Impact of Compositional Fluctuation on Dislocations in Metamorphic III-V Solar Cells Revealed by Cathodoluminescense Spectrum Imaging

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National Renewable Energy Laboratory

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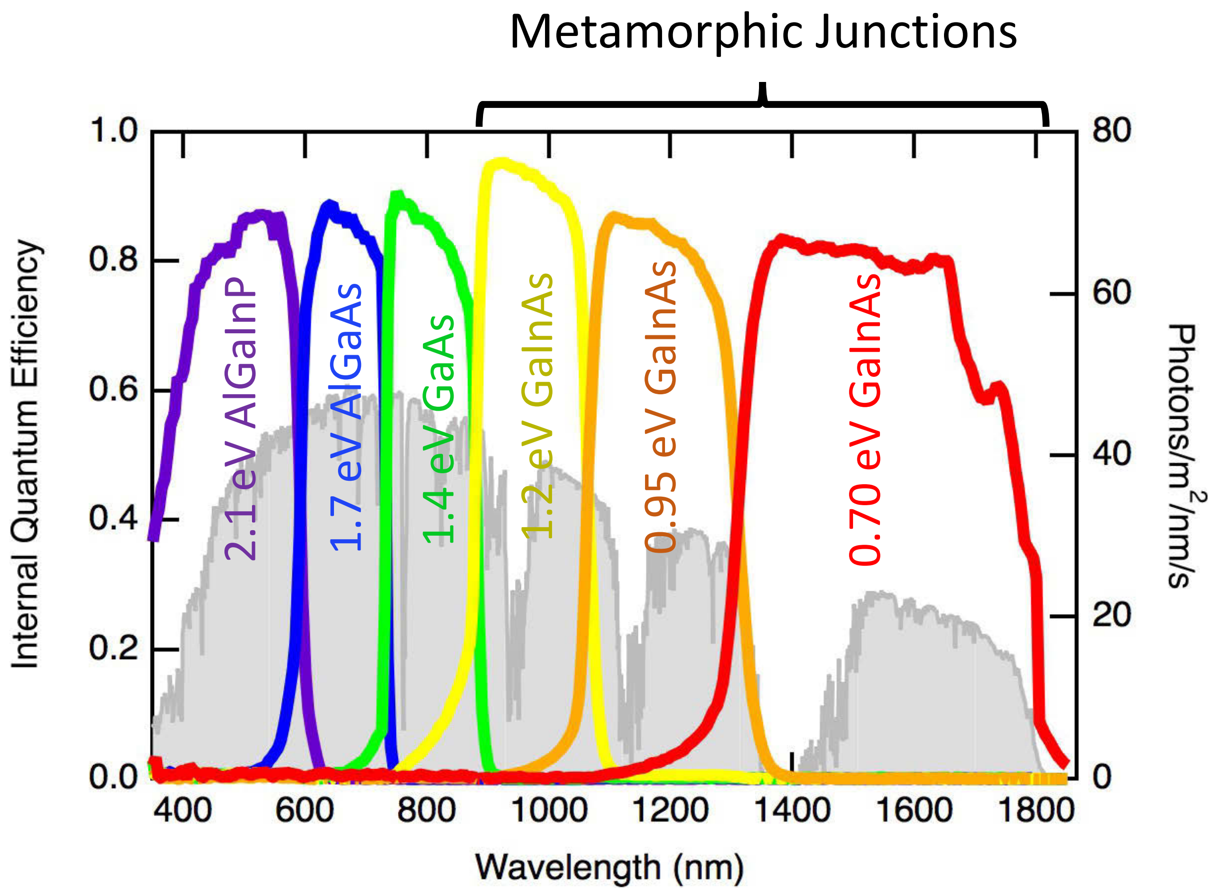
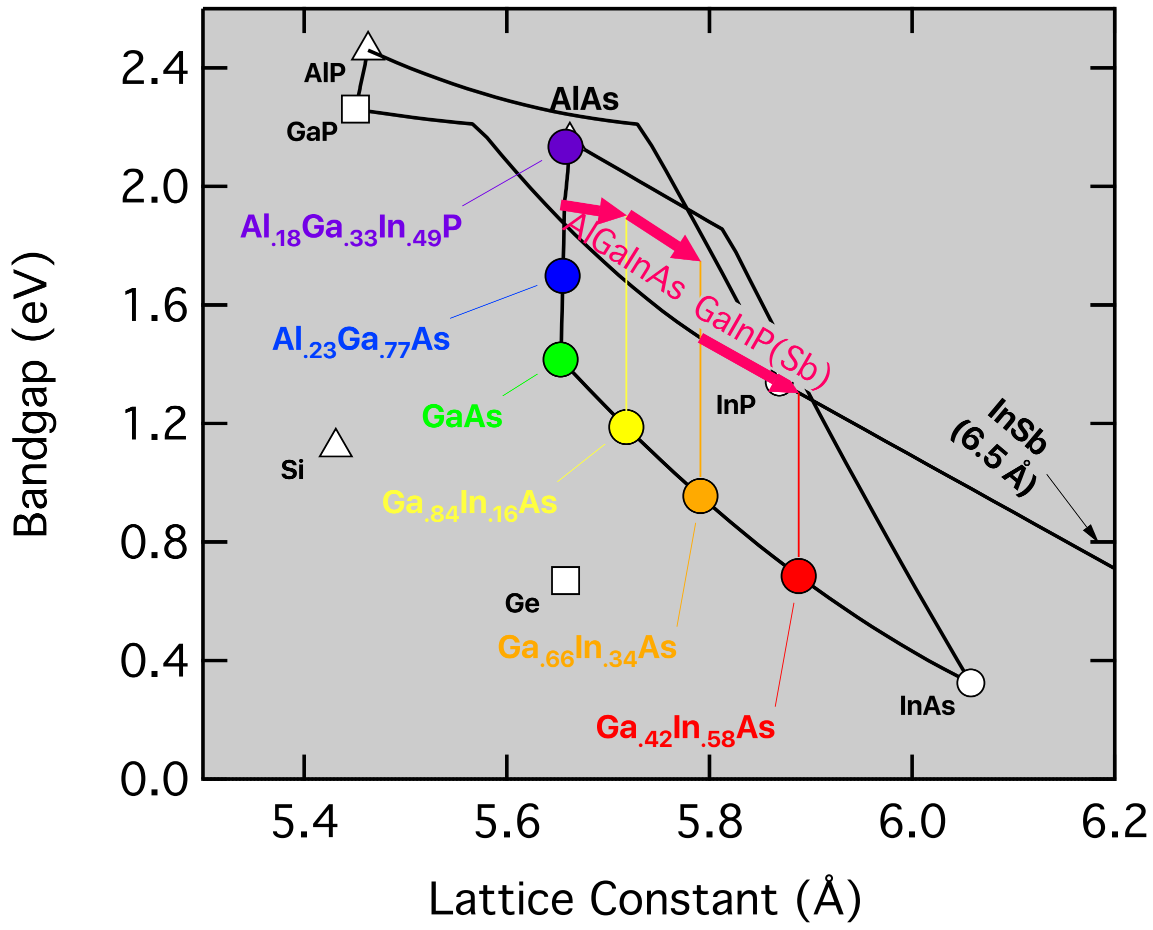
Inverted Metamorphic Multijunction Solar Cells

