

On the Relation Between Growth, Quantum-Dot Morphology, Optoelectronic Properties, and Performance in InAs/GaAs Quantum Dot Intermediate Band Solar Cells

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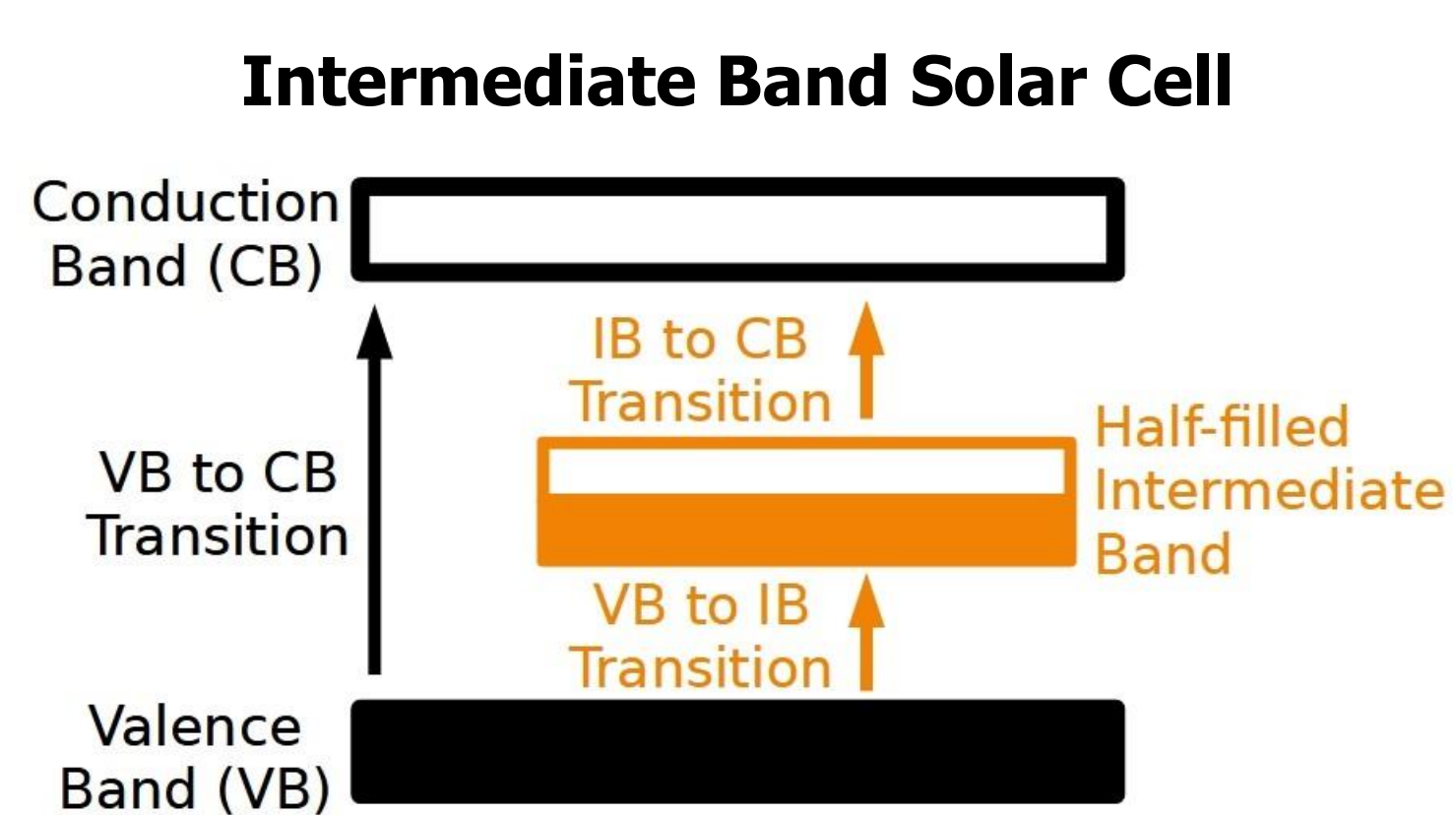
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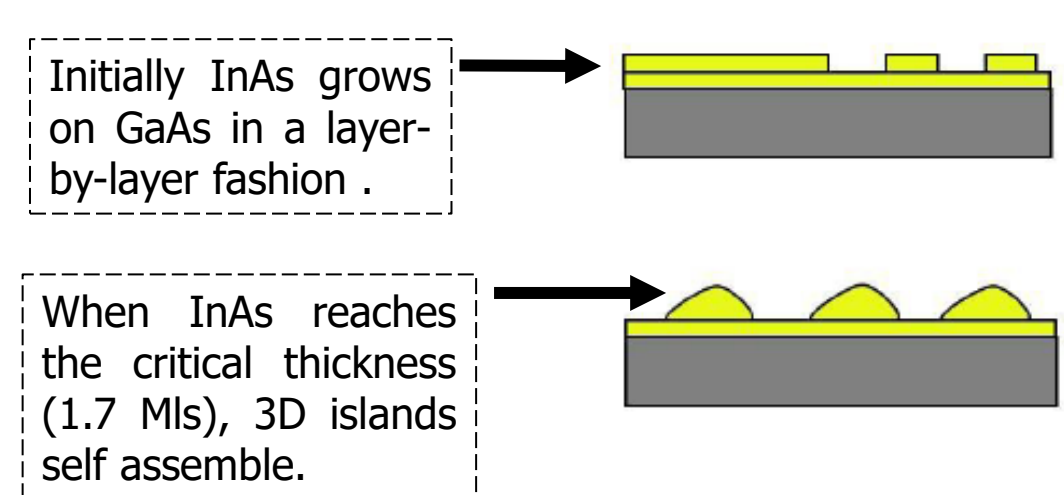
Introduction

➤ Intermediate band solar cells take advantage of nanostructures to allow absorption sub-bandgap photons.

