Digital stress compensation for stacked InAs/GaAs QDs solar cells

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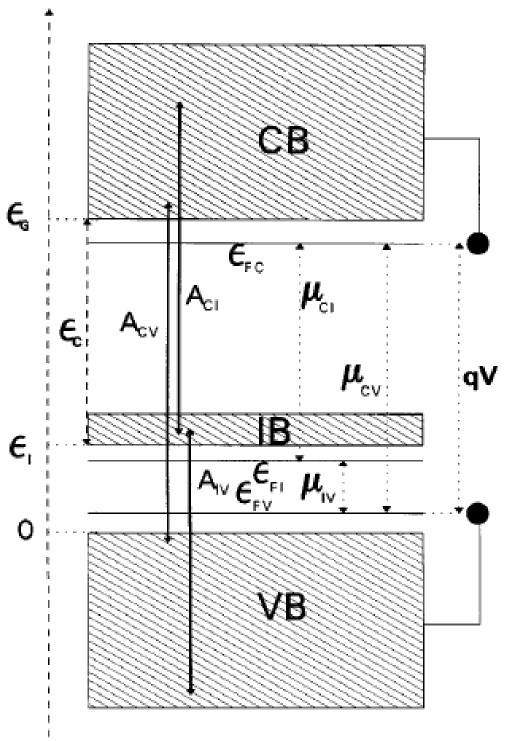
Outline

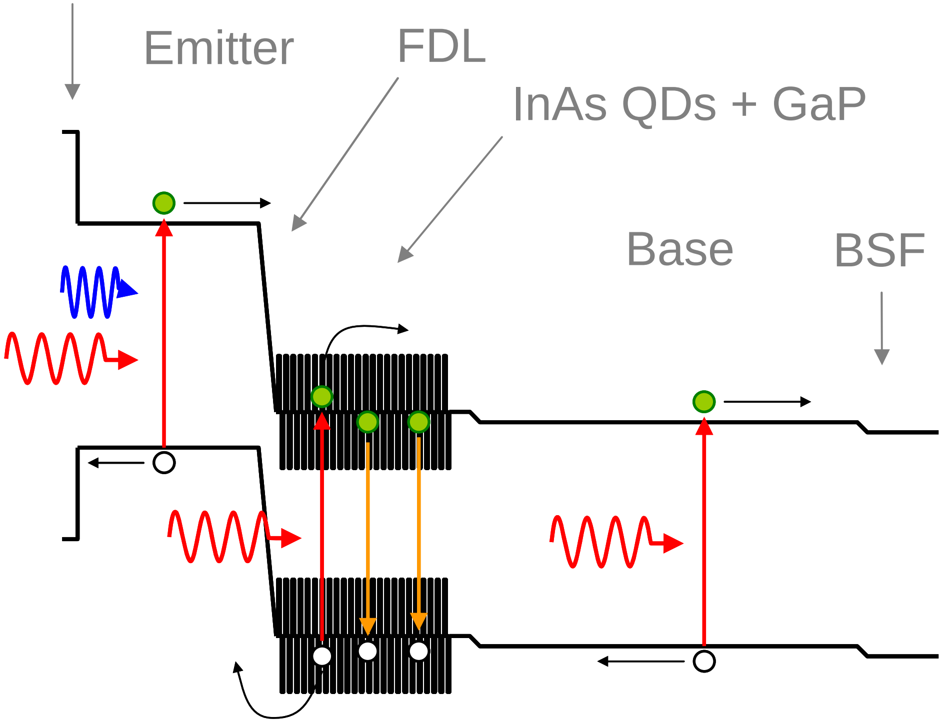
1. Introduction: GaAs/InAs QDs Solar Cell
2. MBE growth for zero average stress:
   Digital stress compensation with GaP monolayers
3. Structural quality: XRD, AFM and TEM
4. Optical properties: photoluminescence and photocurrent
5. Conclusions

GaAs InAs QDs Solar Cell:

A basic device to study the physics of the IB concept



Band diagram of a solar cell with an intermediate band.



Antonio Luque and Antonio Martí, Phys.Rev.Letters, VOLUME 78, NUMBER 26 30 JUNE 1997

Objetive:

