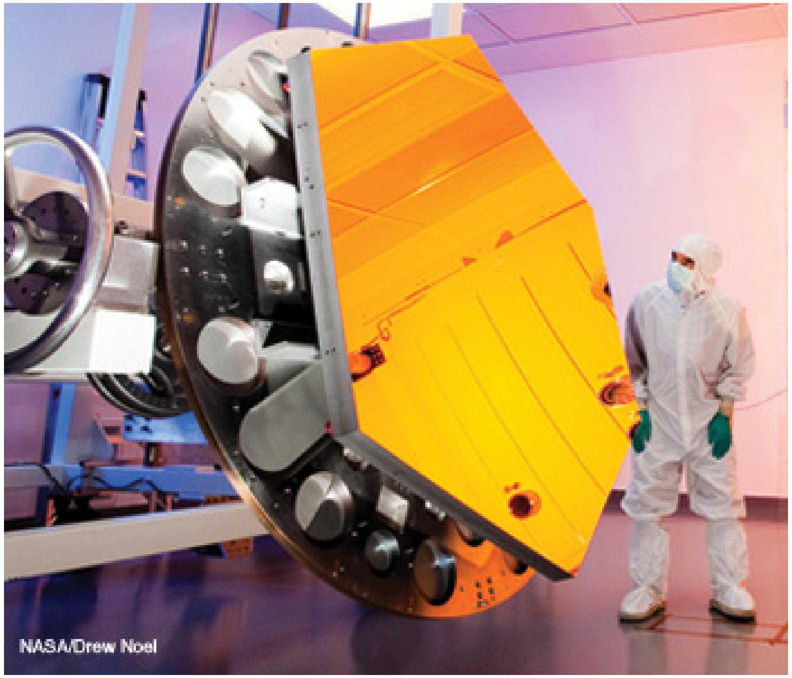
CMS

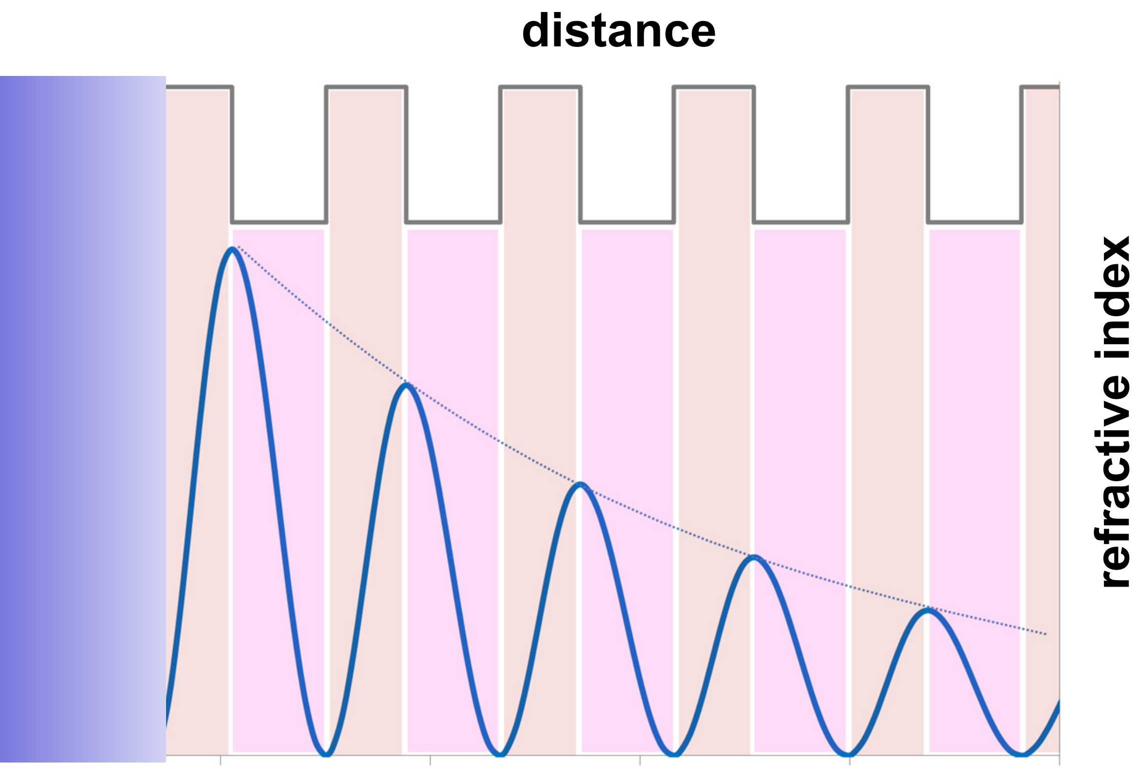
CRYSTALLINE MIRROR SOLUTIONS

Semiconductor Supermirrors: When planar wafer bonding just isn't hard enough…

September 5, 2019



- Two main classes of thin-film reflective optical coatings
    1. simple metallic mirrors: single or protected Ag, Al, or Au layer
    2. interference coatings: alternating transparent dielectric films
- Properly designed interference coatings exhibit lower losses



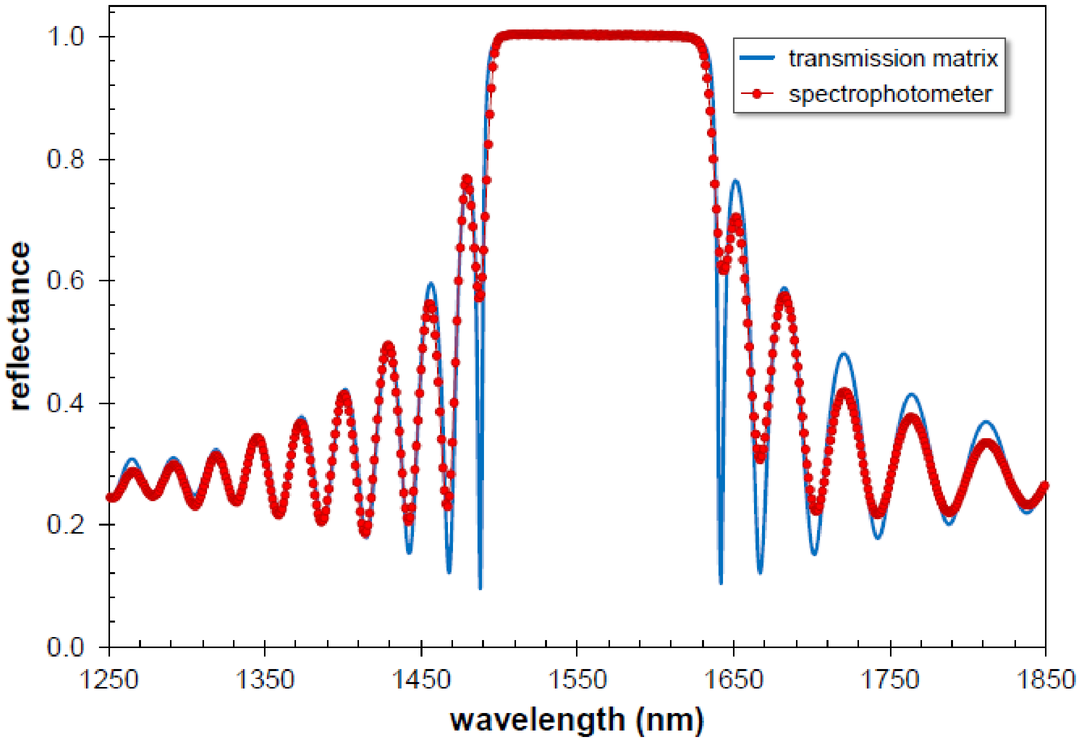
Interference leads to rapid decay of optical field in Bragg reflector

Three loss mechanisms:

i) transmission
ii) absorption
iii) scatter

- Alternating layers of high / low index quarter-wave thickness thin films
  - at Bragg wavelength internal reflections add in phase, max. reflectivity
- Individual layers are transparent, yielding low absorption reflectors
  - losses ultimately constrained by layer design, impurities, and roughness

Interference Coatings (a.k.a. Bragg Mirrors)



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Timeline of Competing Coating Technologies

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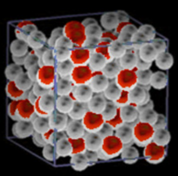
Current amorphous coatings



1857
Arc
Evaporation

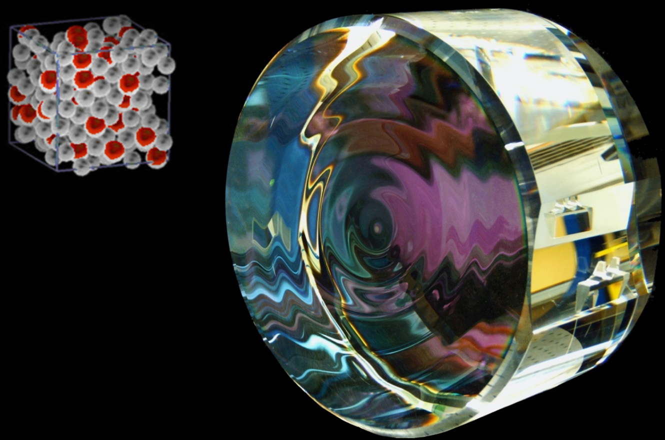
1907
E-beam
Evaporation

1939
Magnetron
Sputtering

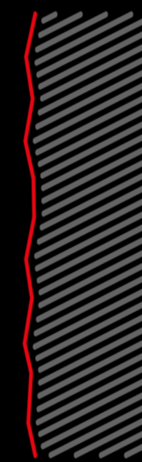
1979
Ion-beam
Sputtering

Timeline of Competing Coating Technologies

Fluctuating mirror



Brownian noise



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Timeline of Competing Coating Technologies

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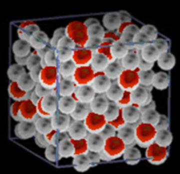
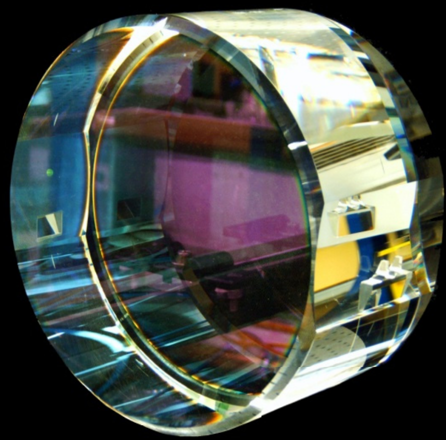
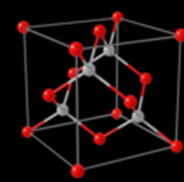




Semiconductor Supermirrors



1857
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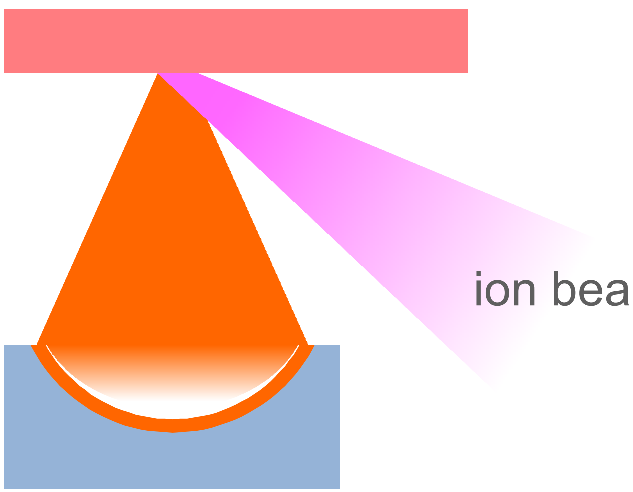
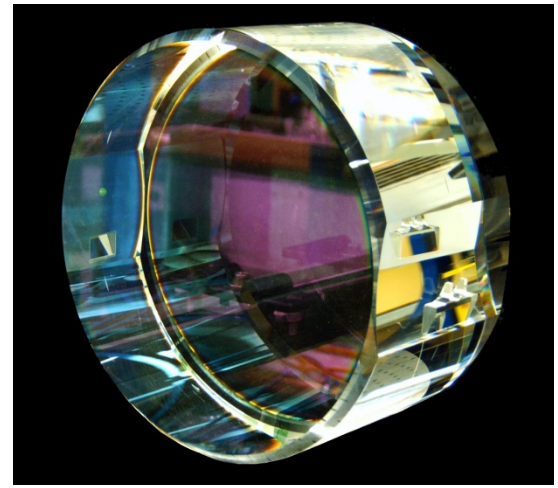
Sputtering

