Lattice-mismatched GaAsP Solar Cells Grown on Silicon by OMVPE

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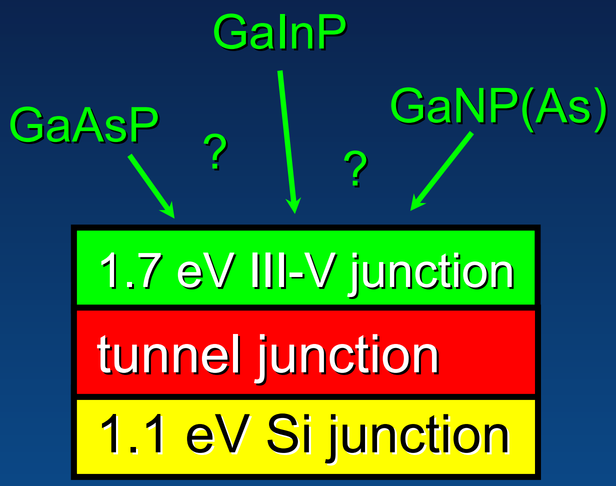
Motivation

- Monolithic, two (or more) junction single crystal solar cell on Si
- Old idea (SERI 1980's)



Advantages of silicon substrates:

- Excellent solar cell material
- Lower cost than III-V or Ge
- Mature Si technology
- Mechanically robust
- Two-junction cell using Si bottom junction is nearly optimal theoretical efficiency
  - 34% efficiency at 1 sun AM0
  - 44% efficiency at 500 sun AM1.5G

Challenges for III-V on Si growth

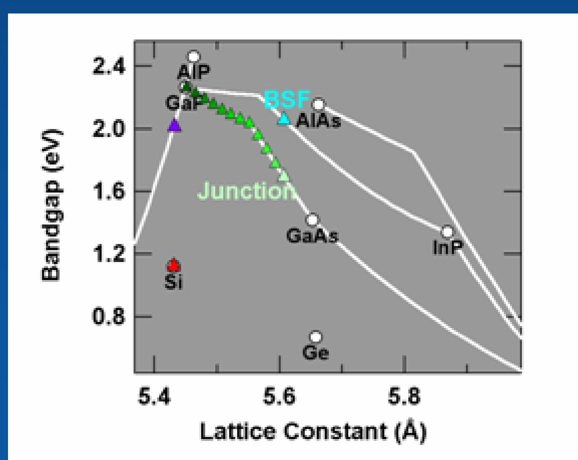
- Silicon oxides
- Surface contamination
- Antiphase domains
- Etching by sources
- Interdiffusion
- Lattice-mismatch
- Thermal expansion mismatch

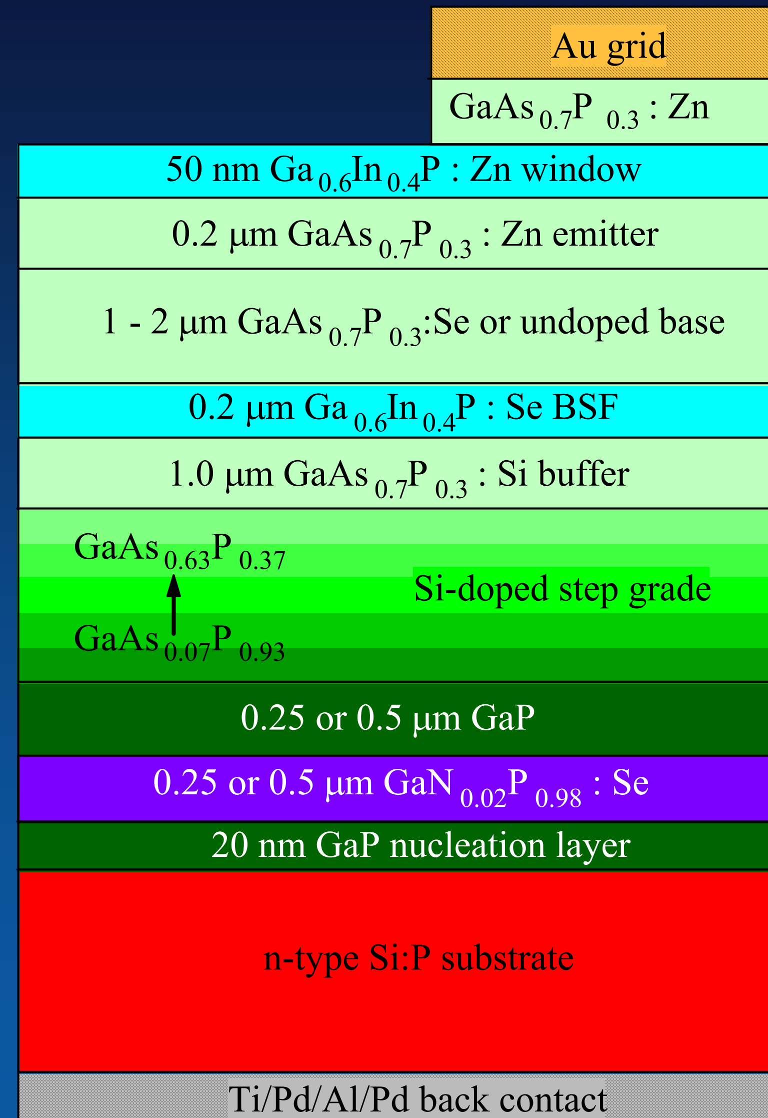
New developments

- Improved characterization techniques
- Better understand for III-V nucleation
- Lattice-matched GaNPAs materials

P-on-N GaAsP Cell Structure

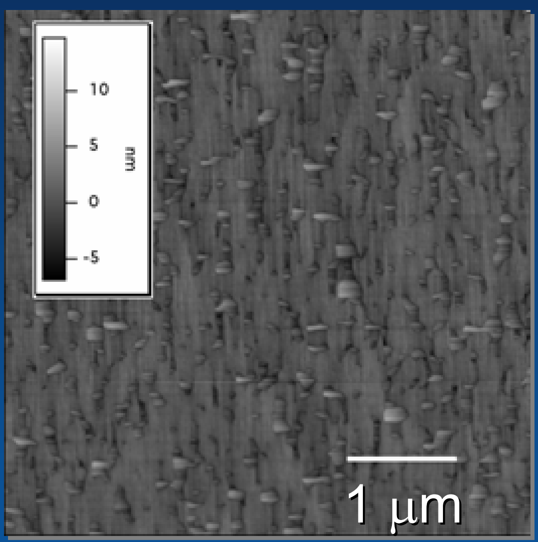
- III-V grown by OMVPE
- Smooth GaP nucleation on Si
- Step graded GaAsP buffer to reduce dislocations
- Constant lattice GaAsP junction with GaInP passivation



