Dawn Coating Summary

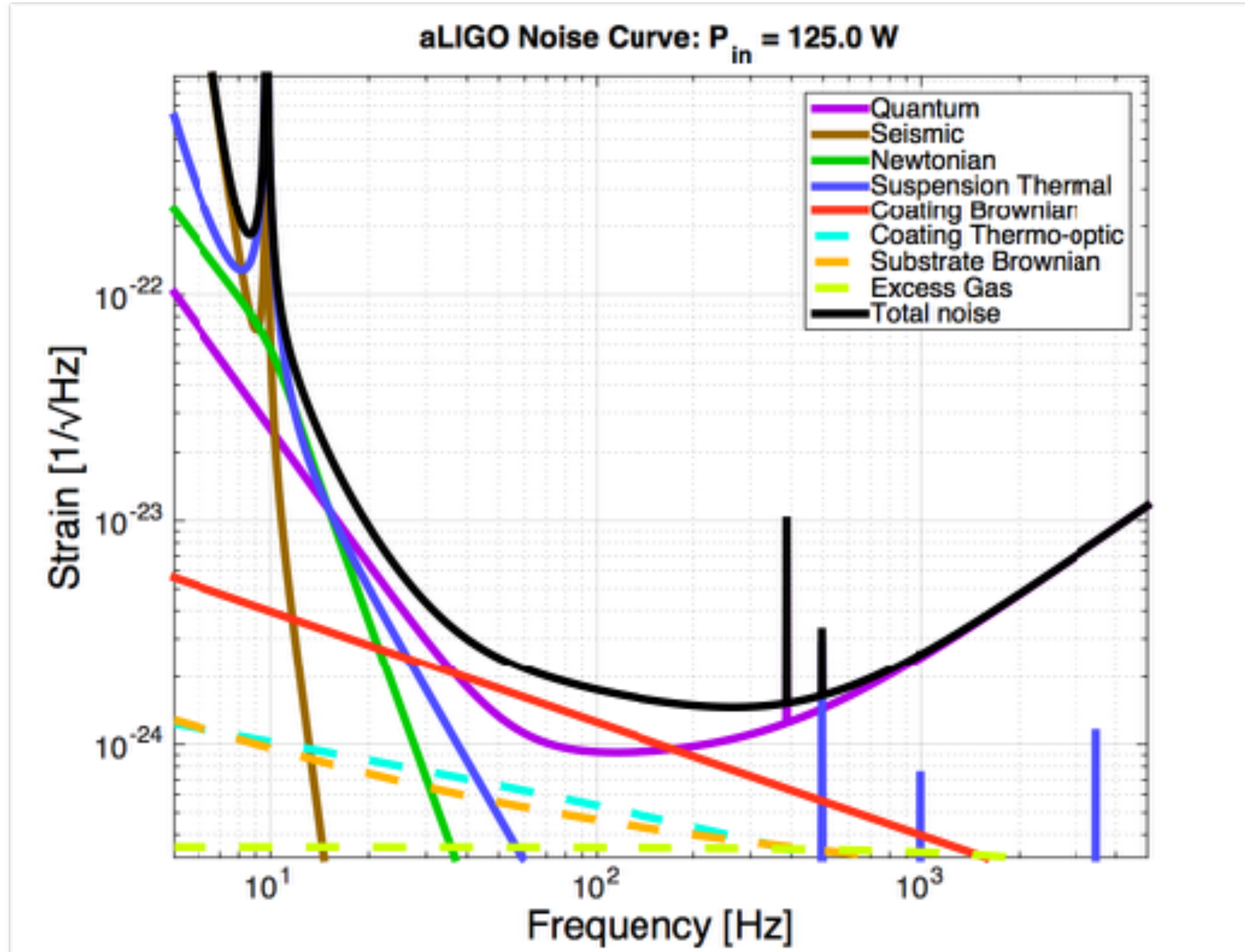
S. Penn

Current Research

- **Ideal Glass (Heated Substrate, Ion-Beam Assist, IBS)**
    - Rapid Data Acquisition: Multimodal & Nodal Suspension
- **Stabilized, High-T Annealed, Metal-oxide:**
- **Stabilized, Nanolayer Coatings**
- **Crystalline Coatings:** AlGaAs & AlGaP
- **a-Si:** (Voyager, 1.5 μm) Ideal Glass
    - Cryogenic Low loss: 2×10^{-6}
    - Absorption < 20 ppm, (and lowering??)

A+: Advanced LIGO improved

With Advanced LIGO at full power (P_{in} = 125 W) Quantum Noise reaches Coating Thermal Noise



Injecting frequency-dependent squeezed light lowers Quantum Noise (2018?)

Coating Thermal Noise reduced by 2x (2020?).
⟹ BNS detection range to 340 Mpc

How do we lower Coating Thermal Noise by 2x in 3-4 years?

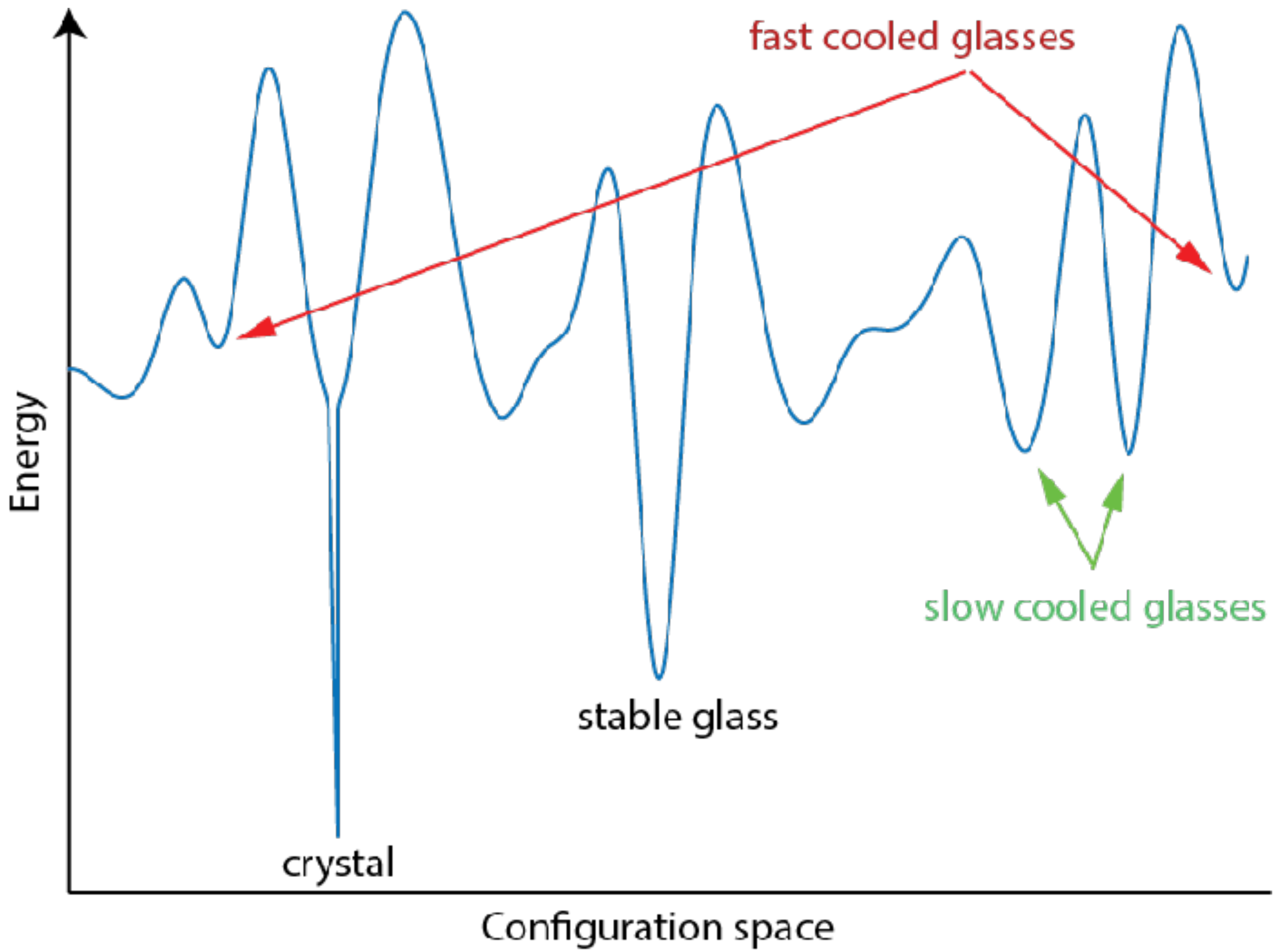
LIGO Instrument Science White Paper 2015, https://dcc.ligo.org/DocDB/0120/T1500290/002/T1500290.pdf