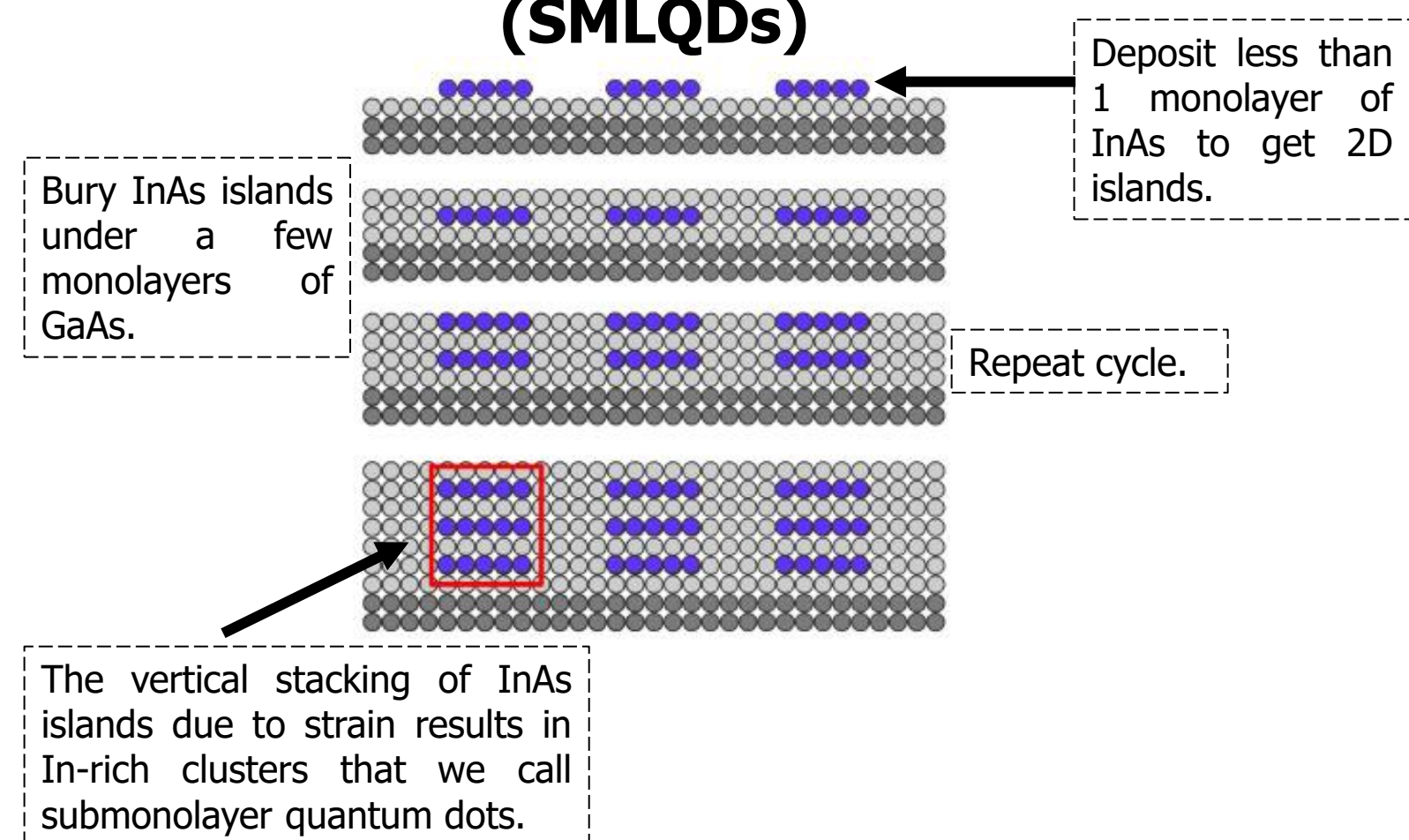


➤ We used two types of InAs/GaAs quantum dots to create intermediate bands in GaAs-based solar cells grown by molecular beam epitaxy.

Stranski-Krastanov Quantum Dots (SKQDs)



Submonolayer Quantum Dots (SMLQDs)



Objective

➤ Can InAs/GaAs SMLQDs yield better intermediate band solar cells than InAs SKQDs? Why?

➤ Can InAs/GaAs SMLQD intermediate band solar cells perform better than conventional GaAs solar cells? Why?

Materials and Methods

➤ Growth → solid source molecular beam epitaxy.

