Minimizing test mass thermal noise with crystalline coatings

Redefining precision laser optics

Garrett D. Cole

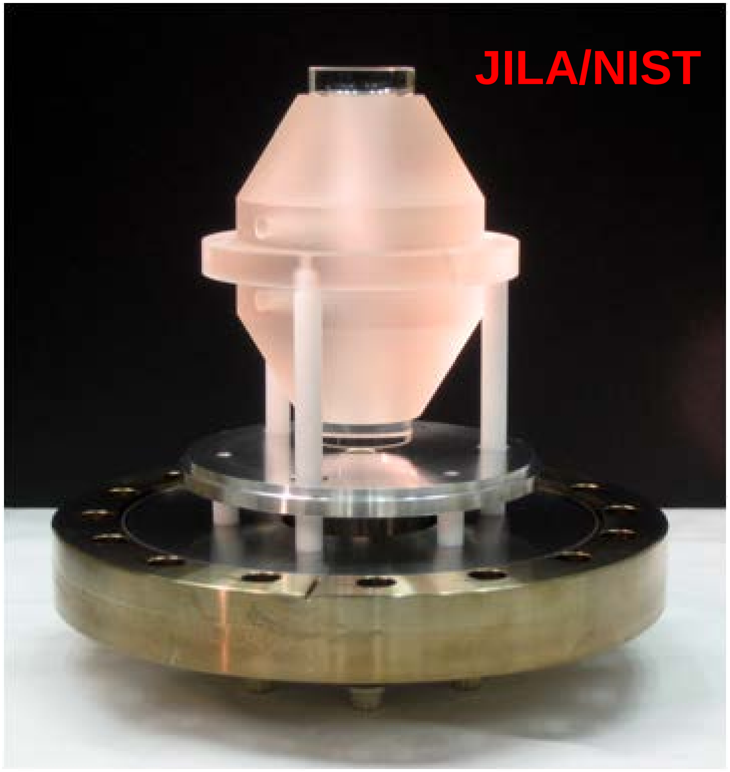
Crystalline Mirror Solutions LLC & GmbH

May 27, 2016

Outline

- Brief introduction to Brownian thermal noise
  - background on the problem and its consequences
- Overview of substrate-transferred crystalline coatings
  - timeline of the technological development and current status
- Prospects for realizing GW-relevant crystalline coatings
  - discussion on the next steps for developing low-loss GW optics

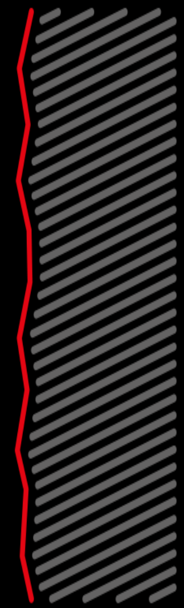
Thermal (Brownian) Noise



- Precision interferometers are now limited by Brownian noise
  - from cm-scale reference cavities to km-length GW detectors

Ultimate Limits of Cavity Performance

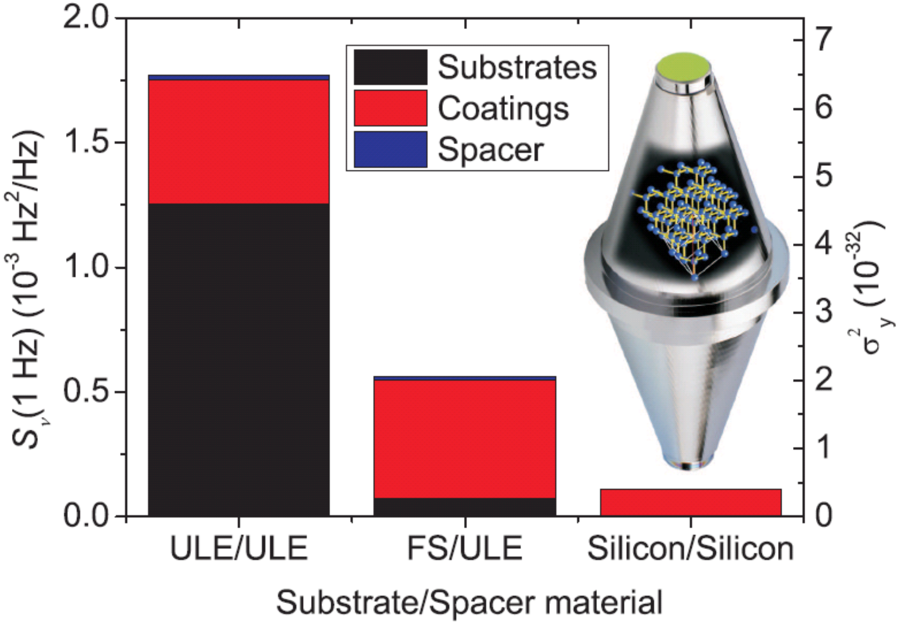
Brownian Noise

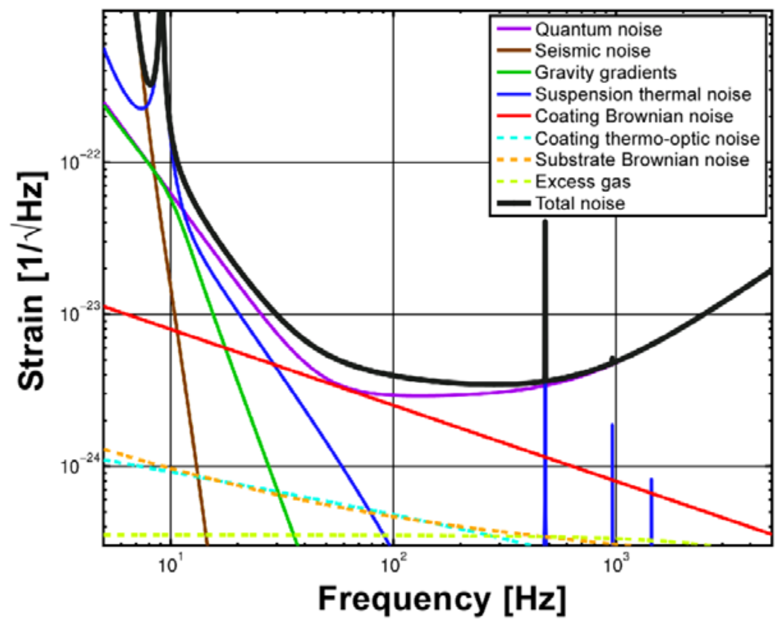


Fluctuating Mirror

Mechanical fluctuations set the ultimate stability limit

Brownian Noise Consequences

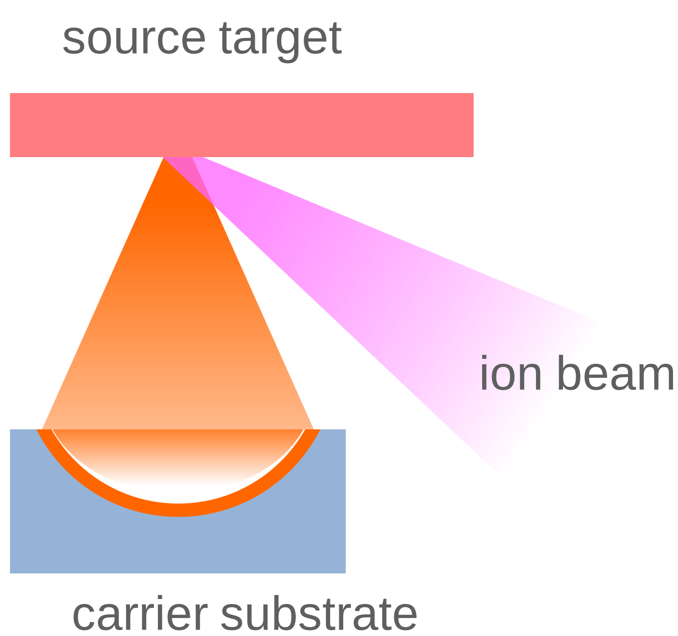




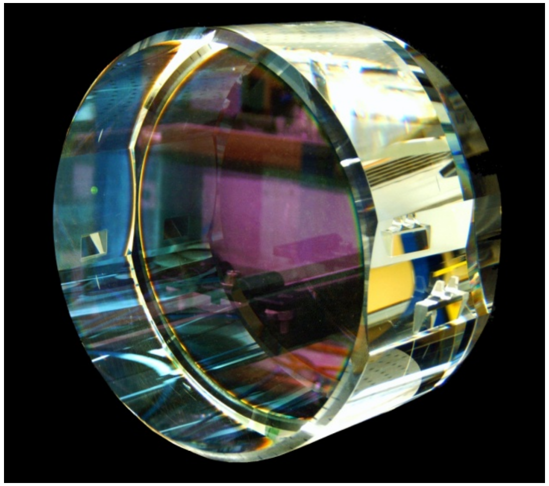
- Dielectric optical coatings (Ta_2O_5/SiO_2) are a major limitation
  - from LSC studies by Crooks, Harry, Penn, etc. Ta_2O_5 is the culprit
  - loss angle has been reduced by a factor of ~2 over the last decade
- Crystalline coatings represent an exciting alternative solution
  - simultaneous achievement of high optical and mechanical quality

Kessler, et al. Nature Photonics 2012 | Harry, Bodiya, DeSalvo eds., Cambridge Univ. Press 2012

