Advanced Characterization of Intermediate Band Solar Cells

Antonio Luque, A Martí
Instituto de Energía Solar
Universidad Politécnica de Madrid

Spain-Japan Joint Workshop on

Nanoscience and New Materials

"Aries", 37th Floor, ANA Intercontinental Tokyo
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Contents

- Introduction
- QD implementation
- Current enhancement
- Voltage preservation
- High flux operation
- Some characterisation Instruments
- Conclusions

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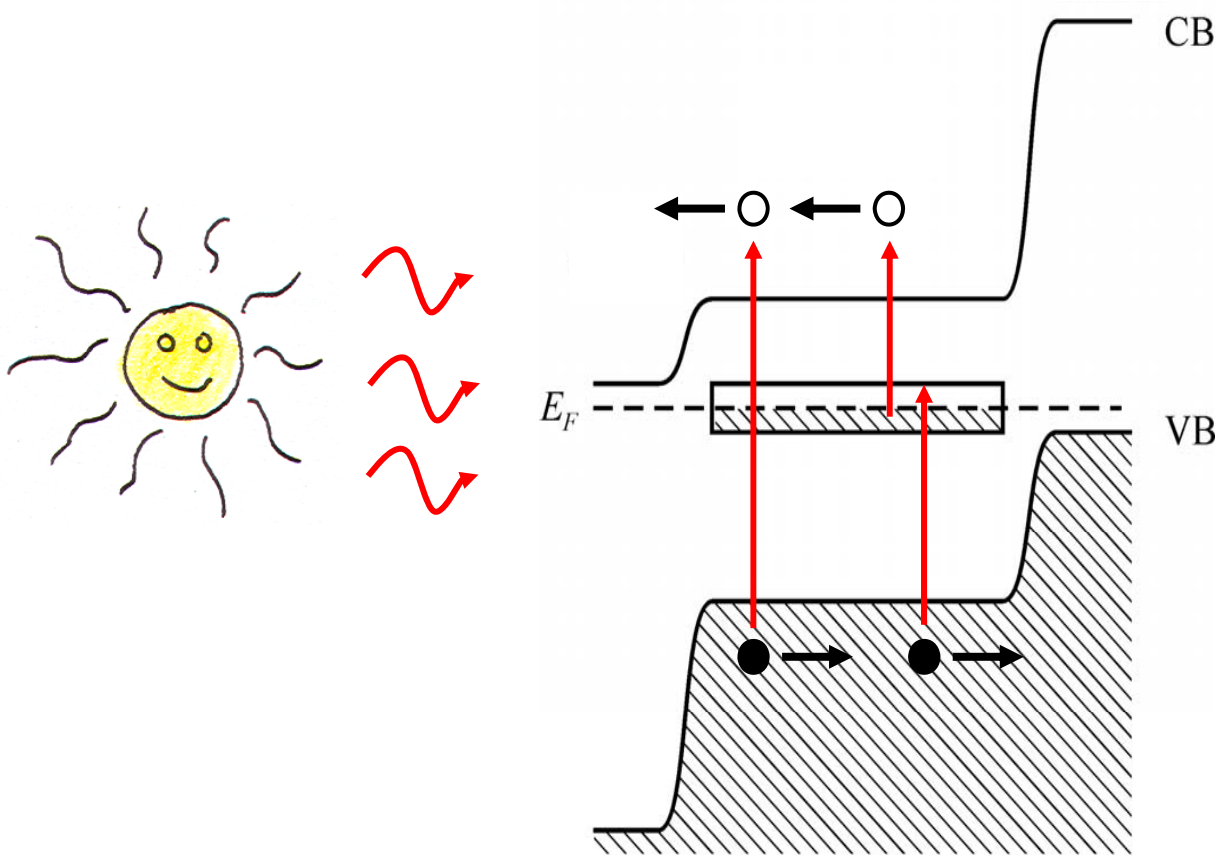
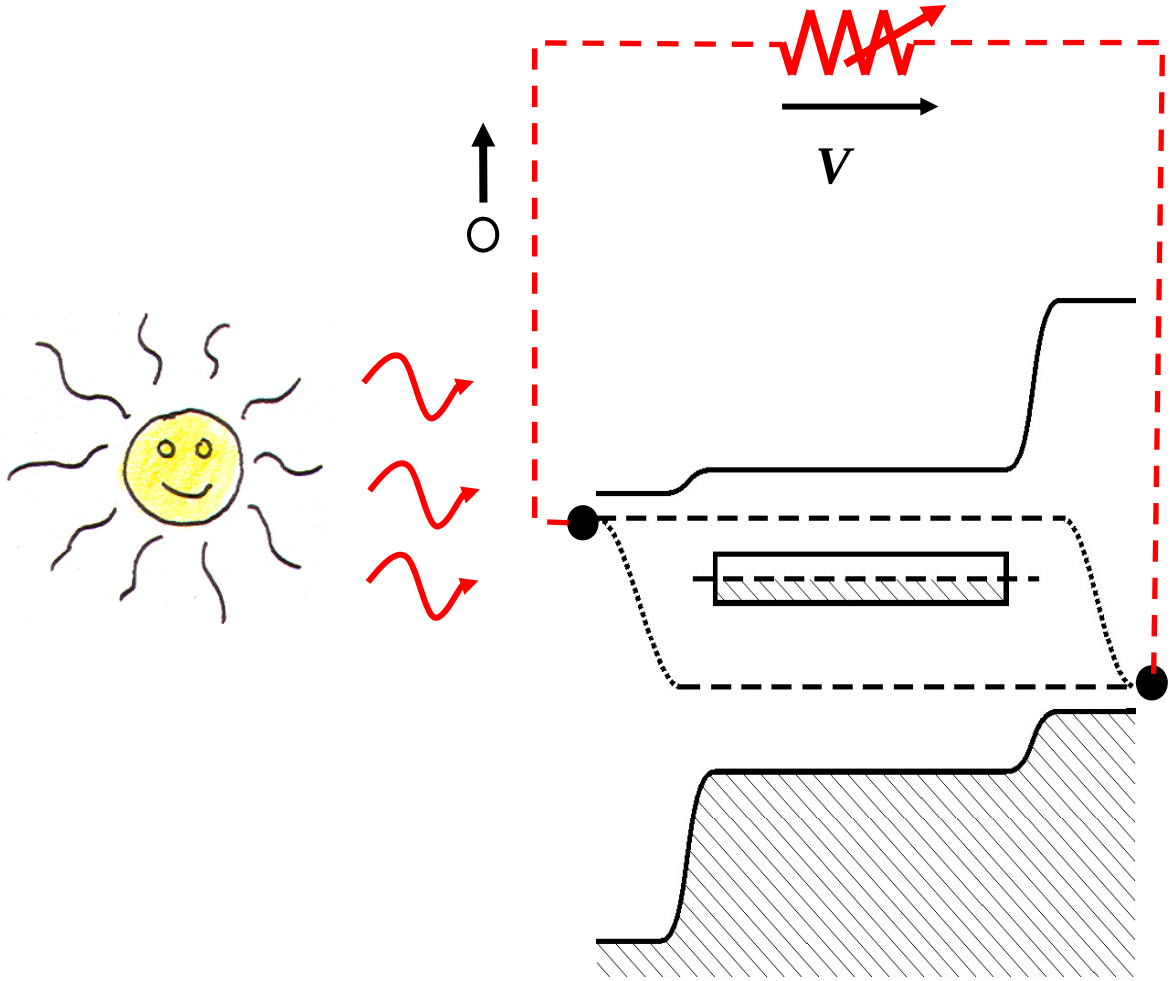
Photocurrent gain



A. Luque y A. Martí, Phys. Rev. Lett. 78(26) 5014–5017 (1997).
A. Luque and A. Martí, Prog. in Photov, Res. and Appl. 9(2) 73–86 (2001).

