solare

Piccoli spessori

- Stabilità dei costi
- Sostenibilità degli approvvigionamenti
- Flessibilità nella scelta del substrato
- Moduli integrati

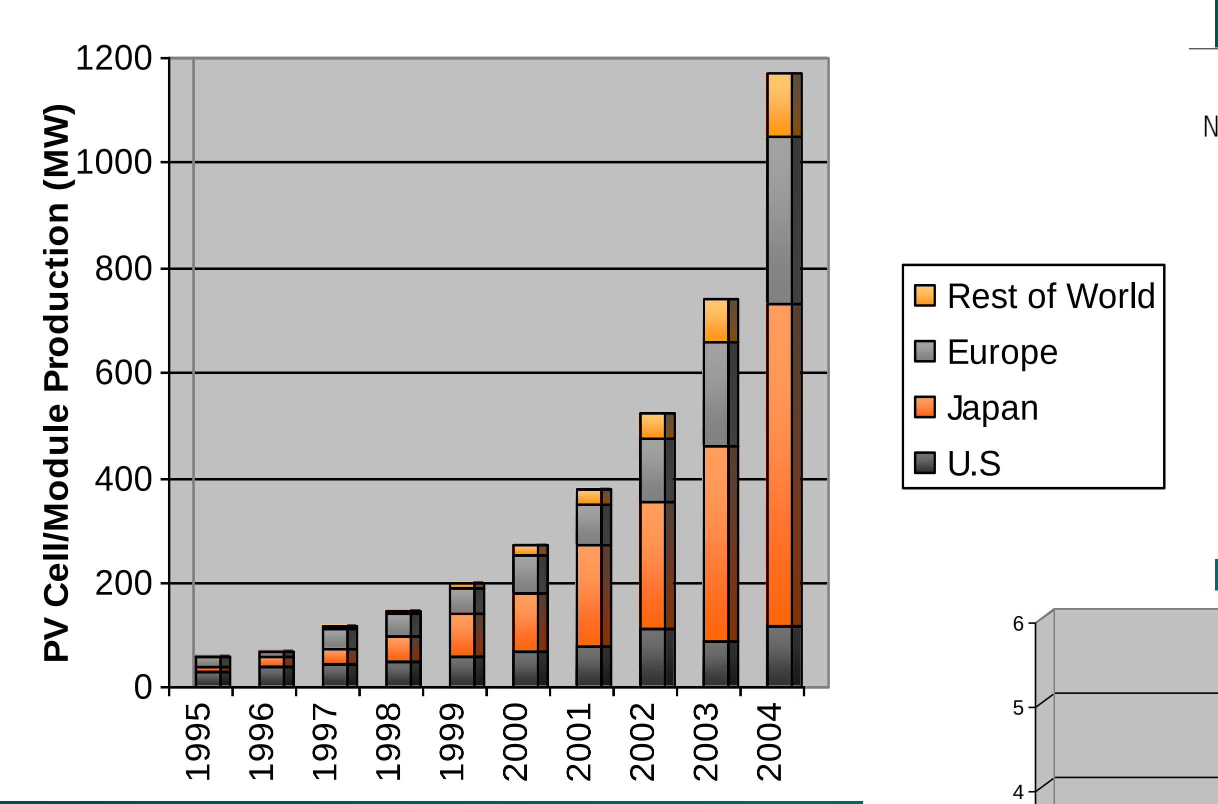
Esempi: Silicio amorfo; CIGS; CdTe

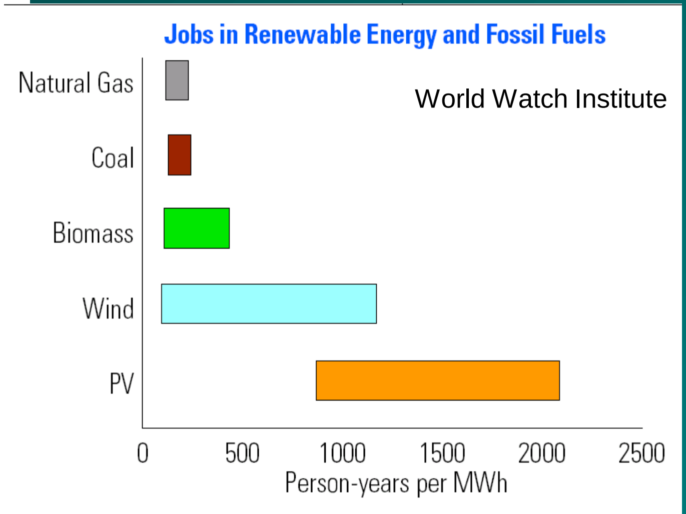
Moduli basati su film sottili di CdTe

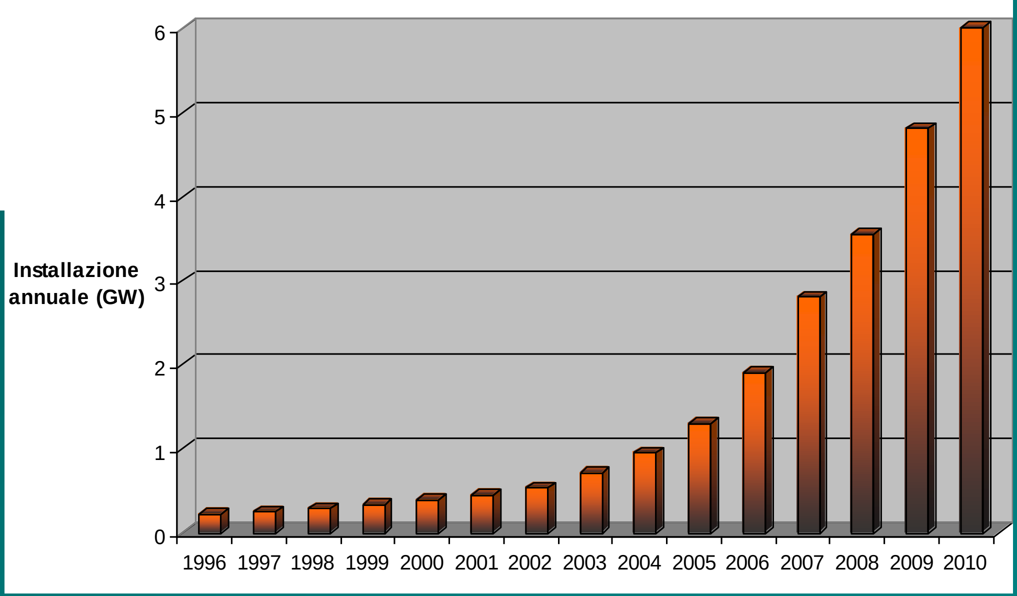


- Proprietà elettroniche ideali (bandgap 1.5 eV – massimo utilizzo della radiazione solare)
- Disponibilità delle materie prime
- Robustezza e varietà di processi produttivi disponibili
- Provata fattibilità industriale (First Solar; Antec)