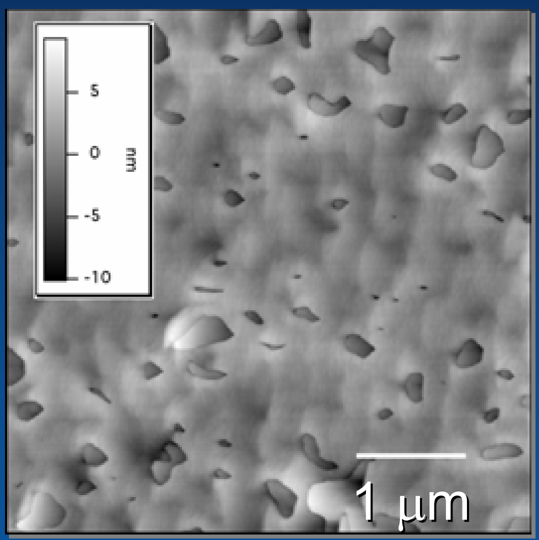


GaP Nucleation on Si

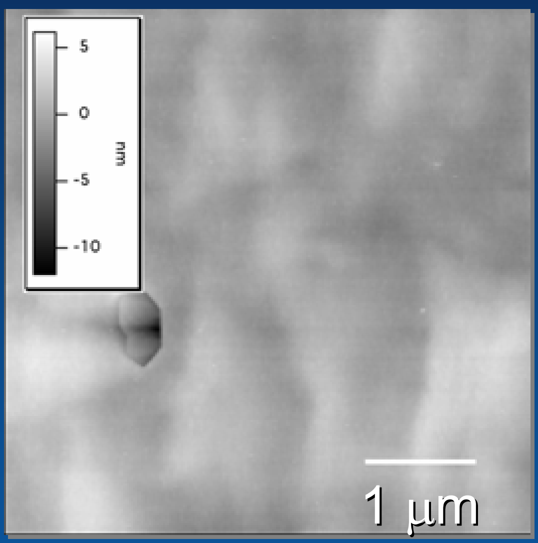
- Antiphase domains during GaP nucleation revealed by AFM
- Growth of LM GaNP smoothes surface and reduces APD