Increase the light absorption of QDs based devices

- LEDs
- Lasers
- Infrarred photodetectors
- Solar cells
- …

Increase the QD density per layer

Increase density → Reduce size → Increase transition energy

Increase the number of QDs layers

☒ Devices usually have a limited active region thickness

Increase the density of QDs layers

☒ Increase of defects due to excesive strain

→ **Strain compensation**

➔ InAs/GaAs QDs with GaP strain compensation monolayers

Reference	Nº Layers	QDs (InAs)	SC layers	Spacer	Application
Nuntawong et al. Appl. Phys. Lett. **85**, 3050 (2004)	10	3 ML	8 ML ($In_{0.36}Ga_{0.64}P$) 8 ML ($In_{0.30}Ga_{0.70}P$)	19 nm	General (MOCVD)
Nuntawong et al. Appl. Phys. Lett. **86**, 193115 (2005)	5	3 ML	2 ML (GaP) 4 ML " 6 ML " 8 ML "	17 nm 17.58 nm 18.12 nm 18.66 nm	Lasers (MOCVD)
Tatebayachi et al. Appl. Phys. Lett. **88**, 221107 (2006)	6	2.6 ML	6 ML GaP	27 nm	Lasers (MOCVD)
Fu et al. Appl. Phys. Lett. **91**, 073515 (2007)	10	5.7 ML ($In_{0.5}Ga_{0.5}As$)	1.83 ML GaP	50 nm	QD IR photodetectors (MOCVD)
Lever et al. J. Appl. Phys, **95** 5710 (2004)	3	5.8 ML ($In_{0.5}Ga_{0.5}As$)	1.83 ML GaP	30 nm	General (MOCVD)
Oshima et al. Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on Volume 1, May 2006 Page(s):158 - 161	20	2 ML	40 nm $GaN_{0.005}As_{0.995}$	40 nm	Solar Cells (H-MBE)
This Work	**50**	**2 ML**	**1 + 1 ML GaP**	**18 nm**	**Solar Cells (MBE)**

Stack design for zero stress condition

Strain components due to a biaxial stress

$$\begin{cases} \varepsilon_{xx} = \varepsilon_{yy} = \varepsilon = \dfrac{a_0 - a_1}{a_0} \\ \varepsilon_{zz} = \nu \varepsilon_{xx} \\ \varepsilon_{xy} = \varepsilon_{xz} = \varepsilon_{yz} = 0 \end{cases}$$

Strain energy density in the layer

$$U = \left[C_{11} + C_{12} - \frac{2C_{12}^2}{C_{11}} \right] \varepsilon^2 = A\varepsilon^2$$

Strain relation between two layers pseudomorphically grown on GaAs

Average strain energy density

$$U_{av} \approx \frac{A_1\varepsilon_1^2 n_1 a_1 + A_2\varepsilon_2^2 n_2 a_2}{n_1 a_1 + n_2 a_2}$$

Zero stress condition $\dfrac{n_1}{n_2} = -\dfrac{A_2\varepsilon_2}{A_1\varepsilon_1}$

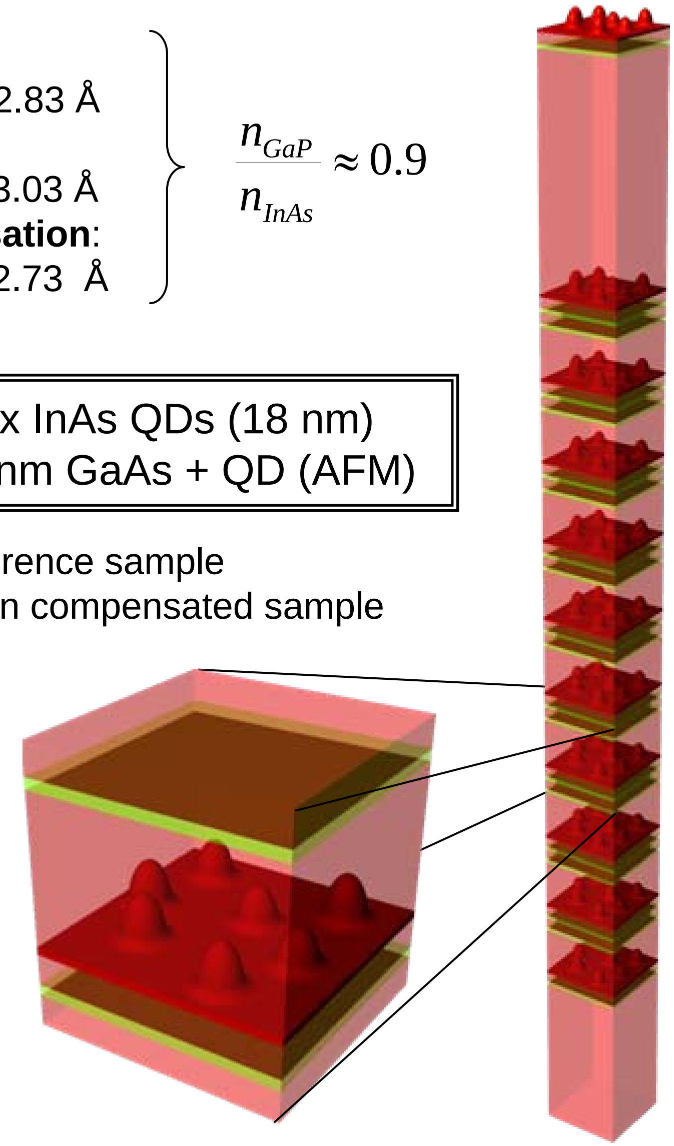
Matrix:
a$_{(GaAs)}$= 2.83 Å
QDs:
a$_{(InAs)}$ = 3.03 Å
Compensation:
a$_{(GaP)}$ = 2.73 Å

$$\frac{n_{GaP}}{n_{InAs}} \approx 0.9$$

10 x InAs QDs (18 nm)
+ 72 nm GaAs + QD (AFM)