Economia dell'industria fotovoltaica



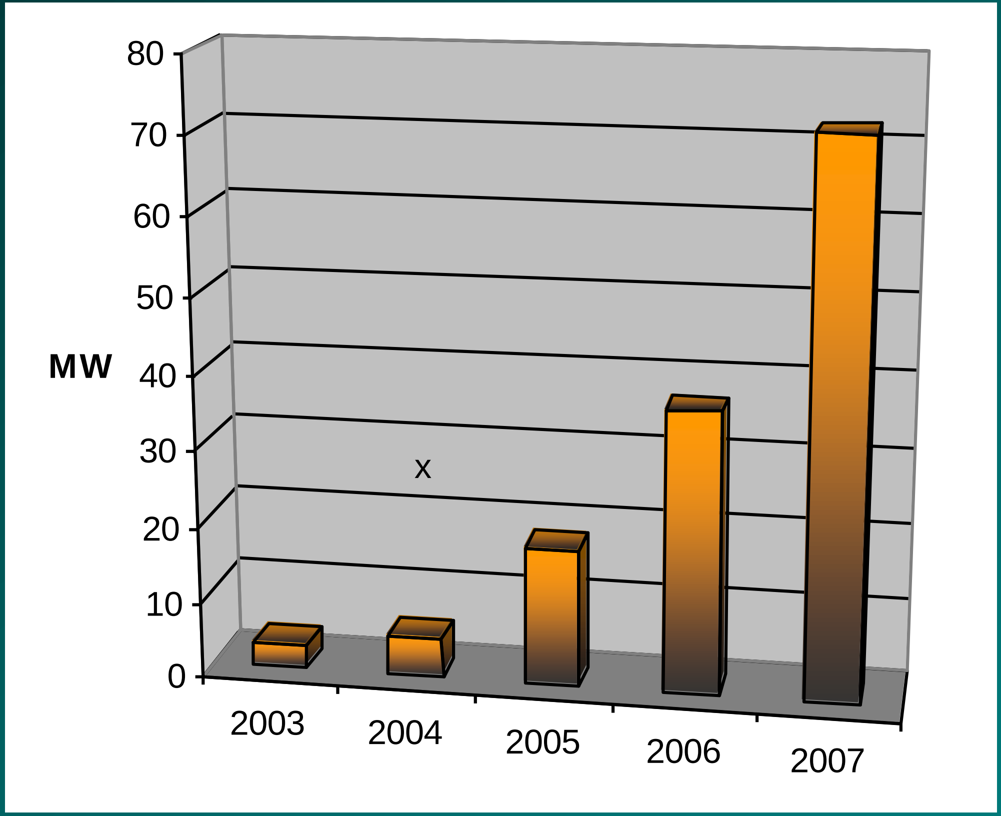




Fatturato complessivo ~ 10 Mld. €/anno

Crescita media ~ 35%/anno

Vendite First Solar



Costo dell'energia fotovoltaica

\$/peak watt ~ [module cost(\$/m²) + BOS cost (\$/m²)]/Eff + 0.1

where:
Eff = cell conversion efficiency x 1000 W/m² (W_p/m^2)
BOS = balance of systems (support structure,installation,wiring, land, etc)
\$0.1 = power conditioner, AC – DC inverter

Also: 1\$/W_p ≅ \$0.05/kWh

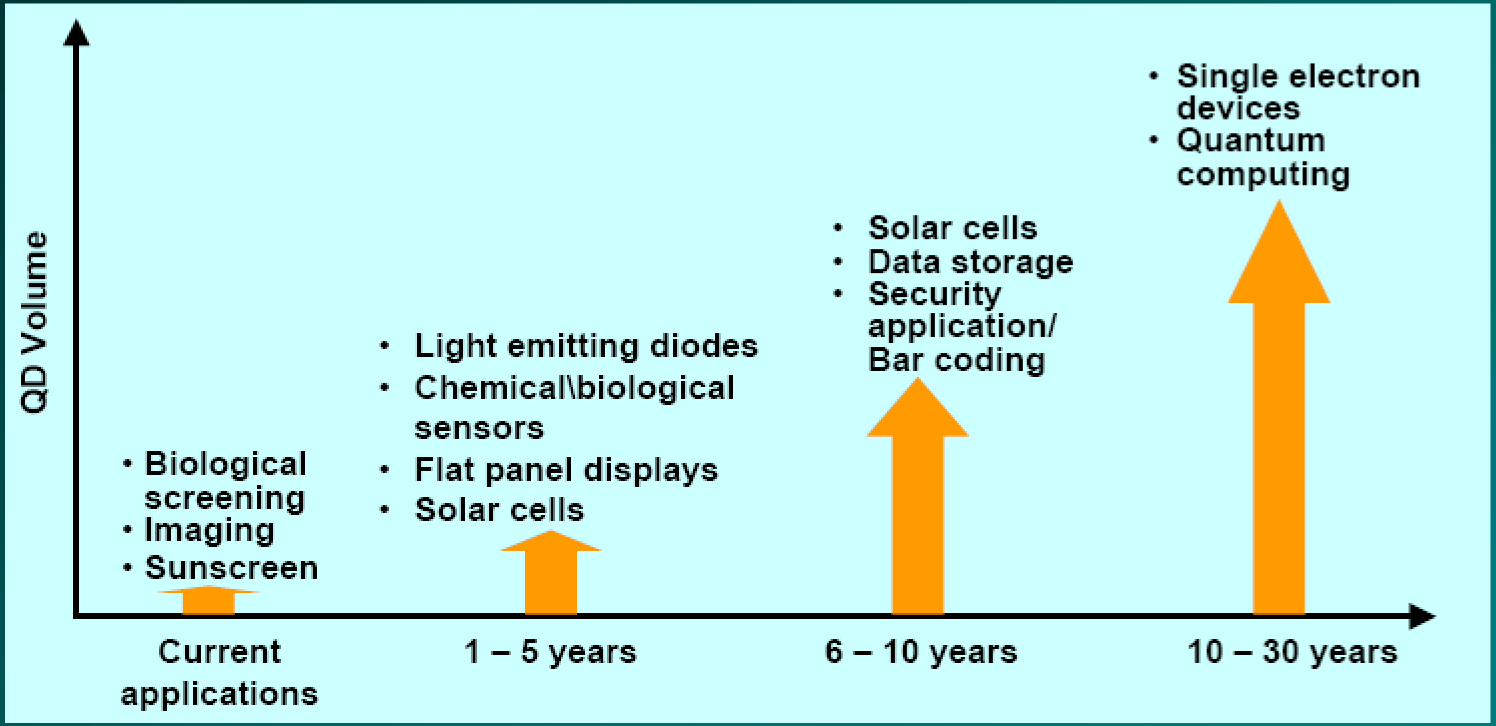
To achieve \$0.02/kWh (fossil fuel cost), total cost ≅ \$0.40/ W_p