5.7 nm GaP
RMS = 1.2 nm

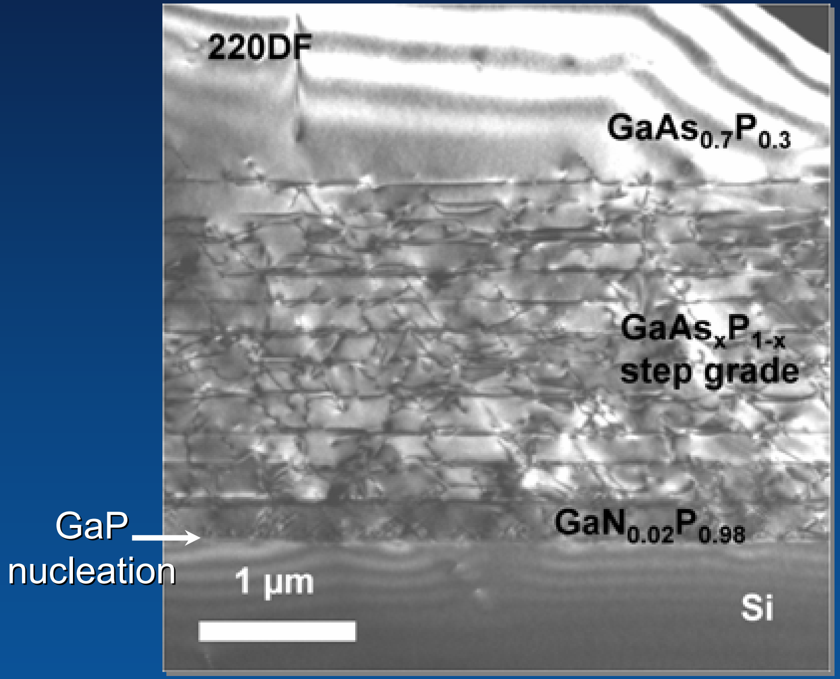


17 nm GaP
33 nm GaNP
RMS = 1.9 nm



18 nm GaP
403 nm GaNP
RMS = 0.4 nm

Step graded buffer layer

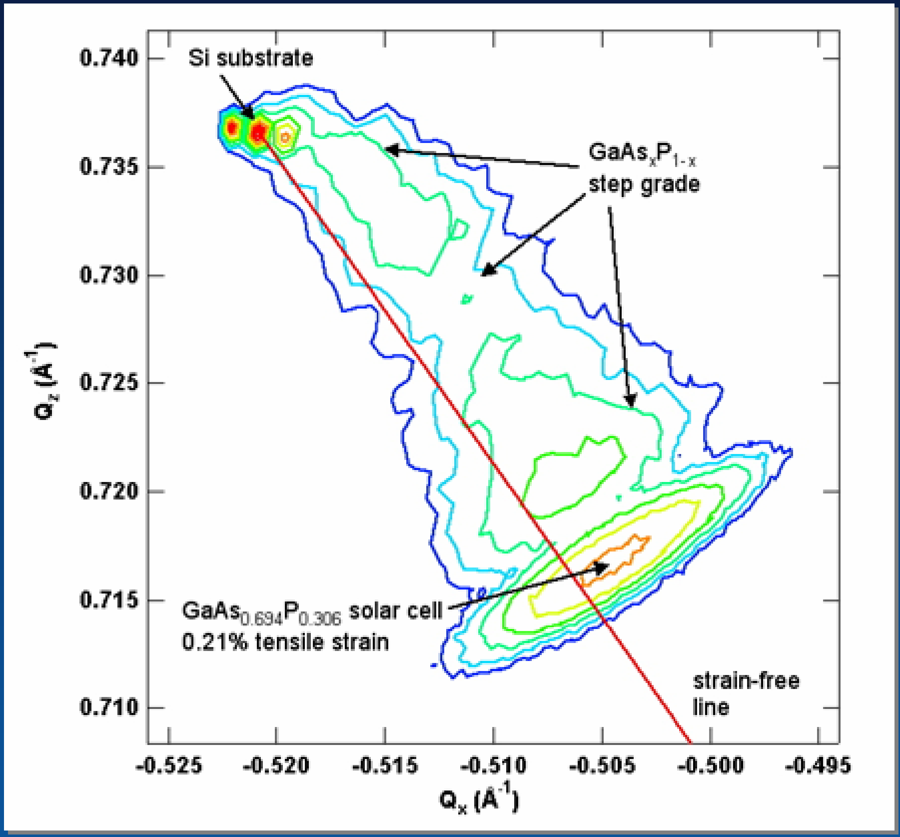


Cross-sectional TEM

- 0.25 or 0.5 μm $GaAs_xP_{1-x}$ steps
- Composition change $\Delta x = 0.07$ per step
- 3.75 or 6.5 μm total buffer thickness
- Many dislocations in grade, but few in active layers

Composition and Strain

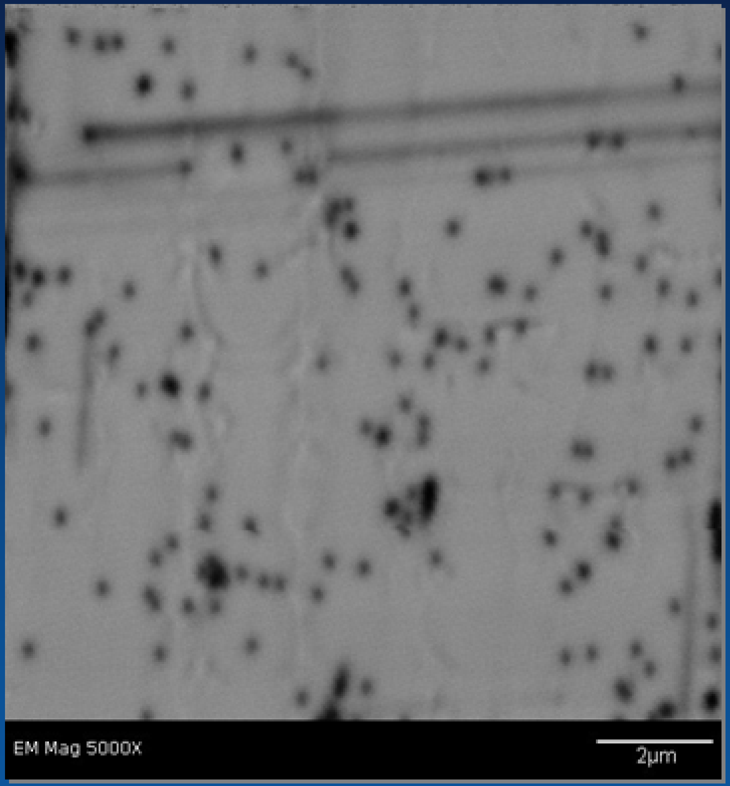
- Grown under compression because growing epilayers have larger lattice constant
- Relaxes at T_g above critical thickness
- Cools toward tension
- Residual compressive strain at T_g results in less tension at RT (no cracks)



X-ray diffraction
224GI reflection RSM

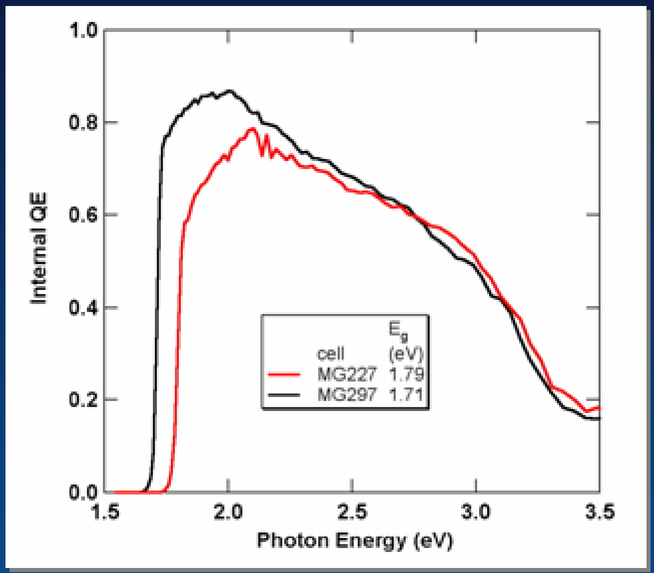
Threading Dislocations

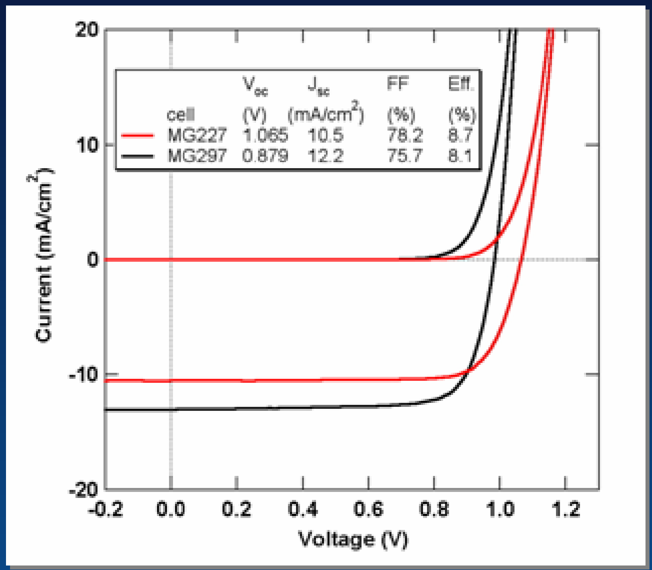
- Electron-Beam-Induced Current (EBIC)
- 9×10^7 - 1×10^8 cm^{-2} threading dislocations