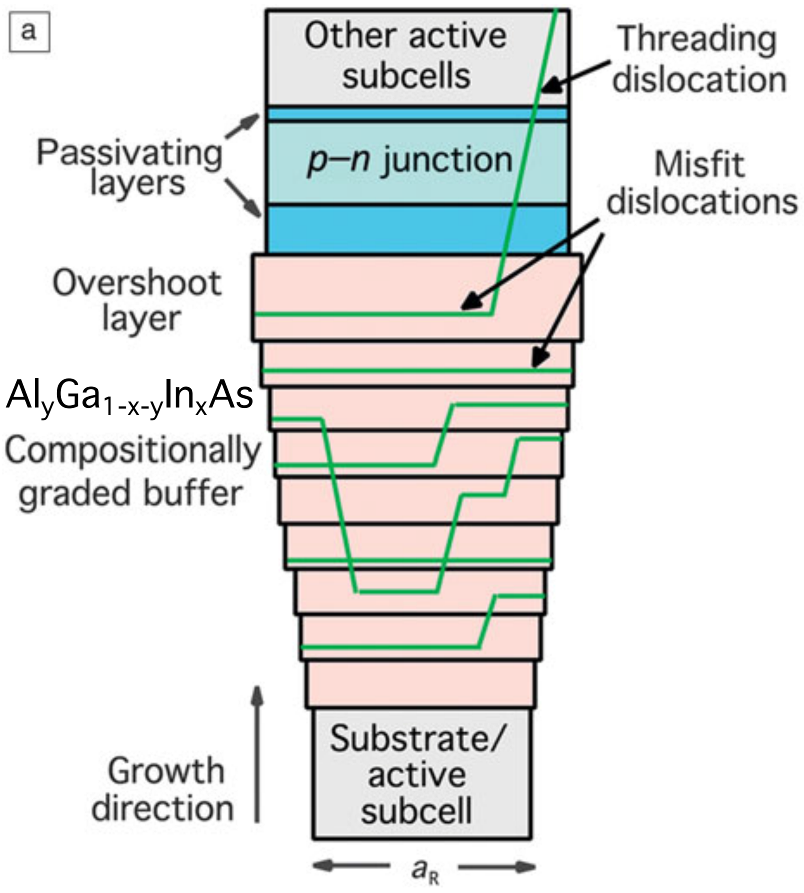




- Grown by Metalorganic Vapor Phase Epitaxy
- Record **47.1% efficiency** enabled by **metamorphic epitaxy**

Compositionally Graded Buffer

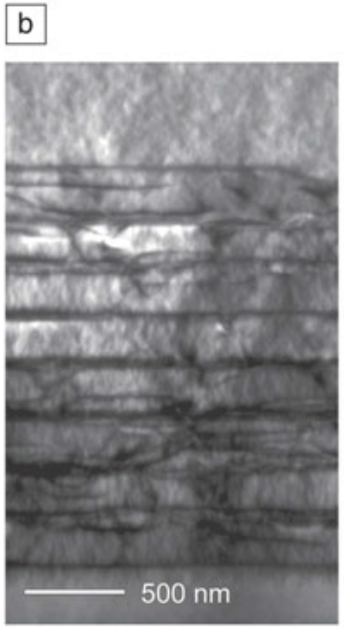
Increasing x_{In}



Schematic

Buffer

Cross-sectional TEM

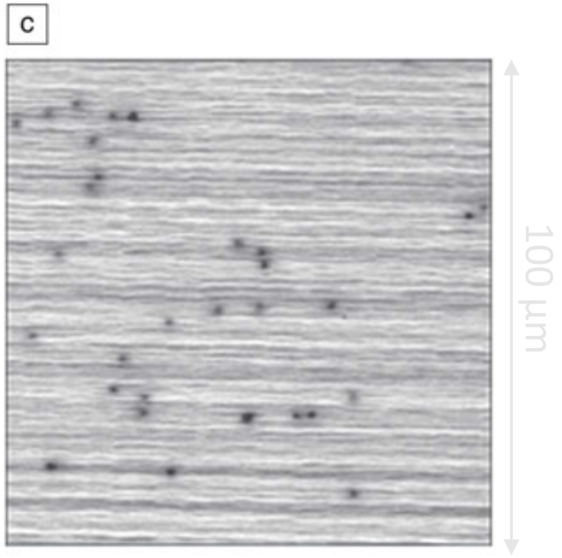


$Ga_{0.70}In_{0.30}As$ (~1.0 eV)

Cell

Plan view EBIC

(Electron Beam Induced Current)

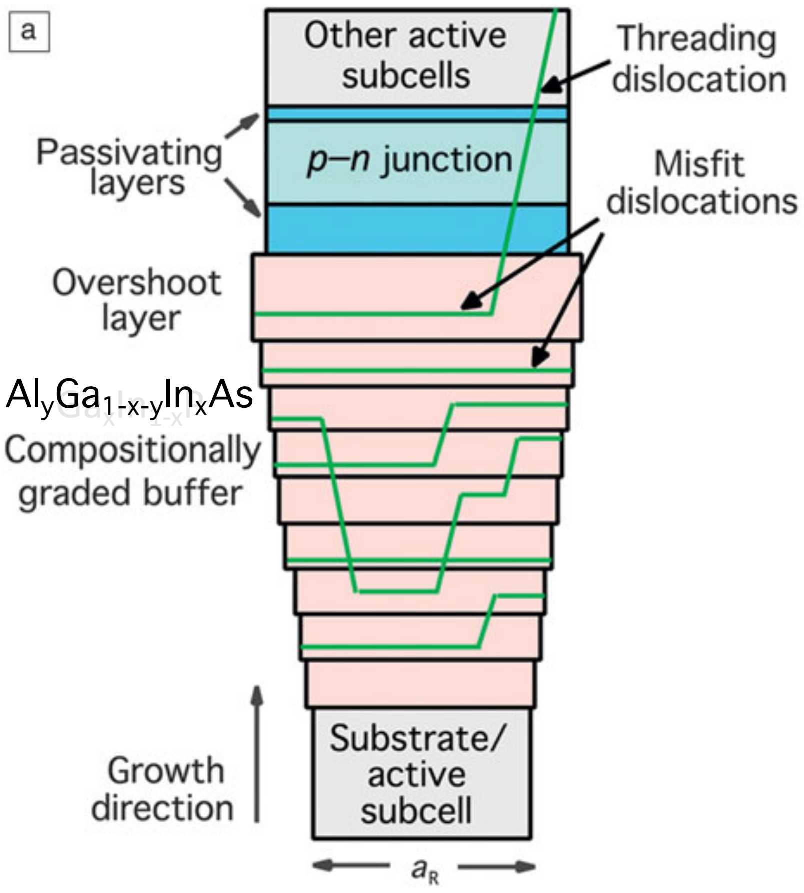


TDD < 10^6 cm^{-2}

(Threading Dislocation Density)

