Growth and characterization of III-V epitaxial mirror coatings on silicon

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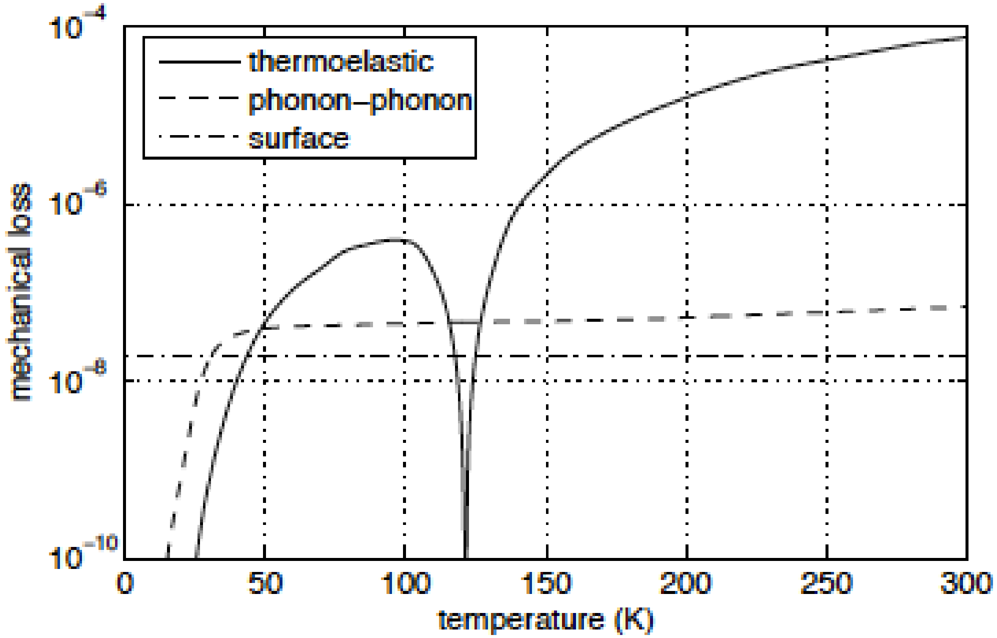
Gravitational Wave Advanced Detector Workshop

May 14, 2012

Single crystalline coatings

Loss sources in a Si flexure[1]

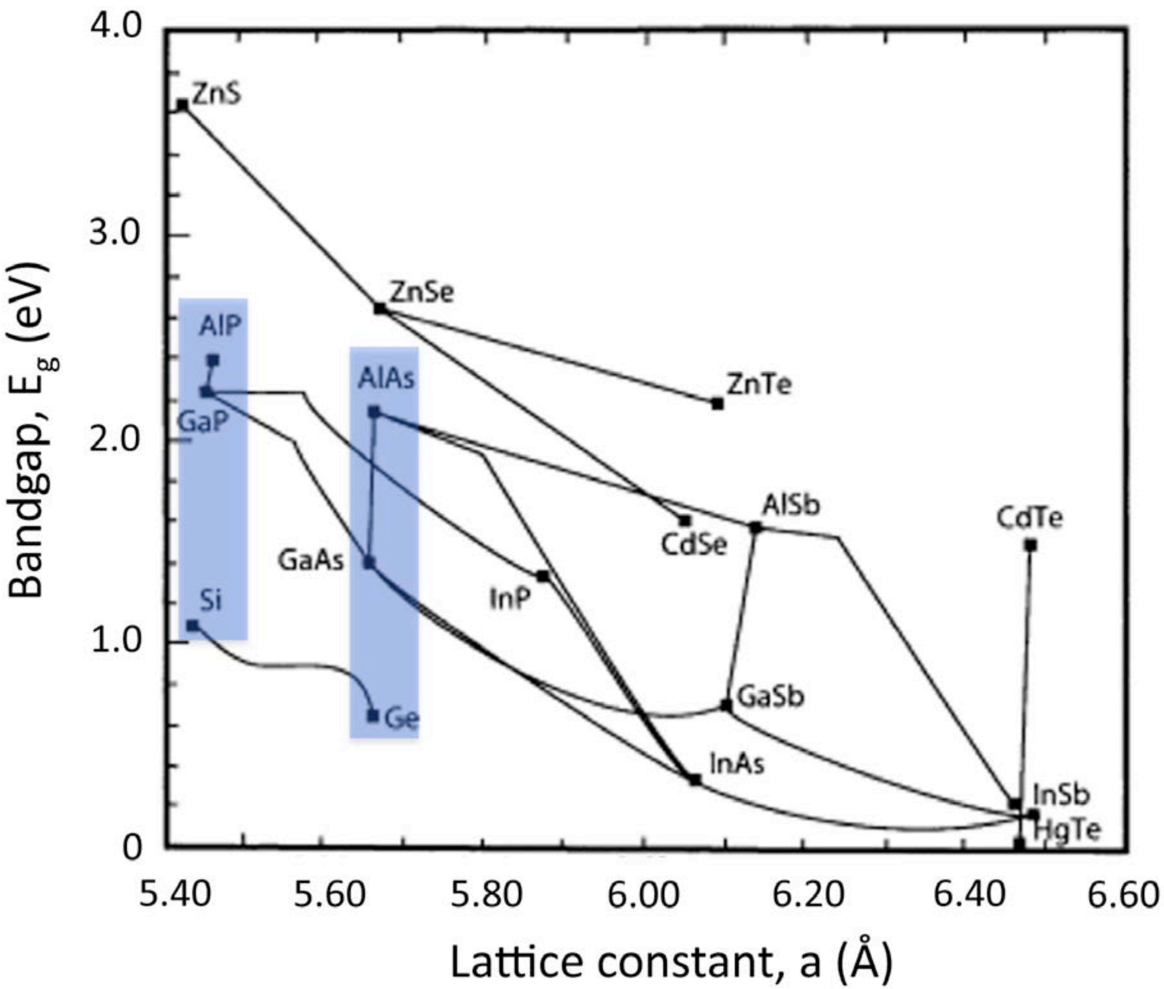


For third generation detectors operating at cryogenic temperatures:

- Low mechanical loss in silicon at low T
- Silicon is available in large sizes:
  - Commercially available: 300 mm (12")
  - Research: 450 mm (18")
- Single crystalline coatings have already been shown to have low mechanical loss[2]

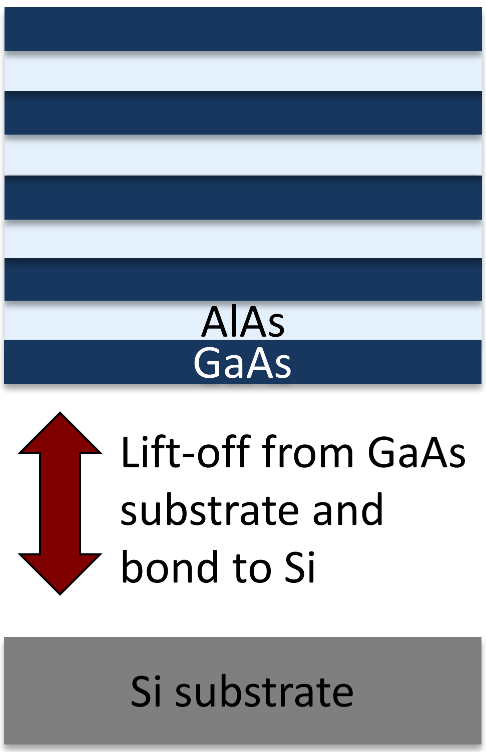
[1] Nawrodt et al. arXiv:1003.2893v1 (2010). [2] Cole et al. Appl. Phys. Lett. 92, 261108 (2010).

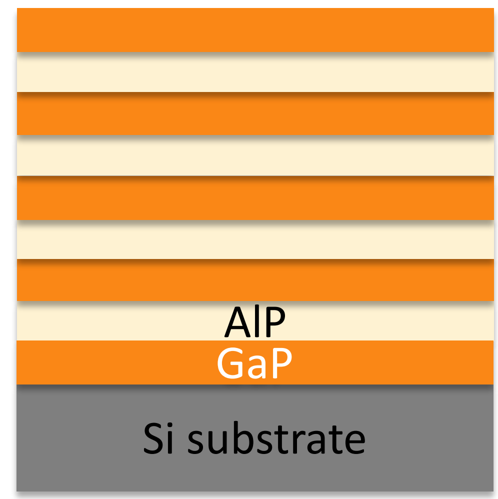
Direct integration of mirrors onto Si



- Materials systems with index contrast but no change in lattice constant

Integration approaches





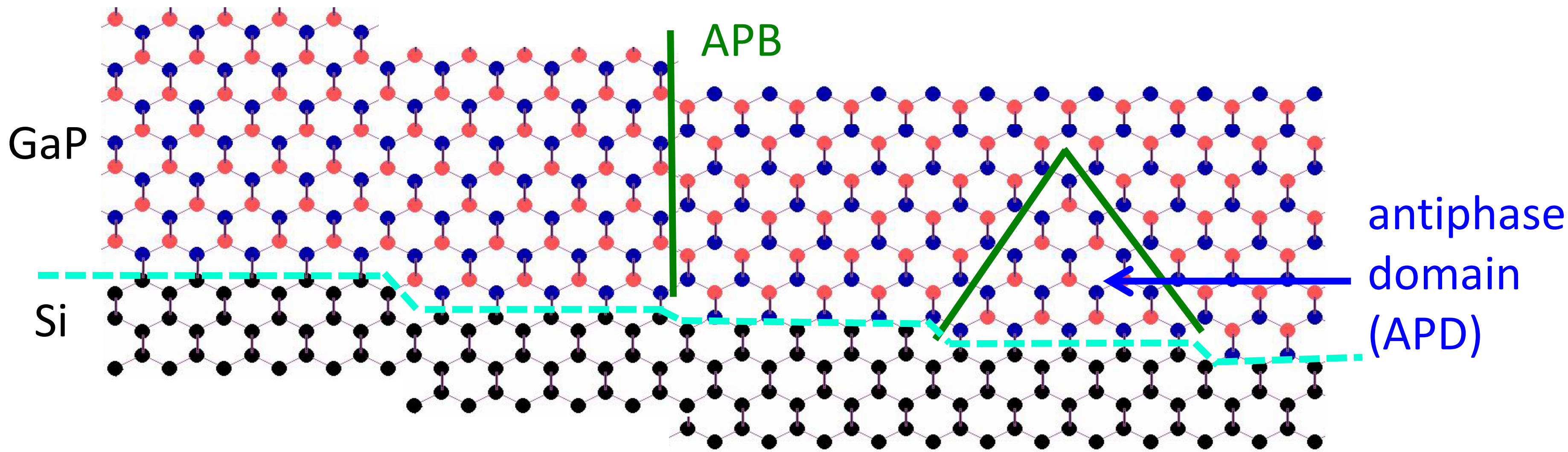
- Commercially available GaAs: 6”
- Dislocations in SiGe arise from 4% mismatch between Si and Ge
- Lattice-matched system, but less studied