Current costs: Modules ~ \$350/m²; BOS ~ \$250/m²;
Thus, \$/W_p ~ \$600/(0.10 x 1000) ~ \$6/W_p ~ \$0.30/kWh

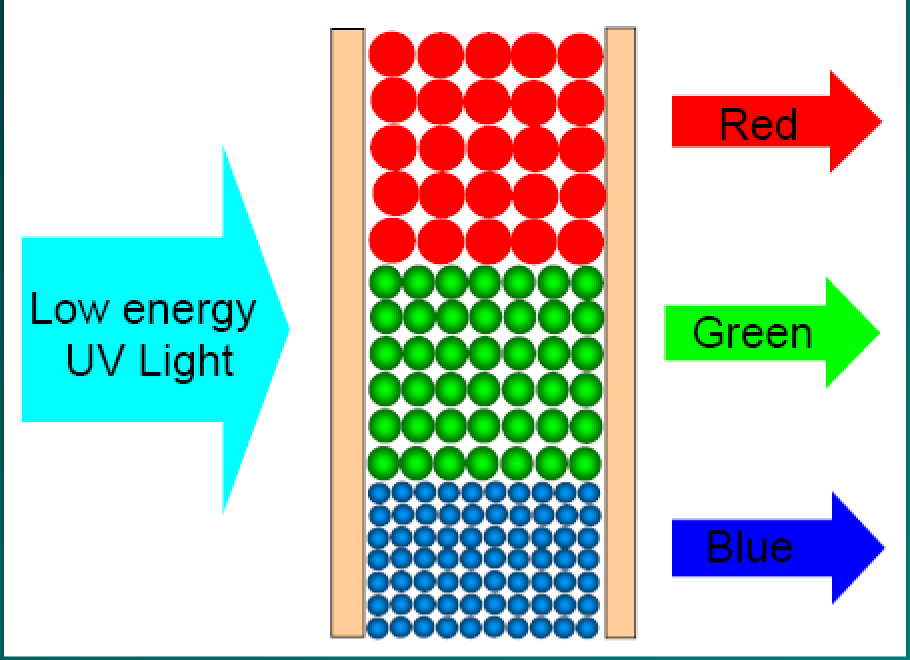
If BOS can be reduced to \$70/ m² and module cost reduced to \$50/ m² then module efficiency needs to be 30% and cell efficiency at least 50%. (Note: this is the new DARPA goal)

Both Low Cost and High Efficiency are Needed !!