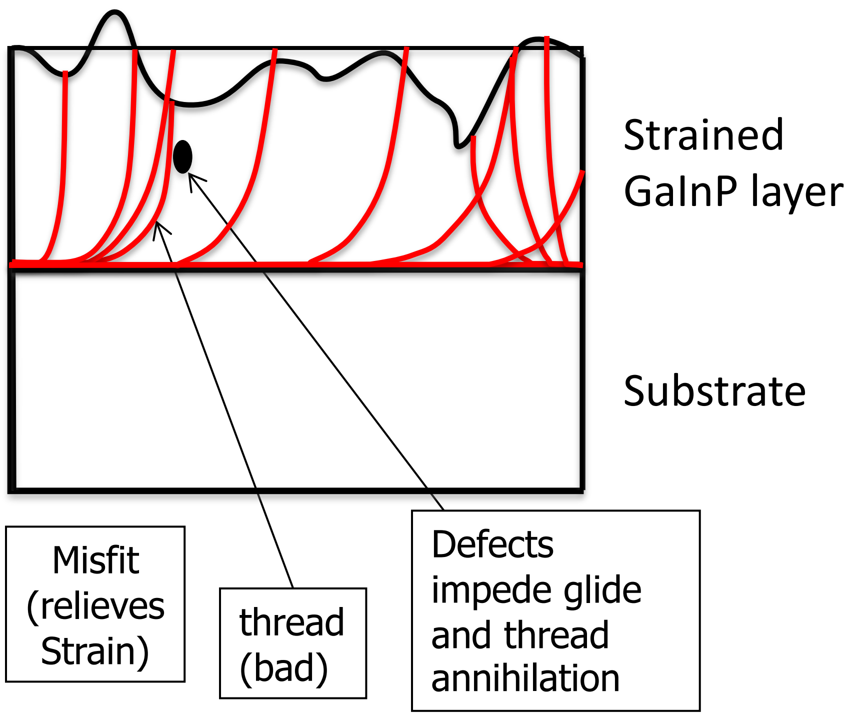
R. France *et al.*, MRS Bulletin, March 2016

Compositionally Graded Buffer



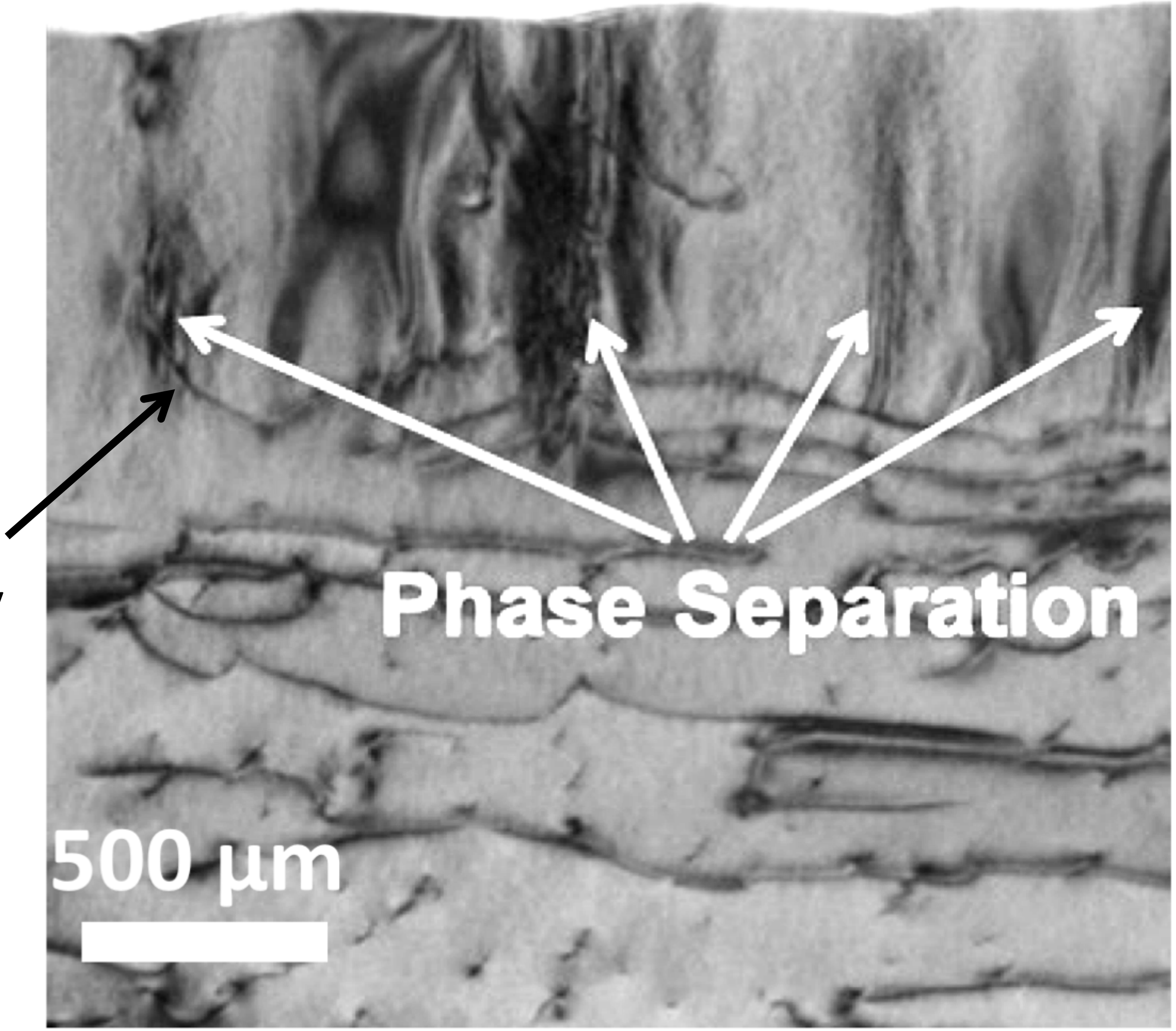
Schematic

- Intentionally introduce dislocations to alter in-plane lattice constant
- Need to minimize threading dislocation density for performance
- *Maximize dislocation glide*



