Nanostructured Solar Cells: From Academic Research to Commercial Devices

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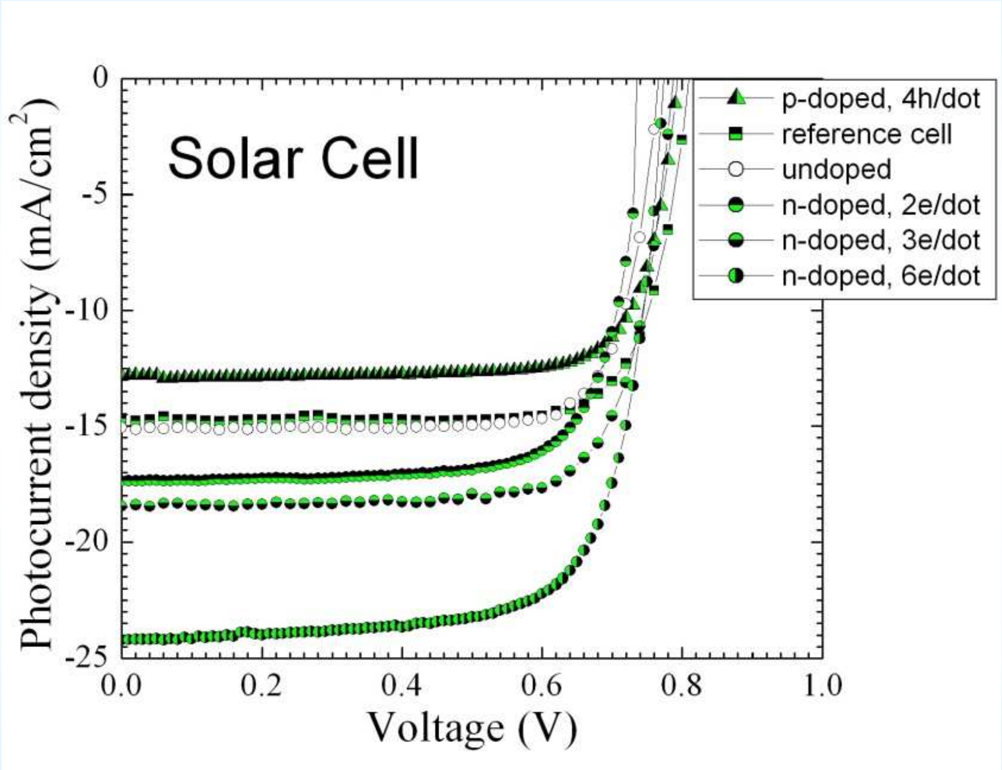
Our Product

We demonstrated radical improvement of quantum-dot solar cells (**SC**s) provided by strong interdot doping, which creates Quantum dots with Built-In-Charge (Q-BIC):



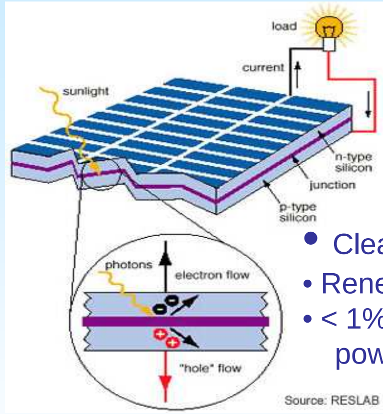
a **50%** increase in photovoltaic efficiency in the n-doped GaAs solar cells that have quantum dots with built-in-dot charge (Q-BIC) of ~ 6 electrons per dot.

In these Q-BIC solar cells the short circuit current density increases to 24.30 mA/cm^2 compared with 15.07 mA/cm^2 in undoped SCs without deterioration of the open circuit voltage .

OPEN LLC

OPtoElectronic Nanodevices LLC

➢ *The Next Generation of*
High Efficiency Solar Cells
With Advanced Nanostructures