Plan-view EBIC

GaAsP/Si Device Performance





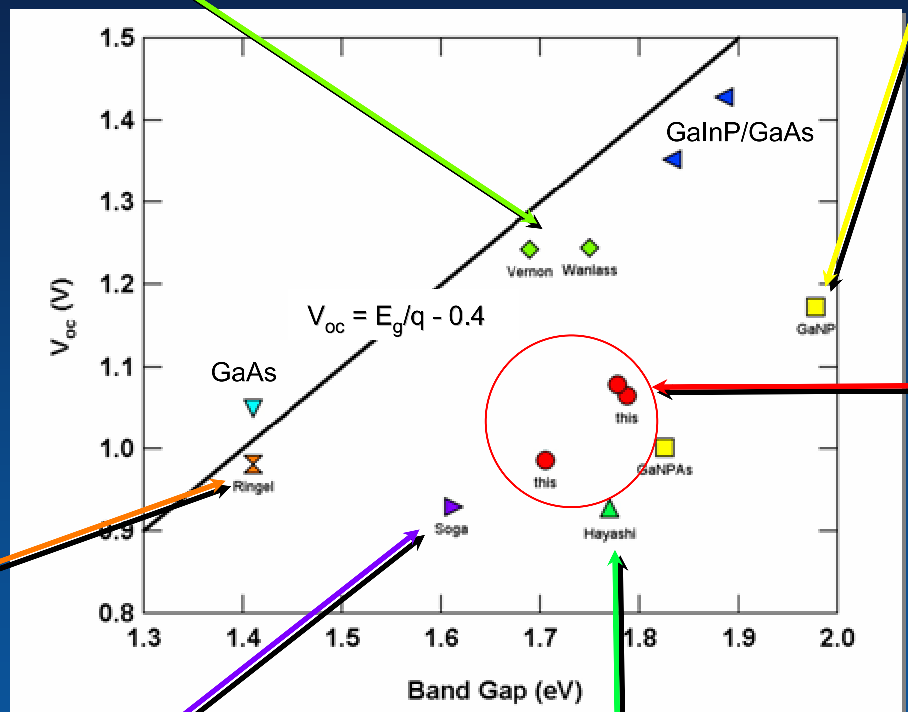
- Single-junction 8.7% efficiency AM1.5G w/o AR coat
- Increase J_{sc} with lower E_g (need about 20 mA/cm^2 for 2-junction current matching)
- Improve QE with better passivation, thinner window

Literature Comparison

GaAsP/GaAs ~ 10^6 cm^{-2}
Vernon, 19th PVSC, (1987),108
Wanlass, 19th PVSC, (1987), 530

LM GaNP(As)/Si or GaP
Geisz, 31st PVSC, (2005), 695

V_{oc} is excellent measure of quality for mismatched solar cells



This work

GaAs/SiGe/Si ~ 10^6 cm^{-2}
Ringel, Prog. PV 10, (2002), 417

AlGaAs/Si ~10^7 cm^{-2}
Soga, J.Appl. Phys., 78, (1995), 4196

GaAsP/Si (TCA)
Hayashi, 1st WCPEC, (1994), 1890

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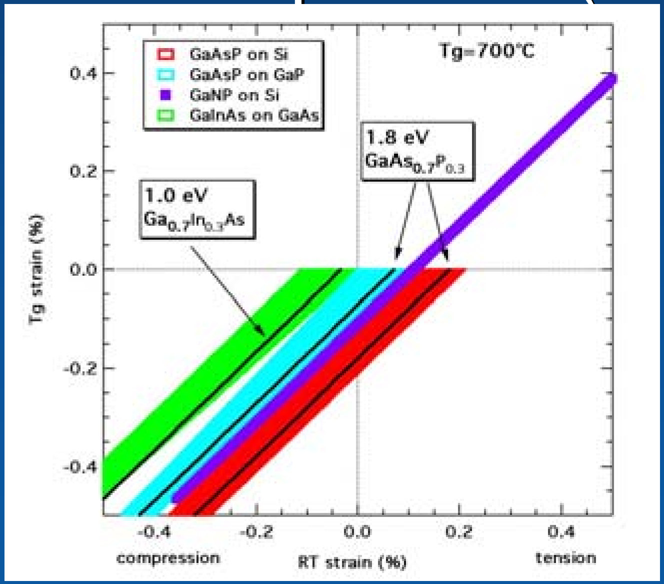
Conclusions

- Lattice-mismatched GaAsP solar cells grown on Si
- Compositional step grade reduced dislocations to ~10^8 cm^{-2}
- V_{oc} not ideal, but comparable to best III-V grown on Si with transparent buffer
- Diffusion lengths better than LM GaNP
- Want to reduce dislocations to 10^6 cm^{-2}