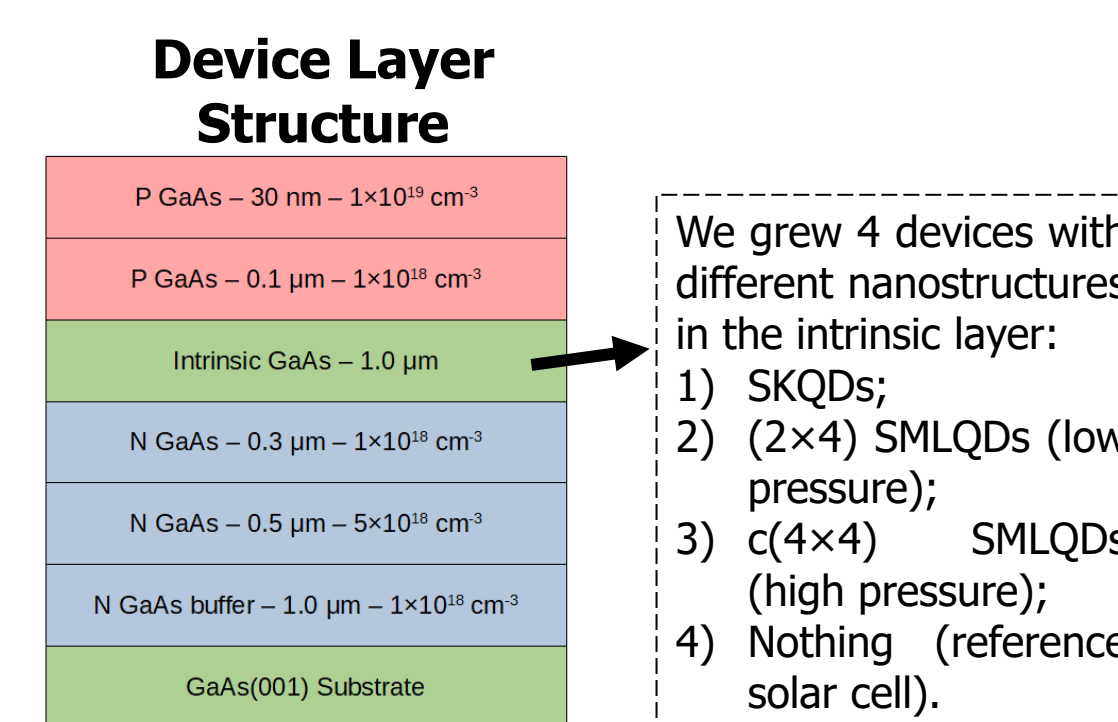
➤ Device processing → Photolithography

➤ Device contacts → E-beam evaporation + rapid thermal annealing

➤ Optoelectronic characterization → photoluminescence + external quantum efficiency

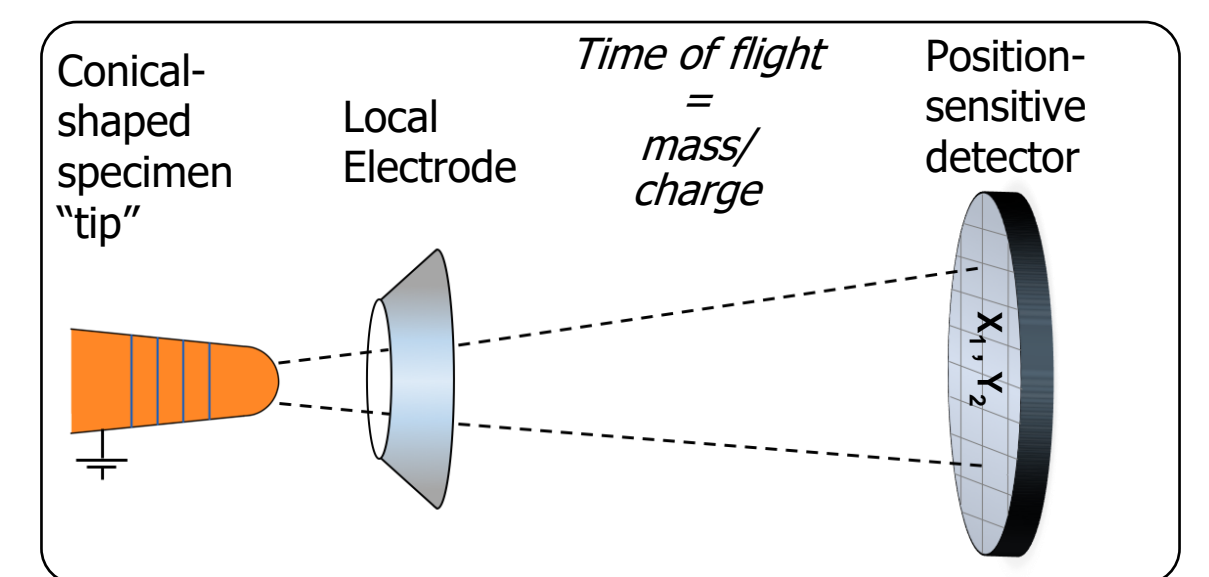
➤ Nanomorphology and composition → cross-sectional scanning tunneling microscopy + atom probe tomography

➤ Device performance → illuminated current-voltage curves (AM1.5G standard).