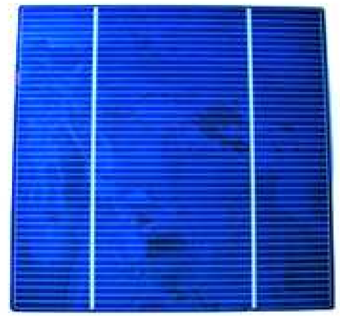


- Clean
- Renewable
- < 1% US power

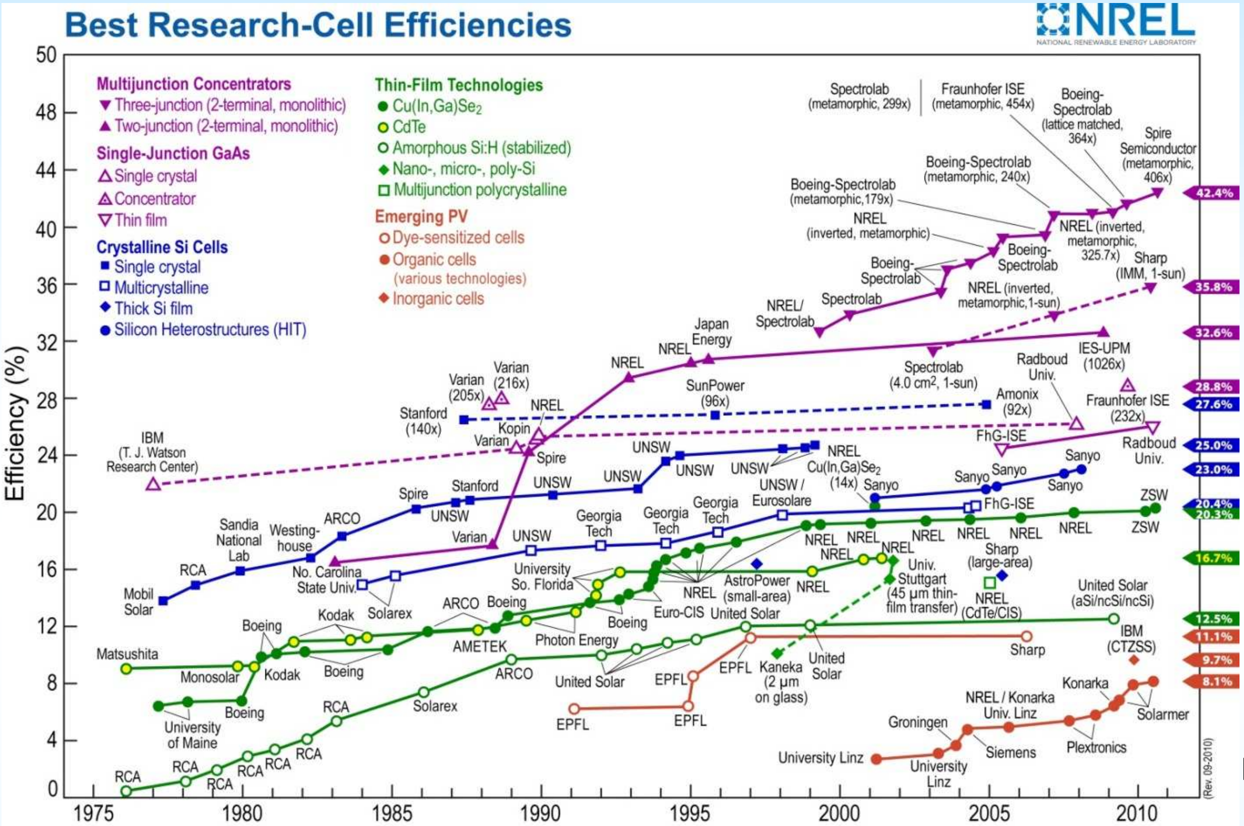
- **OPEN LLC** is a product and technology development company working on improved solar cell structures.
- Our Mission – Develop the next generation of advanced solar cells with advanced nanostructures and license them to key manufacturers. These cells will be at least 50% and up to 100% more efficient than current solar cells.
- Founded upon research conducted at University at Buffalo
- Technologies have taken 5 years and $3 M to develop

Market Need

- Existing cells are:
  - Mostly inefficient (~20%)
  - If efficient (~40%) → extremely expensive
  - Heavy and bulky
  - Conservative design → Slow improvement
- Who cares?
  - DoD – need lighter, more powerful cells
  - DoE – trying to recover a US industry (5%)
    - Both DoD and DoE fund solar projects
  - Commercial users – more affordable, light-weight cells ("10 million rooftops" bill proposal)
- Market size
  - 2010 $5B, 20GW top 15 cell producers average 1 GW ($250M each)

