NEW SOLUTIONS TO IMPROVE THE EFFICIENCY OF SOLAR CELLS

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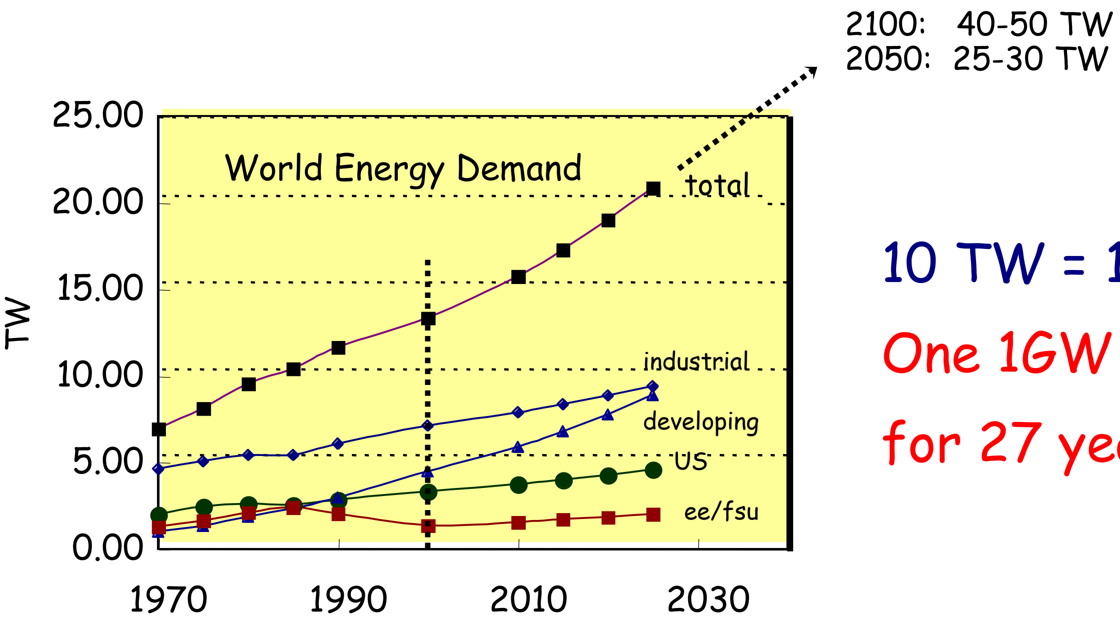
Prelude: why solar energy?

Grand Energy Challenge

Demand gap

- double demand by 2050, triple demand by 2100
- gap between production and demand:
  14TW(2050)-33TW(2100)

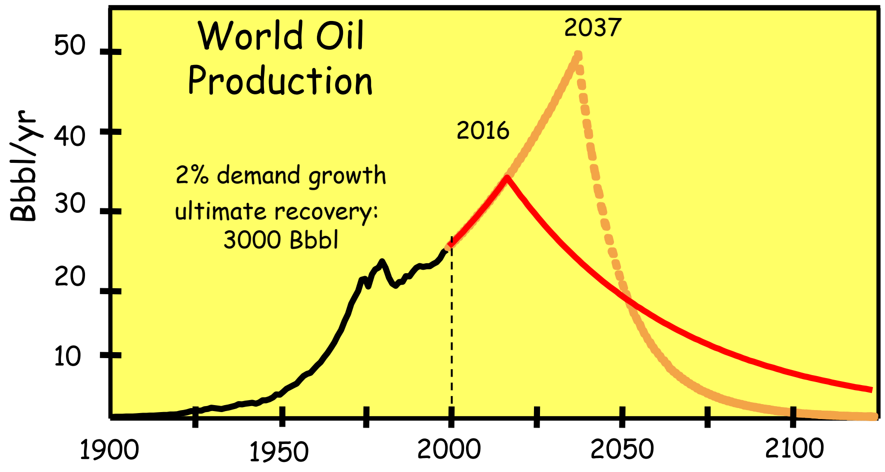


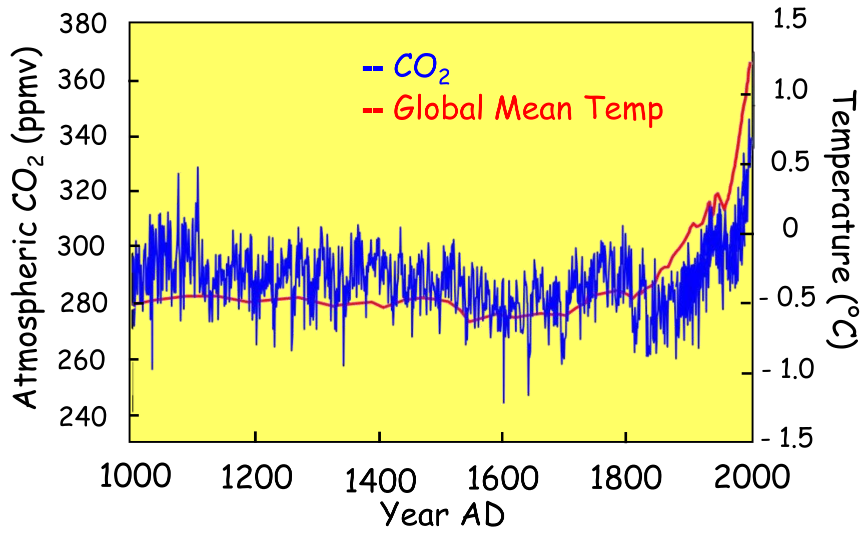
10 TW = 10,000 1GW power plants

One 1GW new power plant/day

for 27 years!