Ion Beam Sputtered Films

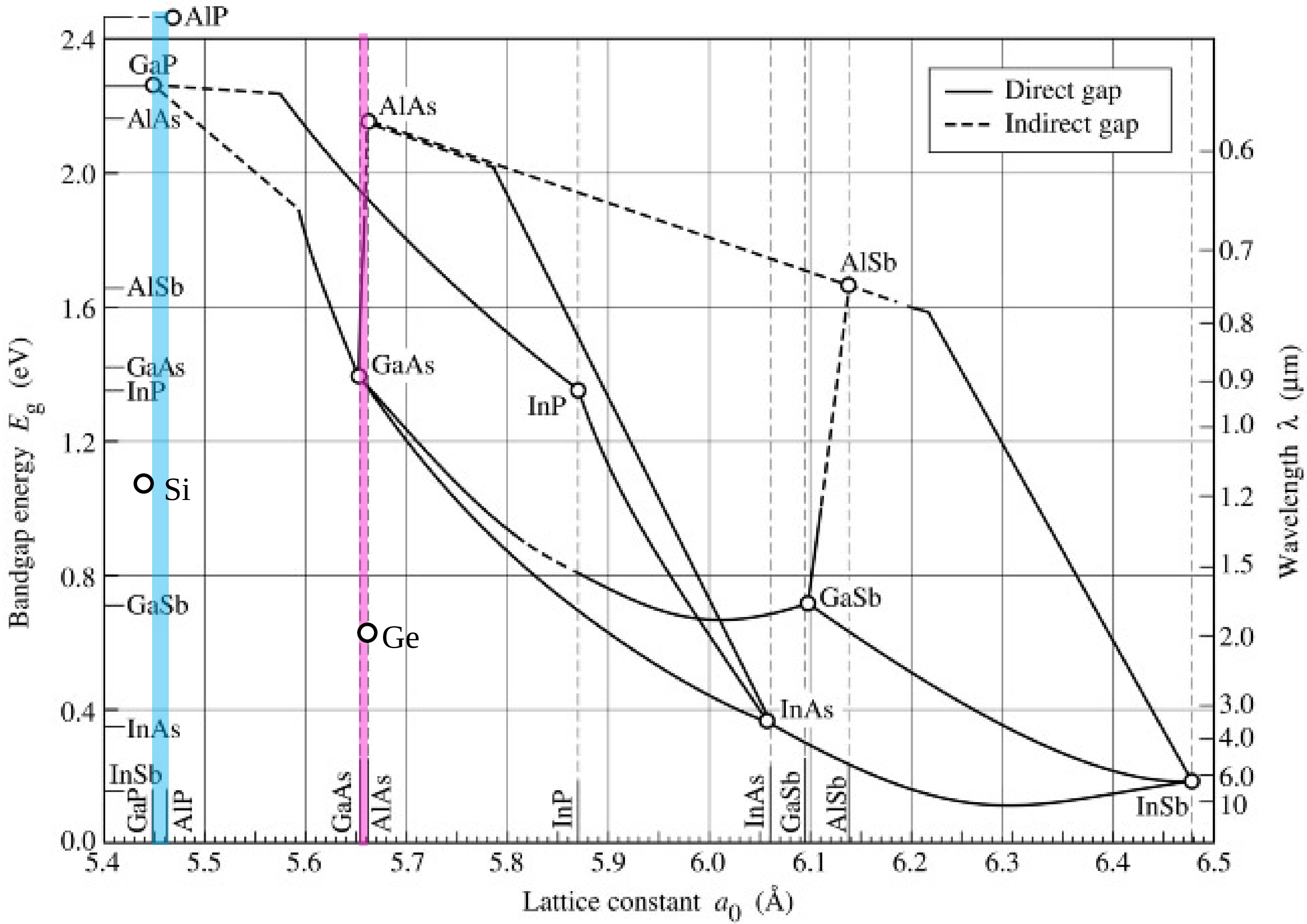


State-of-the-art multilayer mirrors:
sputtered Ta_2O_5/SiO_2



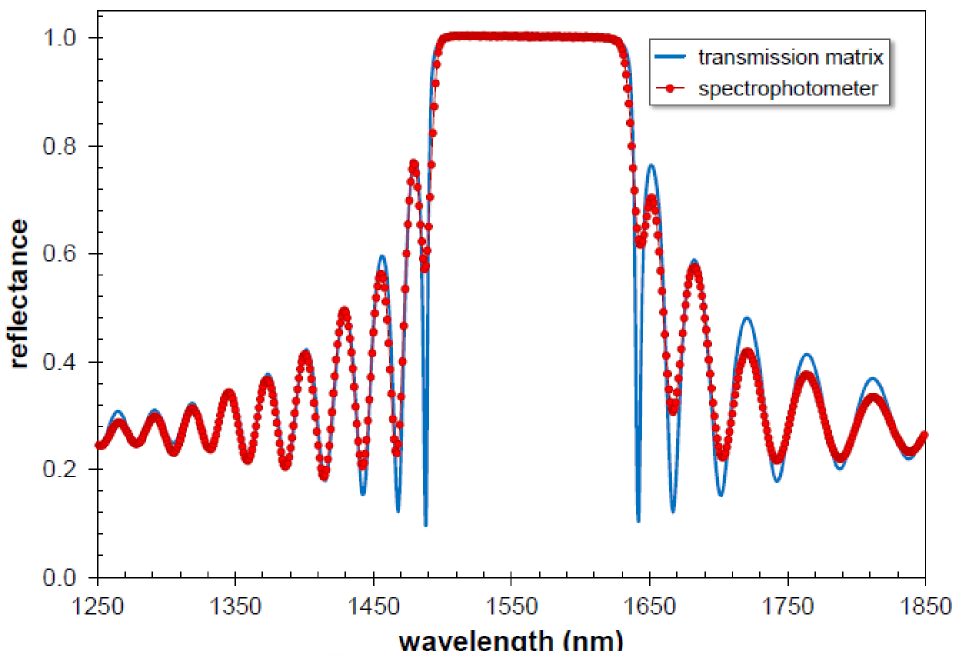
- Multilayer of amorphous thin films via ion beam sputtering (IBS)
- Phenomenal optical properties: high R, low absorption and scatter
- Flexible choice of substrates assuming excellent surface quality
  - super-polished SiO_2, Si, ULE, sapphire, etc.

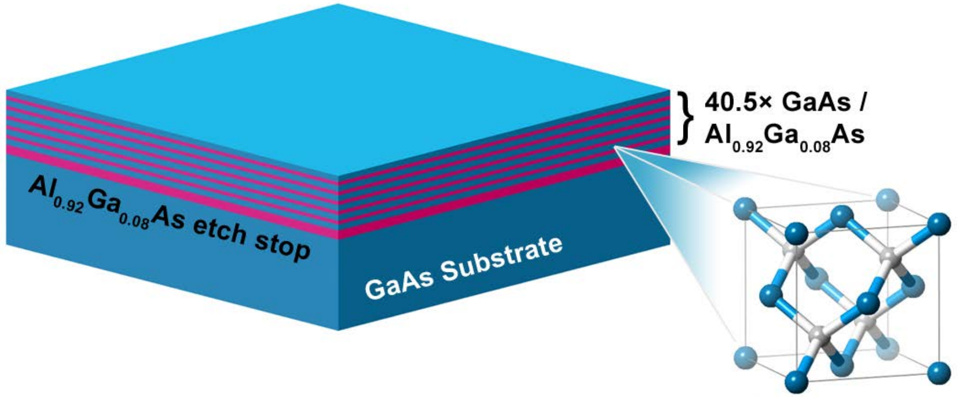
Lattice-Matched Epitaxial Structures



Epitaxial Coating Details

- 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
- Potential for high reflectivity from ~900 nm → 5+ μm
  - peak performance in NIR
- High quality epitaxy requires a lattice matched substrate
  - same crystalline symmetry
  - minimal deviation of lattice parameter (atomic spacing)





G. D. Cole, W. Zhang, M. J. Martin, J. Ye, and M. Aspelmeyer, Nature Photonics (2013)

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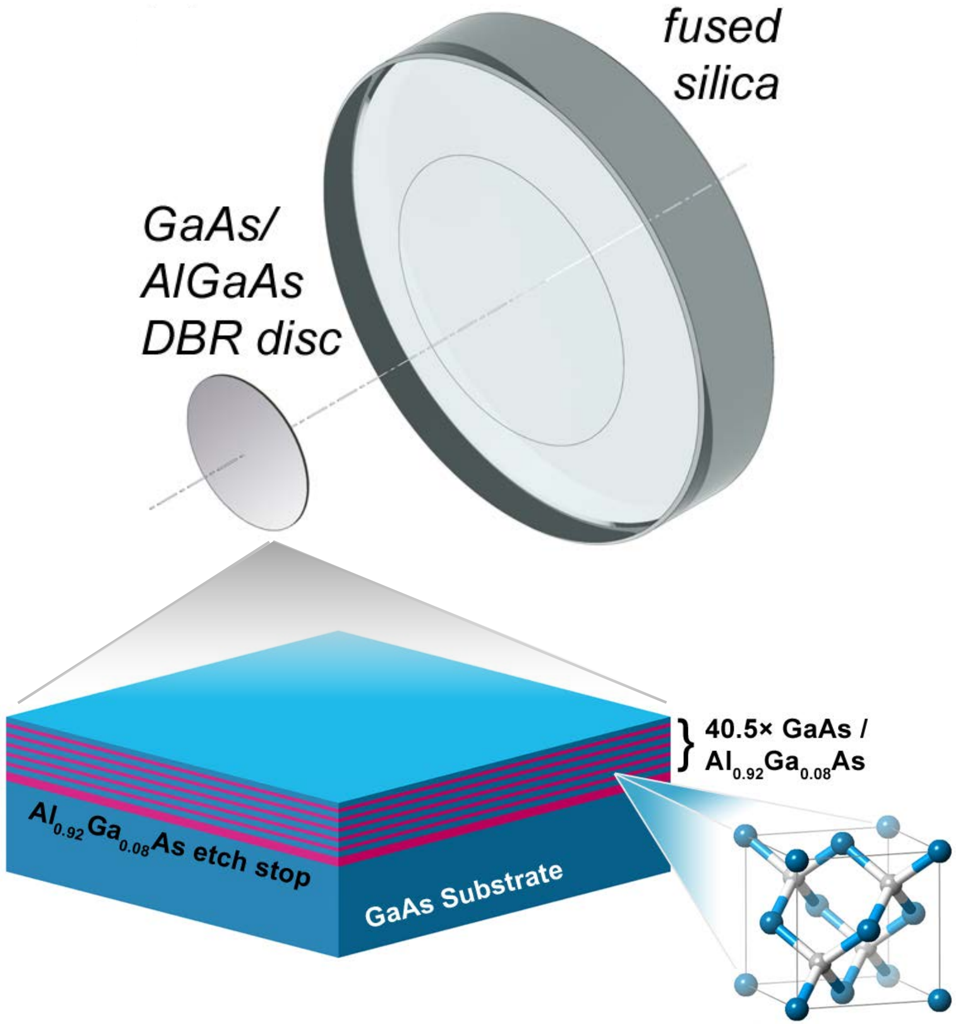

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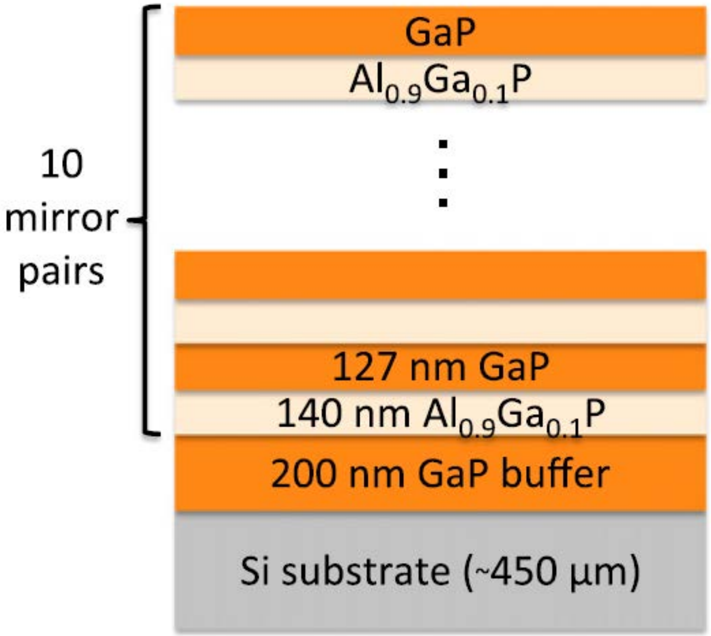
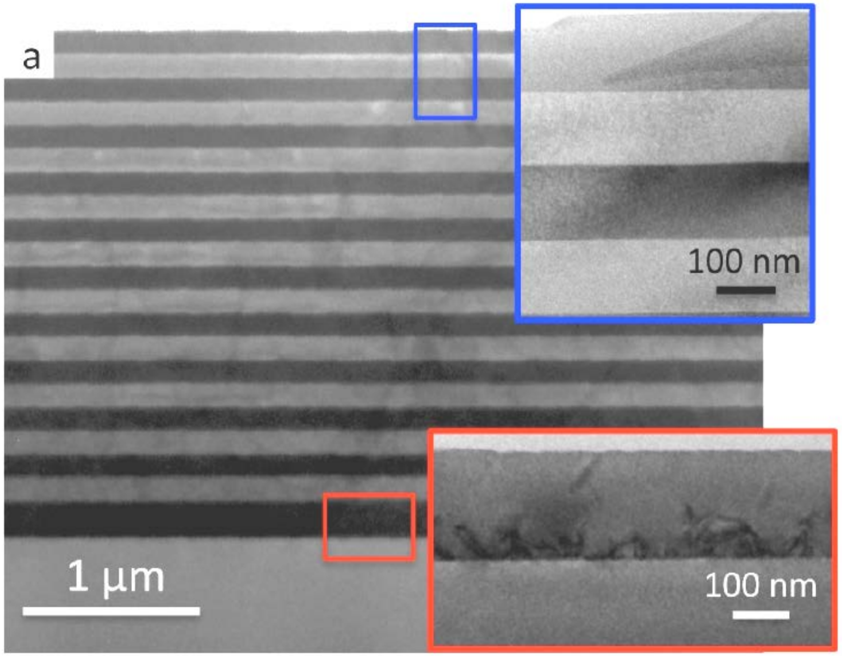
Alternative Technology: $GaP/Al_xGa_{1-x}P$





