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Integrated NanoMaterials Core Lab
Huffaker Group UCLA/CNSI

2009 Annual Research Review

Quantum Dot Solar Cells:
A Novel Approach to Ultra High Efficiency

April 24, 2009

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Electrical Engineering Department

Outline

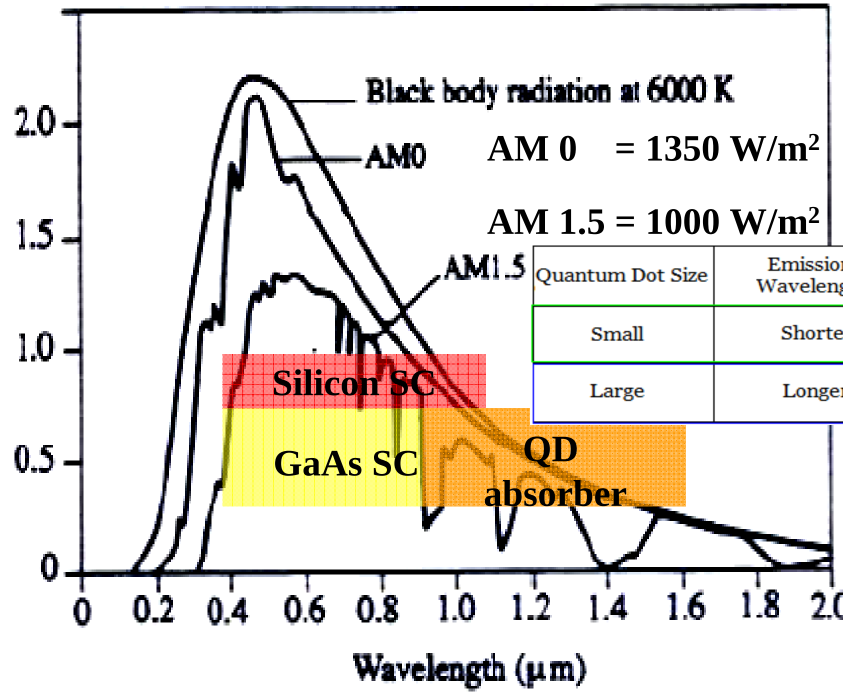
- State-of-the-art
- Intermediate Band and QD Solar cells
- InAs/GaAs and GaSb/GaAs QDs
- Recent results: InAs QD solar cells
- Recent results: GaSb QD solar cells
- Carrier multiplication in QDs
- Future works

State-of-the-art

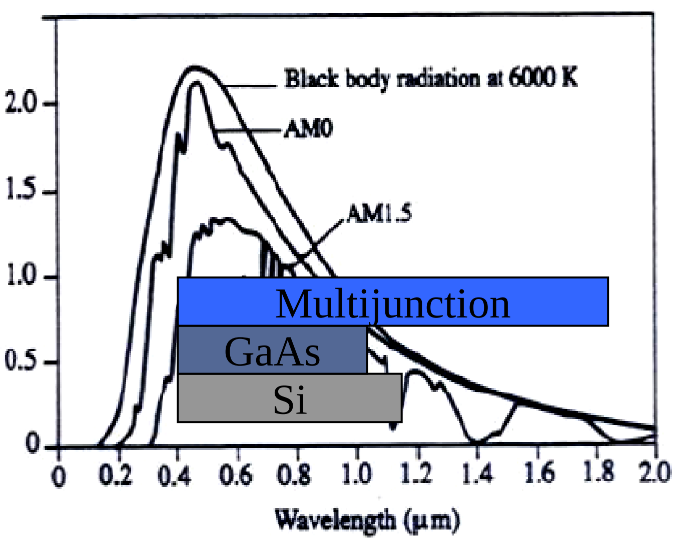
QDs for high efficiency solar cells

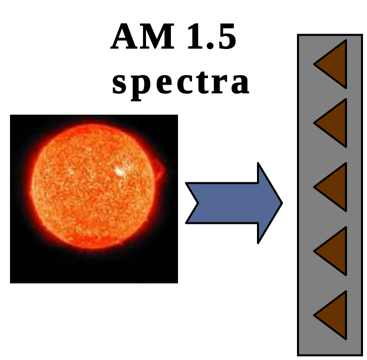
- ❑ Single junction
  - Silicon (~15%, 1 sun)
  - GaAs (~ 27%, 255 sun)
  - Organic (~8%)

- ❑ Multi-junction (40%, 240 suns)
- ❑ Quantum dot solar cells
  - Self-assembled (InAs, GaSb, InGaAs)
  - Colloidal (PbSe)



Quantum Dot Size	Emission Wavelength
Small	Shorter
Large	Longer





- Increased NIR absorption in a single junction solar cell from QDs in GaAs matrix.

- Less complex than triple junction and higher efficiency than Si or GaAs based solar cells!