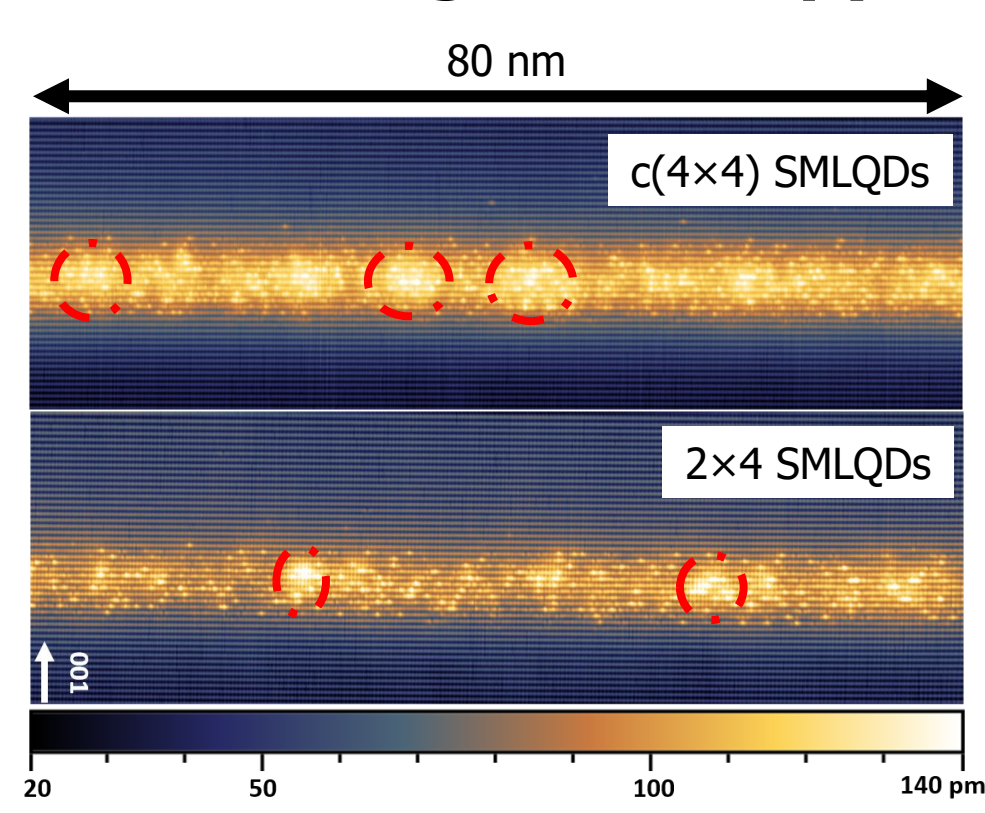
We grew 4 devices with different nanostructures in the intrinsic layer:
 1) SKQDs;
 2) (2x4) SMLQDs (low pressure);
 3) c(4x4) SMLQDs (high pressure);
 4) Nothing (reference solar cell).

Local Electrode Atom Probe Tomography¹



Results

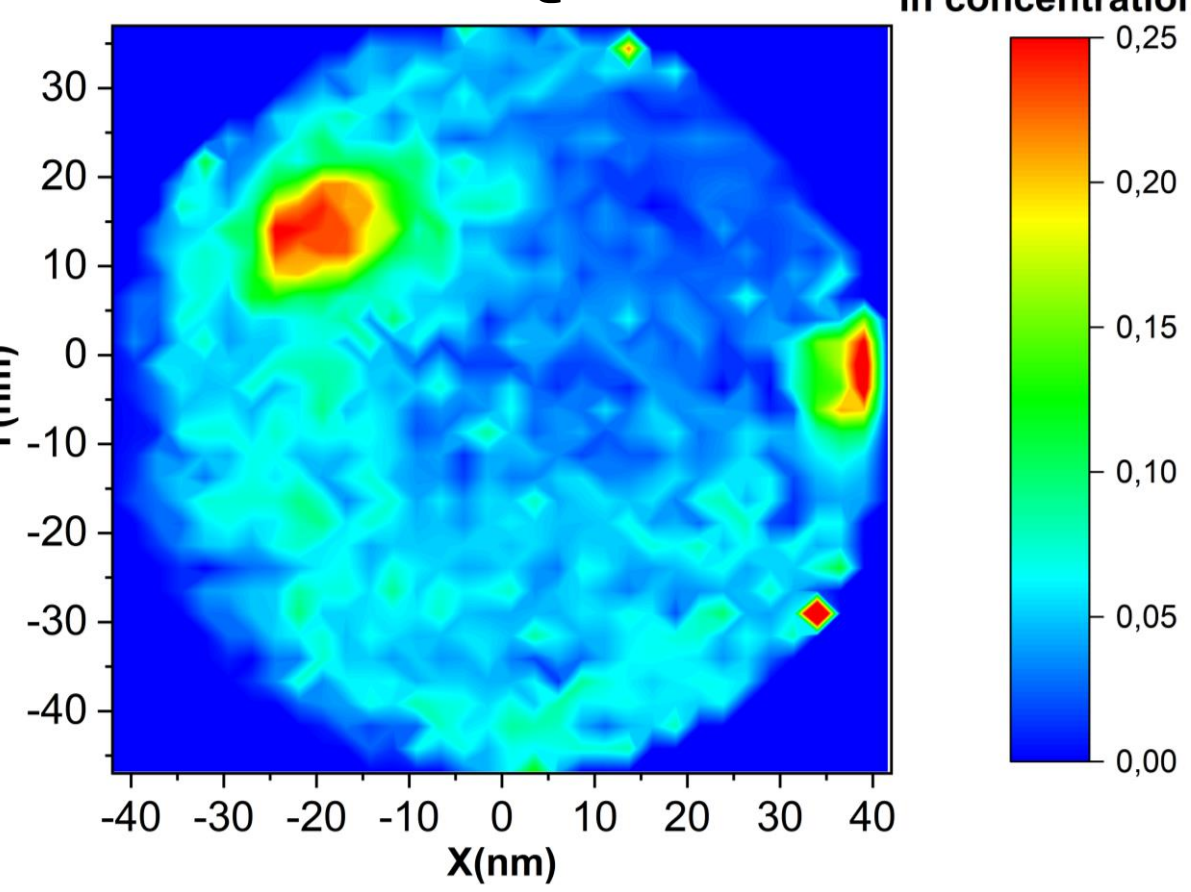
Cross-sectional Scanning Tunneling Microscopy