Phase Separation in III-Vs

Dislocation Trapped by Phase Separation

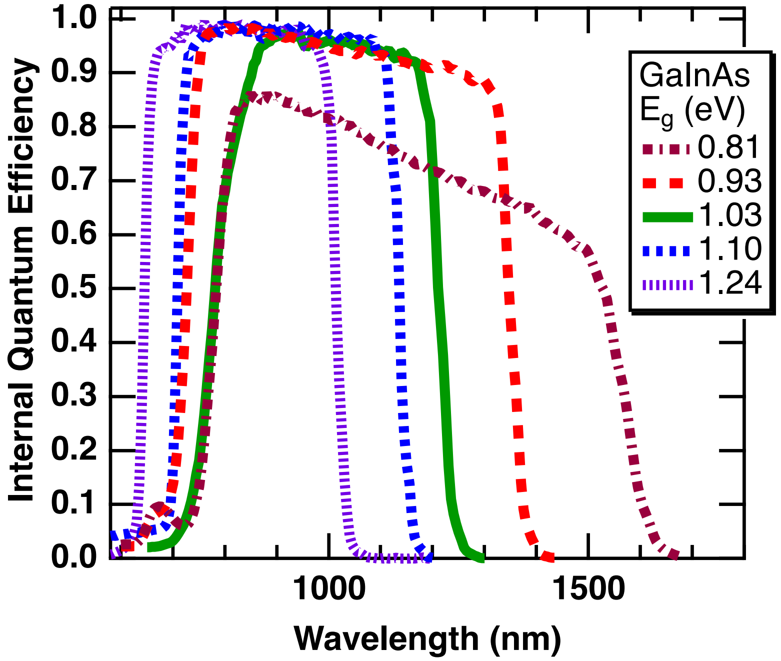


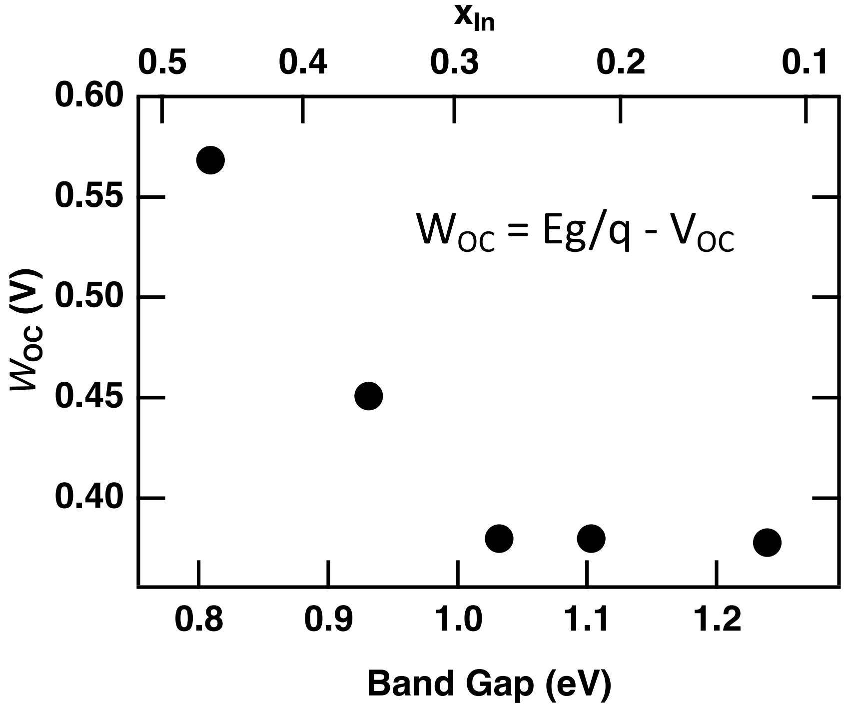
X-TEM Image

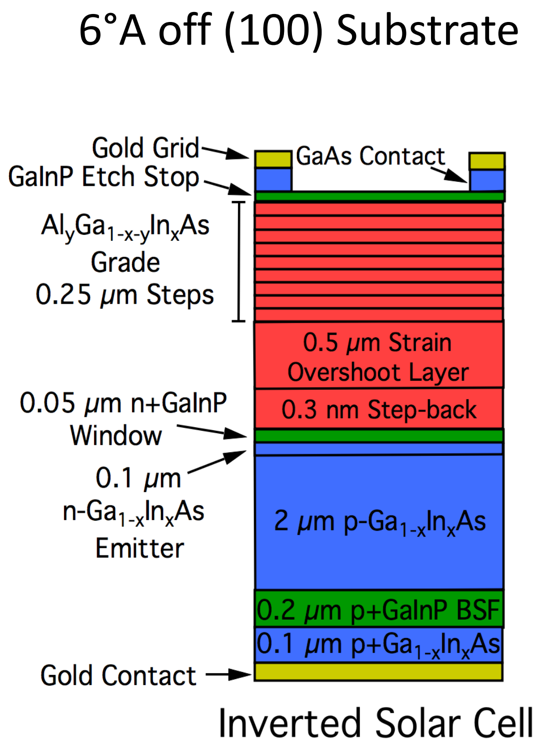
L. Yang et al., *J. Cryst. Gr.*, **324**, 103-109 (2011).

- (Al)GaInAs alloys often exhibit **phase separation** into high-In and low-In phases
- Driven by **differences** in **atomic sizes**/strain
- Leads to **dislocation pinning** -> high threading dislocation density (TDD)

Metamorphic GaInAs Solar cells

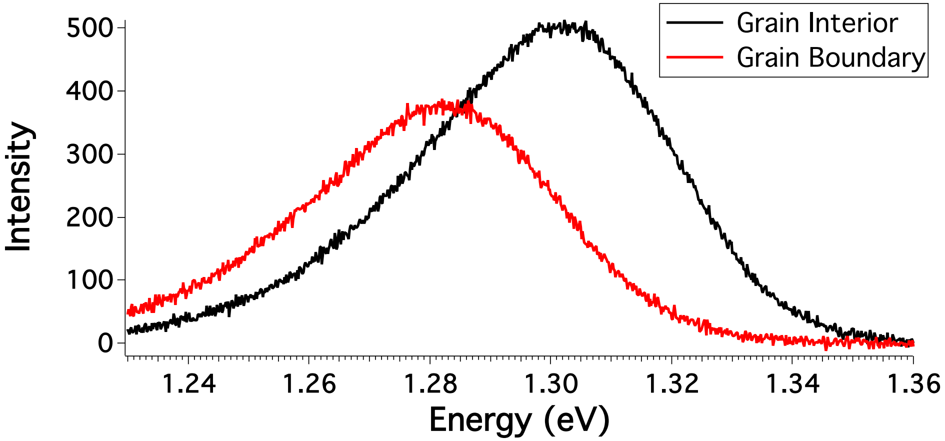




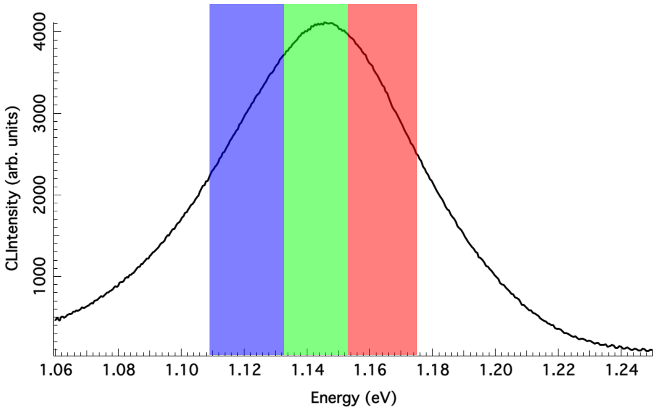


- Grew series of GaInAs cells using AlGaInAs graded buffers out to varying energies
- Sharp increase in band gap-voltage offset below 1.0 eV, where $x_{In} > 0.30$

Cathodoluminescence Spectrum Imaging (CLSI)

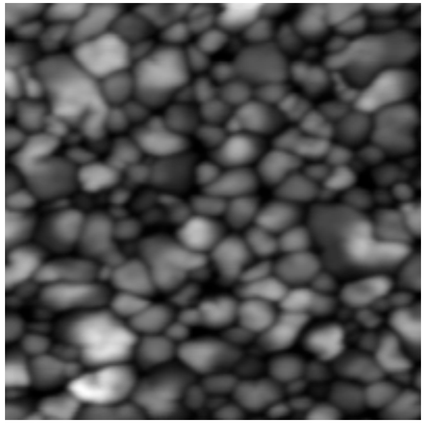


False Color Spectrum Images

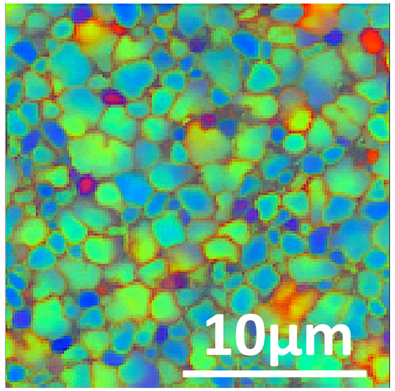


- SEM based technique
- Commonly used to analyze thin-film materials
- Spectrum-per-pixel acquisition exposes emission intensity and spectra from defect features