Extra Slides

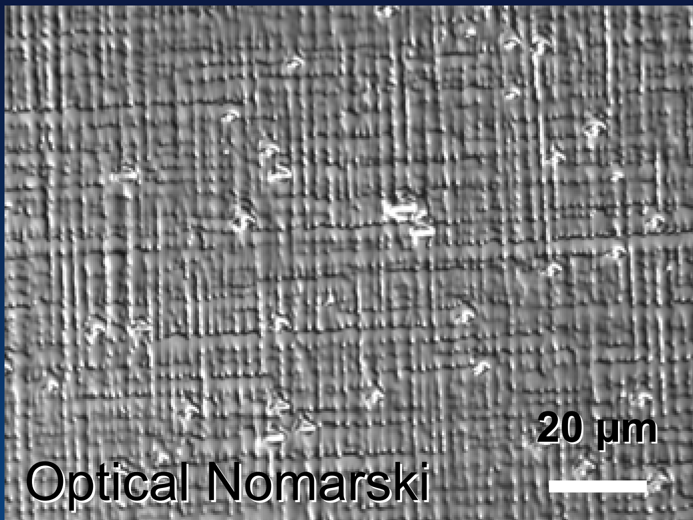
Thermal Expansion

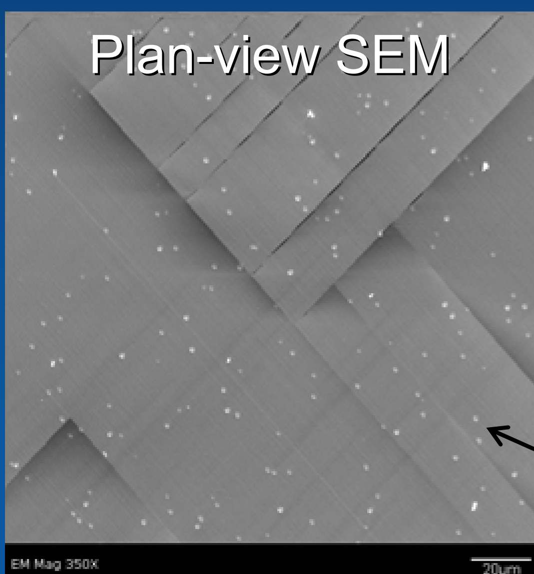
- Can measure strain at RT with XRD
- Would like to measure strain during growth
- Can calculate strain state at Tg assuming
  - change in in-plane lattice constant of epilayers constrained by thick Si
  - no relaxation upon cool-down
- Linear coefficients of thermal expansion (K^{-1})
  - Si: 3.7×10^{-6}
  - GaP: 5.3×10^{-6}
  - GaAs: 6.8×10^{-6}
  - GaN: 6×10^{-6} ?
  - InAs: 5.2×10^{-6}



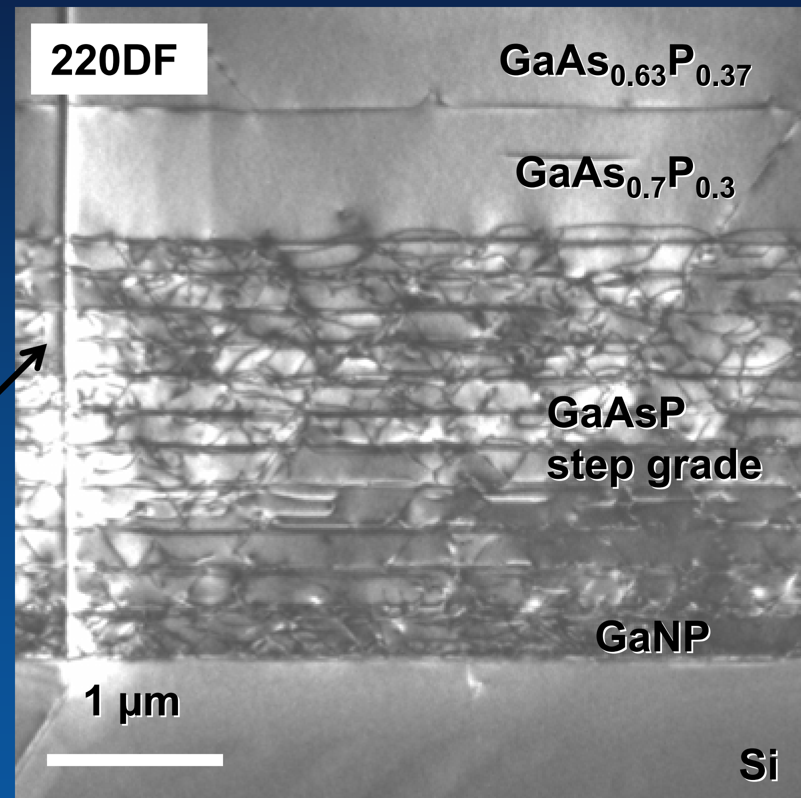
- Scales with Tg
- Biaxial strain energy
  $U = Y \varepsilon_x^2 t$