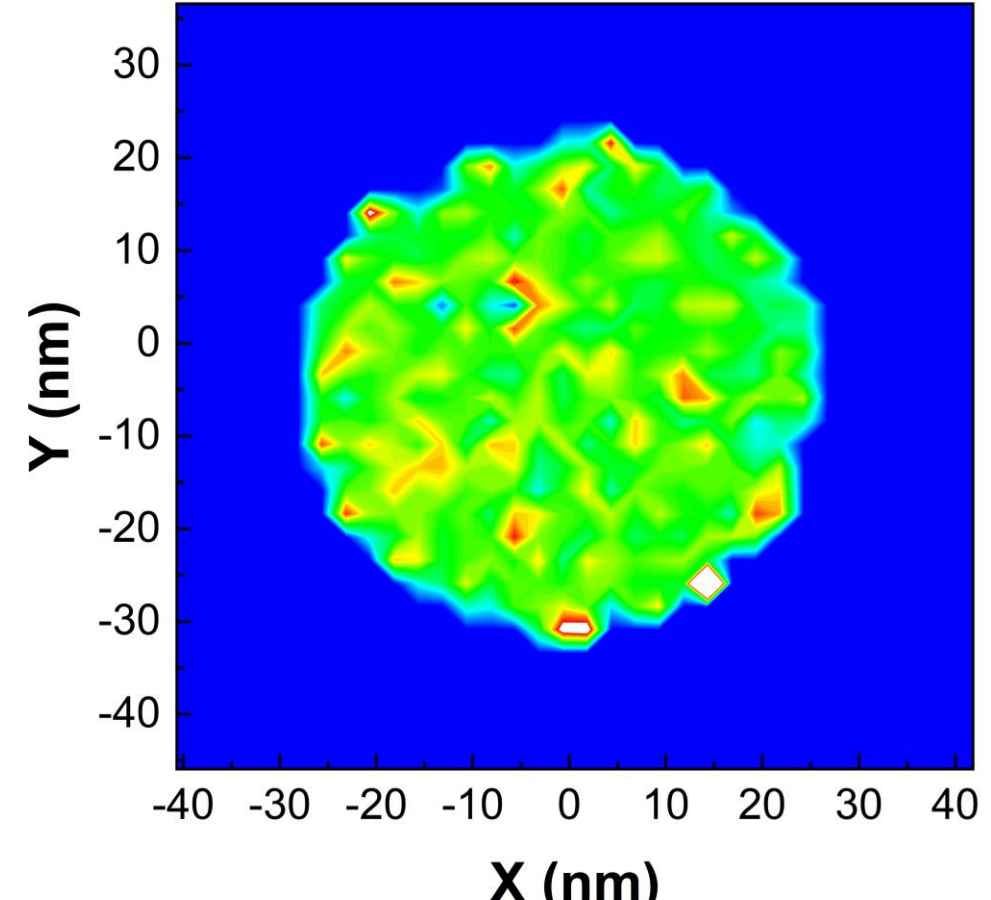
The piling-up of 2D InAs islands is not ideal, In atoms are slightly spread out. InAs/GaAs SMLQDs are in an In_{0.5}Ga_{1.5}As quantum well.

c(4x4) sample has more and brighter InAs clusters.