Outline

- Epitaxial integration of III-V coatings on Si
- Anticipated challenge: antiphase domains
  - Growth technique: molecular beam epitaxy
  - Film characterization techniques
  - Reducing antiphase domains through growth conditions
- GaP/AlP mirror coating on Si: initial results
  - Materials characterization
  - Optical absorption
  - Mechanical loss
- Summary and future work

Anticipated challenge: antiphase defects

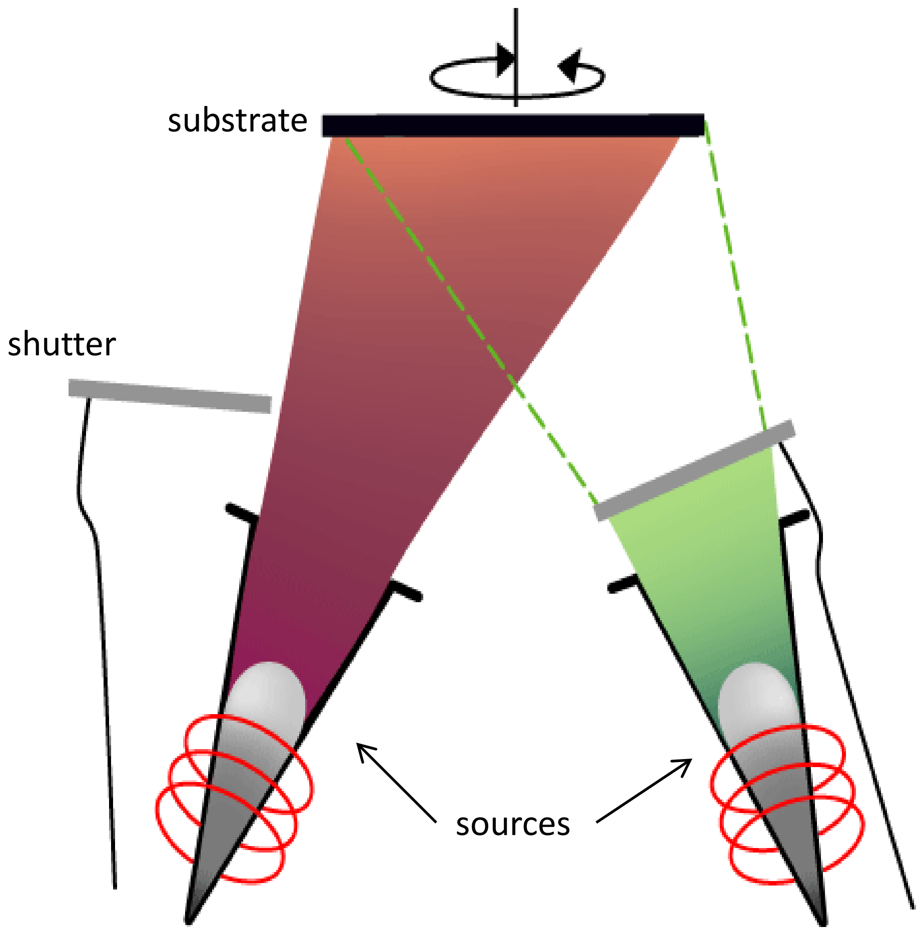
Antiphase boundary (APB): defect with incorrect bonds (P-P or Ga-Ga)



Double atomic steps on Si surface
→ correct bonds

Single atomic steps on Si surface
→ wrong bonds

Growth by molecular beam epitaxy



Sources and components:

- Group III: Ga, Al, In
- Group V: As, P
- Group IV: Ge, Si
- In-situ reflection high-energy electron diffraction (RHEED)

Advantages of using MBE:

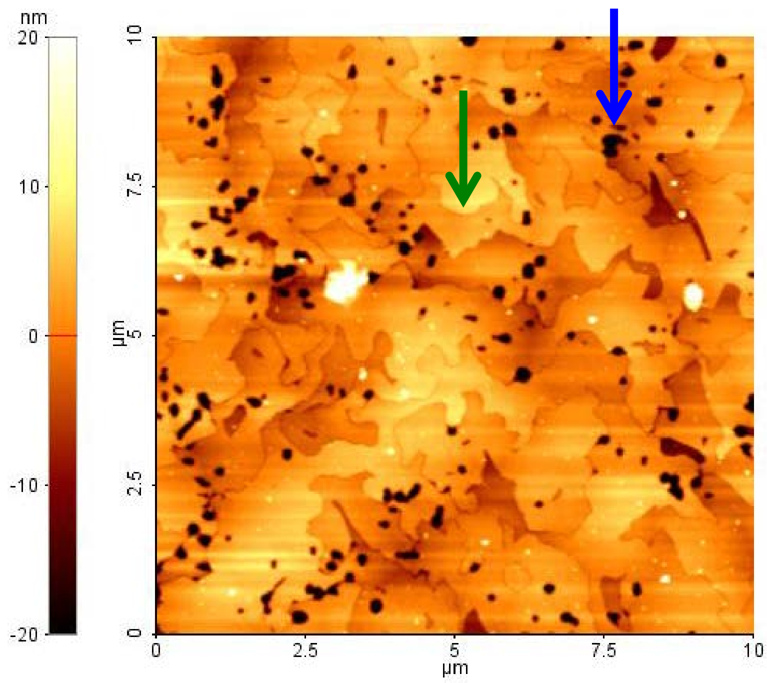
- Low impurity incorporation (UHV)
- Monolayer control
- Growth rate and substrate temperature decoupled

Control over growth rate, substrate temp, V/III flux ratio

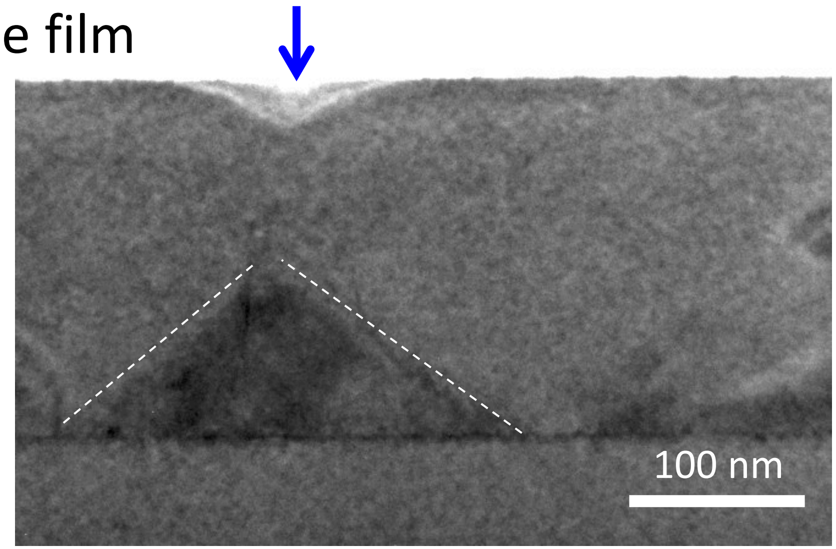
Ex-situ characterization techniques

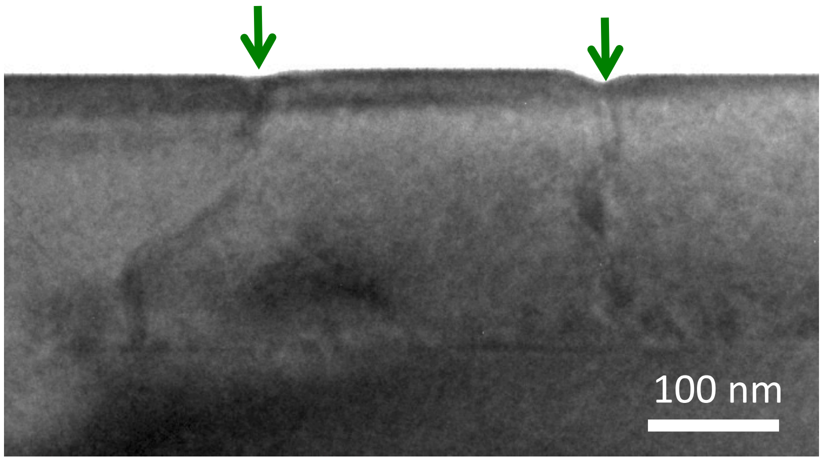
Detect APDs with atomic force microscopy (AFM) and transmission electron microscopy (TEM)