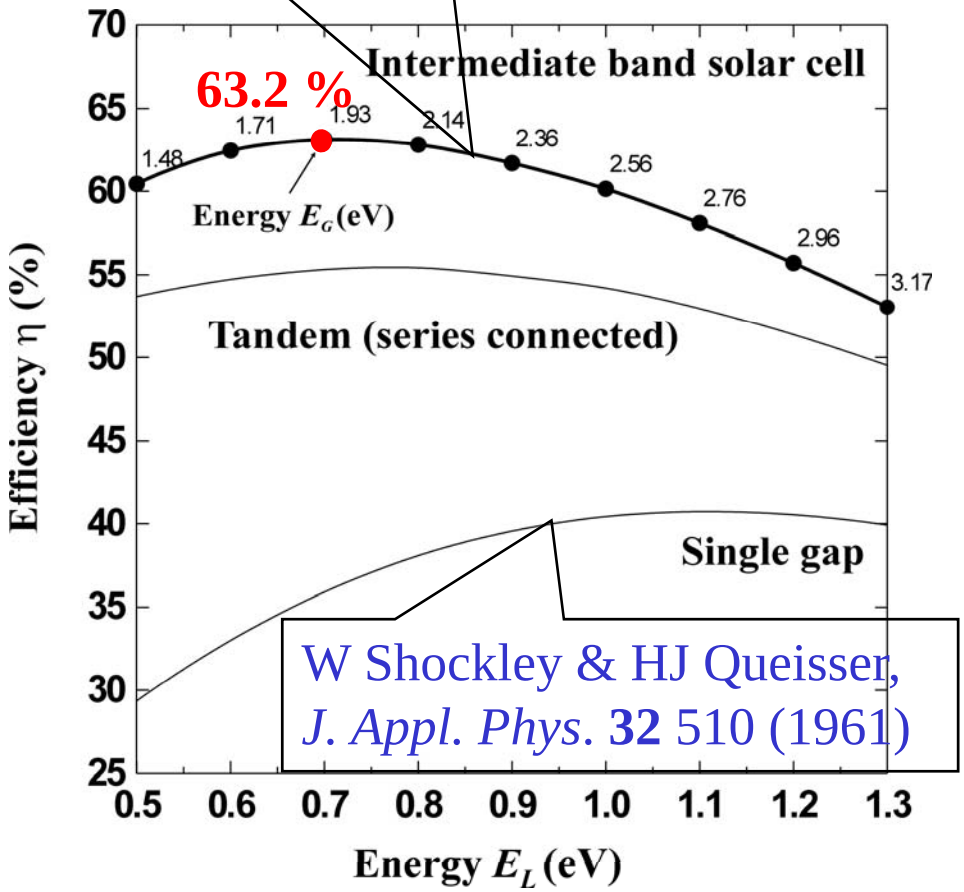
Voltage preservation



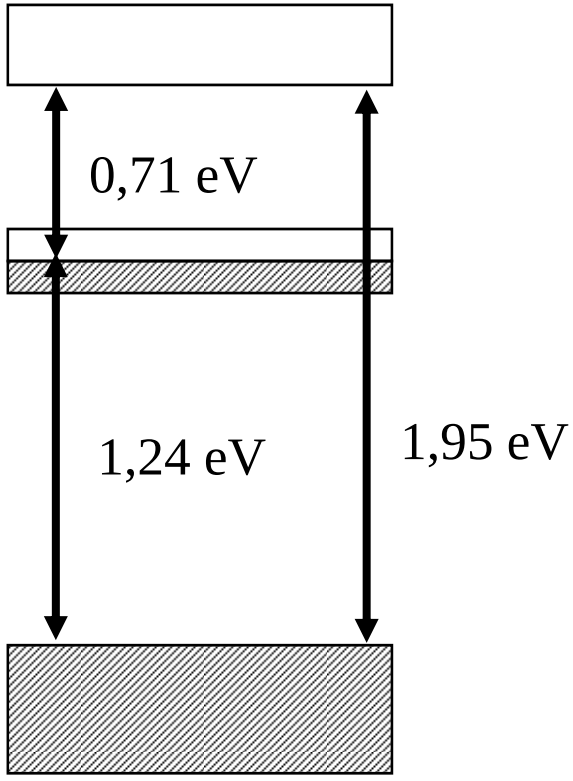
A. Luque y A. Martí, Phys. Rev. Lett. 78(26) 5014–5017 (1997).
A. Luque and A. Martí, Prog. in Photov, Res. and Appl. 9(2) 73–86 (2001).

Optimum gaps

A. Luque & A. Martí, *Phys. Rev. Lett.* **78** 5014 (1997)



W Shockley & HJ Queisser, *J. Appl. Phys.* **32** 510 (1961)



Two-photon mechanism necessary

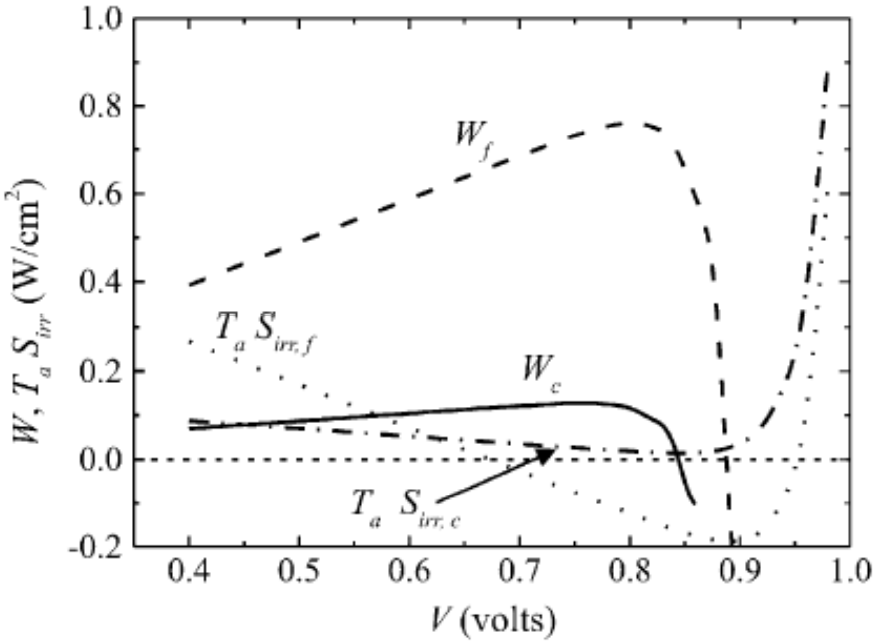
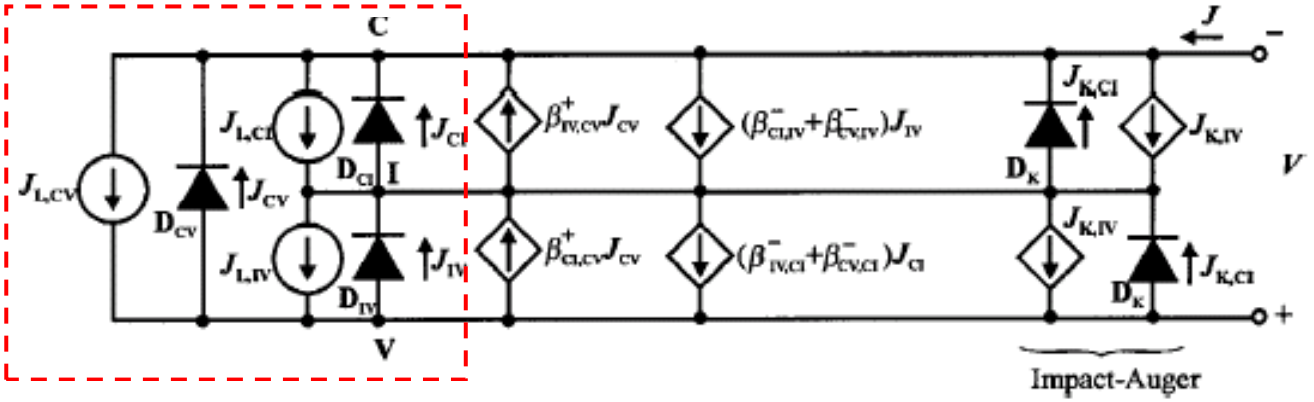


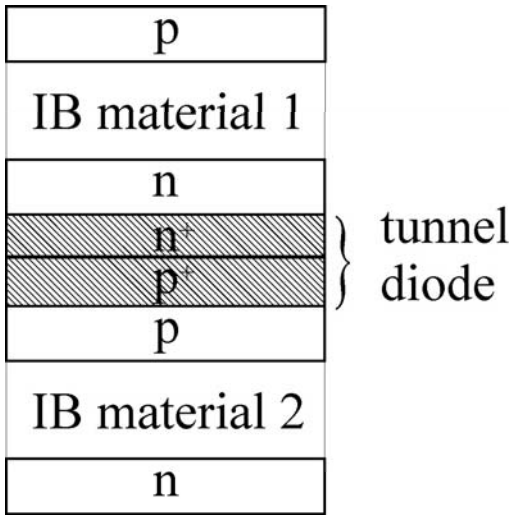
Fig. 2. Power (W) and entropy multiplied by temperature ($T_a S_{irr}$) for an ordinary cell (c) of gap 1 eV and one violating thermodynamics (f) with barrier energy 1 eV and well energy 0.7 eV. The radiator and cell temperatures have been assumed at 1491 and 298 K, respectively.



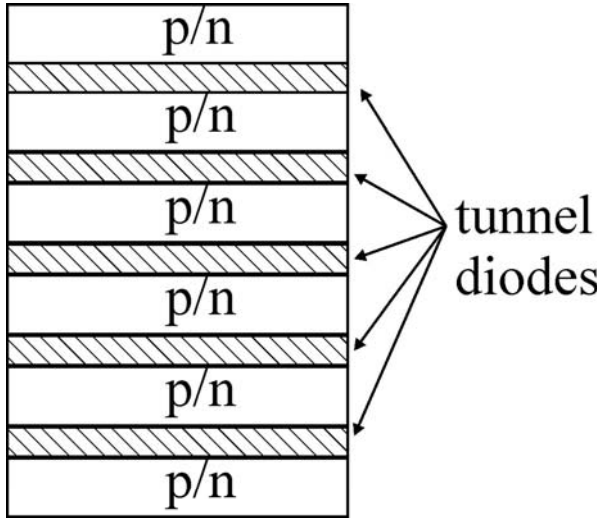
A. Luque, A. Martí, and L. Cuadra, Physica E **14**, 107 (2002).

