Prospects and progress in crystalline coatings: AlGaP

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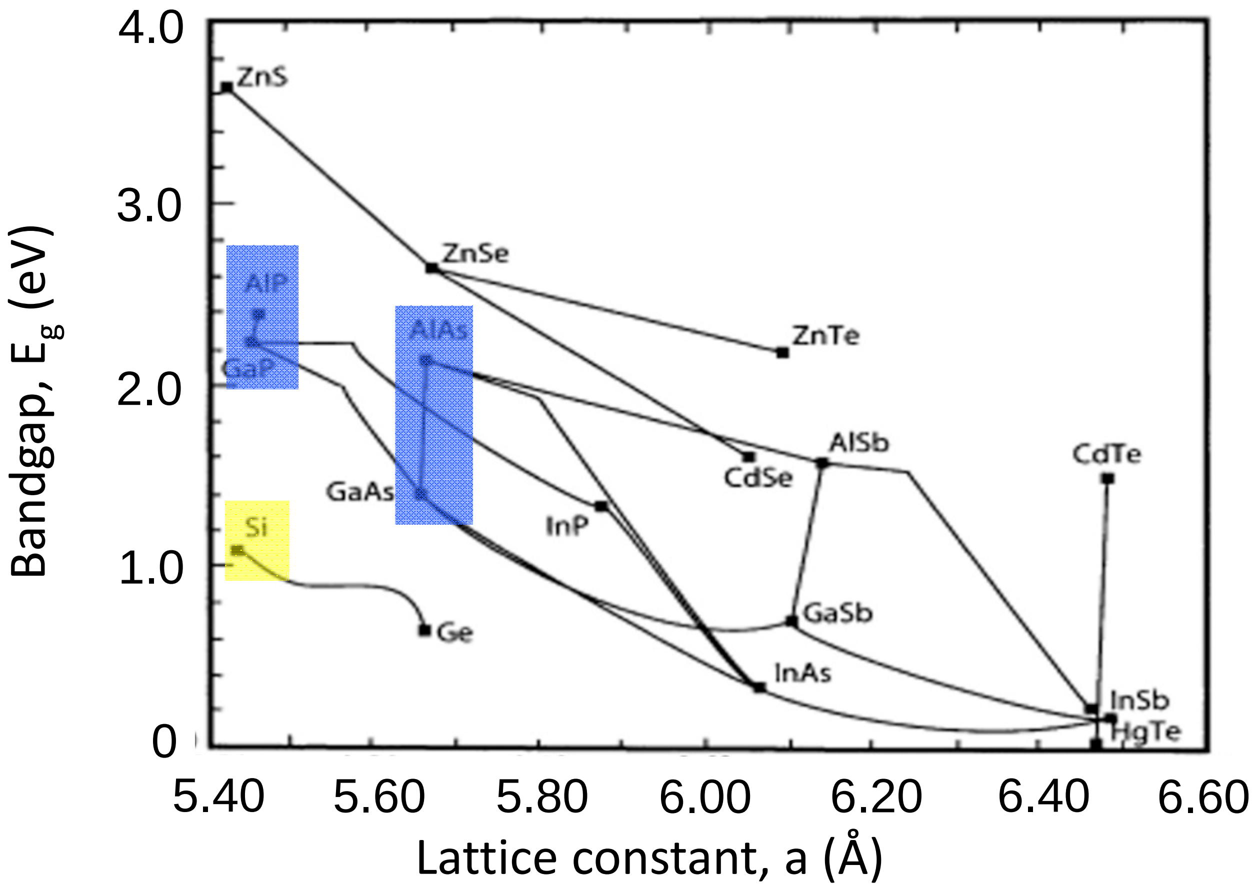
[1] Stanford University

[2] University of Glasgow

Gravitational Wave Advanced Detector Workshop 2013

Elba, Italy

Lattice-matched materials systems

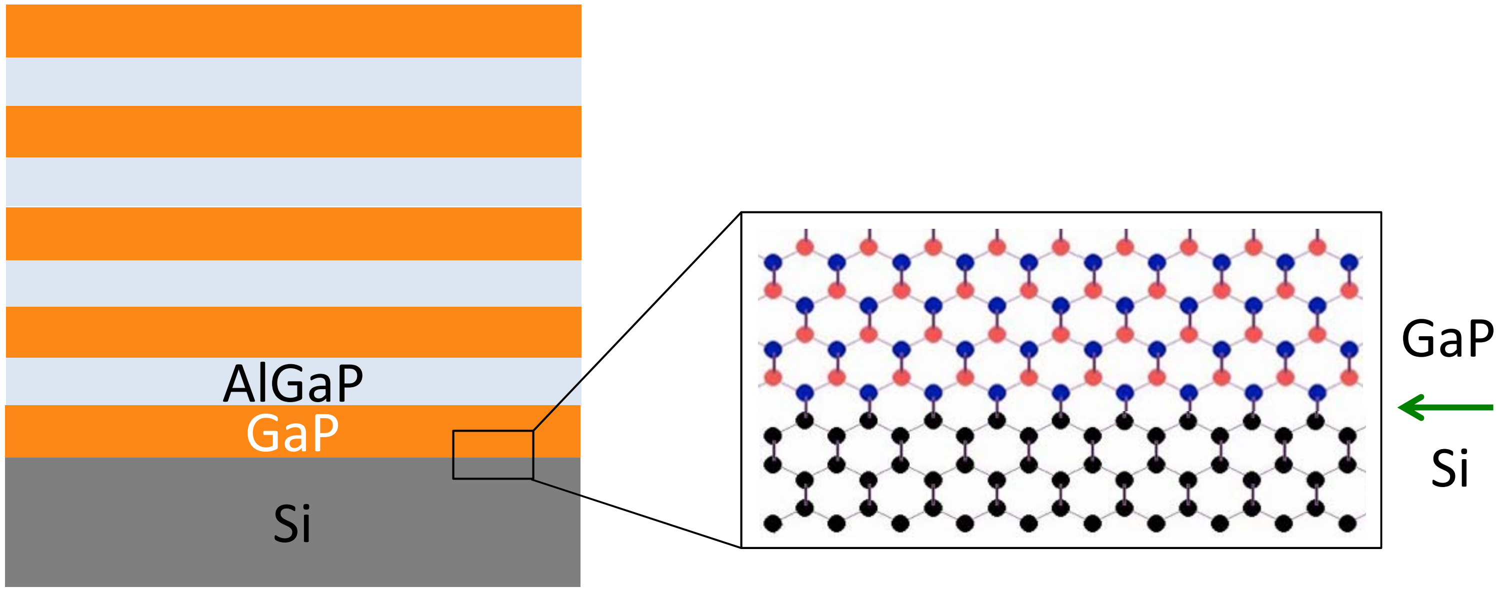


In crystalline materials, high/low-index layers need to be lattice-matched to avoid dislocations

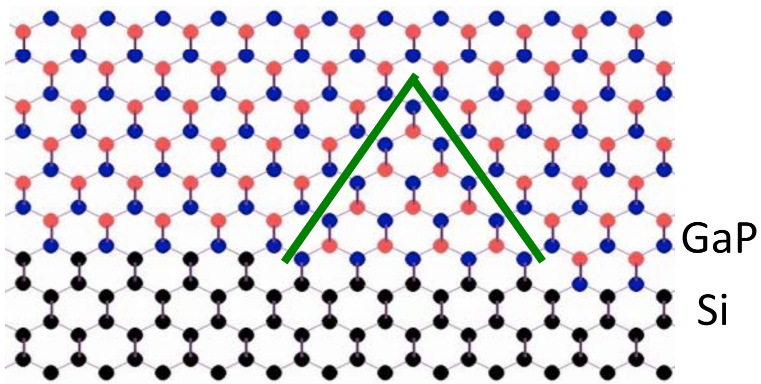
GaP and its ternary and quaternary compounds also used in:

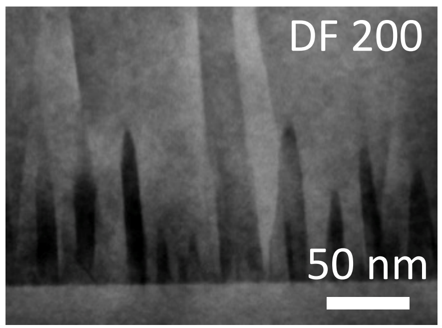
- Red and amber LEDs
- Multijunction solar cells
- Integrating III-V optoelectronic devices onto a Si CMOS-compatible platform

