AlGaAs Crystalline Coatings:
Recent Progress and Future Prospects

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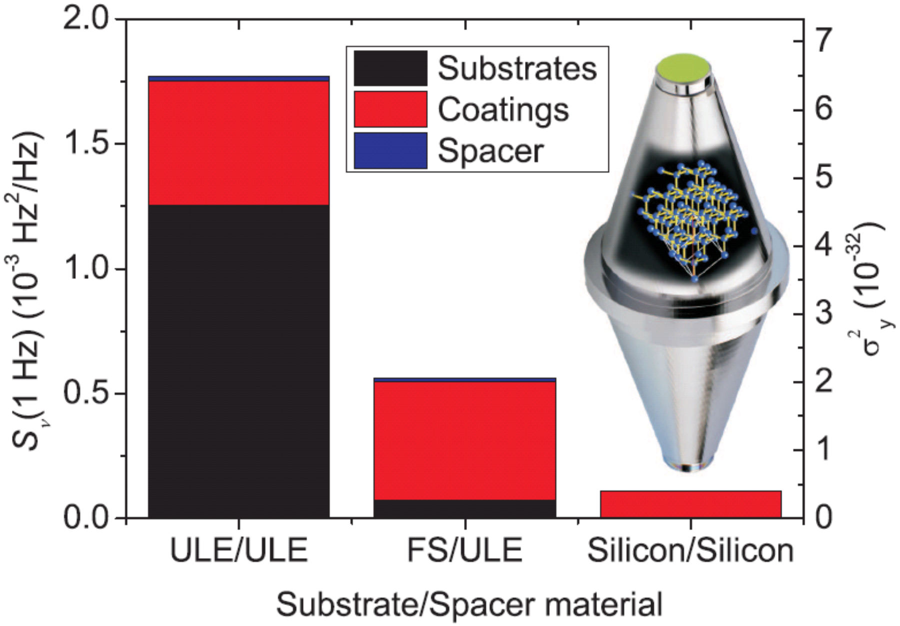
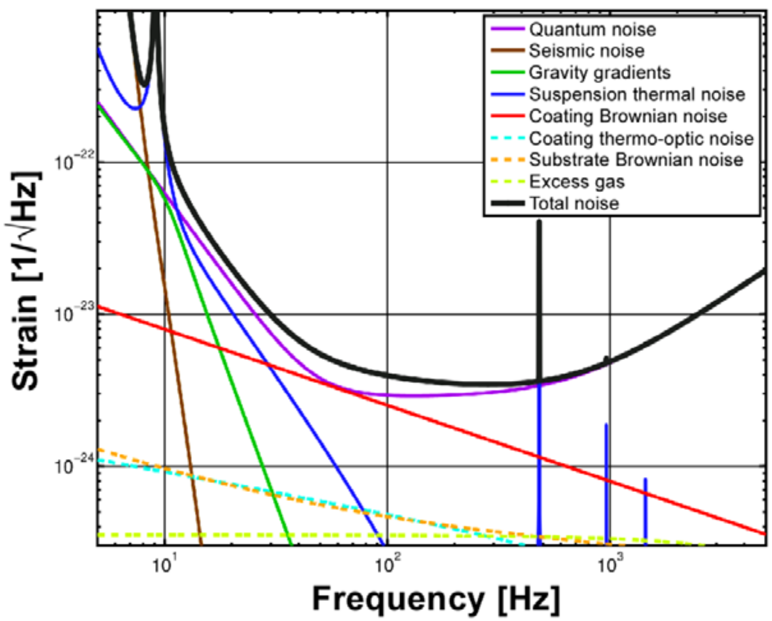
Coating Thermal Noise Consequences

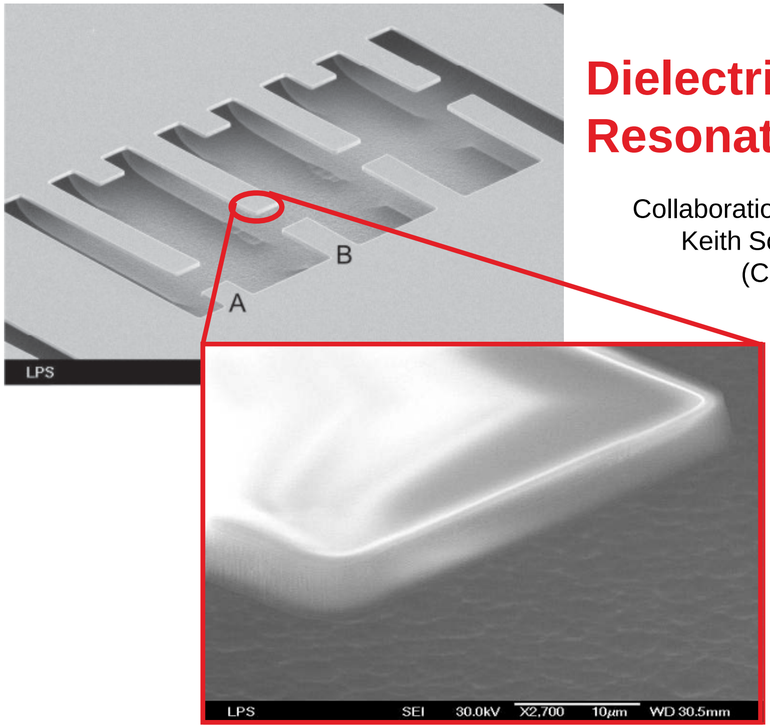




- State-of-the-art systems now (or will be) coating limited (Ta_2O_5/SiO_2)
  - from LSC studies by Crooks, Harry, Penn, etc. Ta_2O_5 is the culprit
  - titania doping enables a factor of ~2 improvement (loss angle: 2×10^{-4})
- Alternative solution to this vexing problem: *crystalline coatings!*
  - semiconductor industry has a long history with such materials systems