Center for Coating Research

- **Dawn II Meeting:** Talks & discussion refined ideas for CCR
- **Final Proposal:** 10 institutions, $4M
- **Research**:
  - Ideal Glass
  - Stabilized coatings
  - Nanolayer coatings
- **Funding???**

Energy Landscape And Stable Glasses

- Potential energy is a function of the position of all particles (3N d.o.f.s!!)
- Going lower means fewer internal dissipations due to two level systems



Parisi et al. Nature Materials 12, 94 (2013)

Increased Mobility Lowers Loss?

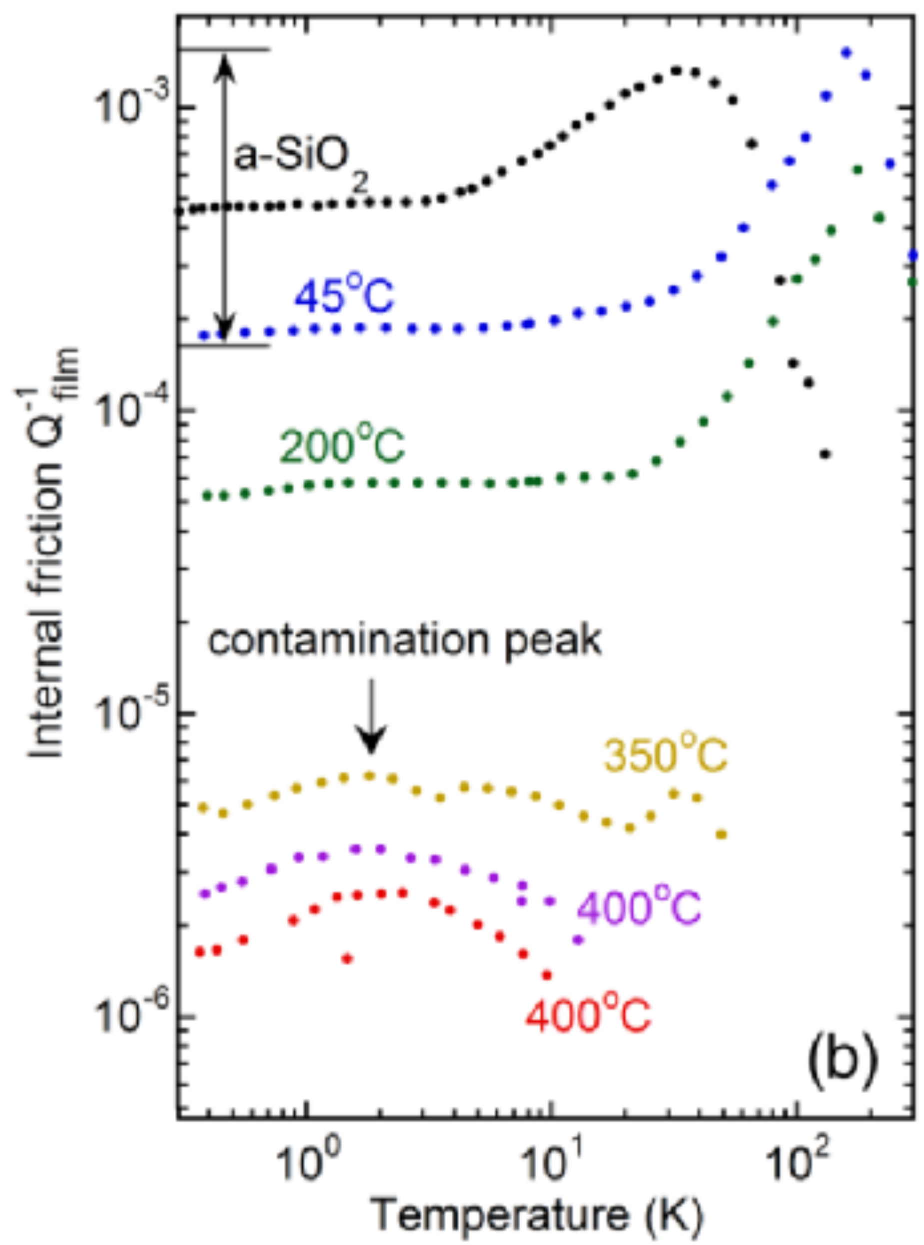
Ultrastable a-Silicon:

- EBD coating on 400 C substrate, $\phi = 2 \times 10^{-6}$ [Liu , et alia, PRL 113, 025503 (2014)].

Ultrastable High-index Metal-oxide Coating:

Goal: allow molecules that are freshly deposited to explore a a larger part of the energy landscape

1. **Increase the substrate temperature** to increase the mobility (showed very promising results with a-Si)
2. **Reduce the deposition speed** (giving more time to the newly deposited molecules to move around before a new layer comes in).
3. **Ion beam assisted deposition** (increase the mobility by hitting the molecules already on the surface with an additional ion beam)