Oil: Works today, Hurts tomorrow

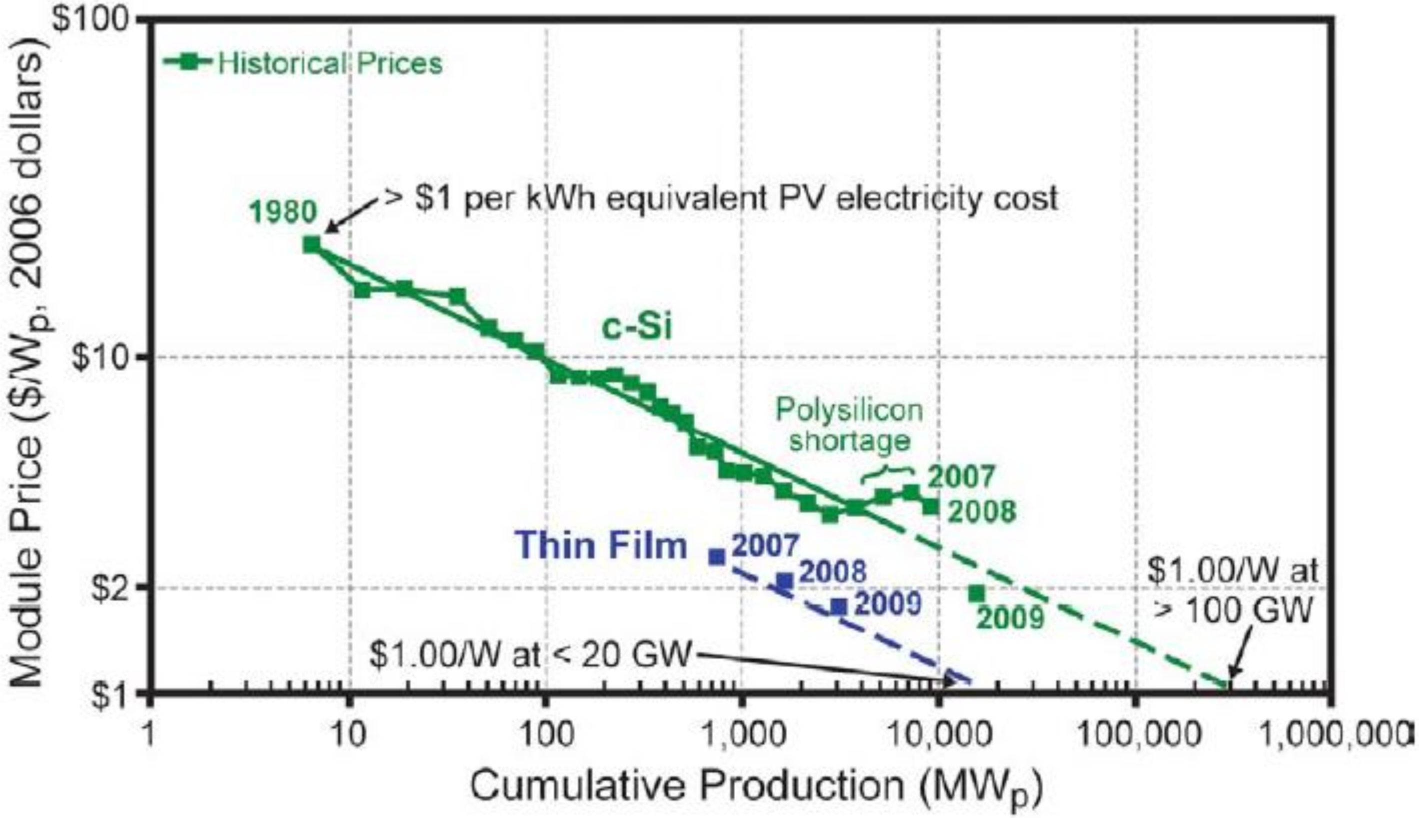




1. Oil and coal will run out
2. Produced by regions of conflict
3. Uneven distribution of production, wealth
4. Primary cause of climate change

The Solar Moore's Law

DOE



Price drops by 20% for every doubling of production
No doubling per 18 months as area is not scaled down as in chips

Sources of Renewable Energy

Solar
1.2×10^5 TW on Earth's surface
36,000 TW on land (world)
2,200 TW on land (US)

energy gap
~ 14 TW by 2050
~ 33 TW by 2100

Wind
2-4 TW extractable

Biomass
5-7 TW gross (world)
0.29% efficiency for all cultivatable land not used for food