Intensity-Only CL



Spectrally-Resolved CL

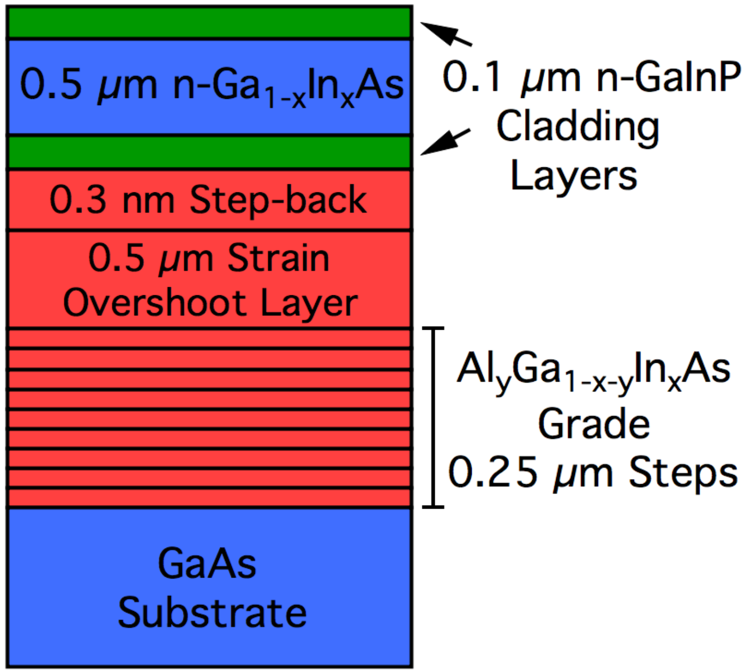


CIGS Sample

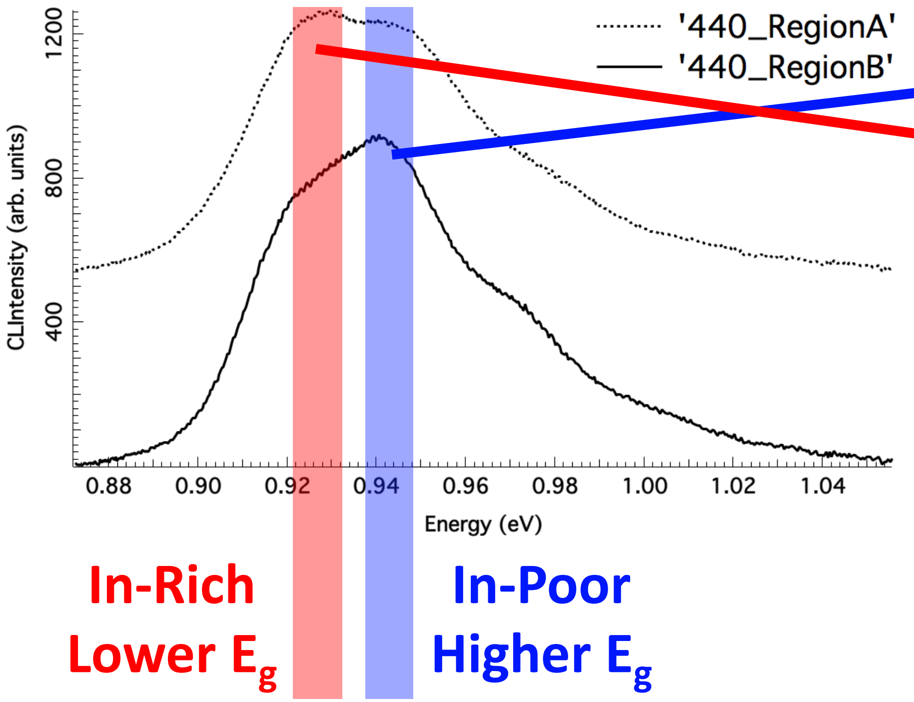
0.99eV **1.1eV**

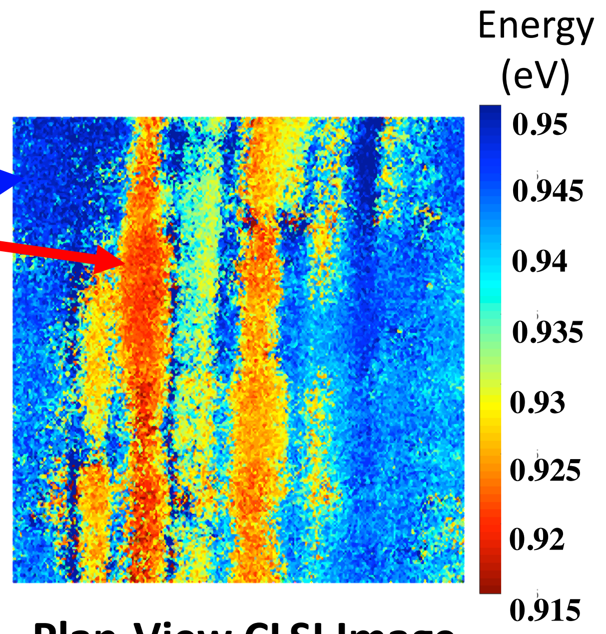
Energy (eV)