Kessler, Hagemann, Grebing, Legero, Sterr, Riehle, Martin, Chen, Ye, Nature Photonics 2012

Optomechanics: Sculpted DBRs



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

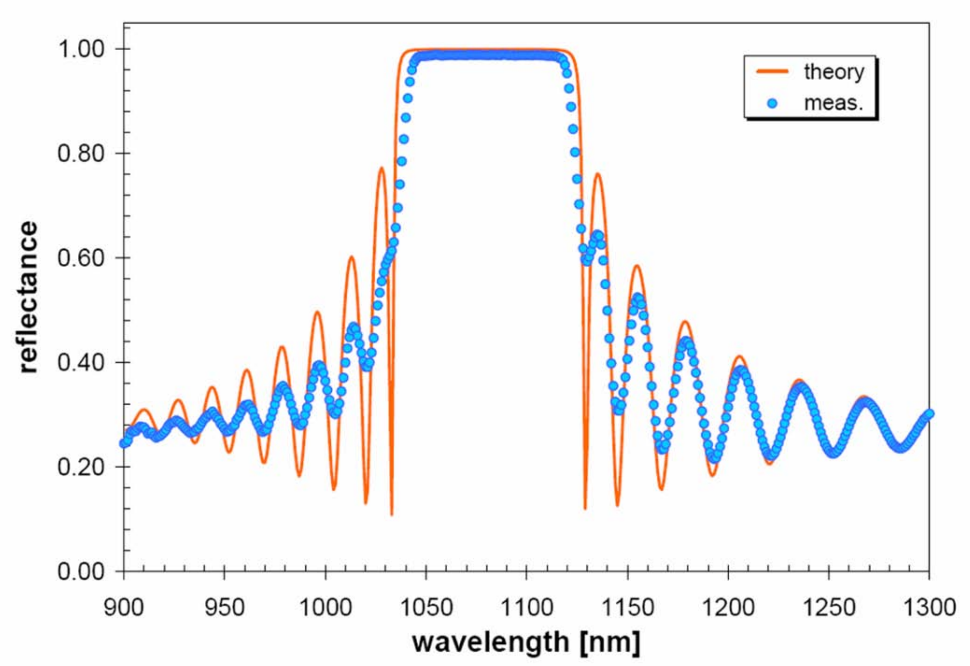
FBH and Aspelmeyer
Group (UniVie)

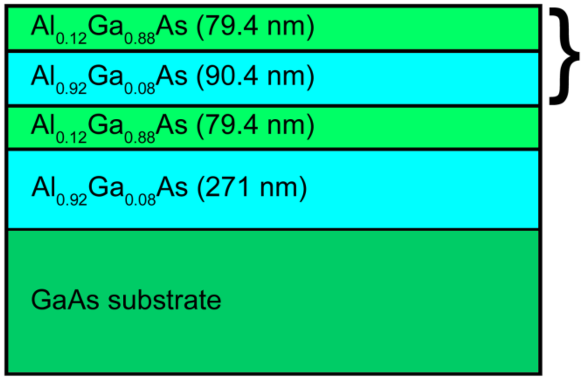
free-standing epitaxial AlGaAs DBR
Reflectivity > 0.9999, Q ~ 2×10^4 – 2×10^5
Significantly reduced damping, similar R

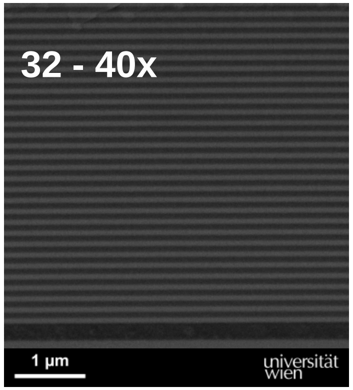
a) Cole, et al., Appl. Phys. Lett. 92, 261108 (2008)
b) G. D. Cole, Proc. SPIE. 8458–07 (2012)

AlGaAs Multilayer Details

- AlGaAs multilayer with varying Al content for index contrast
  - high index layers contain low Al content (0-12%)
  - 8% Ga incorporated in low index film to slow oxidation in ambient
- Potential for high reflectivity from ~650 nm – 3 μm
  - measurements @ 1064 nm
- High quality epitaxy requires a lattice matched substrate
  - same crystalline symmetry
  - minimal deviation of lattice parameter (atomic spacing)