- Epitaxial DBR directly deposited on silicon (Stanford/UWS)
  - interference coatings based on $GaP/Al_{0.9}Ga_{0.1}P$ epitaxial multilayers
- Proof-of-concept yields promising cryo loss angles ($\sim 1 \times 10^{-5}$)
  - reflectivity of 83% at RT (as expected), ~2% absorption (first pass)

A. C. Lin, Optical Materials Express (2015) | A. V. Cumming, Classical and Quantum Gravity (2015)

Why Choose Crystalline Reflectors?

- Current deposition techniques make imperfect thin film materials
- Crystalline films seem to have inherently lower defect densities
  - epitaxy apparently yields better crystals than IBS yields glasses

VOLUME 59, NUMBER 18 PHYSICAL REVIEW LETTERS 2 NOVEMBER 1987

Two-Level Systems Observed in the Mechanical Properties of Single-Crystal Silicon at Low Temperatures

R. N. Kleiman, G. Agnolet,[a] and D. J. Bishop
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
(Received 8 June 1987)

Using the high-Q mechanical-oscillator technique we have measured the sound velocity and mechanical dissipation of high-purity single-crystal silicon as functions of temperature (0.005–4.2 K), frequency (0.6–6.0 kHz), and strain amplitude (10^{-5}–10^{-8}). In the mechanical properties we find a surprisingly strong temperature dependence with the same qualitative behavior for silicon as for vitreous silica. This implies a density of two-level systems only 2 orders of magnitude lower for silicon than amorphous silica.

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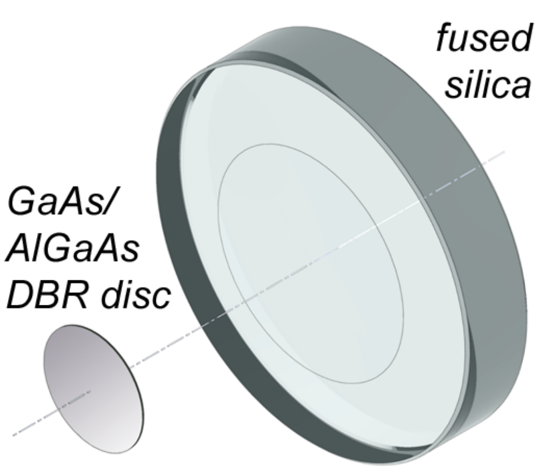
Crystalline Mirror Solutions

CMS

- We offer an entirely unique technology for precision laser optics
  - Applications span fundamental R&D + emerging industrial uses
    - cutting-edge research efforts in spectroscopy and metrology
    - advanced industrial applications in manufacturing and sensing



i) substrate-transferred single-crystal coatings

ii) end mirrors for ultrastable cavities

iii) cavity employed for laser stabilization

Crystalline Coating Timeline

2007 GaAs/Al_xGa_{1-x}As micro-resonator development begins at LLNL

2008 moved to Vienna (IQOQI) to continue optomechanics research, first contact with Gregg Harry, Nergis Mavalvala, & Achim Peters

2009 (September) initial thoughts on transferred coatings

2010 (July) seminar @ MIT, introduced transferred coating concept

2011 first time attending GWADW (Elba) revisited bonding idea

2012 first “real” mirrors fabricated and presented at GWADW Hawaii

2012 (December) JILA direct thermal noise measurements completed

2013 significant external interest, CMS GmbH & LLC incorporated

2014 return to US to setup manufacturing, first products shipped

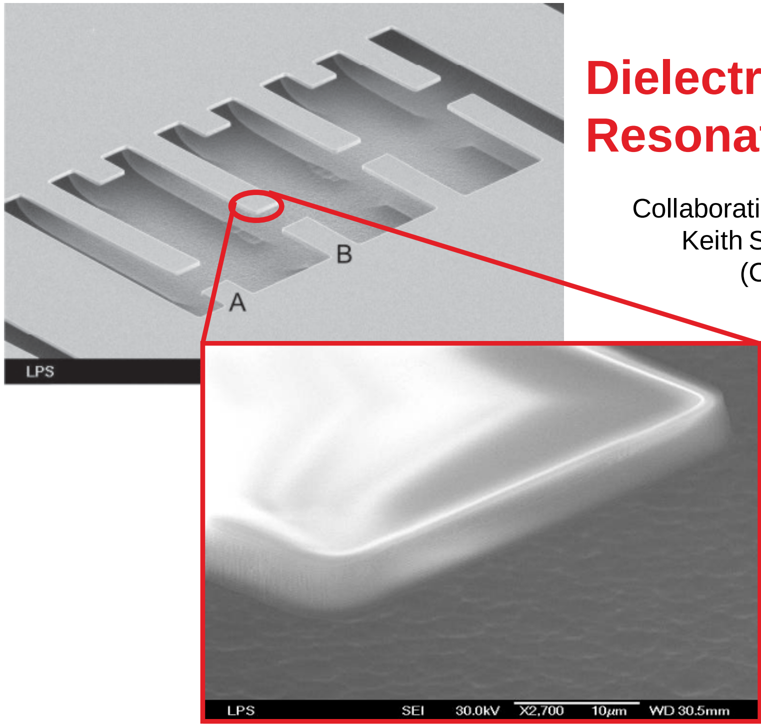
2015 finesse reaches 200,000, sub-ppm absorption verified at a center wavelength of 1064 nm (with SPTS), bonding area up to 10 cm

2016 finesse of ~360,000 measured, first tests of mid-IR optics

Mechanical Loss of Optical Coatings

Dielectric Resonators

Collaboration with
Keith Schwab
(Cornell)



free-standing Ta_2O_5 / SiO_2 HR coating
Reflectivity >0.9999, Q ~ 2000 – 6000
loss angle (Q^{-1}) similar to LIGO data

S. Gröblacher, S. Gigan, H. Böhm, A. Zeilinger, M. Aspelmeyer, Eur. Phys. Lett. 81, 54003 (2008)

Epitaxial AlGaAs Bragg Mirrors

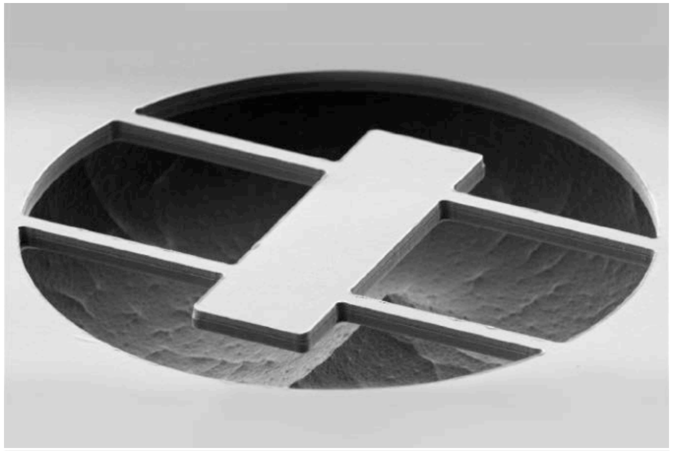
FBH and Aspelmeyer
Group (UniVie)

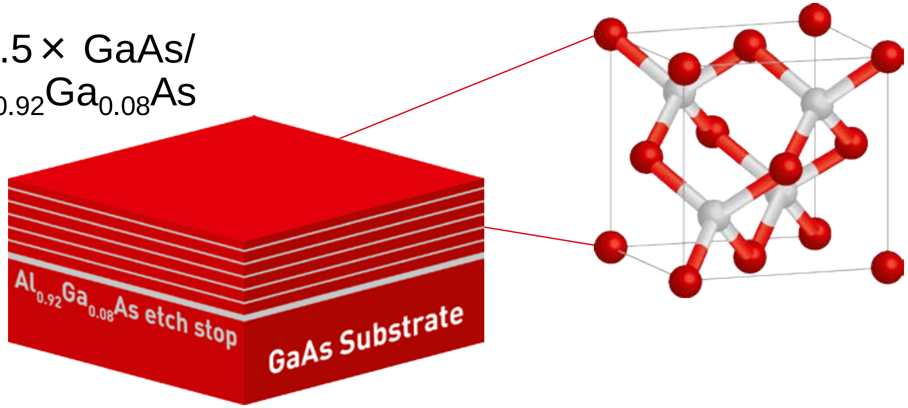
free-standing epitaxial AlGaAs DBR
Reflectivity >0.9999, Q ~ 2×10^4 – 2×10^5
Significantly reduced damping, similar R

a) Cole, et al., Appl. Phys. Lett. 92, 261108 (2008)
b) G. D. Cole, Proc. SPIE. 8458–07 (2012)

Spin-Off of Quantum Optomechanics

Epitaxial AlGaAs
micro resonators





free-standing epitaxial AlGaAs

reflectivity >0.9999 (ppm losses)

loss angle $<2\times10^{-5}$ to $<5\times10^{-6}$

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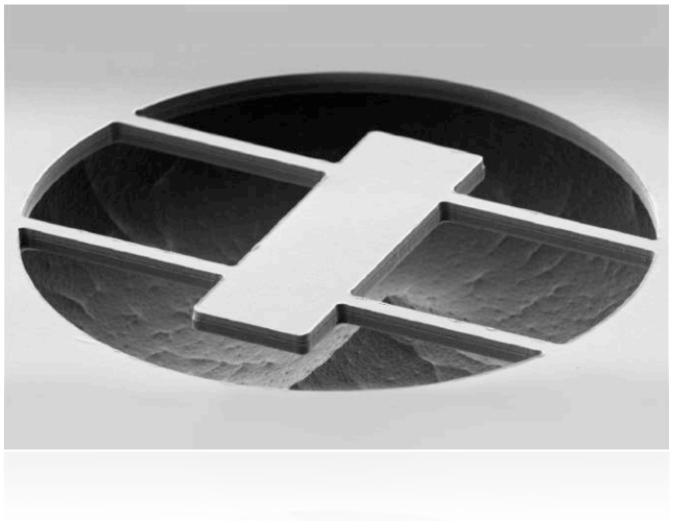
c) Aspelmeyer et al., *RMP* 86, 1391 (2014)