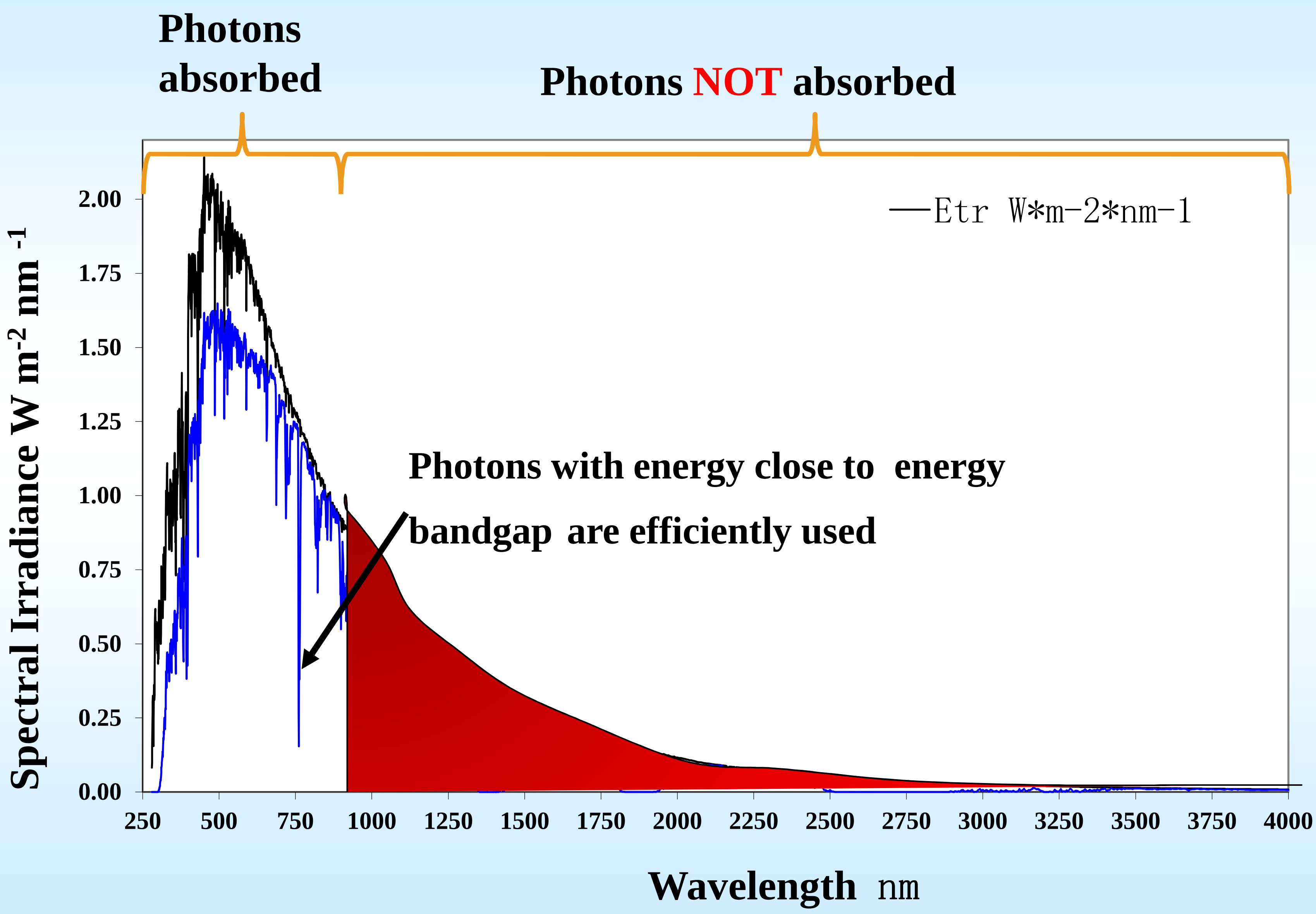


Best Research-Cell Efficiencies



From NREL.GOV

- Little progress in standard technologies (c-Si, μc-Si, CIGS, CdTe).
    - e.g. Best efficiency for single crystal Si demonstrated in 1995.
    - Extremely difficult to generate new IP. Mostly cost-driven development.
- New approaches are needed !



Photons absorbed
Photons NOT absorbed
—Etr W*m-2*nm-1
Photons with energy close to energy bandgap are efficiently used
Spectral Irradiance W m-2 nm -1
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000
3250
3500
3750
4000
Wavelength nm

High-efficiency solar cells: Background

Multi-junction cell approach:

•Several junctions with different bandgaps connected in series

•**Maximum demonstrated efficiency** for any solar cells: 42% with a 3-junction cell AlInGaP/GaAs/Ge

•Challenges:

- Need to match currents of all the junctions
- May have to match lattice constants
- Close thermal expansion coefficients
- Expensive integration
- Some commercial use, e.g. for Mars rovers

Intermediate band approach:

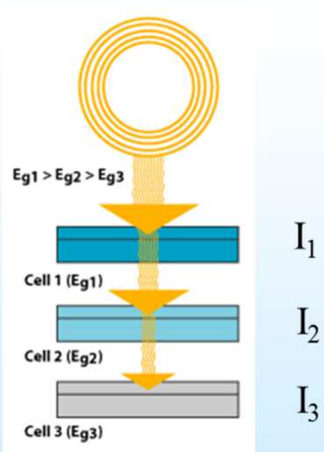
•Additional electron levels within the bandgap of host semiconductor

•No need to match currents of all transitions

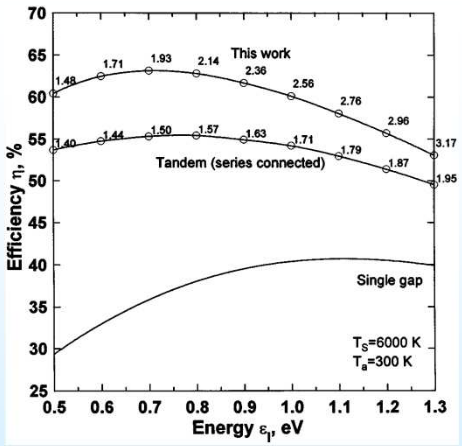
•Can be realized with one material system (e.g. InAs quantum dots in AlGaAs matrix)