Epitaxial integration on silicon



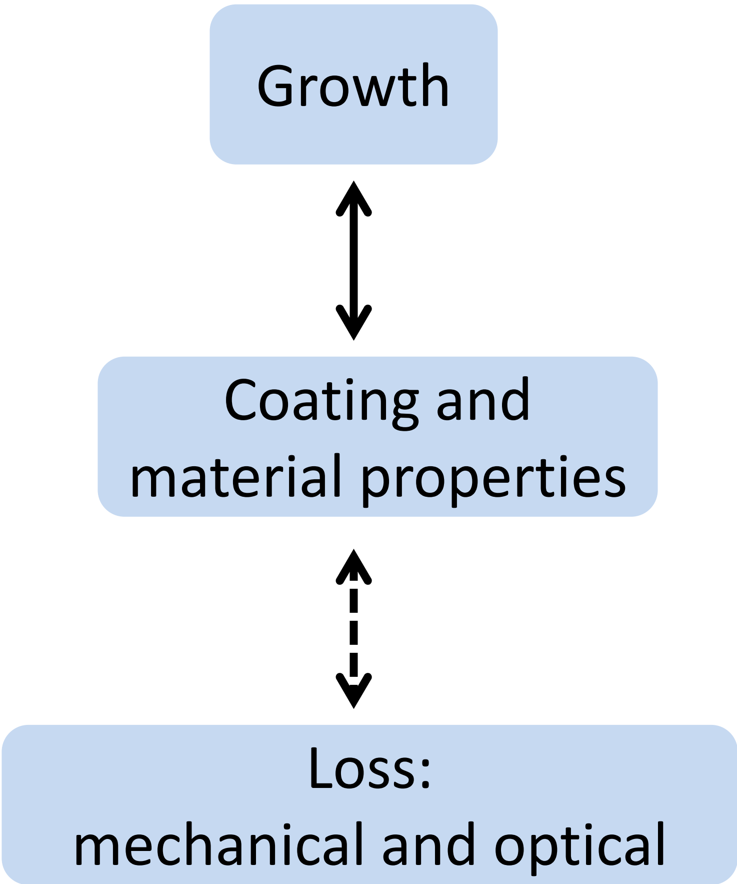
Challenge: antiphase defects (wrong bonds)





Example of antiphase defects in film

AlGaP coatings research

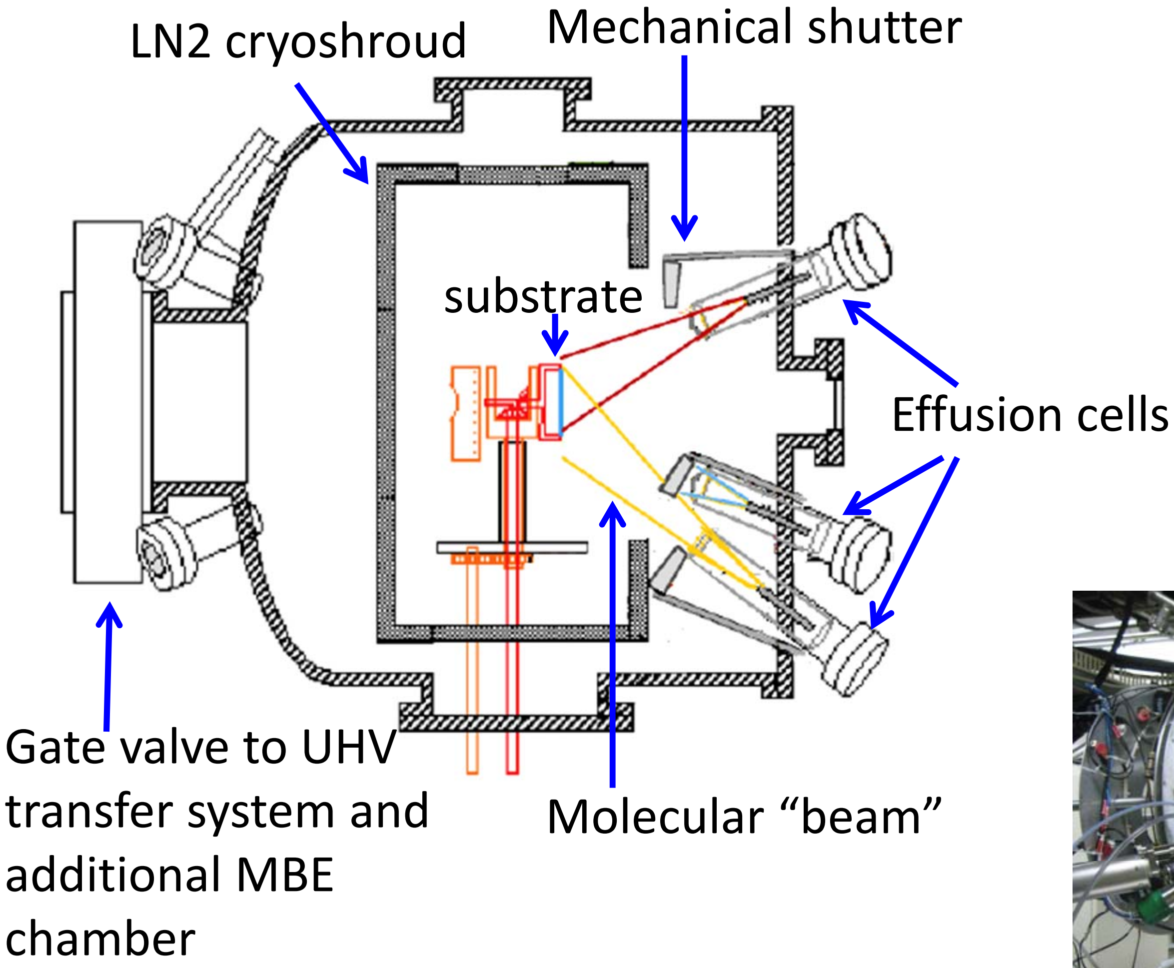


- Si surface preparation
- Nucleation of III-V on Si to minimize defect formation
- Overgrowth to annihilate defects

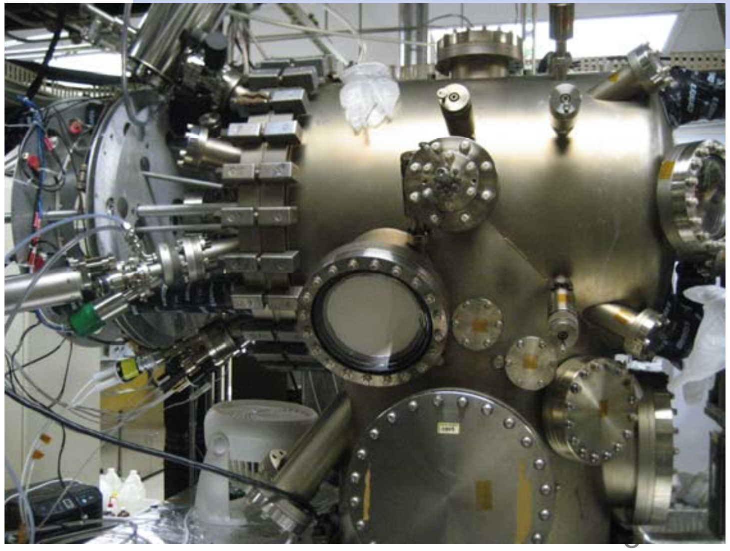
- Crystal quality and defects
- Interfacial quality
- Strain in multilayers
- Surface and interface morphology

- Source of coating mechanical loss: interfaces, crystalline defects?
- Source of absorption: free carriers, defect levels?

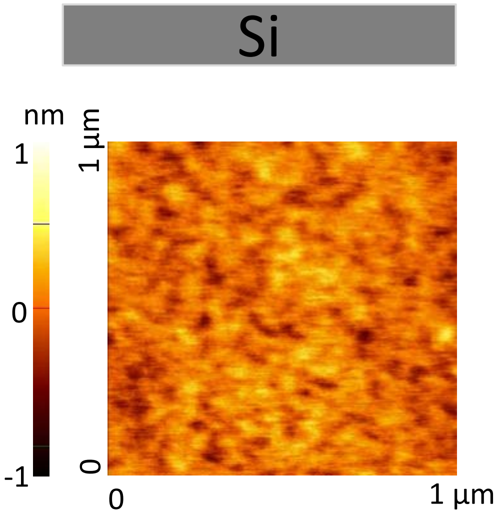
Molecular beam epitaxy enables high-quality films



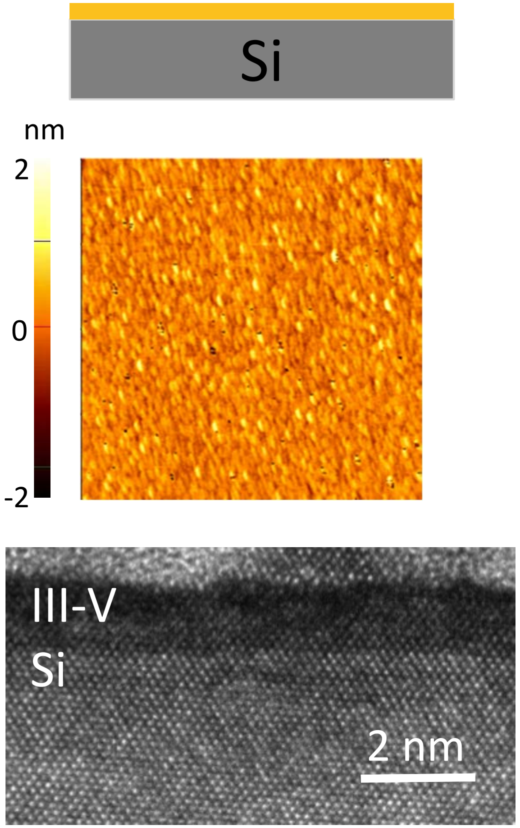
- Background pressure ~10^{-10} torr
  - Long mean free path
- High-purity (> 6N) elemental sources
  - low impurity incorporation
- Substrate temperature and growth rate are decoupled
  - better control over the growth process