- AFM: surface pit density
- TEM: how APBs propagate in the film



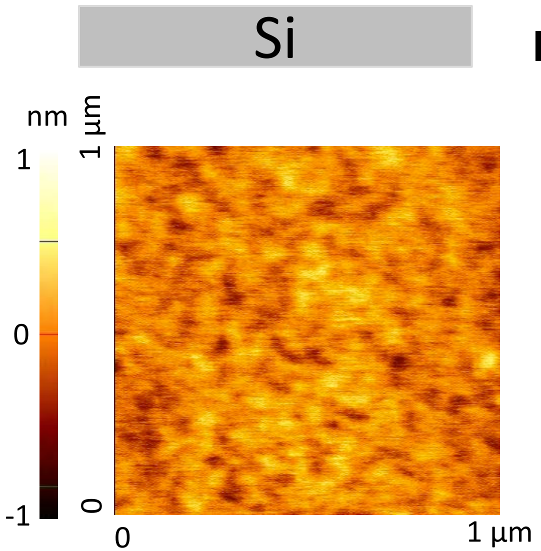
A film with many antiphase domains





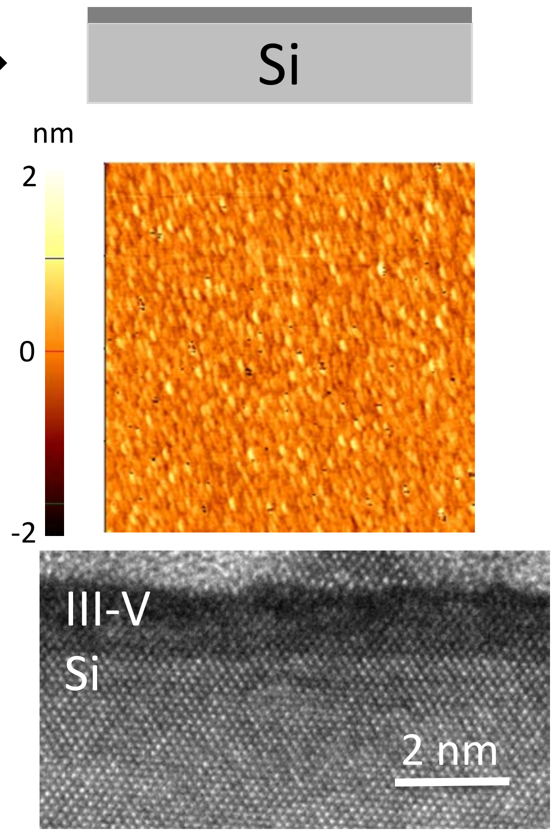
Sample courtesy of D. Liang, Y. Kang (Stanford)

Achieving high quality GaP on Si



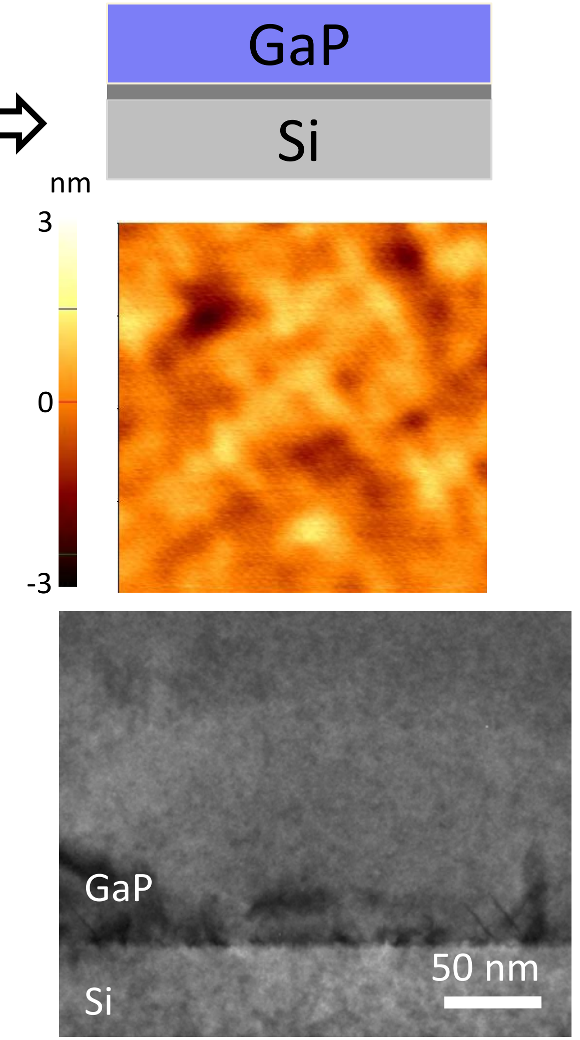
Si surface prep:

- Standard clean
- Si buffer
- High T anneal



III-V nucleation:

- 2D growth



GaP overgrowth:

- Annihilate defects

A.C. Lin et al. J. Vac. Sci. Technol. B 29 (2011) 1201.

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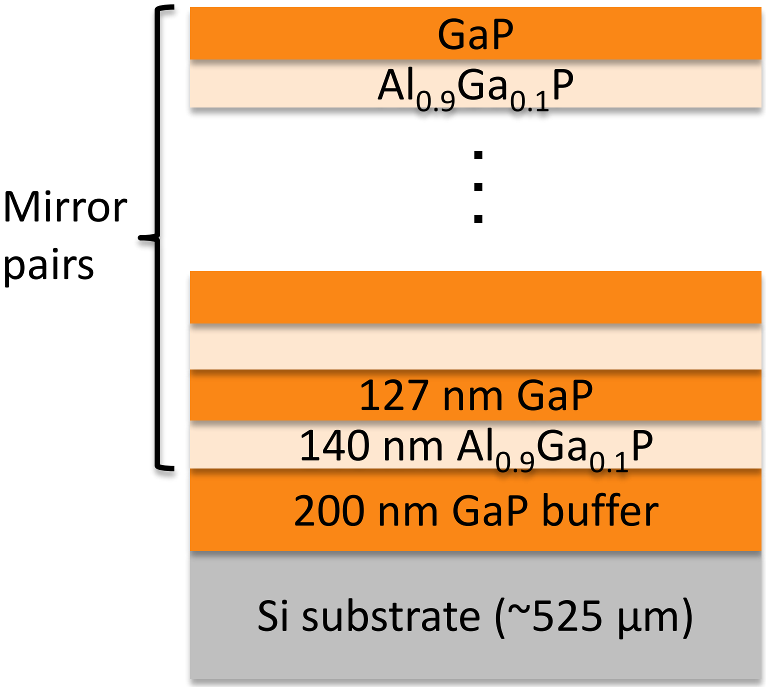
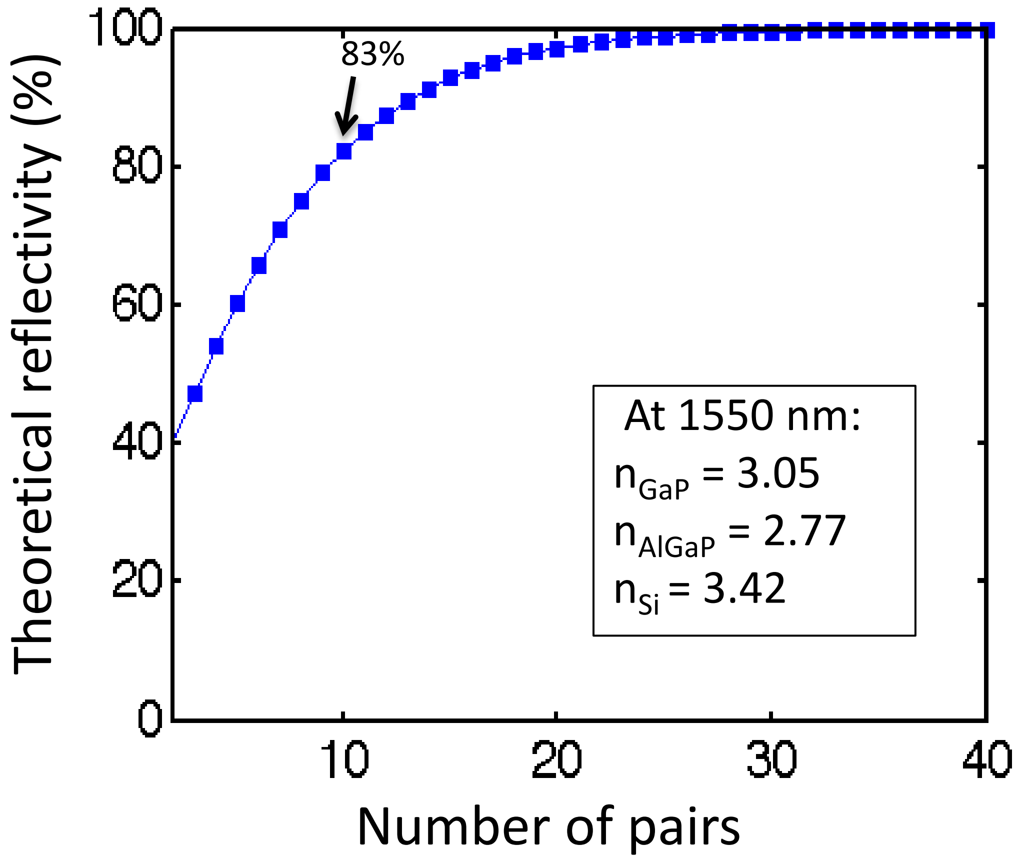
Epitaxial GaP/AlGaP layers on Si