Altre applicazioni



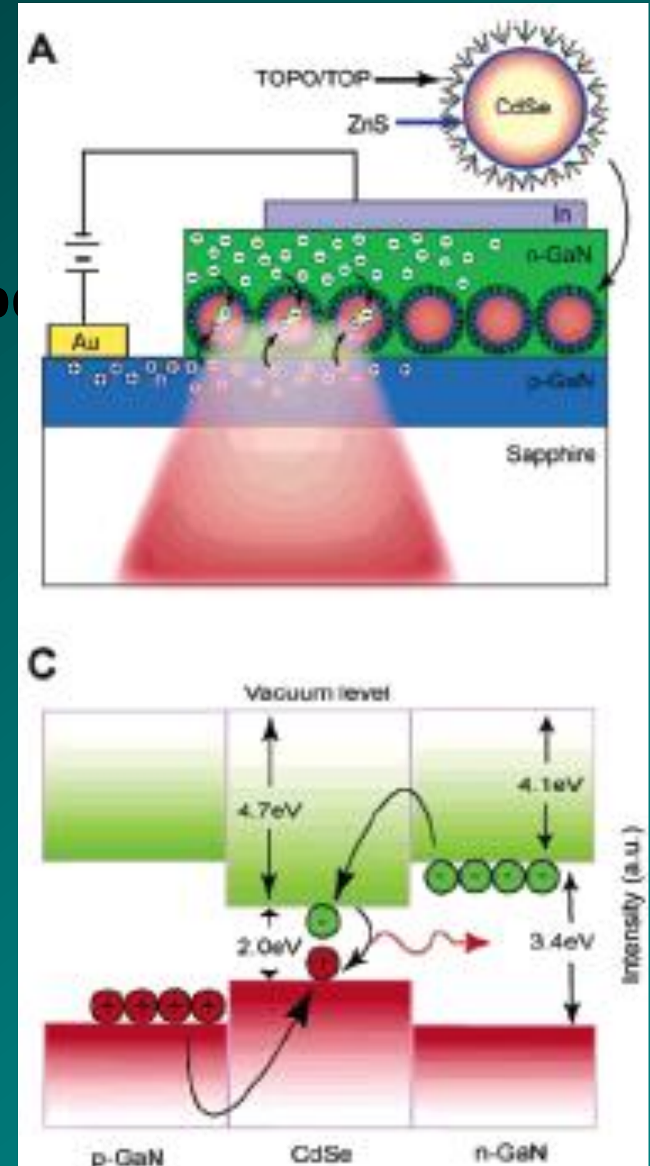
Schermi piatti



Basso consumo
Alta efficienza
Un solo materiale per vari colori

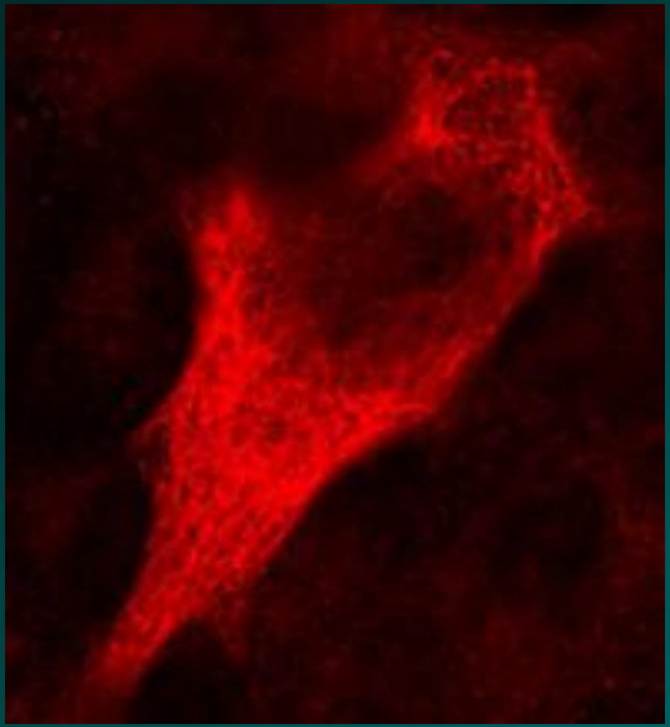
QD-LED

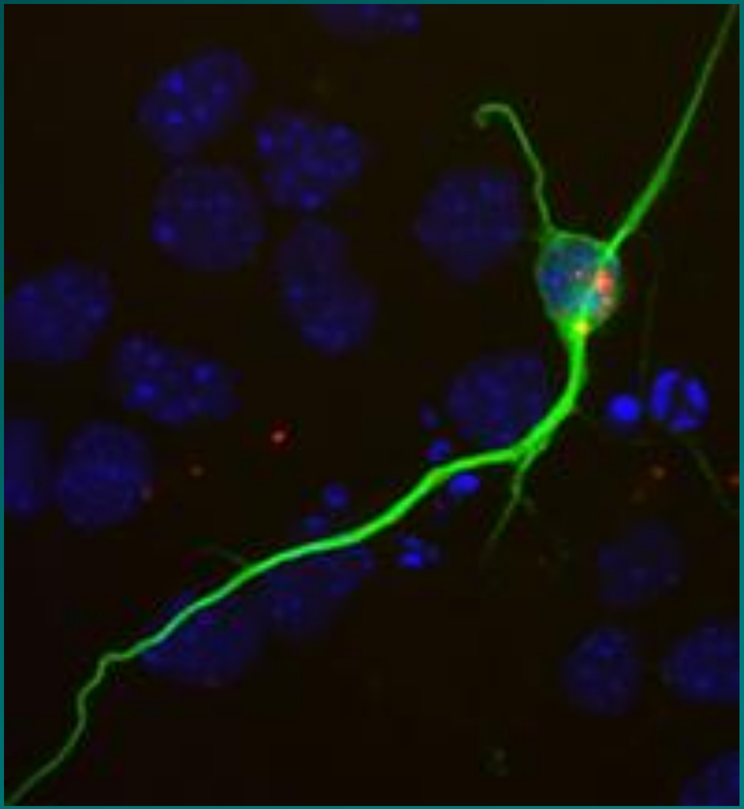
Quantum Dot-Based Light-Emitting Dio

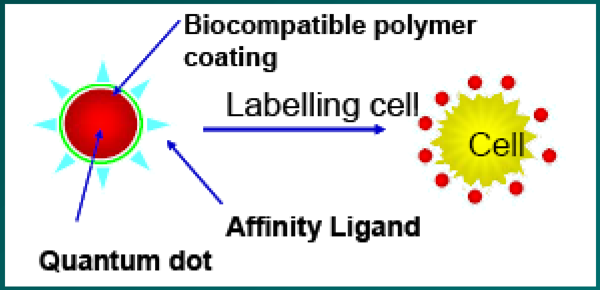


La selezione della **dimensione dei nanocristalli** consente la **scelta del colore** da uno spettro continuo
Applicazioni: Display più luminosi, con miglior riproduzione del colore, a basso consumo

Dyes biocompatibili

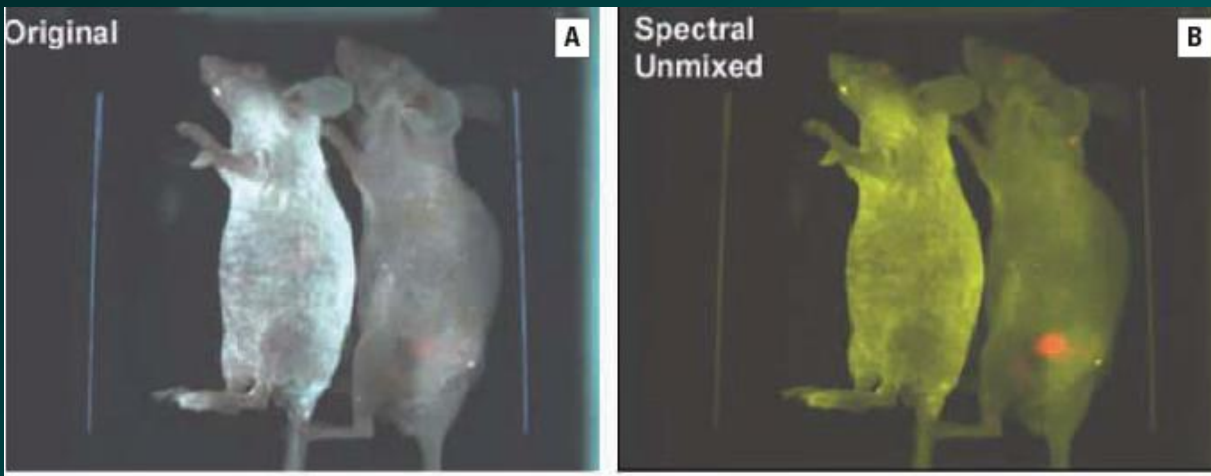


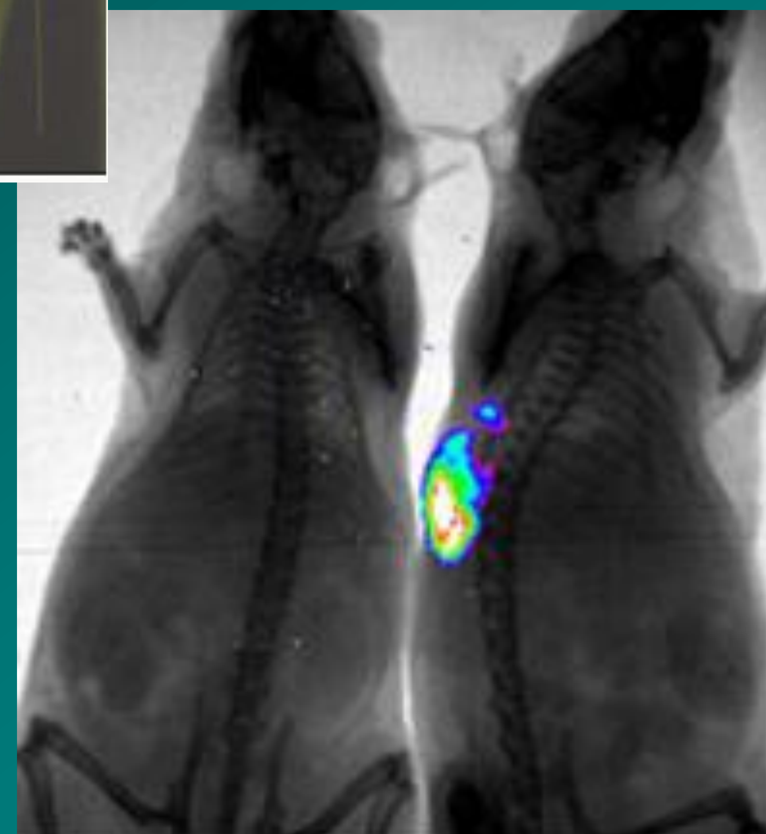




Studio del comportamento di cellule, ed in generale degli esseri

Diagnosi e cura dei tumori





Le nanoparticelle vengono funzionalizzate in modo da venir accumulate presso il tumore