2012
Crystalline Coatings

Physical Vapor Deposition of Amorphous Coatings

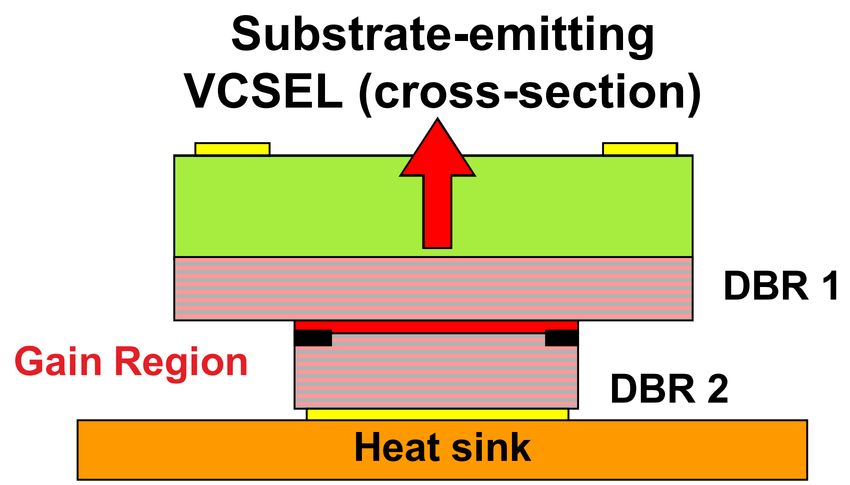


State-of-the-art multilayer mirrors:
ion-beam sputtered Ta_2O_5/SiO_2



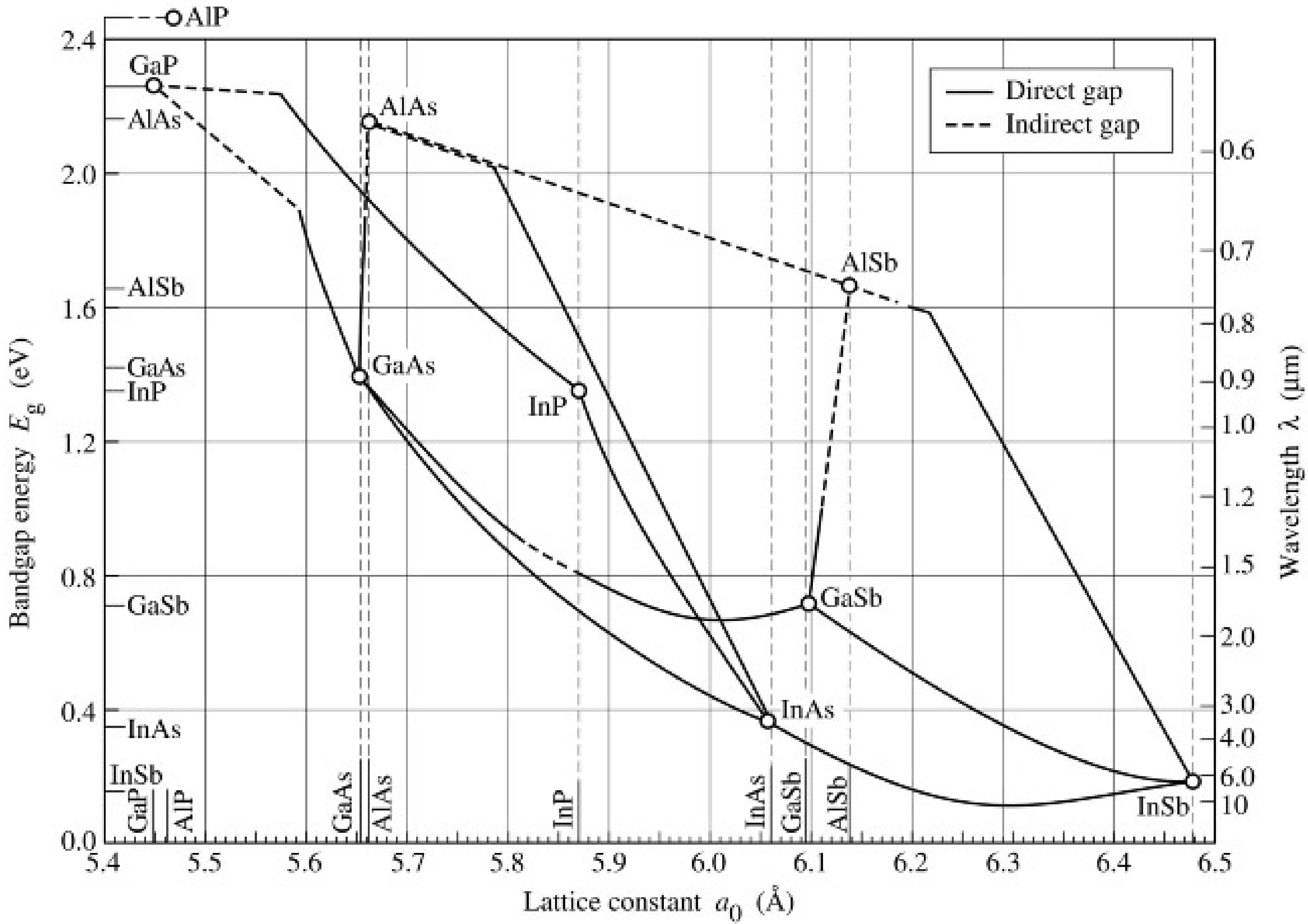
- Multilayer of amorphous thin films via ion beam sputtering (IBS)
- Phenomenal optical properties: high R, low absorption and scatter
- Flexible choice of substrates assuming excellent surface quality
  - super-polished SiO_2, Si, ULE, sapphire, etc.

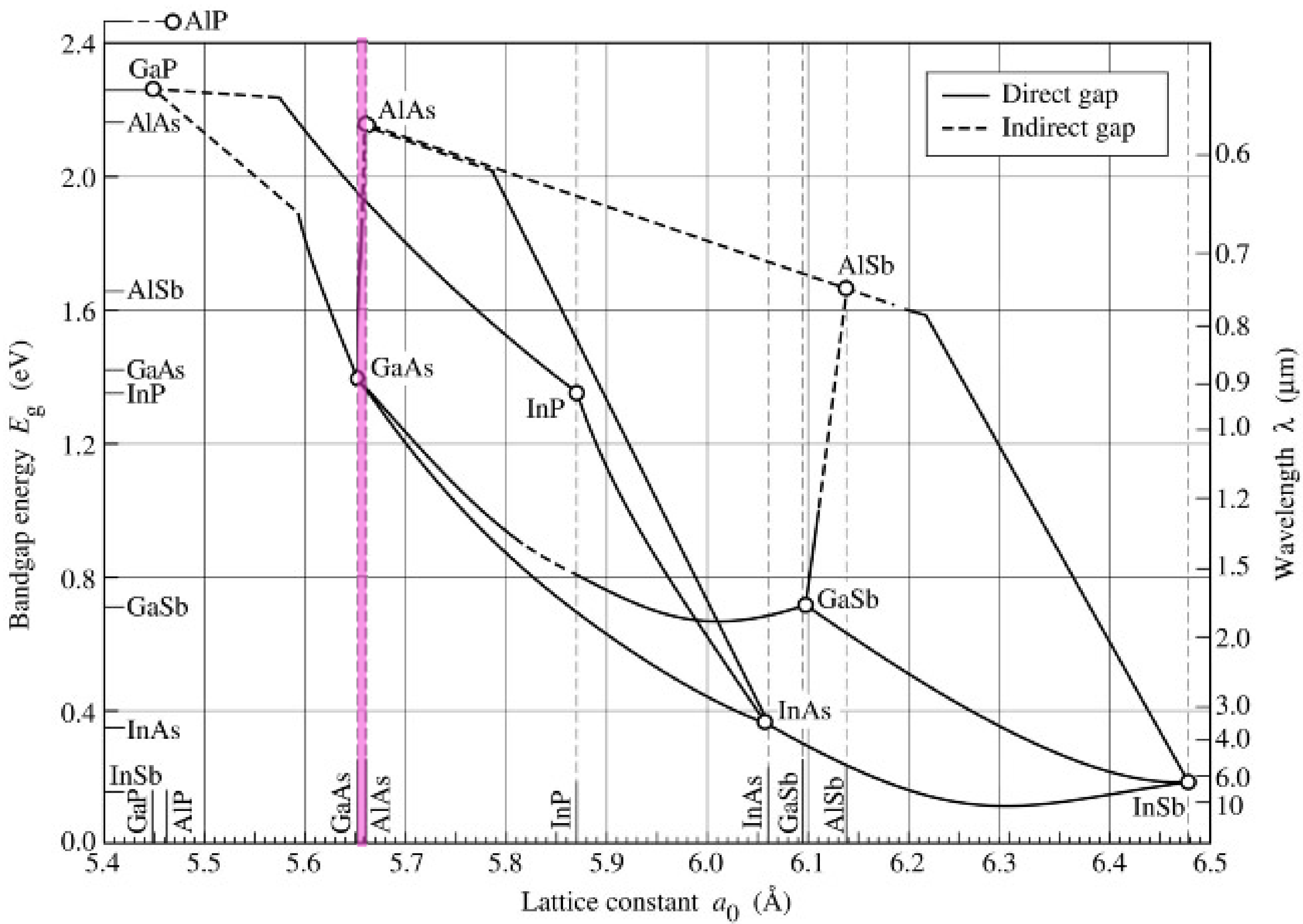
- First demonstrated in 1975
  - interference coatings by van der Ziel and Ilegems, Bell Labs
- Primary application: VCSELs
  - K. Iga's group (Tokyo) and Bell Labs (Jewell et al.)
  - VCSELs consist of high-reflectivity mirrors surrounding a semiconductor microcavity
  - global VCSEL market estimated to be worth $3.6B by Q4 2020
- Lattice matching constraints limit substrate selection
  - monocrystalline multilayers require a crystalline template



Large-aperture linear VCSEL array, Aerius Photonics, LLC (FLIR Electro-Optical Components)