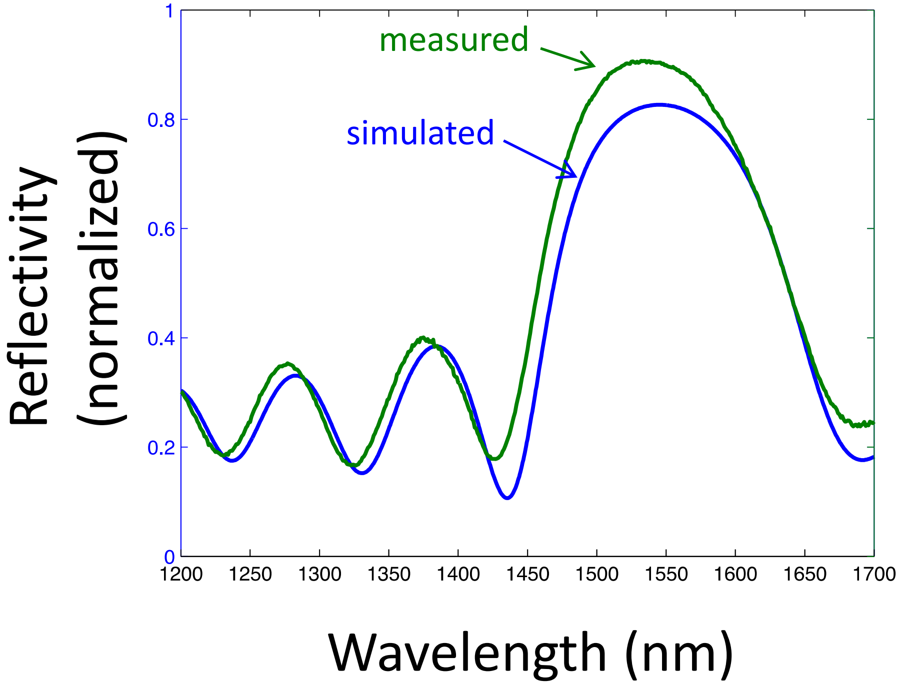


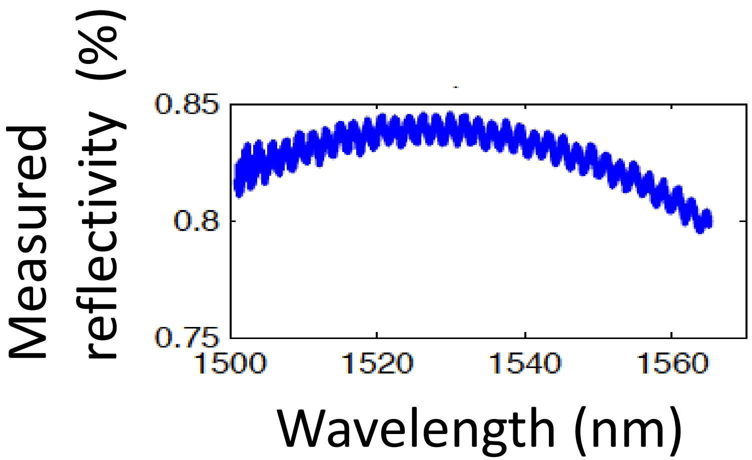


- Index contrast $\Delta n = 0.28$
- Pure AlP oxidizes easily

Dispersion relations from N.A. Pikhtin et. al. Soviet Phys. 9 (1967) 107.
Transfer matrix Matlab code courtesy of Tomás Sarmiento (Stanford)

Achieved expected reflectivity

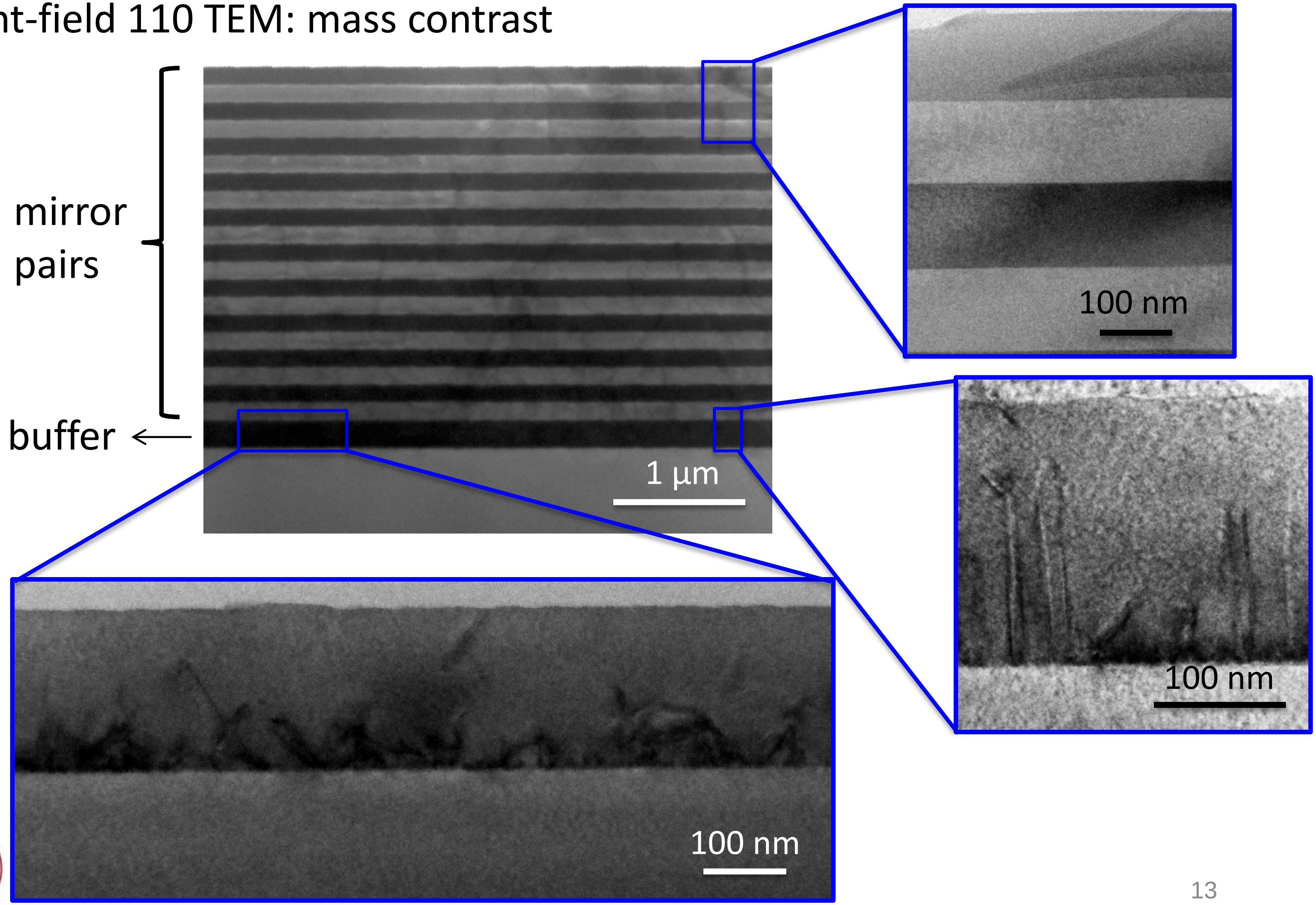




For 10 pairs: measured reflectivity matches theoretical reflectivity (83%)