Cracking from Tensile Strain on Si





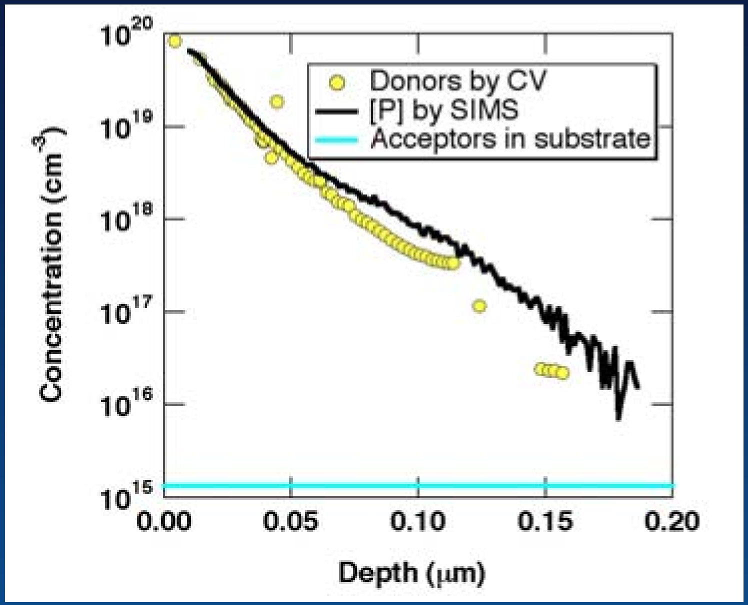
Cross-sectional TEM



crack

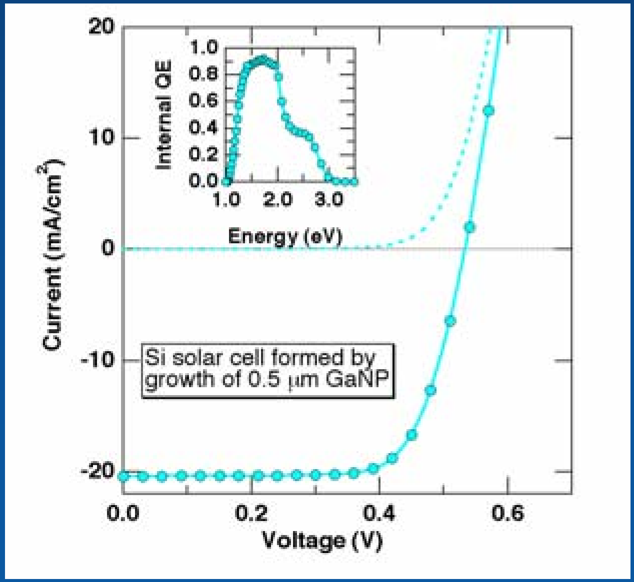
Charging effect reveals cracks

Si junction



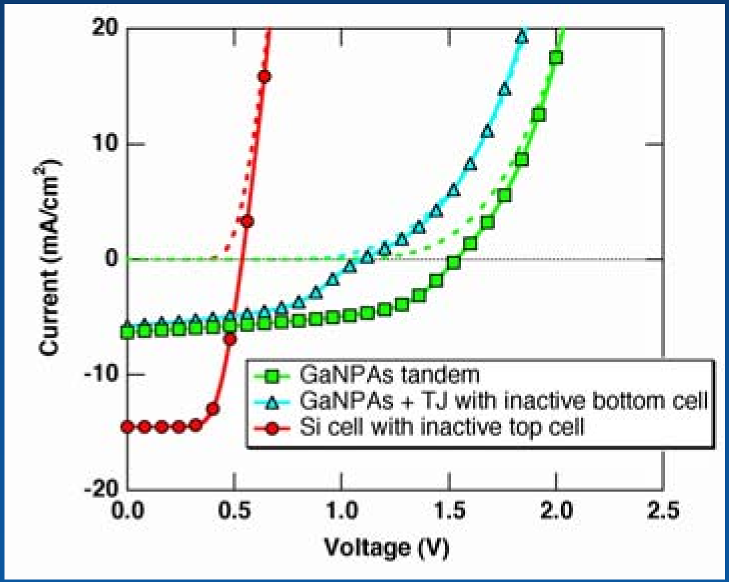
- Under current growth conditions, more P than Ga diffusion into Si from GaP
- Creates n-type emitter in silicon
- Emitter passivation from GaP if no interface defects

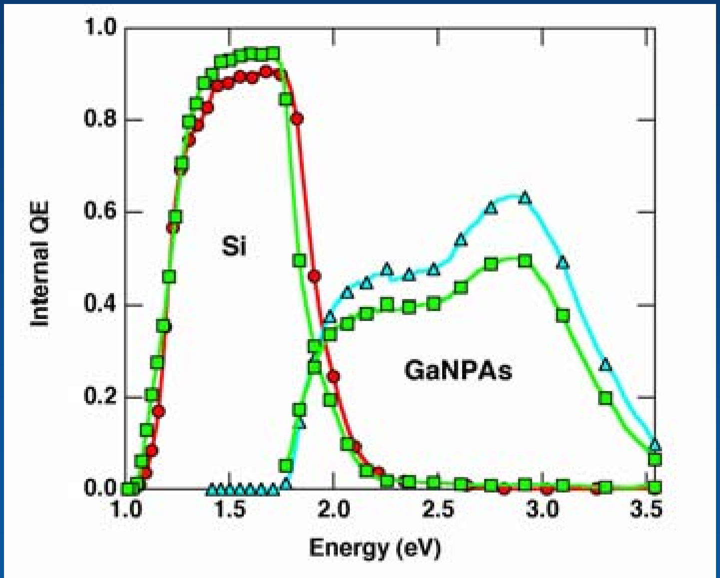
- V_{oc} of silicon junction ~535mV
- Currently using CZ Si, but float-zone may be better
- BSF from annealed Al contact



GaNPAs/Si Tandem Solar Cell Results

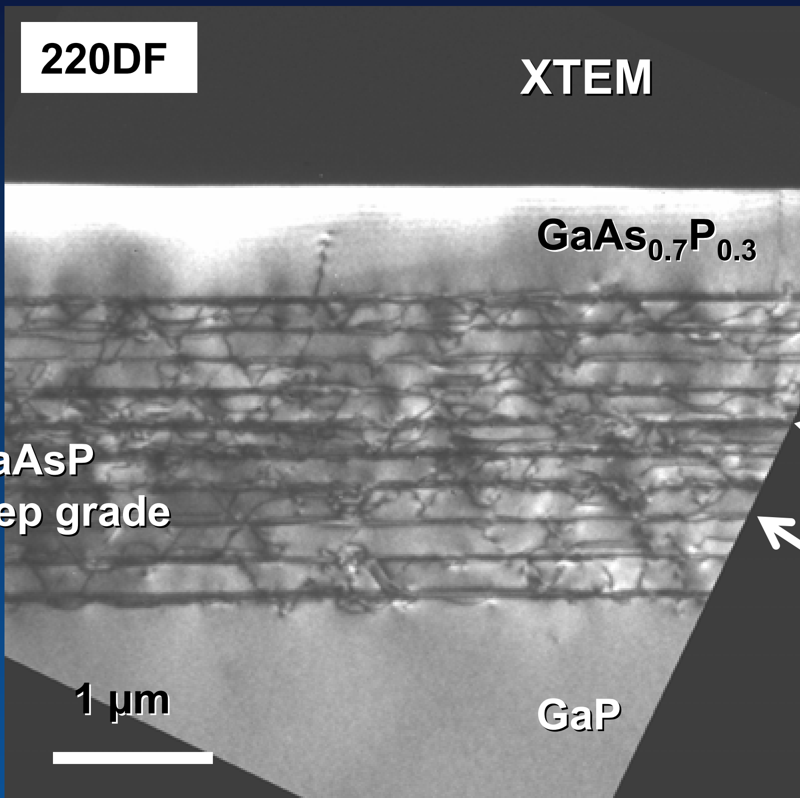
- Working tandem
- Good current in Si junction, but Voc could be a little better
- GaNPAs delivers half the current necessary to current match tandem