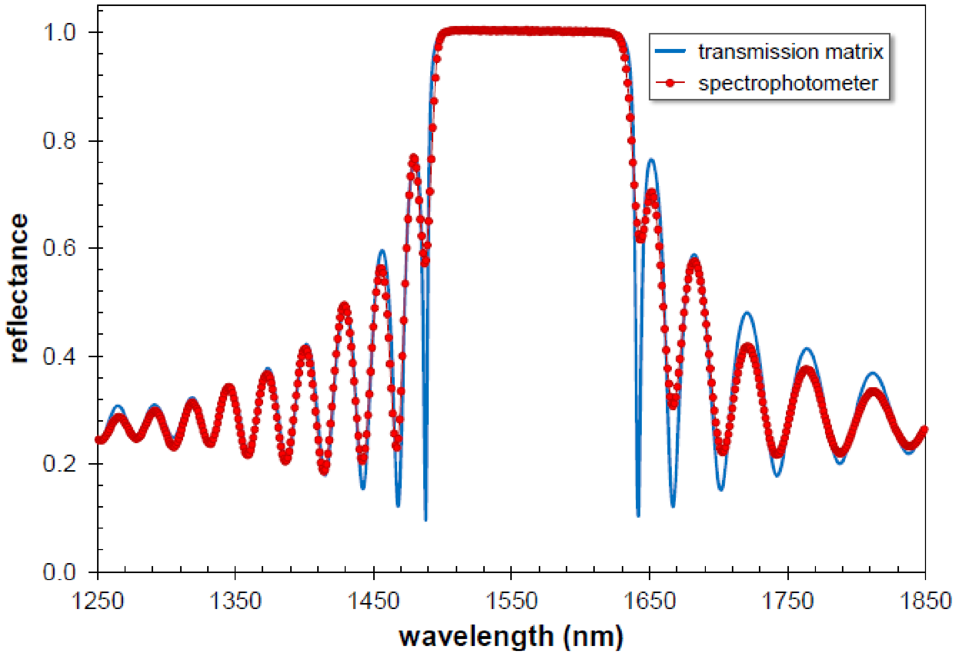
Lattice Matched Epitaxial Multilayers

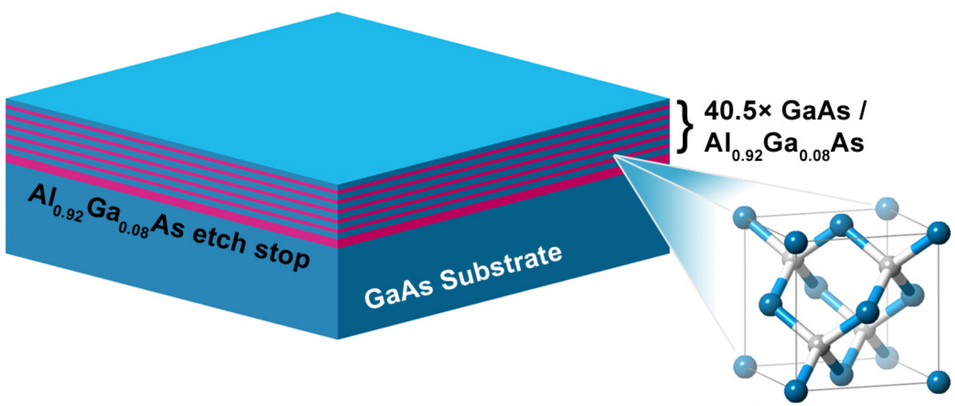




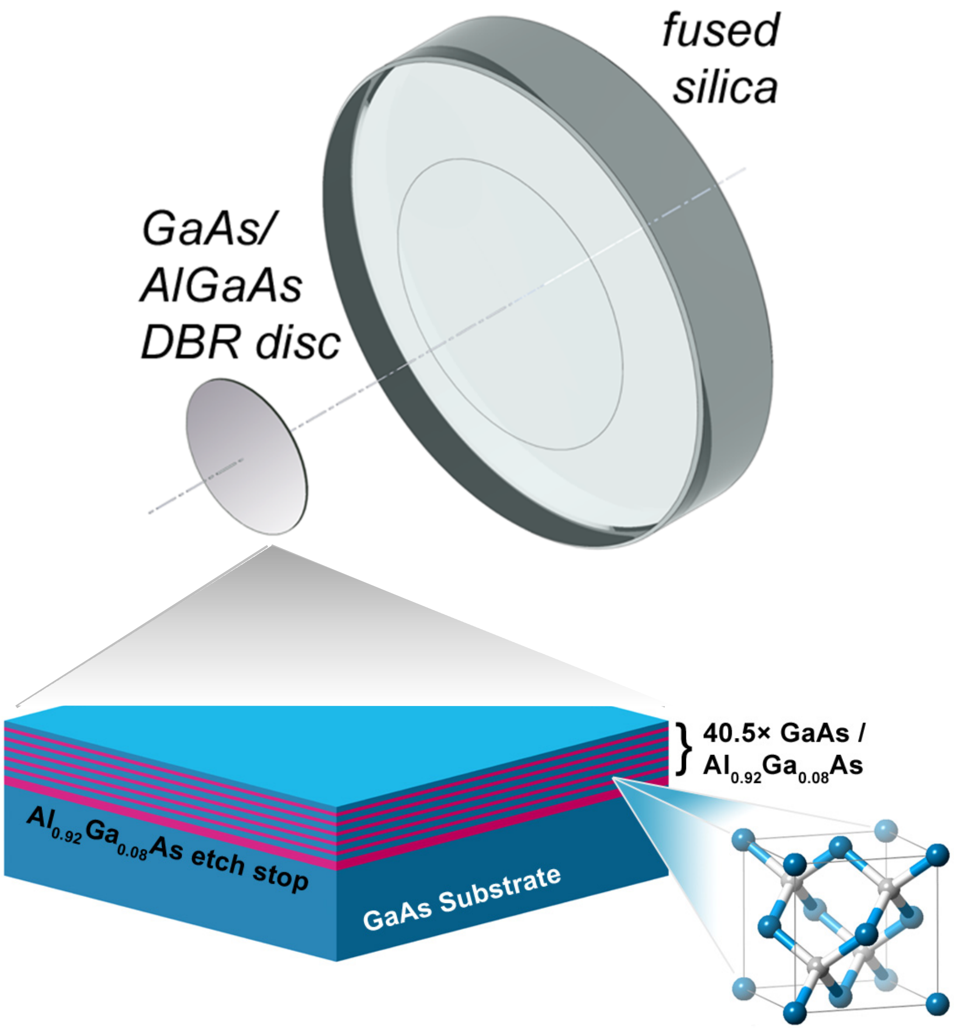
AlP
GaP
AlAs
GaAs
InP
AlSb
GaSb
InAs
InSb
Direct gap
Indirect gap
Bandgap energy E_g (eV)
Wavelength λ (μm)
Lattice constant a_0 (Å)
2.4
2.0
1.6
1.2
0.8
0.4
0.0
5.4
5.5
5.6
5.7
5.8
5.9
6.0
6.1
6.2
6.3
6.4
6.5
0.6
0.7
0.8
0.9
1.0
1.2
1.5
2.0
3.0
4.0
6.0
10

Epitaxial Bragg Mirrors





- 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
- Epitaxy generates DBRs with low defect density, high purity, and excellent thickness control
  - limited by lattice matching…
- Leverage transfer & direct bonding to overcome this
  - commonly employed process, e.g. for manufacturing SOI (silicon-on-insulator) wafers up to 45 cm in diameter



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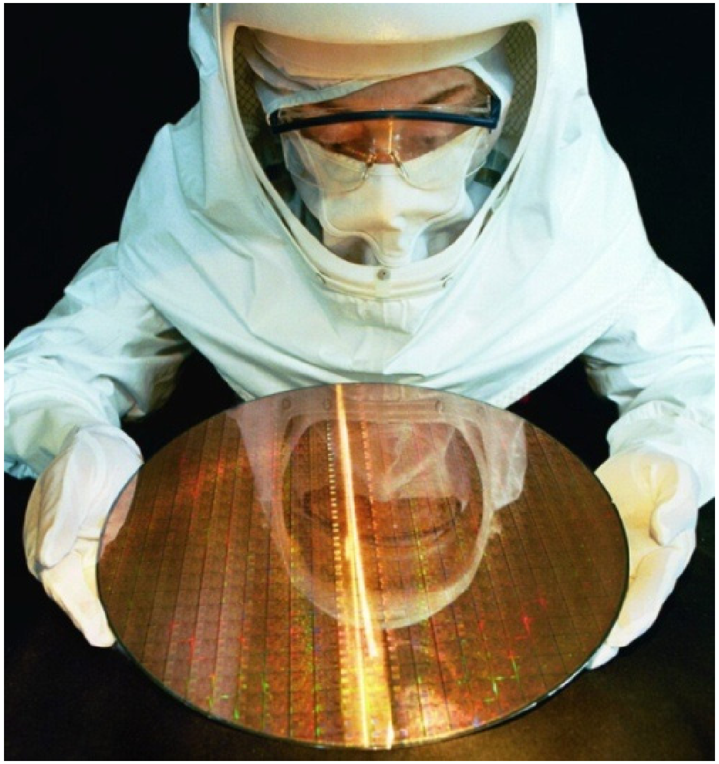
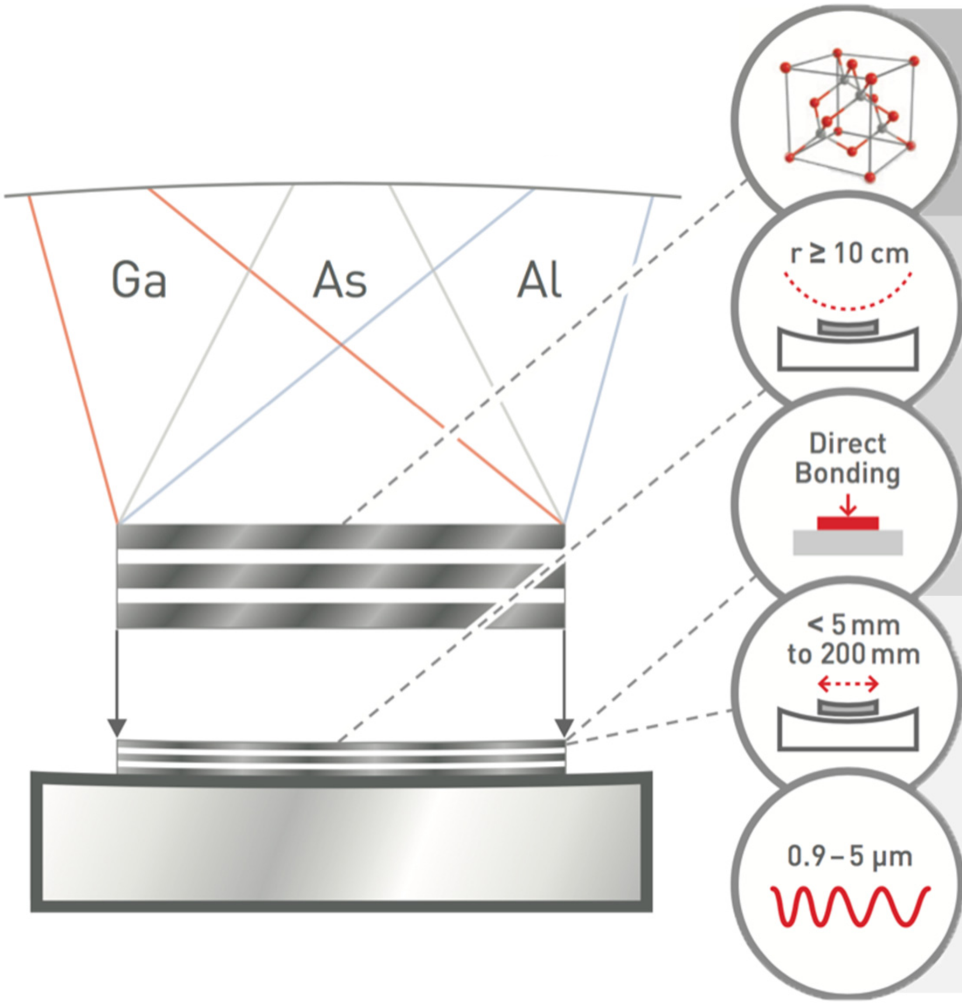


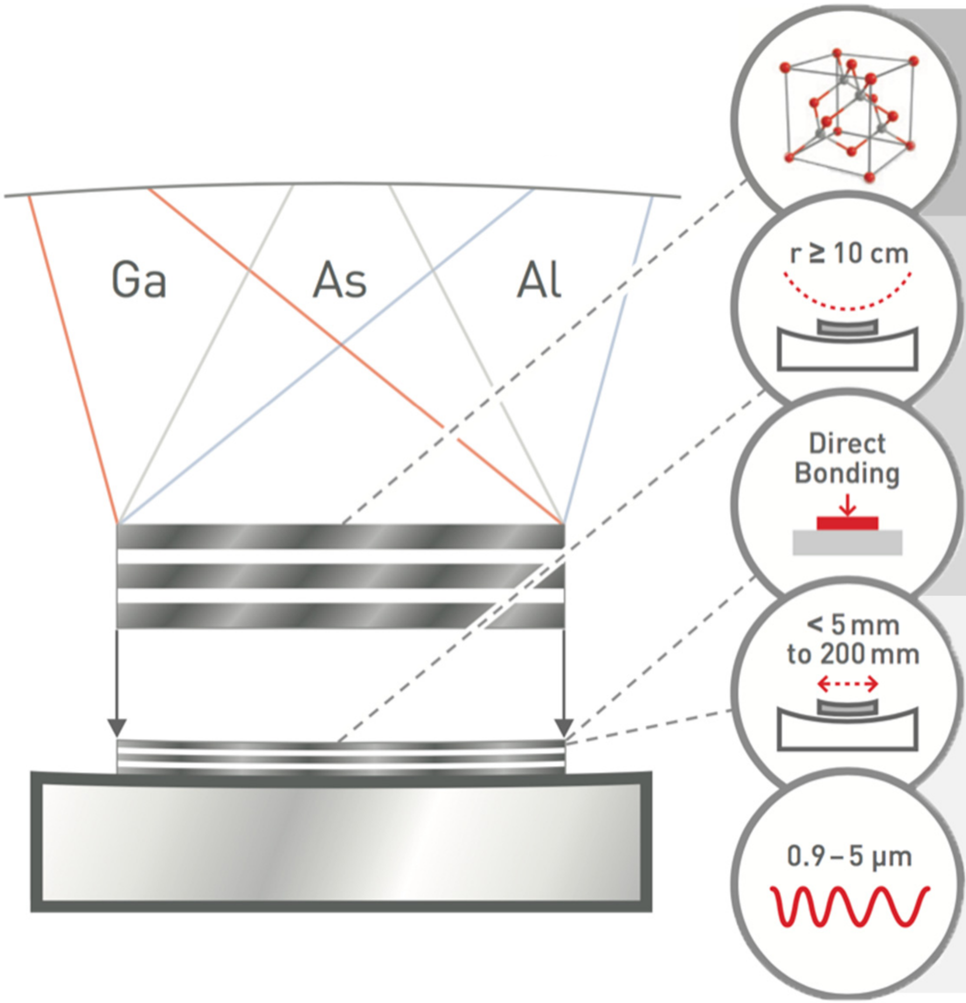
Merging Semiconductor Manufacturing with Bulk Optics



Monocrystalline GaAs/AlGaAs heterostructures grown on GaAs wafers by molecular beam epitaxy

Using semiconductor manufacturing techniques, the multilayer is extracted from the original GaAs wafer

Direct bonding is used to attach the single-crystal interference coating to the final optical substrate



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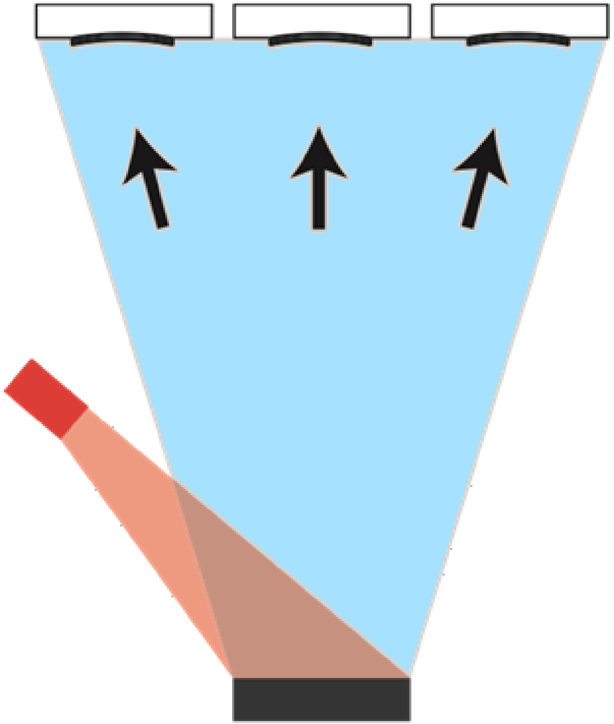
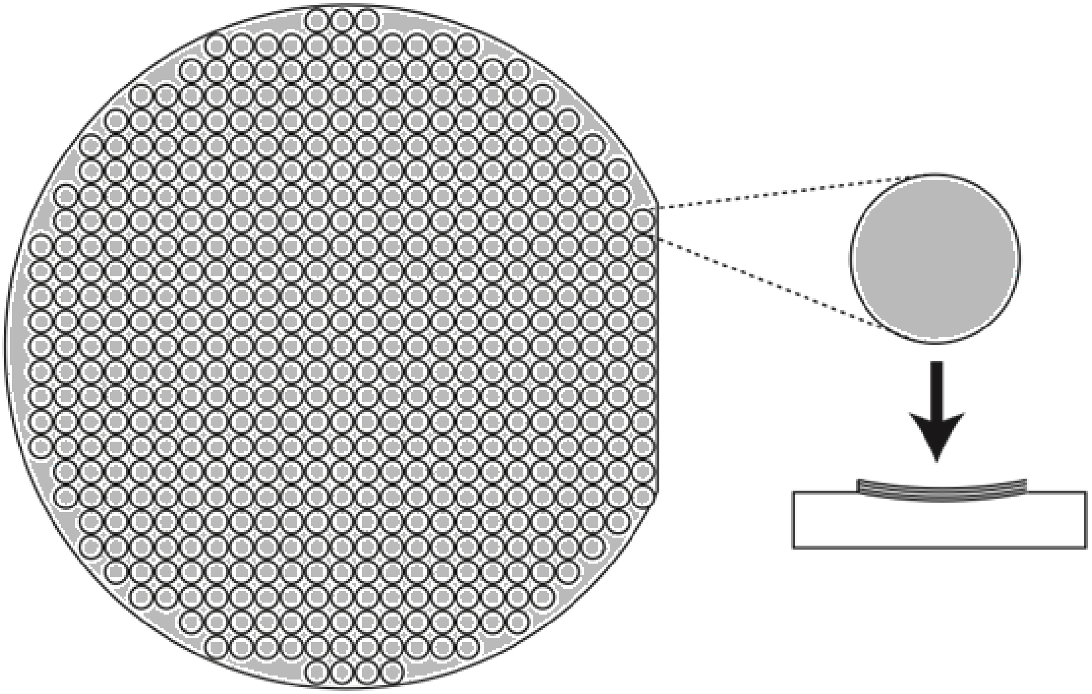
Epitaxial multilayers on arbitrary substrates