CLSI of III-V Materials



Double Hetero-structure



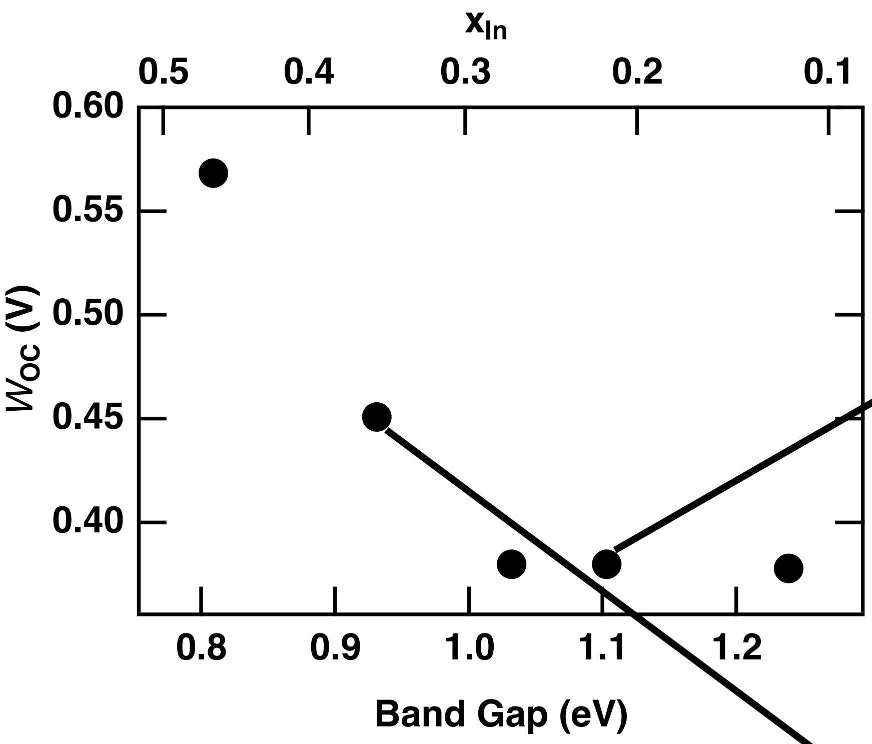


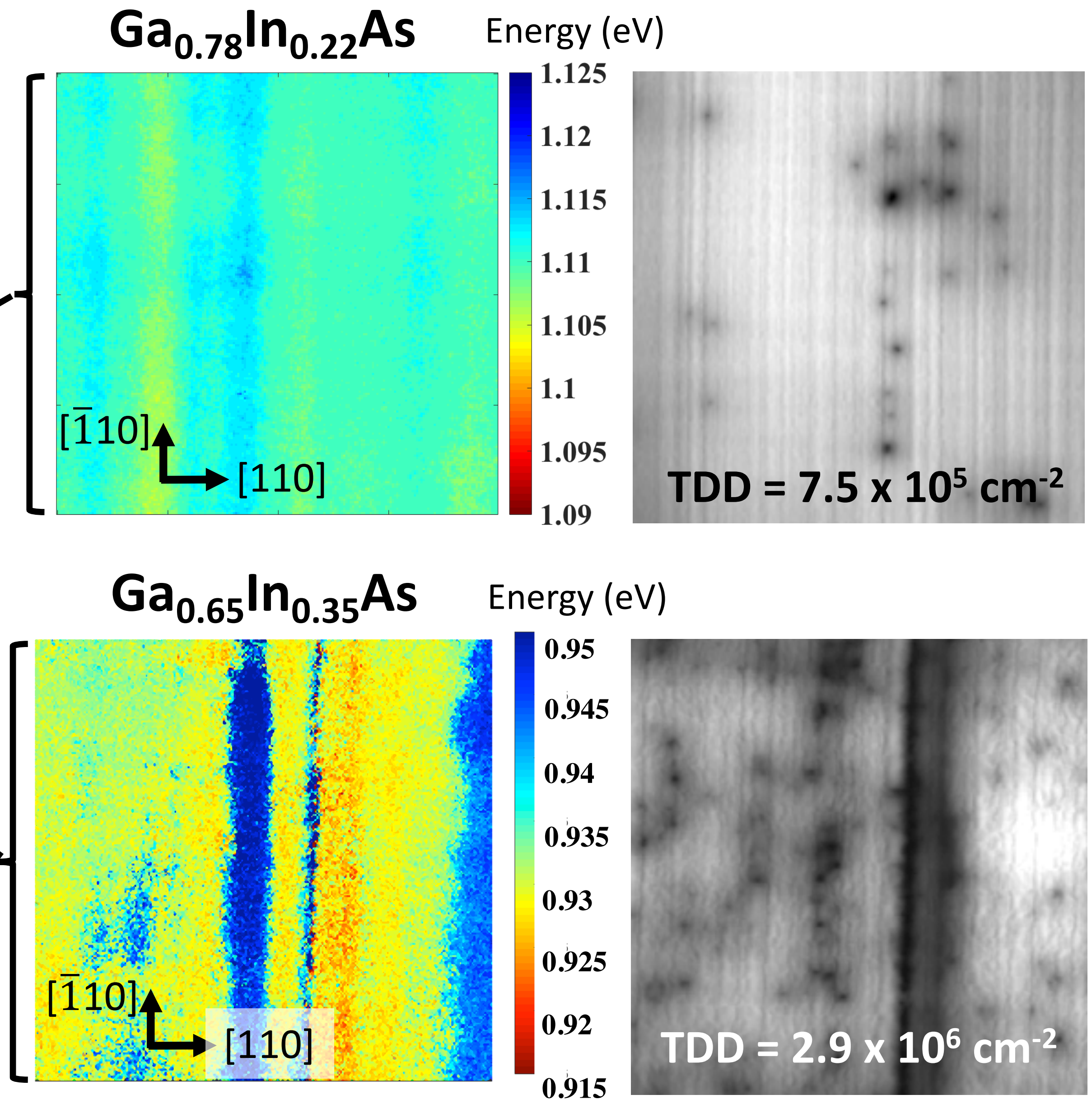
Plan-View CLSI Image

60 µm x 60 µm

- CL emission energy directly related to local band gap
- Lower band gap implies In enrichment, and vice-versa