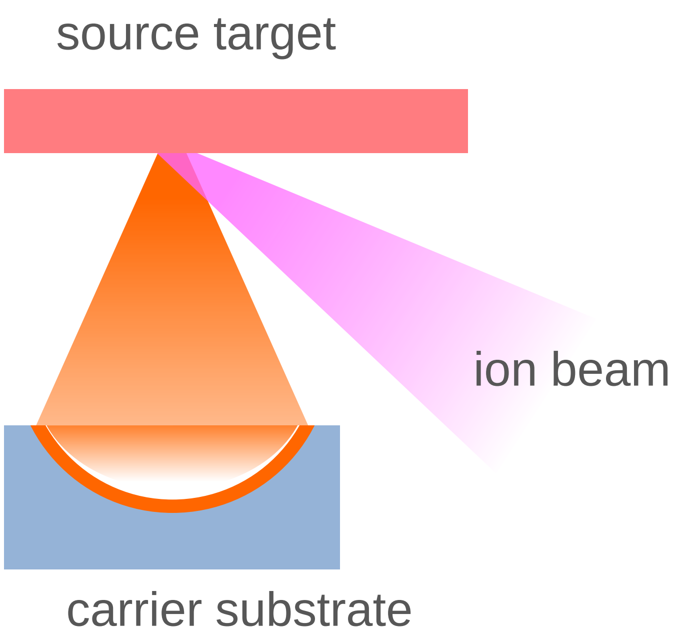






G. D. Cole, et al., Appl. Phys. Lett. 92, 261108 (2008)

Ion Beam Sputtered Dielectric Films



State-of-the-art mirrors
alternating dielectric films, typically Ta_2O_5/SiO_2

Allows for deposition onto essentially arbitrary substrates

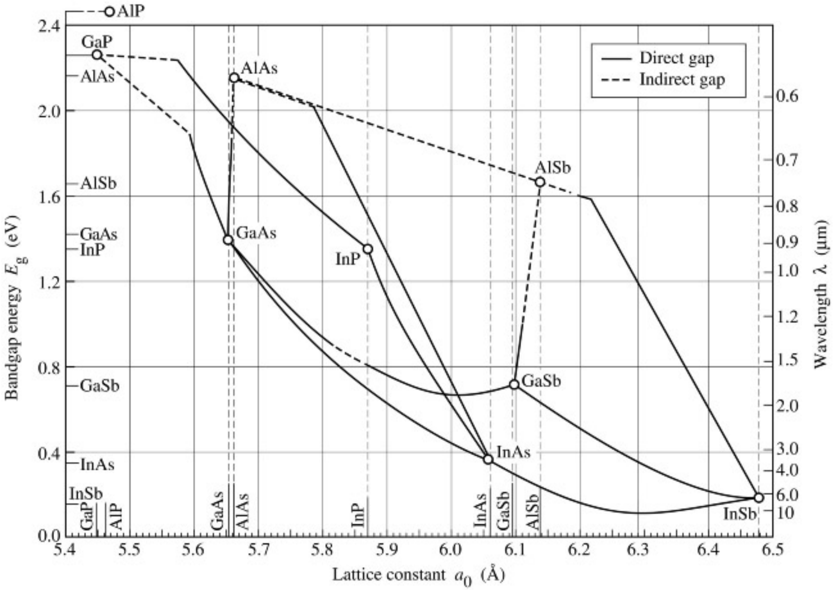
- Multilayer of amorphous films generated via ion beam sputtering
- Phenomenal optical properties (high R, low absorption and scatter)
- Flexible choice of substrates (assuming proper surface quality)
  - super-polished SiO_2, Si, ULE, sapphire, etc.

Monocrystalline Mirrors

<u>Ultra-low coating thermal noise</u>

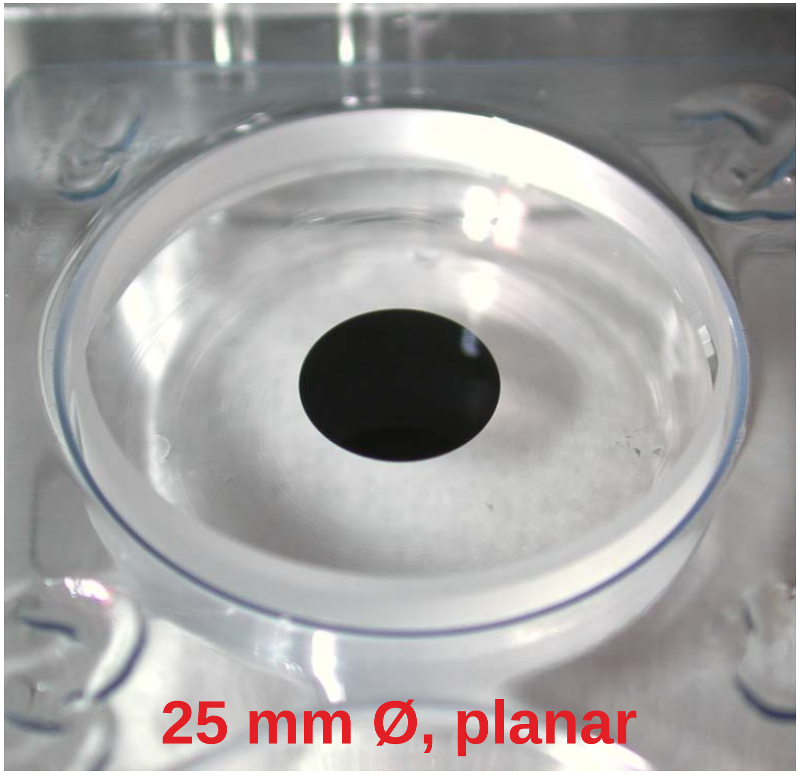
Macroscopic mirrors based on epitaxial AlGaAs alloys

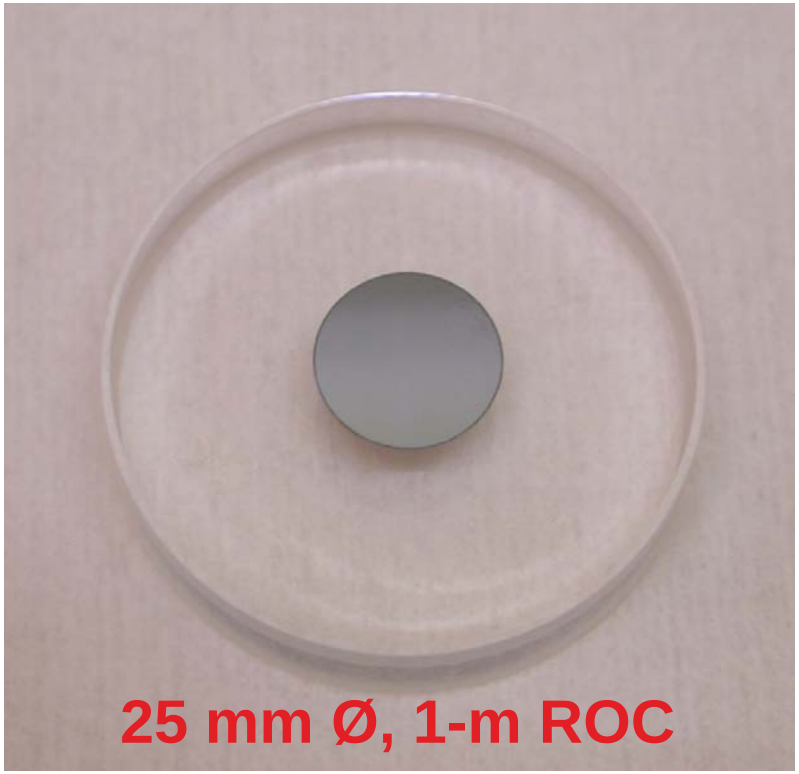
Direct deposition onto arbitrary substrates precluded by lattice matching condition



