Nano/Energy Journal Club
Topic: Intermediate Band Solar Cells

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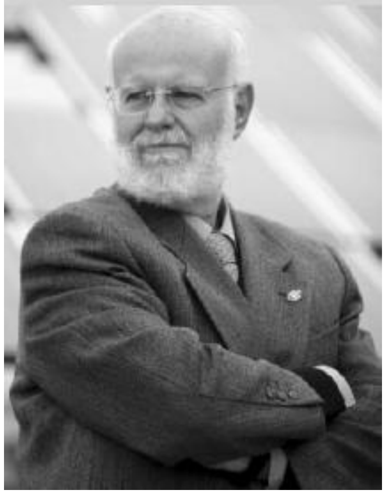
01/15/2010

Intermediate Band Solar Cell (IBSC)

- Paper: **A. Luque and A. Martí, "The Intermediate Band Solar Cell: Progress Toward the Realization of an Attractive Concept,"** ***Advanced Materials, vol. 22, pp. 160-174, 2010.***
- Paper received: July 17, 2009
- These guys first described the concept in Phys. Rev. Lett. in 1997.

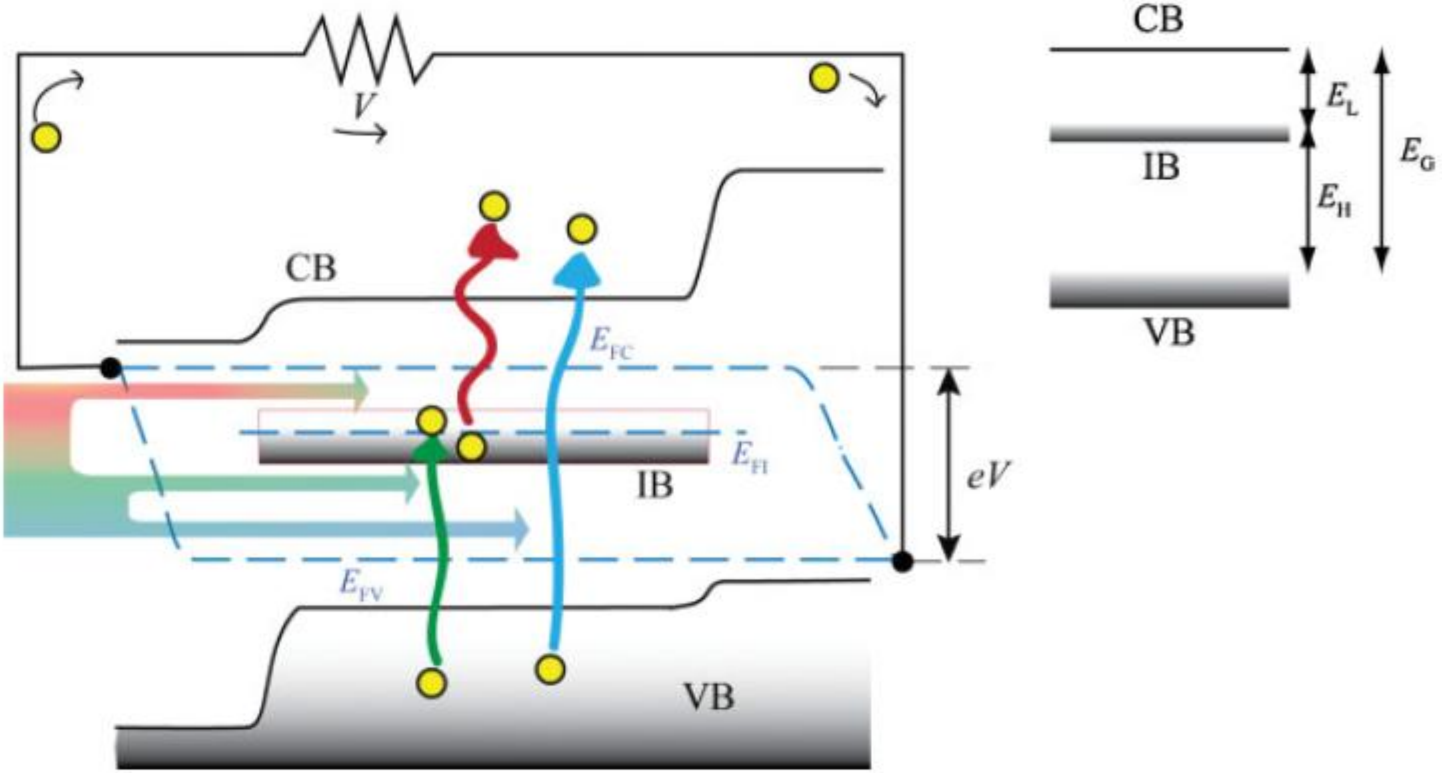
Luque and A. Martí, "Increasing the Efficiency of Ideal Solar Cells by Photon Induced Transitions at Intermediate Levels," *Physical Review Letters, vol. 78, p. 5014, 1997.*