Tide/Ocean Currents
2 TW gross

Hydroelectric
4.6 TW gross (world)
1.6 TW technically feasible
0.6 TW installed capacity
0.33 gross (US)

Geothermal
9.7 TW gross (world)
0.6 TW gross (US)
(small fraction technically feasible)

Solar is the Most Promising Energy Resource

Sunlight is a singularly suitable energy resource

1. the only resource in sufficient quantity
2. environmental impact is minimal and benign
3. no catastrophic breakdown mode
4. politically safest, conflict-free
5. price volatility is minimal

Outline

1. Third generation solar cells
2. Multiple exciton generation (MEG)
3. MEG in colloids and MEG device
4. Results

Generations

Value: Power/Price

1st generation: Increase power by increasing quality crystalline silicon: *SunPower*: 20-22%

2nd generation: Decrease price (decrease production temperature) amorphous Si, CIGS, CdTe: *First Solar*: 13-15%

3rd generation: Increase power, decrease price

Generations

Definition of 3rd generation:

(1) a power conversion efficiency greater than the Shockley–Queisser limit of 31%
(2) a very low cost per unit area.

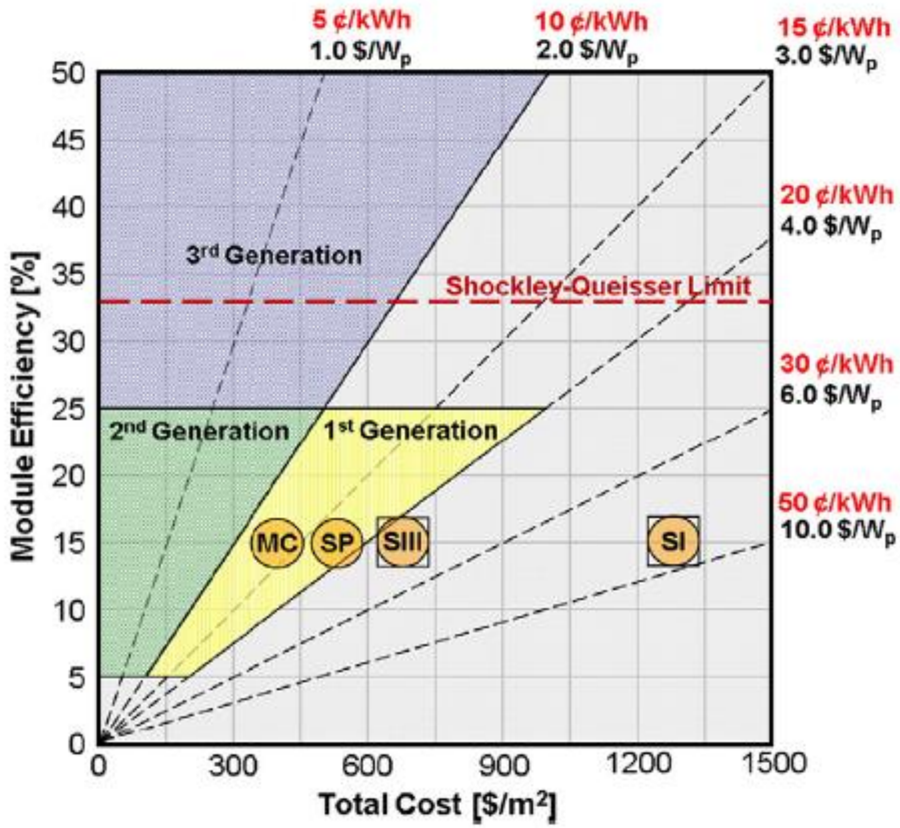
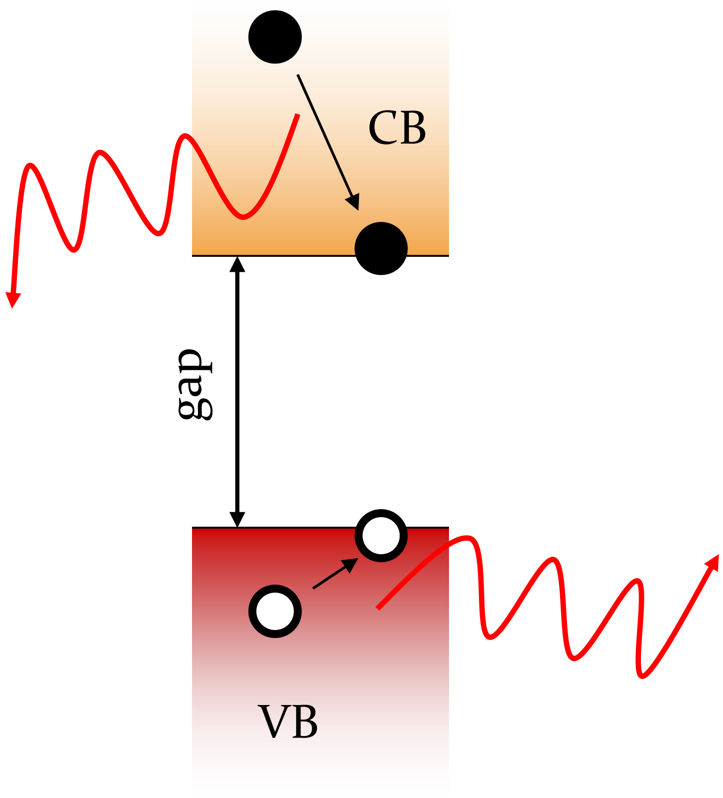