- Employ semiconductor microfabrication techniques to transfer AlGaAs multilayers onto arbitrary substrates (SiO_2, sapphire, etc.)
  - ideal process allows for used of curved mirror blanks
  - identical form factor, no change in overall system design

Transferred Mirror Development

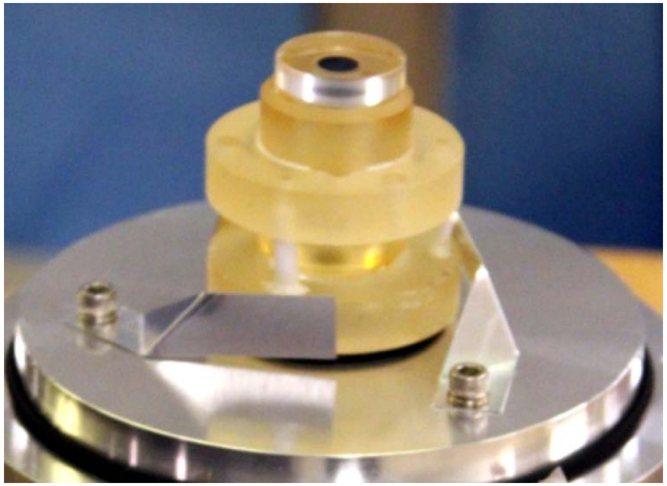




- Monocrystalline mirror discs transferred onto arbitrary substrates
  - temporary mounting and handling is the limiting process step
  - cleanliness is key to success, no voids or trapped particles!

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



G. D. Cole, W. Zhang, M. J. Martin, J. Ye, and M. Aspelmeyer, arXiv:1302.6489 (2013)

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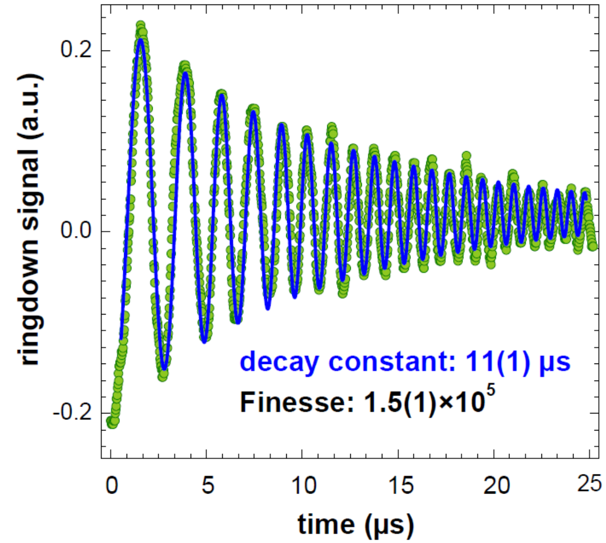