Spin-Off of Quantum Optomechanics

Epitaxial AlGaAs micro resonators



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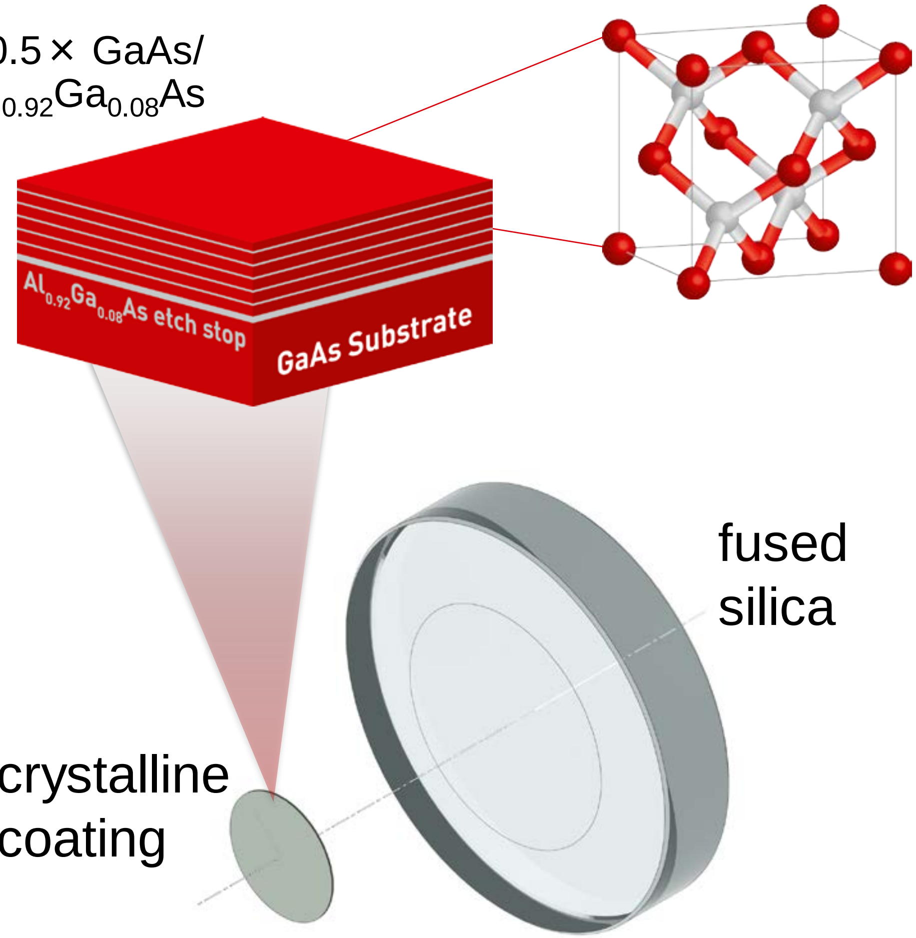
Substrate-transferred crystalline coatings

40.5 × GaAs/ $Al_{0.92}Ga_{0.08}As$

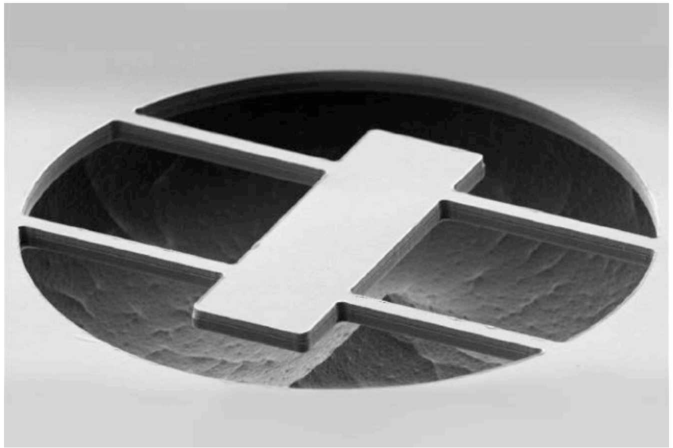


fused silica

crystalline coating

Spin-Off of Quantum Optomechanics

Epitaxial AlGaAs micro resonators



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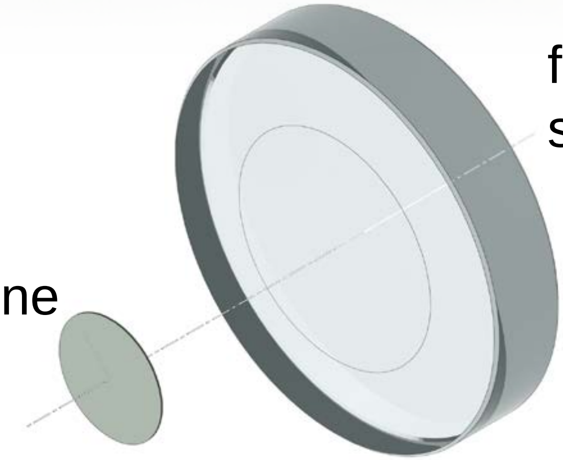

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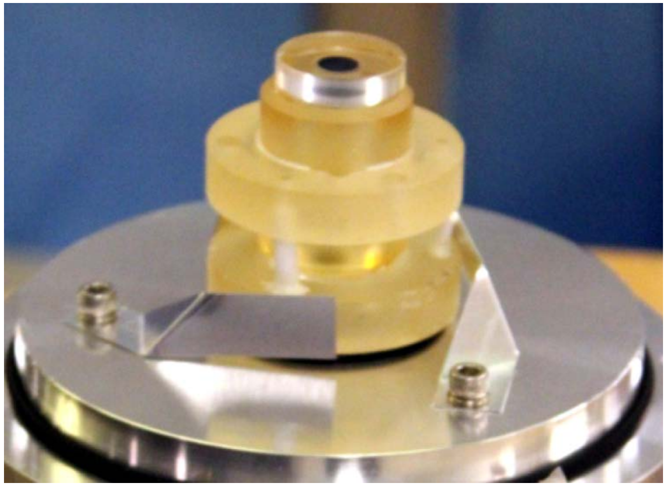
Fixed-Spacer Reference Cavity

- Zerodur spacer with optically contacted AlGaAs-on-silica mirrors
  - short cavity length to accentuate mirror thermal noise effects
- Cavity mounted in a temperature controlled vacuum chamber
  - eliminate index variations and spacer thermal fluctuations
  - nodal support to minimize acceleration sensitivity
- Prototype and test-bed for opto-mechanical performance verification
  - cavity used for the construction of a stabilized laser at 1064 nm



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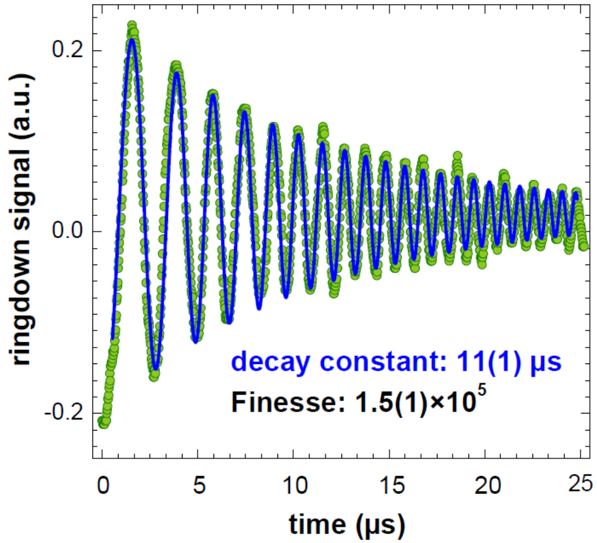