Antonio Luque



Antonio Marti

IBSC: The Basics



IBSC: Benefits

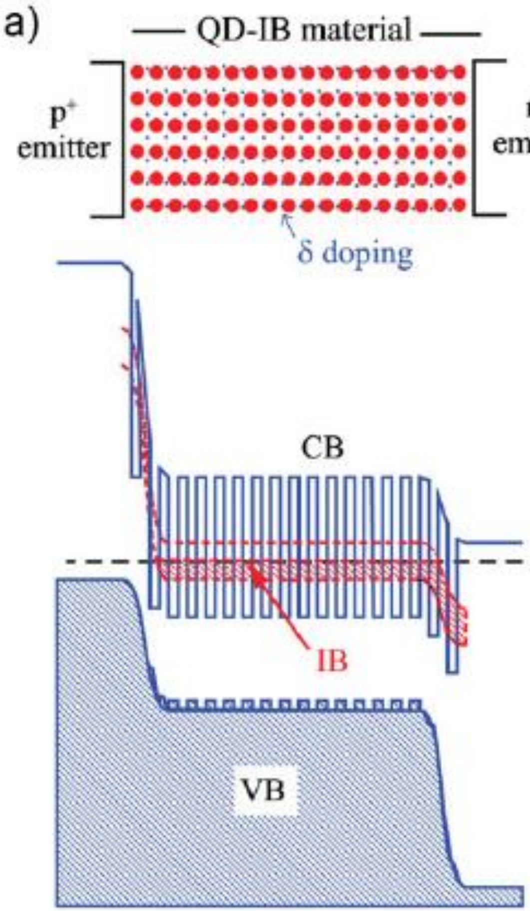
- Increased photocurrent due to absorption of sub-bandgap photons
- No reduction in voltage (ideally) over single bandgap cell
- Limiting efficiency: 63.2% for IBSC vs. 40.7% for single junction (assuming max concentration)

IBSC: Essentials

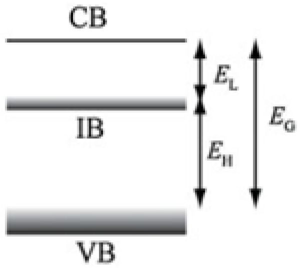
- 3 quasi-Fermi levels (CB, VB, IB)
- IB is disconnected from n- and p-contacts so that extracted voltage is the difference between CB and VB
- Selective absorption
- IB needs to be partially filled with electrons
- OPTION: Energy transference - 2 sub-bandgap photons pump 2 electrons from VB to IB, and then 1 electron returns to VB and pumps the other to the CB

Minibands through Quantum Dots

- QDs (as opposed to wells or wires) are necessary to isolate the IB from the CB through zero DOS
- QDs typically undoped, so the barrier layer in between is n-type