Atom Probe Tomography SKQD

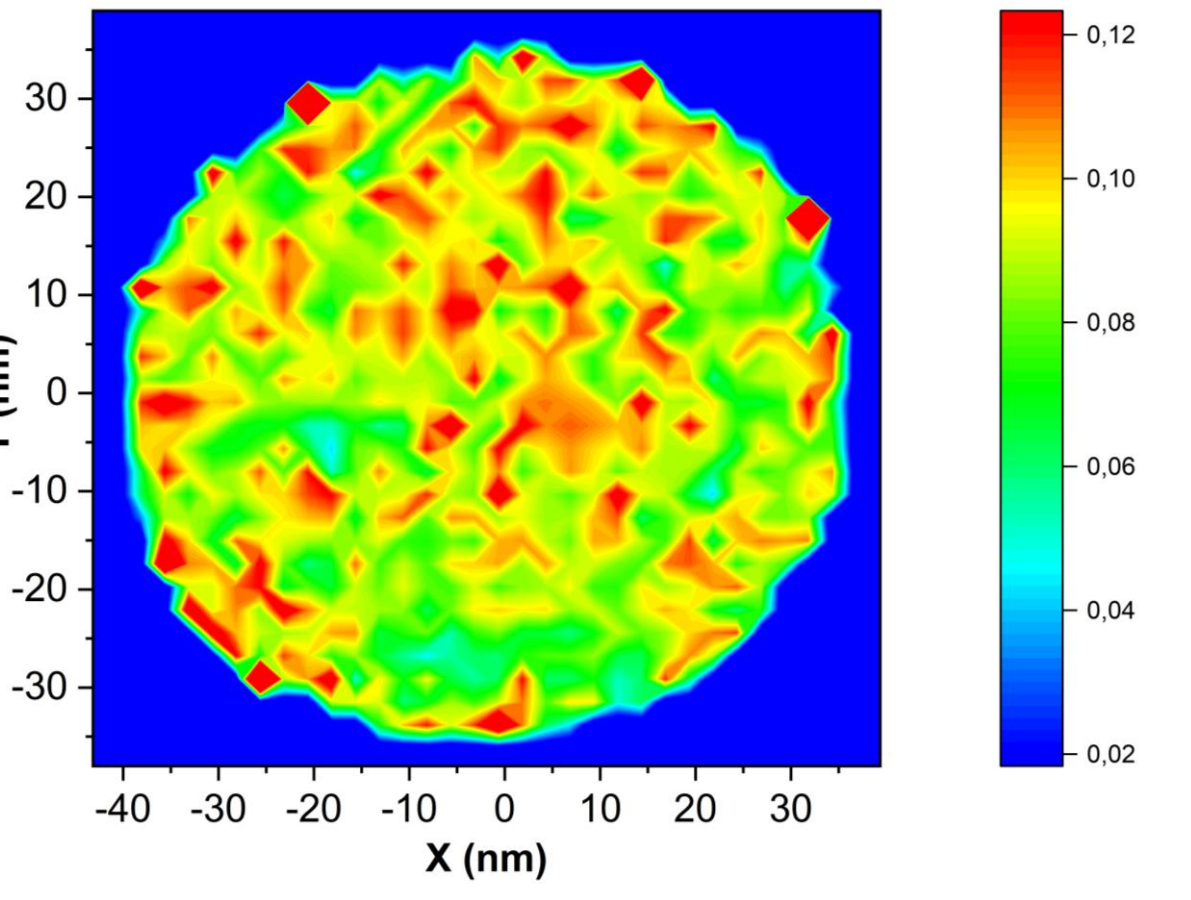


Atom Probe Tomography (2x4) SMLQD



Background In concentration (2x4) ≈ 5.0%
 c(4x4) ≈ 6.5%
 SKQD ≈ 6.0%

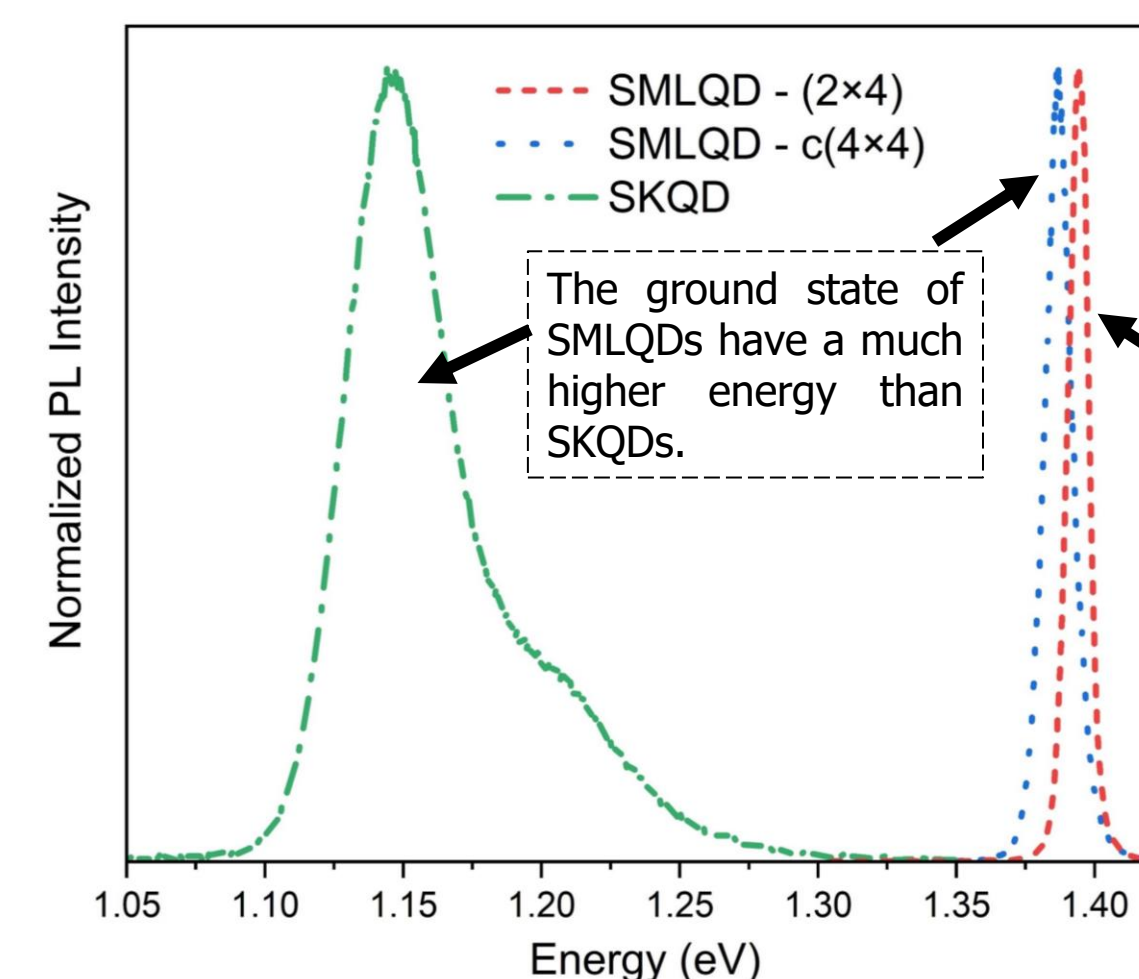
Atom Probe Tomography c(4x4) SMLQD