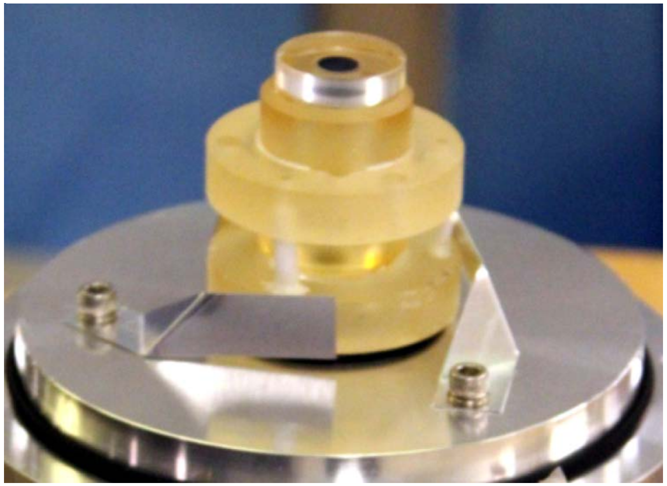

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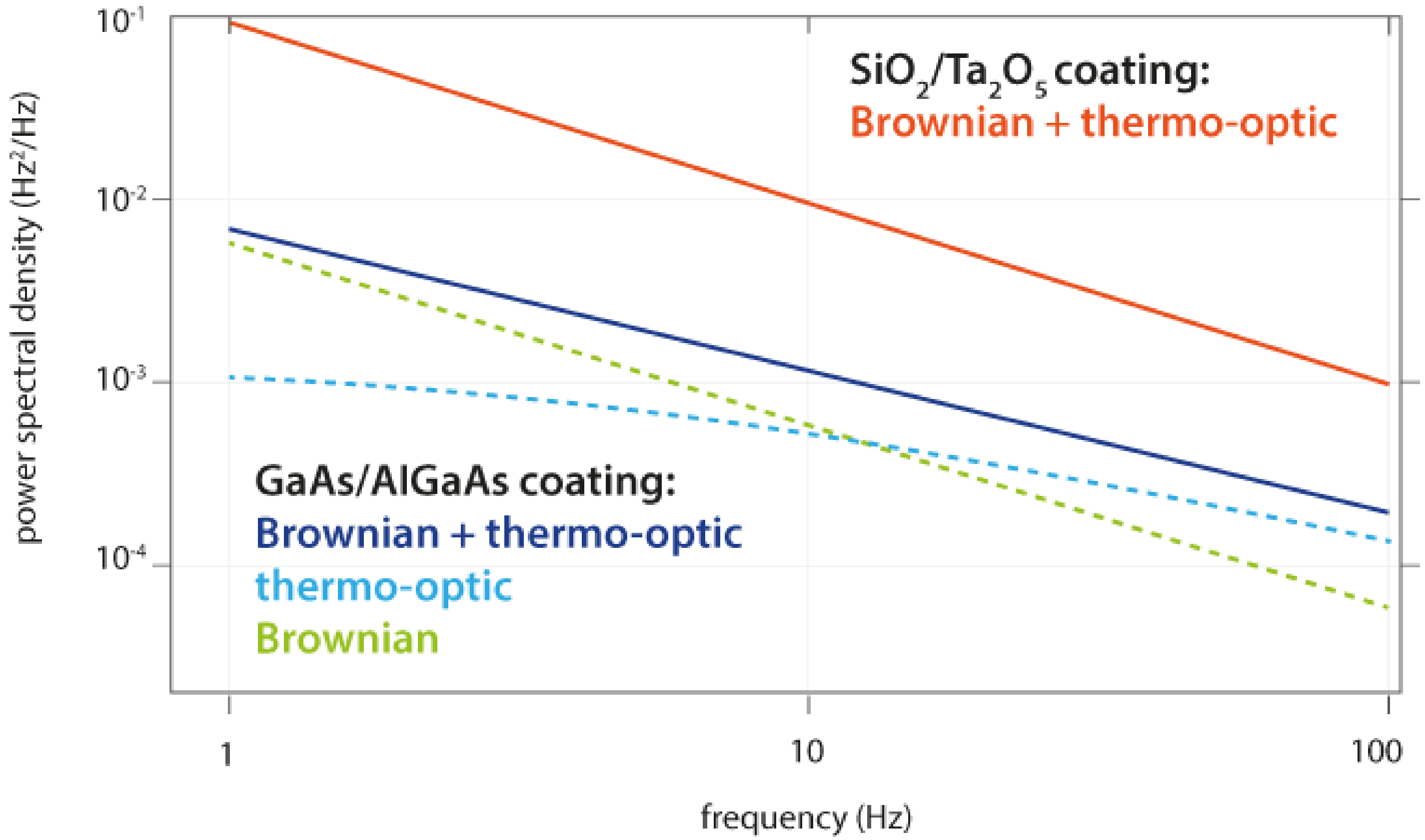
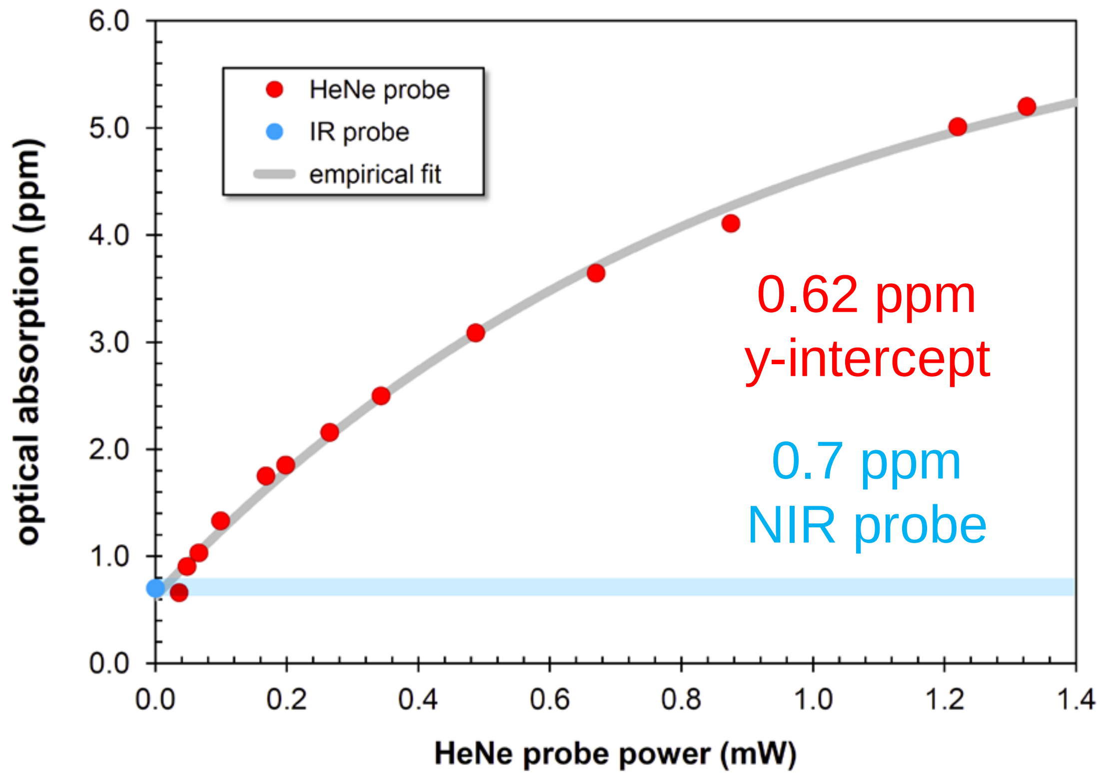
Reduced Brownian Noise



- Tenfold reduction in mechanical dissipation at room temperature
- Further 10 × improvement upon cooling to cryogenic temperatures

G. D. Cole, W. Zhang, M. J. Martin, J. Ye, and M. Aspelmeyer, Nature Photonics (2013)

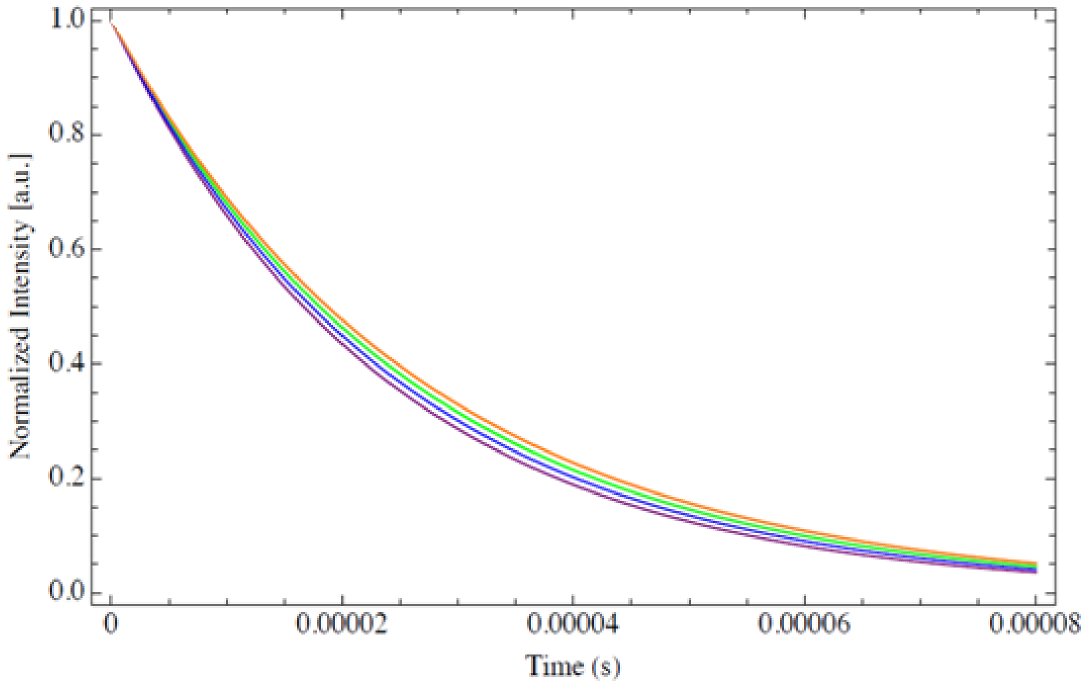
Sub-ppm NIR Absorption

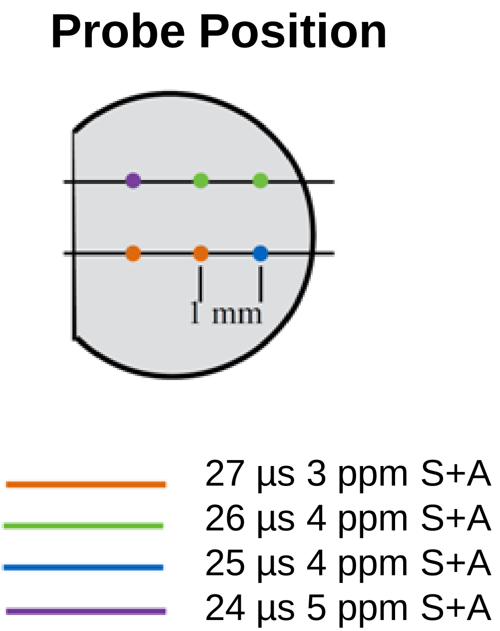


- Red HeNe probe in PCI system limits minimum absorption value
  - the use of a transparent near-IR probe is now being investigated
- Probe-power dependent measurements yield sub-ppm absorption

Measurements by Dr. Alexei Alexandrovski, SPTS Pahoa, HI

Optimized Coating Process

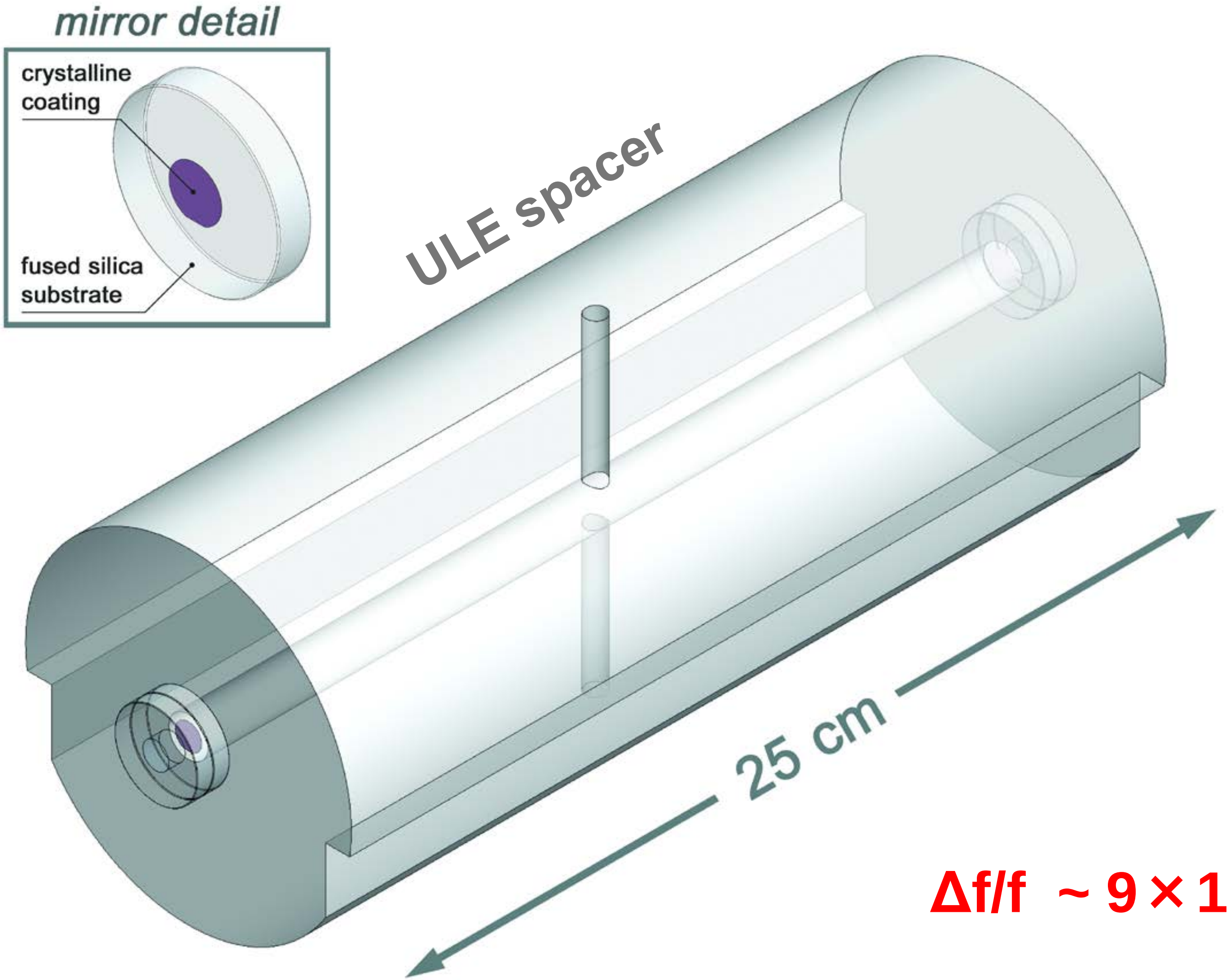




- Epitaxial growth process has been optimized for low defect density
  - full effusion cells, clean chamber walls, optimized subs. temperature
- Microfabrication-based transfer process also optimized (cleaning)
  - consistent, position-independent losses as low as 3 ppm now possible