- Reference sample
- Strain compensated sample

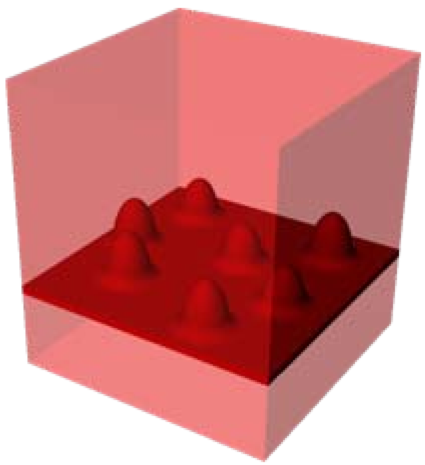
33.3 Å GaAs
1 ML GaP
126 Å GaAs
15.3 Å GaAs
1 ML GaP

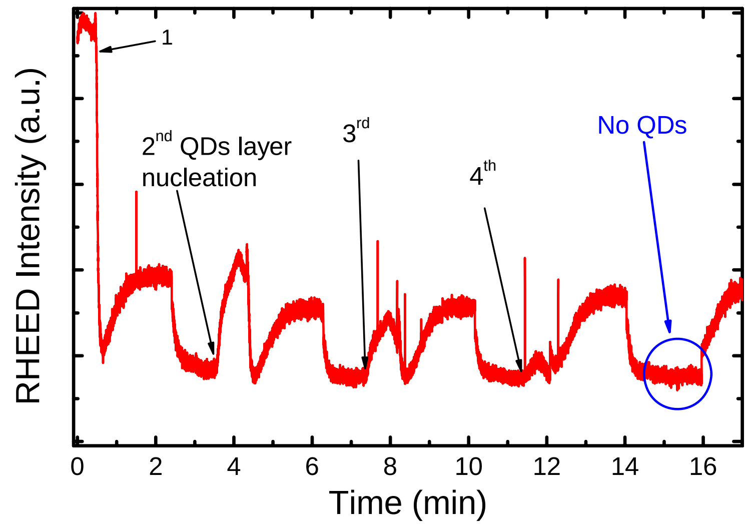


N. J. Ekins-Daukes *et al*. Procedings of the 28th IEEE PV Specialist Conference, IEEE Press, New York, USA, 2000. pp. 1273-1276