A. Luque, A. Martí, C. Stanley, et al., Journal of Applied Physics **96**, 903 (2004).

IBSC & Tandems



tandem of 2 IBSC:
6 gaps only one tunnel junction



conventional 6 gaps tandem
5 tunnel junctions

E. Antolín, A. Martí, and A. Luque, in Proc. of the 21st European Photovoltaic Energy Conference, 2006, pp. 412--415.

Some proven IB bulk materials

- $Zn_{0.88}Mn_{0.12}Te_{0.987}O_{0.013}$ detected by photo-reflectance
  - K. M. Yu *et al.*, Physical Review Letters **91**, 246403 (2003)
- $GaN_xAs_{1-x-y}P_y$ alloys with y>0.3 detected by photo-reflectance
  - K. M. Yu *et al.*, Applied Physics Letters **88**, 092110 (2006)
- $V_{0.25}In_{1.75}S_3$ detected by absorption coefficient
  - R. Lucena *et al.*, Chem. Mat. **20**, 5125 (2008)
  - P. Palacios *et al.*, Phys. Rev. Lett. **101**, 046403 (2008)
- Si:Ti (~0.2%) detected by Hall experiments
  - G. Gonzalez-Díaz *et al.*, Submitted for publication (2009)

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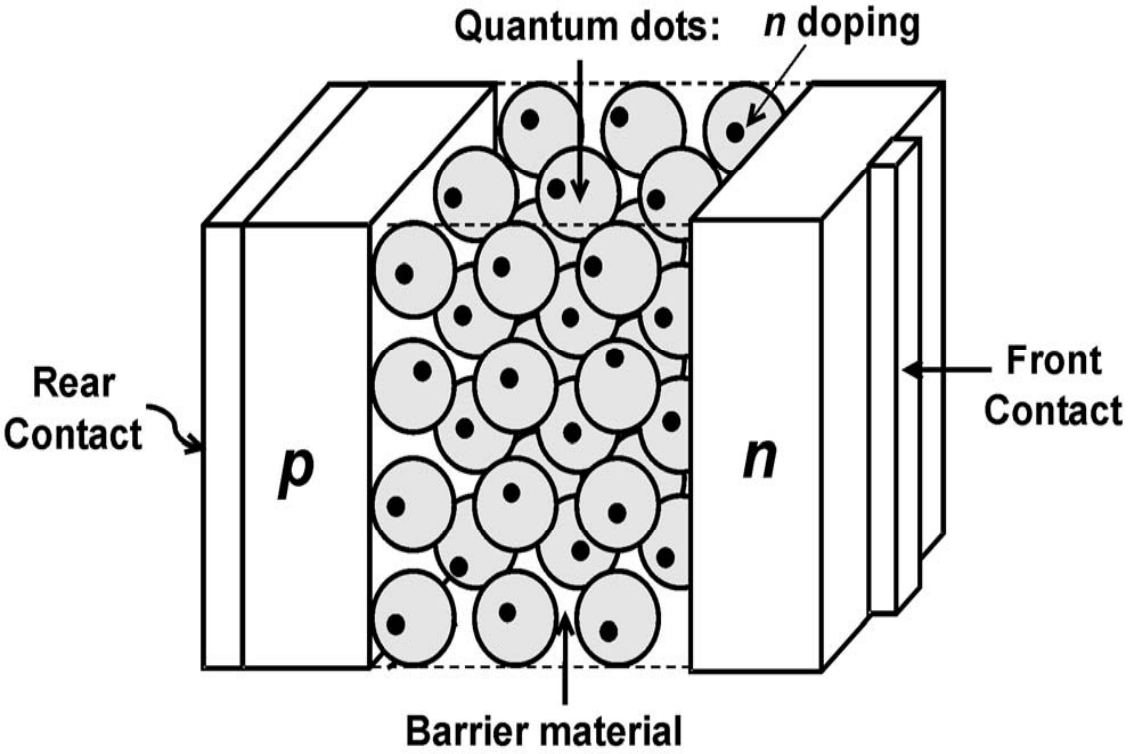
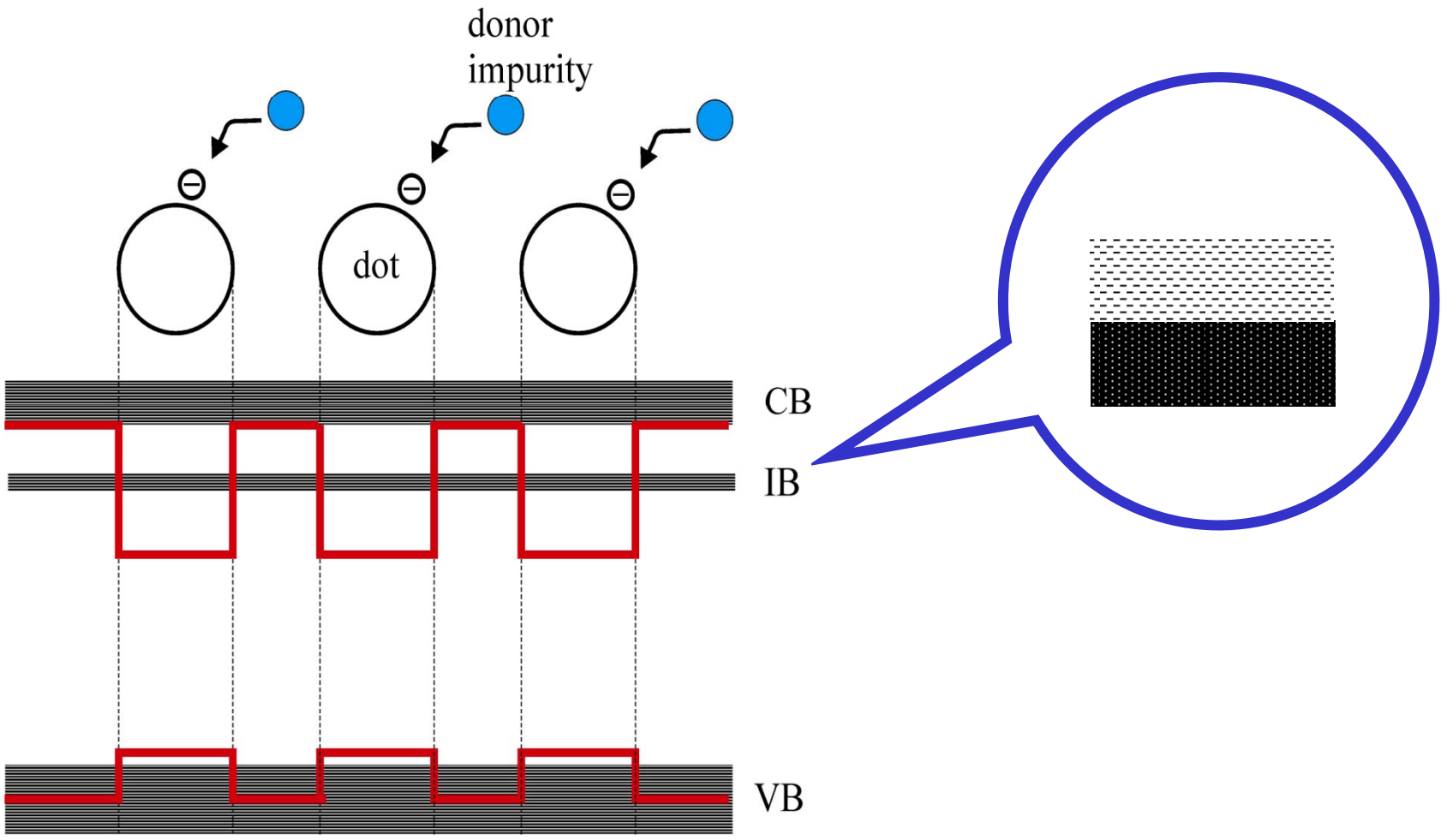
Quantum dots for the IBSC



A. Martí, L. Cuadra, and A. Luque, in Proc. of the 28th IEEE Photovoltaics Specialists Conference, edited by IEEE (New York, 2000).

QD-IBSC



A. Martí, L. Cuadra, and A. Luque, in Proc. of the 28th IEEE Photovoltaics Specialists Conference, edited by IEEE (New York, 2000).

Structures grown

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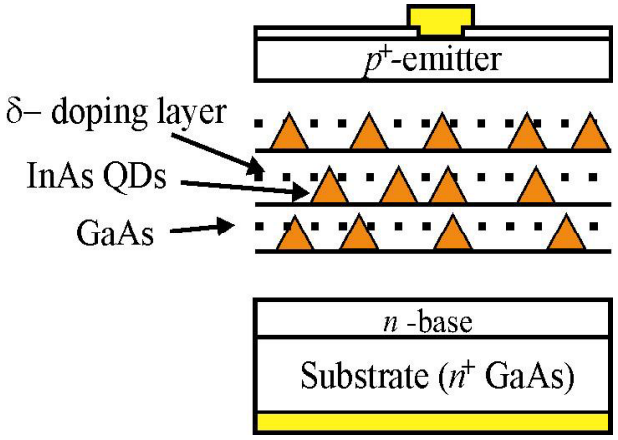
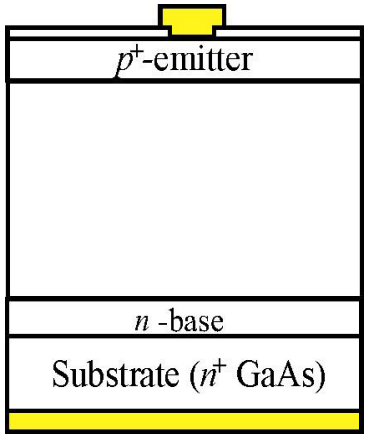
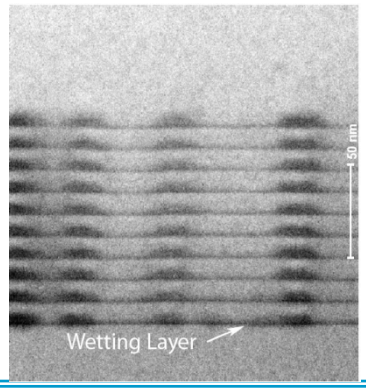
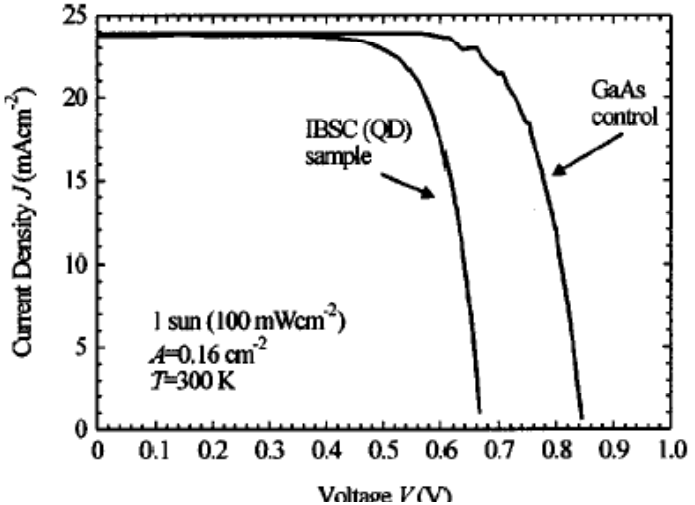
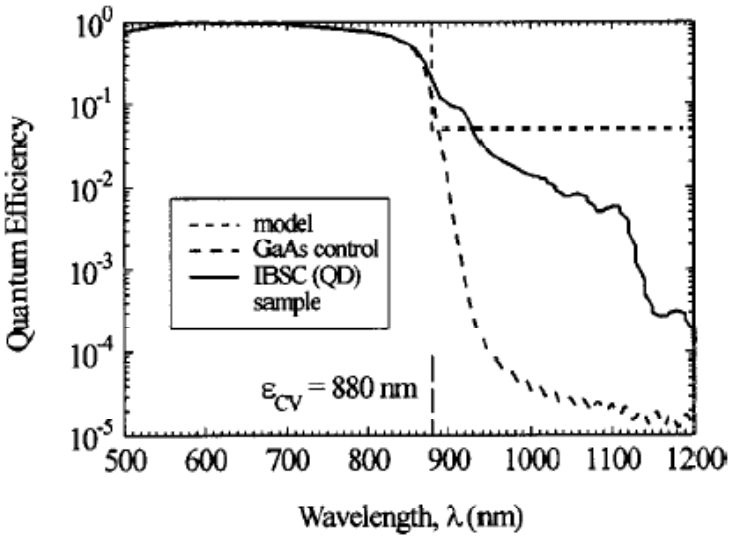