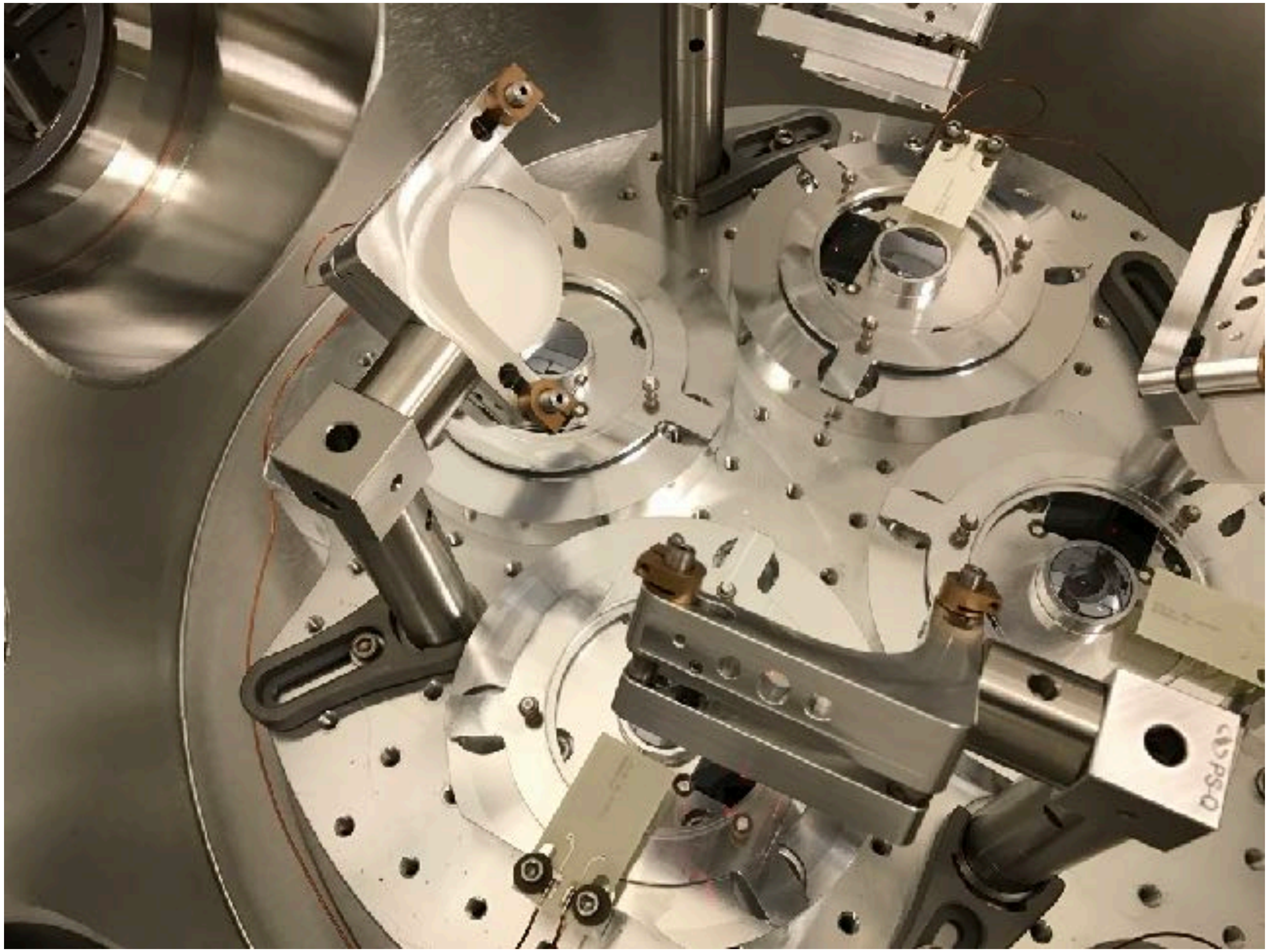


Liu , et alia, PRL 113, 025503 (2014)

Rapid Loss Measurements

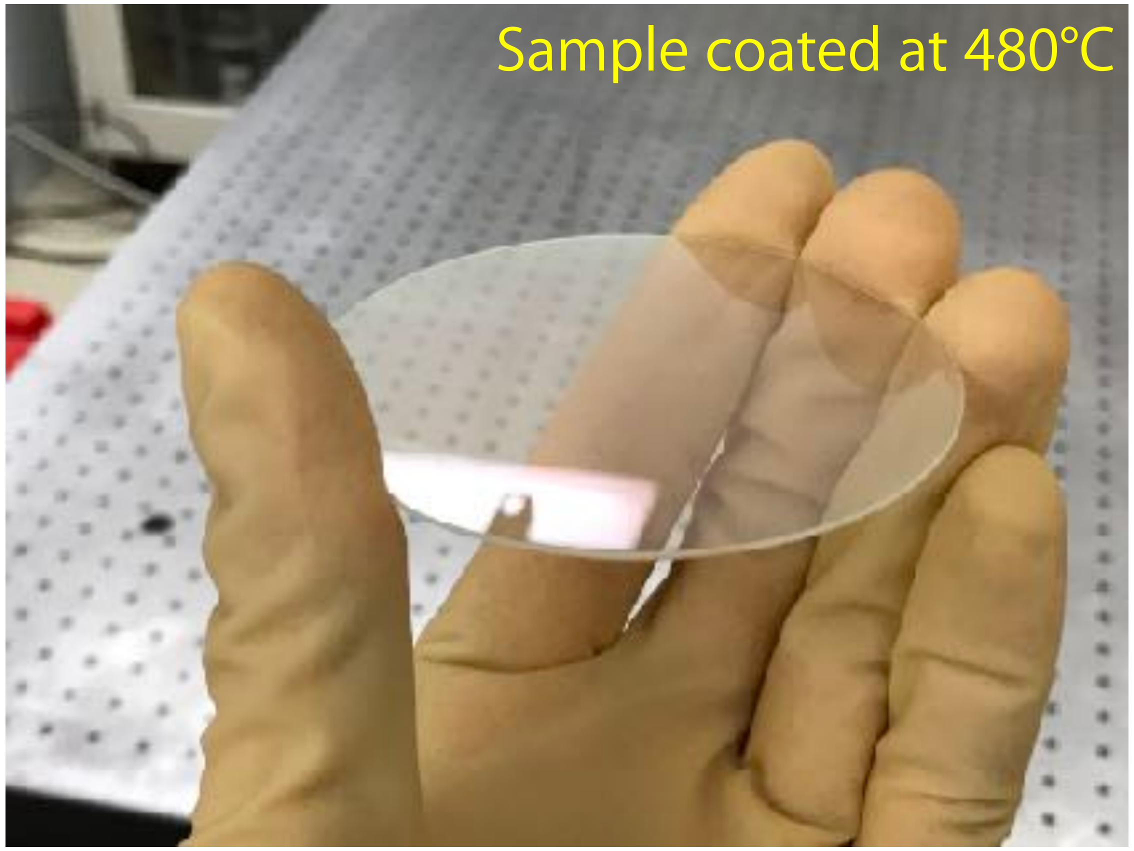
- Measure four samples in parallel in the same chamber
- Digital control system running at a sampling rate of 65 kHz allows us to excite and measure all modes simultaneously

	Time
Install samples and align	15 min.
Pump down	2 hours
Measurement time (depends on Q)	2-5 hours
Venting	30 min.
Total	**5-8 hours**



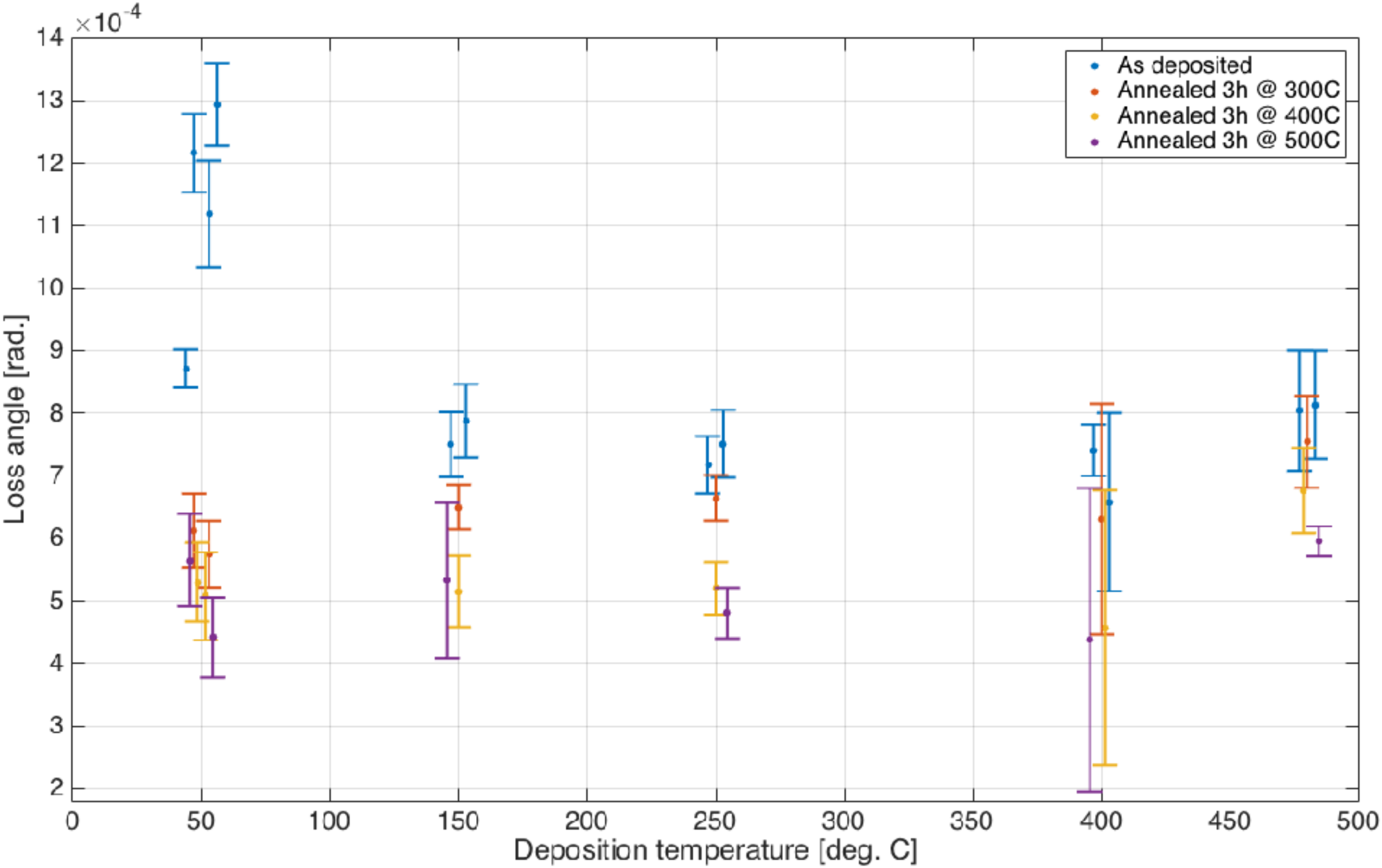
Elevated substrate temperature deposition