MBE growth sequence

Without GaP SC layers

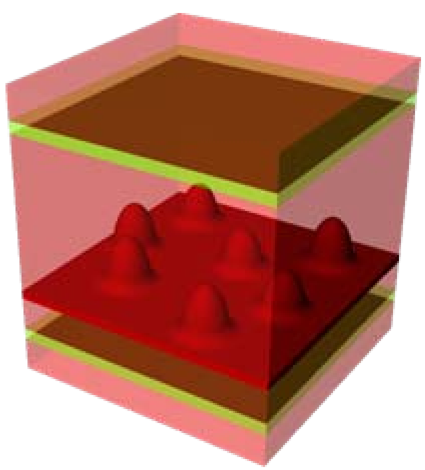


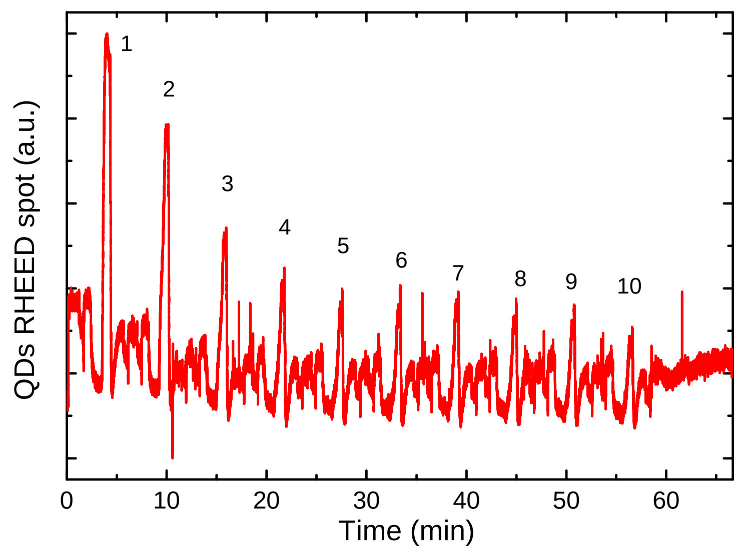


No QDs nucleation observed by RHEED beyond the 4th layer

Acumulated strain creates too many defects

With GaP SC layers

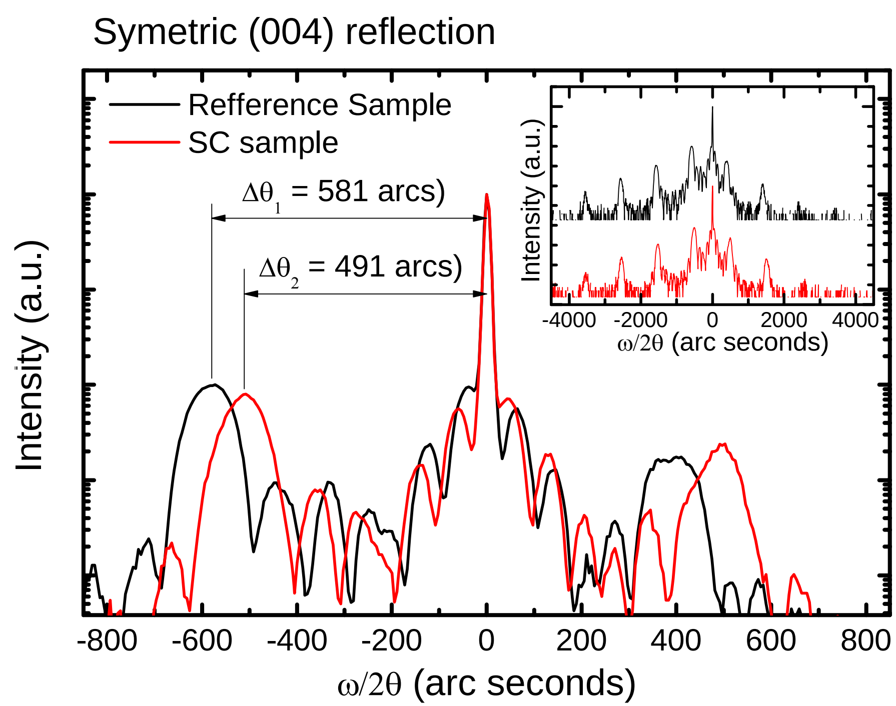




Uniform QDs nucleation time

Evidence of correct strain compensation

Structural characterization: XRD



Average perpendicular strain

	No SC	SC
$\Delta\theta$ (arcs)	581	491
$\langle\varepsilon_t\rangle$	0.004368	0.003679
Relative strain Reduction (%)	--	19

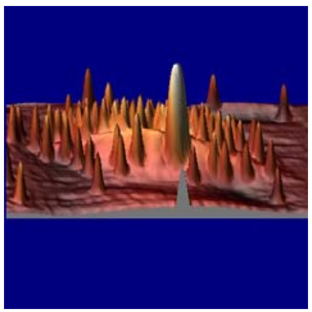
- GaP thickness
  < nominal thickness
- $GaAs_{(1-x)}P_x$ alloy
- Both