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Intermediate Band Solar Cell (IBSC)

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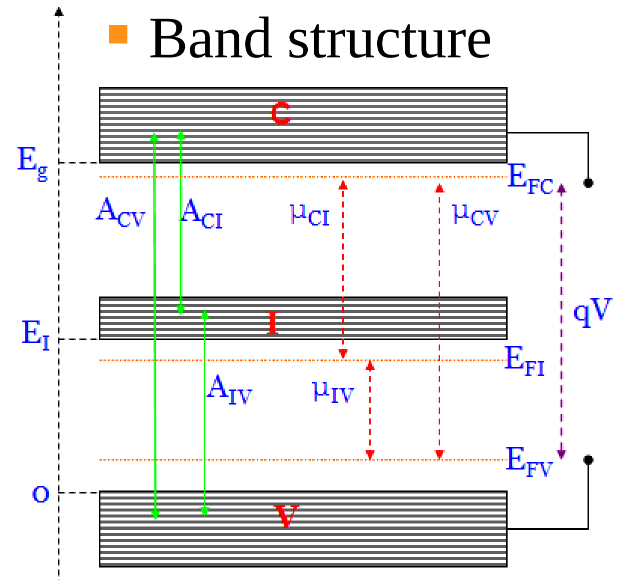
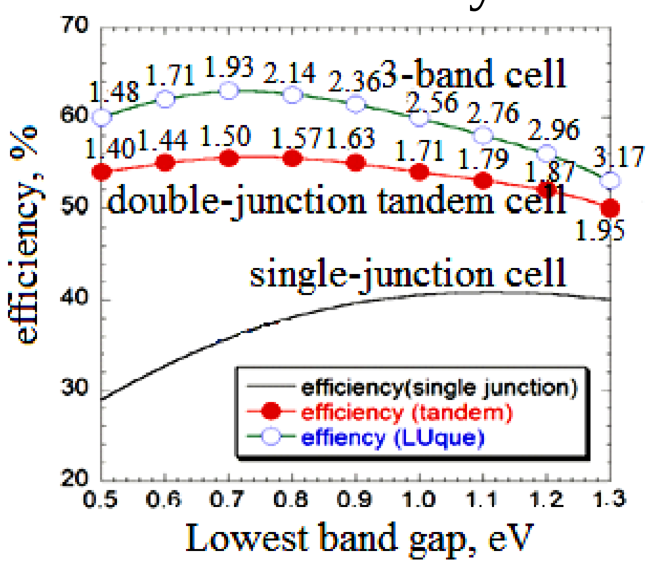
- Band structure

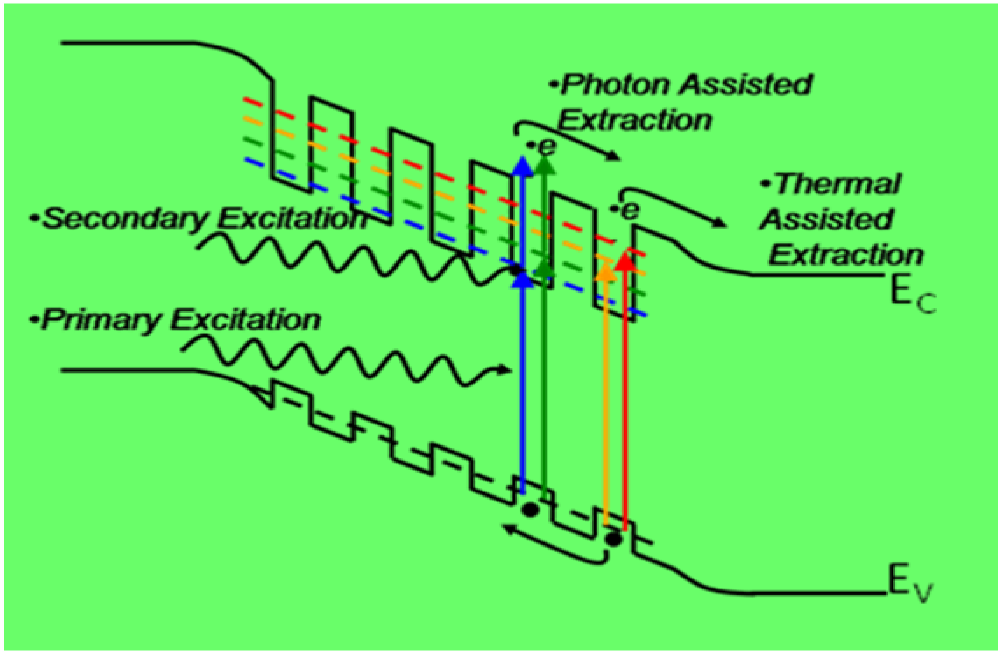


A. Luque, A. Martí, *Phys. Rev. Lett.* **78**, 5014 (1997).

- Maximum Efficiency with IBSC



- IBSC process



E_g = 1.95eV, E_{CD} = 1.24eV

$In_{0.58}Ga_{0.42}As$ /$Al_{0.4}Ga_{0.6}As$

η = 63%

- InGaAs QDs are significantly more complex than InAs or GaSb QDs.

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InAs/GaAs and GaSb/ GaAs quantum dots

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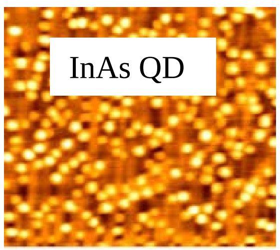
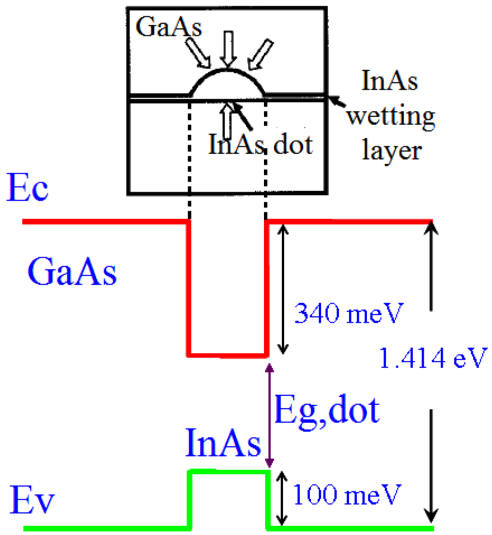
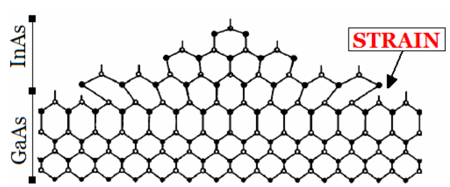
- InAs/GaAs SK QD bandstructure