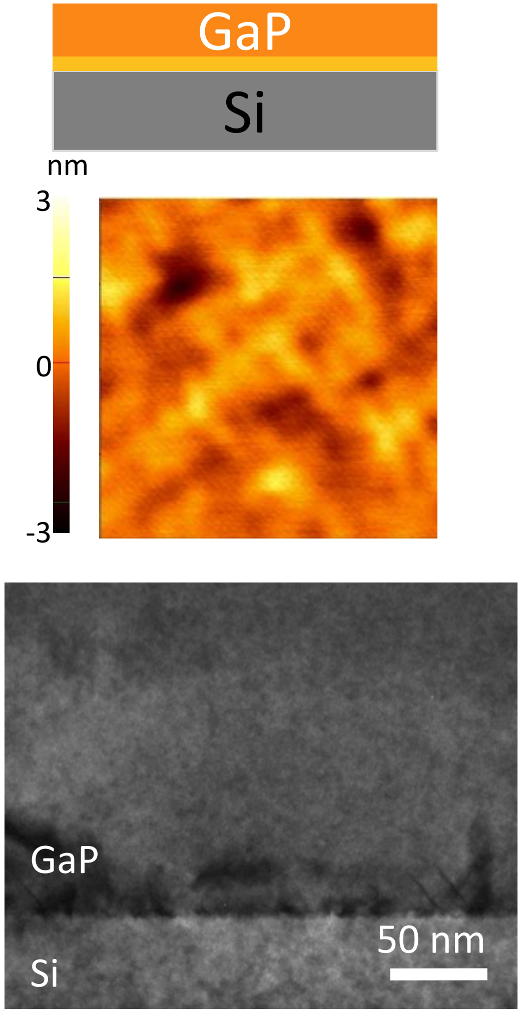
Coating deposition process



Si surface prep:
- Standard clean
- Si buffer
- High T anneal



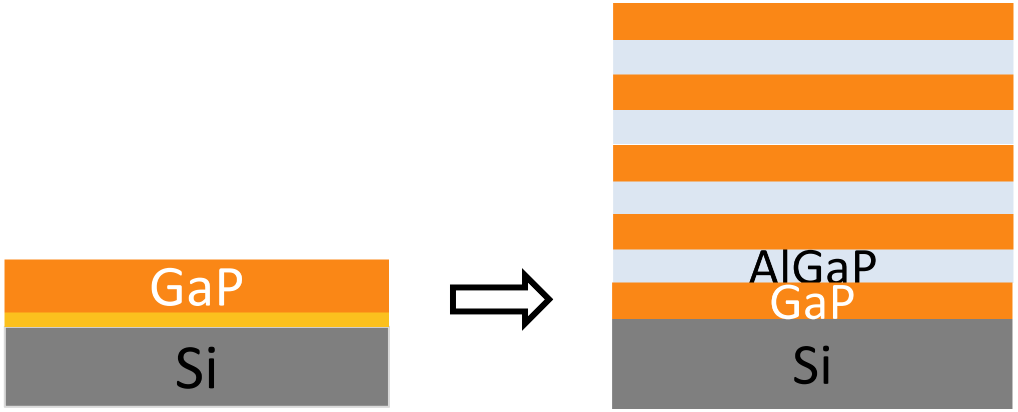
III-V nucleation:
- 2D growth



GaP buffer layer:
- Annihilate defects

A.C. Lin, M.M. Fejer, J.S. Harris. J. Vac. Sci. Technol. B 29 (2011) 1201.
A.C. Lin, M.M. Fejer, J.S. Harris. J. Crys. Growth 363 (2013) 258.

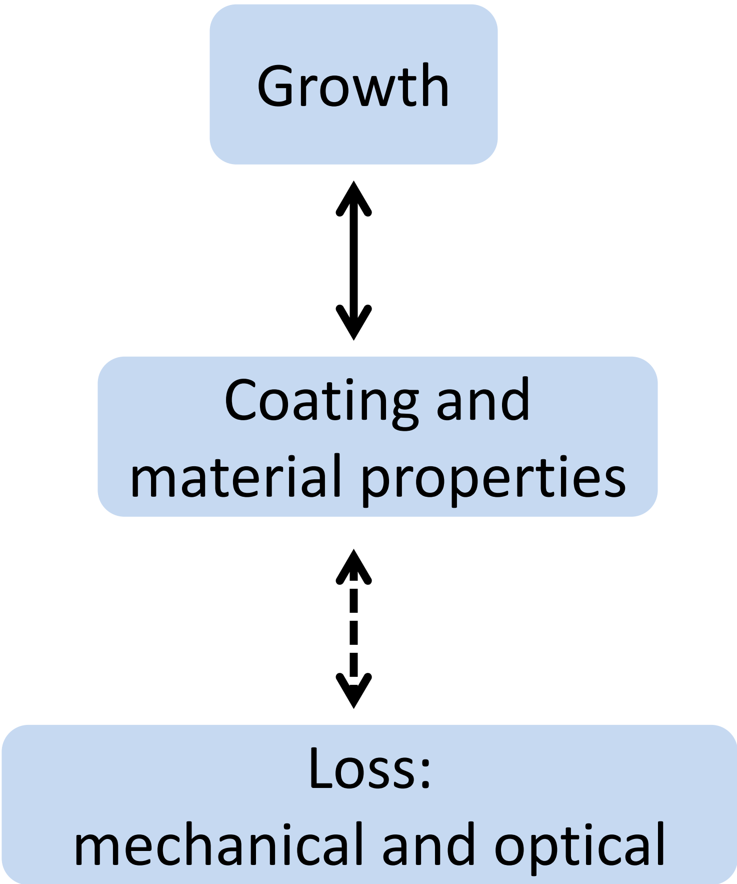
Coating depends on quality of buffer layer



Once GaP buffer layer is deposited on Si, the growth of GaP/AlGaP mirror layers is straightforward, however, growth studies are still important:

- Further improvement of AlGaP/GaP coatings, if the buffer layer is a source of loss
- Determining robust growth conditions to yield consistent coatings