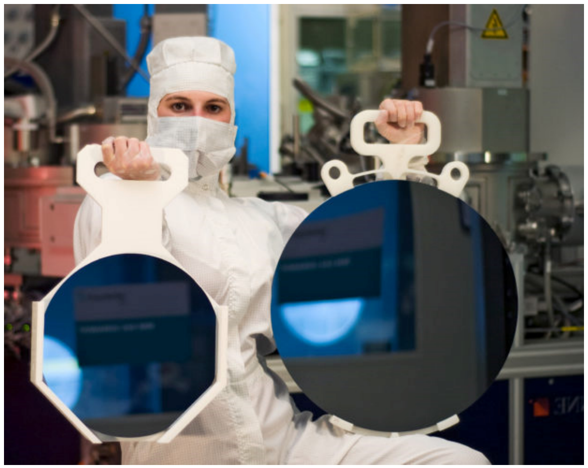
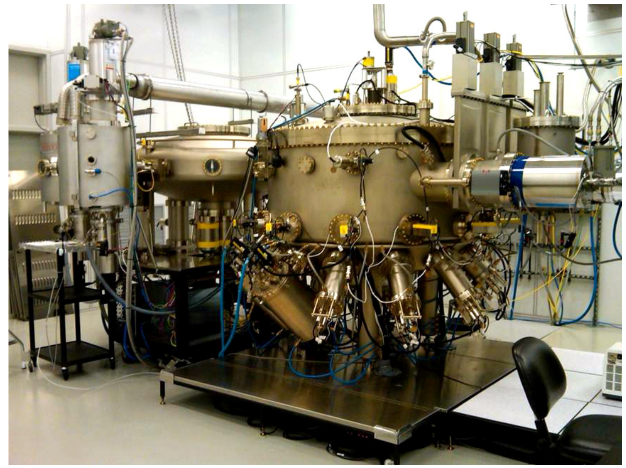
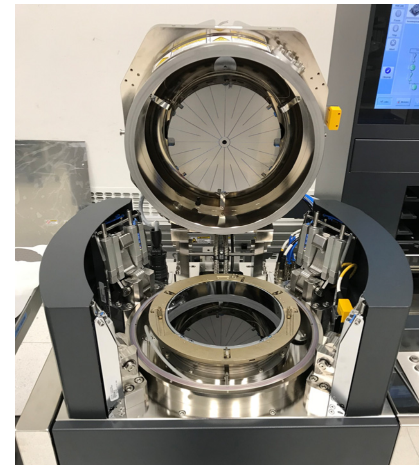




Physical vapor deposition can be realized on multiple substrates simultaneously

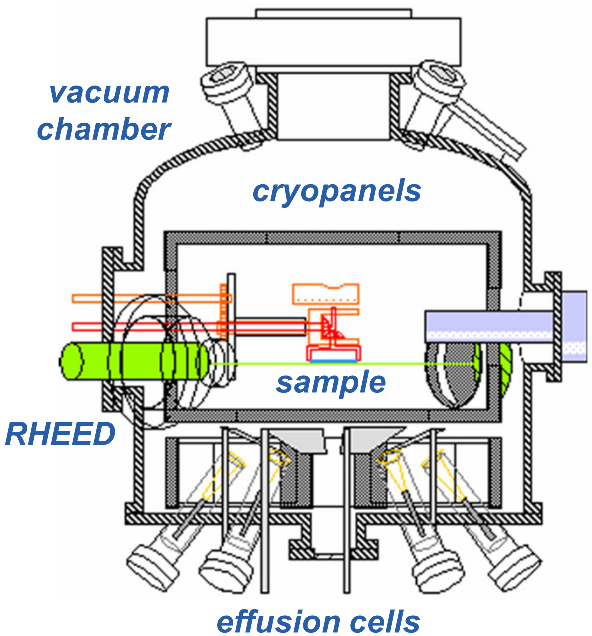
Wafer-scale batch fabrication enables the generation of many GaAs/AlGaAs mirror disks, though bonding remains a serial process

Manufacturing Inputs

GaAs wafers (seed crystal)	Crystal growth via MBE	Microfab & bonding
		

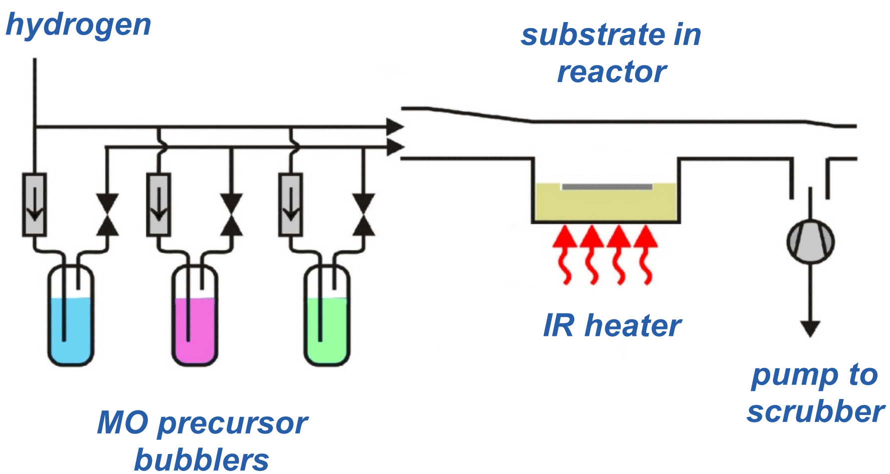
- Crystalline coatings entail a unique manufacturing process
  - we purchase base GaAs wafers from an external supplier
  - epitaxial growth of a custom designed multilayer w/ MBE
  - using a proprietary process we remove and directly bond the single-crystal multilayer to a super-polished substrate

Molecular beam epitaxy



- MBE enables low background doping, minimizing absorption
- Oval defects in GaAs (spitting Ga source) are a persistent problem

Metal organic chemical vapor deposition



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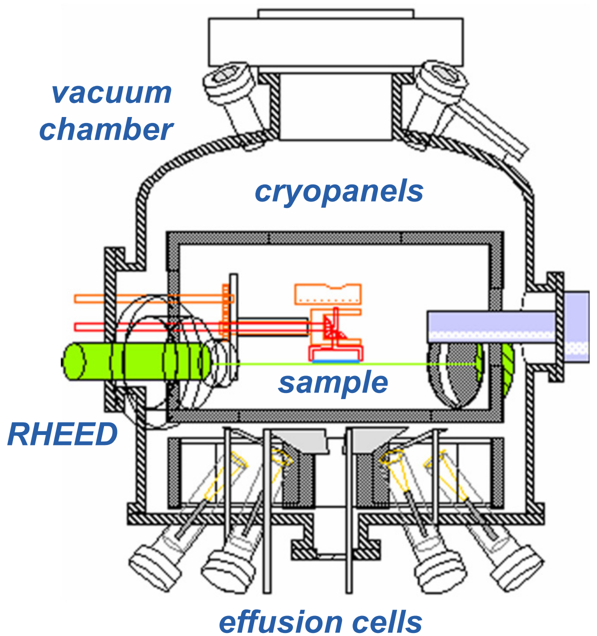
- An optimized MOCVD process can generate defect free films

Molecular beam epitaxy



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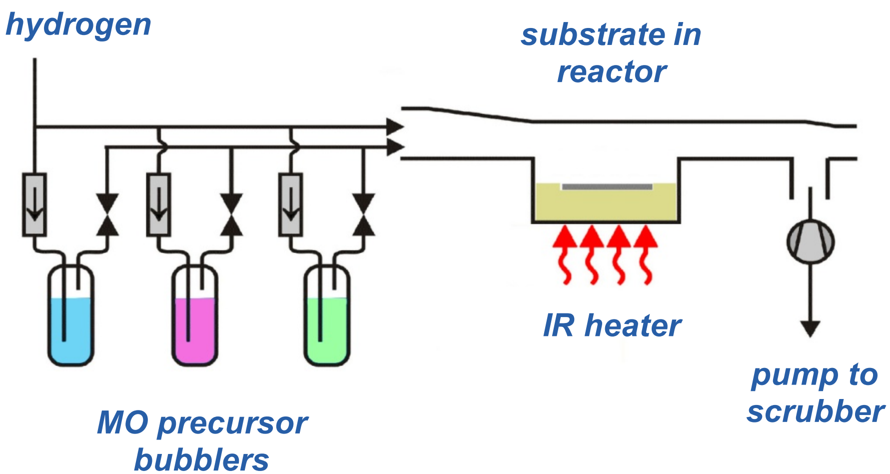

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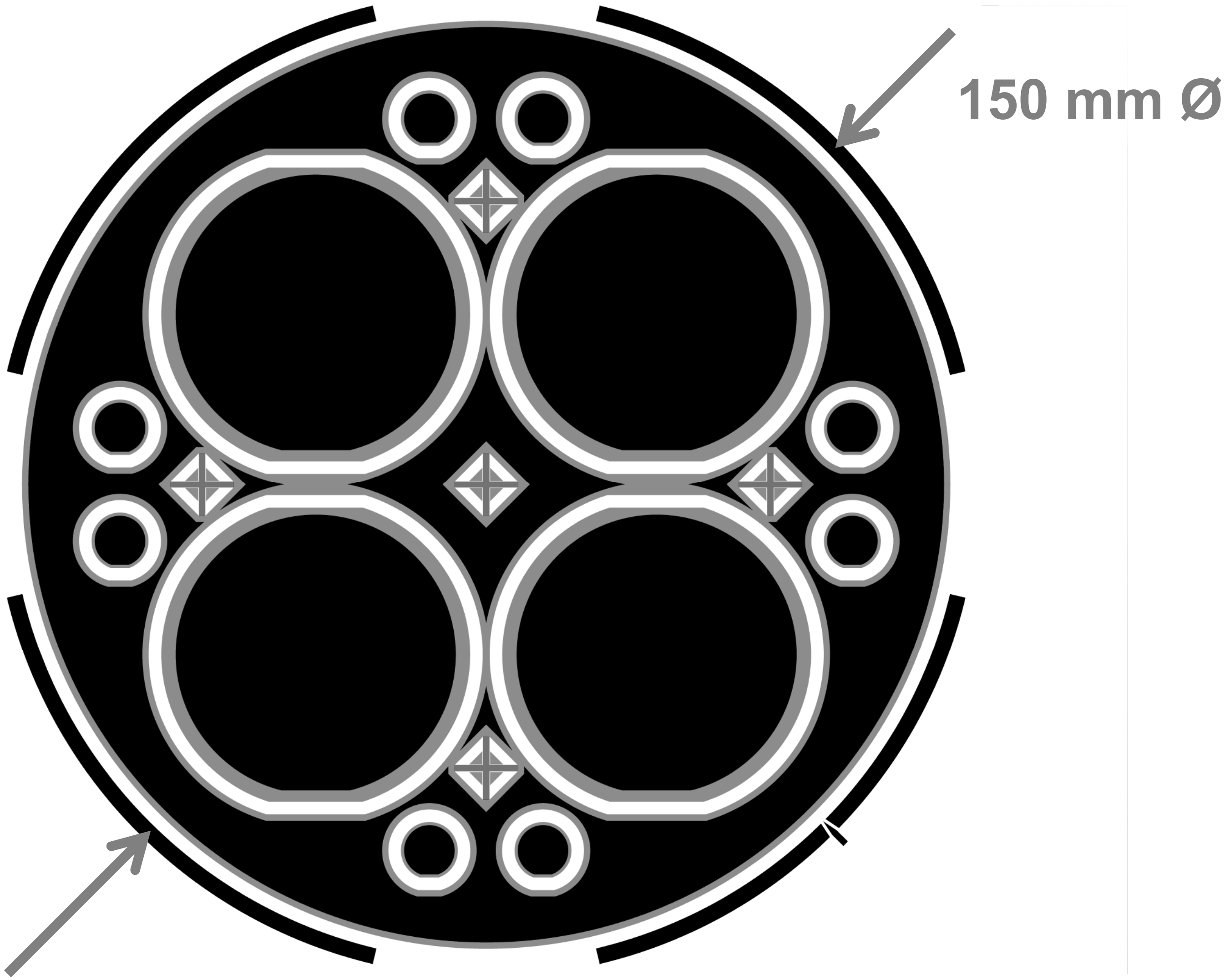
Substrate-Transfer Process: Step 1, Litho and Etch