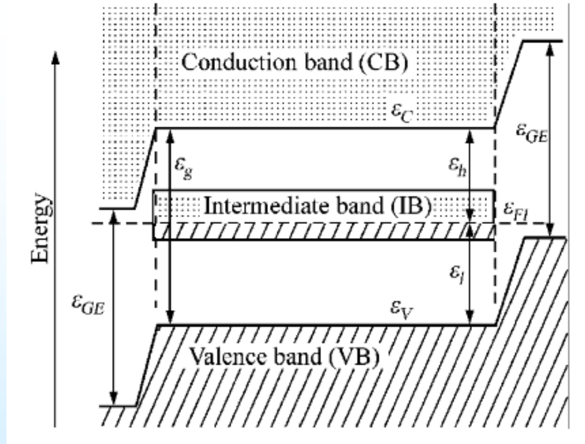
•Less expensive and less complex compared to multi-junction systems

•In research stage, still has to be proved viable



Schematic of multi-junction cell:
$I_{total} = \min(I_1, I_2, I_3)$



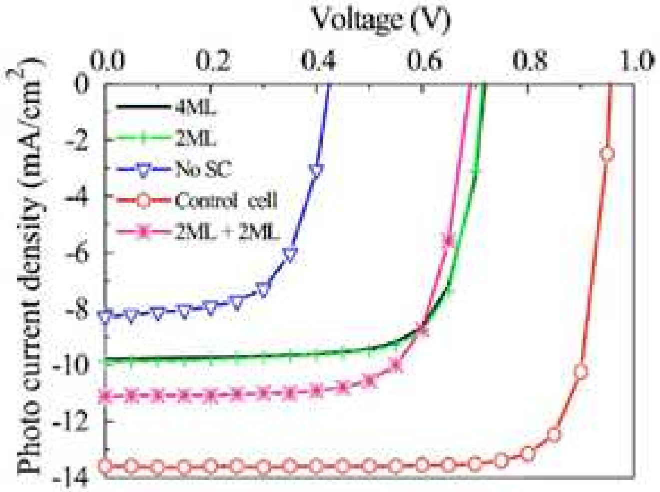


Schematic of an intermediate band cell, and theoretical efficiency limit for different cell designs (**A. Luque et. al. 1997**)

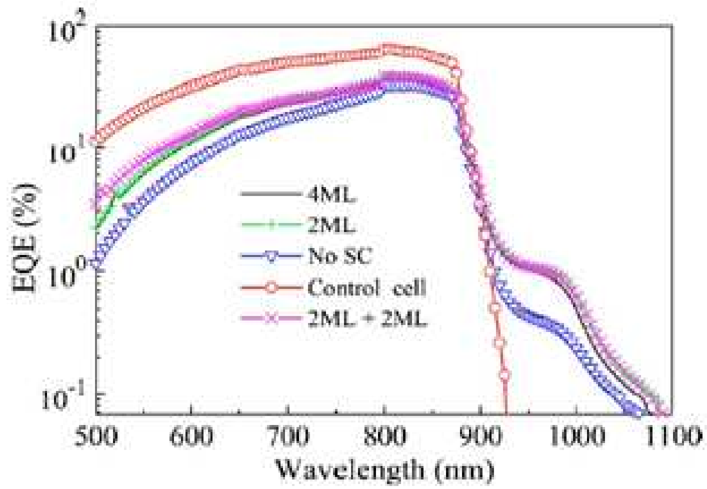
InAs QDs as Intermediate Band: Issues and the State of the Art

- No credible demonstration of efficiency improvement in QD SCs by others
- Our team, UB/ARL, is the first to show real improvements
- Issues:
  - QDs act as recombination centers
  - Band-to-band photocurrent reduced
  - Open circuit voltage drop
  - Reduced power output

Example of published paper, where these issues are being addressed:



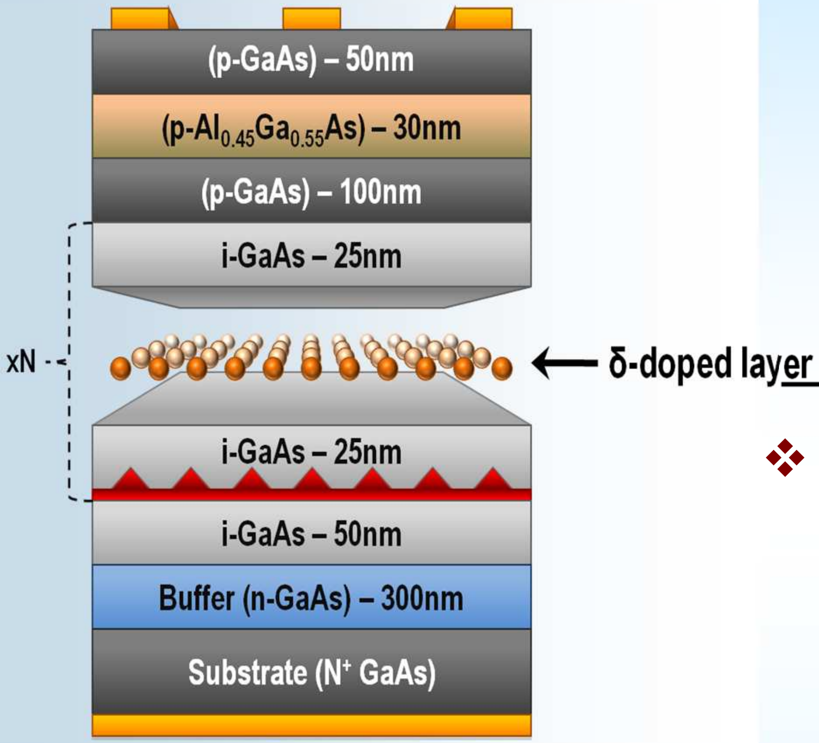
I-V characteristics show the drop of open circuit voltage in QD cells (290 mW/cm^2)

