Silicon as a low thermal noise test mass material

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Research for advanced interferometer suspensions

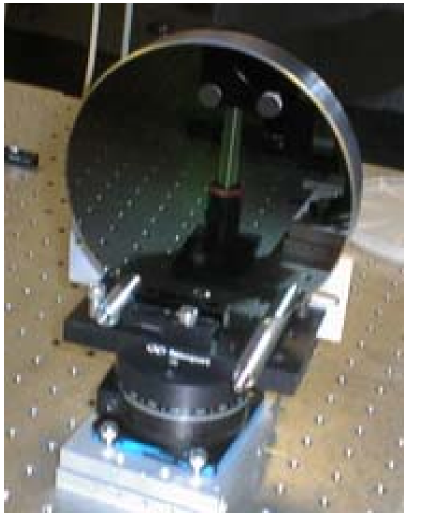
- Q measurements in progress of silicon samples
- 2 samples:
  - Dimensions 4 inch diameter x 4 inch long
- Sample (a) un-doped (100) material
- Sample (b) boron doped (111) material
- Measure Q factor of both samples at room temperature
- Results so far : Q of order few x 10^7

- Most likely suspension limited - work continuing
- Very promising LIGO III material - particularly re: thermo-elastic damping

Proposed work - materials for test masses/suspensions

- **Future improvements**
  - **Thermal noise** from test masses and suspensions important below few 100 Hz
  - **Silicon** has various desirable material properties (optical and thermal noise)
  -
    - High thermal conductivity, κ
    - Available in large pieces (~100kg)
    - Can be polished and coated to form high quality dielectric mirrors
    - Measurements suggest intrinsic mechanical loss (and **thermo-elastic loss***) comparable to sapphire at room temperature
    - Can be silicate bonded to silica (and by extension to itself)

Coated silicon mirror



  - At room temperature, thermo-elastically driven displacement noise forms hard limit to detector sensitivity
  - **By cooling test masses, expect significant gains in thermal/thermo-elastic noise performance**

*** Braginsky et al**

Power spectral density of noise due to thermo-elastic damping in a bulk substrate

$$x^2(\omega) = \frac{8}{\sqrt{2\pi}}\alpha^2(1+\sigma)^2\frac{k_b T^2}{\rho C}\frac{a^2}{r_0^3}\frac{1}{\omega^2}$$

Braginsky et al, Phys. Lett. A

where:

α = coefficient of thermal expansion
σ = Poissons ratio
ρ = density
C = specific heat capacity
$a^2 = K_{th}/\rho C$: K_{th} = thermal conductivity

→ material parameters

r_0 = beam radius at which intensity drops to 1/e
ω = angular frequency

Reduction of "thermo-elastic" noise by cooling

From Braginsky et al

$$x^2(\omega) = \frac{8}{\sqrt{2\pi}} \alpha^2 (1+\sigma)^2 \frac{k_b T^2}{\rho C} \frac{a^2}{r_0^3} \frac{1}{\omega^2}$$

(1) Need values for $\alpha(T)$, $C(T)$, $K_{th}(T)$

(2) Formula is valid for $\omega >> a^2/r_0^2 \sim 1/\tau$

$$x^2(\omega) = \text{Constant} \frac{\alpha^2 T^2}{C} \frac{1}{r_0} \frac{a^2}{r_0^2} \frac{1}{\omega^2}$$

$$= \text{Constant} \frac{\alpha^2 T^2}{C} \frac{1}{r_0} \frac{1}{\omega \tau} \frac{1}{\omega}$$

Following classical thermo-elastic damping - more generally replace $\frac{1}{\omega\tau}$ by $\frac{\omega\tau}{1+\omega^2\tau^2}$

→ Evaluate $x^2(\omega)$ as a function of temperature

Proposed work - materials for test masses/suspensions (3)

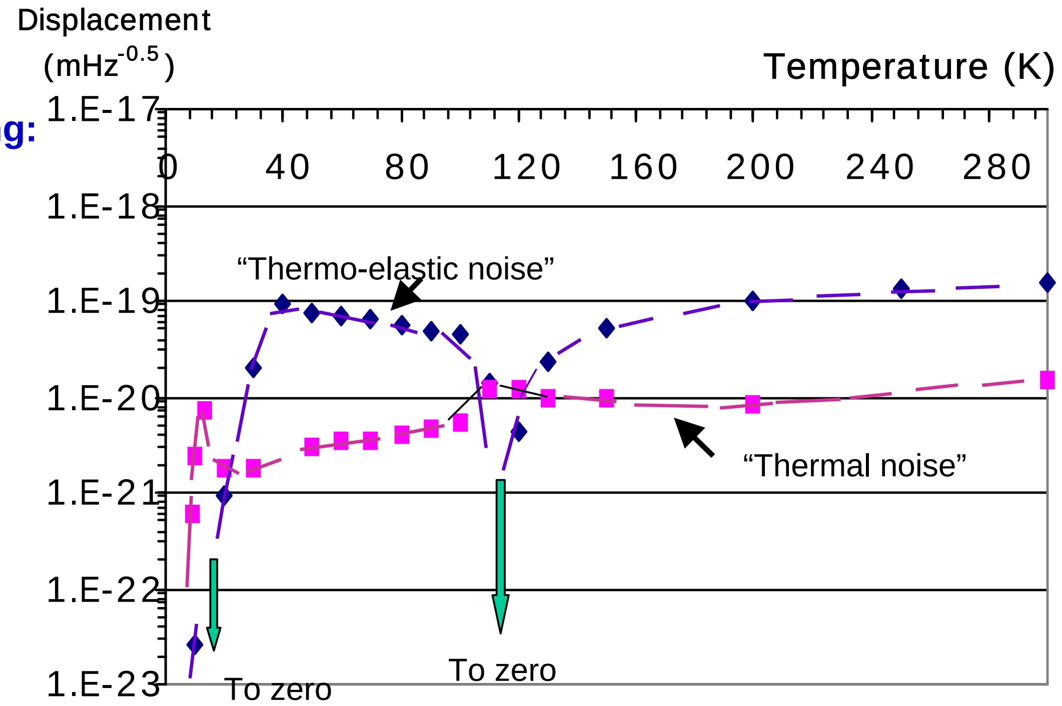
– Silicon: unique material properties on **cooling:**
  - Intrinsic mechanical loss decreases
  - Two zero's in coefficient thermal expansion, α, at ~130K and ~20K

Dual benefits:

– thermal deformation proportional to α/κ

– thermo-elastic noise proportional to α

– **both should vanish as α tends to zero**



"Thermo-elastic" displacement noise and "thermal" noise in a silicon test mass as a function of temperature

– **silicon substrates opens avenues for significant thermal noise improvements at low temperatures but material properties need further study**

Proposed work - materials for test masses/suspensions

- Need to investigate, in collaboration with LSC colleagues :
  - **Effects of coatings** on mechanical loss of silicon substrates (room T and cryogenic)
  - **Silicate bonding** to joint silicon suspension elements to the silicon test masses
  - Measurement of **loss factors** associated with the all-silicon silicate bonding
  - Use of **GEO600 detector** for demonstration of silicon technology