Fig. 1. The cost of electrical power from photovoltaic systems is shown as a function of the total upfront cost and the module power conversion efficiency. MC, SP, SIII, and SI are the manufacturing cost, average selling price, installed cost for a utility scale system, and installed cost for a residential system, respectively. SIII includes BOS cost for an on-grid system, and SI includes BOS for on- and off-grid operation with battery storage. The $/Wp were converted to ¢/kWh assuming a module lifetime of 20 years, a 5% cost of borrowing, a 1% yearly operating (maintenance) cost, and an average solar insolation of 200 W/m² (which is about 5 h of full intensity sunlight/day). Costs are based on 2009 data. The designation of 1st, 2nd, or 3rd Generation is based on the manufacturing cost and potential module efficiency.

1. Third generation solutions

First & Second generation



Shockley-Quessier limit
~31%

- single junction
- Fermi-Dirac absorption above band edges
- one exciton/photon
- relaxation to band edges

↓

- 47% heat
- 18% transmission of sub band gap photons
- 1.5% radiative recombination

Improving the absorber material I

Physics:
1. Nanostructure forms on surface,
multiple reflections enhance absorption
2. High density of defect states in gap
3. "Hyper-doping" of top junction layer: sulfur (Mazur @ Harvard)

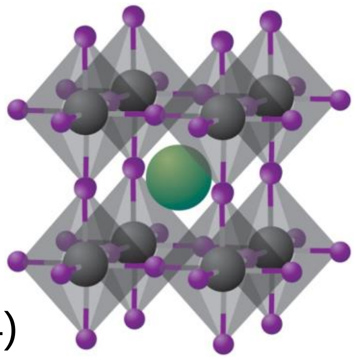
Nano-sized "coaxial cable" (M. Naughton @ BC)
formed in amorphous Si
can optimize these constraints

Redirect and capture light with plasmon resonance of Ag nanoparticles

New materials:

Perovskite crystals

ABX_3



17.9% efficiency

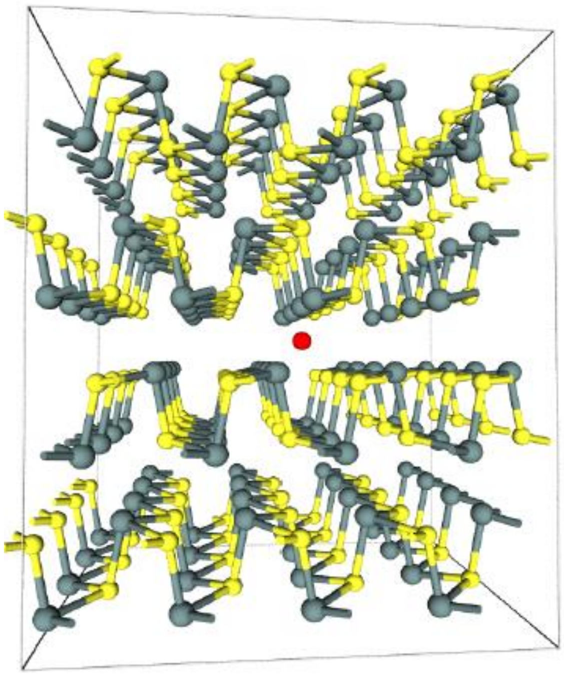
5X enhancement over the past 5 years

Stability and Toxicity??

Nature Materials **13**, 838–842 (2014)

Improving the absorber material V

Tin monosulfide (SnS) crystals (Roy Gordon @ Harvard)



Absorbs light much more effectively than Si

But

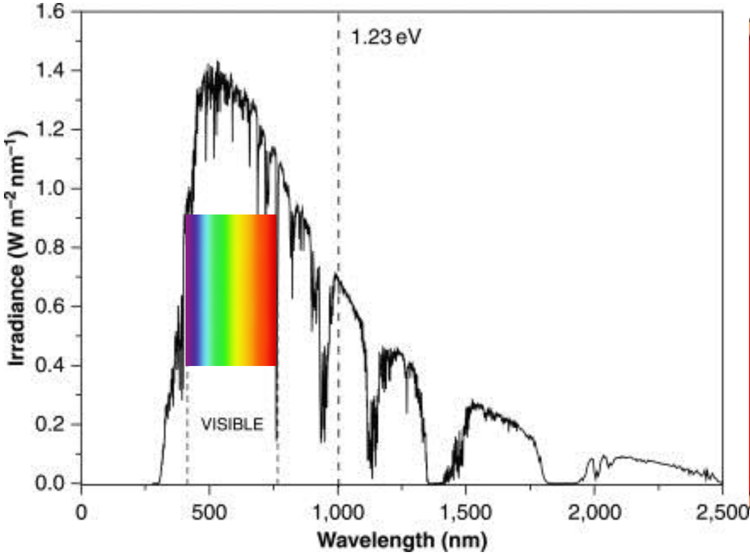
crystal is p-type "self-doped"