- Carried out with magnetron sputtering at Université de Montréal / Polytechnique Montréal
  - Pure tantala, 1 micron thick layer
- Five temperatures:
  - Room temperature (50°C, 150°C, 250°C, 400°C and 480°C)
  - Sample coated at 480°C looks hazy
- Coating mechanical losses measured at Caltech
  - As deposited, and after annealing (3 hours @ 300°C / 400°C / 500°C)
- Ellipsometry measurements at Montreal
- XRD measurements at HWS and Stanford

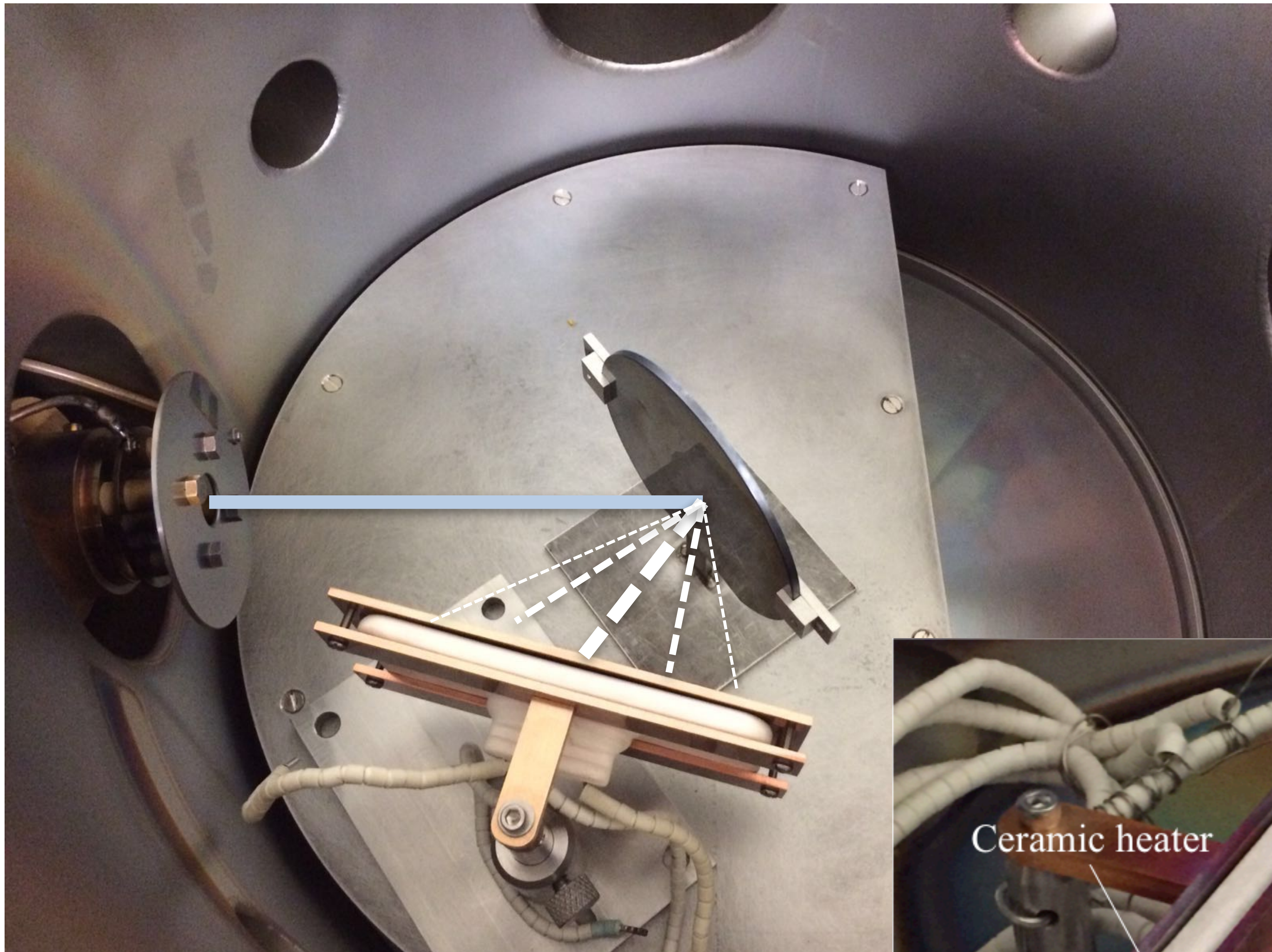


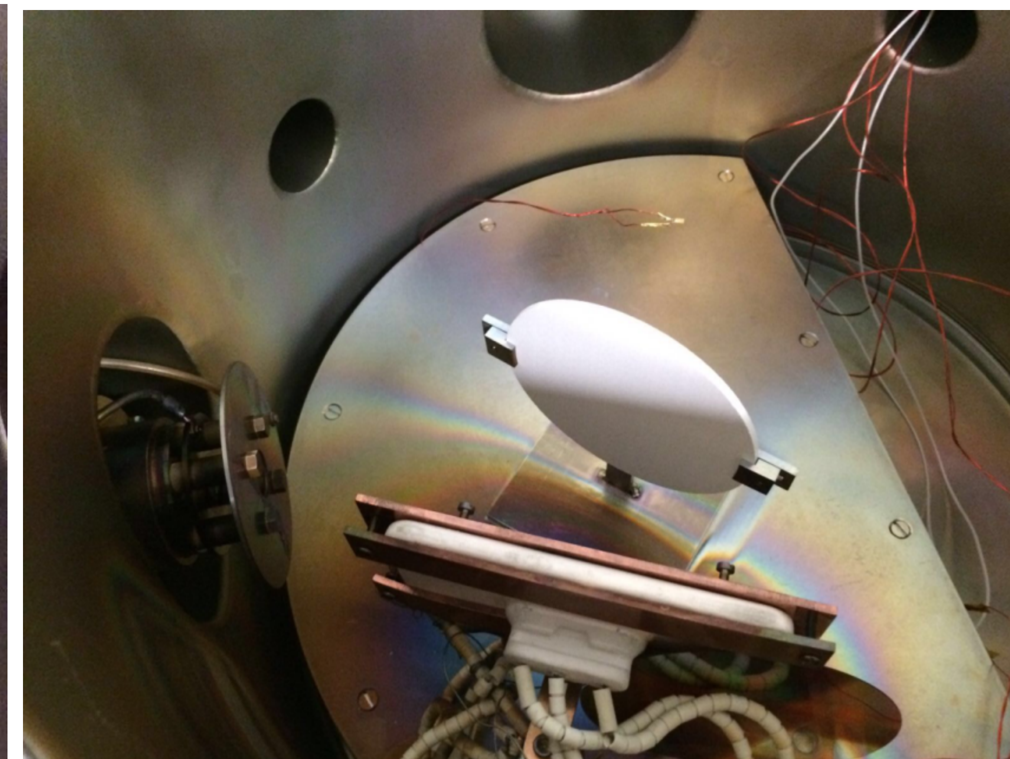
- CMS-18 sputtering system by Kurt J. Lesker
- Base pressure typically 8-9e-8 Torr
- Deposition conditions: 2 mTorr, 450 W on a three-inch Ta target, 60% O2 vs. Ar, rotation of 20 RPM, pre-sputtered with O2 for 20 minutes prior to deposition to ensure a stable discharge
- All substrates were pre-cleaned using an O2/Ar plasma (50% O2 vs. Ar) for 600 s at 8 mTorr at around -100V.