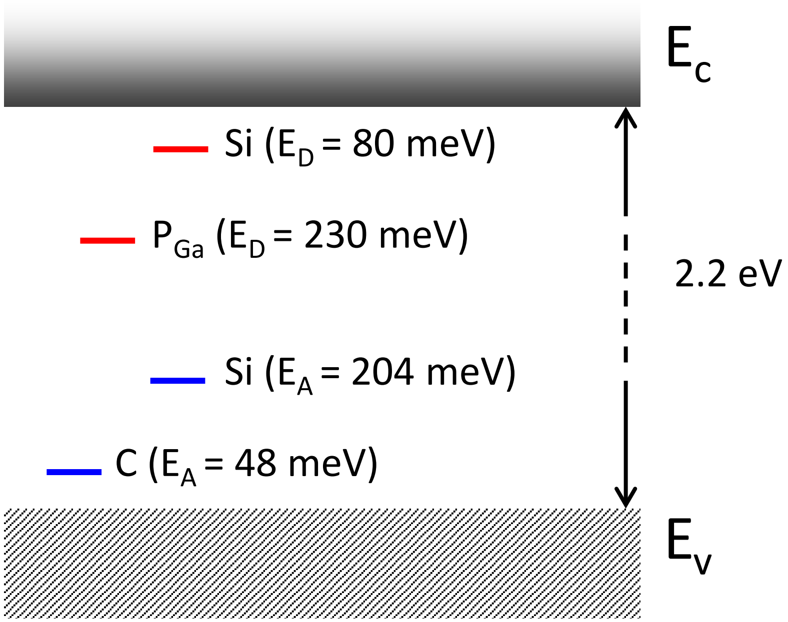
Transmission electron microscopy

Bright-field 110 TEM: mass contrast



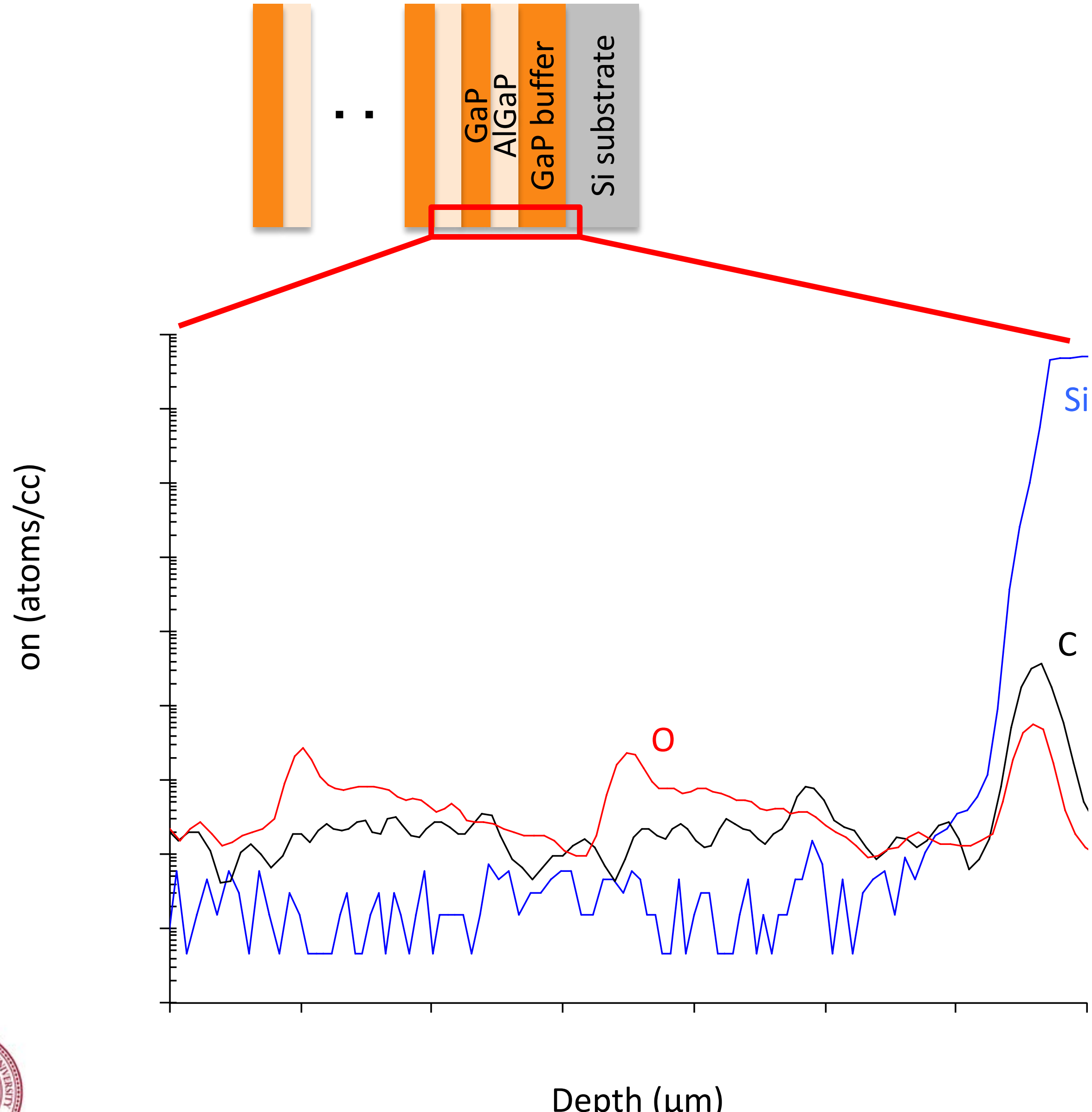
Optical absorption

- Using photothermal common-path interferometry (PCI) to measure absorption
- Possible source of absorption: free carriers in GaP[1,2]
  - Si outdiffusion from substrate
  - Carbon, oxygen incorporation
  - Antiphase domains (Ga-Ga, P-P)
- Low temperature will freeze out the carriers



[1] P.J. Dean et al. J. Appl. Phys. 39, 5631 (1968).
[2] K.W. Nauka, Imperfections in III/V Materials (1993).

Secondary ion mass spectroscopy

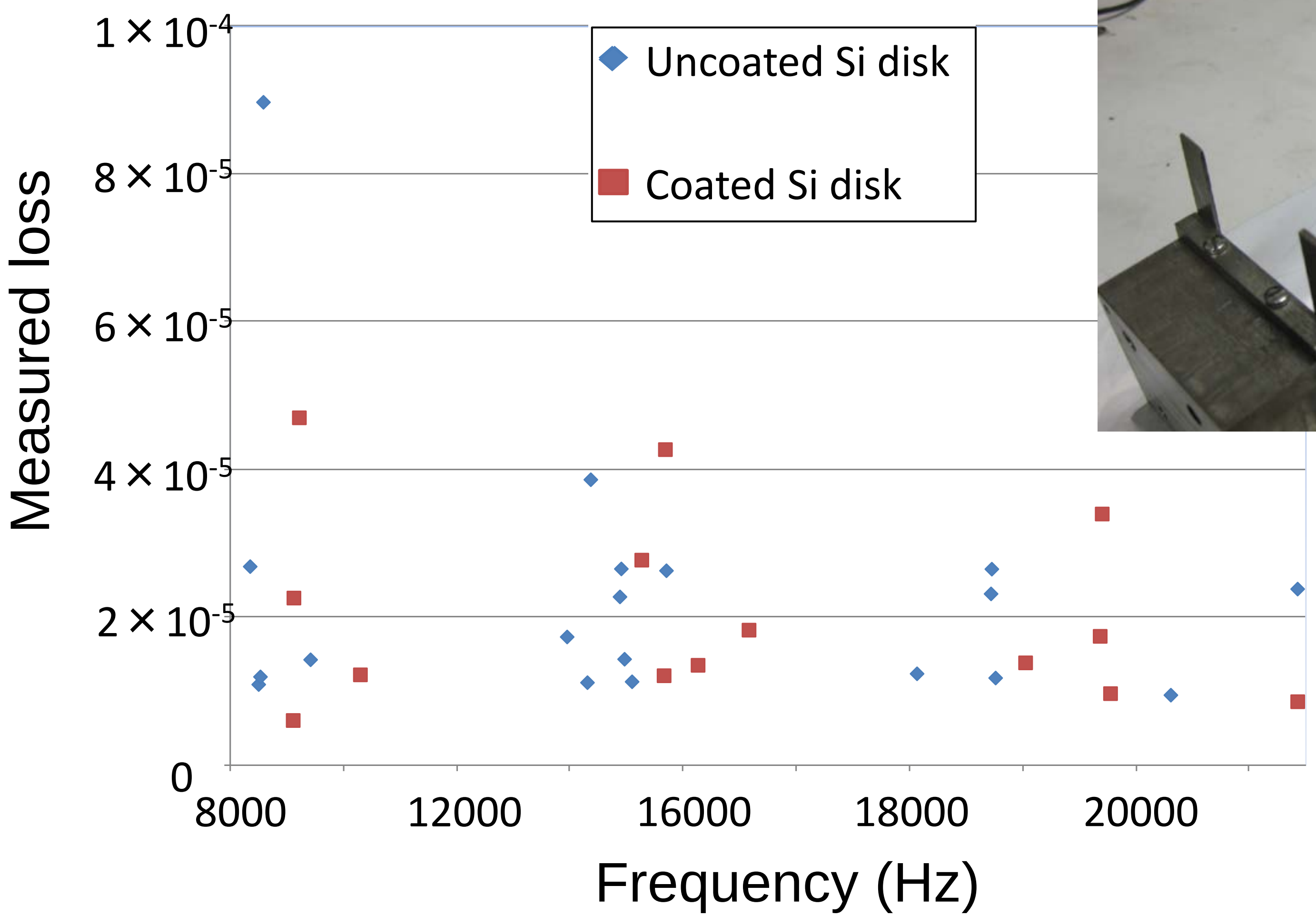


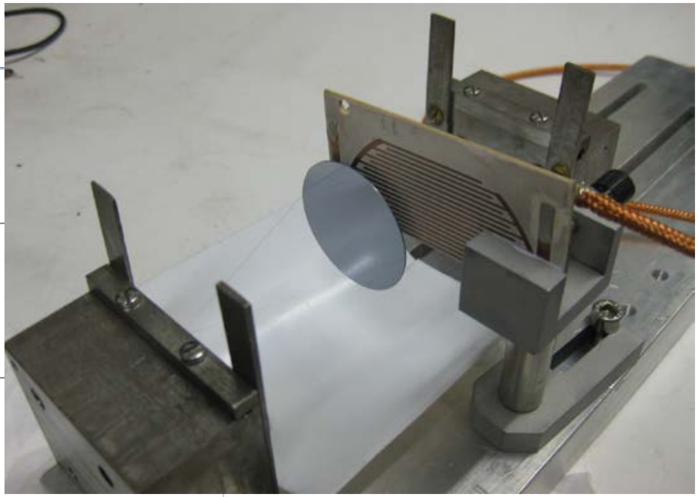
Is there a source of free carriers?