AlGaP coatings research



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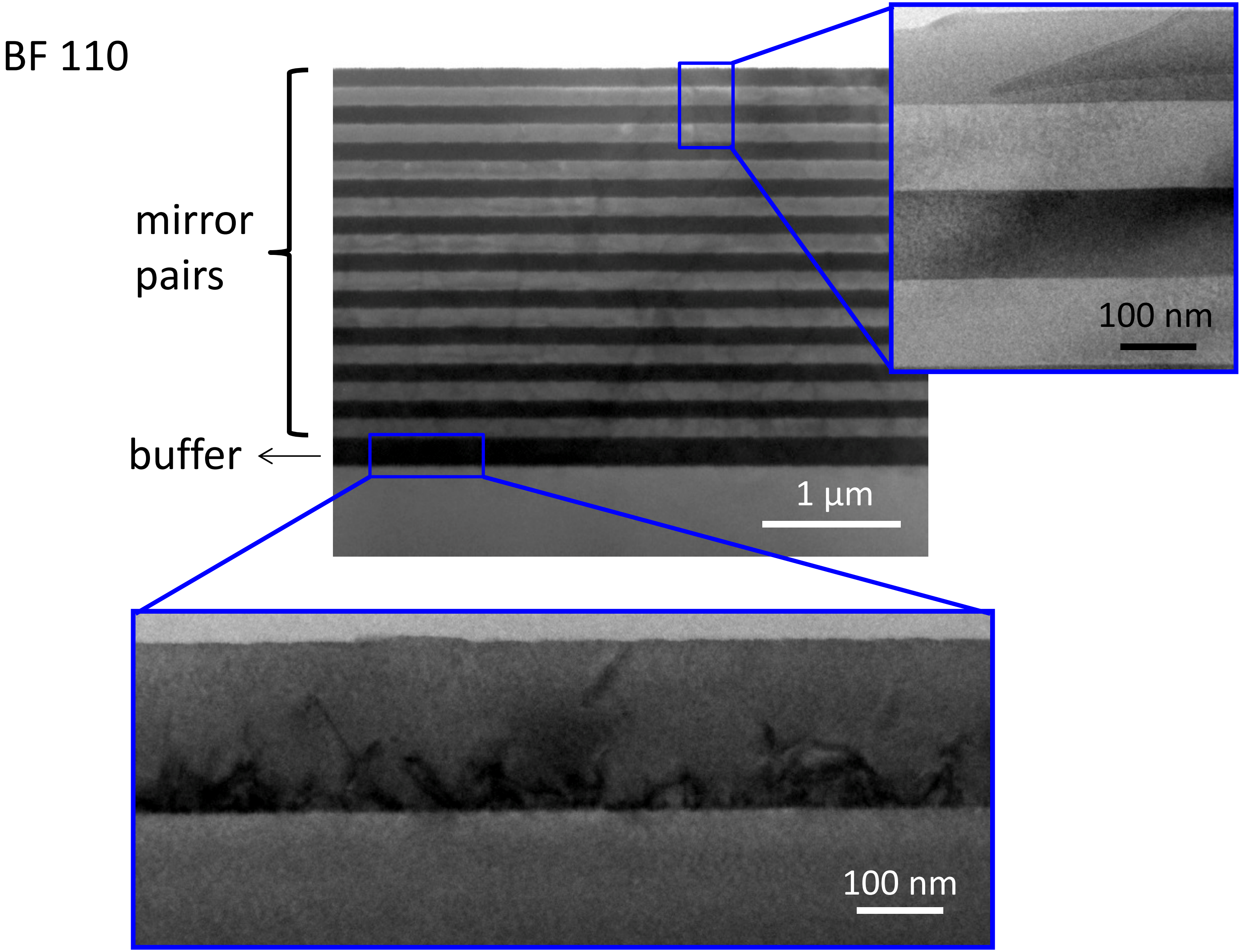
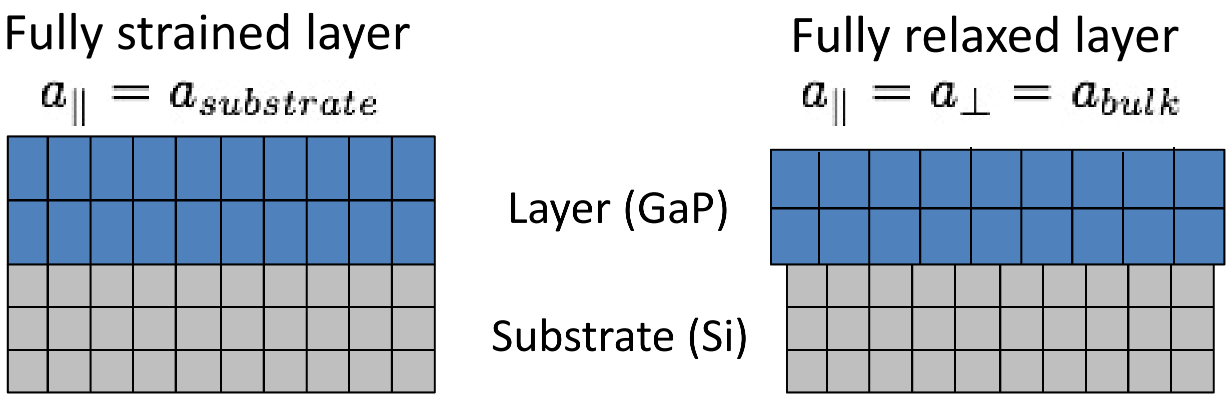
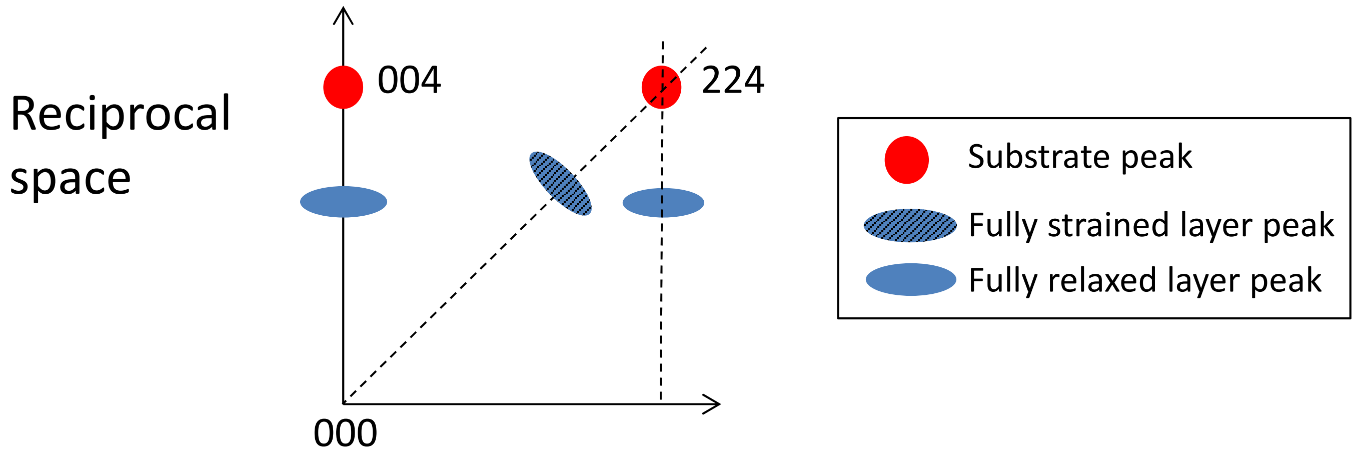
Transmission electron microscopy



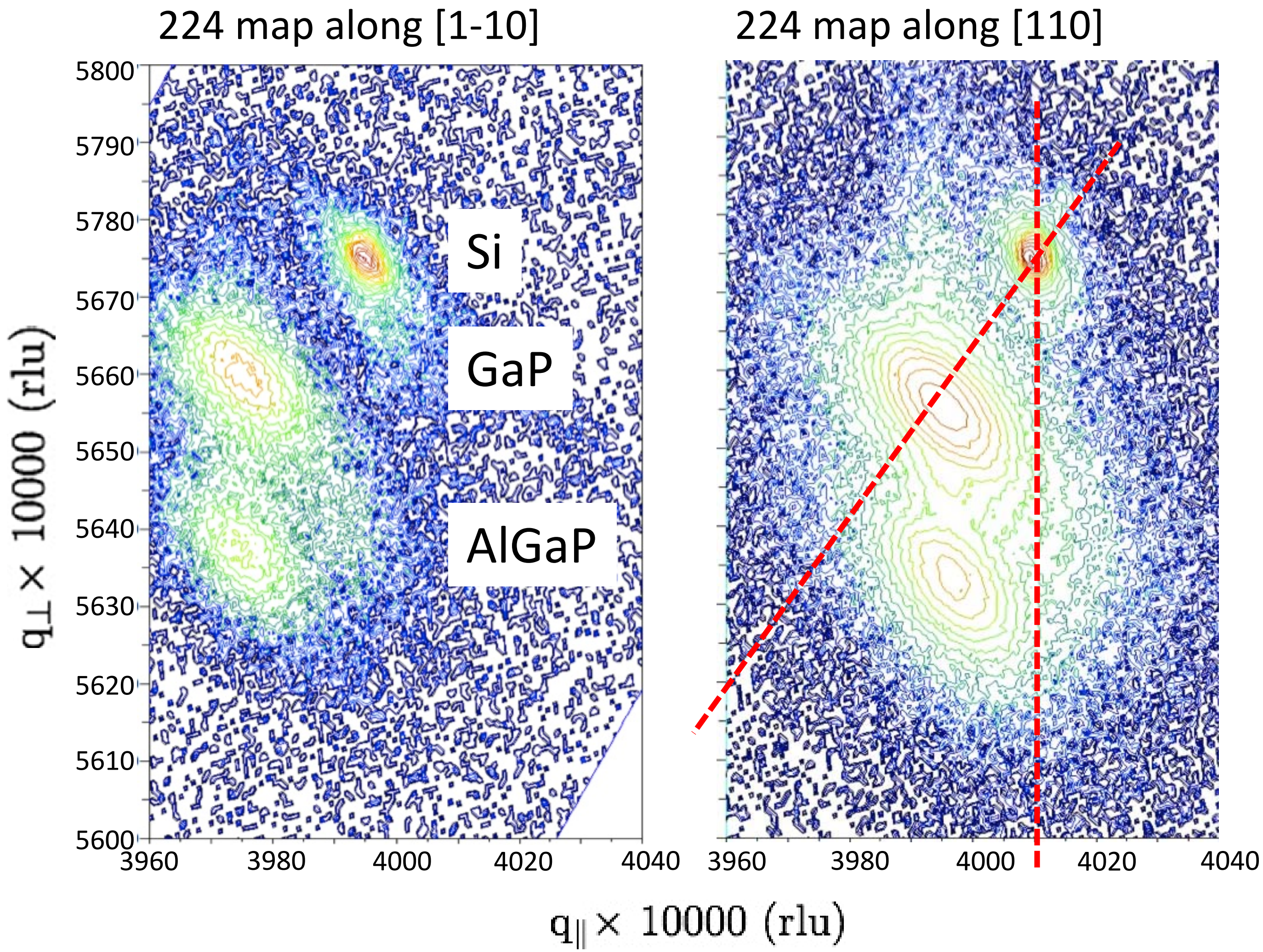
Structural analysis with reciprocal space maps