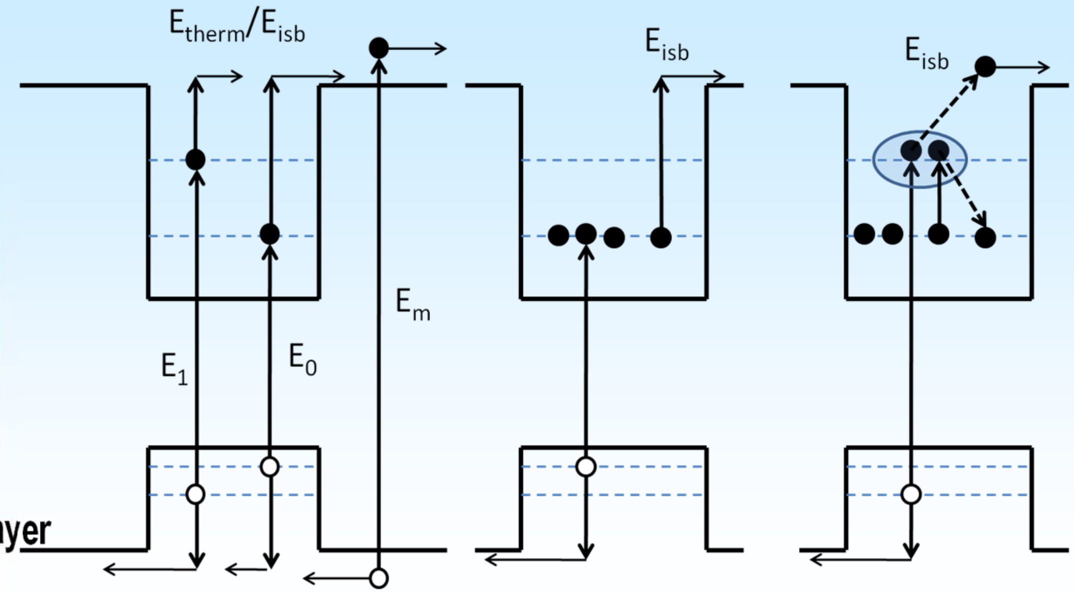


The spectral dependence of the quantum efficiency in QD SC: increase in IR is accompanied with the drop in visible part of the spectrum

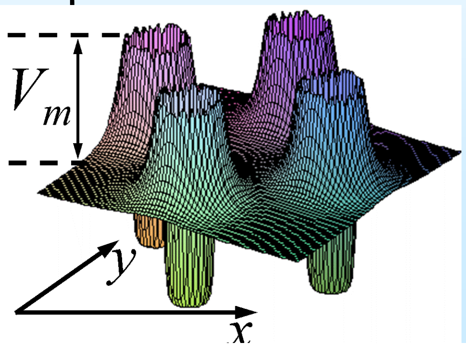
R. B. Laghumavarapu, et al., Appl. Phys. Lett. 91, 243115 (2007)