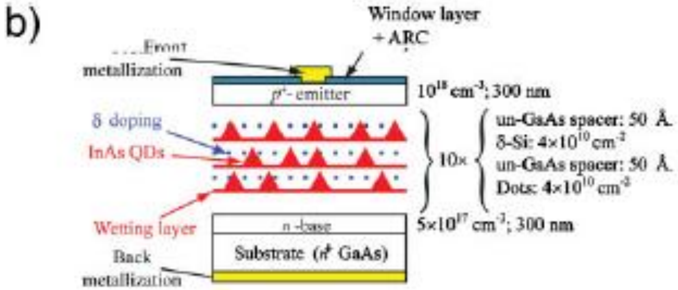
Optimal QD Design

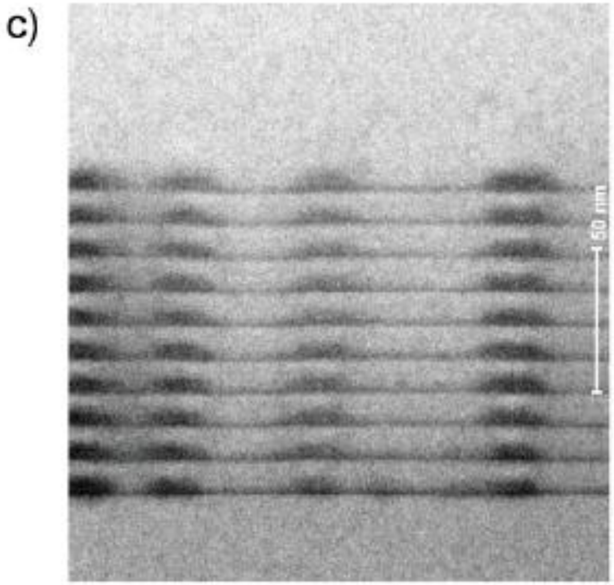


- Optimal bandgaps: 0.71, 1.24, 1.95eV
- Corresponds to $In_{0.55}Ga_{0.45}As$ QDs in $Al_{0.44}Ga_{0.56}As$ barrier material after strain is considered
- Apparently, this is non-trivial in terms of growth, so InAs QDs in GaAs barrier has been studied (0.30, 1.02, and 1.30eV)

InAs QDs in GaAs

- Grown by MBE under the Stranski-Krastanov growth mode
- S-K growth means a wetting layer is grown first, which introduces a quantum well
- QDs not spherical

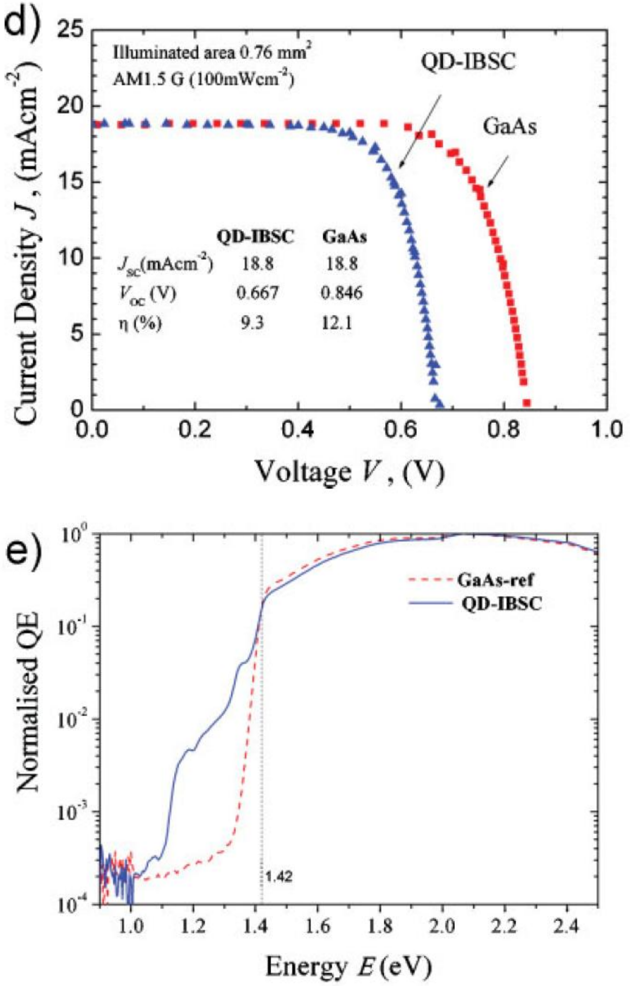




[35] A. Marti, N. Lopez, E. Antolin, E. Canovas, A. Luque, C. R. Stanley, C. D. Farmer, P. Diaz, *Appl. Phys. Lett.* **2007**, *90*, 233510.