- C, O present at Si/GaP interface
- Si diffusion limited to GaP buffer layer

SIMS done by Evans Analytical Group

Initial results for mechanical loss





No discernible difference between lowest measured losses in coated and uncoated samples

Summary and future work

- GaP/AlP mirrors can be grown directly on Si
- Challenges with epitaxial integration onto Si can be addressed by nucleation and growth conditions
- Preliminary structural, optical absorption, and mechanical loss measurements have been done on GaP/AlGaP mirrors

Future work:

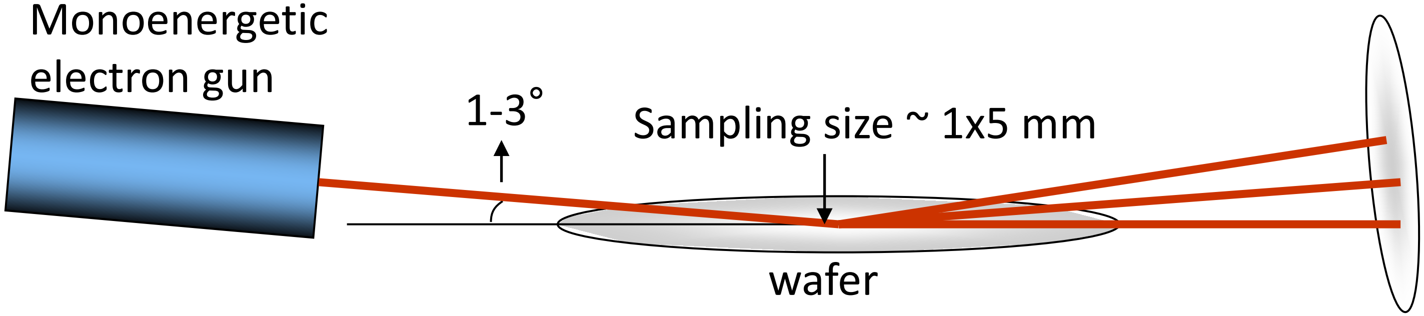
- Low temperature absorption measurements
- Low temperature mechanical loss measurements
- Investigating other growth conditions to further reduce defects and impurities

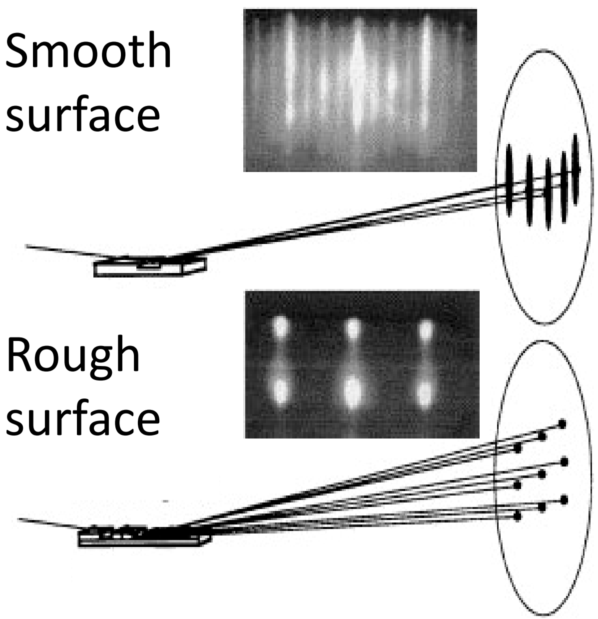
Acknowledgements: This work was supported by NSF grant PHY-10 68596.

Material properties

Material	Lattice constant (Å)	Mismatch (%)	Refractive index (near-IR)	Linear thermal expansion coefficient ($^\circ C^{-1}$)
AlP	5.4510		2.75	$6.10*10^{-6}$
GaP	5.4505	Z	3.02	$4.65*10^{-6}$
Si	5.4310	0.4	3.42	$2.60*10^{-6}$
AlAs	5.6611		2.86	$5.20*10^{-6}$
GaAs	5.6533		3.30	$5.73*10^{-6}$
Ge	5.6580	0.08	4.00	$5.90*10^{-6}$

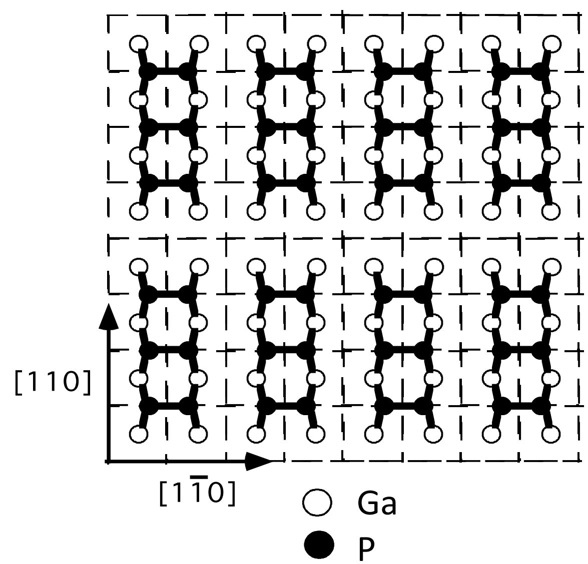
In-situ characterization: RHEED

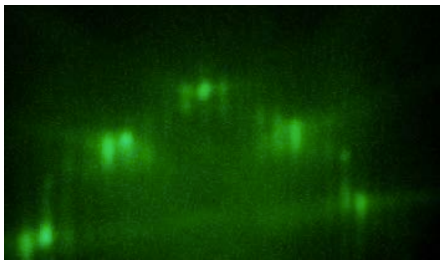




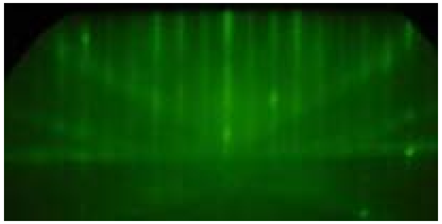
S.A. Chambers, Surf. Sci. Rep. 39, 105 (2000).

GaP (001) 2x4 surface





Beam along [1$\bar{1}$0]



Beam along [110]

Observe how the film is growing: island or 2D growth mode

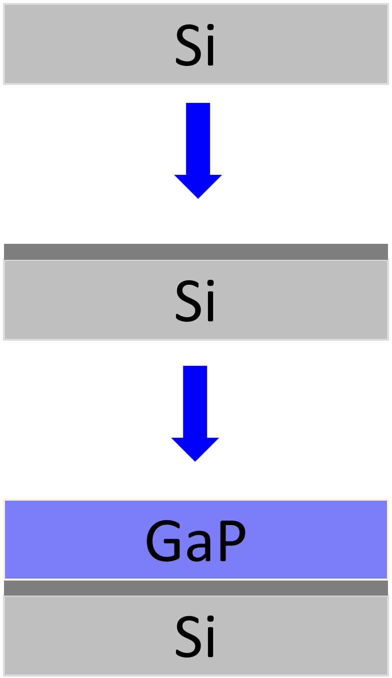
Achieving high-quality GaP on Si

In order of growth sequence:

1. Start with a smooth, double-stepped Si surface
   - High temp anneal under H_2 flow [1]

1. Reduce APD formation
   - 2D nucleation of GaP on Si [2-5]

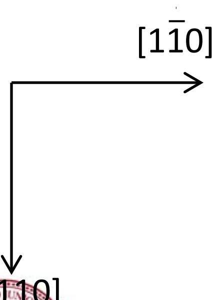
2. Encourage APD annihilation
   - Control APB propagation [6]

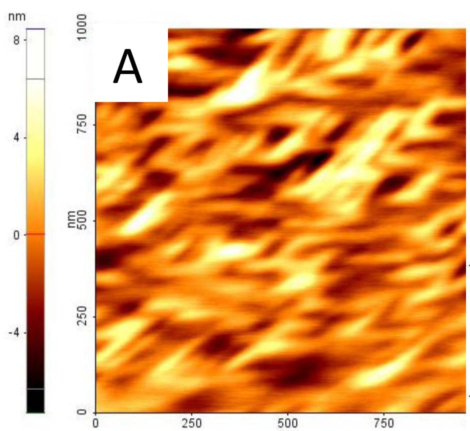


[1] B. Kunert et al. Thin Solid Films 517 (2008) 140.
[2] K. Yamane et al. J. Crys. Growth 311 (2009) 794.
[3] T.J. Grassman et al. Appl. Phys. Lett. 94 (2009) 232106.
[4] I. Nemeth et al. J. Crys. Growth 310 (2008) 1595.
[5] A.C. Lin et al. J. Vac. Sci. Technol. B 29 (2011) 1201.
[6] X. Yu et al. J. Crys. Growth 301-302 (2007) 163.

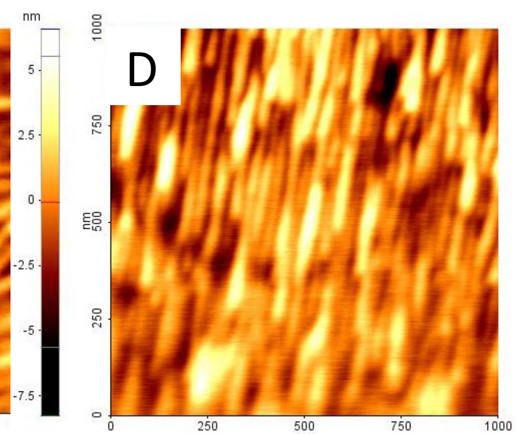
Control GaP orientation with temperature

	High T nucleation		Low T nucleation	
Sample	A	B	C	D
Nucleation layer	525° C	500° C	325° C	325° C
GaP film	525° C	550° C 600° C	550° C	550° C 600° C
RHEED	4x2	4x2	2x4	2x4
orientation	-	-	+	+