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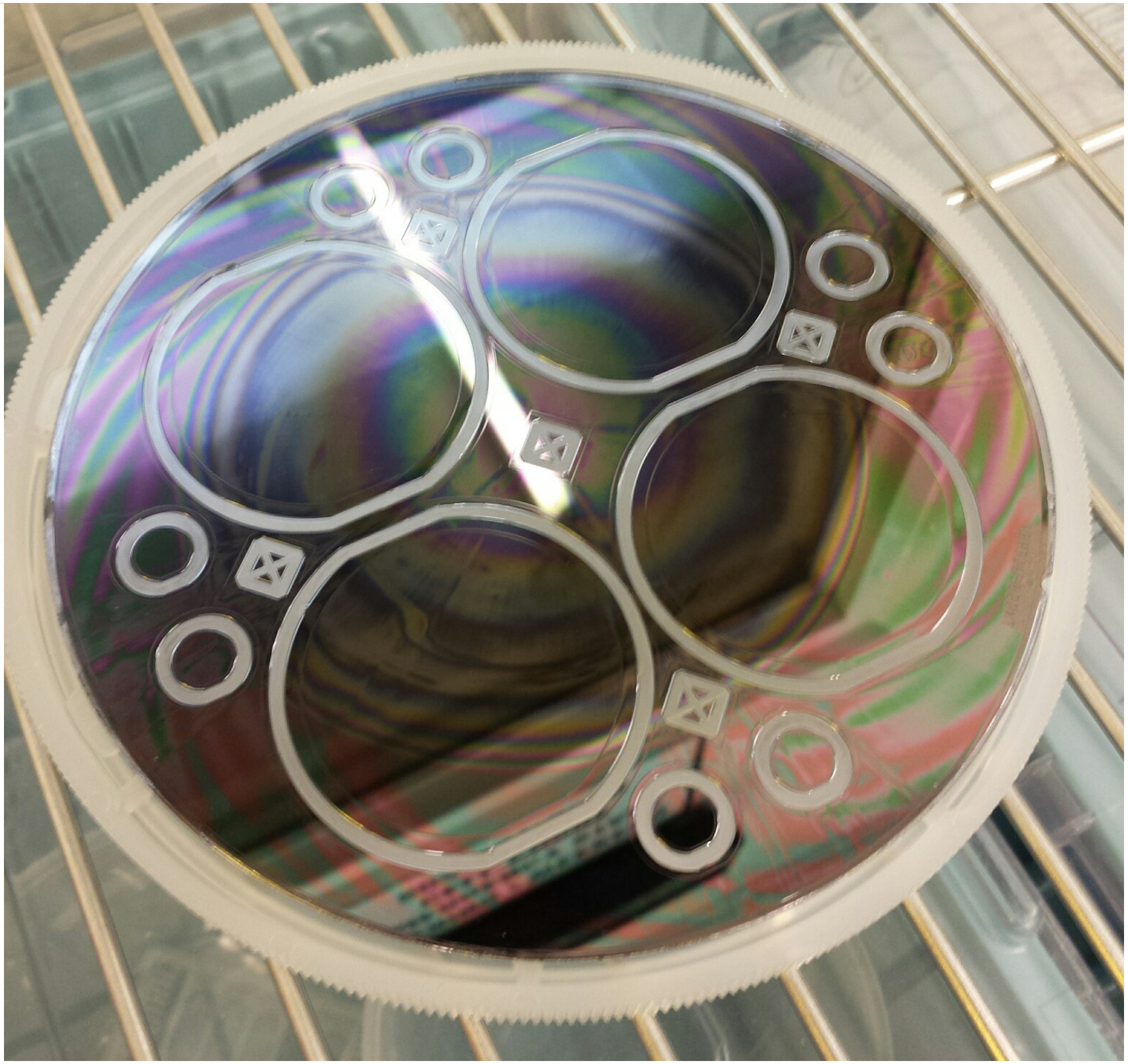
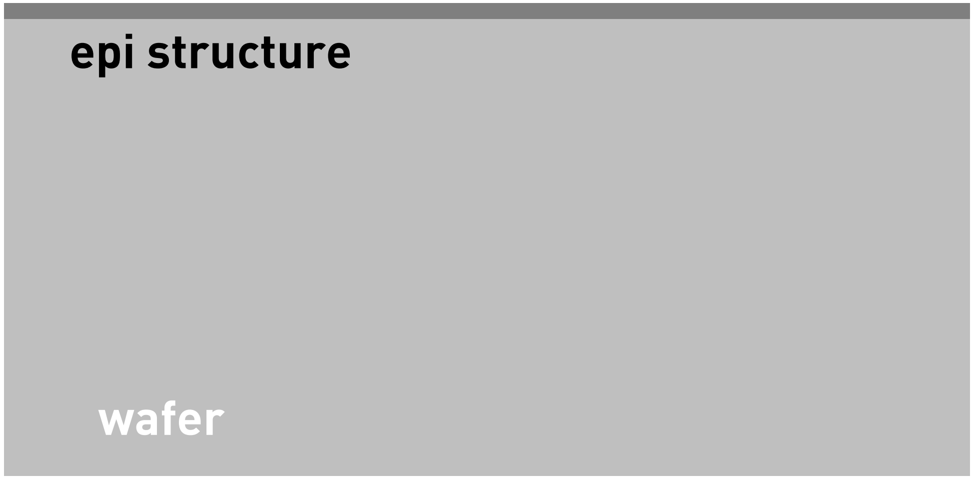


Step 2: Die Singulation via Lapping



- Contact lithography is used to define the coating geometry
  - a non-selective wet etch (H_3PO_4:H_2O_2:H_2O) transfers this pattern into the DBR and partially into the GaAs wafer
- A second mask is used to define a slightly larger mesa
  - the same chemistry is used to deep etch (150-250 μm) into the substrate (which is typically 675 μm thick)
- Lapping is used to thin the underlying wafer to ~100 μm
  - singulated die are generated with excellent control of the lateral geometry

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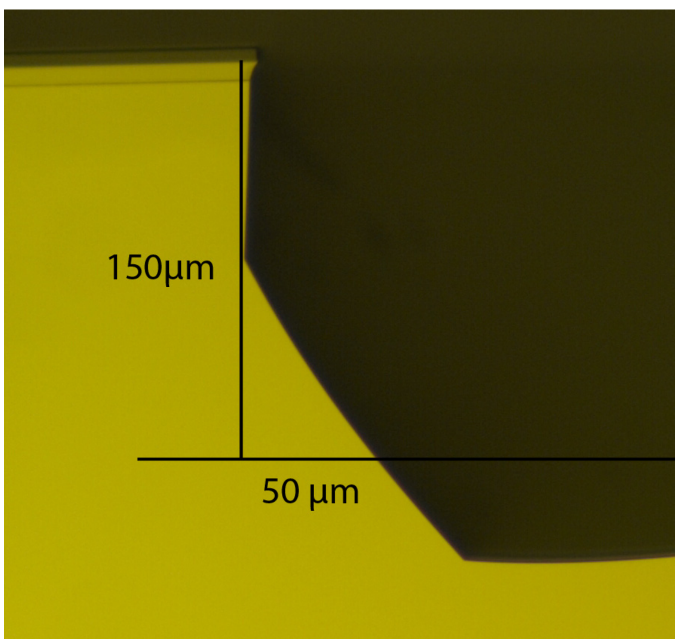

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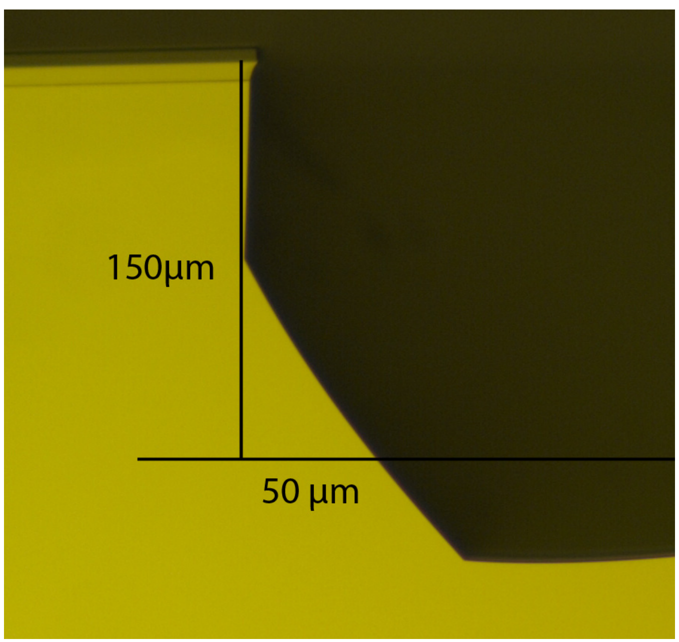

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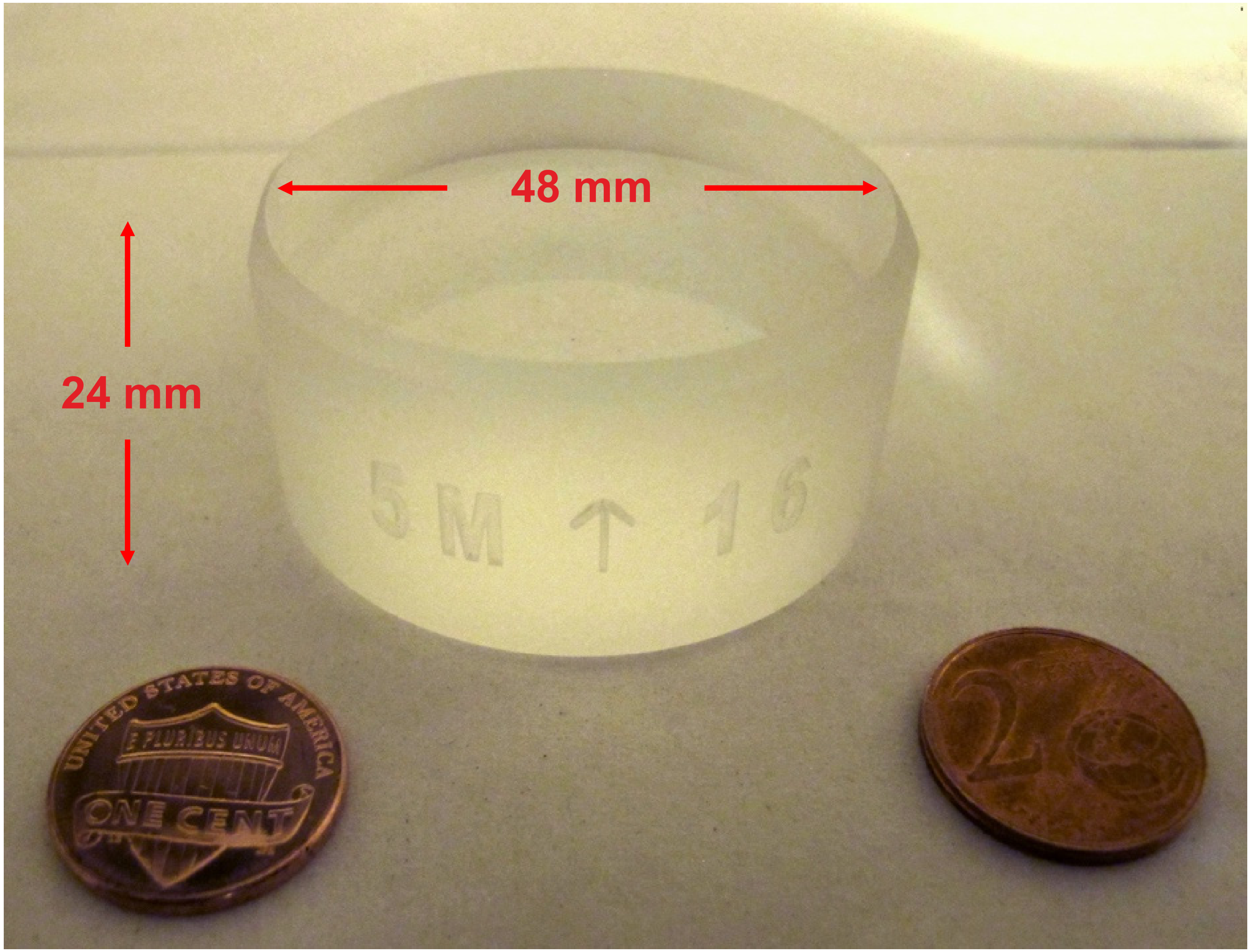
Step 3: Direct Bonding of Cleaned and Activated Components