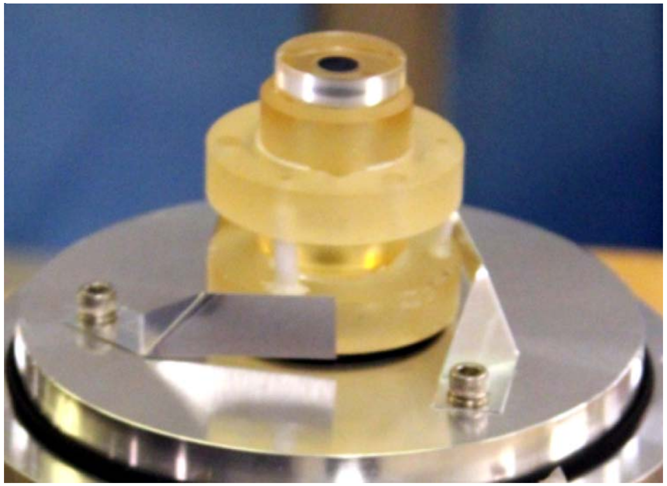

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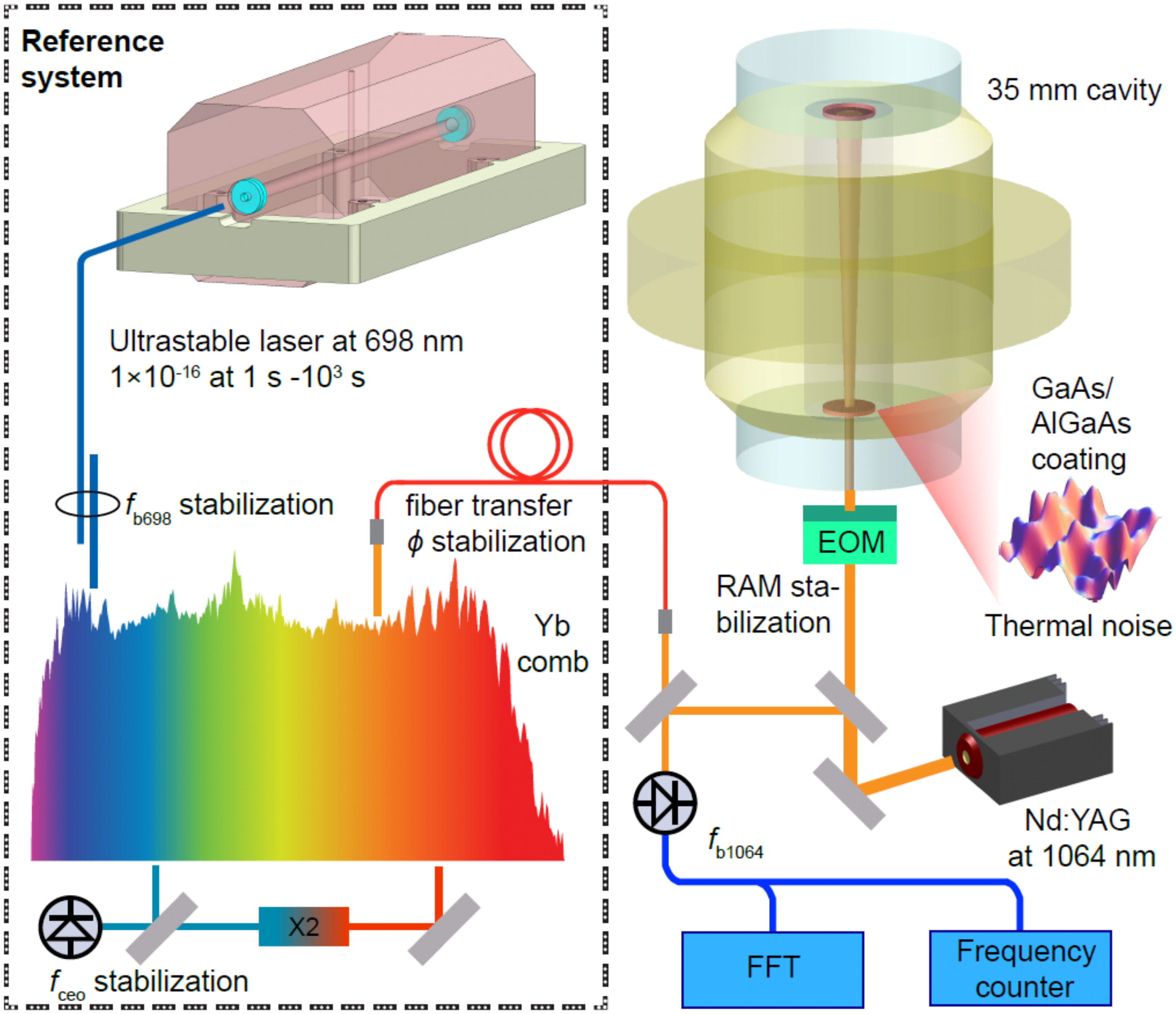
Stabilized Laser Comparison



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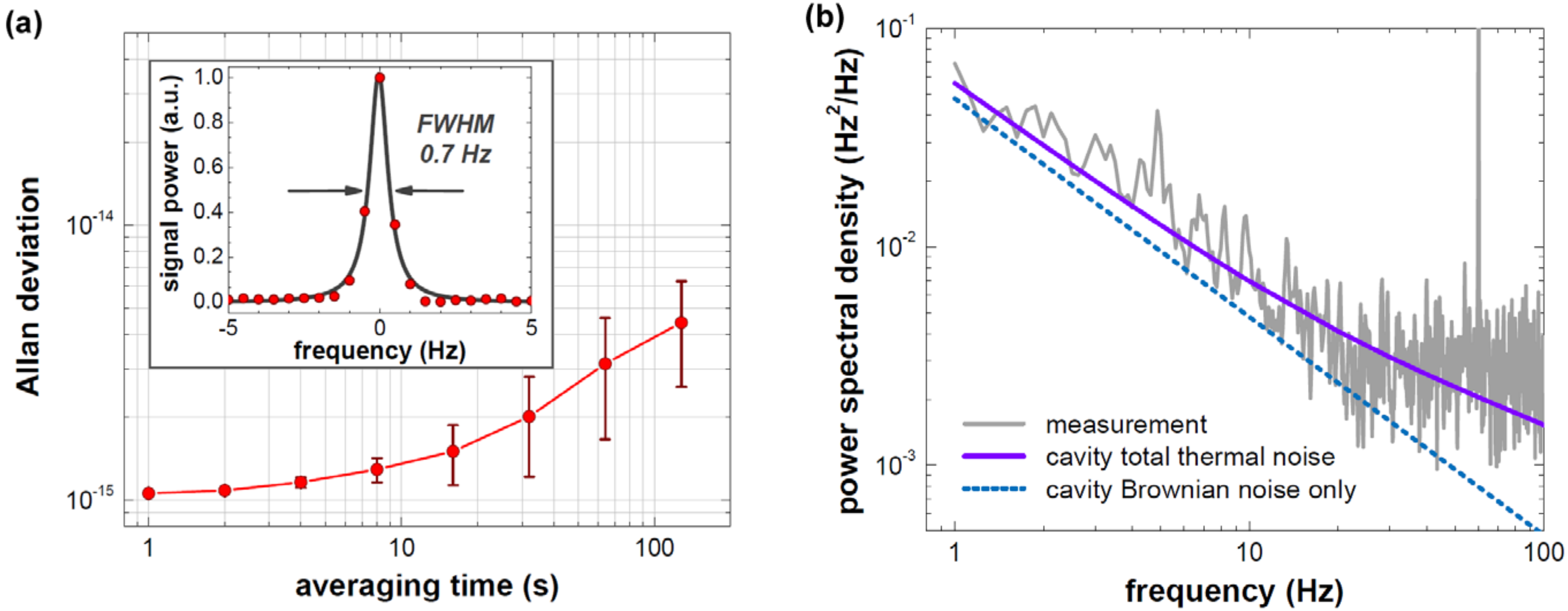
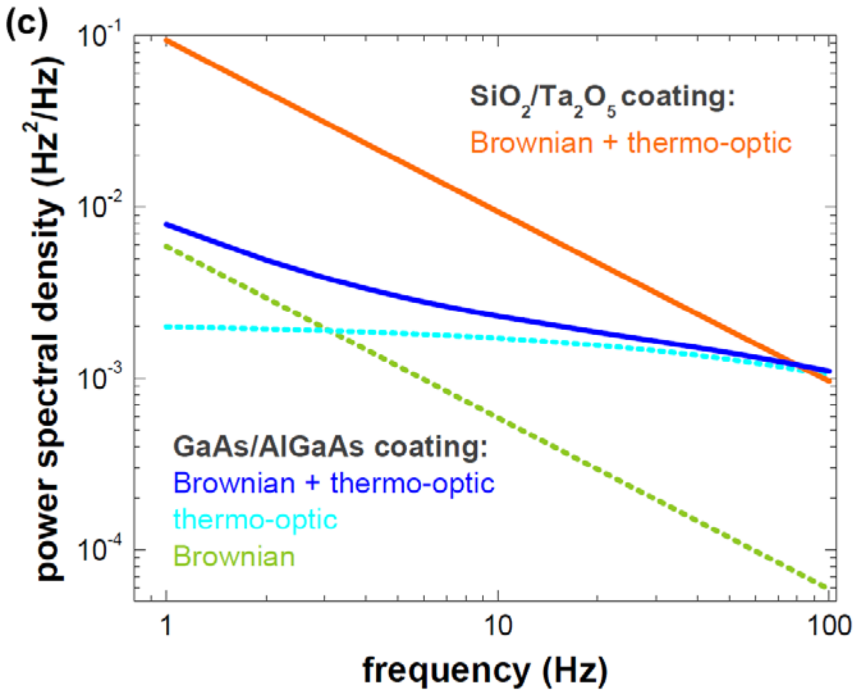
Thermal Noise Performance