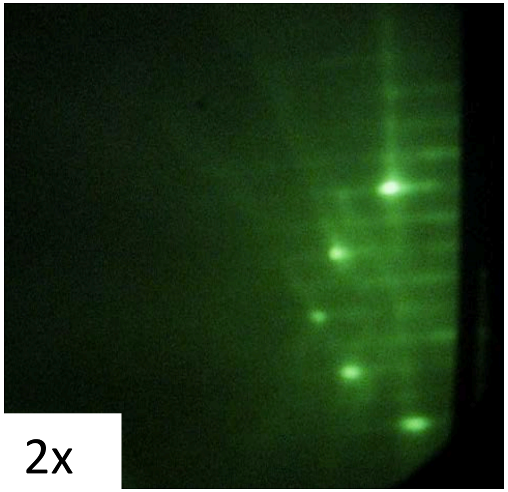


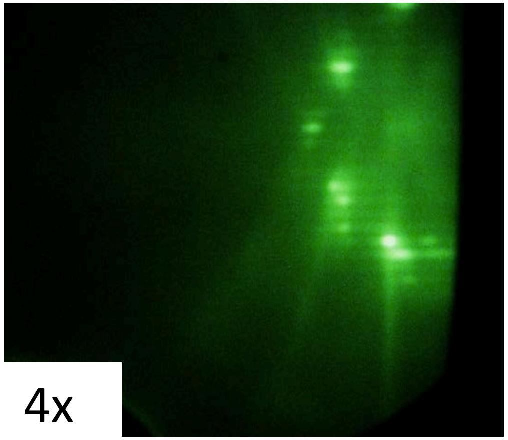


rms = 1.93 nm

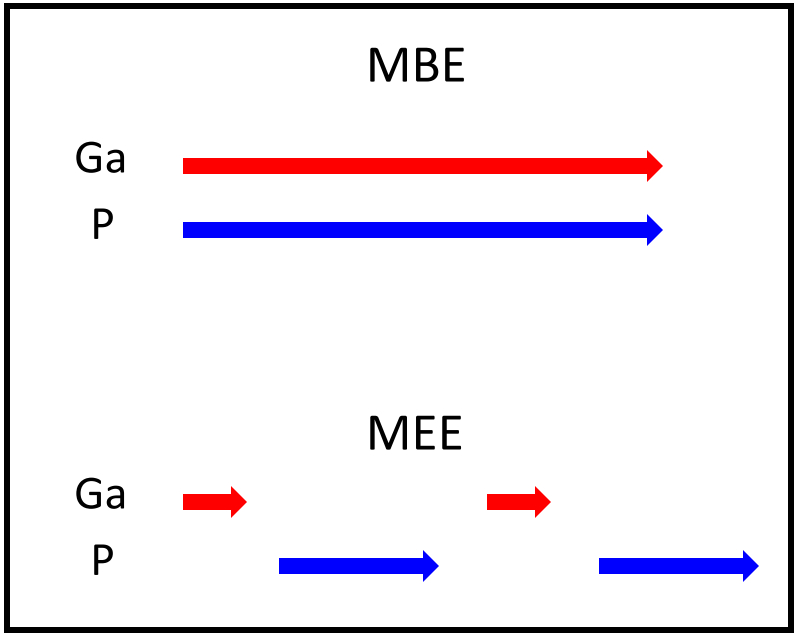


rms = 1.74 nm

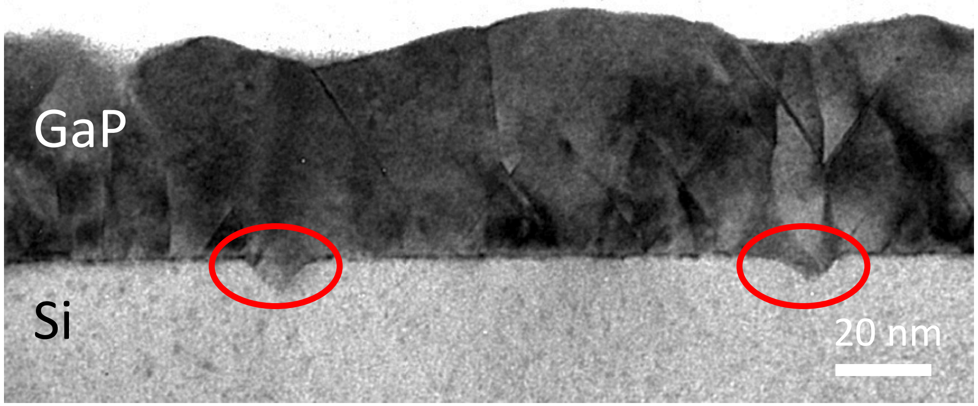


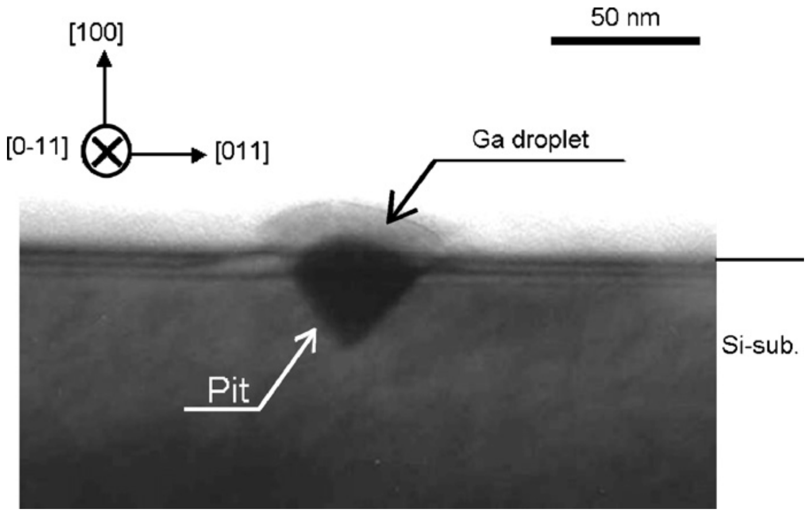


Need well-controlled nucleation



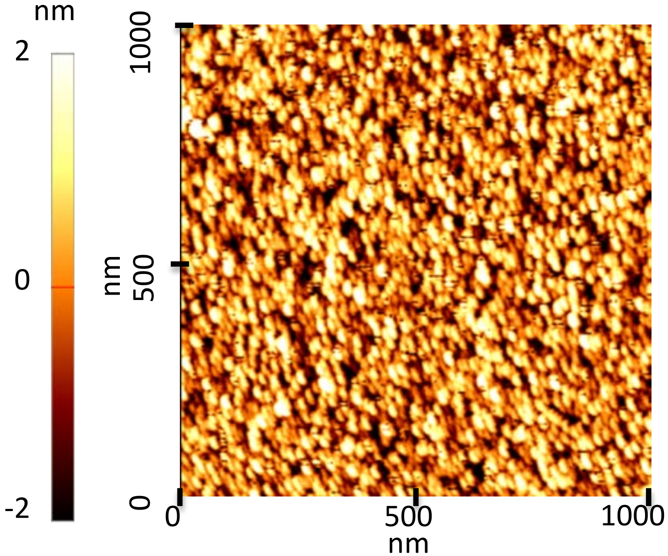
GaP film nucleated with
migration enhanced epitaxy (MEE)