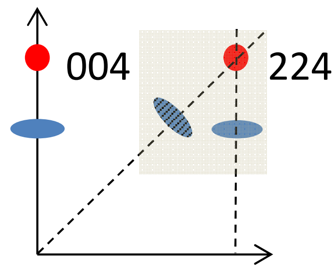




- High resolution XRD-RSM allows us to determine amount of strain between layer and substrate
- 004 symmetric scan gives out-of-plane strain and lattice constants
- 224 asymmetric scan gives out-of-plane and in-plane strain

Structural analysis: in-plane strain

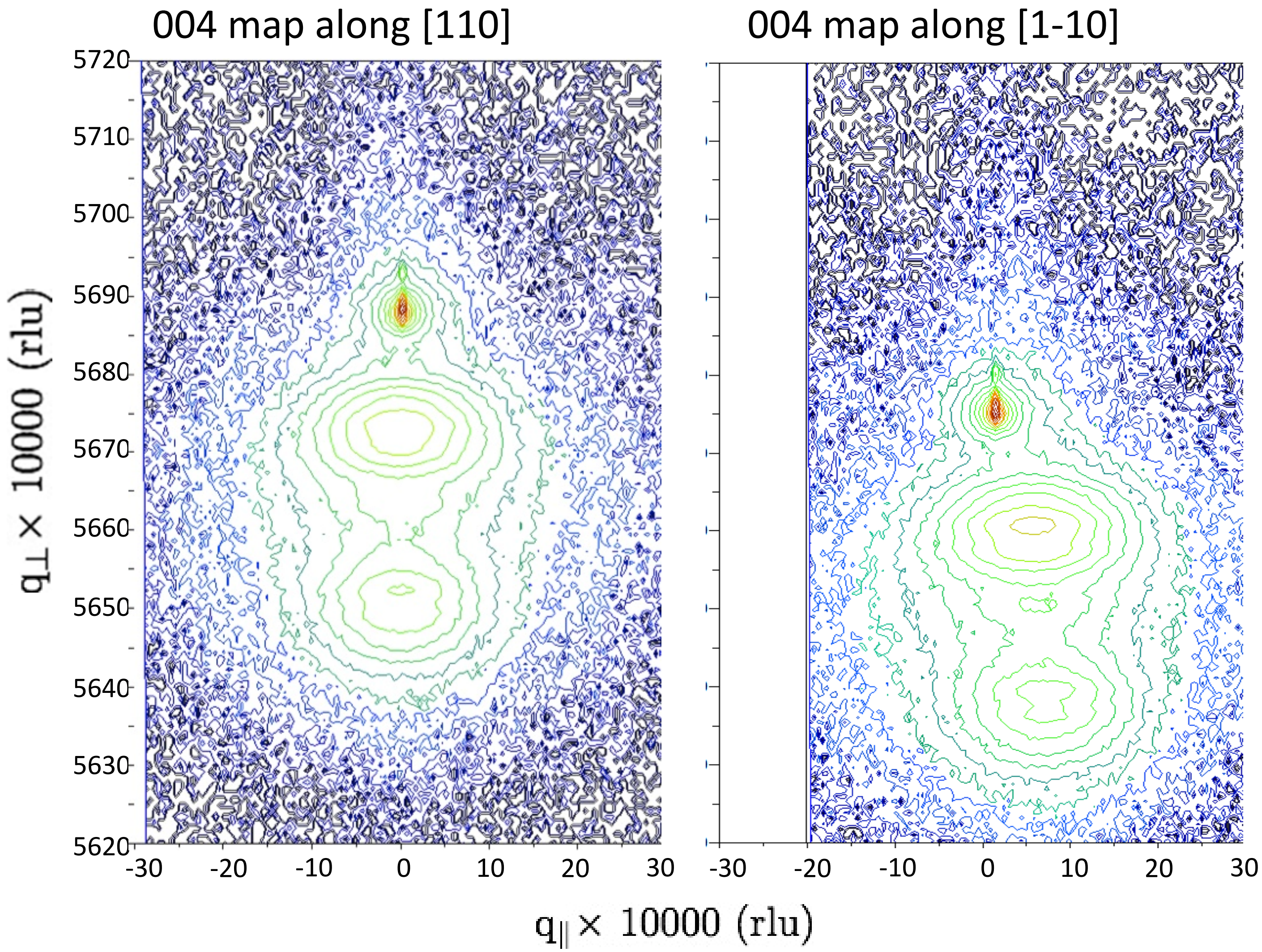


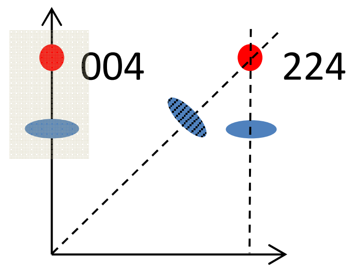


Average in-plane strain Si – GaP: 0.423%

- GaP/AlGaP layers are strained than relaxed
- Consistent with TEM data and lack of dislocations observed

Structural analysis: out-of-plane strain





Average out-of-plane strain:0.284%

With more data, it may be possible to link strain to mechanical loss

Characterization techniques

Structure

TEM: atomic-scale defects and interfacial quality

XRD: strain and lattice constants

AFM: surface and interfacial morphology

RDS: atomic reconstruction at Si/GaP interface

Coating and material properties

Optical defects

FTIR: presence of free carriers

CL: presence of non-radiative recombination centers

Chemical/composition

SIMS: impurity concentration

XPS: surface analysis

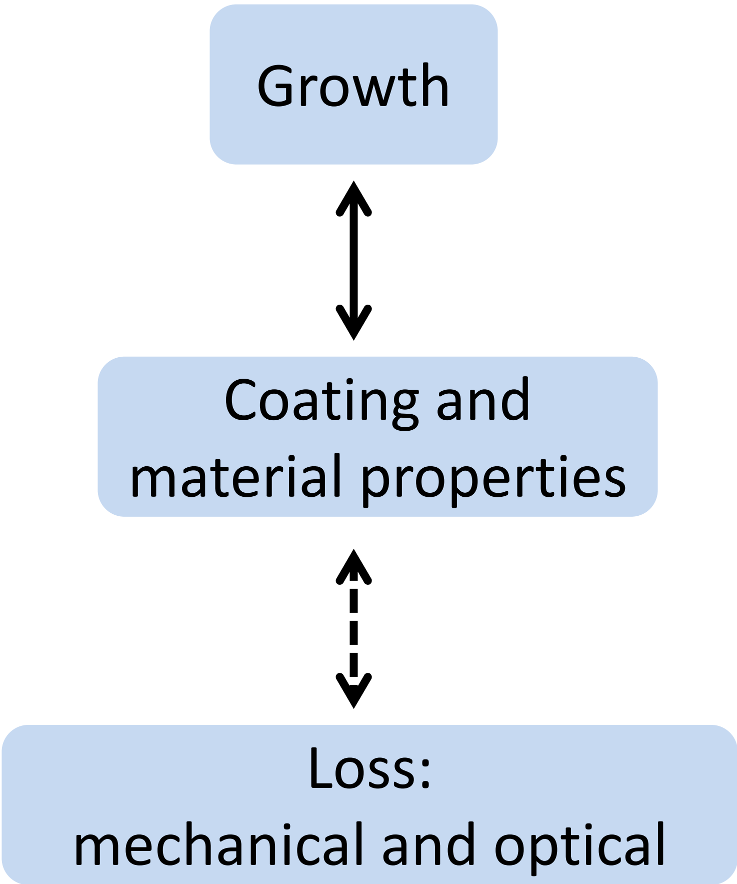
Mechanical

Nanoindentation: Young's modulus

Abbreviations:
TEM: transmission electron microscopy
RDS: reflectance difference spectroscopy
SIMS: secondary ion mass spectroscopy
FTIR: Fourier transform infrared spectroscopy
CL: cathodoluminescence
XRD: x-ray diffraction
AFM: atomic force microscopy