- Allan deviation of ~1×10^{-15} at 1 s; linewidth of 700 mHz via FFT
  - long term stability limited by measurement setup and spacer
- Reference cavity noise measurement is thermally limited
  - fitted NPSD yields loss angle consistent with μ-resonators (<4×10^{-5})

G. D. Cole, W. Zhang, M. J. Martin, J. Ye, and M. Aspelmeyer, arXiv:1302.6489 (2013)

Thermo-Optic Noise



- Extracted quality factor matches measurements on µ-resonators
  - loss angle falls between 0 and 4×10^{-5} (depends on Q of fused silica)
- Excess thermo-optic noise anticipated at high frequencies
  - arises from thermoelastic + thermorefractive noise in crystalline AlGaAs

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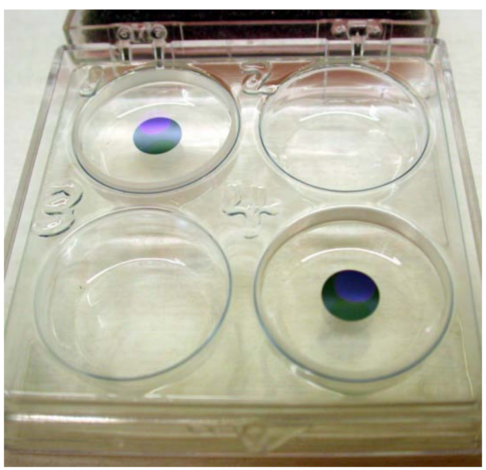
Summary of AlGaAs Mirror Properties

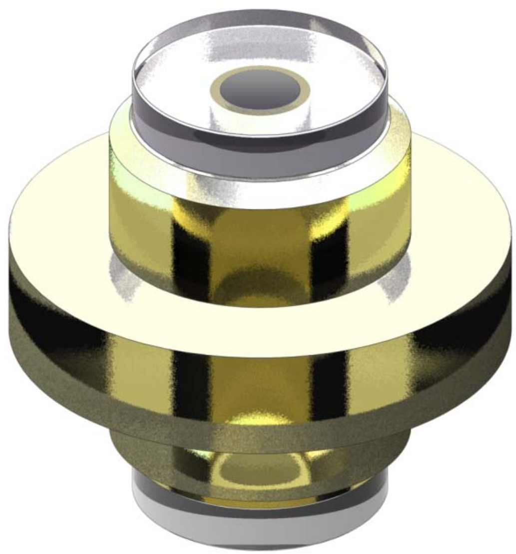
- We have realized tremendous progress in only 6 years, with the last ~2 being dedicated to cavity end mirrors
- Damping reduced by 10-100× compared with dielectrics
  - room temperature Q-values ~4×10^4 ($\varphi_{RT} \approx 2.5\times10^{-5}$)
  - cryogenic Q >1×10^5 ($\varphi_{min} \approx 4.5\times10^{-6}$) from 180 Hz to 4 MHz
  - compare with typical φ of $2\text{-}4\times10^{-4}$ for Ta_2O_5/SiO_2 films
- Demonstrated low scatter loss and absorption
  - RMS surface roughness of 1.3 Å RMS (~2 ppm at 1064 nm)
  - absorption (probe limited) of 4.8 ppm (0.15 cm^{-1}) at 1064 nm
- Reflectivity >>99.99% measured for 40.5 layer pairs
  - highest measured finesse of ~1.5×10^5, potential for ~10^6