Catholdoluminescence at High and Low x_{In}

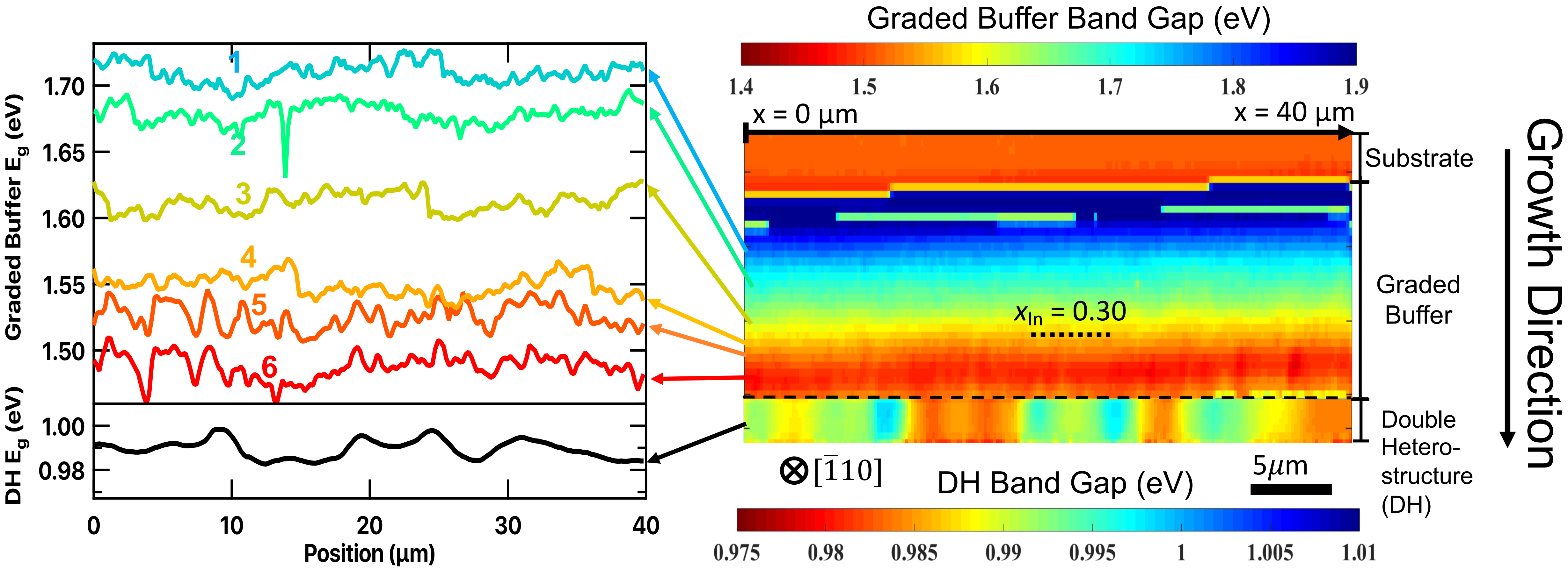




60 µm x 60 µm Images

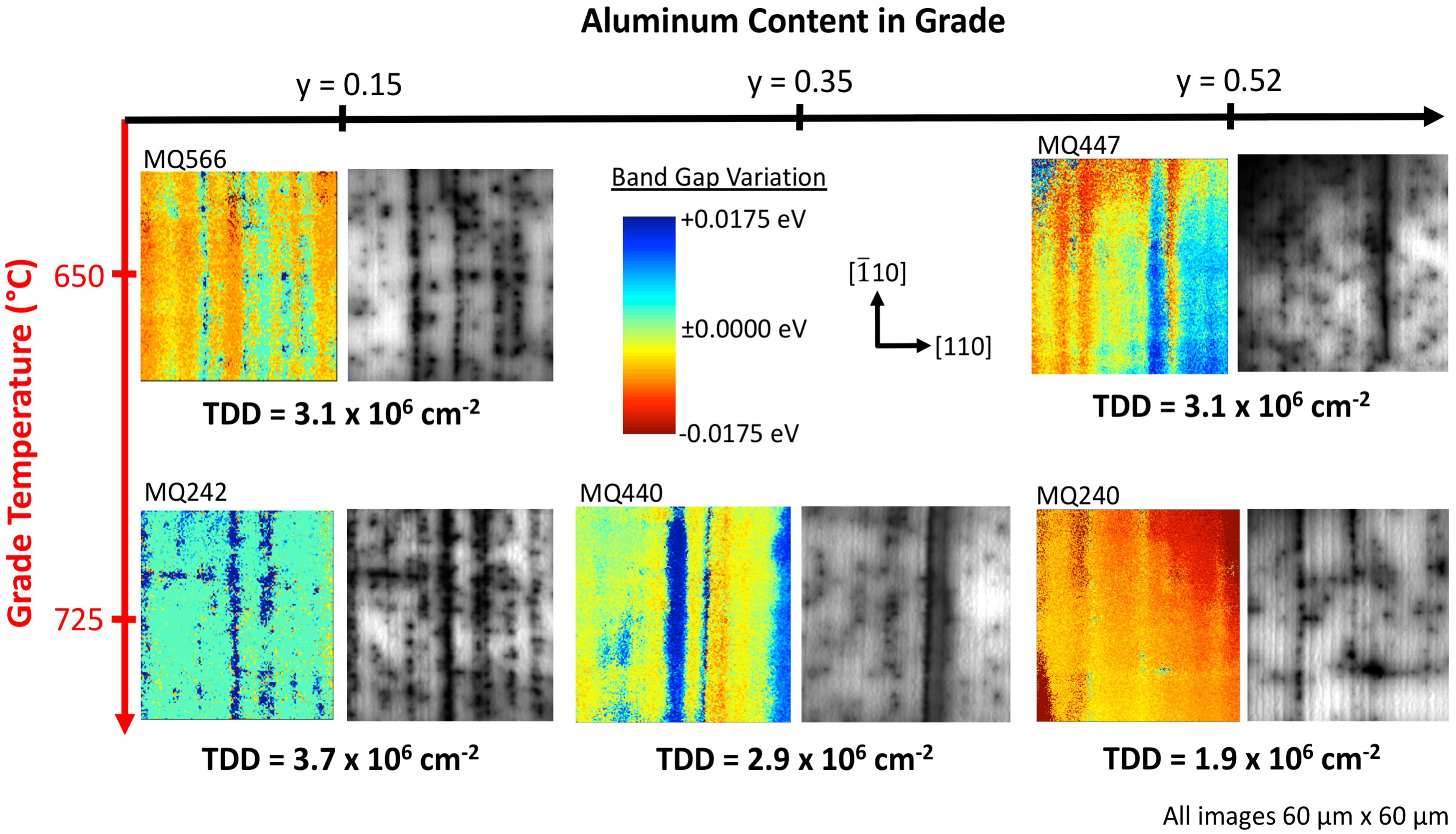
- Vertical stripes of compositional fluctuation
- More intense in higher-In material
- Dislocations aligned with compostion

Cross-sectional CLSI of Higher x_{In} Sample



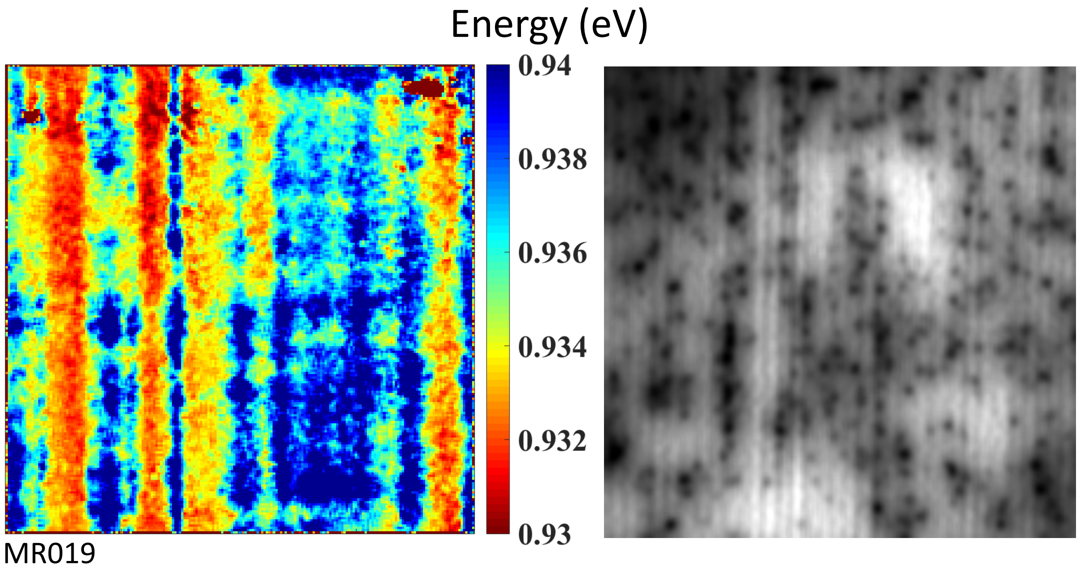
- Short period fluctuations appear for $Al_yGa_{1-x-y}In_xAs$ compositons where x_{In} >0.3
- Double-heterostructure fluctuations influenced by fluctuation in layers below