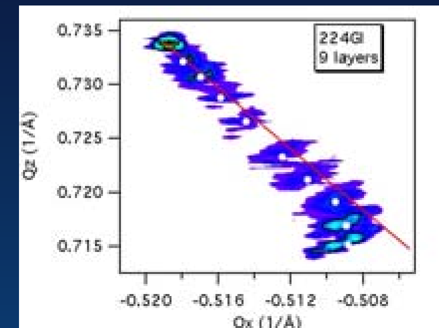
Geisz et al., PVSC **31** (2005) 695

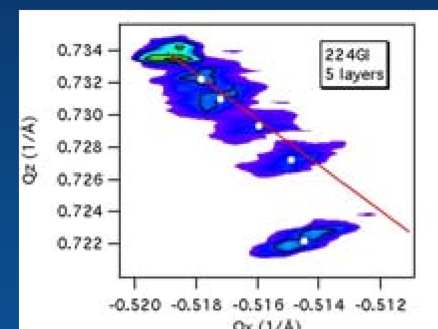
Step Grading for Mismatch on GaP

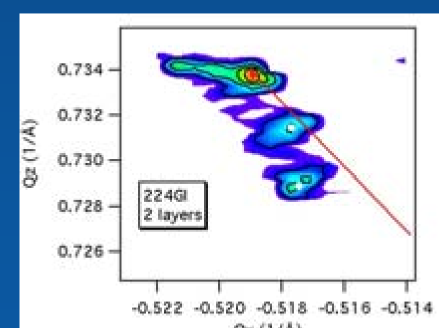


GaAsP step grade

XRD Reciprocal Space Maps

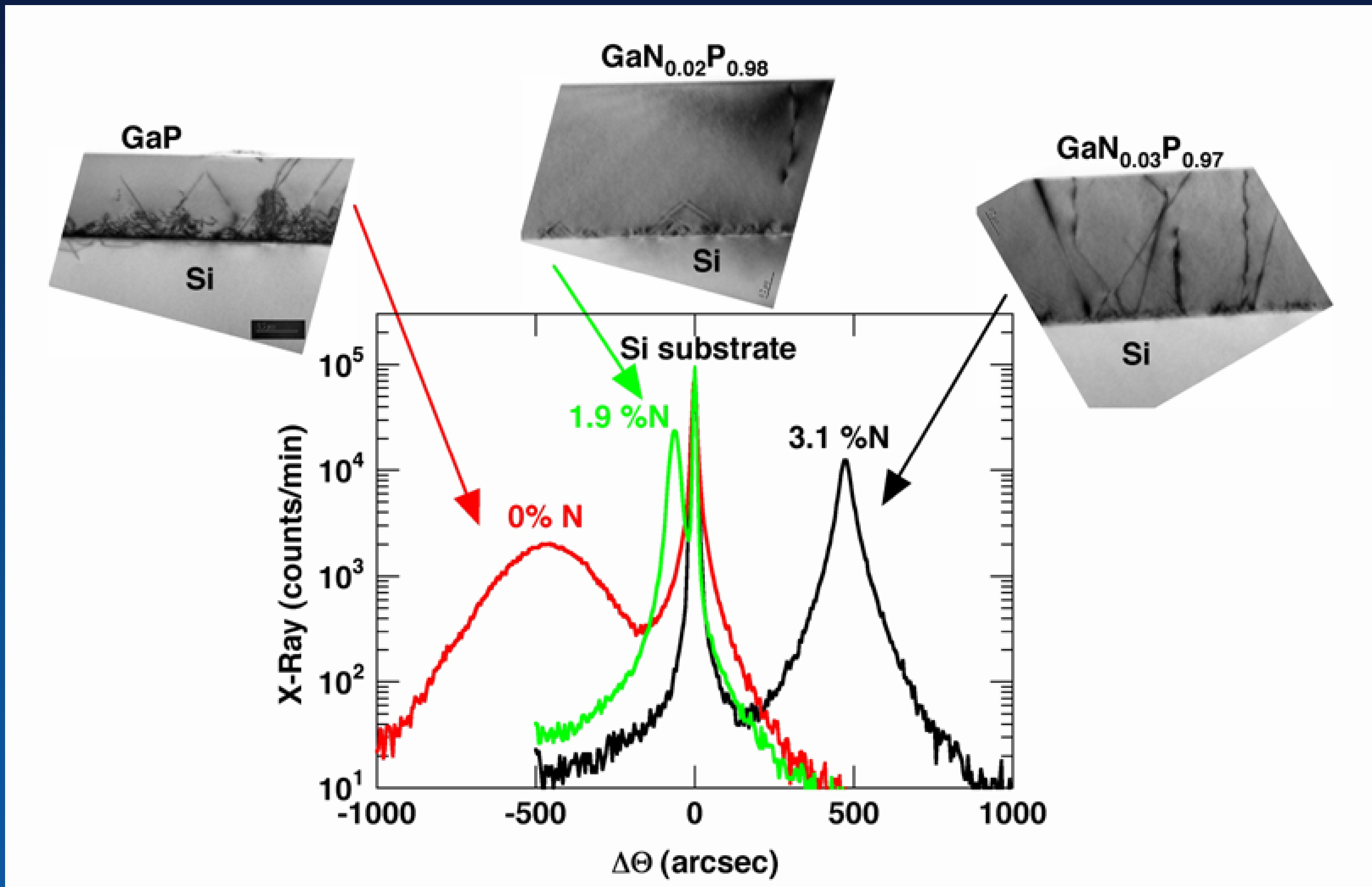




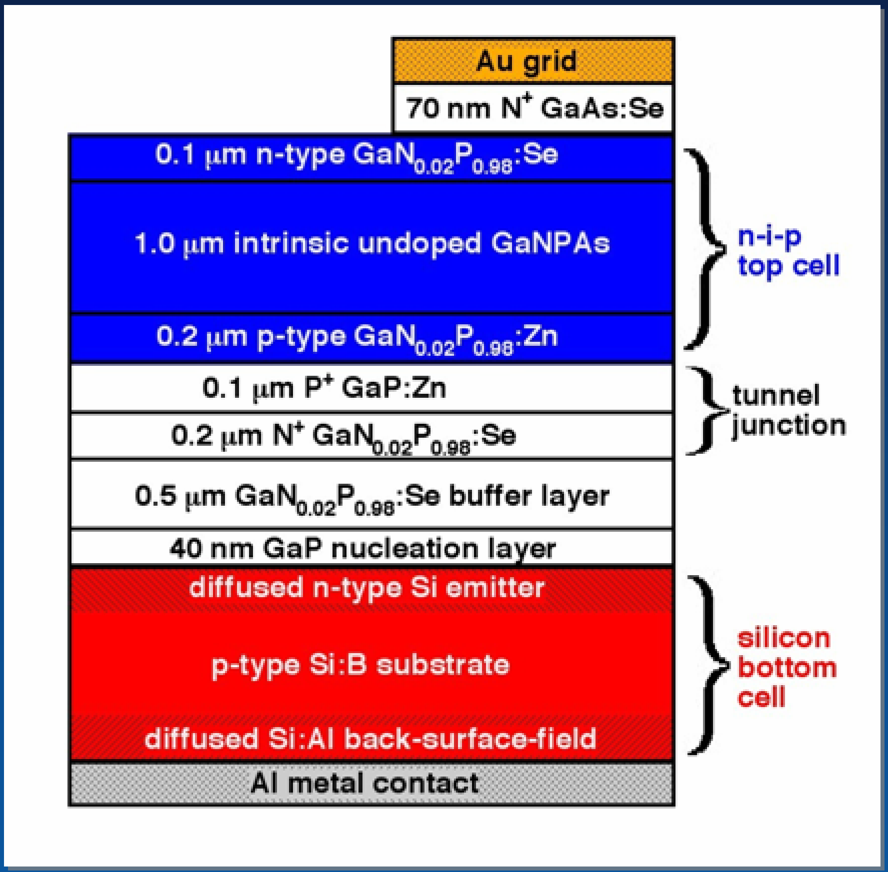


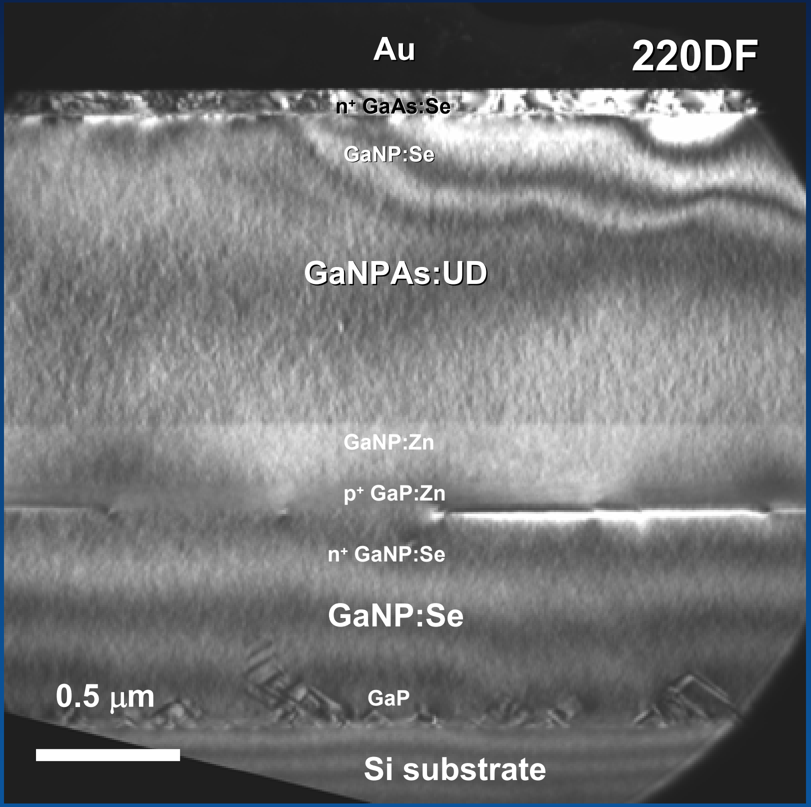
- Top layer strained to match next in-plane lattice constant (residual strain)
- Mostly relaxes while next layer growing