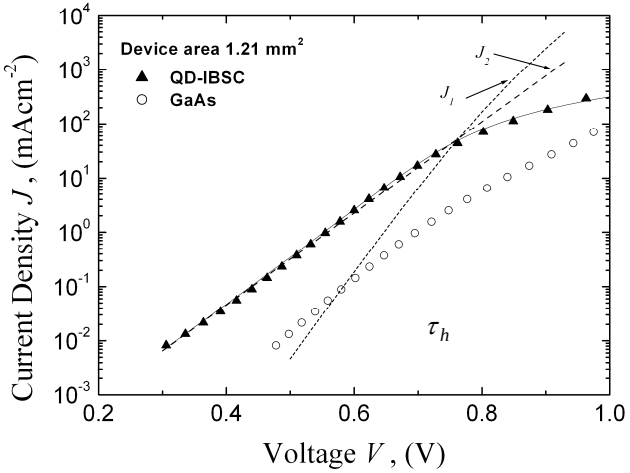
Grown in MBE, in Stranski-Krastanov mode

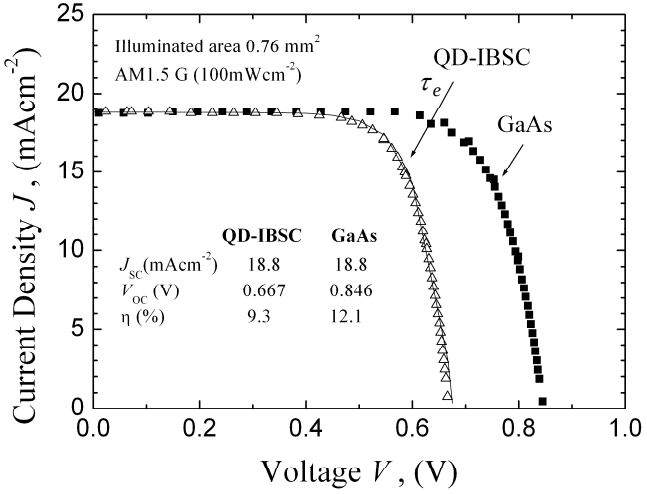


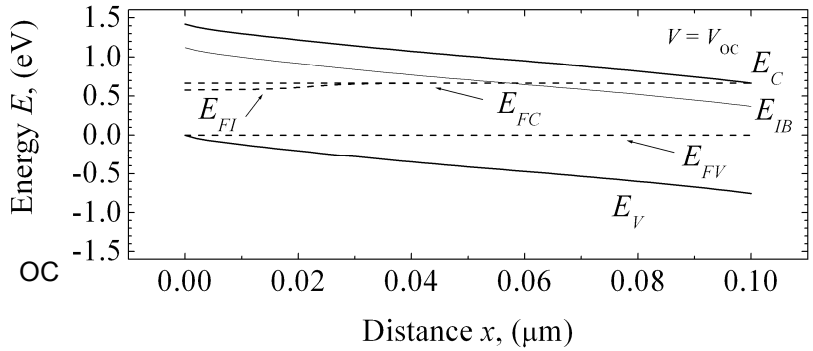


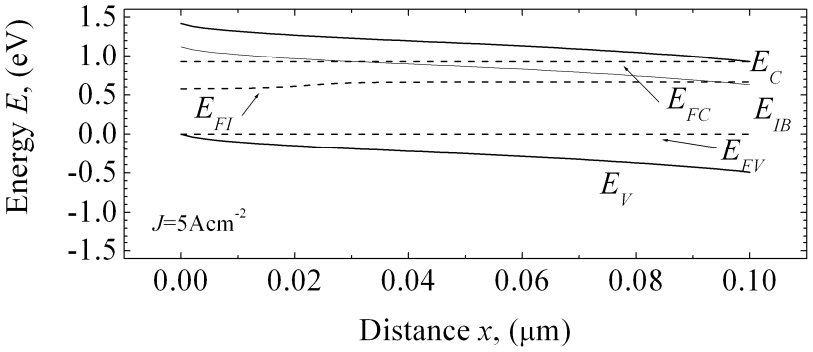
A. Luque, A. Martí, C. Stanley, N. López, L. Cuadra, D. Zhou y A. Mc-Kee, J. Appl. Phys. 96(1) 903, 2004.