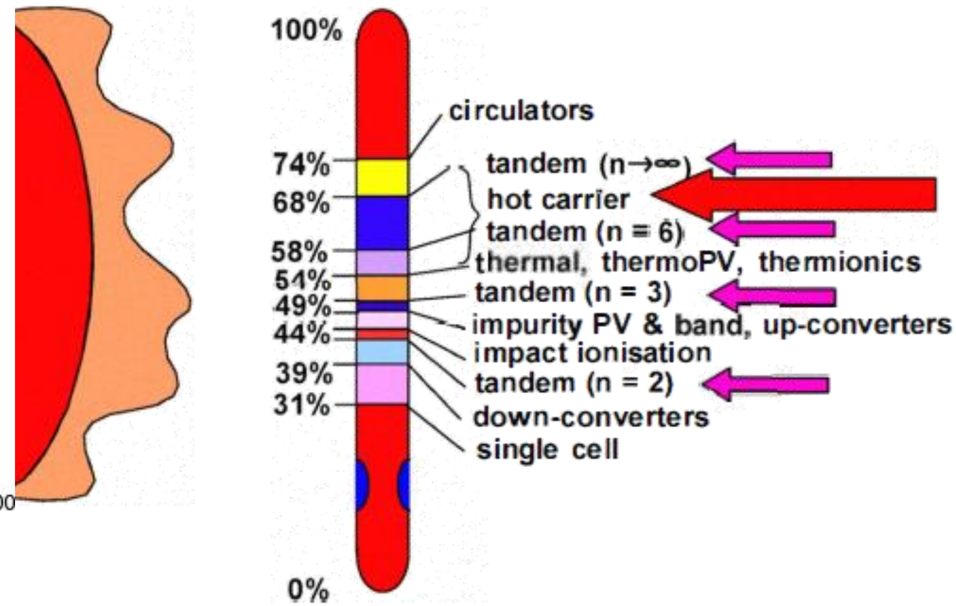
Calculations by
Malone, Kaxiras @ Harvard
&
Gali @ Wigner

p-type "self-doping" due to Sn-vacancies

Sb is suggested for compensation

Third generation solutions





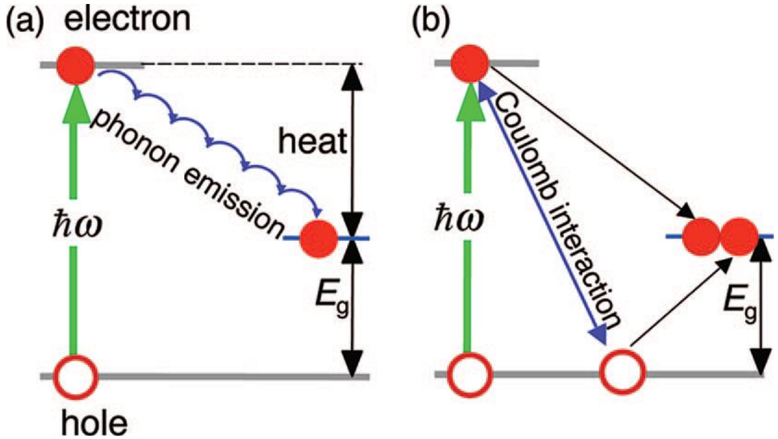
2. Multiple Exciton Generation

Achieving MEG

Carrier Multiplication, faster than phonon assisted decay and gives us additional excitons (enhanced current)

- Confine charge carriers in normal semiconductors (Nozik)

+ phonon bottleneck



Semiconductor Nanocrystals

Proof of MEG in solution ≠ MEG in device

- MEG in colloids, simplified situtation
- MEG in devices, more complicated issue