AFM plan view



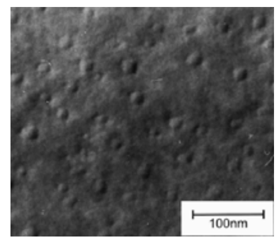


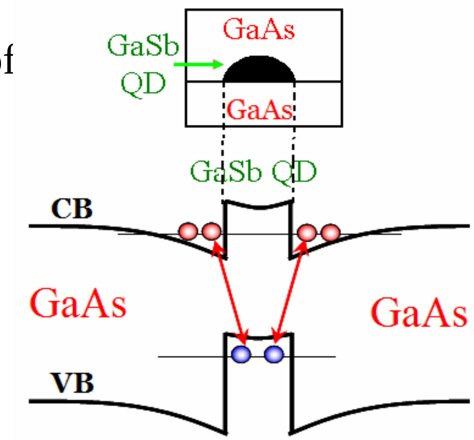
- Features
  - Emission wavelength 1150-1300nm
  - Average dot diameter 10nm
  - Type I (both e^- and h^+ confined)
  - Strain mismatch 6.7%



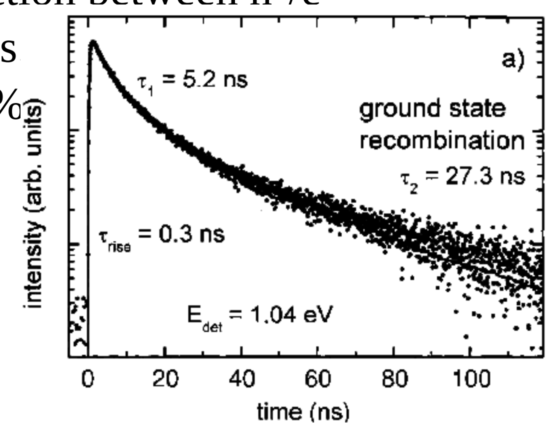
- GaSb/GaAs SK QD bandstructure

Plan view TEM of GaSb/GaAs QDs





- Features
  - Emission wavelength 1150-1300nm
  - Average dot diameter 10nm
  - Type II (only h^+ confined)
  - High Coulomb attraction between h^+/e^-
  - Long carrier lifetimes
  - Strain mismatch 7.3%



Recent results: InAs QD solar cells

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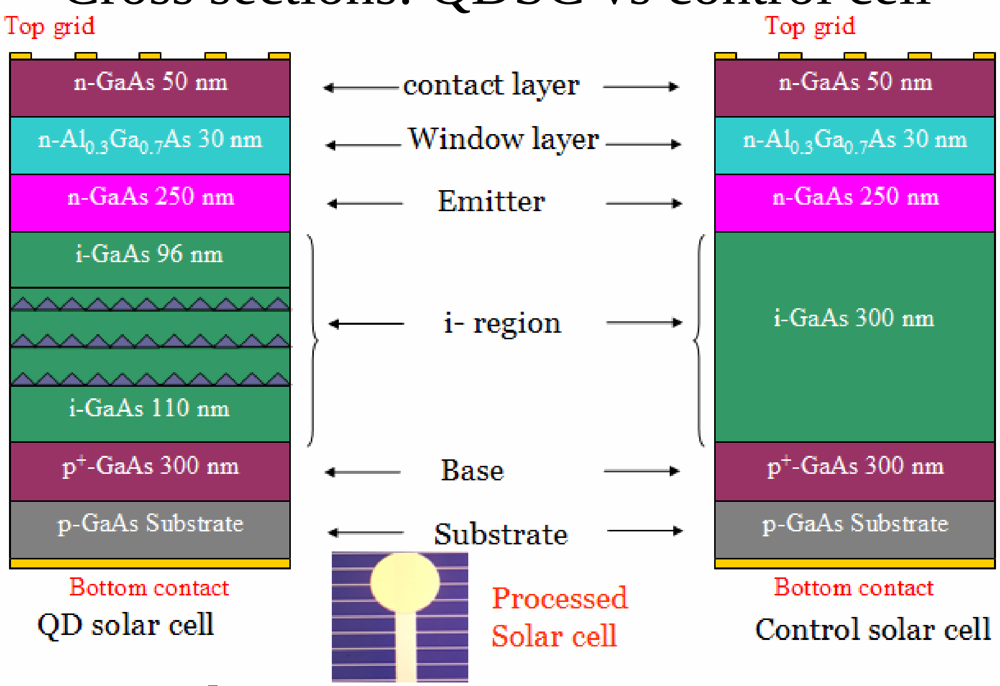
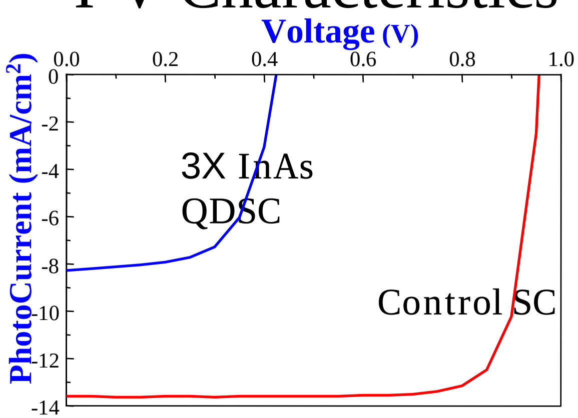
- Cross sections: QDSC vs control cell