Measurements by W. Zhang and L. Sonderhouse, JILA, at SLS (Mark Notcutt), Boulder, CO

JILA 25-cm Long RT Reference Cavity



$\Delta f/f \sim 9 \times 10^{-17}$

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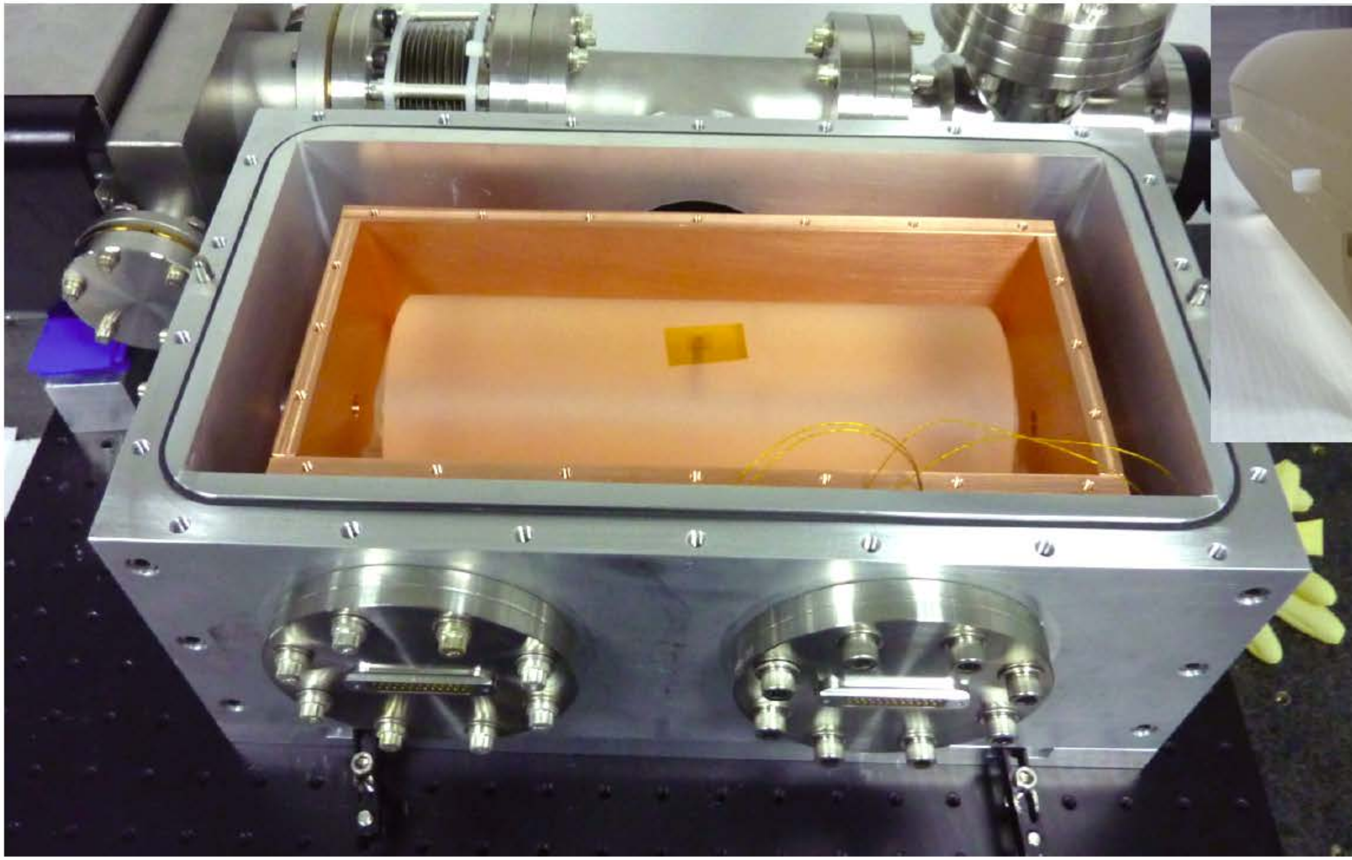
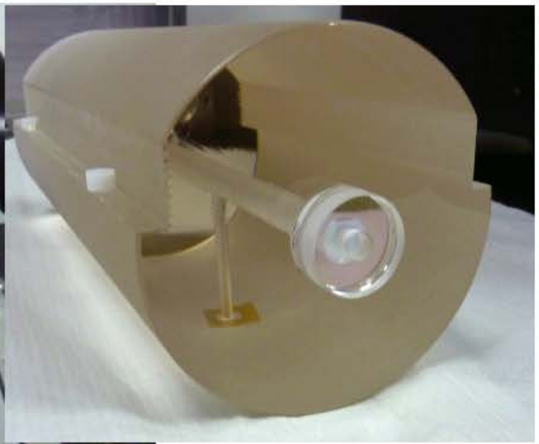
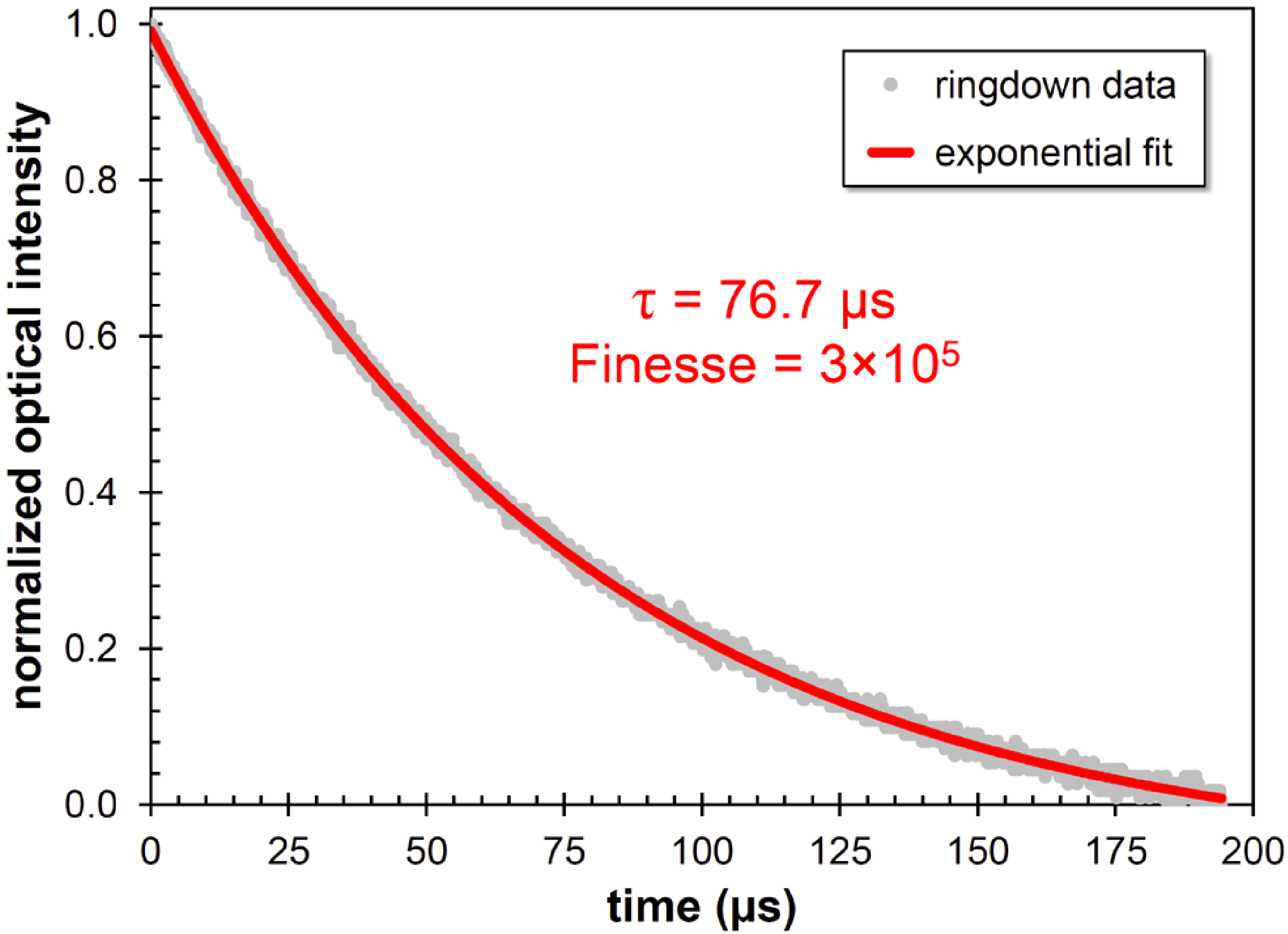




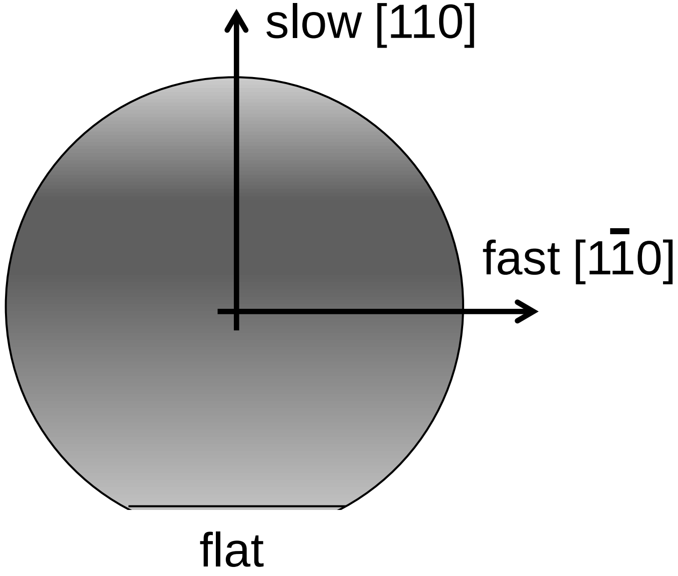
- “Cutout” spacer design for minimizing acceleration sensitivity
- Cavity will ultimately be used for fiber stabilization system @ JILA