Le proprietà di emissione vengono utilizzate per individuare il tumore

Le proprietà di assorbimento vengono utilizzate per eliminare il tumore

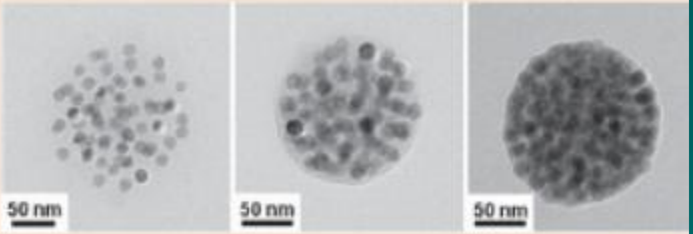
Considerable efforts are being directed toward developing multifunctional nanomedicines. Researchers from the Korea Advanced Institute of Science and Technology and Seoul National University have developed polymer nanoparticles (NPs) that act as multimodal imaging probes and use magnetic guidance to improve drug delivery [Kim *et al.*, *Adv. Mater.* (2008) 20, 478].

The platform comprises four key components: (i) biodegradable poly(D,L-lactic-co-glycolic acid) (PLGA) NPs (100–200 nm in diameter) as the polymer matrix; (ii) hydrophobic, inorganic nanocrystals embedded into the matrix, either superparamagnetic Fe_3O_4 nanocrystals (15 nm diameter) for MRI contrast and magnetically guided drug delivery or CdSe/ZnS semiconductor quantum dots (3 nm in diameter) for optical imaging; (iii) the chemotherapeutic drug doxorubicin (DOXO) incorporated into the polymer matrix in NP form; and (iv) finally, cancer-targeting folate conjugated onto the modified PLGA NPs via polyethylene glycol (PEG) groups.

MRI and fluorescence imaging tests were performed on untreated cancer cells over-expressing folate receptors and cells mixed with either folate-free or folate-coated functionalized PLGA (containing Fe_3O_4 or CdSe/ZnS, as appropriate). Both techniques detected cancer cells treated with the NPs, with the best results achieved for folate-coated particles. When an external magnetic field is applied, the sensitivity of MRI to the cancer cells increases even further. Fluorescence observations confirm that CdSe/ZnS-impregnated NPs can deliver a chemotherapeutic payload into target cells. Confocal laser scanning microscopy and flow cytometry similarly confirm cellular uptake of the Fe_3O_4-containing NPs. As expected, uptake of these particles is improved when an external magnetic field is applied.

In vivo studies are now planned to test whether the fully functionalized NPs can, indeed, be used to image tumor volumes and target drug delivery in the presence of an external magnetic field. Taeghwan Hyeon of Seoul National University is optimistic. "We expect the NPs will accumulate at the tumor site, allowing the tumor to be detected and destroyed at the same time," he says.

Paula Gould

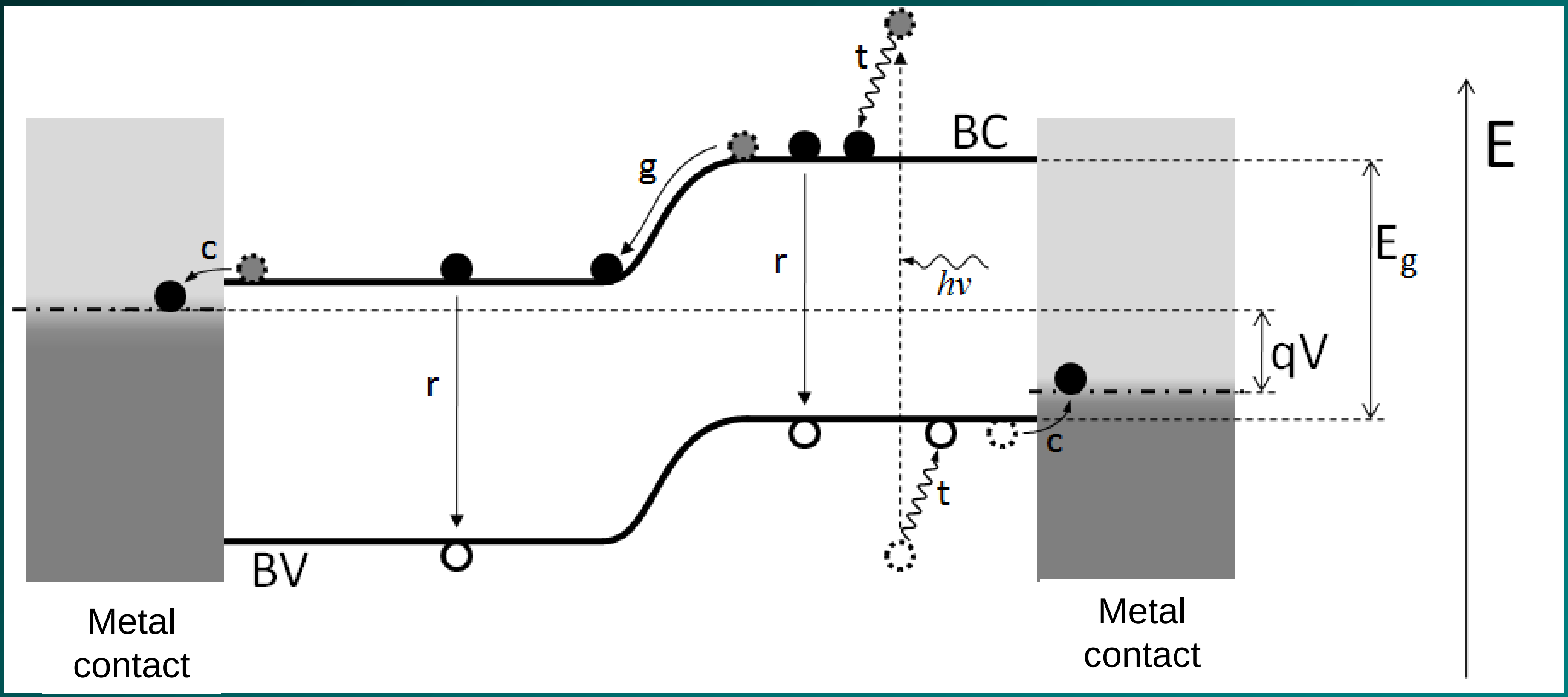


Transmission electron micrographs of uncoated PLGA NPs containing the chemotherapeutic drug DOXO and superparamagnetic Fe_3O_4 nanocrystals. (Credit: Jaeyun Kim, Seoul National University.)