Crystalline Mirror Solutions

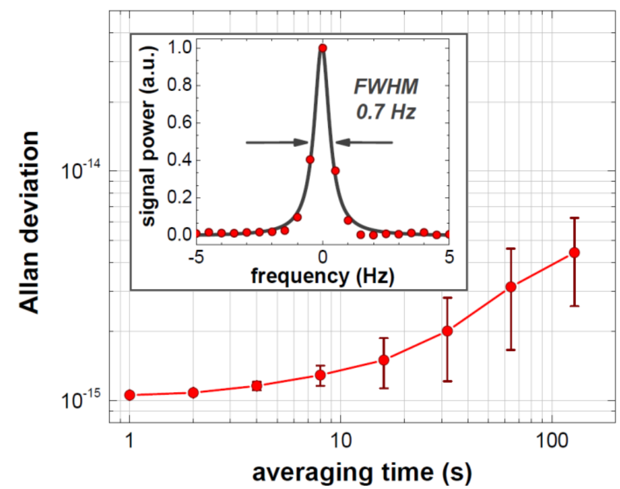
- Manufacturing low-noise substrate-transferred mirrors
  - used to construct ultra-narrow (<1 Hz) linewidth light sources
    - advanced optical atomic clocks, microwave generation, LIDAR/LADAR
    - next generation telecom frequency references and navigation systems