- I-V Characteristics



Sample	V_{OC} (V)	J_{SC} (mA/cm²)	FF (%)
Control cell	0.96	13.6	81.6
3 stack QDSC	0.42	8.3	62.5

- Open circuit voltage has been reduced due to the presence of defects.
  Recombination in the dots causes reduction in the short circuit current.
- Reduction in FF with dots: 23.4%

Appearent negative presence of QDs

- $Voc = \frac{nKT}{q} \ln\left(\frac{Isc}{I_0} + 1\right), I_0 = T^{\frac{3}{2}} e^{-\frac{E_g}{nKT}}$ if $E_g \uparrow$, $V_{oc} \uparrow$
- $I = Io\left\{e^{\frac{qV}{nKT}} - 1\right\} - I_L$ if $E_g \uparrow$, $I_{sc} \downarrow$

- With defects, both V_{oc} and I_{sc} are descreased due to higher recombination rates.

Recent results: InAs QD solar cells – cont'd

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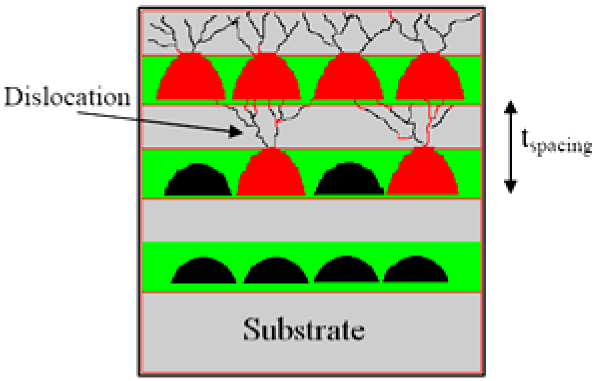
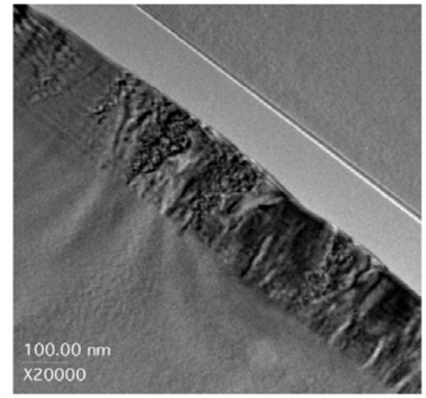
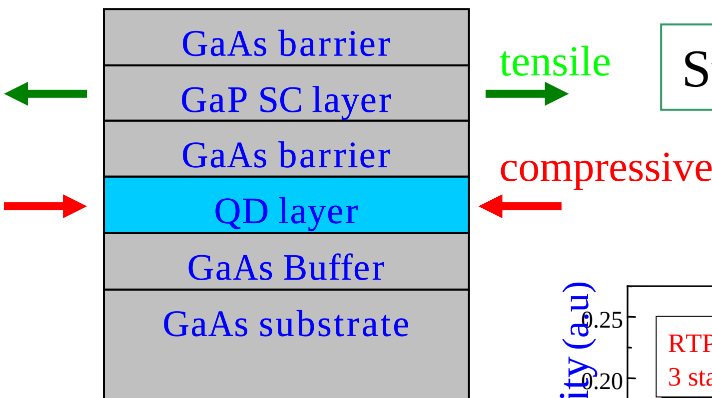


- InAs QD based solar cells require numerous stacks for significant NIR absorption.
- Highly strained QDs can only be stacked to ~ 1-3 layers without the propagation of threading dislocations.

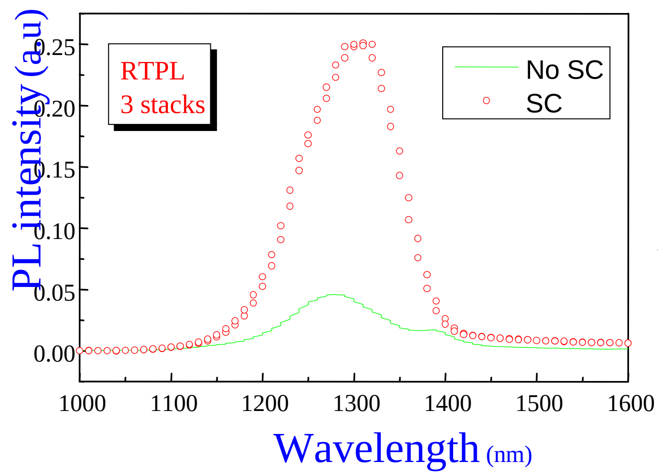


TEM image without SC

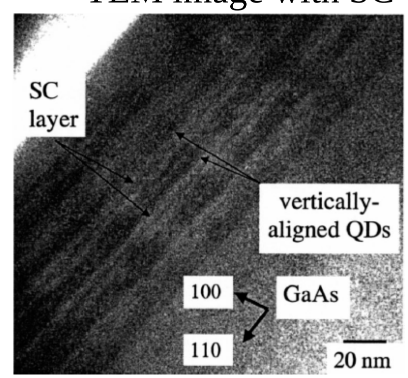


Strain compensation

- With strain compensation:
  - Reduction in strain propagation
  - Reduction in defect density
  - Increase in dot size
  - Red shift in PL peak