Inchiostri a fluorescenza

Sicurezza e tecnologie anti-contraffazione

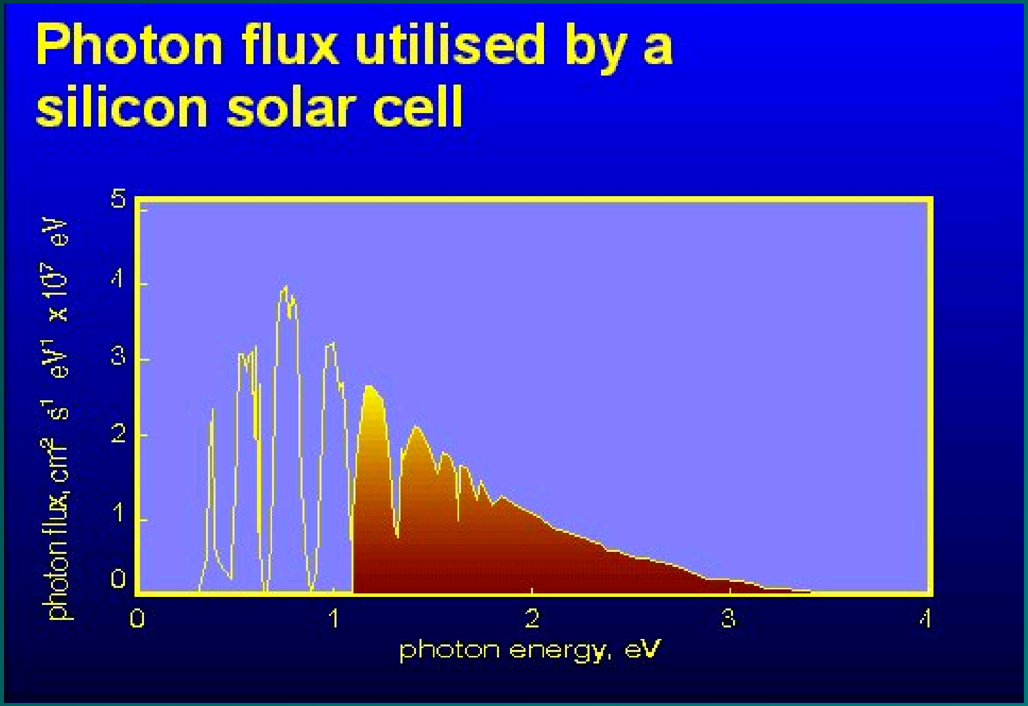
Main Losses in PV Devices



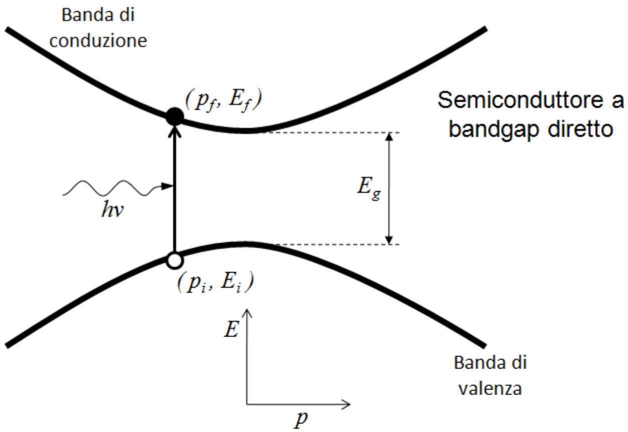
Sommario

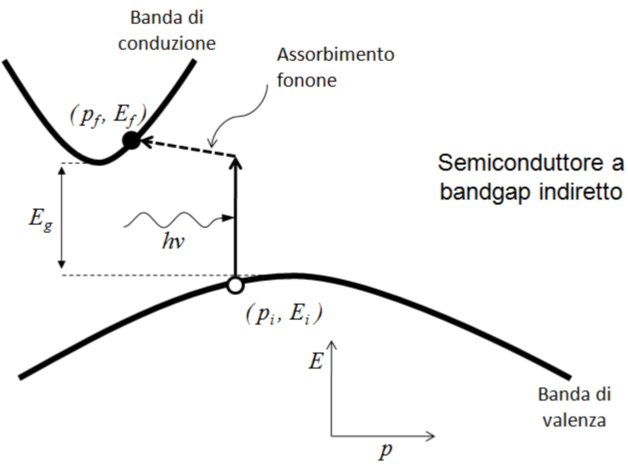
Tecnologia	Rendimento	Costo €/Wp	Tempo di ritorno dell’energia [anni]	Ritorno investimento energetico (EROI)
Silicio monocristallo	15-22%	4-5	2-5	5-15
Silicio policristallo	12-15%	4	1.7-3.5	8-17
Film sottili	5-13%	2-3	1-1.5	17-30
Celle tandem	30-42%	alto	?	?
DSSC	5-10%	*(2-3)*		
Materiali organici	3-6%	*(1-2)*	*<1*	*>50*
Nanomateriali	?	*(<1)*		