I-V and EQE Results

- Though I-V shows minimal increase in current, EQE clearly shows boost in long wavelength absorption
- Loss of voltage leads to lower efficiency compared to single junction GaAs



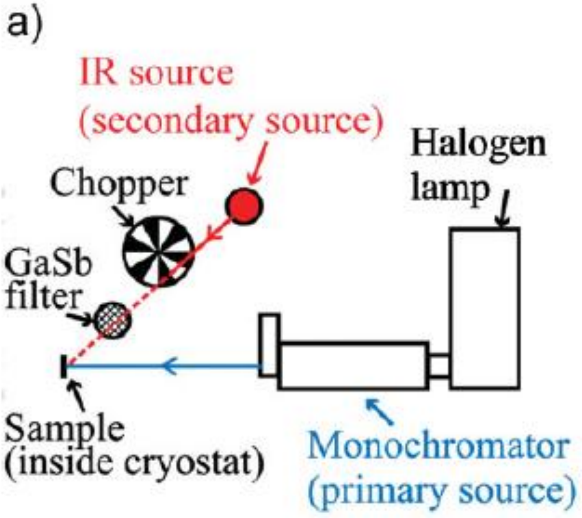
[36] A. Luque, A. Martí, N. López, E. Antolín, E. Cánovas, C. R. Stanley, C. Farmer, P. Díaz, *J. Appl. Phys.* **2006**, *99*, 094503.

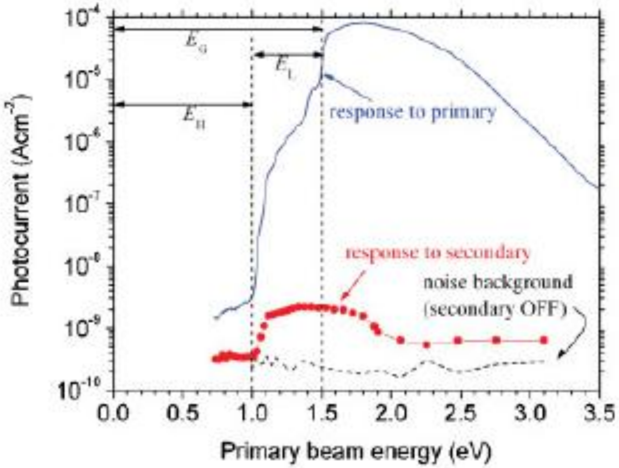
Thermodynamics

- Thermodynamic requirement: absorption of a second photon is necessary to getting full voltage (between CB and VB) out.

Proving Two-Photon Absorption

- IB→CB transition was thought to be due to thermal escape or field-assisted tunneling, so the following experiment was performed
- IR source provided boost in current