Cross-section of a δ-doped QD solar cell



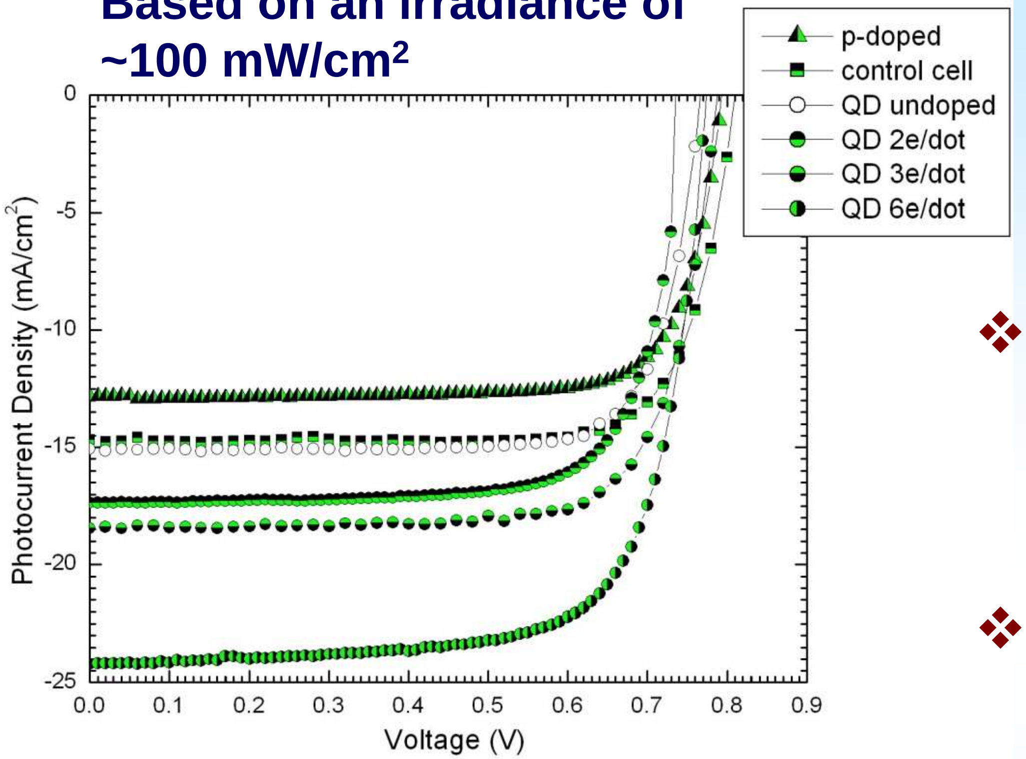


- ***Undoped:*** EHPs are photoexcited into the ground state (E_0) and an excited state (E_1) in the QD, followed by thermionic emission (E_{therm}) or intersubband photoexcitation (E_{isb}) into the conducting channel
- ***Doped:*** Additional intersubband excitations due to doping the QD to provide electrons in the ground state



Sheet densities to provide 2, 3, 4, and 6 carriers per dot

Based on an irradiance of ~100 mW/cm²



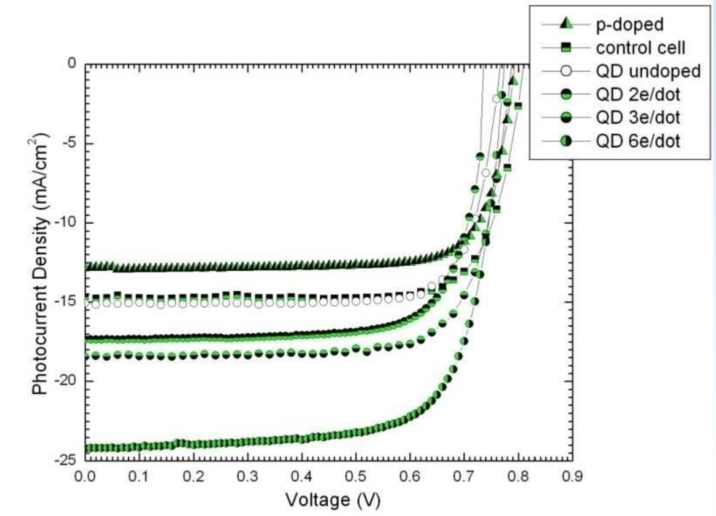
Dot population	J_{SC} (mA/cm²)	V_{OC} (V)	Fill Factor (%)	Efficiency (%)
0	15.1	0.77	77	9.31
2	17.3	0.74	76	9.73
3	18.5	0.79	75	12.1
6	24.3	0.78	72	14.0

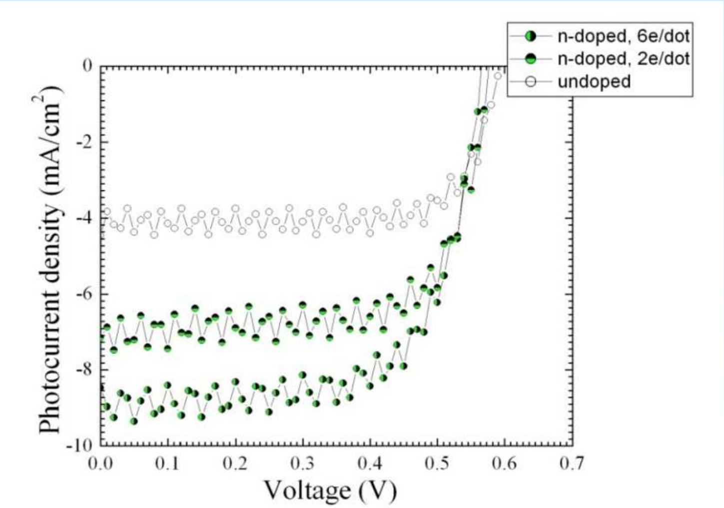
Investigating effects of doping on the J_{SC}, V_{OC} and η

- The photocurrent density, J_{SC} increases from 15.07 mA/cm² to 24.3 mA/cm² with increasing dot population.
- The power conversion efficiency increased by 4.5%, 30%, and 50% with increasing doping levels to provide 2, 3, and 6 electrons per dot.
- This can attributed to dopant-induced generation processes.