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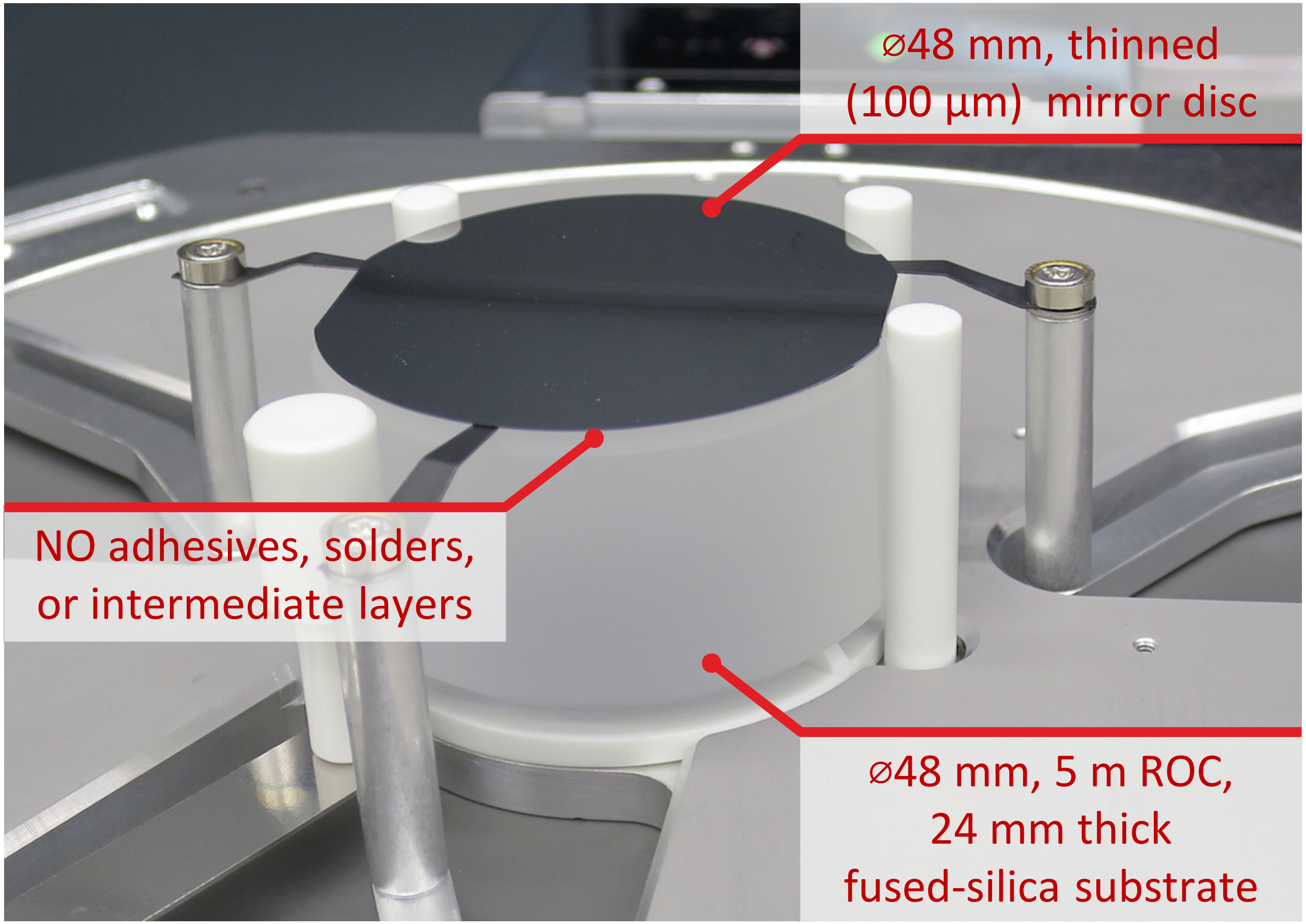
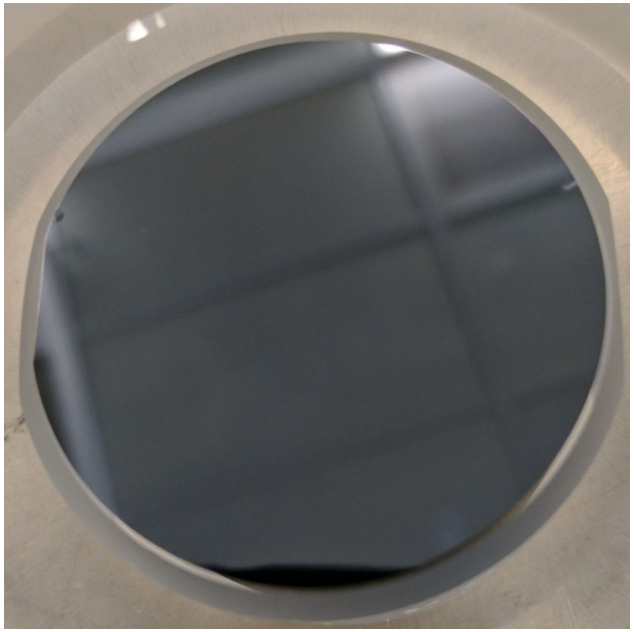
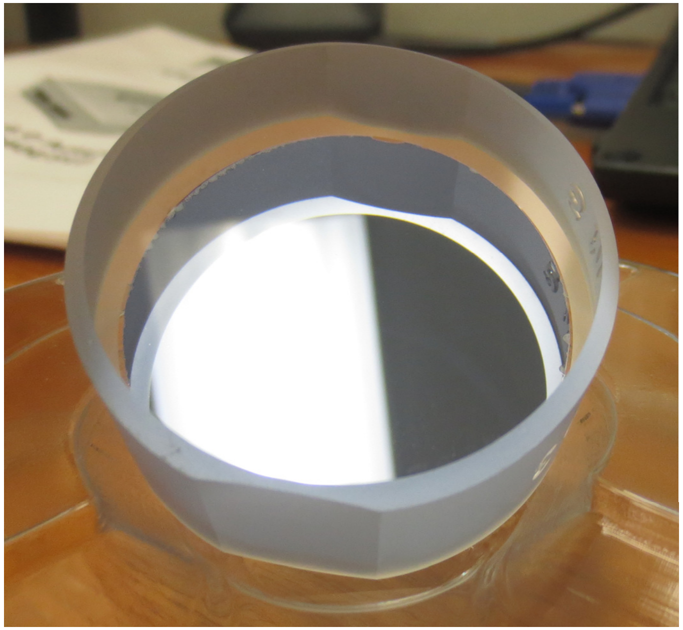


Steps 4 and 5: Substrate Removal and Final Cleaning





- High optical performance realized with acceptable yield
  - typical crystalline coatings are 0.5-1 inch in diameter
  - maximum delivered coating diameter to date is 3” / 76.2 mm
  - we can successfully transfer epilayers onto surfaces w/ a 10-cm ROC

Semiconductor-based optical interference coatings transferred to alternative substrates (SiO_2, Si, SiC, Al_2O_3, YAG, YVO_4, diamond, etc.)

10× LOWER Brownian noise — ULTRAPRECISE measurements of space and time

10× LOWER mid-IR absorption — HIGH RESOLUTION trace gas sensing

30× LOWER thermal resistivity — THERMAL MANAGEMENT in industrial lasers

Based on our unique advantages we have developed 3 products and 1 service line:

xtal stable™

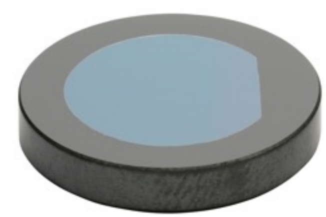
Ultrastable laser resonators for metrology and navigation

xtal mir™

Mid-IR spectroscopy for trace gas detection

xtal therm™

Thermally-optimized optics for high-power laser systems



xtal custom™

Custom bonding services for R&D and industry

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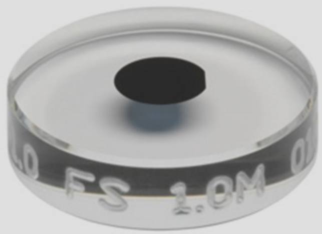

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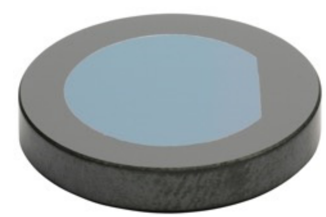

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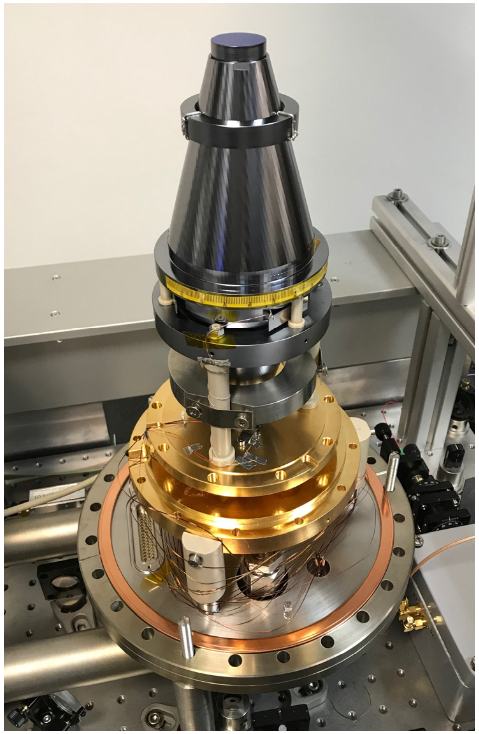
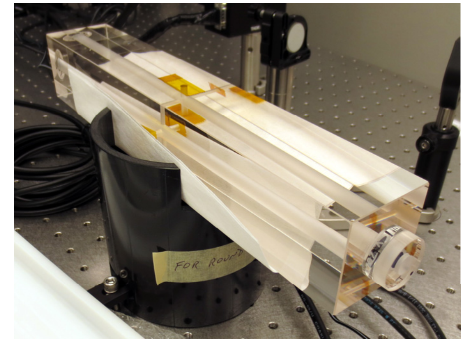
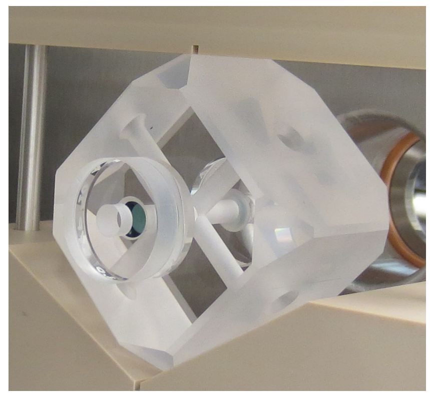
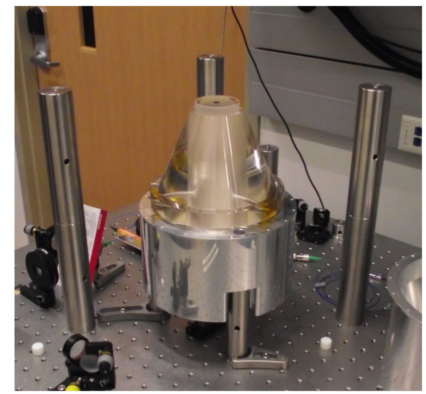
Custom bonding services for R&D and industry

Custom Optical Reference Cavities and Low-Noise Optics









- Dozens of cavities & mirrors deployed on SiO_2, Si, and Al_2O_3 subs.
- Mirror diameters of 0.5" to 2" and spacer lengths up to 30 cm
- Wavelengths from ~1000 nm to 1600 nm, RT and cryo (4-124 K)
    - excess losses < 3 ppm measured via ringdown, reflectivity > 99.999%

Custom Optical Reference Cavities and Low-Noise Optics

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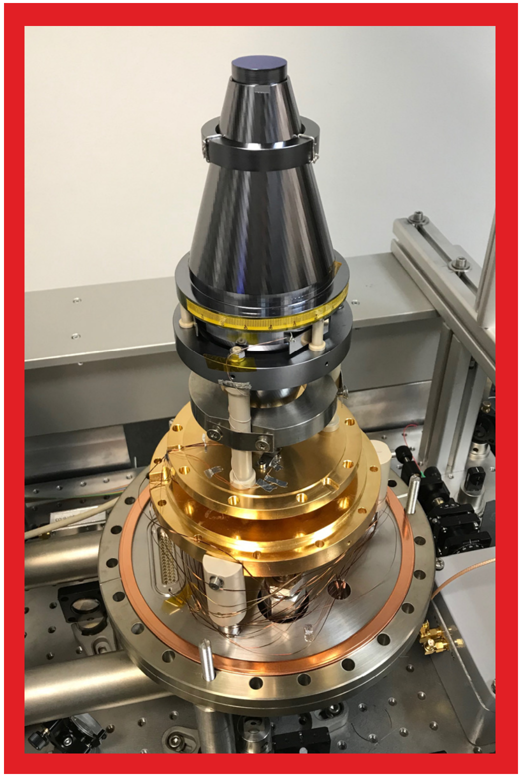