Color code:
Stanford
Glasgow/M. Abernathy
External collaboration/vendor

AlGaP coatings research



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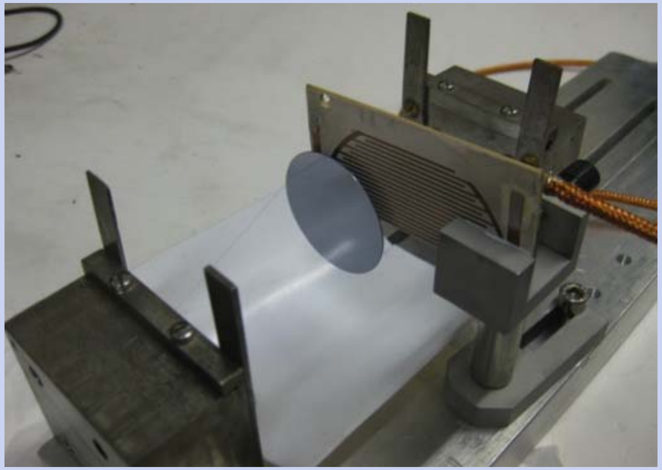
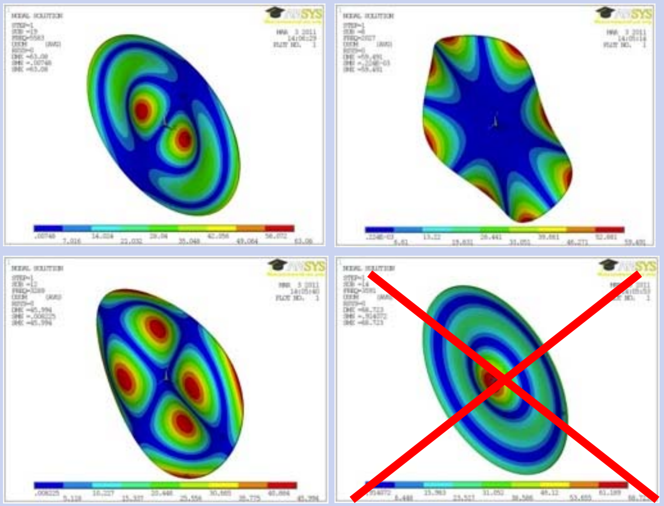
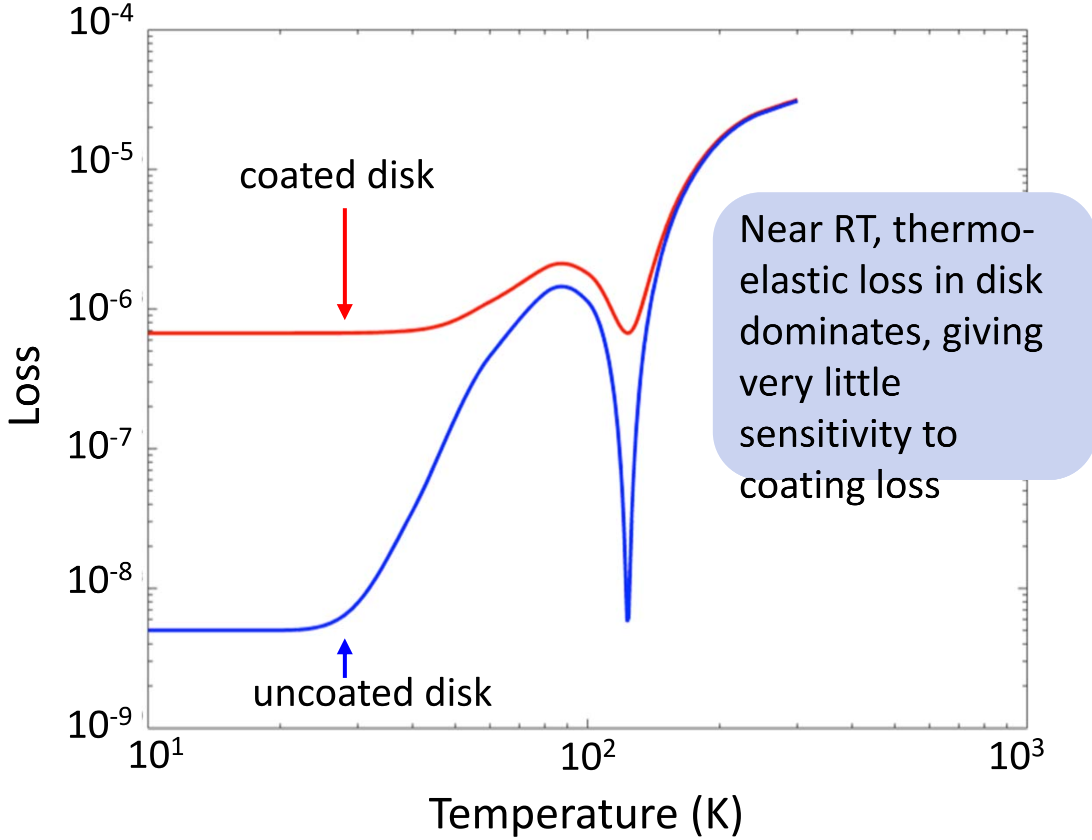
Mechanical loss of coating on Si disks