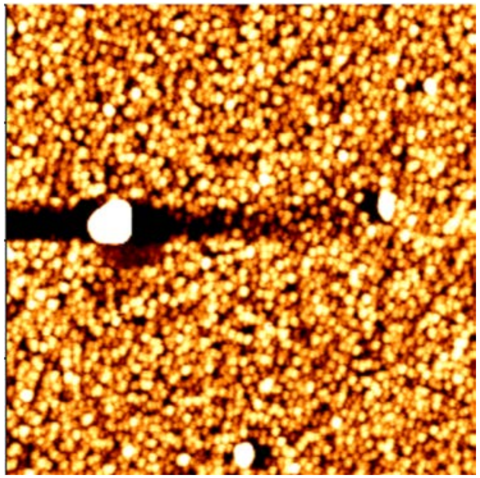


K. Yamane et al. J. Crys. Growth 311 (2007) 794-797.

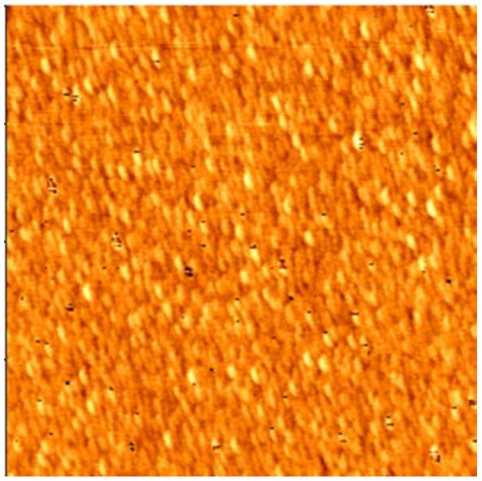
Two-dimensional III-V film on Si



rms = 0.961 nm



rms = 0.863 nm



rms = 0.279 nm

3x reduction in rms roughness with addition of Al

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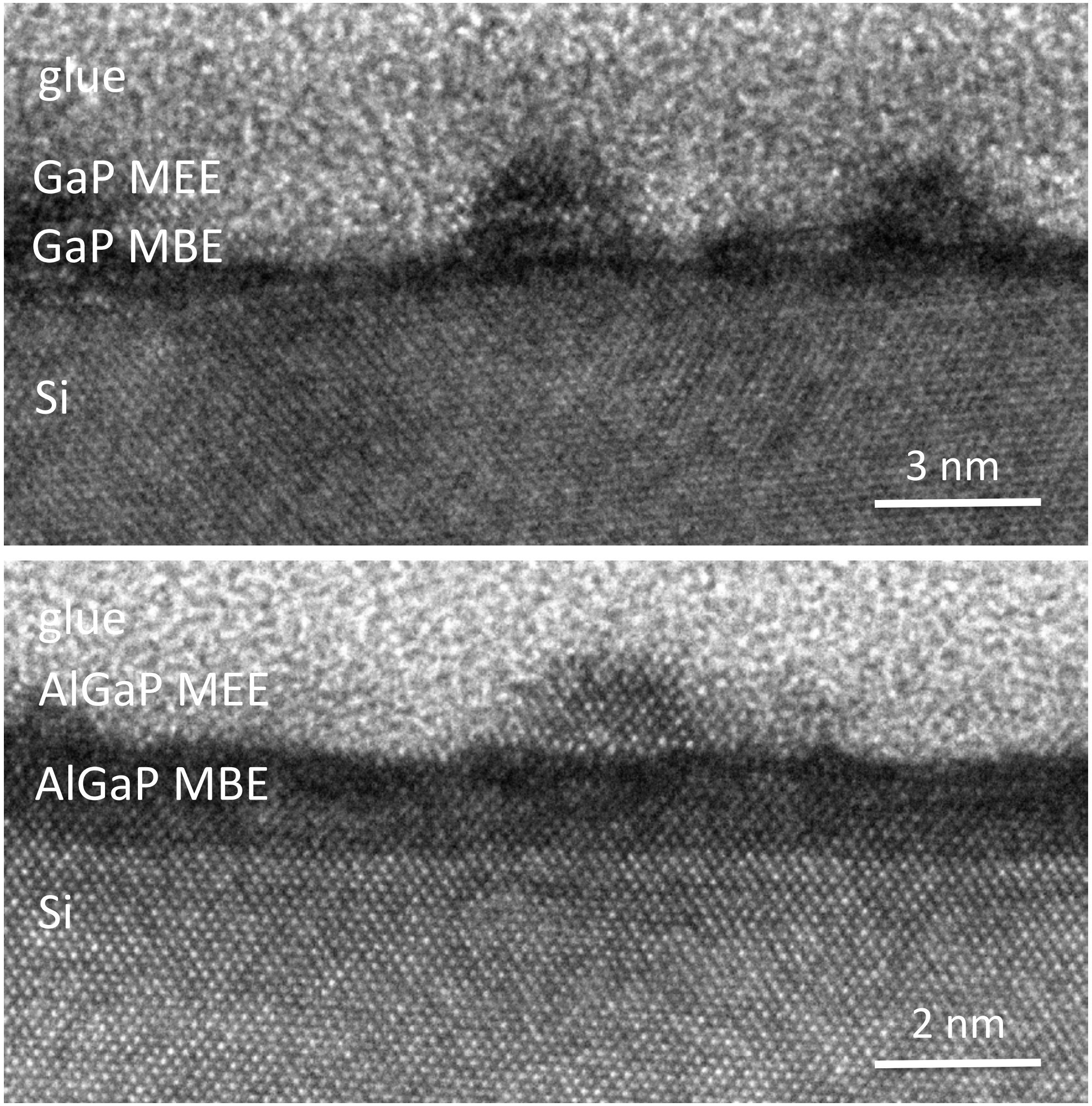
Abrupt interface between III-V and Si



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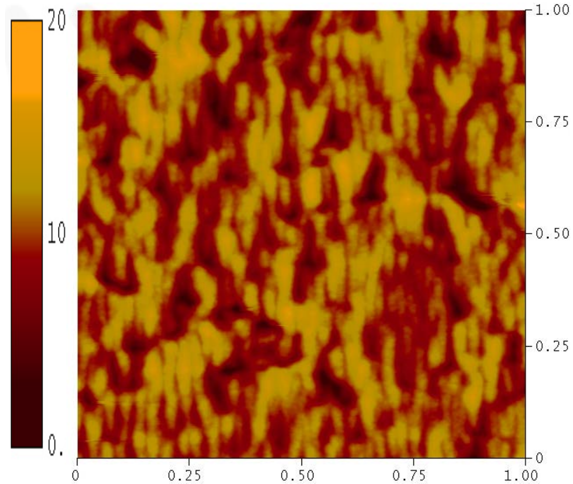
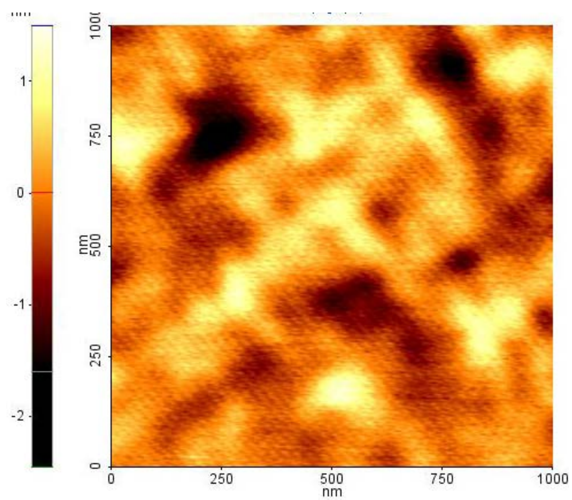
Effect of the first 5 monolayers

200 nm GaP
5 ML GaP
Si

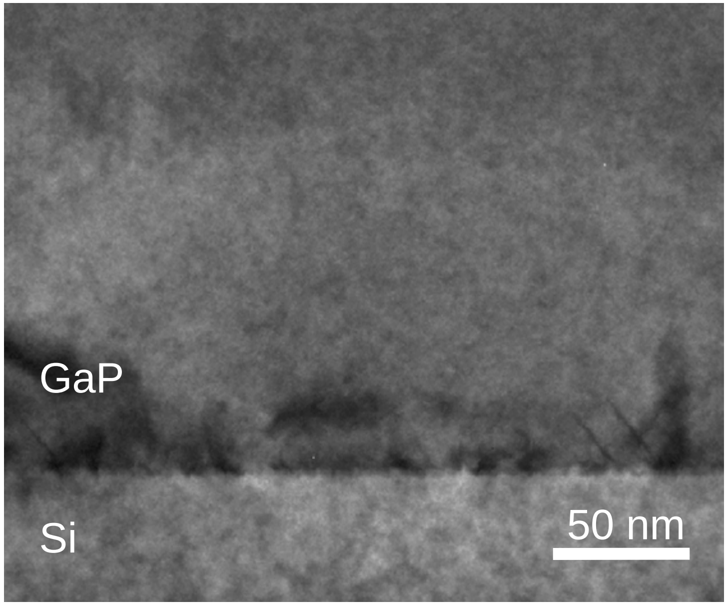


rms = 2.28 nm

200 nm GaP
5 ML $Al_{0.5}Ga_{0.5}P$
Si



rms = 0.50 nm



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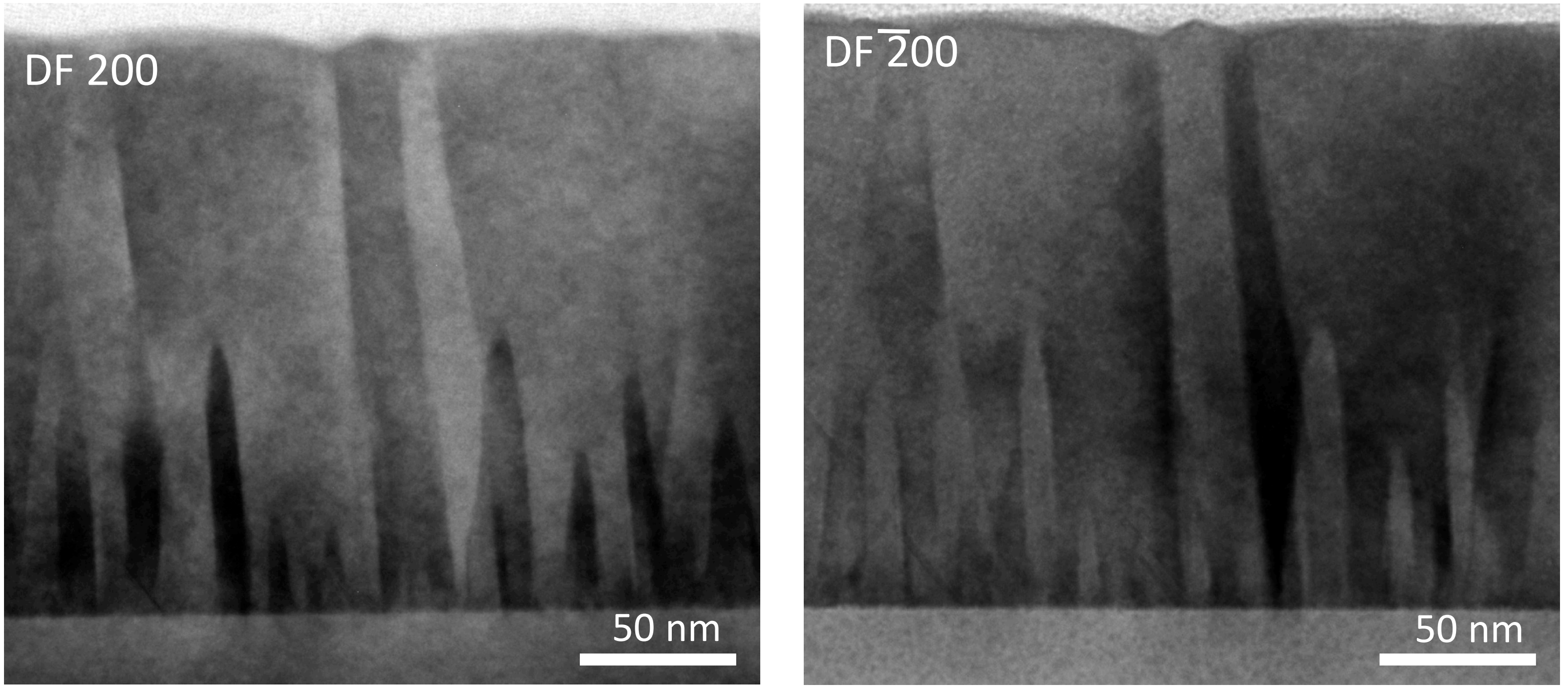
Using TEM to view APDs

GaP

Si



APDs of opposite polarity have contrast under certain diffraction conditions → distinguish antiphase boundaries from other defects (stacking faults, dislocations)