QD In concentration (2x4) ≈ 8-10%
 c(4x4) ≈ 10-14%
 SKQD ≈ 25%

QD density (2x4) ≈ 1x10¹² cm⁻²
 c(4x4) ≈ 4x10¹² cm⁻²
 SKQD ≈ 8x10¹⁰ cm⁻²

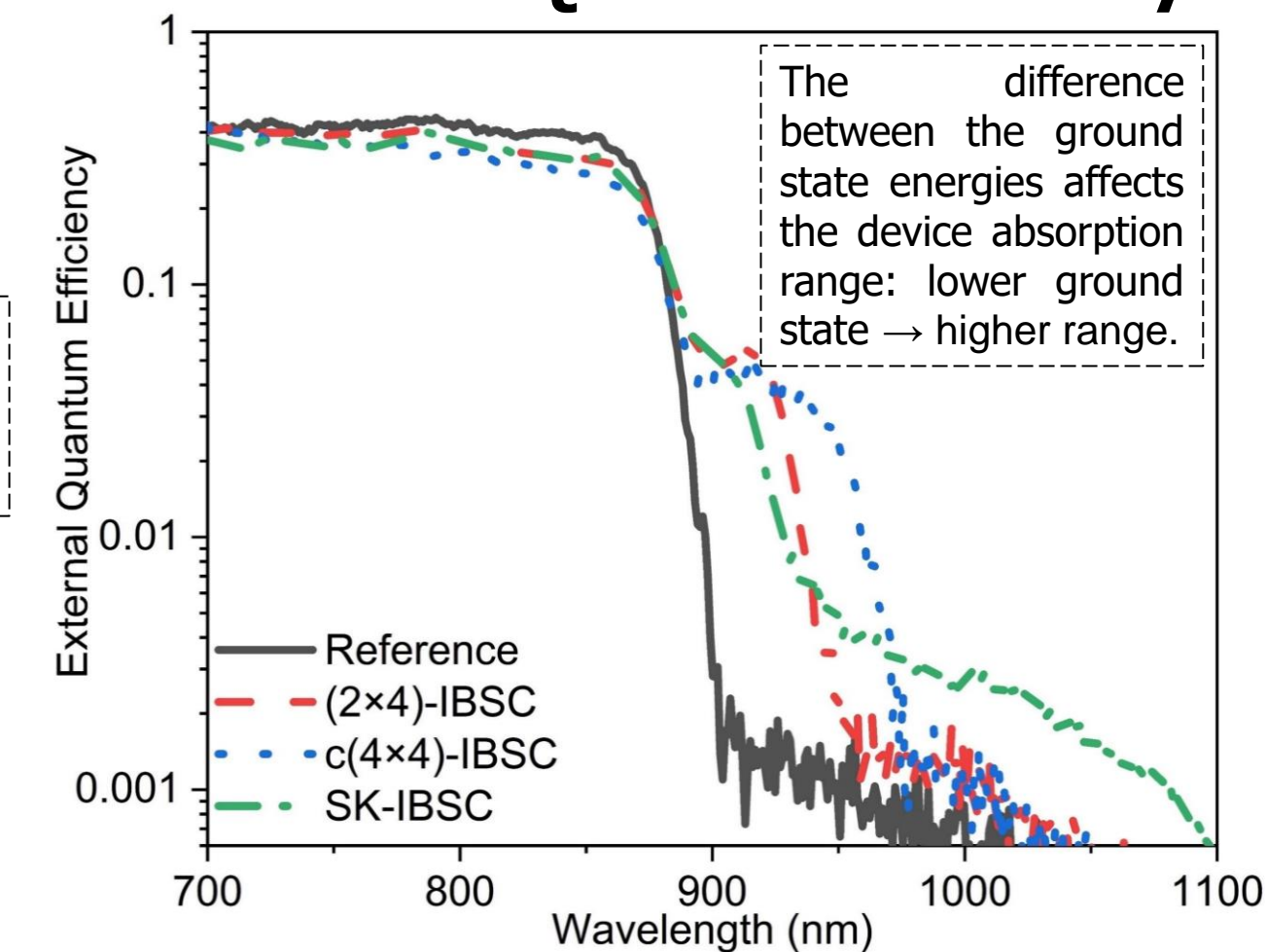
Photoluminescence



The ground state of SMLQDs have a much higher energy than SKQDs.