Coatings on Si disks: nodal support technique supported by 50 µm wires



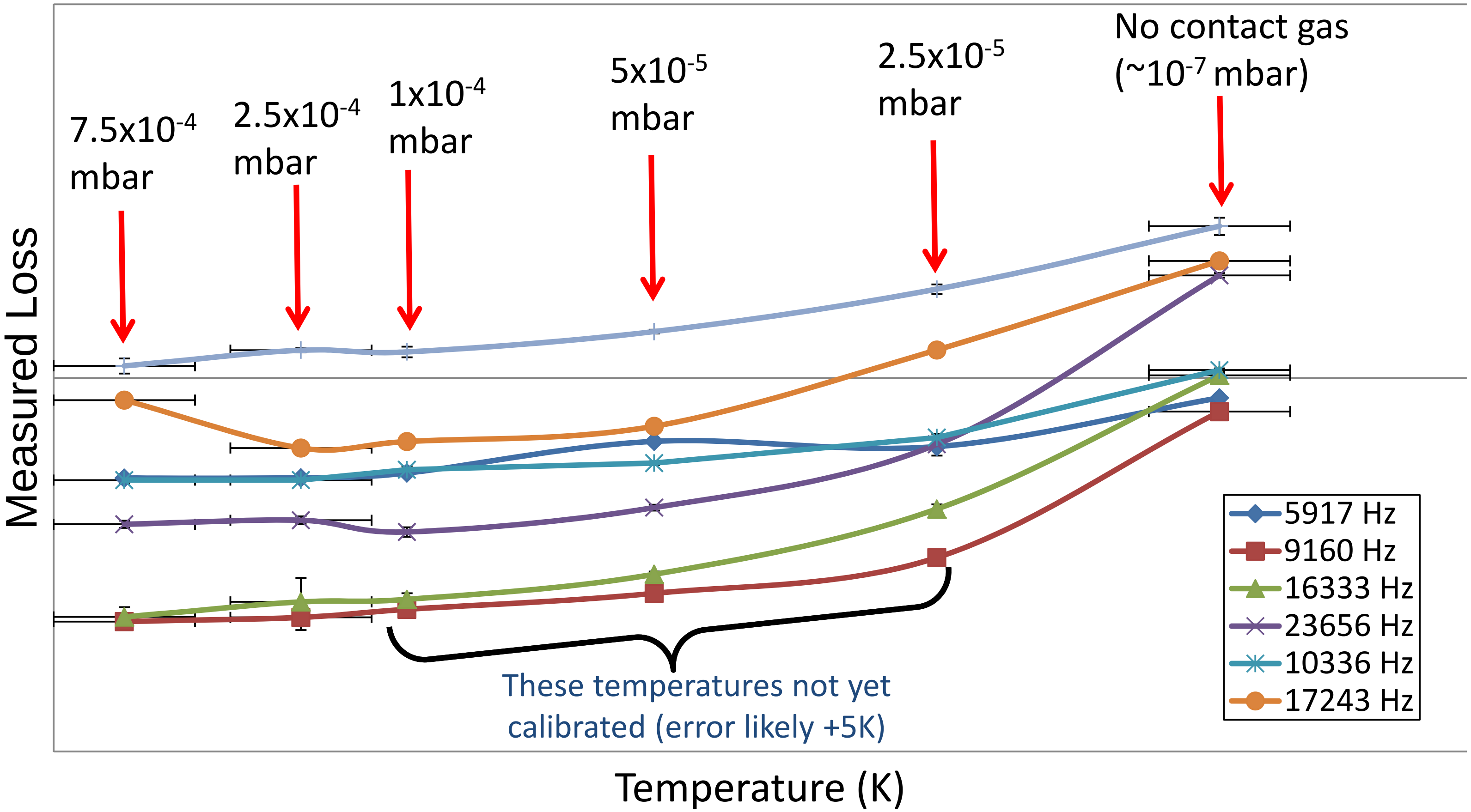


Model of possible loss as a function of temperature



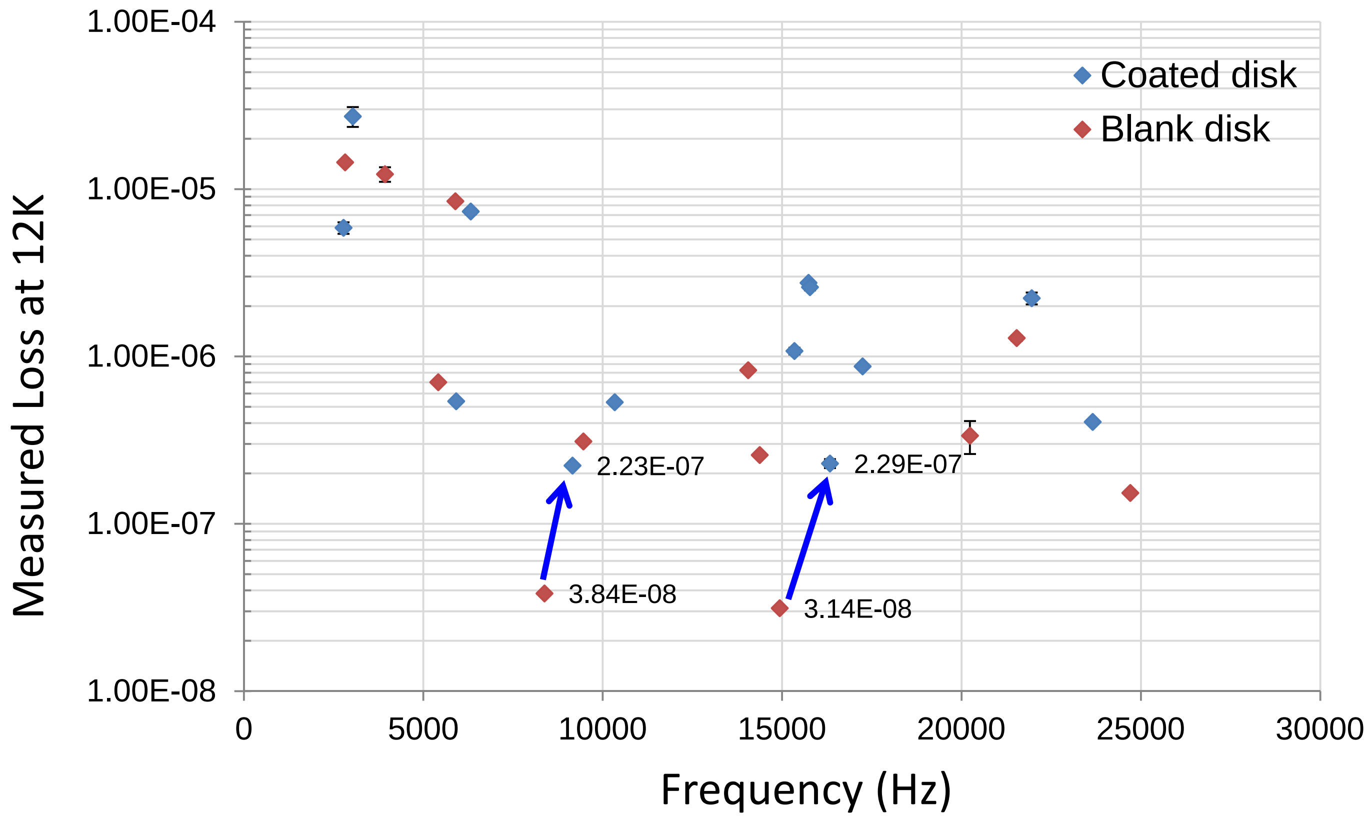
Mechanical loss of coated disk and temp calibration

- GaP/AlGaP-coated disk measured at different temperatures using He contact gas – different pressures balance input power of laser



Mechanical loss measurement at 12K±2K

$$\phi(\omega_o)_{coating} = \frac{E_{Stored_{Substrate}}}{E_{Stored_{Coating}}}\left(\phi(\omega_o)_{Coated\ disk} - \phi(\omega_o)_{Uncoated\ disk}\right)$$



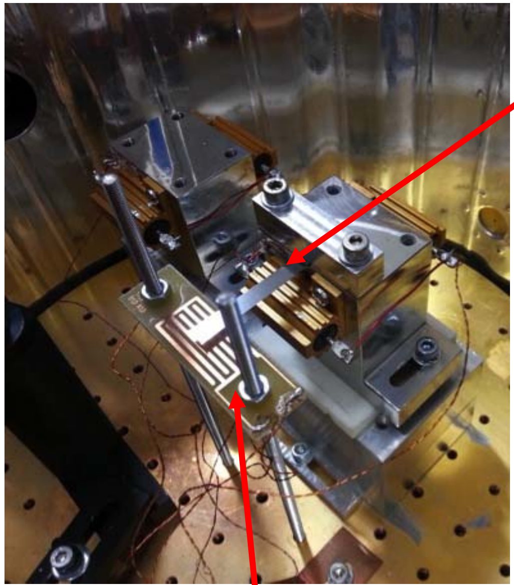
Two lowest loss modes show possible difference in loss between coated and uncoated disk, otherwise coating loss not visible

Average coating loss (at 12K) calculated to be 1.4×10^{-5}

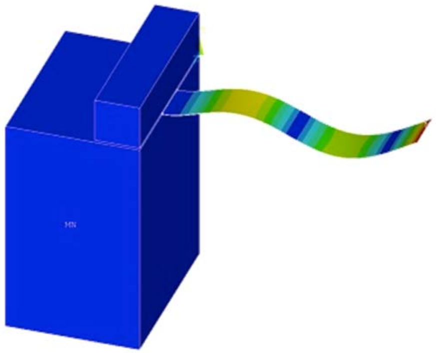
→ A factor of 45x lower than AdvLIGO SiO_2/doped-Ta_2O_5 coating loss at 12K

Fabrication of coated cantilevers

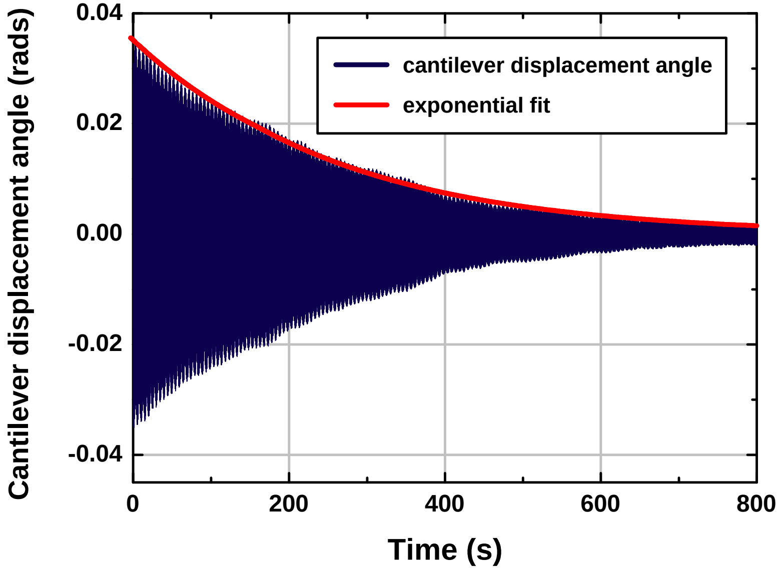
- Worked with Kelvin Nanotechnology in Glasgow to fabricate GaP-on-Si cantilever samples for loss measurements of GaP buffer layer
- Ring-down of bending modes of the cantilevers used to measure mechanical loss



GaP coated silicon cantilever clamped inside cryostat for mechanical loss measurements



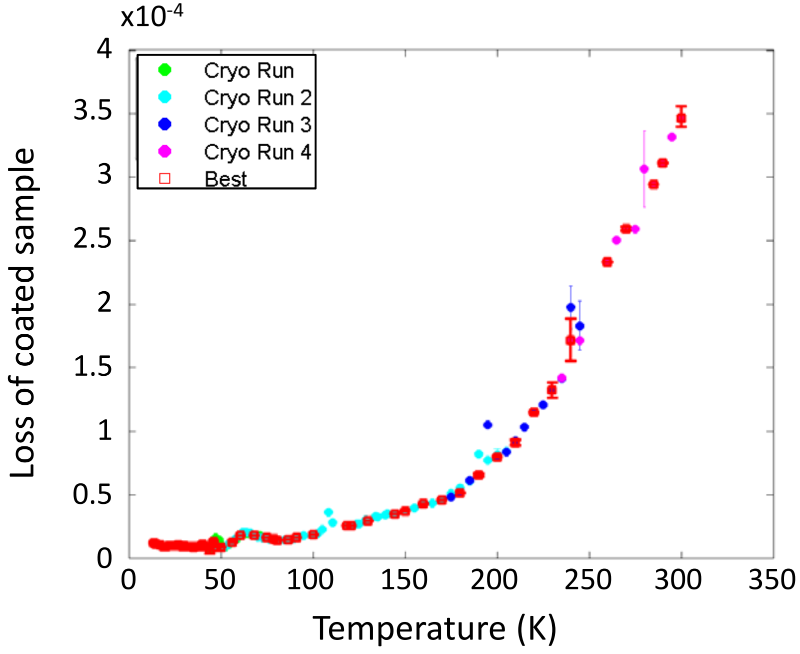
Electrostatic drive used to excited cantilever modes