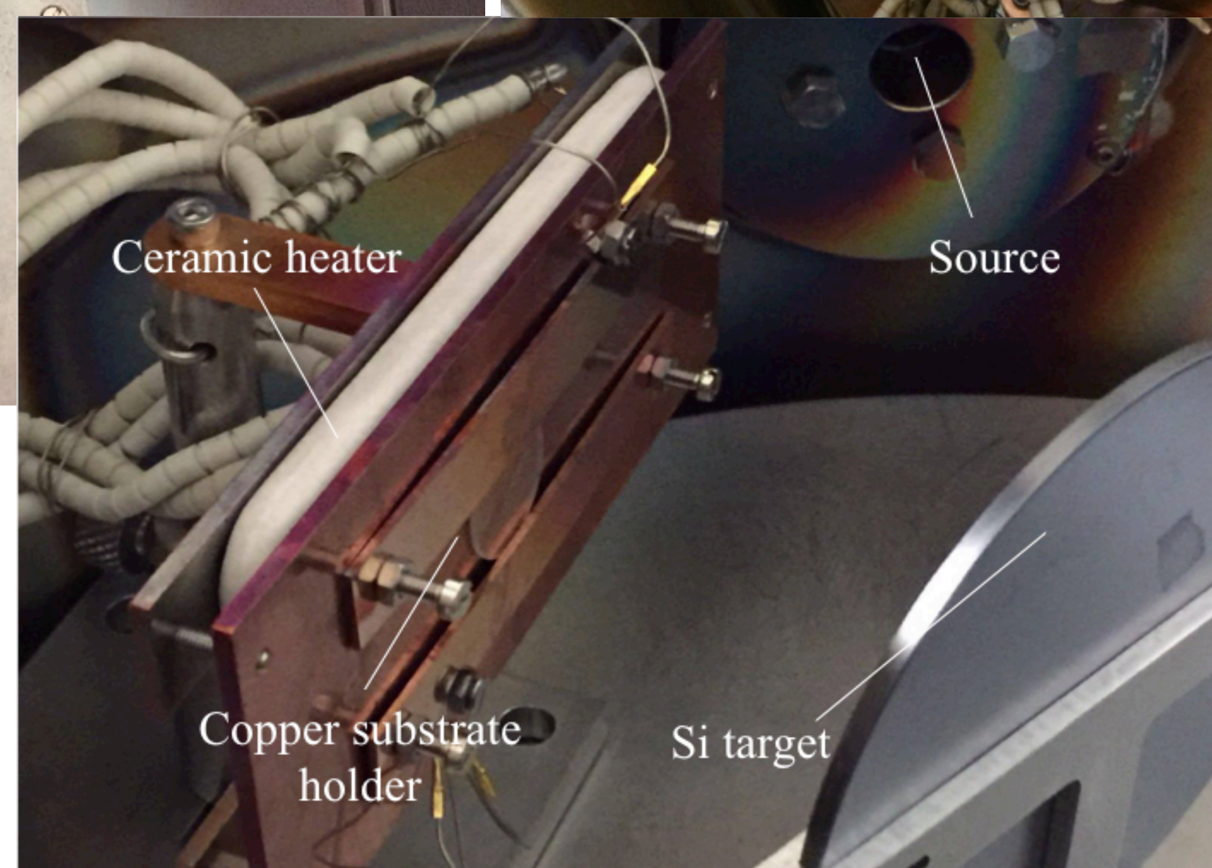
Effect of Annealing



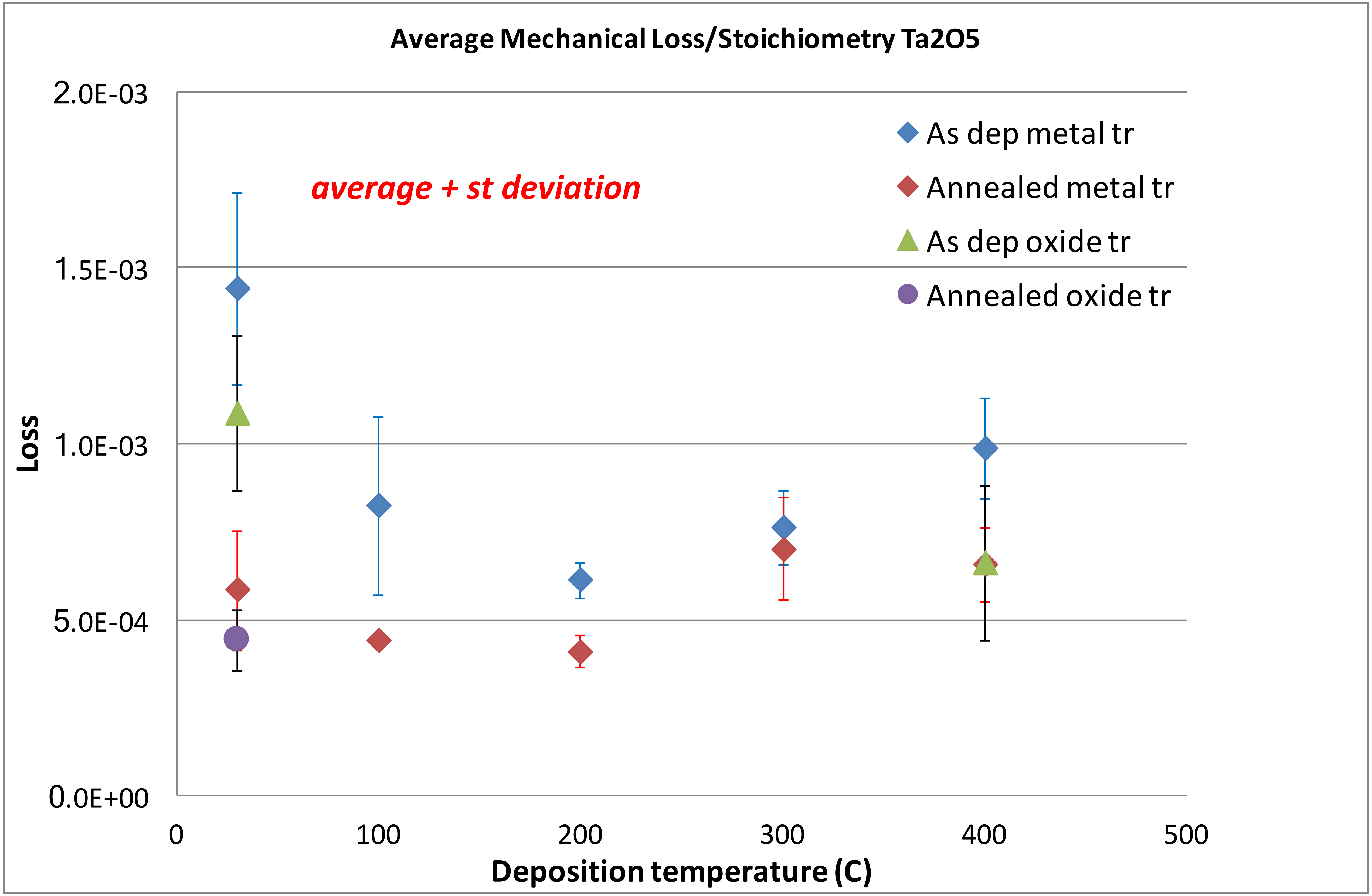
Development of ECR-IBD





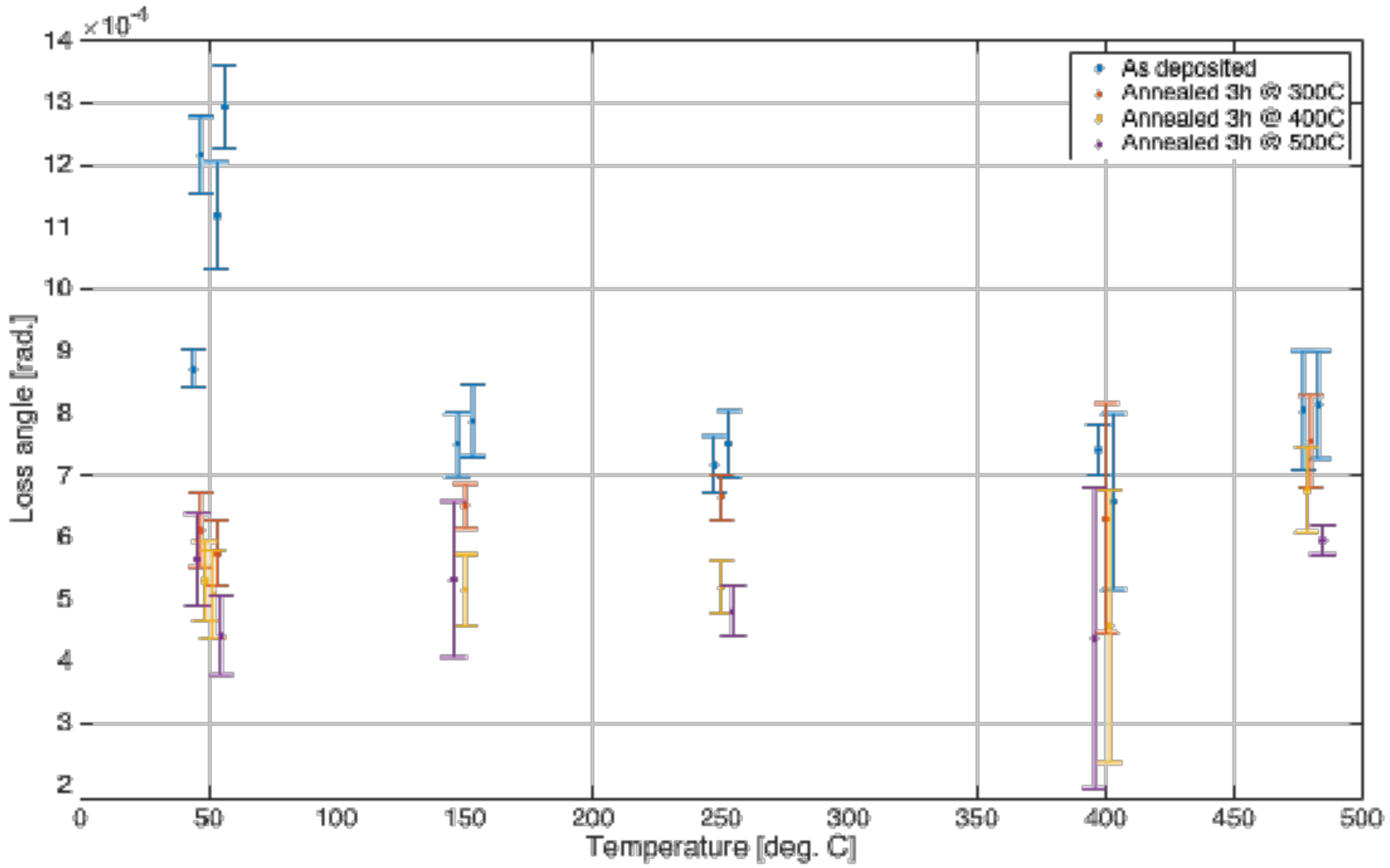


UWS Ta_2O_5 mechanical loss



Heated Substrate Results

- Substrate temperature has an effect on mechanical losses (before annealing)
  - Crystallization at relatively low temperature 480°C, instead of ~600°C observed normally when annealing post deposition
  - Seems to indicate that elevated temperature deposition is somehow more efficient than post deposition annealing



- However, annealing has still a large impact and reduced losses down to a level of $5x10^{-4}$
  - Coating deposited at 400 C is also improved a bit

A+: Stabilized, Annealed Amorphous Coatings

Silica-Stabilized Coatings:

- Stabilized coating $\Longrightarrow$ Higher annealing T $\Longrightarrow$ Lower Mechanical Loss ϕ
- Added silica lowers index $\Longrightarrow$ Thicker coatings $\Longrightarrow$ Higher Mechanical Loss ϕ
- Silica(30%)-Hafnia T_{anneal} = 600 C. $\phi = 3 \times 10^{-4}$ at 14 K
- Silica(20%)-Zirconia T_{anneal} = 800 C. $\phi = 2 \times 10^{-4}$ at 300 K
- No net benefit.

P. Murray: DCC-G1400275

Mutually-Stabilized Coatings:

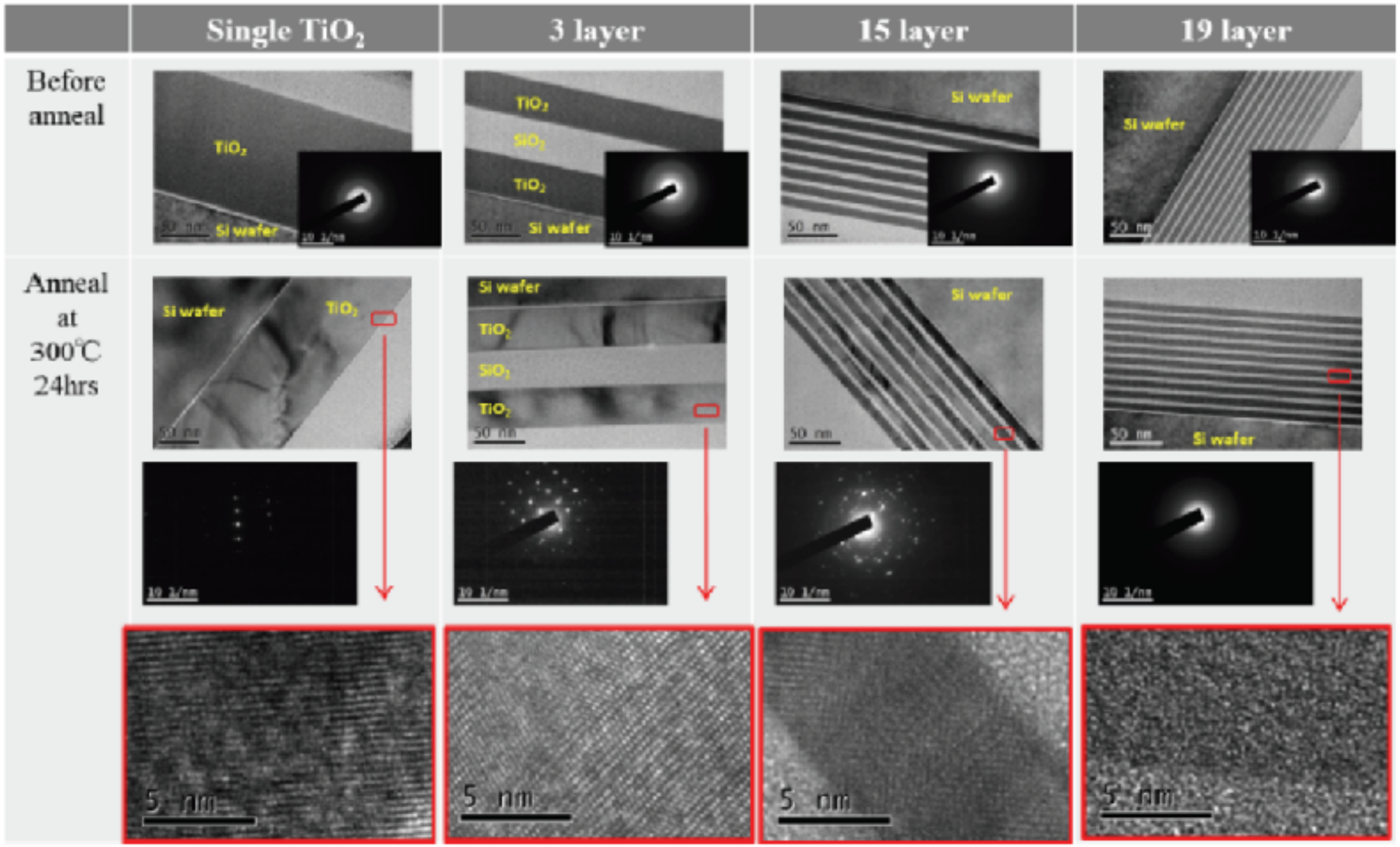
- Stabilized coating $\Longrightarrow$ Higher annealing T $\Longrightarrow$ Lower Mechanical Loss ϕ
- Zirconia(34%)-Tantala T_{anneal} = 800 C, $n \approx$ 2.1-2.2 , Y = 134 GPa
- $\phi = 1.4 \times 10^{-4}$ (shear), $\phi = 4 \times 10^{-4}$ (bulk) [Preliminary] Potentially useful. New Run