Lattice-matched GaNP

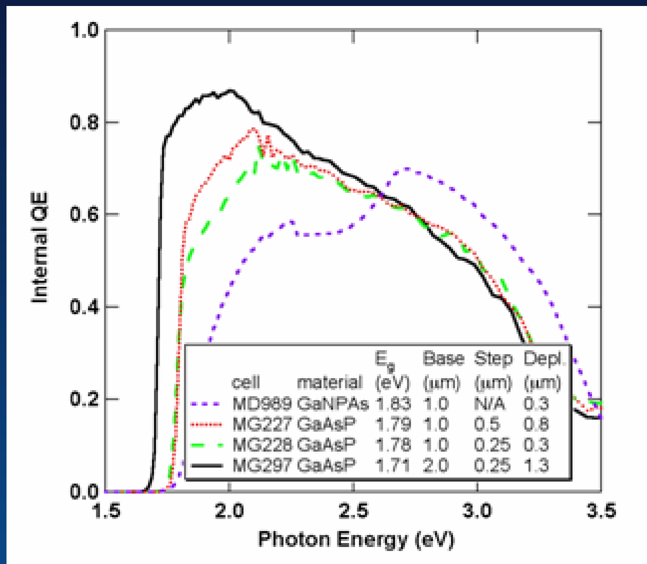


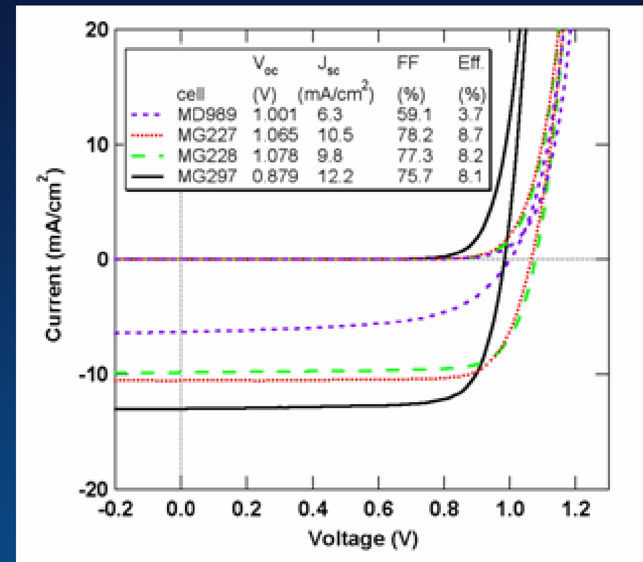
GaNPAs/Si Tandem Solar Cell Structure





GaAsP/Si Device Performance





- Single-junction 8.7% efficiency AM1.5G w/o AR coat
- Increase J_{sc} by lower E_g (need about 20 mA/cm^2 for 2-junction)
- Improved QE with wide depletion region, but decent with thinner depletion region
- GaAsP/Si better than GaNPAs/GaP
  - Longer diffusion length even with 10^8 cm^{-2} TD