Effect of Graded Buffer Growth Temperature, Al-Content

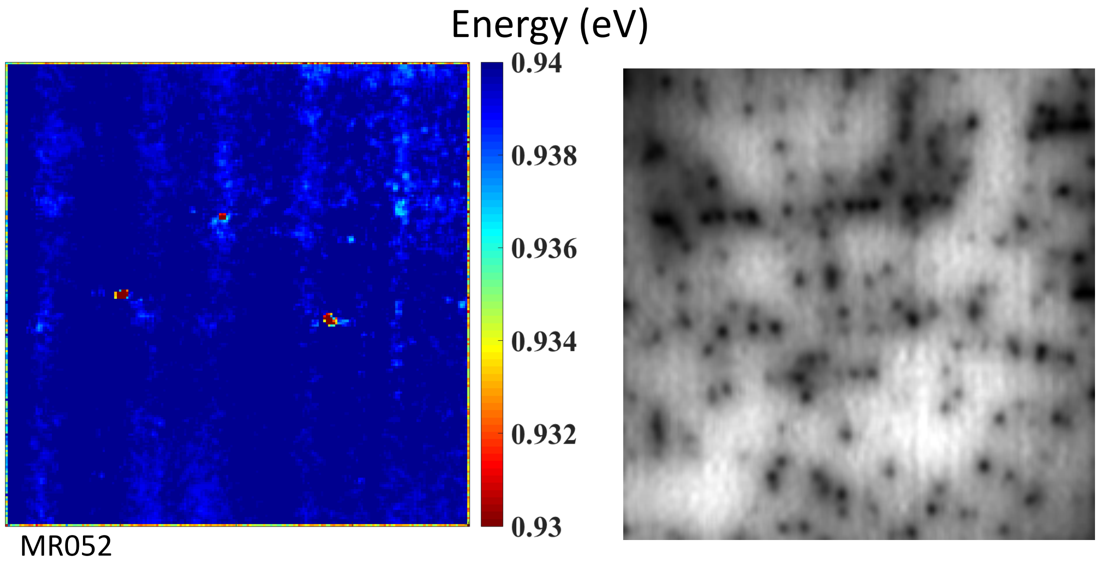


Best graded buffers have high growth temperature and high-Al content

Effect of V/III Ratio



V/III = 70, TDD = 5.0 x 10^6 cm^{-2}



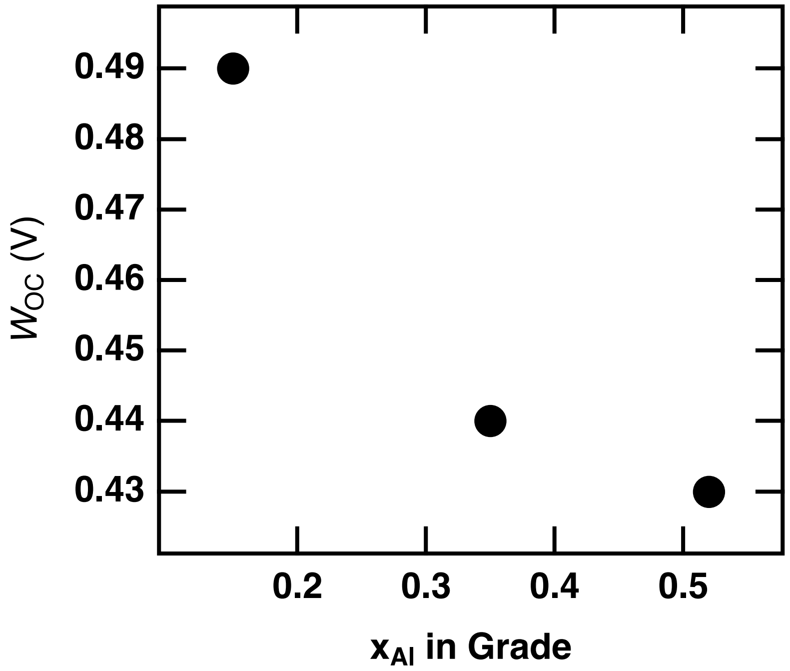
V/III = 300, TDD = 3.9 x 10^6 cm^{-2}

Increasing V/III ratio in growth vapor limits diffusion of surface atoms

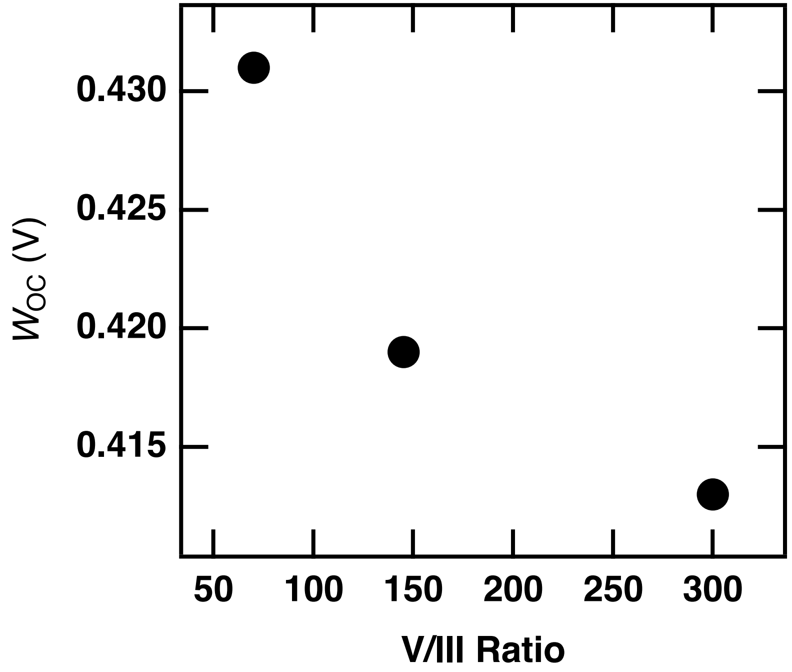
- Suppressed compositional modulation
- Reduced Threading Dislocation Density

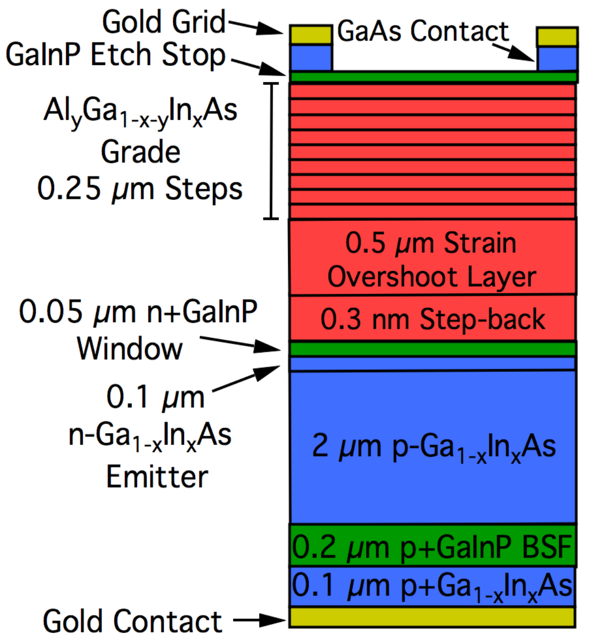
Using CLSI Insights to Optimize Device Efficiency

Vary Al Content in Graded Buffer



Vary V/III in Graded Buffer



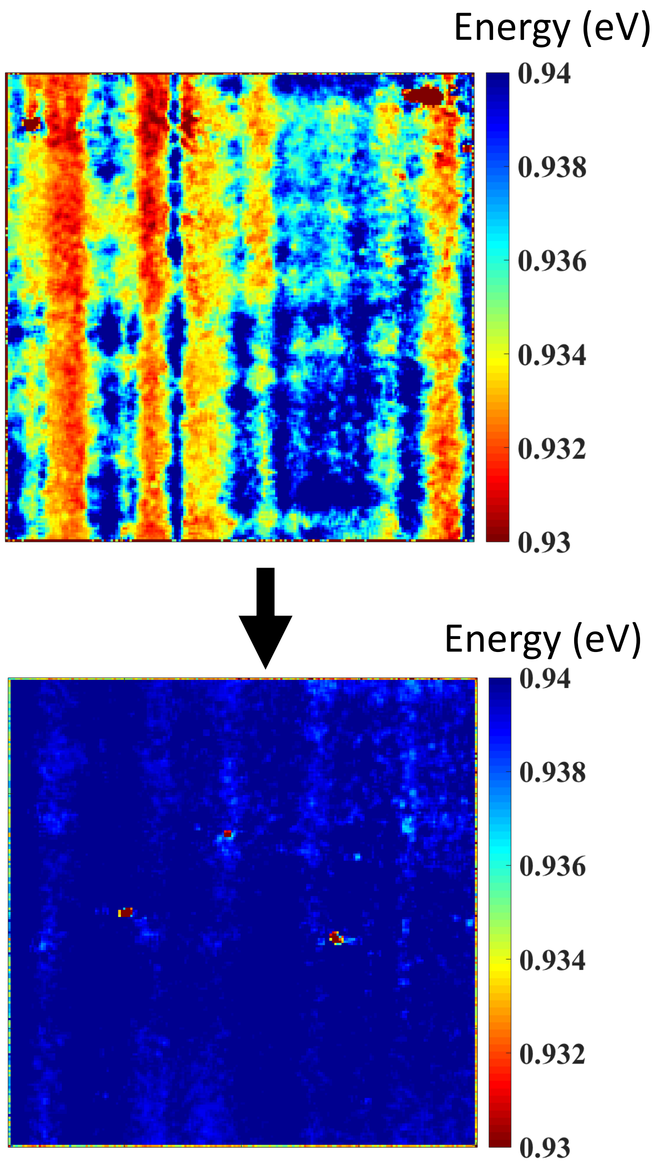


Inverted Solar Cell

W_{OC} down to 0.41 V with optimized growth conditions!

Conclusions

- Cathodoluminescence spectral imaging (CLSI) is an effective method to obtain rapid information about the microstructure of metamorphic III-V materials
- Compositional fluctuation in metamorphic materials hinders dislocation motion, leading to higher dislocation densities in these materials
- Optimization of growth conditions to eliminate compositional fluctuation results in materials with lower dislocation density and improved photovoltaic conversion efficiencies



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