K. Sablon, V. Mitin, et al. , Nano Letters, May 2011

Long Wavelength Effect





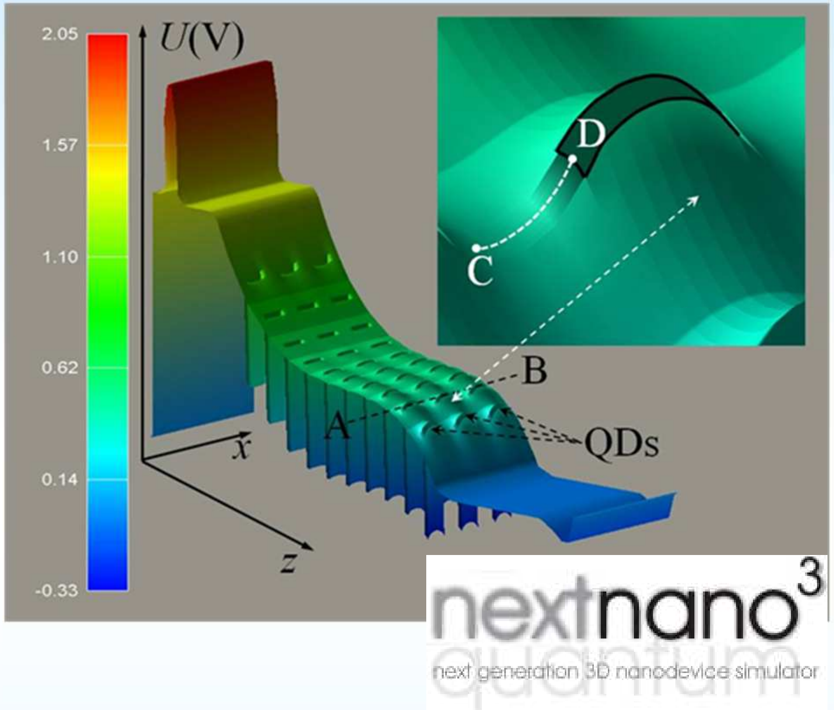
Visible and IR contributions to the QDoSC photocurrent are not additive.

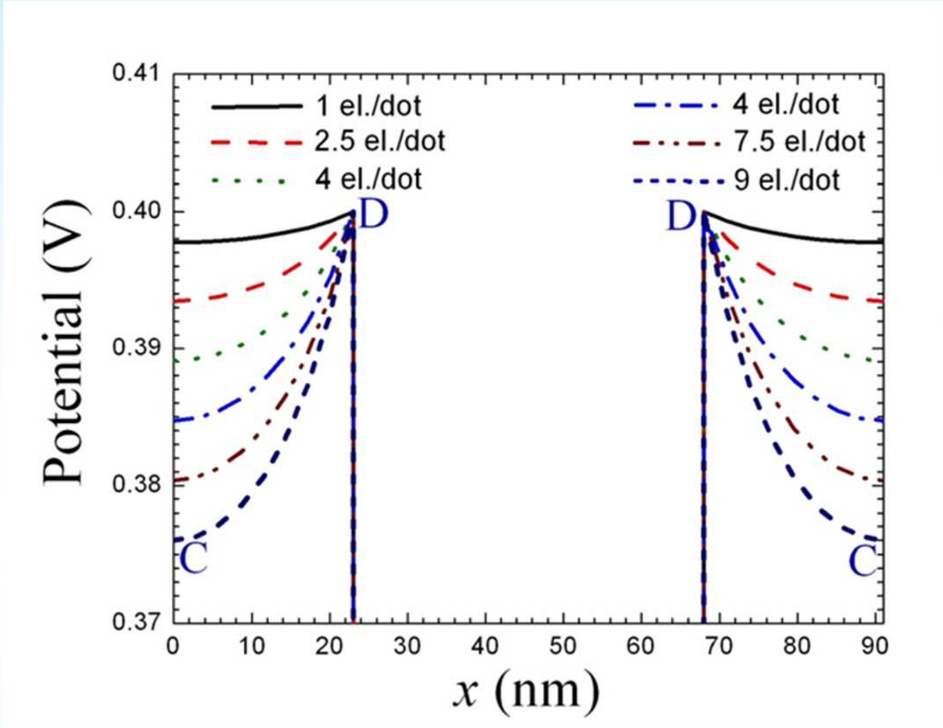
Built-in-dot charge (number of electrons)	**Total enhancement of I_{SC}** (mA/cm^2)	**IR contribution to I_{SC}** (mA/cm^2)
0 (no doping)	0.5	4
2	2.5	7
6	9	9

- Without the built-in-dot charge, the IR harvesting by QDs is practically killed by the recombination losses introduced by QDs.
- The total enhancement is small ~ 0.5 mA/cm^2 compared to 4 mA/cm^2 IR contribution. Such small improvement was observed in a number of recent papers.
- The built-in-dot charge improves IR harvesting and the corresponding potential barriers limit recombination processes.

K. Sablon, V. Mitin, et al. , Nano Letters, May 2011

Capture and Potential Barriers around QDs





❖ Potential barriers around QDs suppress the capture of photo-electrons.

❖ Corresponding potential barriers for electrons in the QD plane A-B as a function of built-in-dot electron charge.