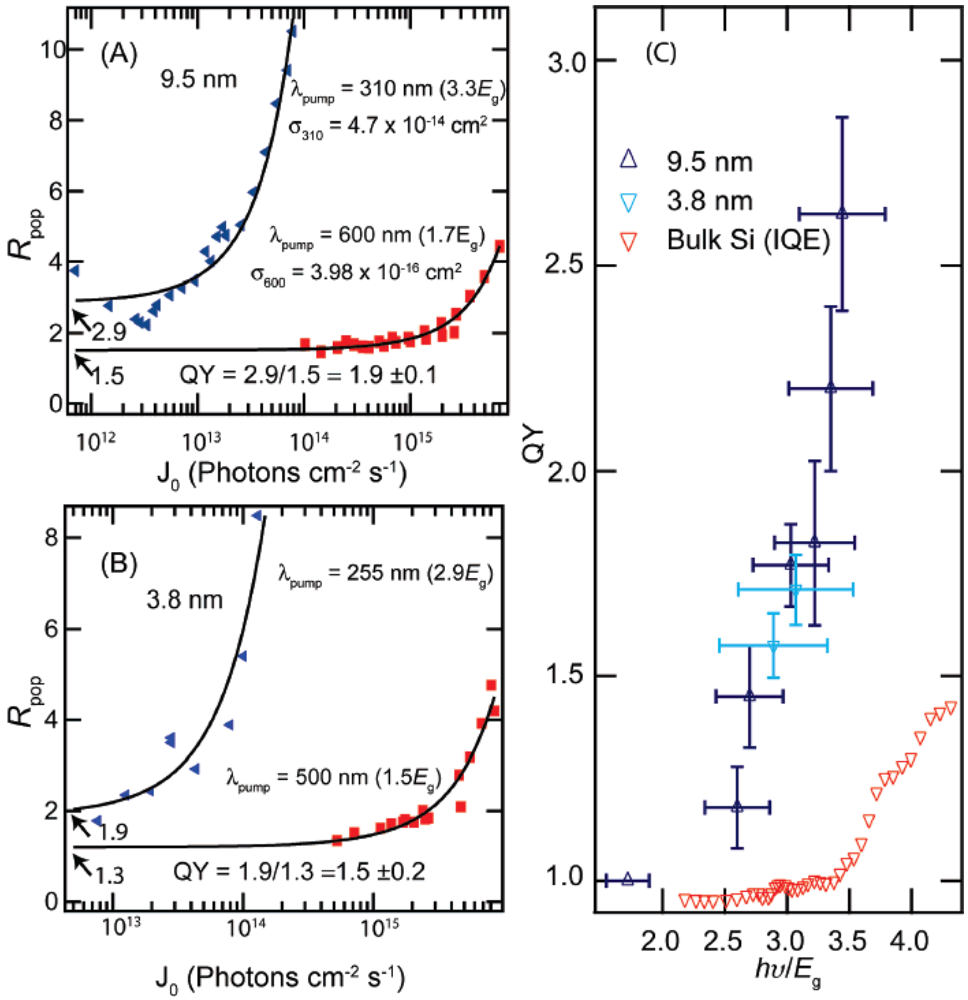
one experimental proof so far

3. MEG in the lab and MEG device

MEG in silicon NPs

Rpop = look at populations right after pump (t=0) and after AR is comple (ps)

Look at pump flux → 0 limit!

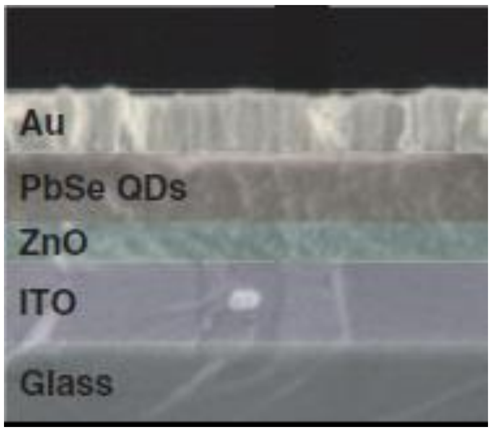


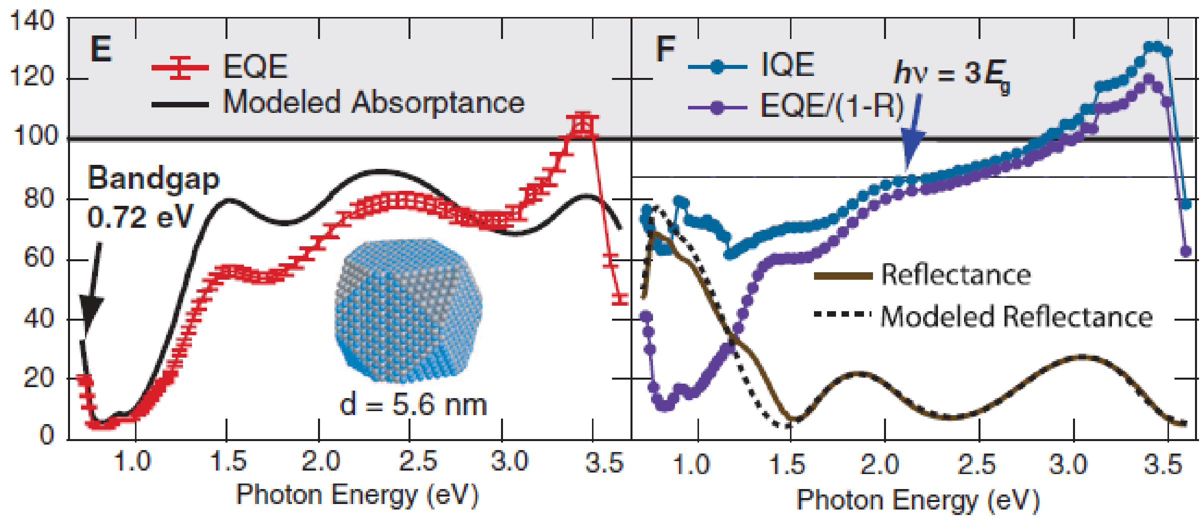
MEG appears in Silicon Nanocrystals

surface-to-volume ratio is large

>100% MEG solar cell

Science **334**, 1530 (2011)