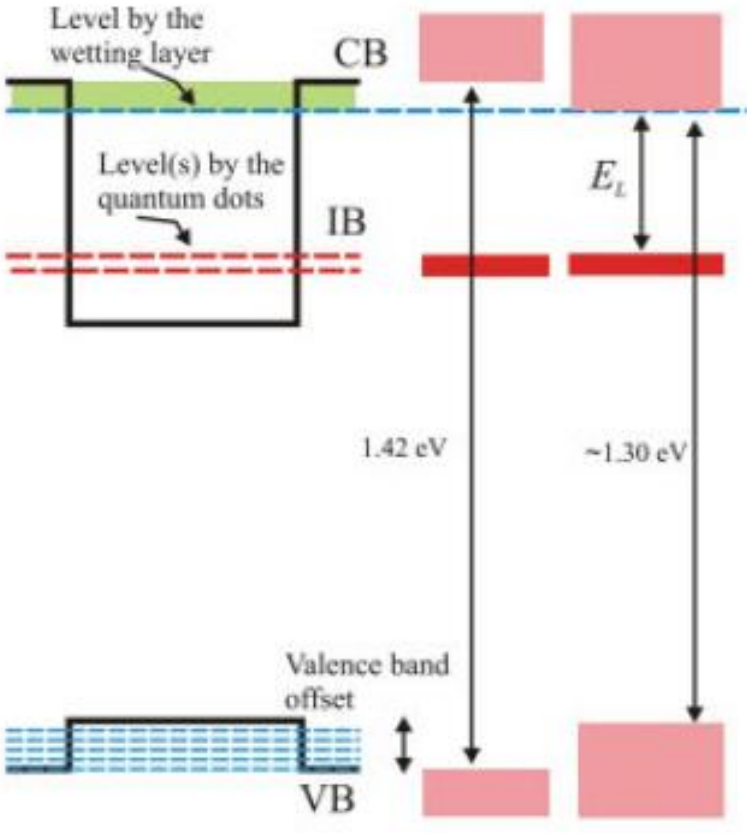


Improving Current

- Increase layers of QDs
  - Result: sub-bandgap current is great, but overall photocurrent is terrible due to dislocations in emitter
- Add stress-compensating layers (GaP, GaNAs, etc)
  - Result: Improves current slightly, but voltage is reduced due to lowering of effective bandgap

Improving Voltage

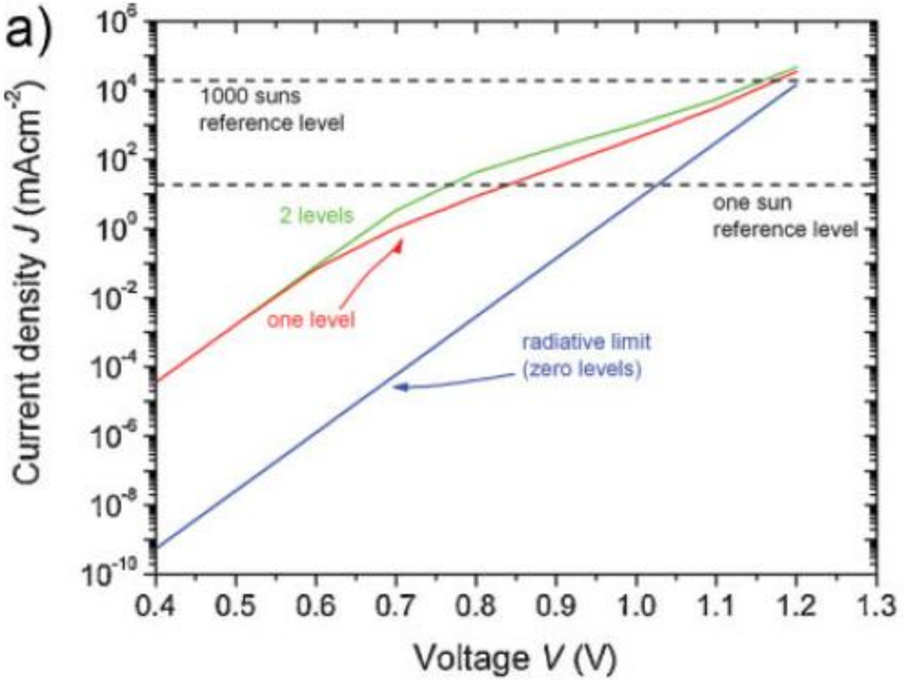
- Reduction possibly due to lower effective bandgap in the nanostructured material
  - compensate by using higher bandgap barrier material (AlGaAs)



[10] A. Marti, E. Antolin, E. Canovas, N. Lopez, P. G. Linares, A. Luque, C. R. Stanley, C. D. Farmer, *Thin Solid Films* **2008**, *516*, 6716.

Improving Voltage (cont.)