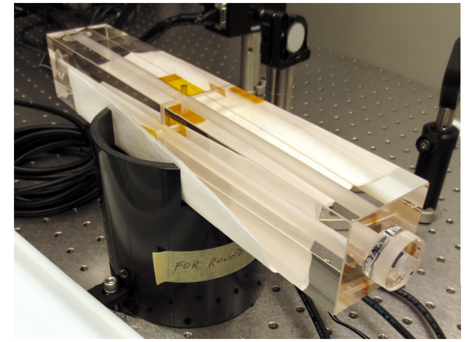

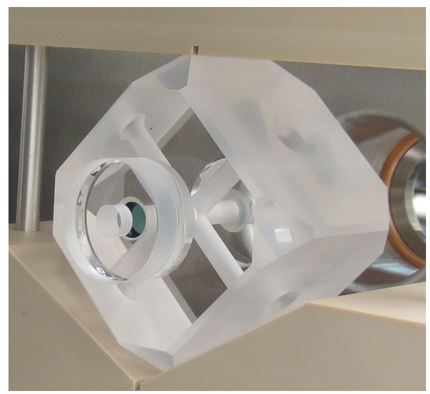

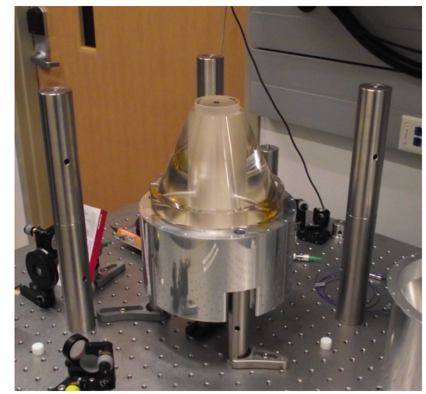

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“All Crystalline” Cryogenic Cavity

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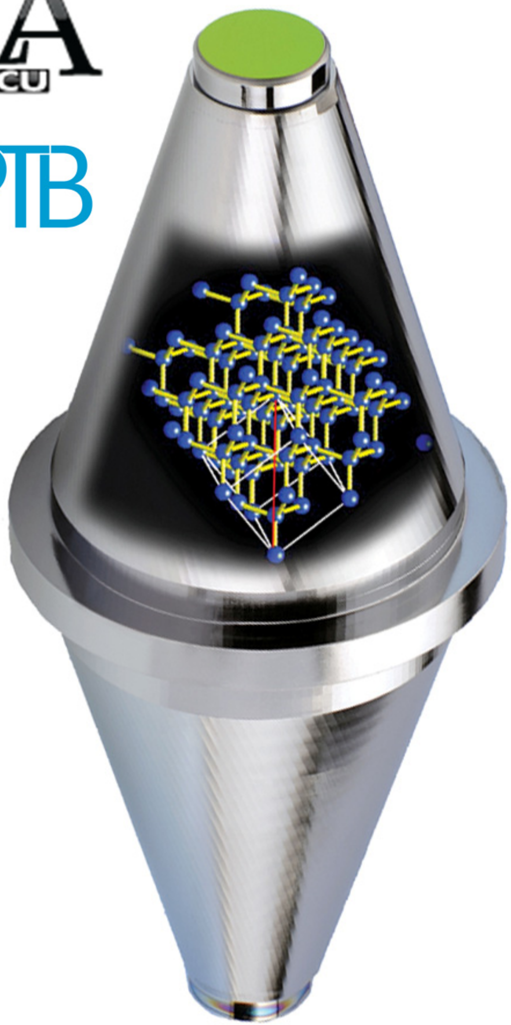
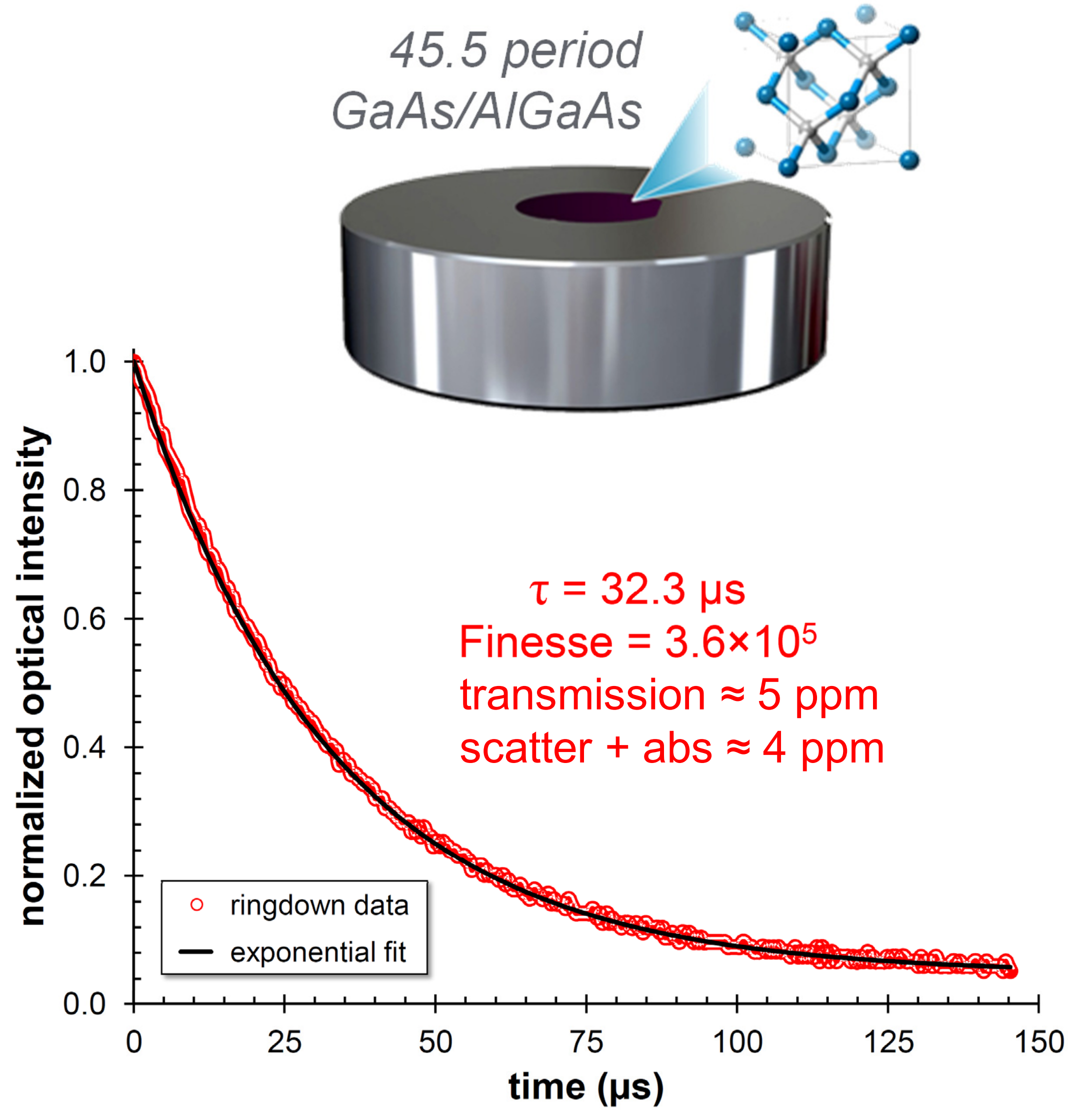
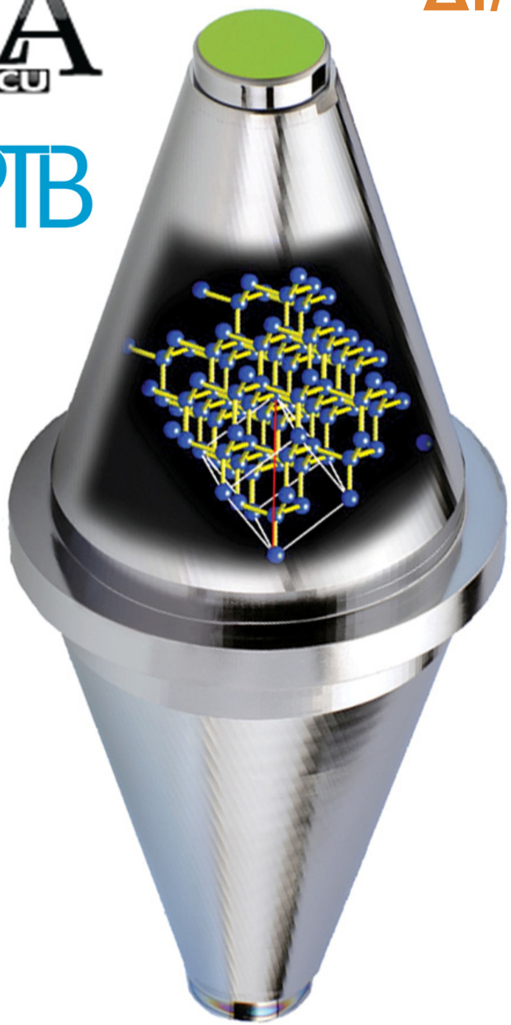
JILA NIST CU