10 stacked layers of InAs QDs Characterization by AFM

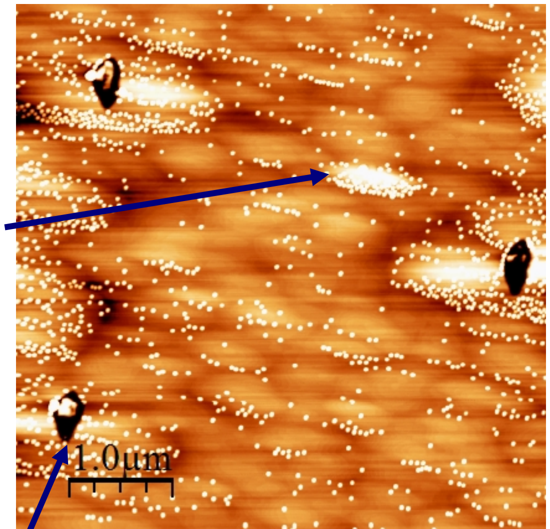
Without Strain Compensating Layers

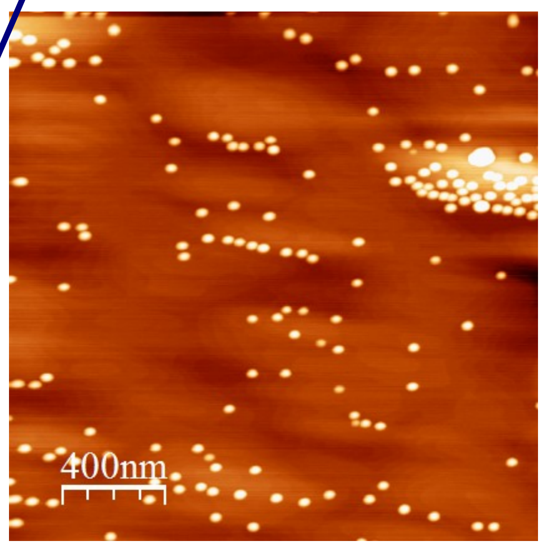
Non uniform QDs distribution

⇒ QDs Colonies

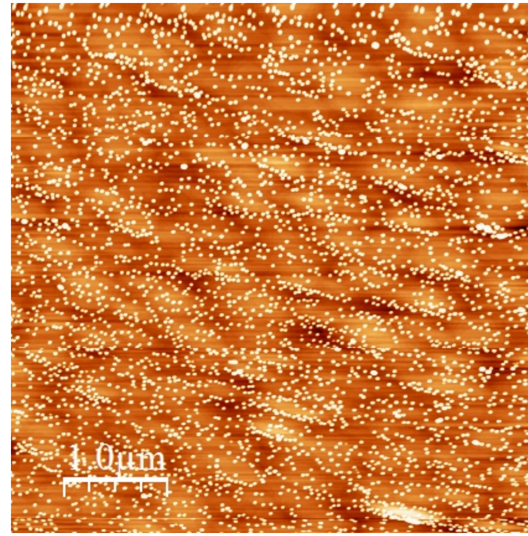


⇒ Dislocations



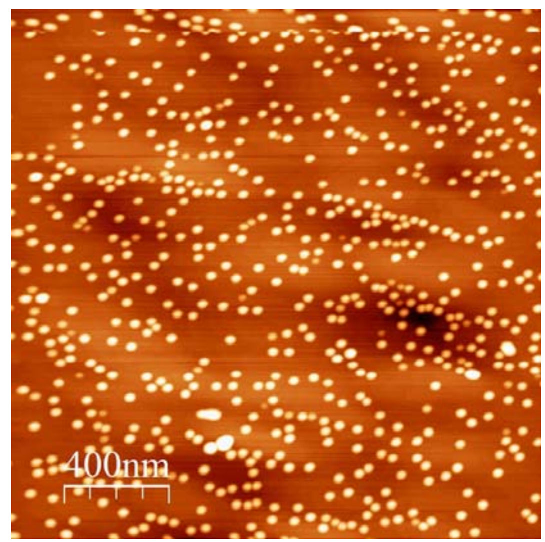


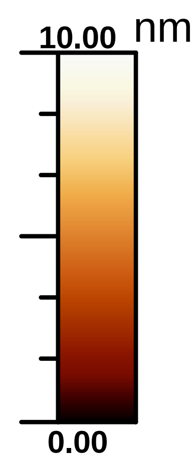
With Strain Compensating GaP MLs



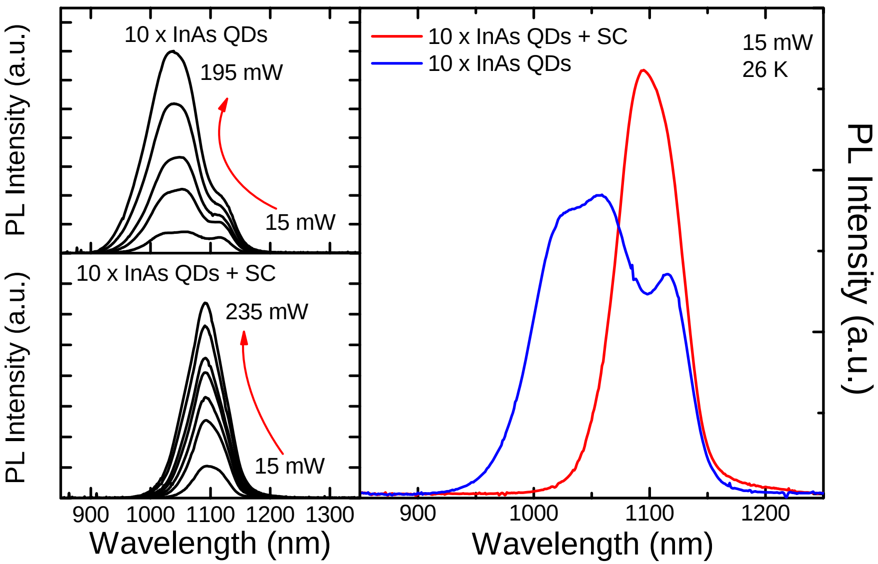
Higher uniformity
QDs Density = $1.7x10^{10}$ cm^2