GSRH Modelling the QD-IBSC









Hole lifetime (ps),	40.0
Electron lifetime (ps),	0.5

A. Luque, A. Martí, N. López, et al., Journal of Applied Physics 99, 094503, (2006)

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Strain destroys the emitter

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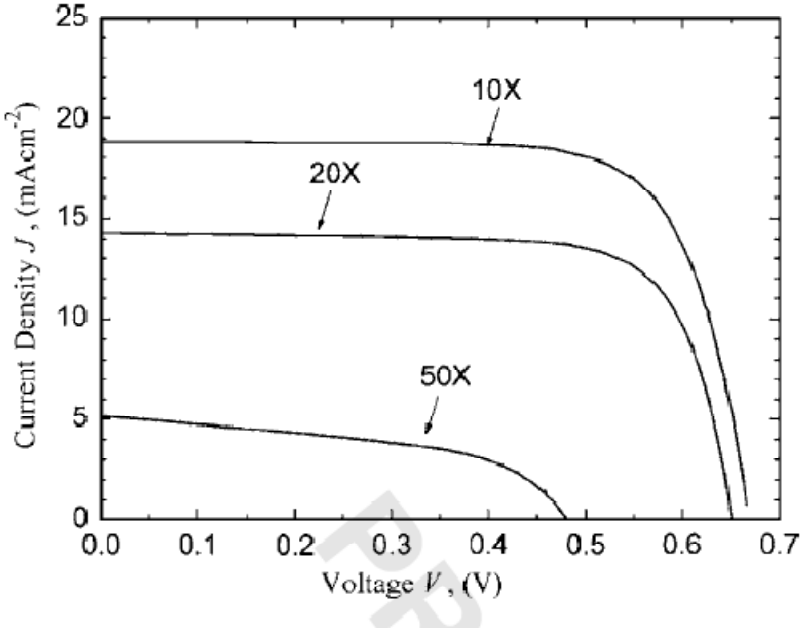
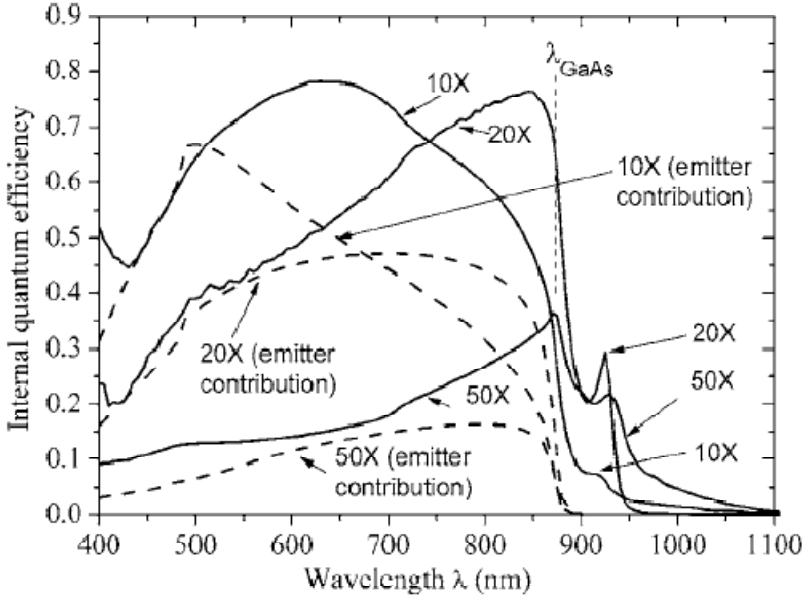
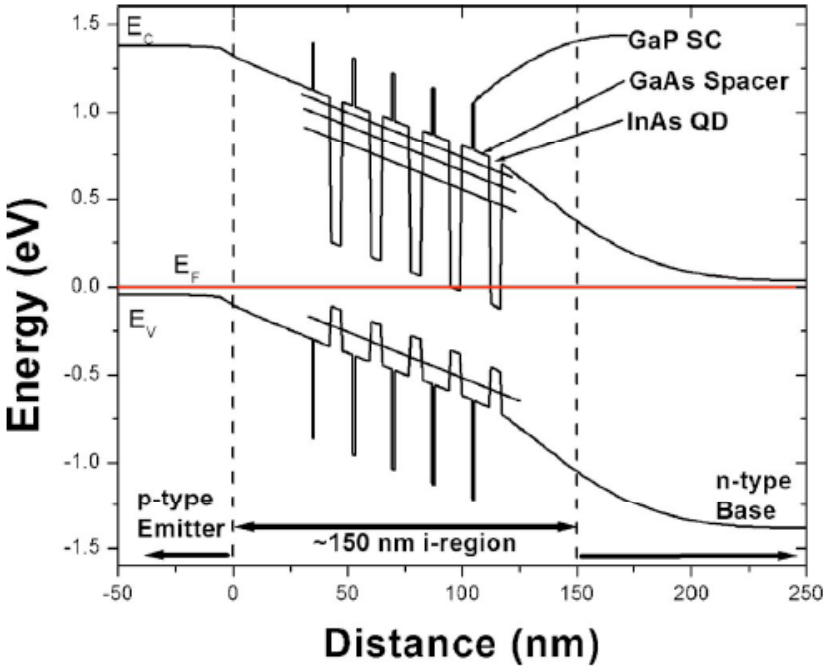
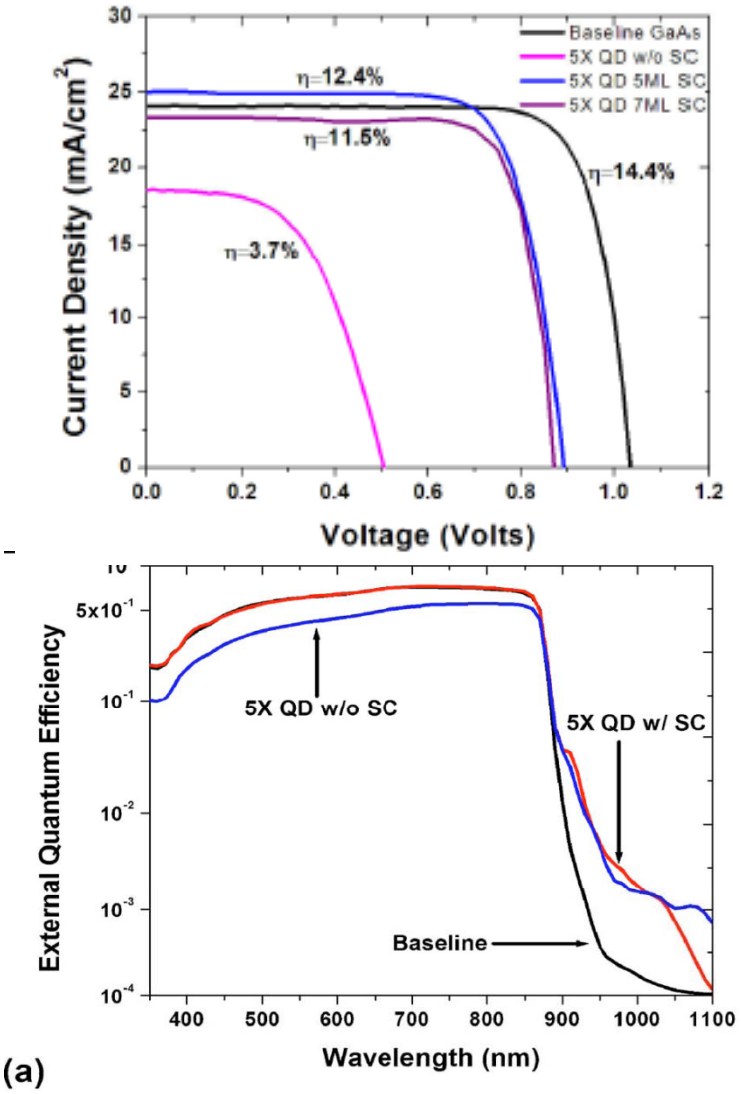




A. Marti et al., Applied Physics Letters **90**, 233510 (2007)

Better results with strain compensated QD





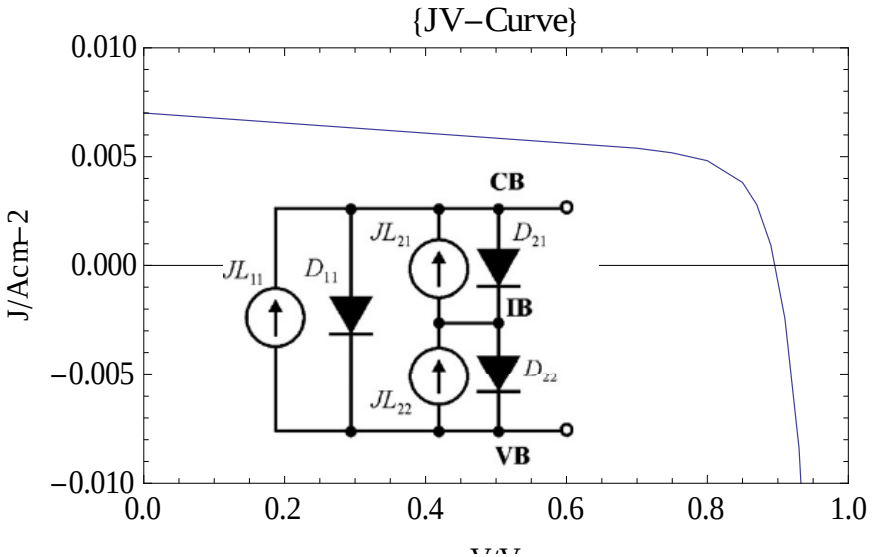
S. M. Hubbard, C. D. Cress, C. G. Bailey, R. P. Raffaelle, S. G. Bailey, and D. M. Wilt, APL 92 (2008)

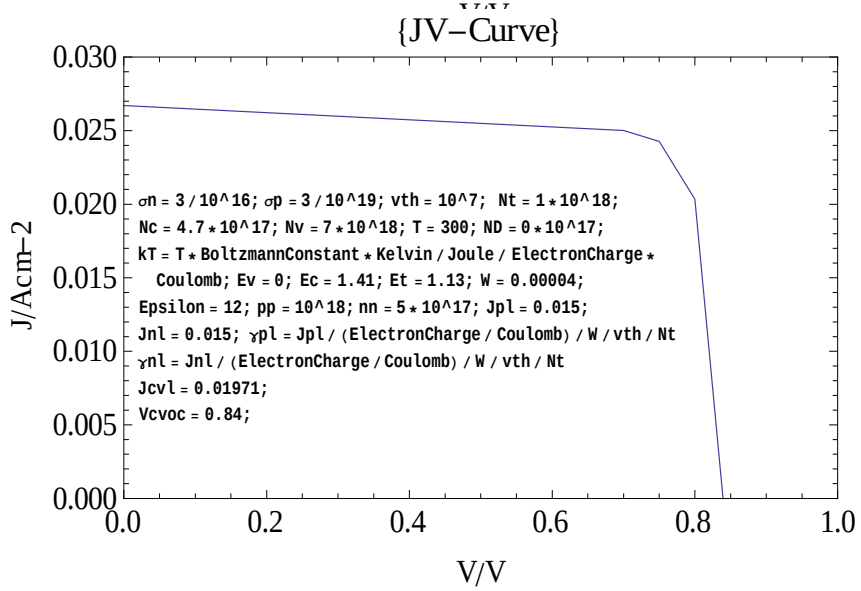
S. M. Hubbard, C. G. Bailey, C. D. Cress, et al. Short circuit current enhancement… 33st IEEE PVSC, 2008

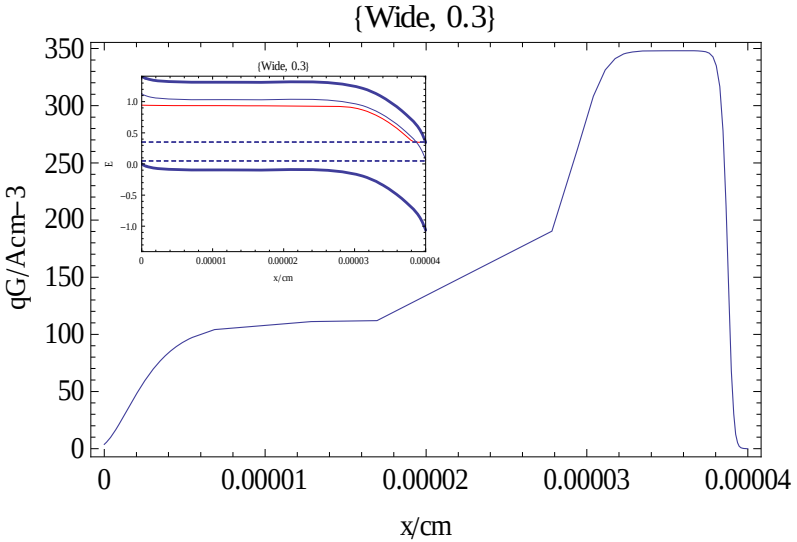
High current no voltage reduction!