Nano-Coatings:

- Thinner coatings layers pin the high index material to prevent crystallization
- Stabilized Titania/Silica coatings: 19 sublayers, T_{anneal} = 300 C, $\phi \approx 10^{-4}$
- New Sannio Coating facility to move beyond few nm layer limit to <= 1 nm.

Nanolayer coatings: I. Pinto, R. DeSalvo, S. Chao

TEM Before/After Annealing

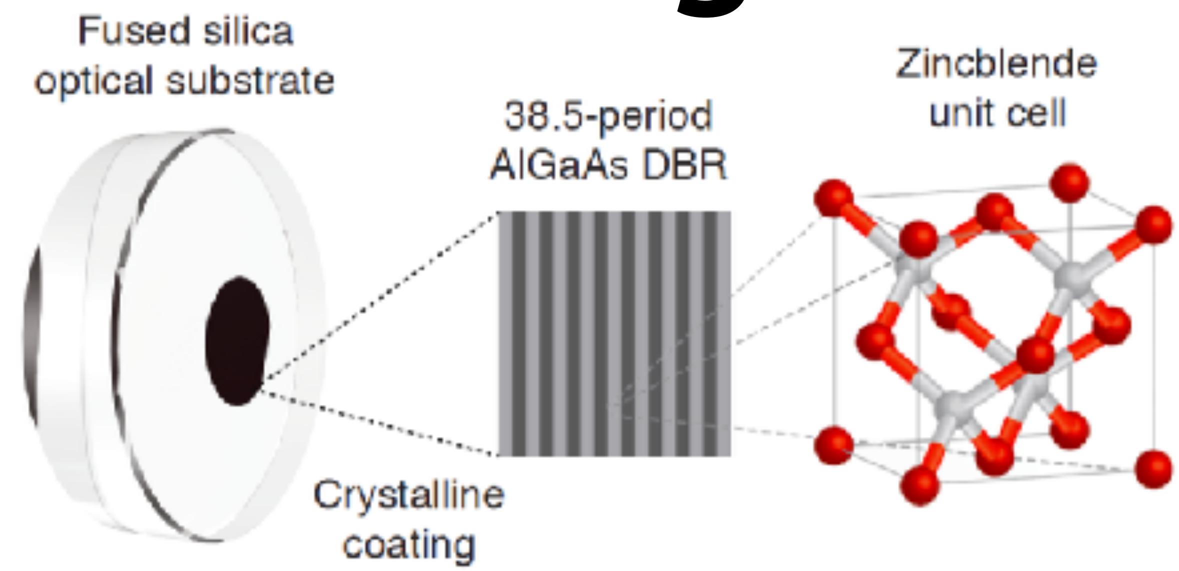


[S. Chao et al., LIGO-G1300921]

TEM shows that no significant across-interface diffusion occurs during annealing

New University Sannio Coating facility to move beyond few nm layer limit to <= 1 nm.

Voyager: AlGaAs Coatings



Credit: G. Cole, et alia, http://arxiv.org/pdf/1604.00065v1.pdf

GaAs/$Al_xGa_{1-x}As$ crystal

MBE grown, then transferred
   Currently limited to 20 cm diameter

Compatible with 1064–1550 nm

At 1064 nm: Absorption < 1 ppm, Scatter < 3 ppm, T = 10 ppm

At 1530 nm: Absorption ≈ 3.6±1.3 ppm [J. Steinlechner, Class. Quantum Grav. 32 (2015) 105008]

Mechanical Loss:

   Optical cavities: (1 mm beam, 1064 nm) $\phi = 2 \times 10^{-5}$
   [Cole, et al., *Nature Photonics*, vol. 7, pp. 644–650, Aug. 2013]

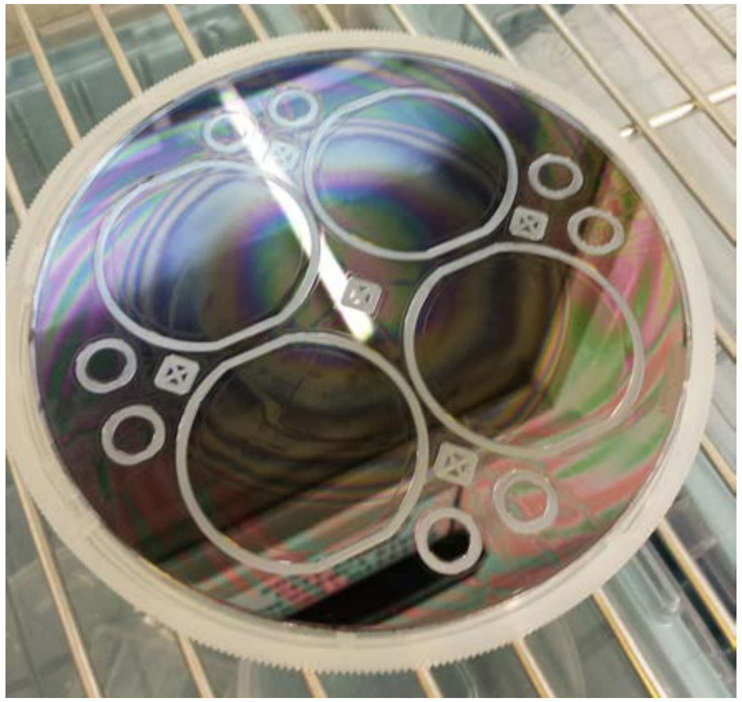
   Mechanical Ringdown:

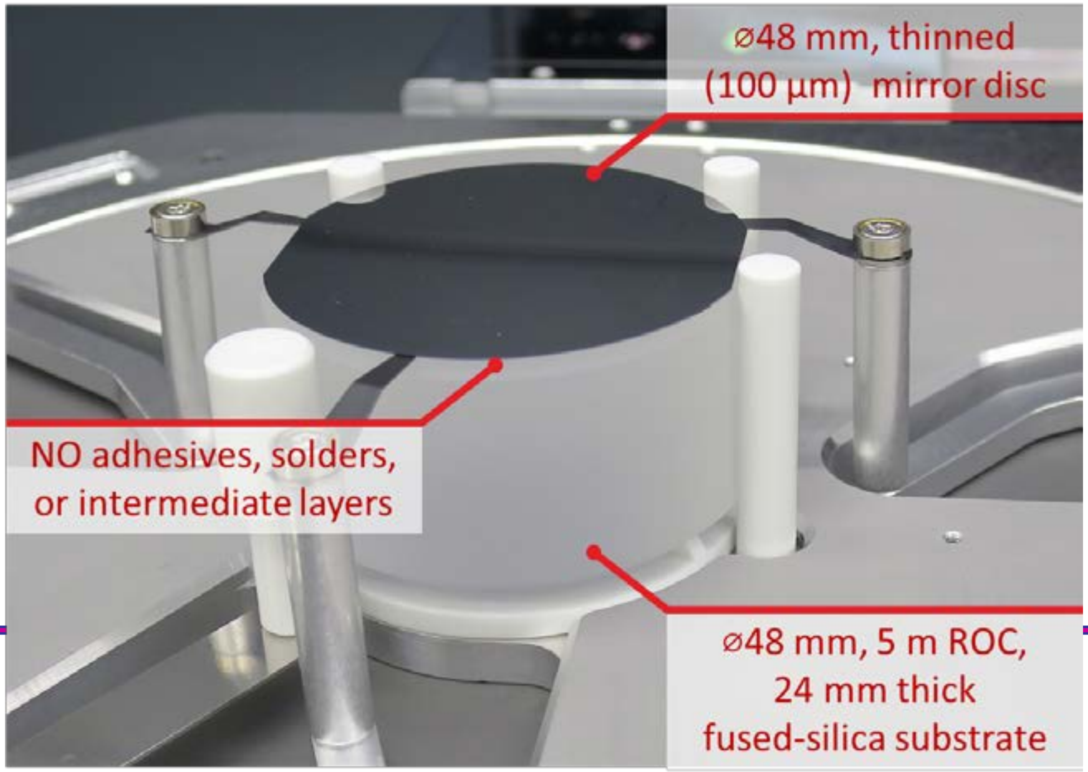
      Initial Bonding: $\phi = 3 \times 10^{-5}$ (bulk), $\phi = 5 \times 10^{-4}$ interface shear modes)
      [Penn, et al., https://dcc.ligo.org/DocDB/0124/G1600660/002/PennCoatingsMarch2016.pdf]