TEM image with SC



Recent results: InAs QD solar cells – cont'd

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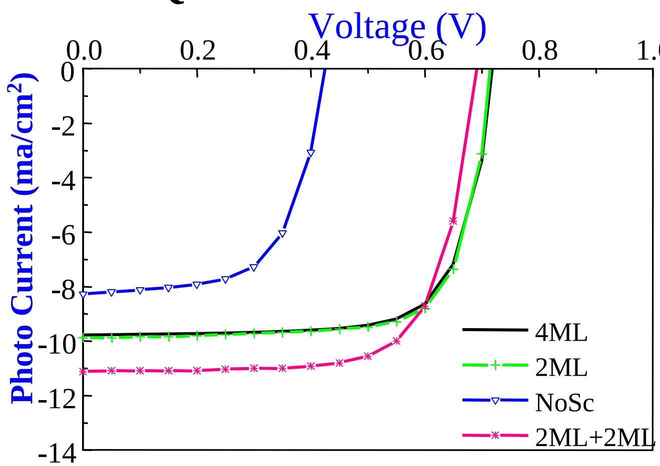
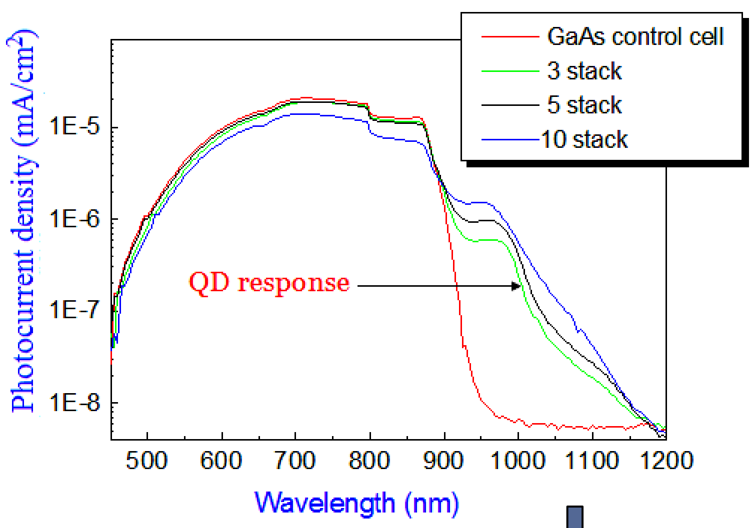
- InAs QD Solar Cell with Strain Compensation (SC)



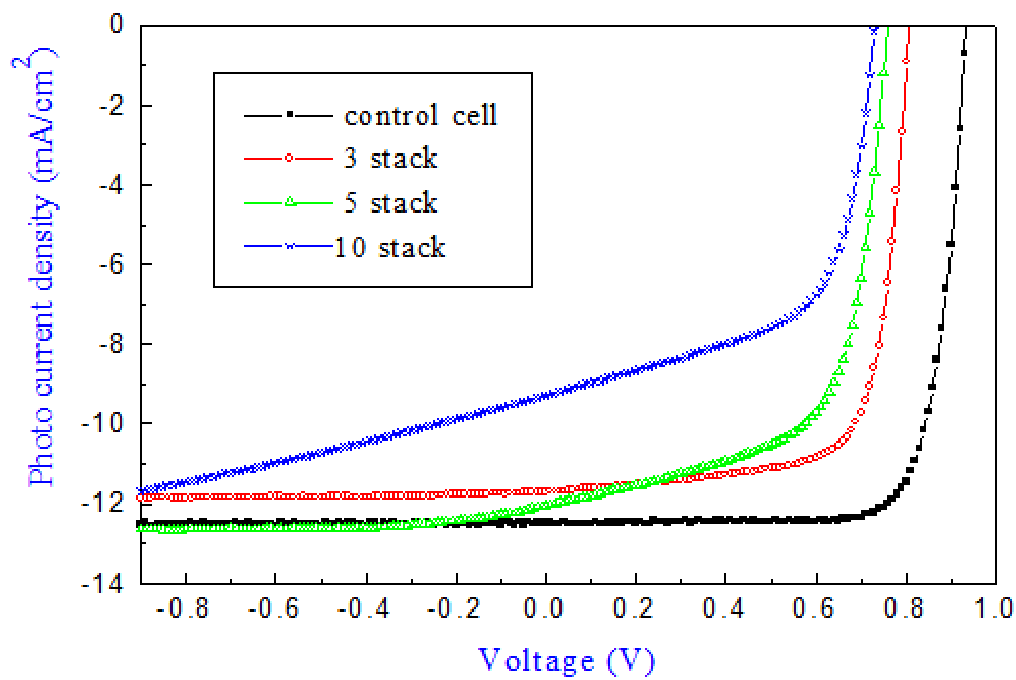
Sample	V_{OC} (V)	J_{SC} (mA/cm²)	FF (%)	Ideality factor
2ML SC	0.73	9.9	73.1	2.2
4ML SC	0.72	9.8	73.5	1.87
2ML+2ML SC	0.69	11.2	73.2	1.92
No SC	0.42	8.3	62.5	2.07

- Improvement in FF with strain compensation
- With SC, both current and voltage have been increased
- SC has reduced recombination

- Enhanced spectral response via QD stack



Increased NIR absorption



GaSb QD solar cells - IMF

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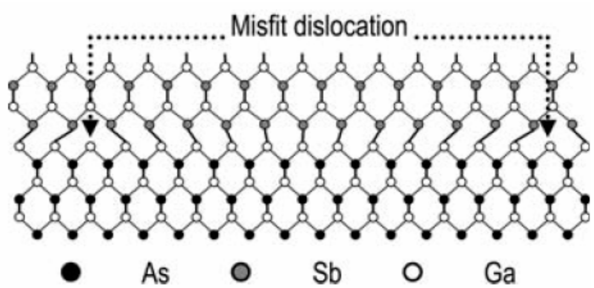
- The IMF growth mode produces strain-relaxed QDs :