PTB

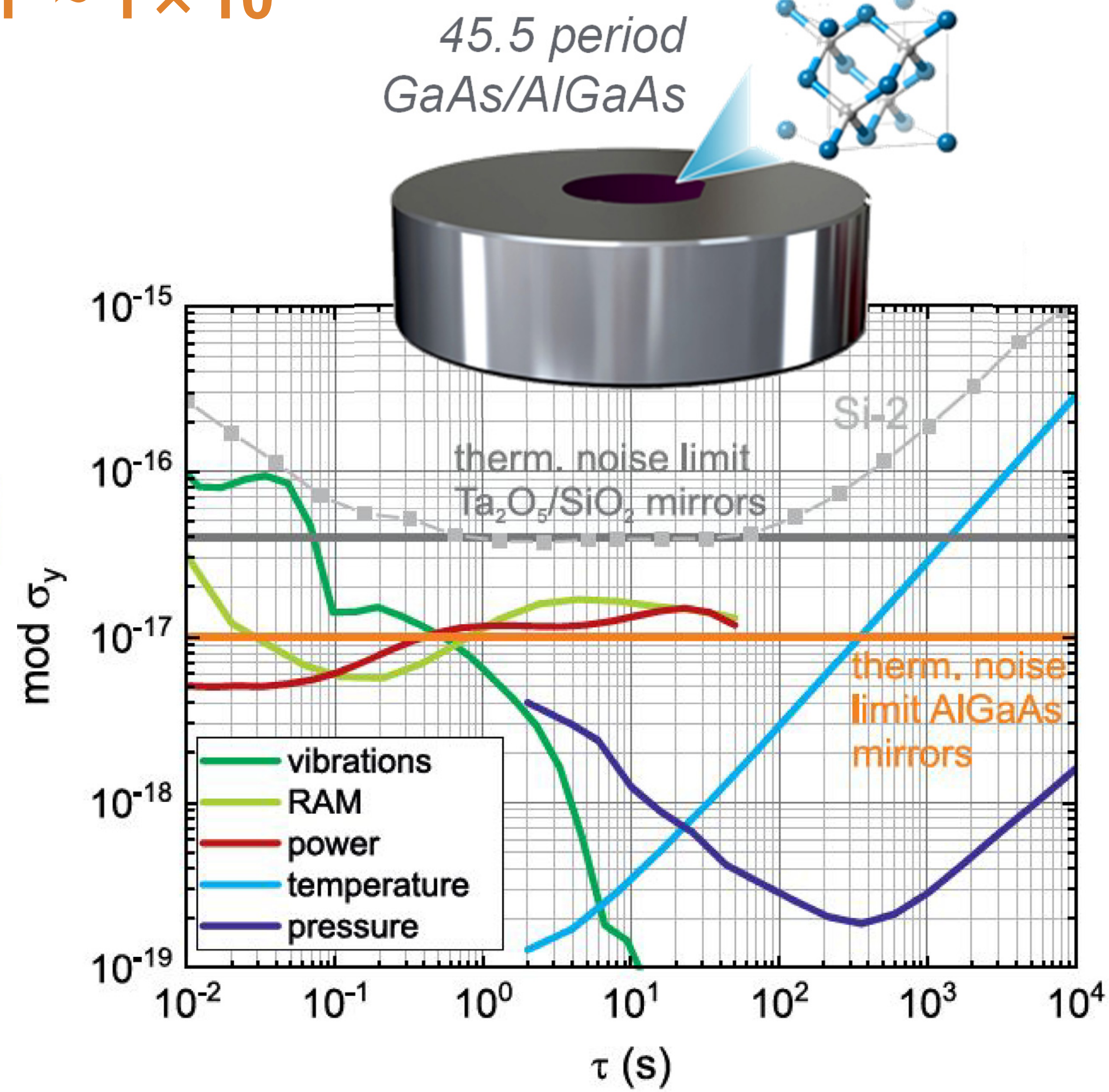




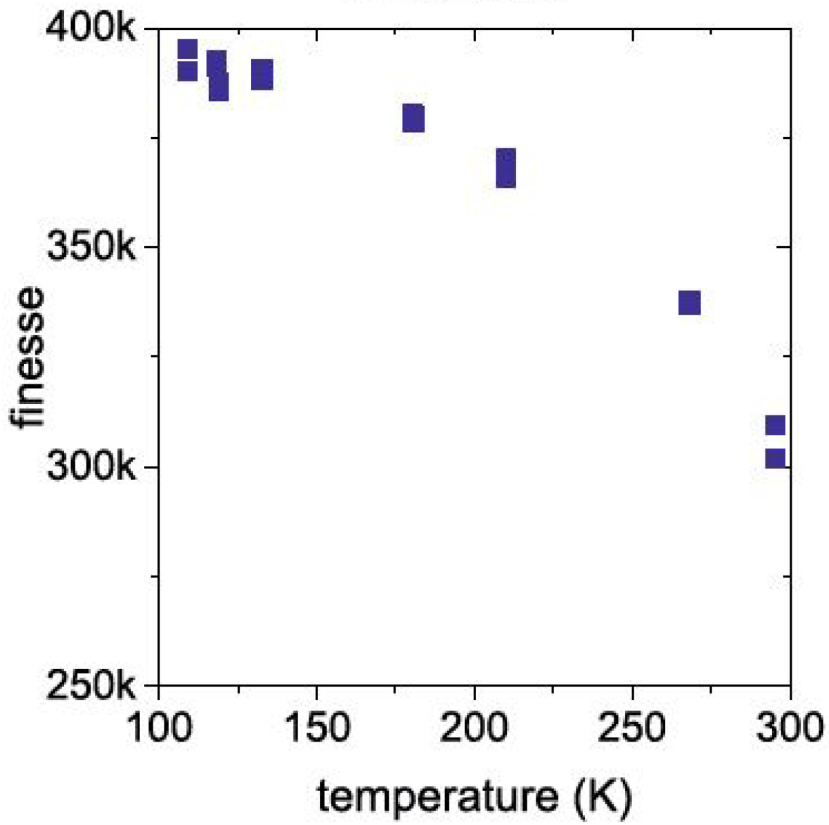
"All Crystalline" Cryogenic Cavity

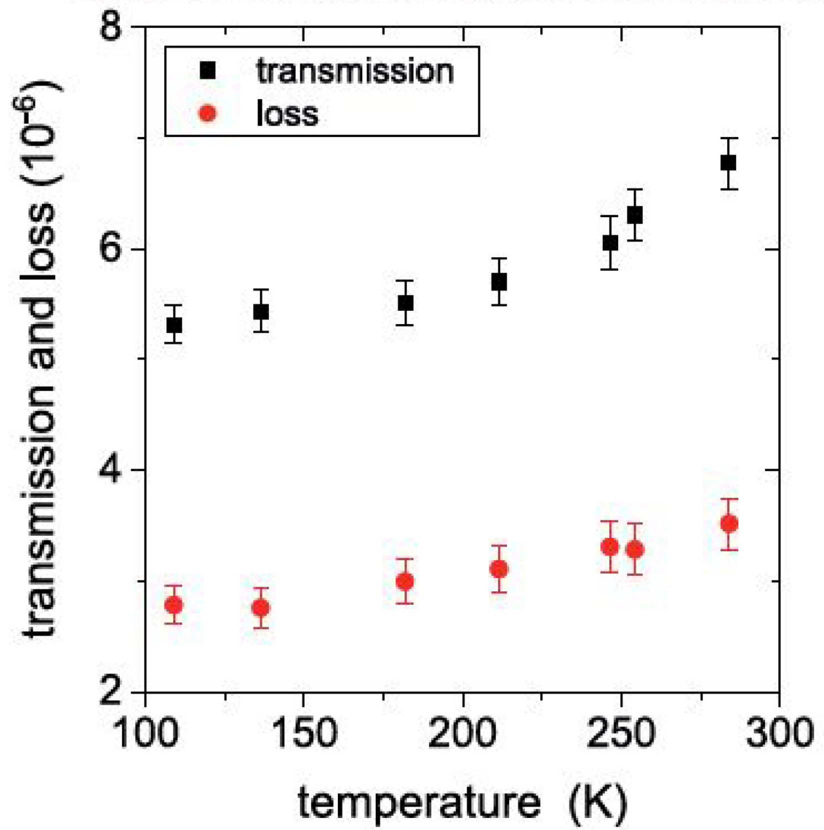


$\Delta f/f \sim 1 \times 10^{-17}$

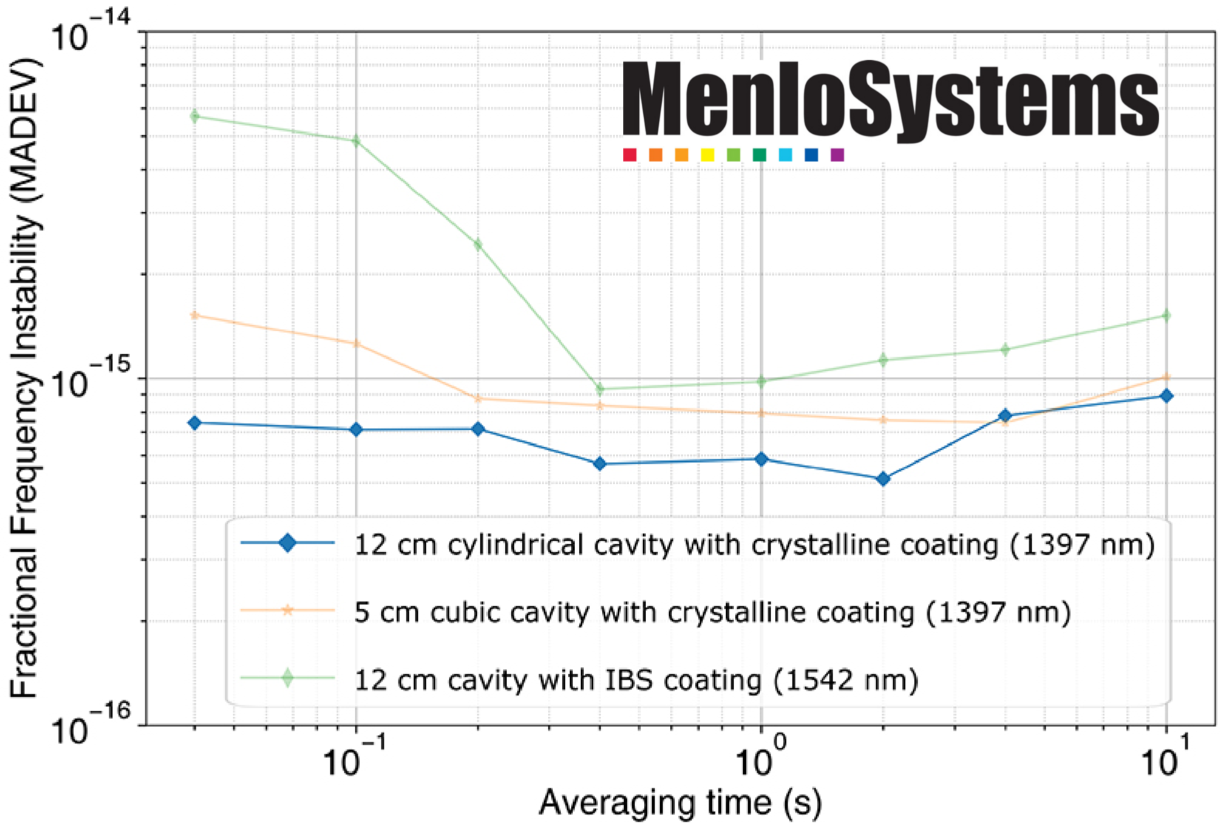


Cryogenic Optical Performance



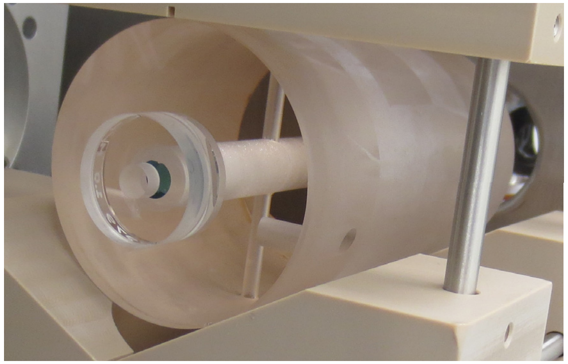


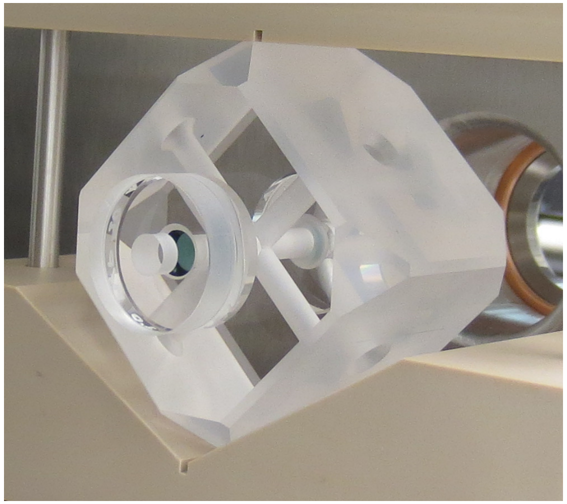
- Finesse of nearly 400,000 @ Si CTE zero-crossing temp. (~123 K)
  - total losses (T+S+A) of 8 ppm at center wavelength of 1542 nm
  - target transmission of 5±1 ppm realized, excess losses (S+A) < 3 ppm

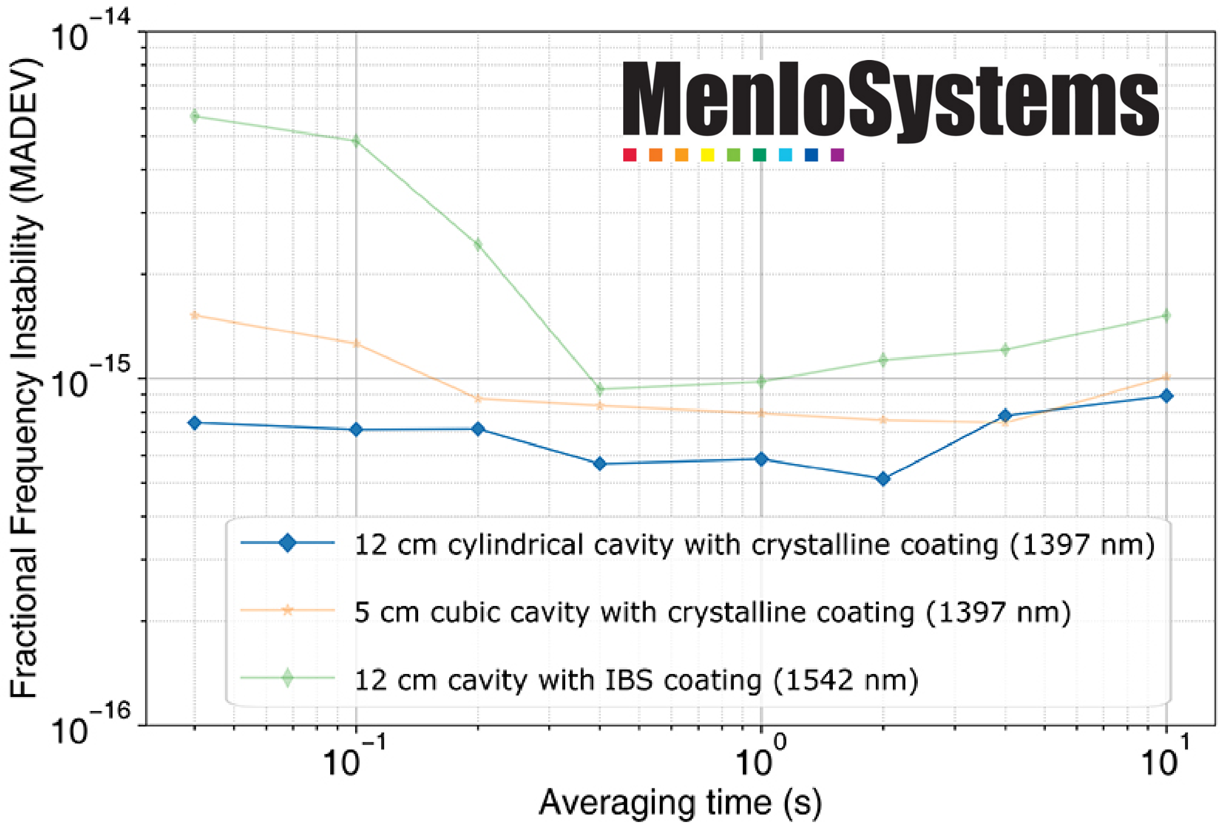


- Ultrastable cavities now available in turn-key low-noise lasers from Menlo Systems
  - the first rack-mounted lasers with a frequency instability ~10^{-16} (<100 mHz linewidth)

Rack-Mounted Commercial Ultrastable Laser Systems







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Substrate-transferred crystalline coatings exhibit excellent optical and thermo-mechanical quality

- Elastic loss reduction of 10-100× over amorphous films
  - AlGaAs room temperature mech. Q ~ 4×10^4 ($\phi_{RT} \approx 2 \times 10^{-5}$)
  - AlGaAs cryogenic performance: Q > 1×10^5 ($\phi_{min} \approx 4.5 \times 10^{-6}$)
- Optical losses on par-with with the best IBS coatings
  - absorption < 1 ppm via PCI in the NIR, scatter loss < 3 ppm
  - cavity finesse > 600,000 (R > 99.9995%) measured at 1550 nm
  - exceptional MIR performance, ppm-level losses to 5+ μm
- High conductivity ($30_{\perp}$, $70_{\parallel}$ $Wm^{-1}K^{-1}$), promising LIDT
  - measured CW > 50 MW/cm^2 without damage (1064 nm)
  - typical LIDT values for ~1 μm & ns pulses: 2-8 J/cm^2, ultimately limited by TPA (βGaAs ≈ 20 cm/GW, Eg ≈ 870 nm)

Thank you for your attention!