Average QDs size:
- Diameter ~ 50 nm
- Heigth ~ 9 nm





photoluminescence of 10 stacked QDs layers

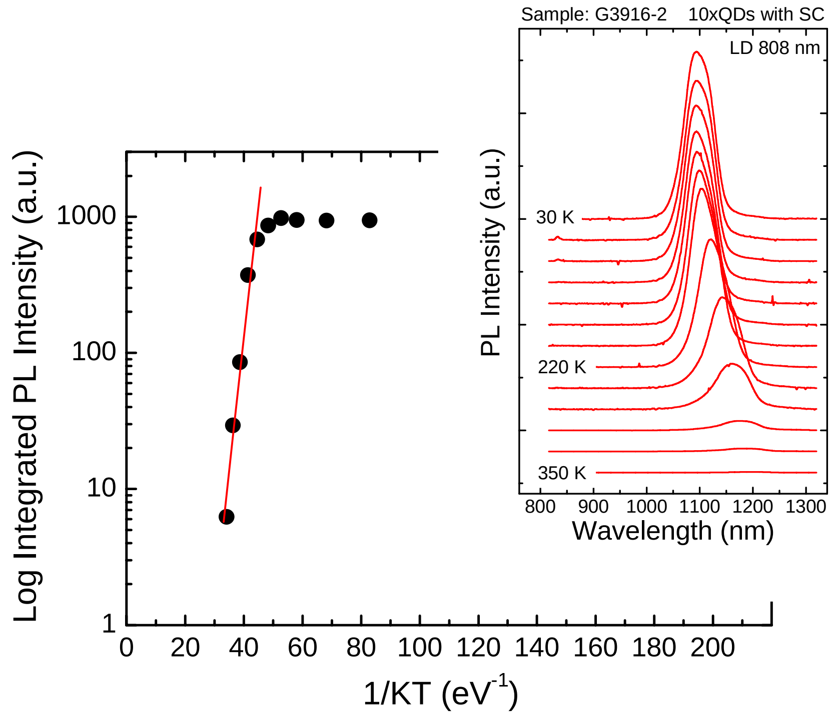


"Quasi" monomodal emission

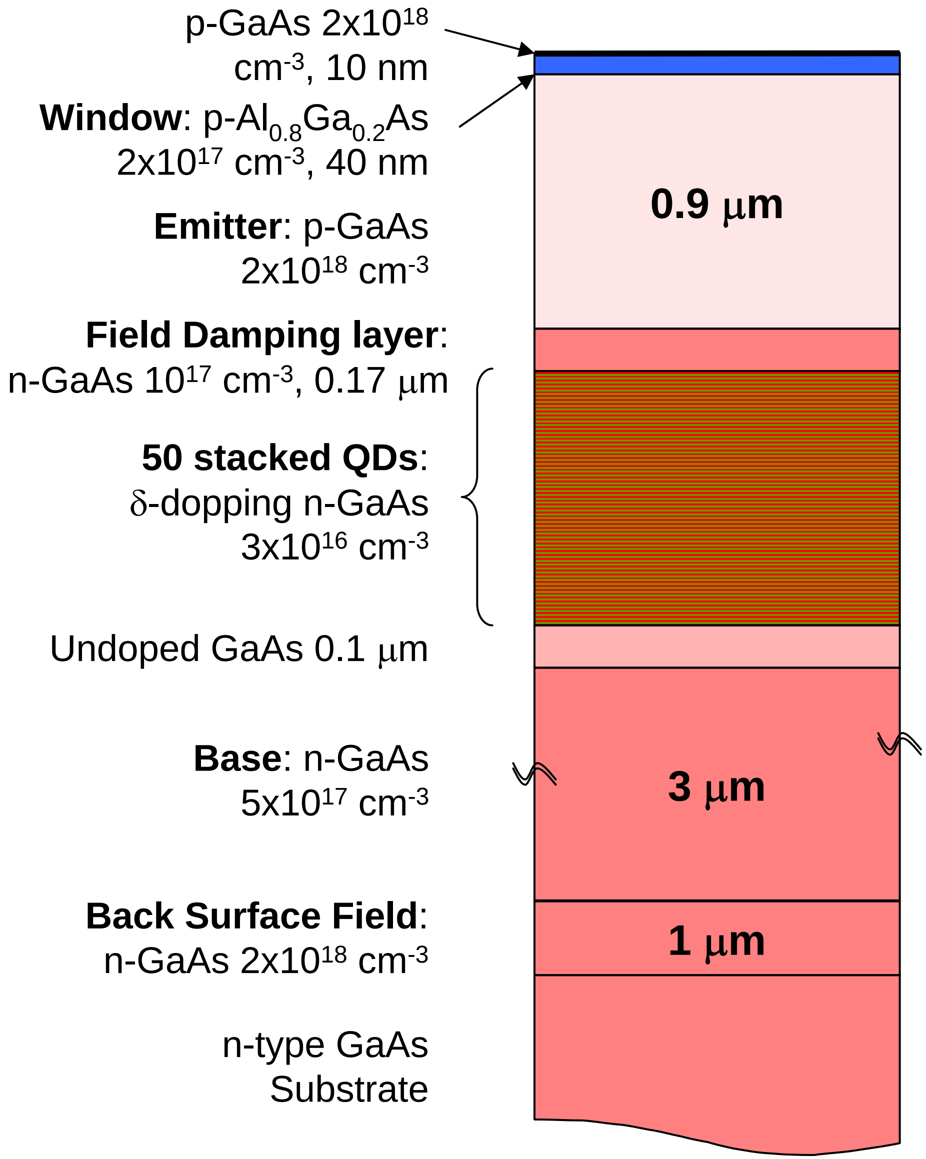
- 1.13 eV at 26 K
- 1.05 eV at RT