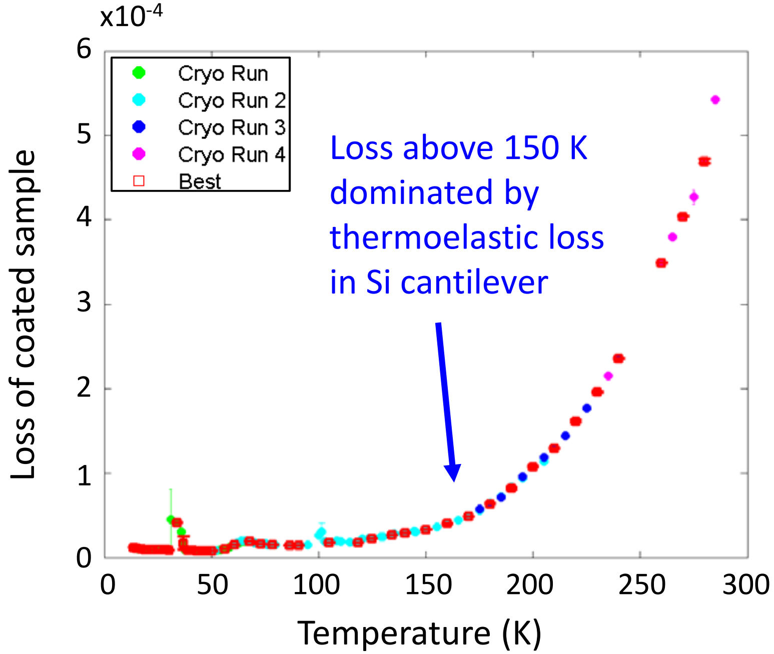


$$A(t) = A_0 e^{-\phi(\omega_0)\frac{\omega_0 t}{2}}$$

Mechanical loss of GaP buffer layer

Loss of coated sample (2 different modes)





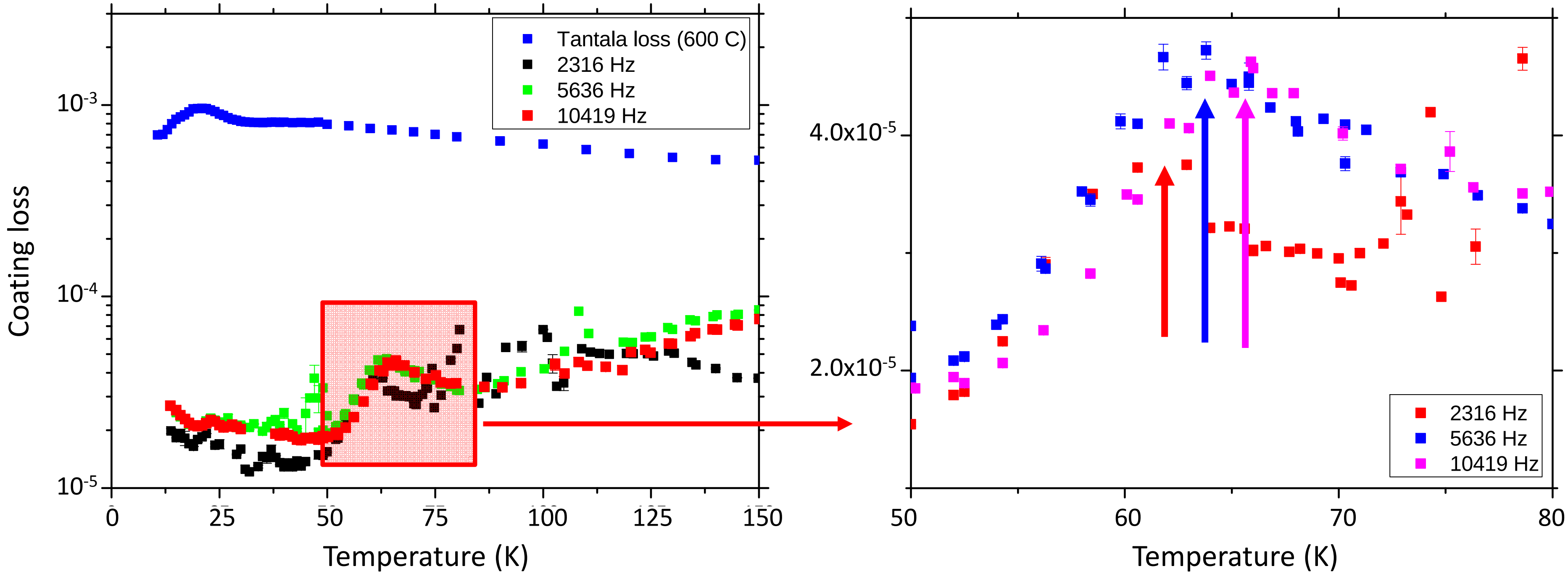
$$\phi_{\text{coating}} = \frac{Y_{cantilever}}{3Y_{coating}} \frac{t_{cantilever}}{t_{coating}} (\phi_{coated} - \phi_{un-coated})$$

Ratio of elastic energy stored in cantilever to energy stored in coating

Measurements of uncoated reference cantilever are underway

To estimate an upper limit on the loss of the GaP layer, we assume that all the loss arises in the coating → real loss of the coating is almost certainly significantly lower than this upper limit

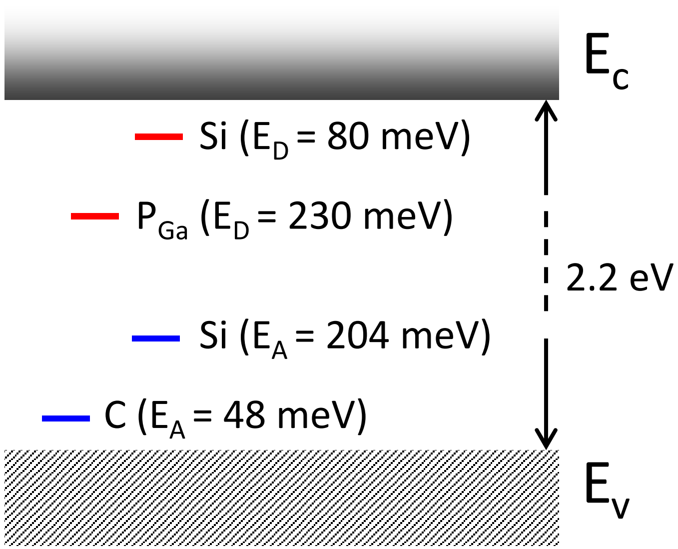
Mechanical loss of GaP buffer layer



- Below 100 K, upper limit loss of GaP layer is > 10x lower than loss of un-doped tantala
- Evidence of a loss peak at ~ 60 K, which appears to shift with increasing mode frequency as expected for a thermally-activated loss mechanism
  - No evidence of this peak has been observed in our previous studies of un-coated Si cantilevers – likely to be associated with the GaP
- Further work ongoing – level of loss is broadly consistent with multilayer measurements

Optical absorption

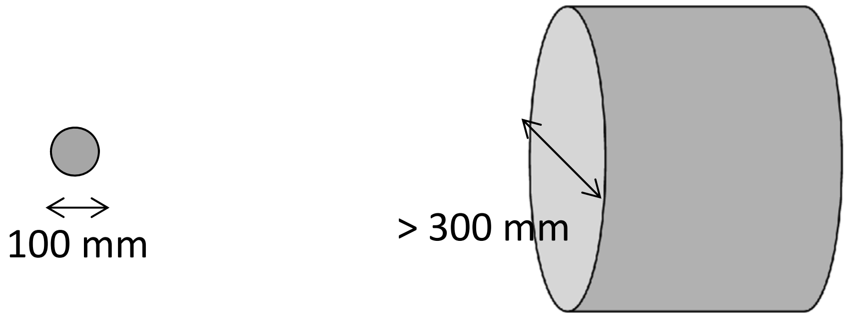
Possible source of absorption	Measurement	Measurement result	Estimated contribution to total coating absorption
Si outdiffusion from substrate	SIMS depth profiling	Small amount within 50 nm of GaP/Si interface	low
Incorporation of carbon, oxygen	SIMS depth profiling	C: 1e16 cm^{-3} O: 5e16 cm^{-3}	med to high
Antiphase defects	TEM cross-section	Defects present in buffer layer	med to high



Defect levels from:

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

Prospects for scaling up



Scaling to LIGO-size optics:

- Limitation is size of deposition chamber (current production-scale systems can hold 4 6-inch wafers on a single platen)
- Currently, MBE is the most promising growth technique
- Defect density should remain constant with scaling

Other potential issues or concerns regarding inherent properties of semiconductors: see Matt Abernathy's talk

Summary

- GaP/AlGaP mirrors can be grown directly on Si
- Understanding growth → material/coating properties → loss will enable further improvement
- Preliminary coating characterization and mechanical loss measurements have been done on GaP/AlGaP mirrors
  → Promising initial result of 45x reduction in mechanical loss compared to AdvLIGO silica/tantala coatings at 12K