Confidential: Unpublished material Y. Okada, Japan-EU collaboration workshop.
See also R. Oshima, A. Takata, and Y. Okada, Applied Physics Letters 93, 083111 (2008)

Preliminary GSRH modeling of Tokyo University IB cells







- Effect of the GaNAs not considered
- Very high density of confined levels (~10^{18} cm^{-3}); large IB region (400 nm)
- Generation does not extend trough the IB region because of good isolation with CB (σ_n~$3*10^{-16}$ cm^{-2}). Go to IB doping? Model first!
- Excellent low-recombination sub-bandgap cells (σ_p<$3*10^{-17}$ cm^{-2})
- No loss of voltage because bulk cell is too poor

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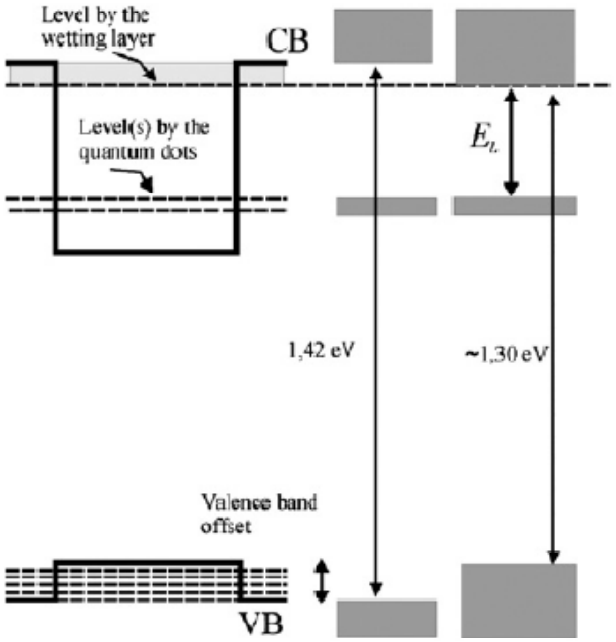
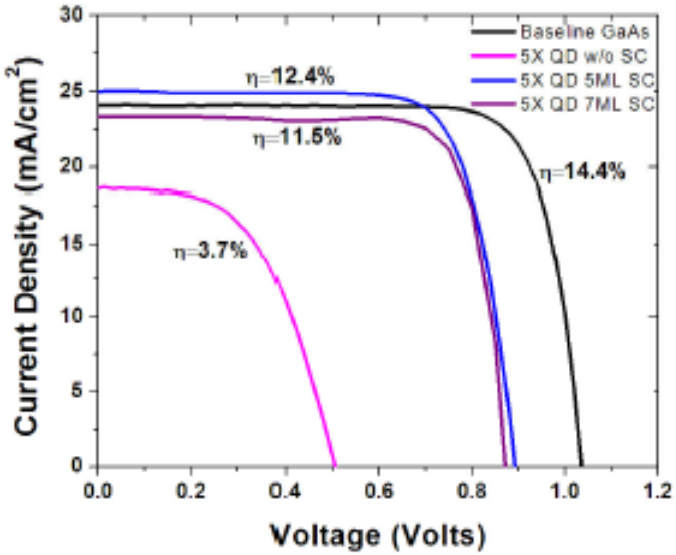
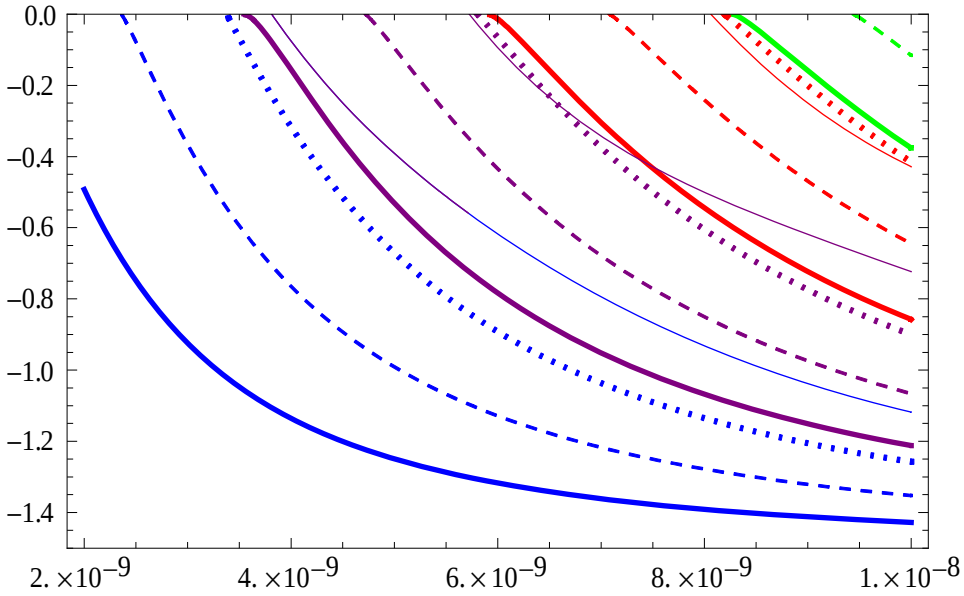
Band shrinkage



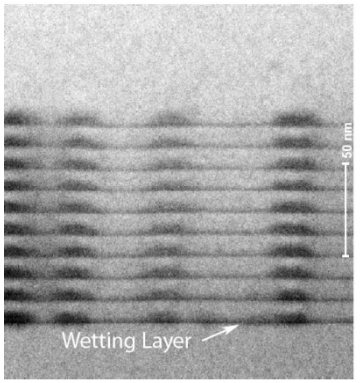


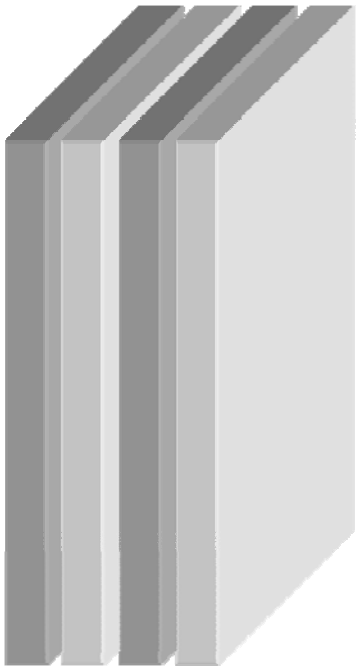
A. Luque, A. Martí, C. Stanley, N. López, L. Cuadra, D. Zhou y A. Mc-Kee, J. Appl. Phys. 96(1) 903, 2004.

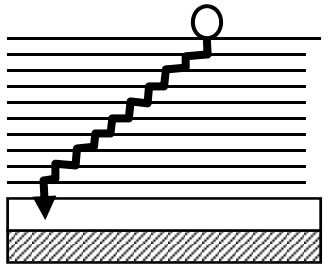
Are we making QDs or QWs?

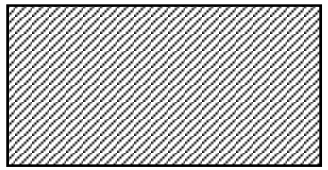


Energy levels in a spherical potential well with s, p, d, f angular symmetry vs. the well radius (colours principal quantum number; line structure, angular symmetry).



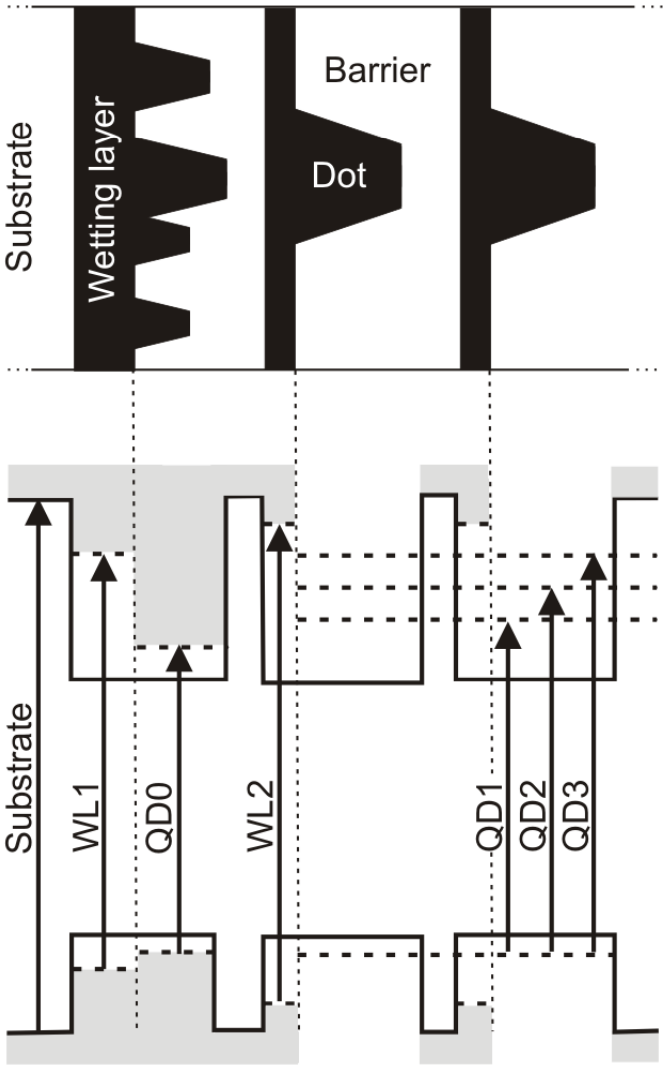






QD level structure:

Comparing photo-reflectance and electroluminescence



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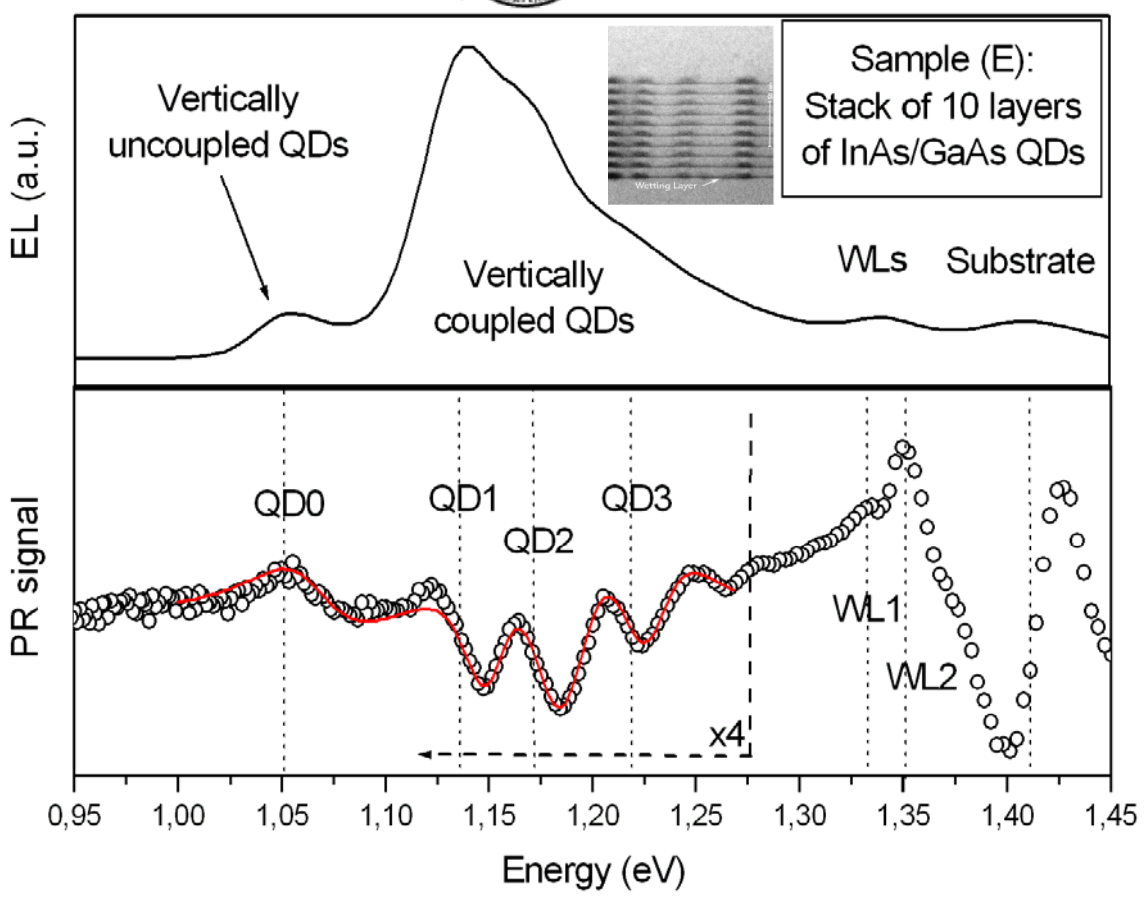


E. Cánovas, A. Martí, N. López, E. Antolín, P. G. Linares, C. D. Farmer, C. R. Stanley, and A. Luque, Thin Solid Films 516, 6943 (2008).

QD level structure:

Comparing photo-reflectance and quantum calculations

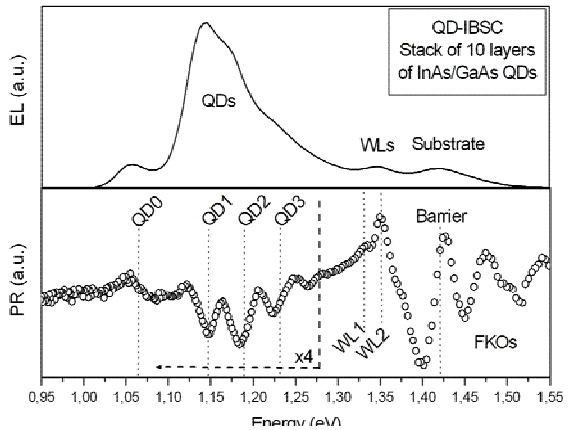
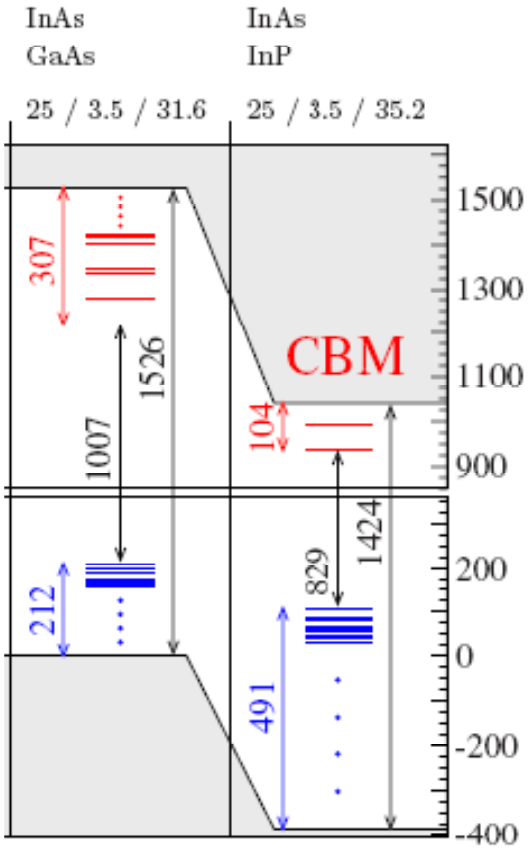


Table 1
Experimental PR energy peaks for InAs/GaAs QDs compared with theoretical energies for QDs with a 10 nm of pyramidal base

Peak	Type of fitting:	Experimental energy (eV)	Theoretical energy (eV)
Substrate	TPM	1.426	1.434, ref.[23]
WL2	Gaussian	1.349	1.388, ref.[23]
WL1	Gaussian	1.334	1.347, ref.[23]
QD4	TPM	1.227	1.225, ref.[4]
QD3	TPM	1.183	–
QD2	TPM	1.147	–
QD1	TPM	1.121	1.125, ref.[4]
defect	Gaussian	1.053	1.03, ref.[22]

TPM refers to Aspnes three point method.



E. Cánovas, A. Martí, N. López, et al, Thin Solid Films 516, 6943 (2008).

V. Popescu, G. Bester, M. C. Hanna, A. G. Norman, and A. Zunger, Physical Review B 78, 205321 (2008).

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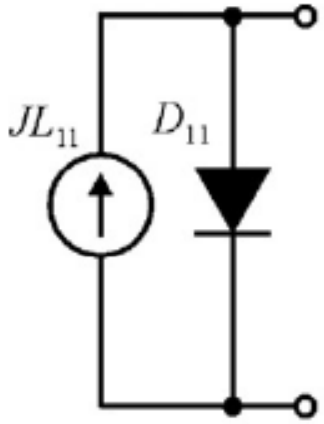
DB modeling; the effect of concentration

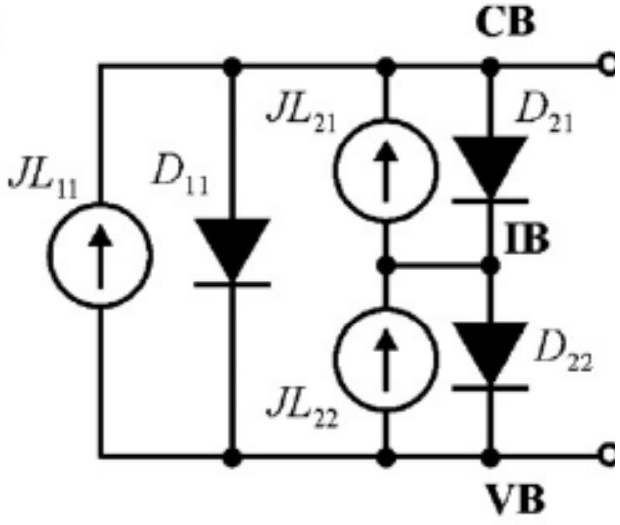
(a)

$$J_{XY} \approx J_{0,XY}\left(\exp\frac{eV_{XY}}{mkT}-1\right)$$

$$J_{0,XY}=\frac{2\pi}{h^3c^2}\int_{\varepsilon_{XY}}^{\infty}\varepsilon^2\exp\left(\frac{-\varepsilon}{kT_C}\right)d\varepsilon$$

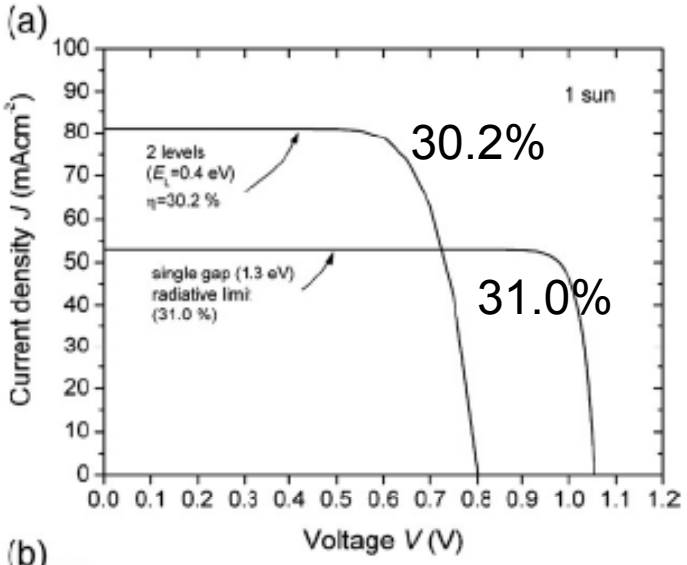


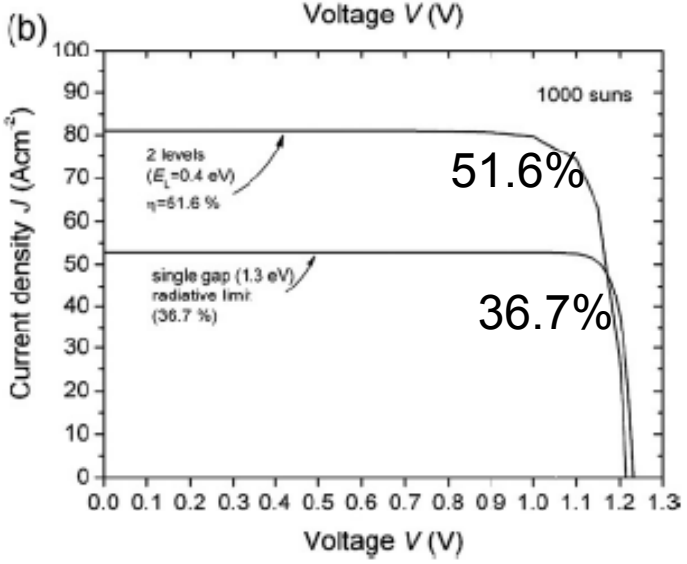
(b)