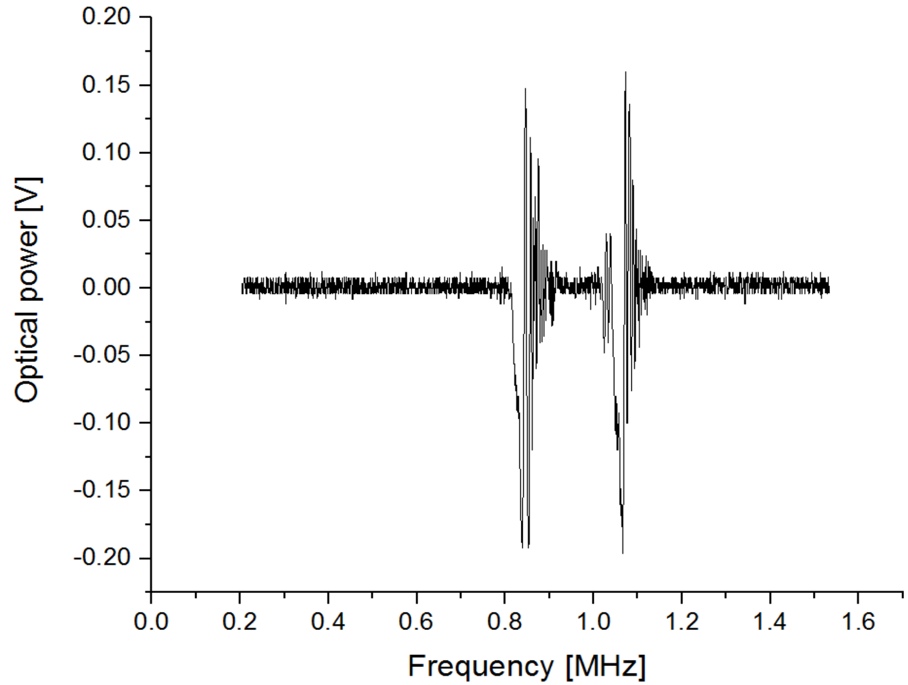
300,000 Finesse



G. D. Cole, et al., pre-print arXiv:1604.00065 (2016)

Cavity Birefringence





- Crystalline coatings yield a relatively strong cavity birefringence
  - ~1-5 $\times$ 10^{-3} compared with 10^{-4} to 10^{-6} for amorphous multilayers
- Polarization eigenmodes are well resolved, splitting >> linewidth
  - 220 kHz splitting compared with 2 kHz linewidth for 25-cm long spacer

G. D. Cole, et al., pre-print arXiv:1604.00065 (2016)

Summary

Substrate-transferred crystalline coatings simultaneously exhibit **excellent optical and mechanical quality**

- Damping reduction of 10-100× compared with IBS films
  - IBS-deposited Ta_2O_5/SiO_2: typical Q ~3000 ($\varphi_{IBS} \approx 2\text{-}4 \times 10^{-4}$)
  - AlGaAs room temperature Q-value of 4×10^4 ($\varphi_{RT} \approx 2 \times 10^{-5}$)
  - AlGaAs cryogenic performance: Q > 1×10^5 ($\varphi_{min} \approx 4.5 \times 10^{-6}$)
- Minimal scattering loss and optical absorption
  - absorption verified at < 1 ppm (< 0.01 cm^{-1} at 1064 nm)
  - RMS micro-roughness of 1.3 Å RMS (< 3 ppm at 1064 nm)
- Excess losses (S+A) down to levels < 5 ppm
  - measured finesse of >2×10^5 at 1064, 1397 and 1550 nm

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Challenges in Implementation

- Minimizing thermo-optic noise in crystalline coatings
  - large thermal expansion coefficient (thermo-elastic noise)
  - large thermo-refractive coefficient (thermo-refractive noise)
- Substrates are a major question mark, 2 paths forward:

  Homoepitaxy (AlGaAs on GaAs): highest material quality
  - maximum wafer size (200 mm) is a serious limitation
  - solution: ~$5M investment for >30-cm Ø GaAs crystal growth

  Heteroepitaxy (AlGaAs on Si/Ge): wafers up to 450 mm Ø
  - background doping (i.e. interdiffusion of Ge) must be minimized
  - surface roughness needs to be improved (nm scale at this point)
  - verified mechanical loss angle of 8×10^{-6} (5 K) w/ T. Corbitt
  - solution: intensive materials development effort required

T. Chalermsongsak, et al., Metrologia, vol. 53, 860 (2016)

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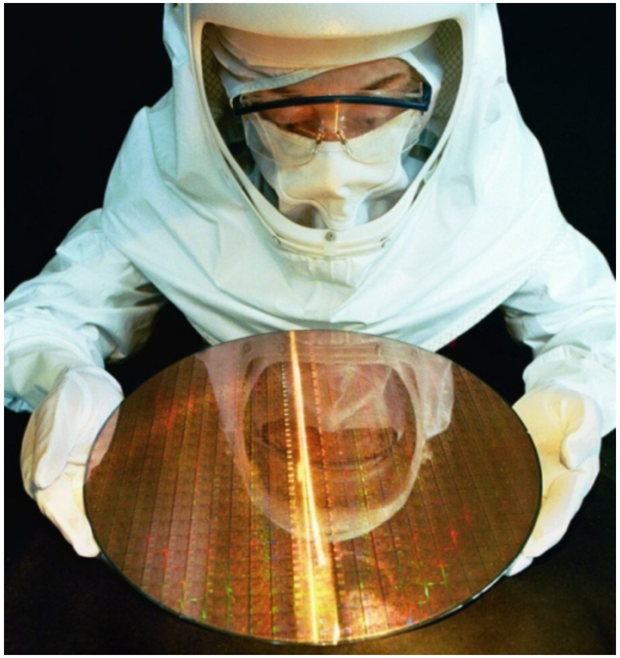
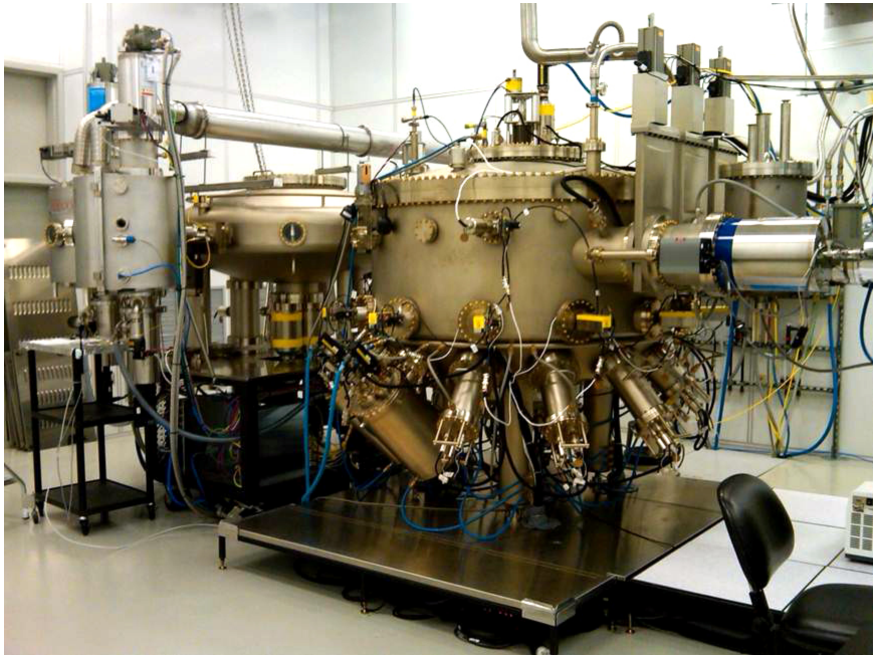
- Development of custom tools, both growth and bonding

Scalable Production Technique



- Substrate-transfer process leverages existing infrastructure
  - high-uniformity epitaxial growth on large-diameter substrates
  - void-free direct bonding of crystalline semiconductors
  - commercial tools available for arbitrary mirror sizes

Exploit Semiconductor Infrastructure



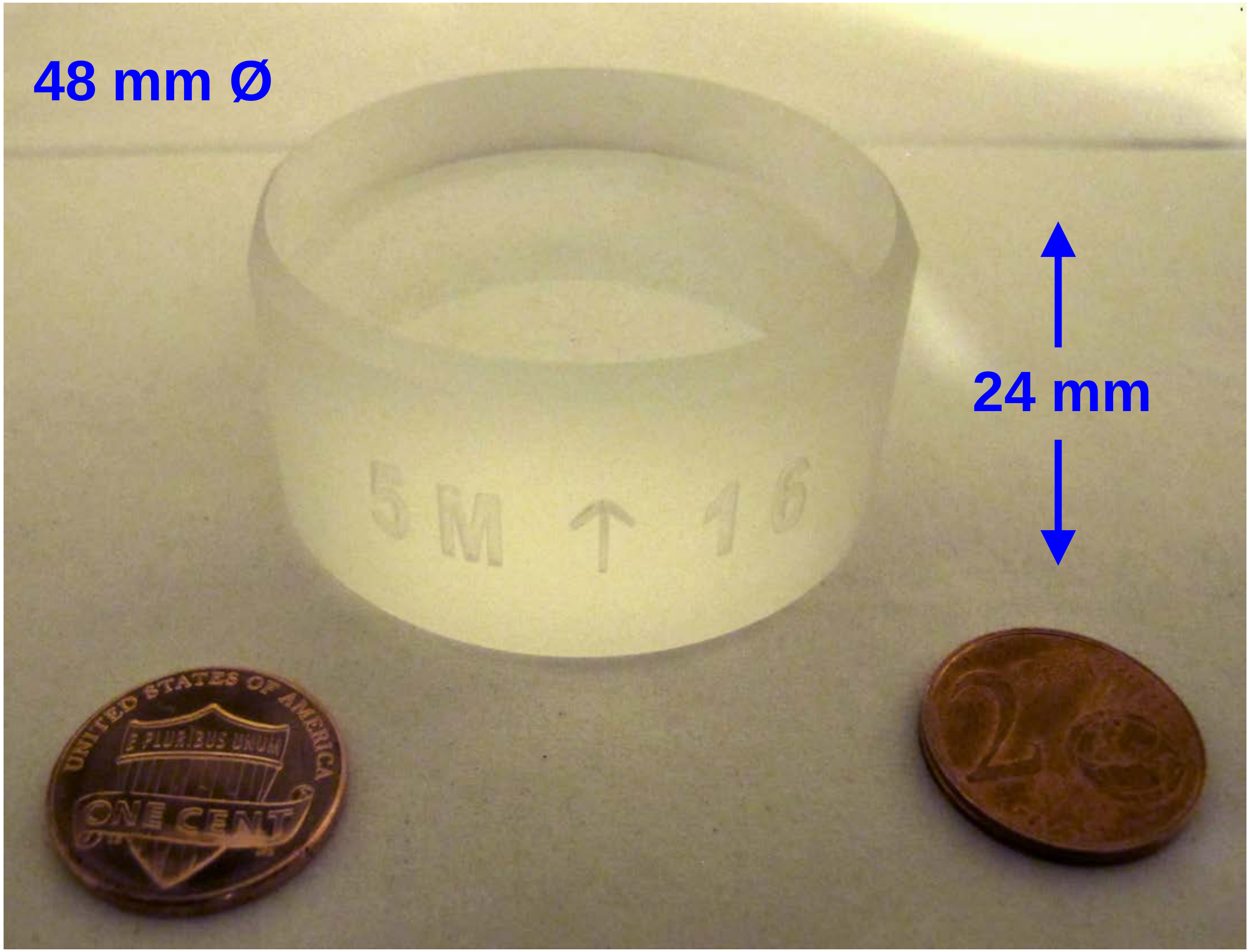
- Production MBE reactors for microwave electronics
  - 7 x 150-mm or 4 x 200-mm wafers (Veeco GEN2k/Riber 7000)
- Direct bonding systems for SOI wafer production
  - industrial tools capable of bonding 450-mm diam. wafers