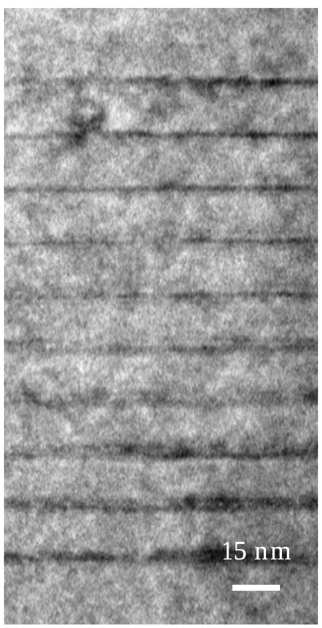


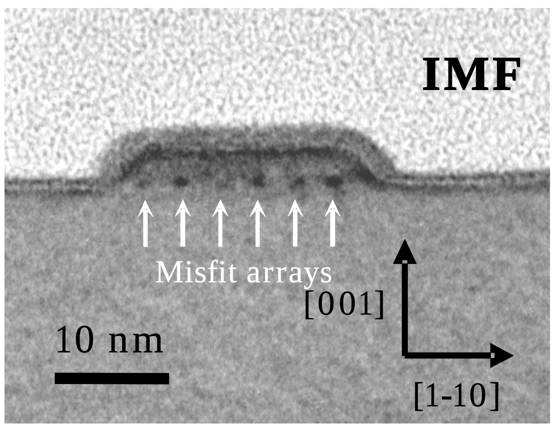
Vertical stacking of QDs causes structural defects → the introduction of IMF array at GaSb/GaAs interface relieves the strain in a localized manner

↓

A larger number of QD stacks can be achieved, avoiding strain accumulation presents in S-K growth mode.

- TEM images of 10 stack and single GaSb/GaAs IMF QD





- Base width = 30nm
- Height = 6nm; directional
- Avg. Dot density~1.5×10^{10} cm-^{2}

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Recent results: GaSb QD solar cells

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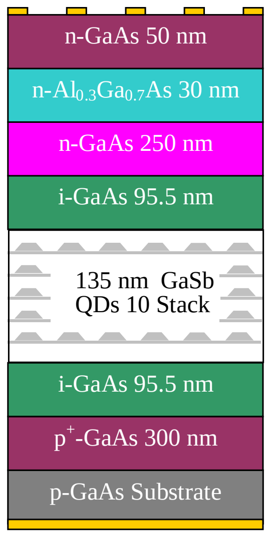
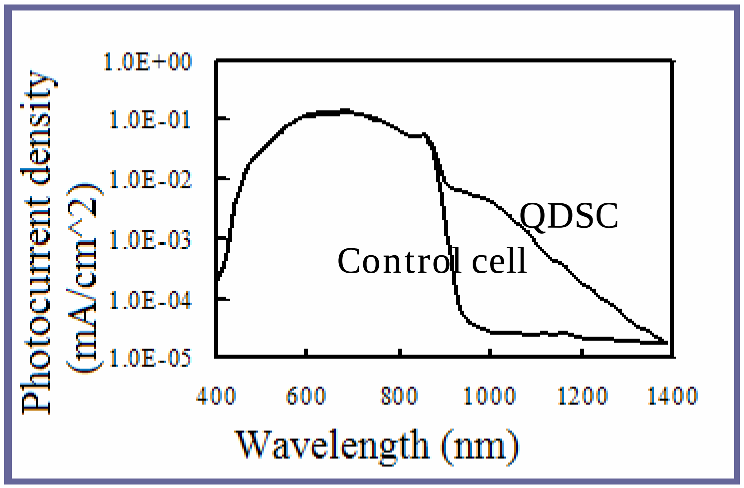
- Cross-section

Top grid

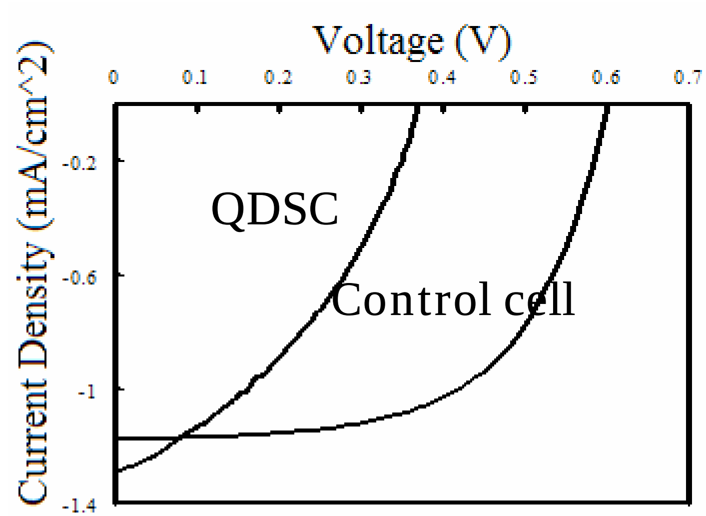


Bottom contact

- Spectral Response



- I-V characteristics



Sample	I_{SC} (mA/cm^2)	V_{OC} (V)	FF (%)	Ideality factor
Control cell	-1.17	0.6	59.6	2.35
QD solar cell	-1.29	0.37	37.7	3.80

R.B. Laghumavarapu *et.al*, Appl Phys. Lett, 90, 173125 (2007)

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Recent results: GaSb QD solar cells - cont'd