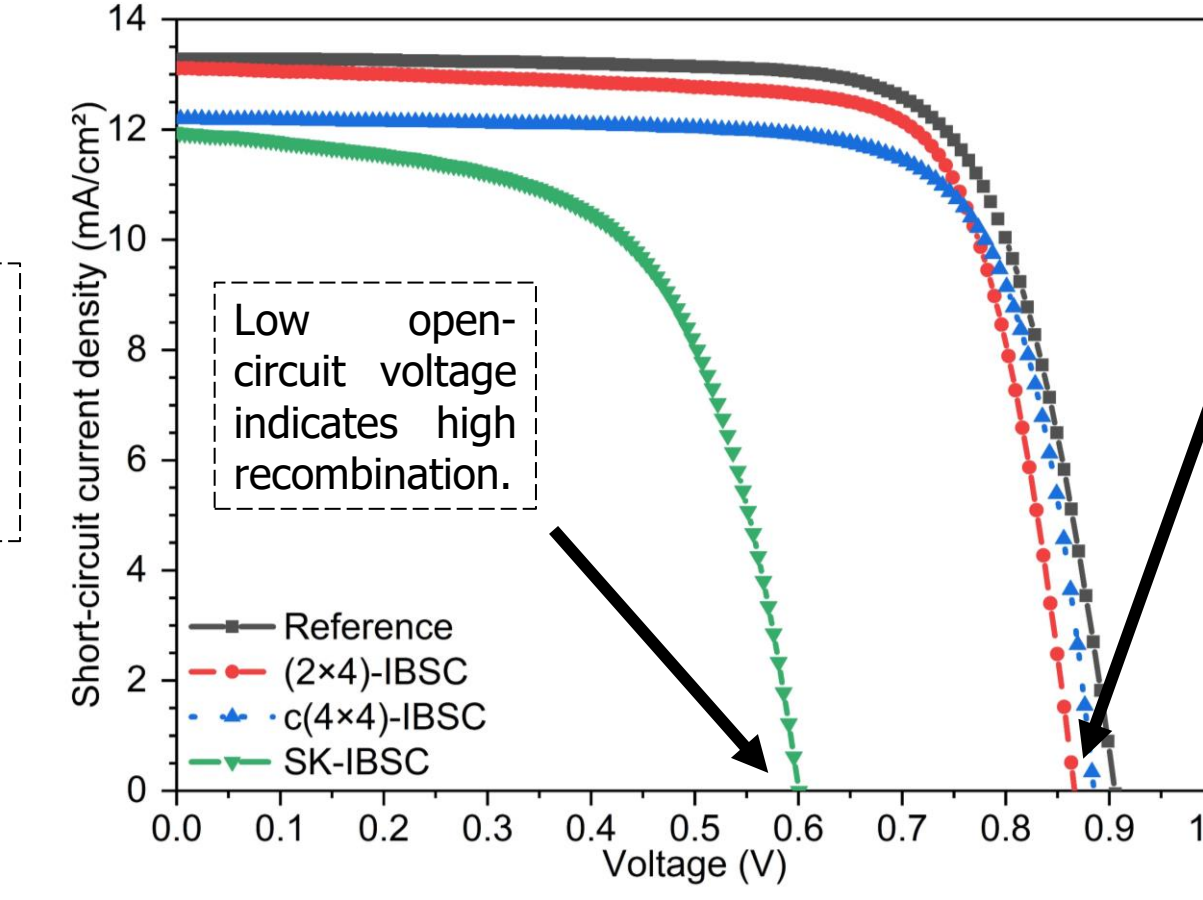
SMLQDs grown on a c(4x4)-reconstructed surface have a lower ground state energy.

External Quantum Efficiency



The difference between the ground state energies affects the device absorption range: lower ground state → higher range.

Illuminated Current-Voltage Curves



SMLQD devices perform much better than the SKQD device and are almost as good as the reference device.

c(4x4) has a higher open-circuit voltage despite having lower intermediate band energy.

This indicates better carrier confinement in c(4x4) SMLQDs → Consistent with APT/XSTM showing higher In content islands in c(4x4) samples.

Conclusion

➤ Can InAs/GaAs SMLQDs yield better intermediate band solar cells than InAs SKQDs? Why?

➤ Yes, SKQD solar cells have much lower open-circuit voltage (i.e., high recombination) due to defects that result from strain.

➤ Can InAs/GaAs SMLQD intermediate band solar cells perform better than conventional GaAs solar cells? Why?

➤ Not yet. The c(4x4) solar cell has a higher open-circuit voltage than the (2x4) solar cell despite the c(4x4) SMLQDs having a lower ground state energy, which indicates better carrier confinement. An optimization process to maximize the short-circuit current could lead to high-efficiency SMLQD solar cells in the near future.

Acknowledgments



References

- [1] C. Greenhill, Influence of Composition and Morphology on the Electronic Properties of Semiconductor Nanostructures and Alloys, PhD thesis, 2021.
- [2] R. S. R. Gajjela et al., Cross-sectional scanning tunneling microscopy of InAs/GaAs(001) submonolayer quantum dots, Phys. Rev. Materials 4, 114601, 2020.