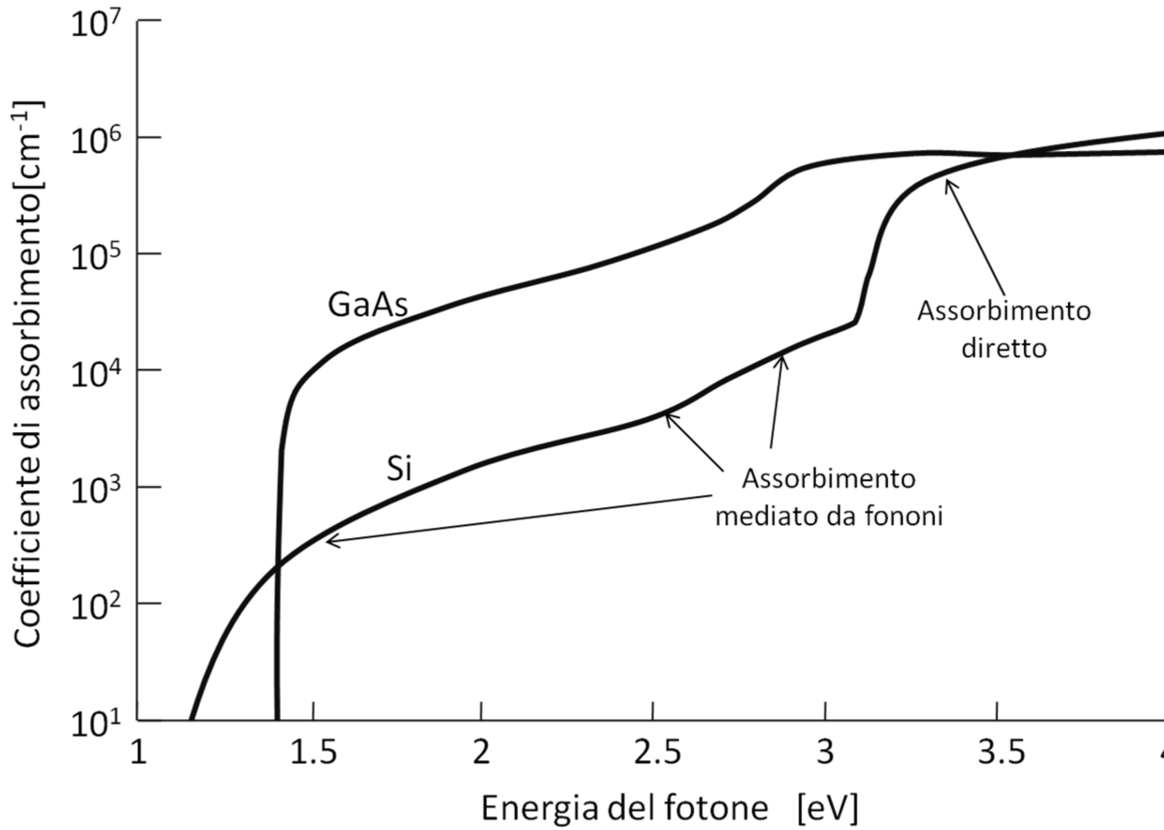
The bandgap dilemma



Absorption coefficients



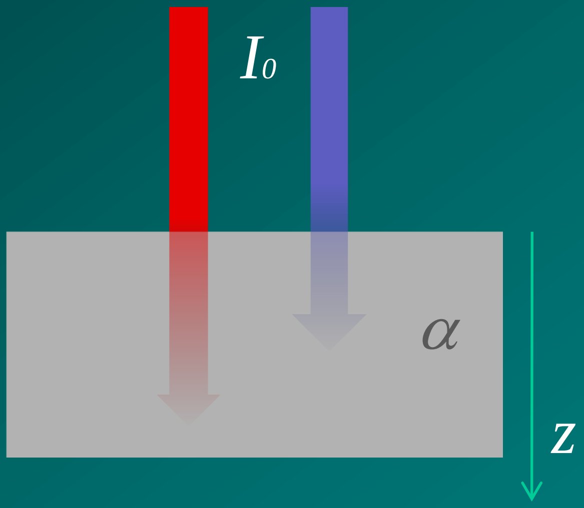




Minimum thickness for full absorption

Legge di Lambert – Beer

$$I = I_0 \exp(-\alpha z)$$

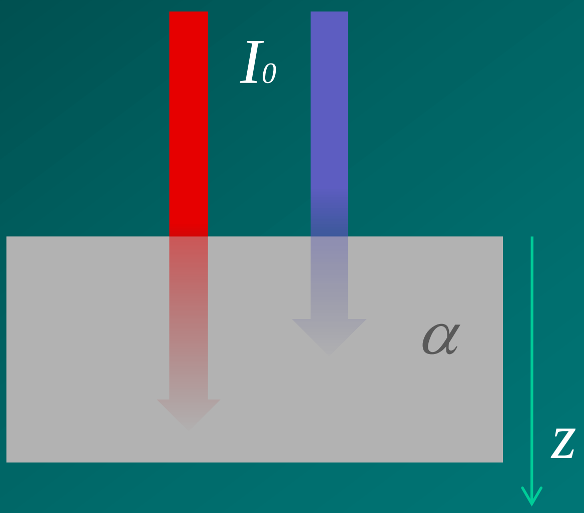


$$f(d) = \frac{\int_0^{\infty} (1 - \exp(-\alpha(\lambda) d) N_{ph}(\lambda) d\lambda}{\int_0^{\lambda_g} N_{ph}(\lambda) d\lambda}$$