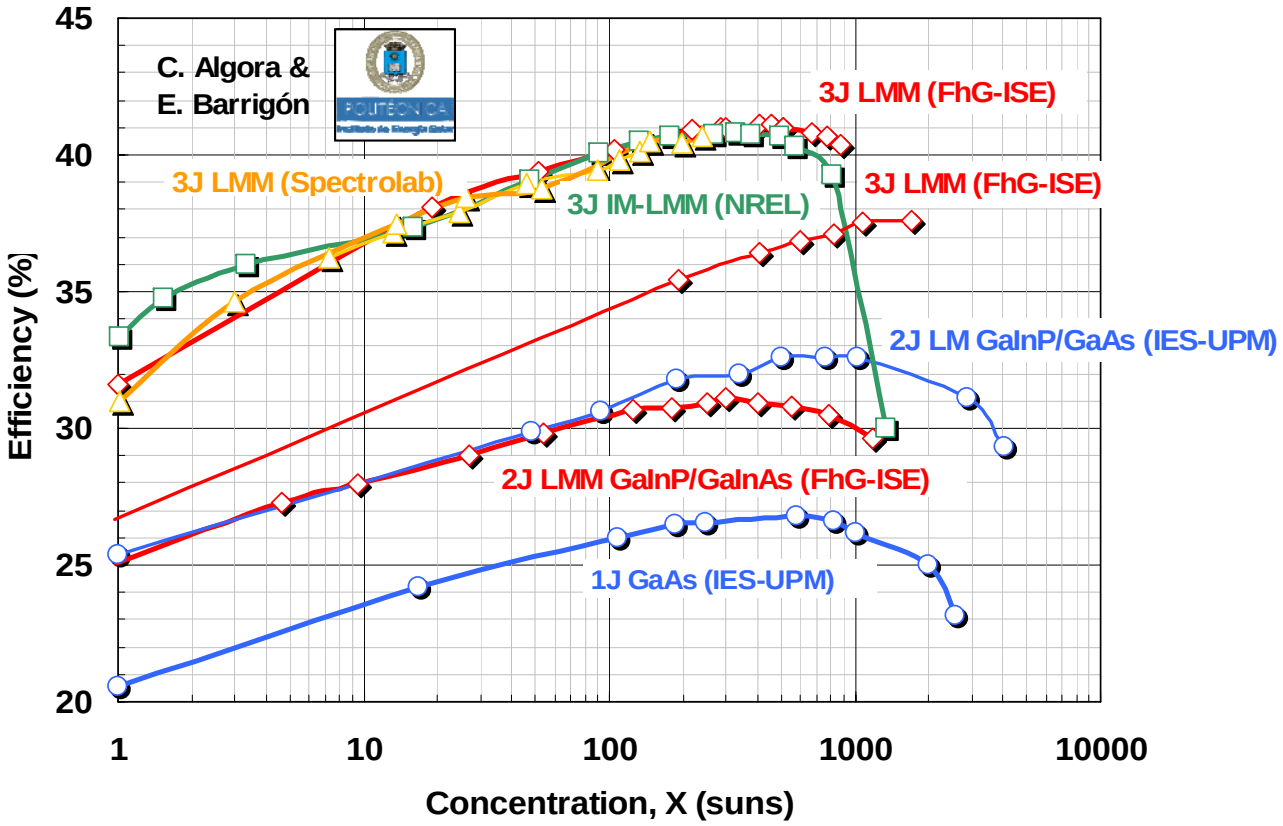
Impossible to exceed ordinary cells!!!

(at one sun with GaAs/InAs)

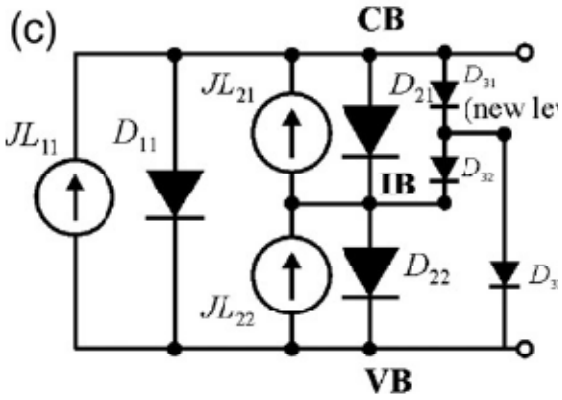


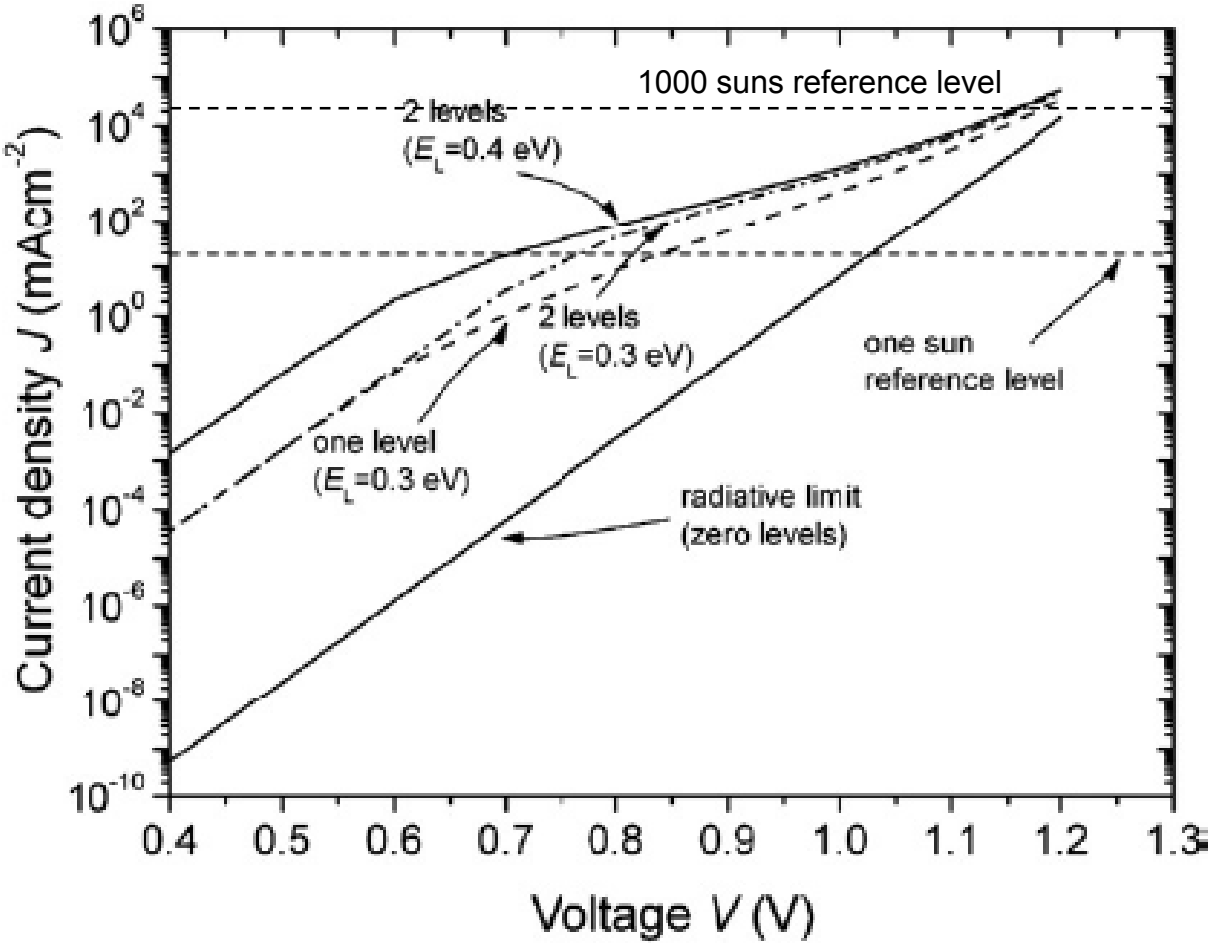


IES experience in concentrator cells



DB modeling; the effect of concentration





A. Martí, E. Antolín, E. Cánovas, N. López, P. G. Linares, A. Luque, C. R. Stanley, and C. D. Farmer, Thin Solid Films, p. doi: 10.1016/j.tsf.2007.12.064, 2008.

Concentration measurements at room temperature

Concentration measurements at 20 K

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- **Capabilities for this cooperation**
- Conclusions

Concentrator cell capability at IES/UPM for this cooperation

- High concentration cell processing on multilayer epitaxied substrates

Modeling & characterization techniques at IES/UPM for this cooperation

- DB Modeling
- GSRH Modeling
- Photo/thermo/piezo-reflectance
- Photo/electroluminescence down to 4K up to 8 microns
- Photon counting down to 4K up to 8 microns
- FTIR
- DLTR
- Quantum efficiency down to 4K up to 8 microns up to 10000 suns
- IV measurements down to 4K up to 10000 suns

Conclusions

- IBSC is an attractive promising new concept that can be implemented with QDs
- Promising results in getting higher current
- Better understanding of the voltage loss
- Better understanding of the role of high flux light
- Important support for IBSC research in Japan. Skills for very high density QDs.
- Modeling and characterization of IBSC and concentrator cell manufacturing skills in Spain
- Cooperation can speed-up results.