- QDs actually result in multiple energy levels in the bandgap (perhaps dependent on shape/size)
  - ➢more recombination paths ($V_{oc}\ \alpha\ \ln(J_L/J_0)$)
  - ➢lower voltage



Dark I-V for 1.3eV IBSC

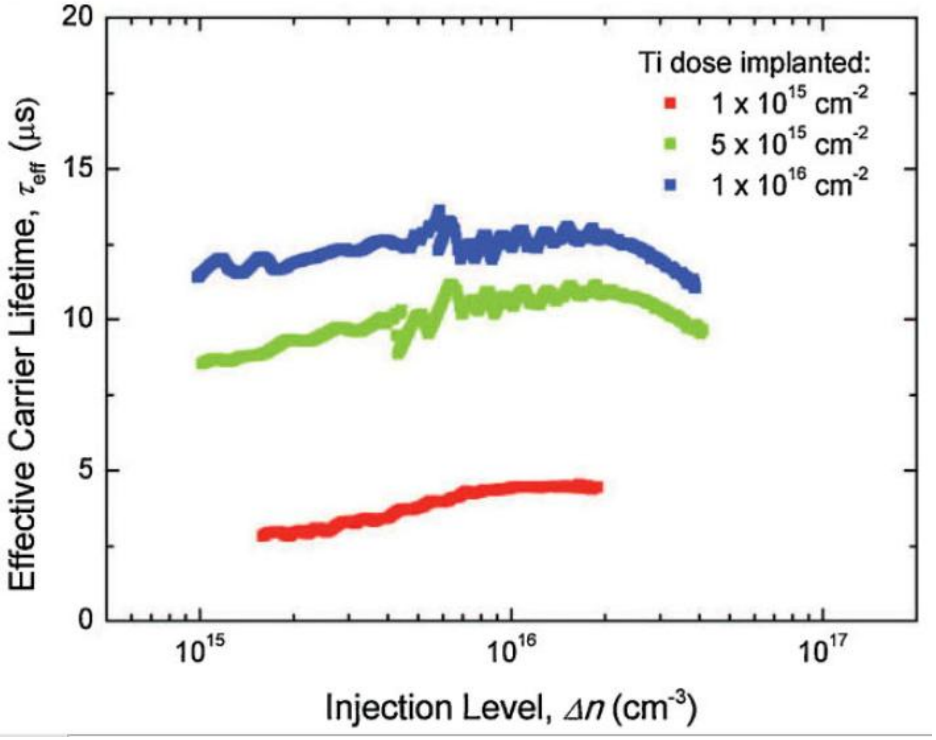
[10] A. Marti, E. Antolin, E. Canovas, N. Lopez, P. G. Linares, A. Luque, C. R. Stanley, C. D. Farmer, *Thin Solid Films* **2008**, *516*, 6716.

Bulk IB Materials

- Benefit: higher density of band states over QD-based devices (limited to ~$10^{17}/cm^3$) leading to higher sub-bandgap absorption
- Requirement: sufficiently deep level to prevent thermal transfer from IB to CB (> 0.2eV)

Impurity Bands

- SRH recombination through deep levels is prevented by reaching a critical concentration of impurities
- Due to a delocalization of impurity wave functions
- Titanium in Silicon is experimentally shown



[24] E. Antolin, A. Marti, J. Olea, D. Pastor, G. Gonzalez-Diaz, I. Martil, A. Luque, *Appl. Phys. Lett.* **2009**, *94*, 042115.

Bulk IB Material Options

- Highly Mismatched Alloys (HMAs): III-V or II-VI material with N or O replacing V or VI anions (e.g. ZnTe:O, ZnMnOTe)
  - have demonstrated 100% increase in Jsc, 15% decrease in Voc, 50% increase in power conversion w.r.t. undoped cell (BUT, $\eta < 1\%$)
- Transition Metals (e.g. V in In_2S_3)
  - difficult to make, no solid results yet
- Impurity bands (e.g. Ti in Si, Fe in $CuGaS_2$)

State of the art IBSC…

- Efficiency: 18.3% (Blokhin et al.)
- Voc: 0.9V, AM0 (Hubbard et al.)
- Current increase over single junction: 23%, 24.26 mA/cm^2, though doubt remains on the cause of the increase (Okada et al.)

IBSC: Concluding Remarks

- Clearly, material growth/synthesis is an inhibitor for either type of IBSC.
  - Are there other ways of integrating QDs in a p-n junction?
  - Can the shape and spacing of the QDs be controlled any better in S-K growth?
- Proper characterization is key (EQE by 2 lamp sources). Beware of results published w/out mention of doing this.
- **Fundamental Limitation: Dark current increases due to addition of the IB!!**