Good carrier confinement provided by P incorporation into the matrix

ΔE_{Th} = 450 meV

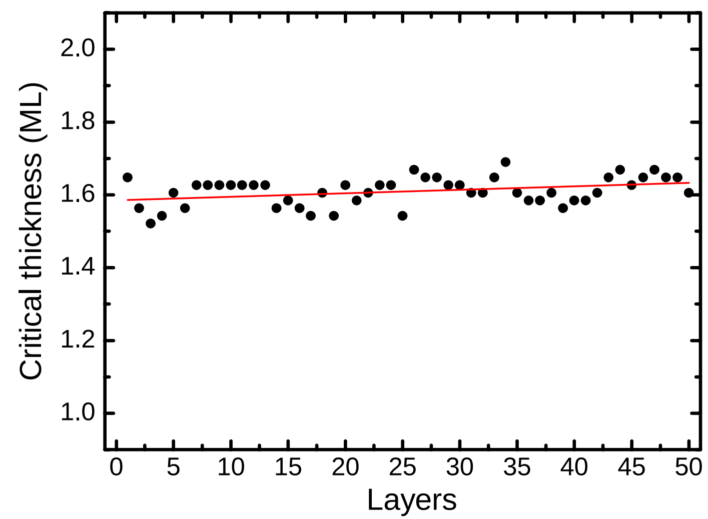


QDs Solar Cell



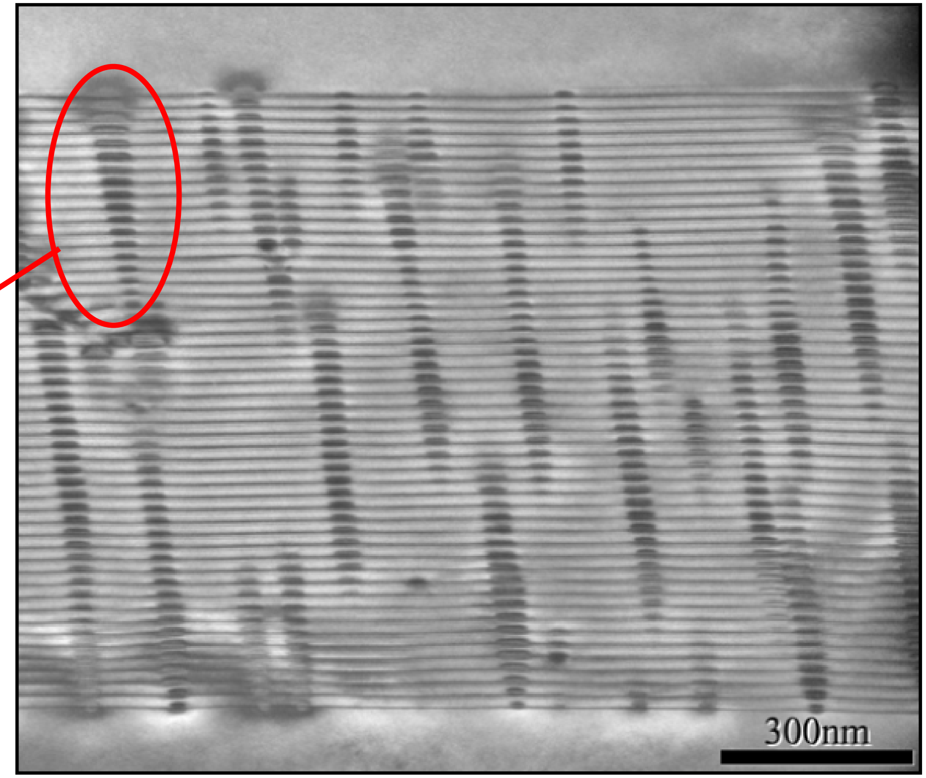
- 50 stacked QDs layers
- 18 nm of spacer