EQE, External Quantum Efficiency:
Quantum efficiency of the whole device

IQE, Internal Quantum Efficiency:
After removal of reflectance

- **Overall efficiency reached >4%**
- **4% of total photocurrent from MEG!**
- **key: hydrazine treatment**

4. Results

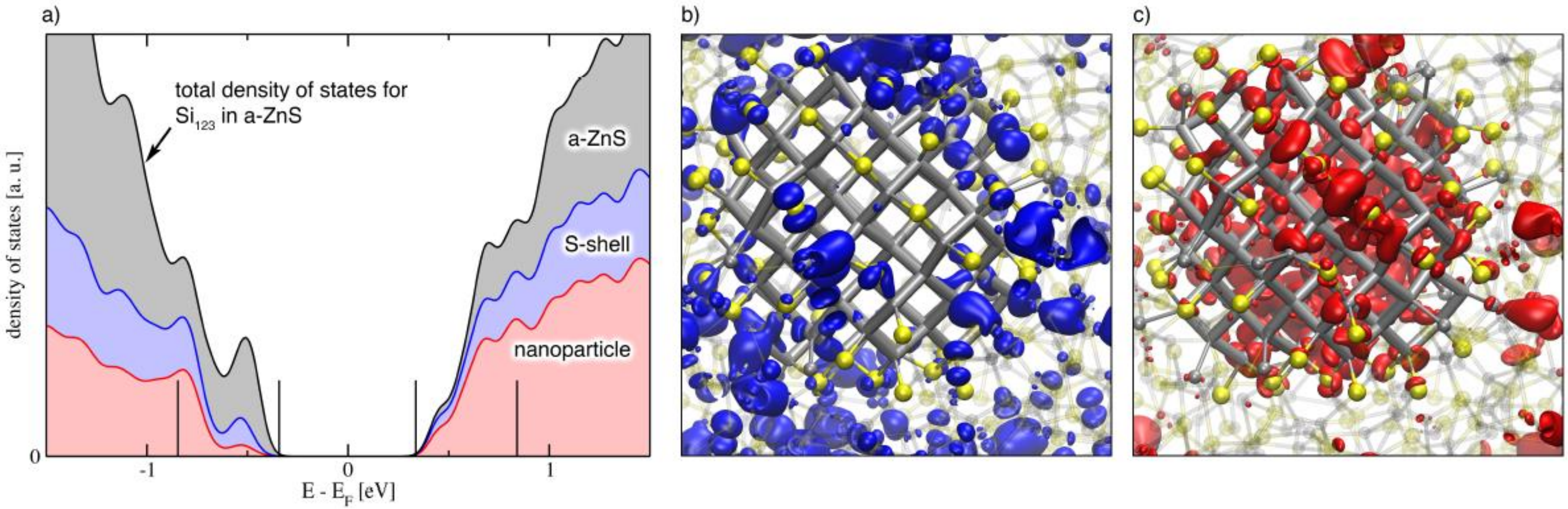
Selected Result I

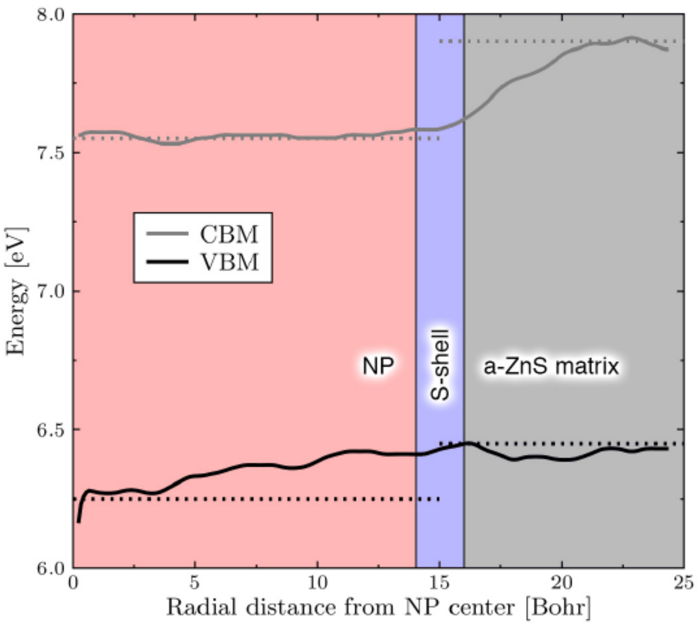
Solar nanocomposites with complementary charge extraction pathways for electrons and holes: Si embedded in ZnS

S. Wippermann, M. Vörös, A. Gali, F. Gygi, G. Zimanyi, and G. Galli

Physical Review Letters **112** 106801 (2014).