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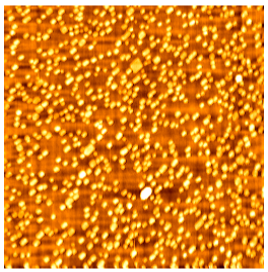
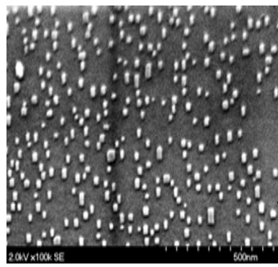
- New growth conditions to improve device performances

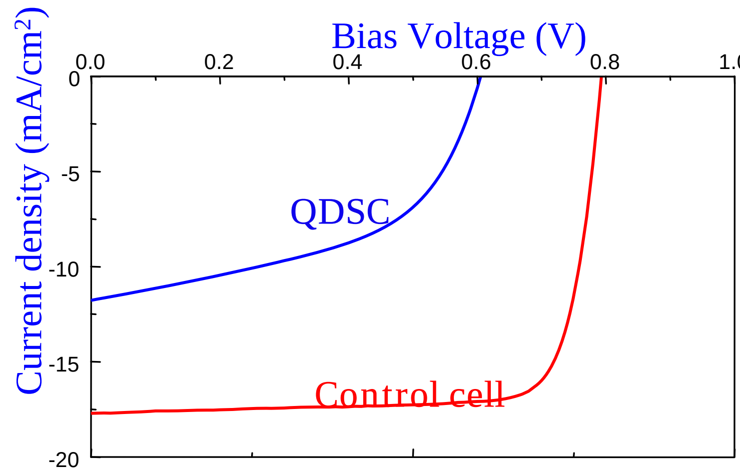




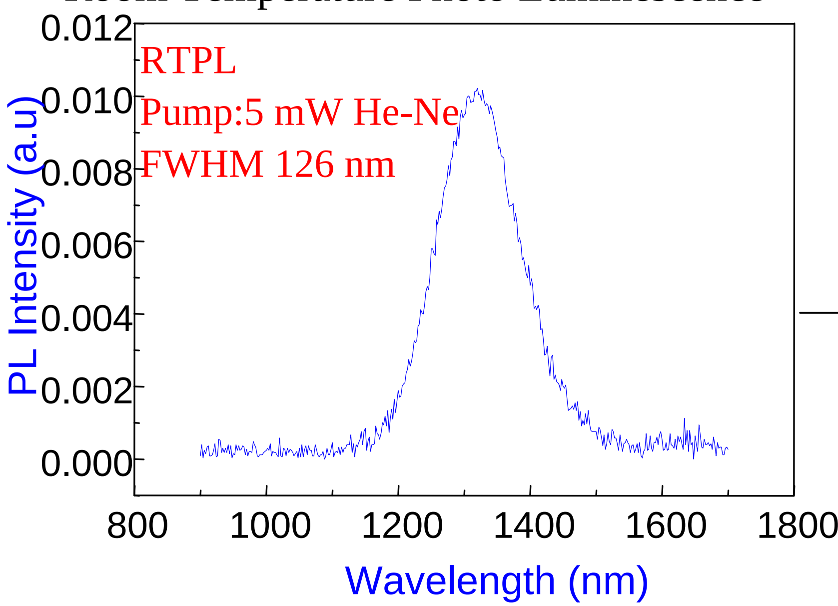
- Avg. Dot density: 1.5x10^{10} cm^{-2}
- Avg. dot height 7.5 nm

Lower Density & smaller QDs size

- Improved I-V characteristics



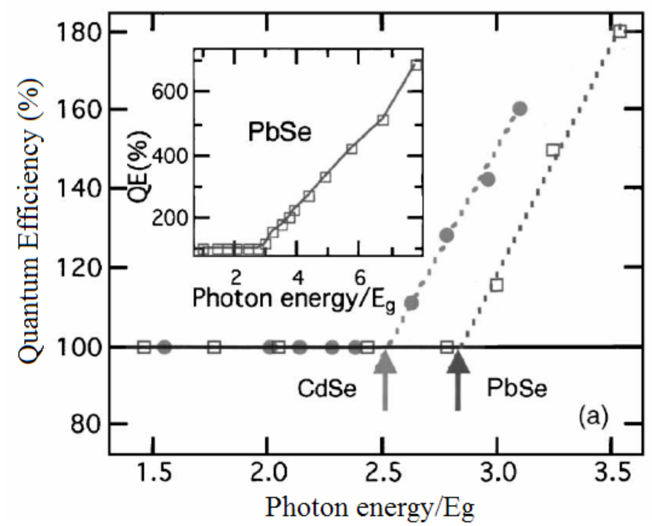
- Room Temperature Photo Luminescence



QD solar cell	FF (%)	Ideality factor
Before growth optimization	37.7	3.80
After growth optimization	50.4	2.86

Carrier Multiplication in colloidal QDs

- **Carrier multiplication** (CM or MEG): process in which absorption of a single photon generates multiple electron-hole pairs (excitons)



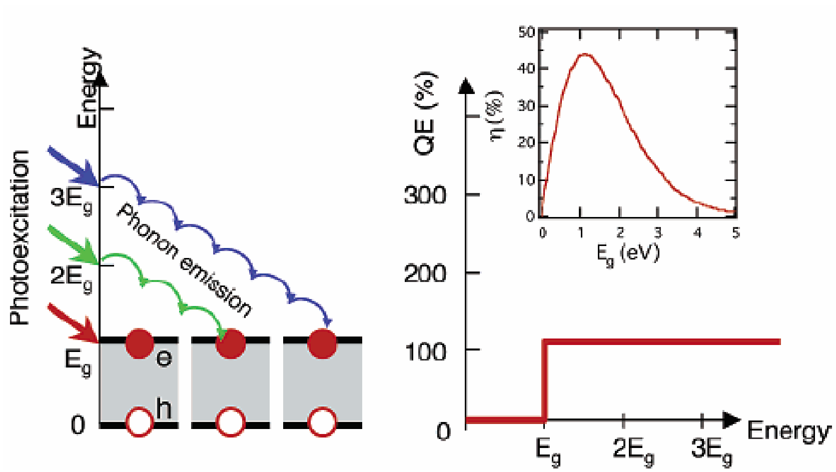
Klimov et al., Appl. Phys. Lett. **87**, 253102 2005

- PbSe/CdSe colloidal quantum dots can efficiently produce multiple electron-hole pairs (excitons) in response to a single absorbed photon.