* Photo credit: Bob Yanka, RFMD; Veeco GEN2000 multi-wafer production MBE system

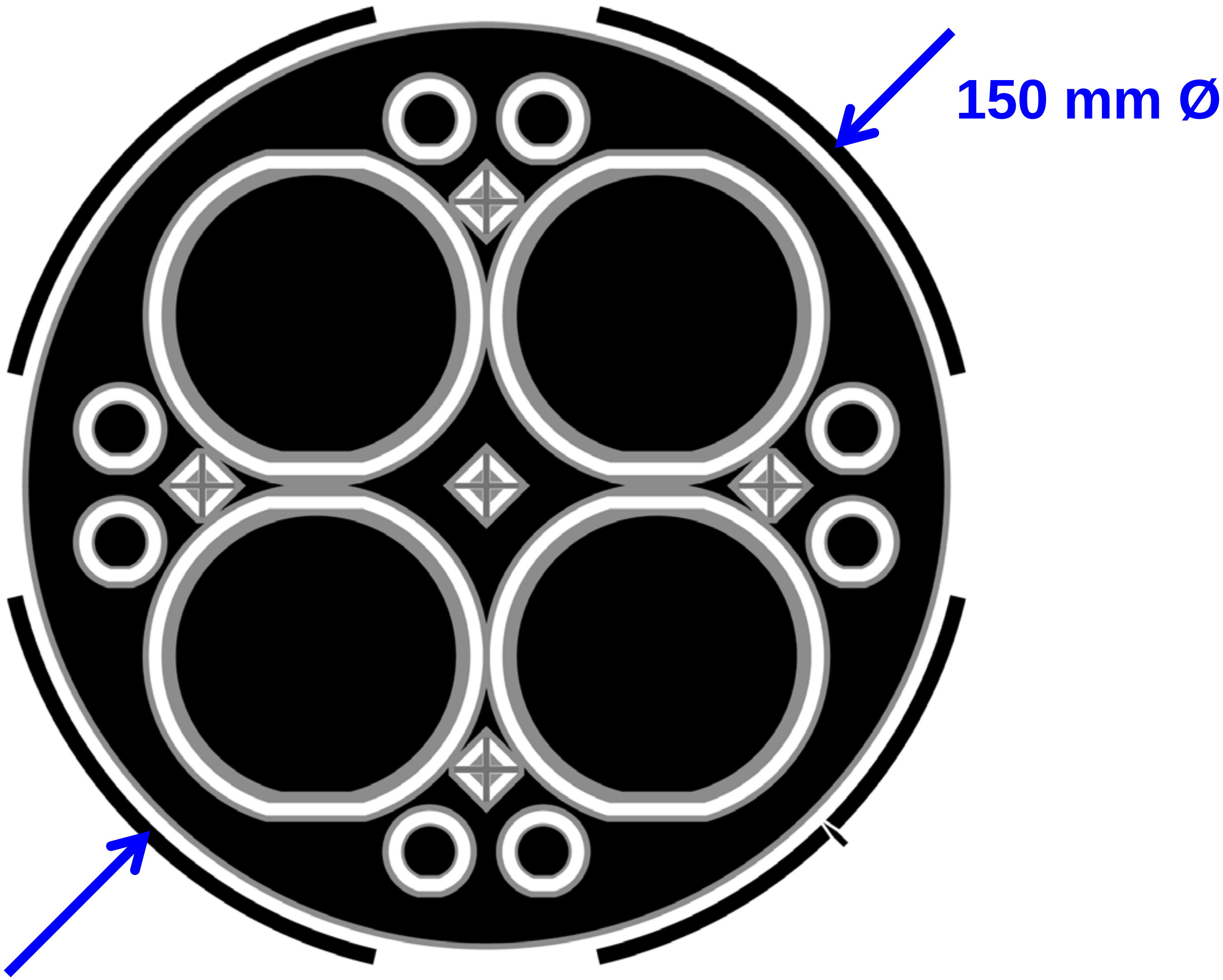
First Test: AEI "SQL Optics" Effort

- Goal: produce high-performance large-area crystalline coatings
  - must realize defect (i.e. void and particle free) direct bonding
  - ensure the highest optical quality, enabling ppm-level optical losses
- Can we achieve a sufficiently high yield to produce such optics?

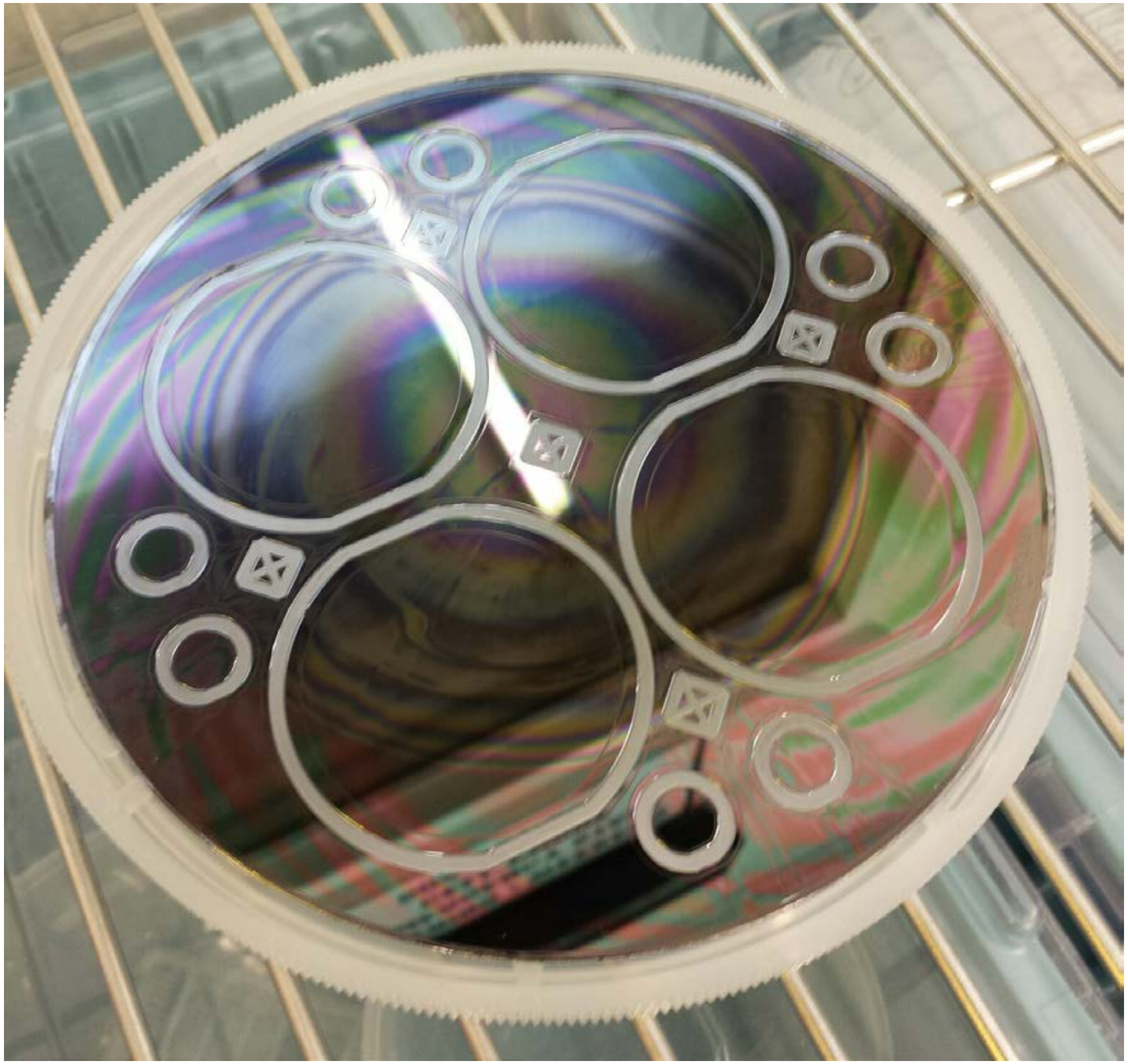
Large-Area Prototype Optics



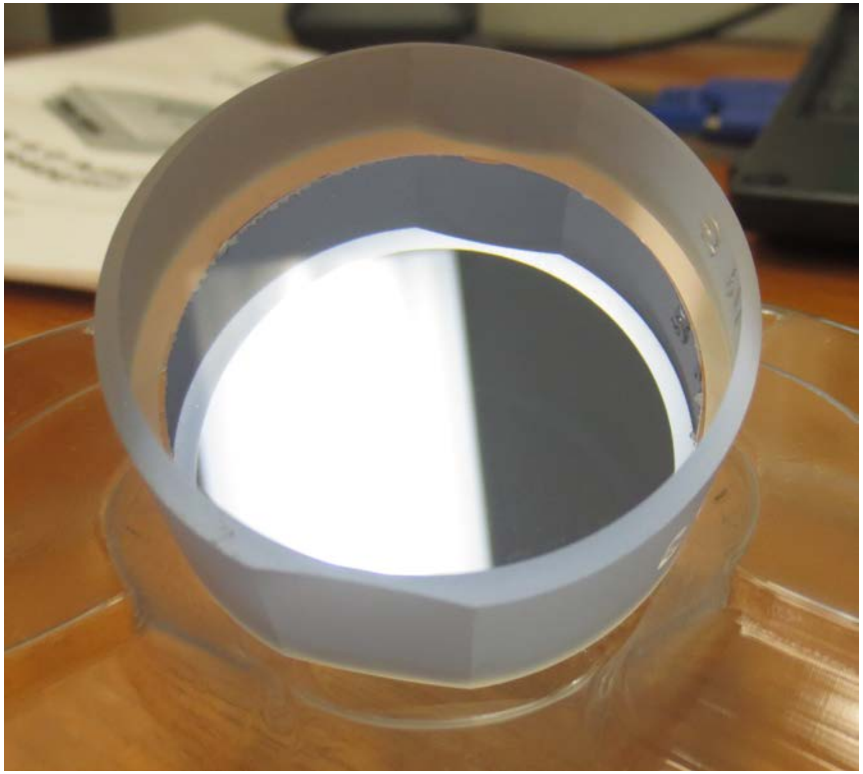
Coating Disc Definition



Partially Processed Coatings



First Test Parts, April 13, 2016



Proposed Next Steps

Crystalline coatings are a viable option for large-area low-noise optics, though a lot of work remains to be done

- Properties must be studied against LIGO specifications
  - wavefront error of large-area coatings must be studied
  - the same samples can be used to verify optical (and potentially mechanical) performance of our coatings
- Further scaling investigations must be initiated
  - a staged approach involving increasingly larger optics should be started as soon as possible (150 or 200 mm diameter parts?)
- GaAs substrate development will have to start soon
  - crystal growth manufacturers need ~2-3 year head-start
  - can be co-funded via semiconductor microelectronics industry

The Current CMS Team












Thank You For Your Attention!