Si NCs in a-ZnS matrix: charge extraction





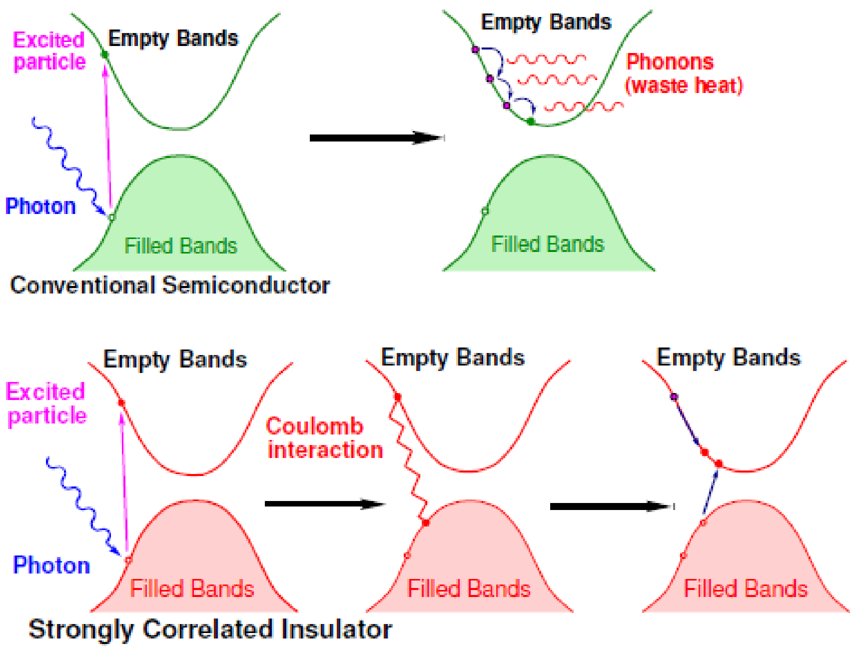
Complementary charge extraction pathways and small gap

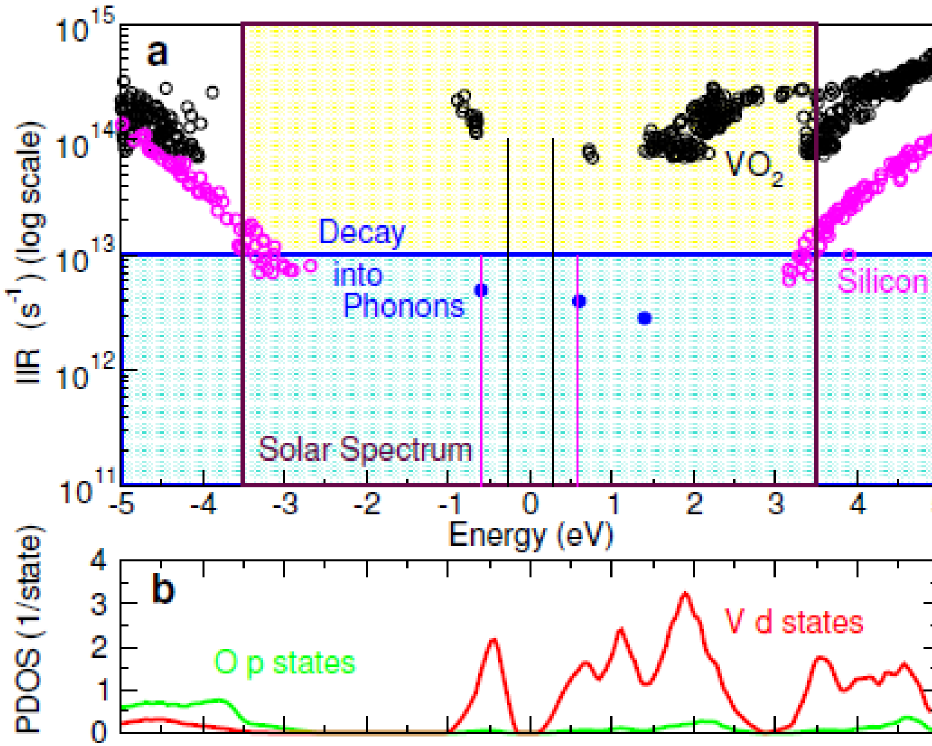
Result II: using Mott-insulators instead of NPs

Limitations of the hybrid functional approach to electronic structure of transition metal oxides
John E. Coulter, Efstratios Manousakis, and Adam Gali
Physical Review B **88** 041107(R) (2013).

Optoelectronic excitations and photovoltaic effect in strongly correlated materials
John E. Coulter, Efstratios Manousakis, and Adam Gali
Physical Review B **accepted**, arXiv:1409.8261

VO2 as a prototypical strongly correlated crystal





Experiments: long recombination lifetime (microseconds) in VO2

strongly correlated materials are promising and completely new candidates

Thank you for your attention