i) AlGaAs mirrors bonded to silica

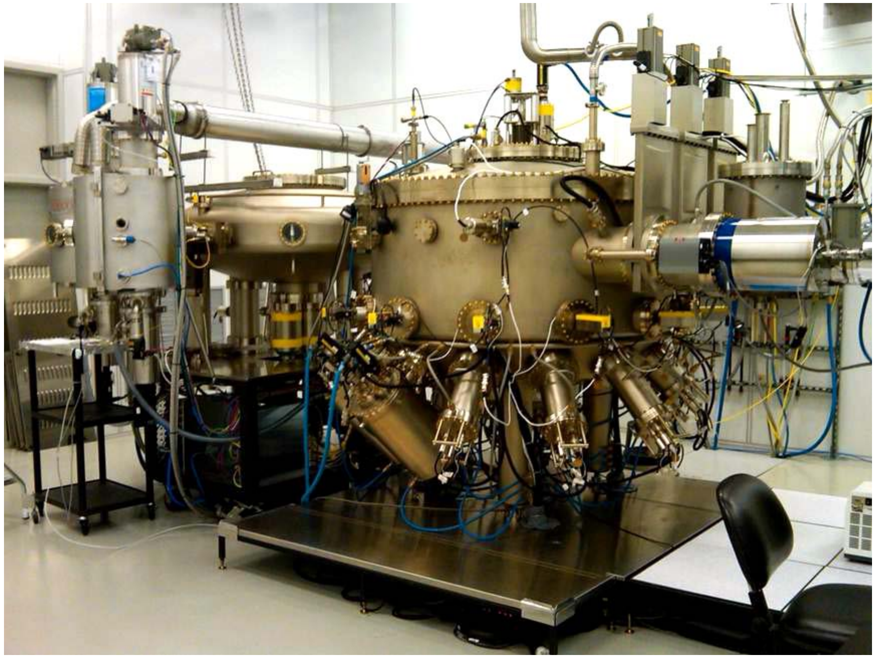


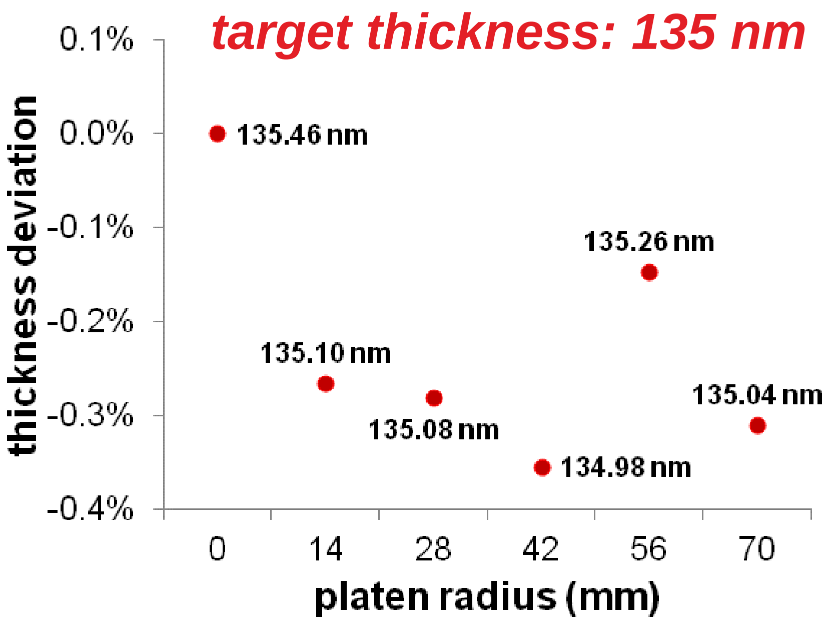
ii) mirrors used to construct a cavity



iii) cavity employed for laser stabilization

Large Area Crystal Growth

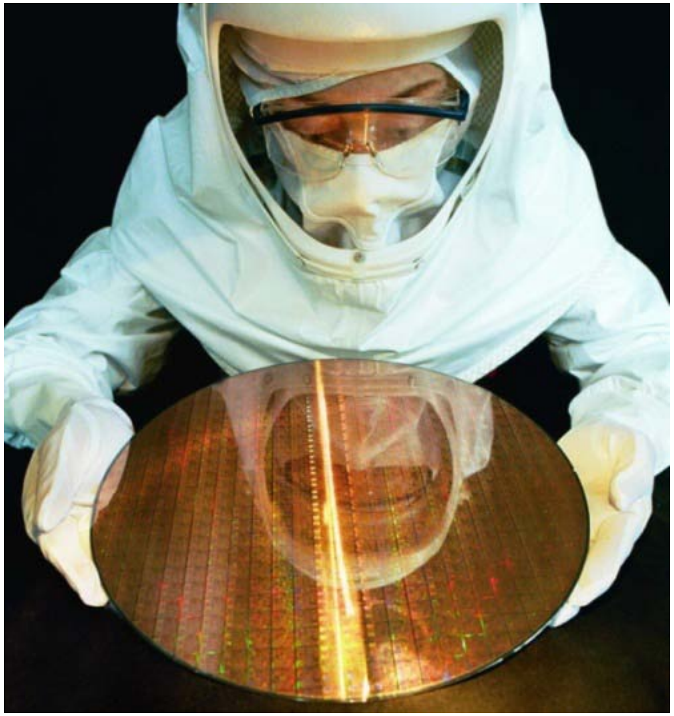




- Production MBE reactors for microwave electronics
  - 7 x 150-mm or 4 x 200-mm wafers (Veeco GEN2k/Riber R7k)
- Preliminary thickness uniformity test: excellent results
  - platen Ø is ~50 cm (current maximum GaAs wafer Ø of 200 mm)

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

Large Area Transferred Coatings

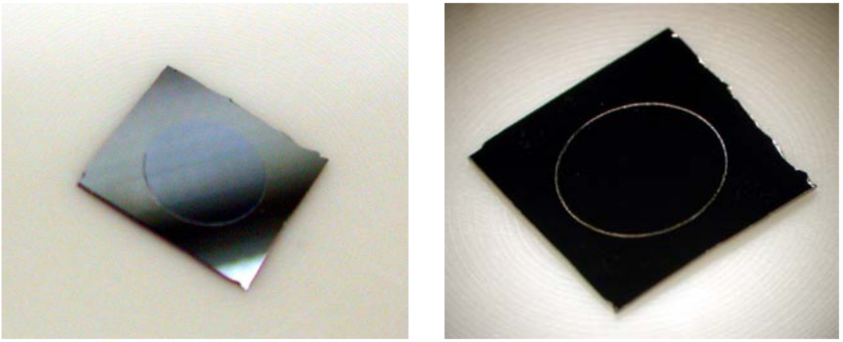


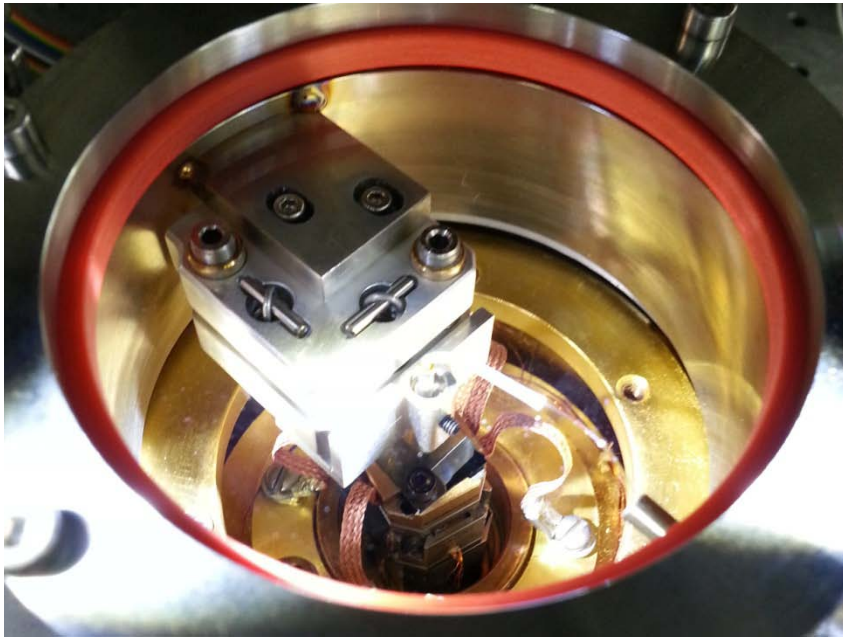
- Defect-free bonding demonstrated for 450-mm Ø wafers
  - commercial bonding system: EVG (St. Florian am Inn, Austria)
- All that is needed: custom tooling for thick substrates

Exploration of Alternative Substrates

- Direct-bonding process enables flexible integration of crystalline coatings onto essentially arbitrary substrates
- Optimized bonding conditions capable of bulk bond strength
  - O_2 plasma assisted bonding
  - in-situ ion cleaning (Mitsubishi)
- Relevant materials combinations have been explored for wafer-bonded micro/optoelectronics
  - AlGaAs on SiO_2 (room temp.)
  - AlGaAs on Al_2O_3 (50 mK)
  - AlGaAs on silicon (10 K)

GaAs/AlGaAs DBR on 111 Si





Tong & Gösele, Semiconductor Wafer Bonding: Science and Technology, Wiley, 1999

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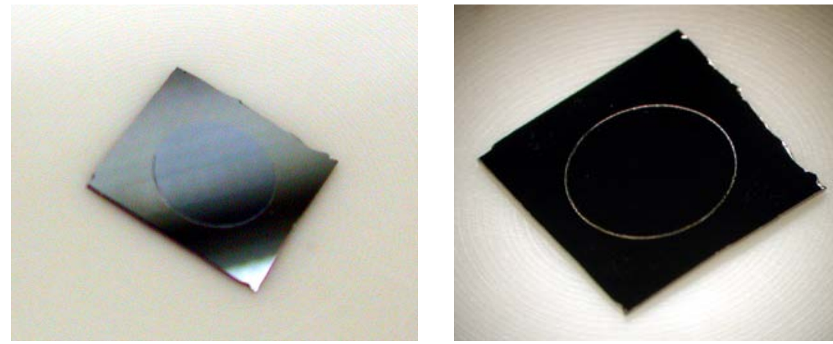

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