Growth by ALMBE

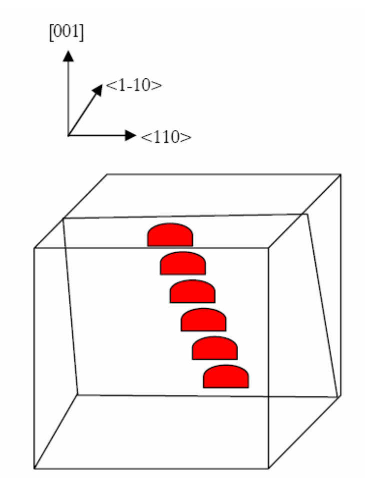


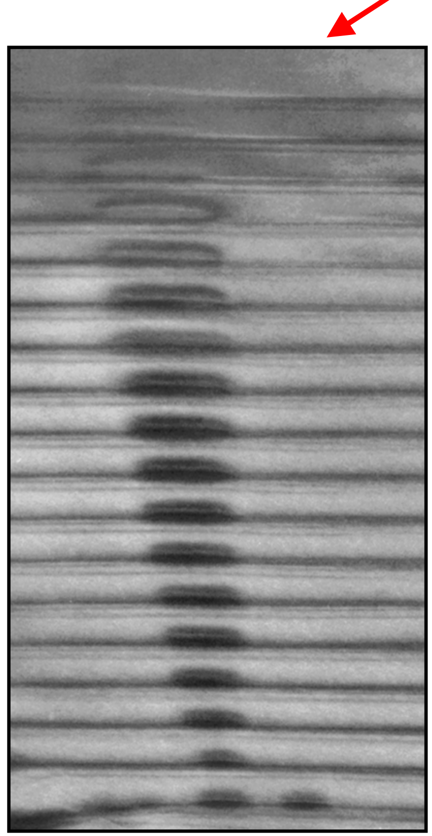
$\theta_c = 1.61 \pm 0.04$ ML

50 stacked SCQDs Solar Cell: Structural characterization: TEM



- Very low defect density
- Vertically aligned QDs





TEM <110>cross-section by
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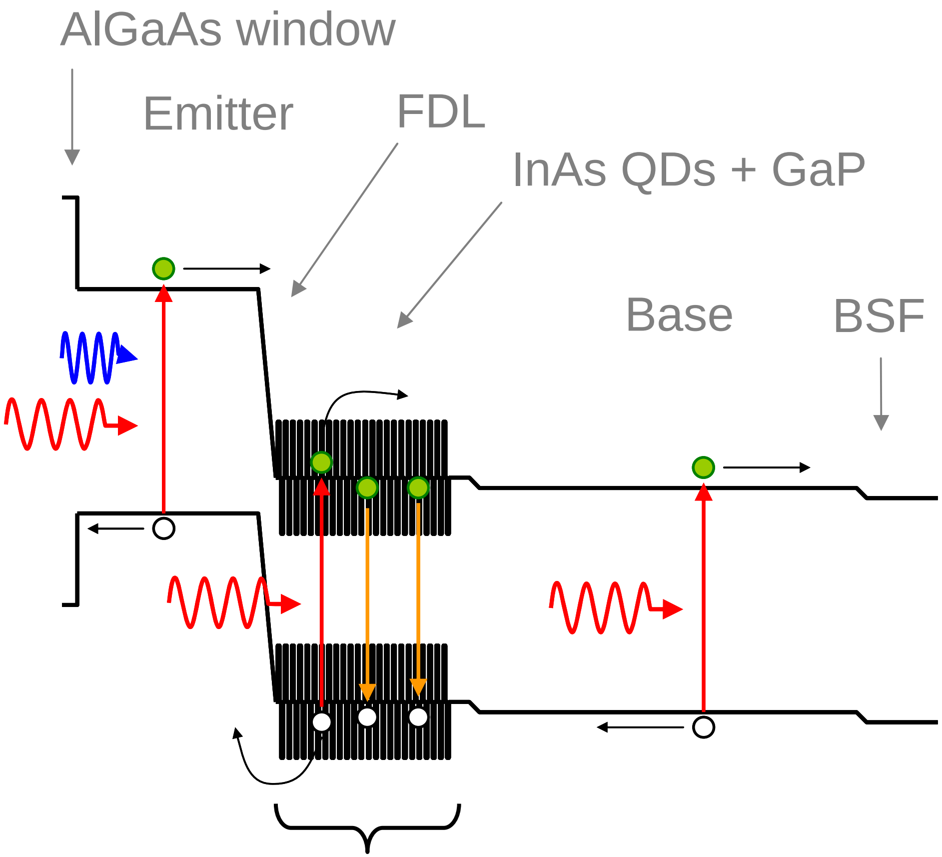
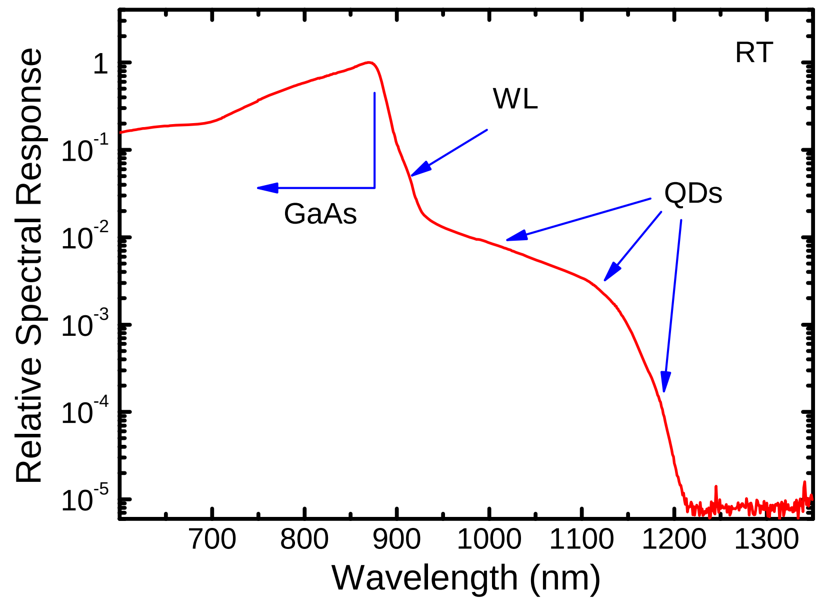
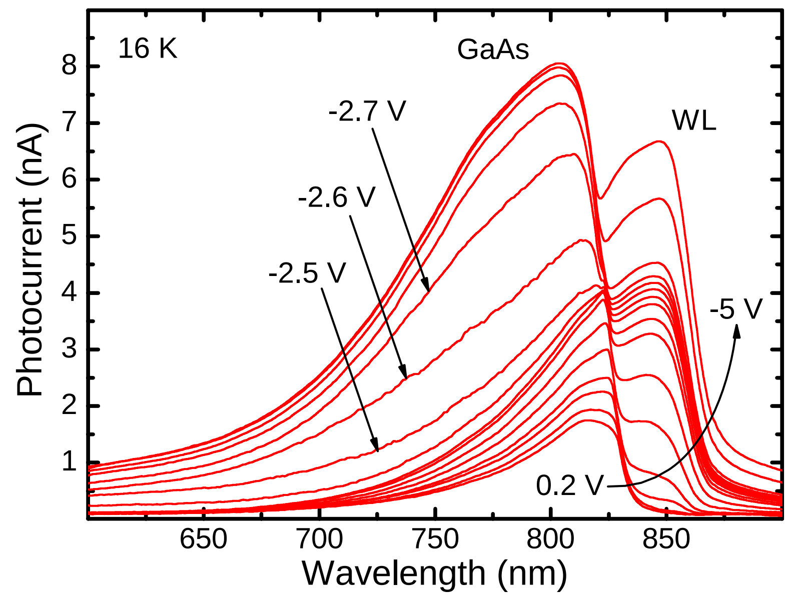
50 stacked SCQDs Solar Cell: Photocurrent







high recombination in the QDs region

⇒ Reduced extraction of electrons photogenerated in the emitter

⇒ Poor high energy response

Conclusions

- Stacks of 10 and 50 InAs QDs layers with only 18 nm of spacer have been grown using 2 ML GaP for strain compensation.

- XRD, TEM and PL experiments suggest good structural and optical quality.

- Photocurrent signal up to 1.2 μm is observed in the 50 layers solar cell due to light absorption in the nanostructures.

Thank you for your attention!!!