      New Bonding: *In progress*

The process

- Epitaxial growth on GaAs wafer
  - AlGaAs multilayer with varying Al content for index contrast
    - » high index layers consist of binary GaAs thin films
    - » 8% Ga incorporated in low index AlGaAs layers to slow oxidation in ambient
  - High quality epitaxy requires a lattice matched substrate, same crystalline symmetry, minimal deviation of lattice parameter (atomic spacing)
- Transfer and bonding to the final optical substrate
  - mirror completely removed from the wafer and bonded to desired substrate





Voyager: AlGaP Coatings

GaP/AlGaP ≈ lattice matched to Silicon

Coating grown using MBE on substrate

- Chamber limits size to ≈ 300 mm

No bonding. Low interface losses.

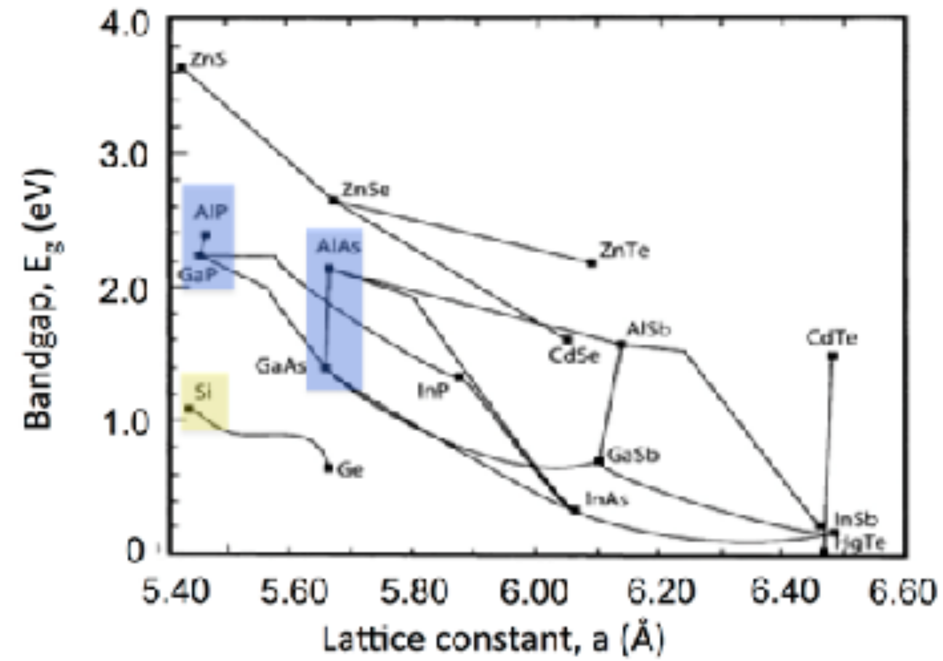
Buffer layer required to adapt lattice

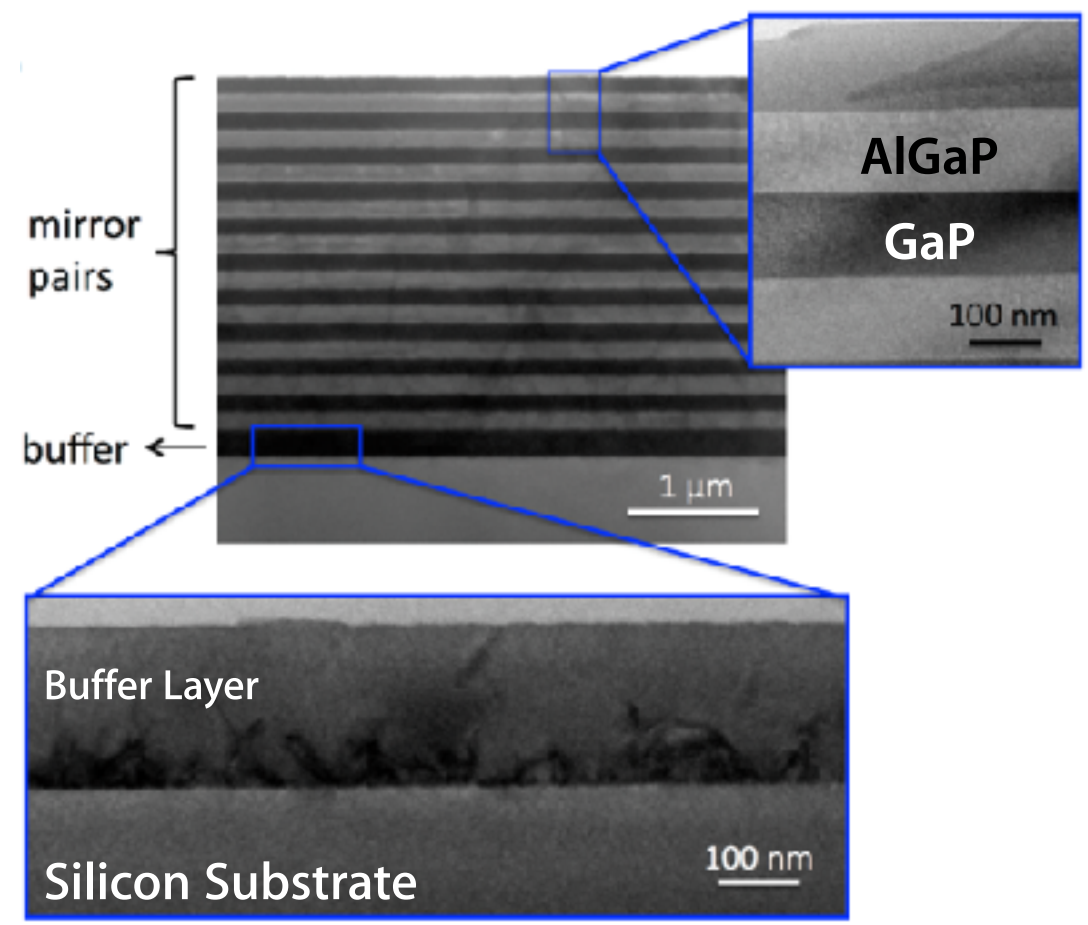
- Adapts lattice spacing, stress change
- Antiphase defects near interface

Cryogenic Loss: $\phi = 1.4 \times 10^{-5}$ at 12 K

High Absorption: 2.3%

- Due to antiphase defects?





A. Lin, et alia, Opt. Mater. Express 5, 1890-1897 (2015)
AV Cummings, et alia, http://iopscience.iop.org/article/10.1088/0264-9381/32/3/035002/pdf

A. Lin, et alia, https://dcc.ligo.org/DocDB/0104/G1300580/001/ACLin-GWADW2013v2.pdf