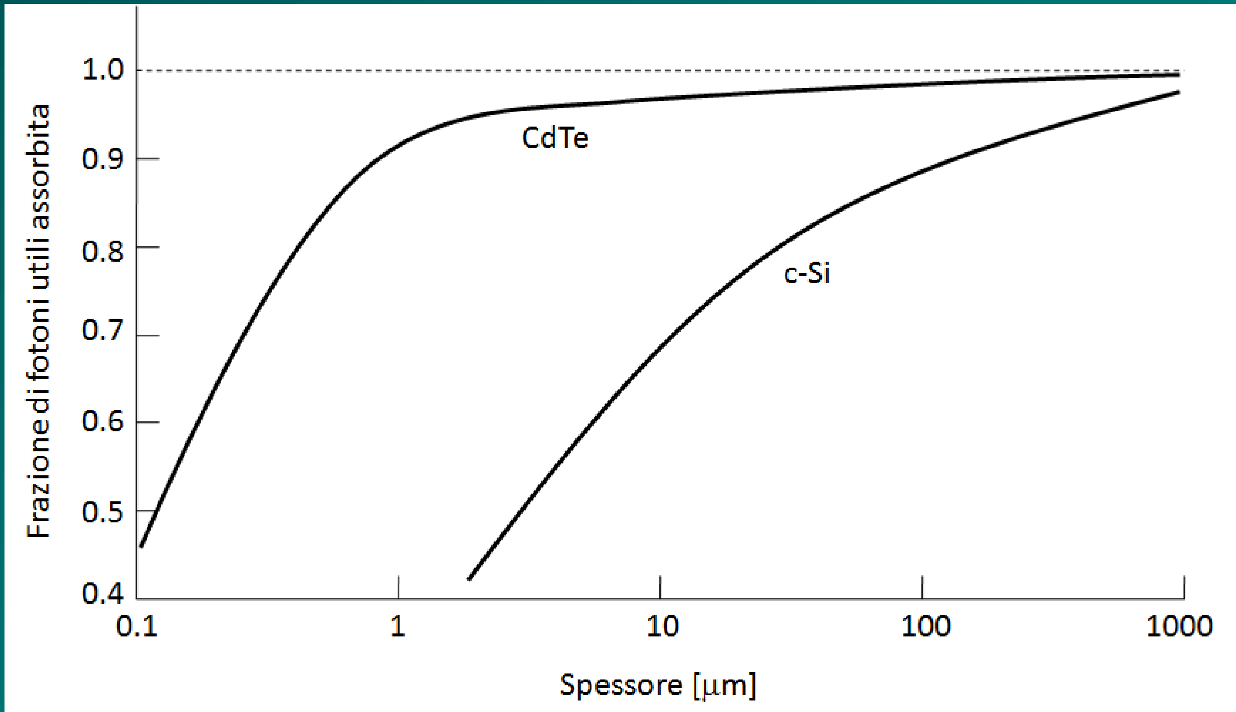
Minimum thickness for full absorption

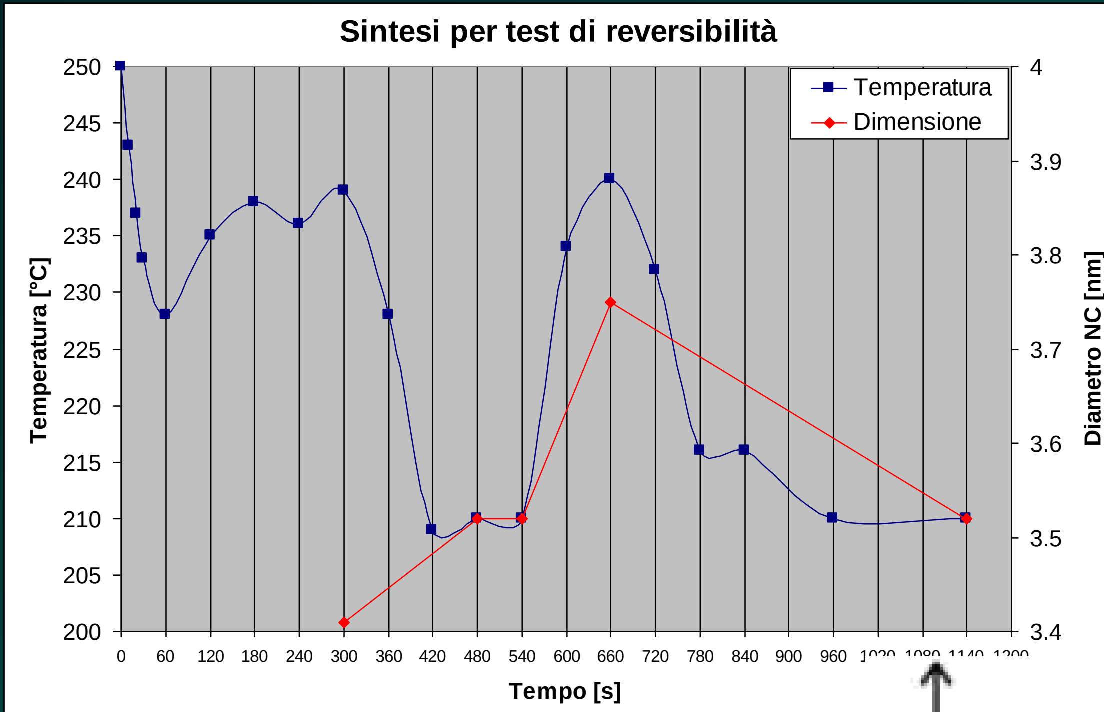
Legge di Lambert – Beer

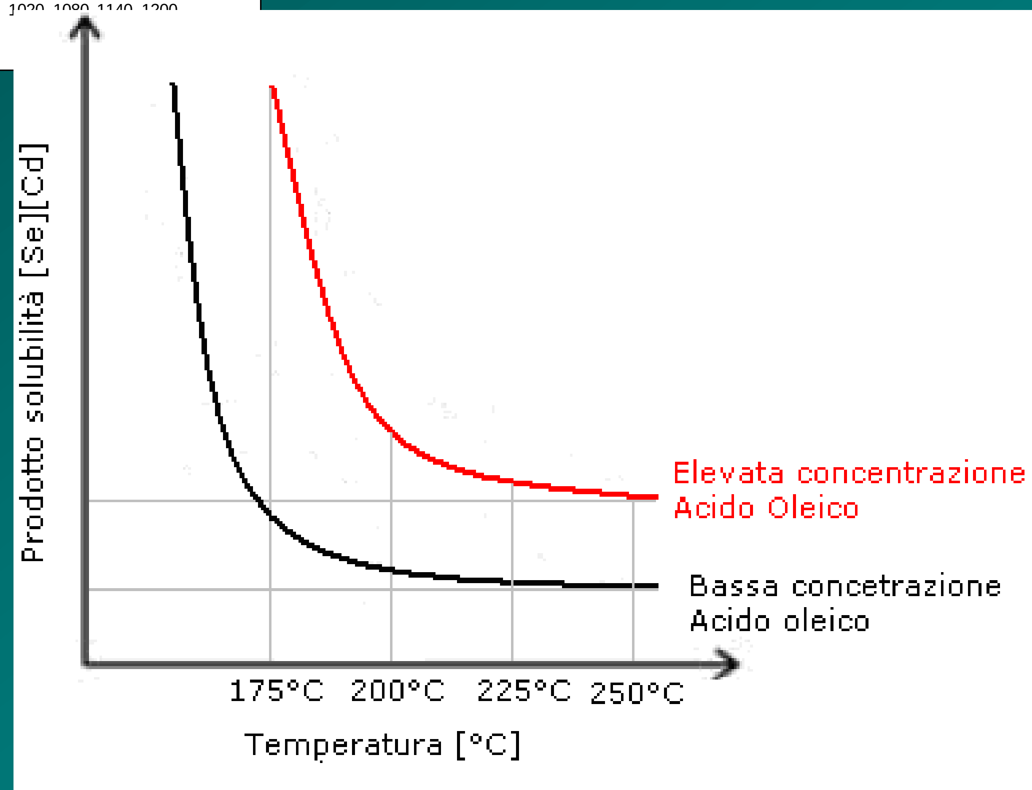
$$I = I_0 \exp(-\alpha z)$$



$$f(d) = \frac{\int_0^{\infty} (1 - \exp(-\alpha(\lambda) d) N_{ph}(\lambda) d\lambda}{\int_0^{\lambda_g} N_{ph}(\lambda) d\lambda}$$




Sintesi per test di reversibilità
Temperatura
Dimensione
Temperatura [°C]
Diametro NC [nm]
Tempo [s]
250
245
240
235
230
225
220
215
210
205
200
4
3.9
3.8
3.7
3.6
3.5
3.4
0 60 120 180 240 300 360 420 480 540 600 660 720 780 840 900 960


Prodotto solubilità [Se][Cd]
Elevata concentrazione
Acido Oleico
Bassa concetrazione
Acido oleico
175°C 200°C 225°C 250°C
Temperatura [°C]