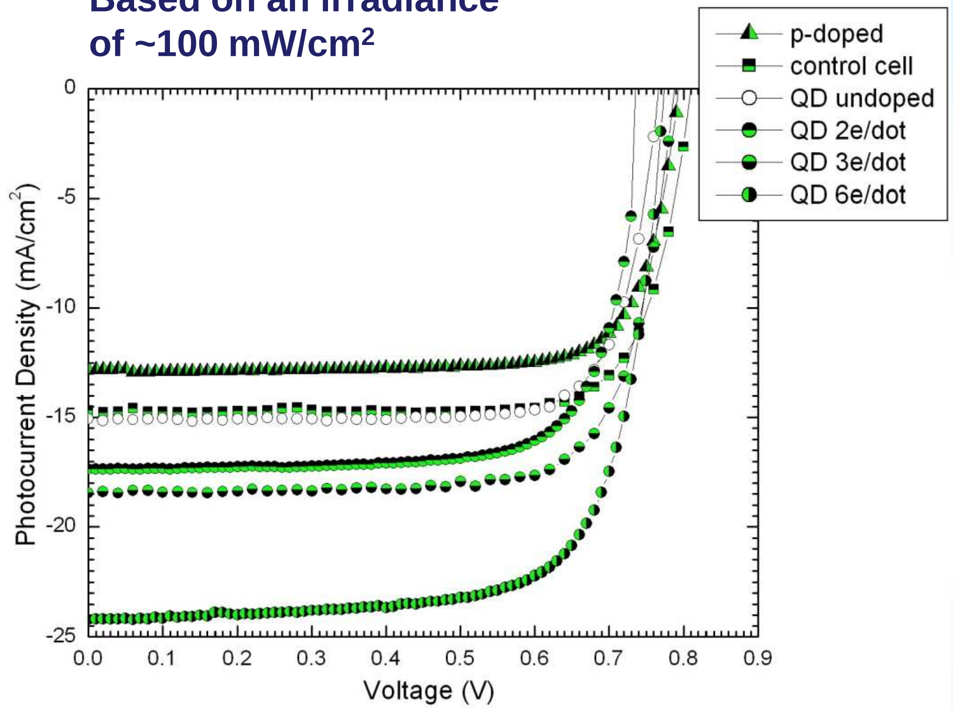
Doping → ***Carrier Capture***
→ ***Built-in-Dot Charge***

K. Sablon, V. Mitin, et al. , Nano Letters, May 2011

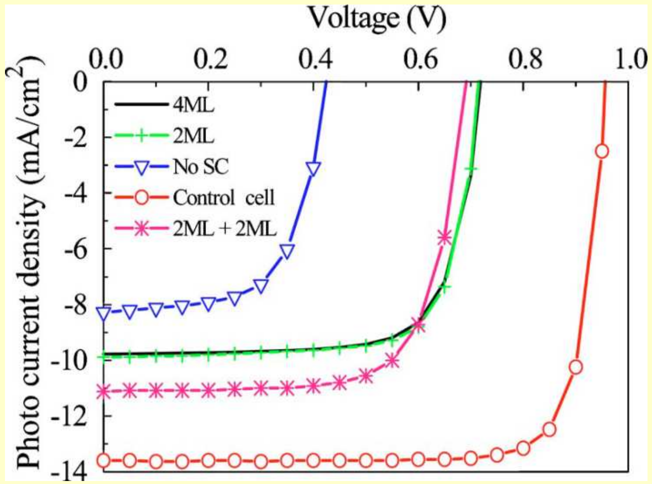
Conclusion for High Photovoltaic Efficiency due to Doping (ARL+UB)

Effects of doping on the J_{SC} , V_{OC} , and η

Based on an irradiance of ~100 mW/cm²



Typical QD cell
(Laghumavarapu et al, APL 91, 243115 (2007))



- The photocurrent density, J_{SC} , increases from 15 mA/cm^2 to 24.3mA/cm^2 with increasing dot population.
- The power conversion efficiency increased by 4.5%, 30%, and 50% with increasing doping levels to provide 2, 3, and 6 electrons per dot.
- This can attributed to dopant-induced generation processes.

Patent: K. A. Sablon, V. Mitin, A. Sergeev, N. Vagidov, J. W. Little, and K. Reinhardt, “Barrier-enhanced quantum-dot solar cell,” provisional patent R-6576.

K. Sablon, V. Mitin, et al. , Nano Letters, May 2011

Summary

1. Radical improvements of SCs due to quantum dots with the built-in-charge (Q-BIC) have been demonstrated;
2. These improvements are associated with
   (i) enhancement of intersubband QD transitions and transitions from localized QD states to conducting states in matrix,
   (ii) suppression of photoelectron capture processes;
3. Strong effects of "**optical pumping**" on IR absorption (harvesting) is demonstrated;
4. The reported data are limited by the value of the built-in-charge of **six electrons per dot**.
   We are still far from saturation of positive effects due to interdot doping.
5. The developed technology is protected by three provisional patents and UB STOR is helping us to commercionalize the technology.
6. Major results are published in

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Strong Enhancement of Solar Cell Efficiency Due to Quantum Dots with Built-In Charge

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