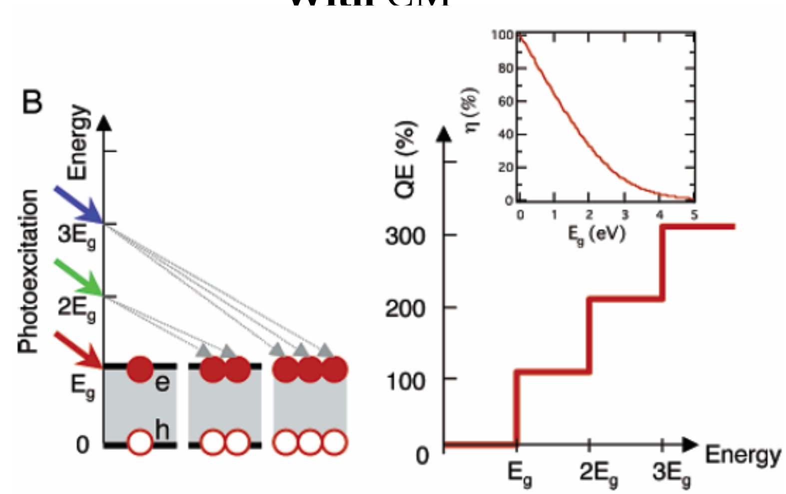
- *Traditional photoexcitation*: absorption of a single photon produces a single exciton independent of photon excess energy dissipated $(\eta\omega - E_g)$ as heat via phonon emission ($QE \leq 100\%$)

- *Nontraditional photoexcitation:* photons with energies *E*g, 2*E*g, and 3*E*g generate one, two, and three excitons, respectively. ($QE > 100\%$)

Without CM



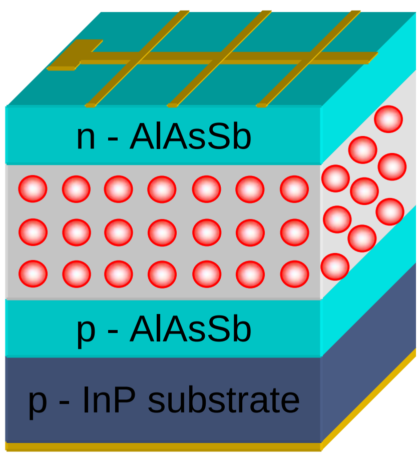
With CM



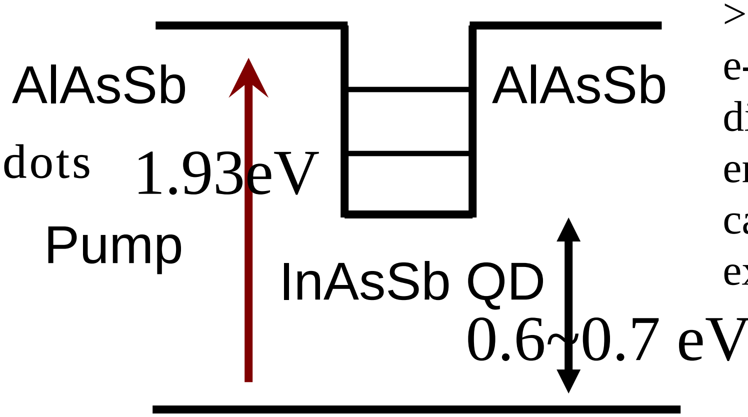
Future work-
Carrier Multiplication in epitaxial QDs

- In our research group, we are duplicating the colloidal QD band structure in epitaxial QDs.
- CM has been demonstrated in colloidal dot but not yet in epitaxial dots
- We still have to demonstrate the CM in epitaxial QDs but a good candidate for that seems to be InAsSb quantum dots layers stacked in the intrinsic region of a single p-i-n junction solar cell.

Structure:



Band diagram:



Idea: a photon with energy >Eg could generate up to 3 e-h pairs. Rather than dissipating the excess energy into the lattice, it can be used to create a new exciton.

- This structure satisfies some of the key requirements for IBSC.
- Possible to observe carrier multiplication.

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Research Group

Advisor

- Prof. Diana Huffaker

Post Docs:

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- Kalyan Nunna
- Anitha Jallipalli
- **Ramesh B Laghumavarapu**
- Jun Tatebayashi
- Jun Hee

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- Charles Reyner
- Joshua Shapiro
- Pradeep Senanayake
- Zhendong Xie

Conclusions

- Experiments performed on InAs/GaAs and GaSb/GaAs QD solar cells demonstrated the basic operation of the phenomenon.
- Strain compensation in InAs has shown improvements in QD solar cells.
- Reduced I_{SC}, V_{OC} and FF are observed in QD Solar cells.
- An infrared response upto 1100 and 1300 nm is observed in InAs and GaSb QD solar cells.
- With the combination of right material and growth conditions, better results can be achieved.