DISSIPATION OF ELASTIC ENERGY IN SAPPHIRE

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Al_2O_3 – trigonal crystal

(6 elastic modulus – moderate anisotropy)

– high density ($4g/cm^3$)

– high thermal conductivity

– high rigidity

– low mechanical losses

To calculate the spectral density of thermal noise

– need to know 6 loss angles as functions of frequency.

But usually we measure Q-factors of several modes for samples of certain crystallographic orientation.

Nevertheless we try to give a picture of mechanical losses in sapphire. The main results are in the book
V.B.Braginsky, V.P.Mitrofanov, V.I.Panov, System with small dissipation, Edited by K.S.Thorne, Univ. of Chicago Press, Chicago, 1985.

Recent works that were carried out in Glasgow, Stanford, Caltech, Tokyo, Perth can supplement this picture.

SAPPHIRE SAMPLES

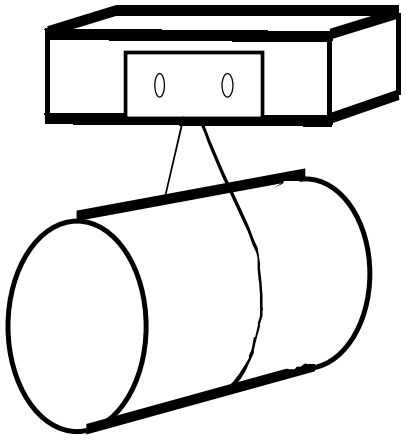
Typical example:

- Manufactured by Moscow Institute of Crystallography (method of horizontal oriented crystallization)
- Cylinder 14cm length x 4.4cm diameter
- 60^{o} orientation
- Fundamental longitudinal mode – 38 kHz

PRINCIPLE SOURCES OF LOSSES

$$Q^{-1} = Q^{-1}_{material} + Q^{-1}_{surface} + Q^{-1}_{support\ structure}$$

SINGLE LOOP WIRE SUSPENSION



Material: silk or polished metal – tungsten, molybdenum, niobium

Diameter: is limited by breaking strength

Length: optimum when is close to anti-resonance in the wire

Additional isolation of sapphire from the wire by grease layer

$Q^{-1}_{support\ structure} \leq \mathbf{3x10^{-9}}$ at room temperature

$Q^{-1}_{support\ structure} \leq \mathbf{2x10^{-10}}$ at $T = 4.2$ K

SURFACE LOSSES

Sources of losses – defects in damaged surface layer (irregularities, microcracks, spallings), adsorbed molecules.

Mechanisms of losses – relaxation in the cracks, thermoelastic loss in crystallites, change of state of adsorbed molecules.

Maximum ***Q*** was obtained after good mechanical polishing of the sample surface which was carried out in our laboratory.

Remark

The Table [Liebowitz H., ed.1972. *Fracture*, Vol.7] illustrates the efficiency of various treatment (the breaking strength can be regarded as an indirect indicator of the quality of the surface).

Maximum Breaking Strength of Sapphire rod at Room Temperature after Various Treatments

Treatments technique	Strength 10^9 Pascal
Flame polishing, selected working area of specimen	7.35
Chemical etching (in borax)	6.86
Mechanical polishing, annealing in oxygen (1600^{o}C)	1.04
Annealing, mechanical polishing	0.78
Grinding	0.59
As manufactured (no additional treatment)	0.44

Thus the surface losses can be further reduced using chemical and flame polishing.

INTERNAL LOSSES IN SAPPHIRE

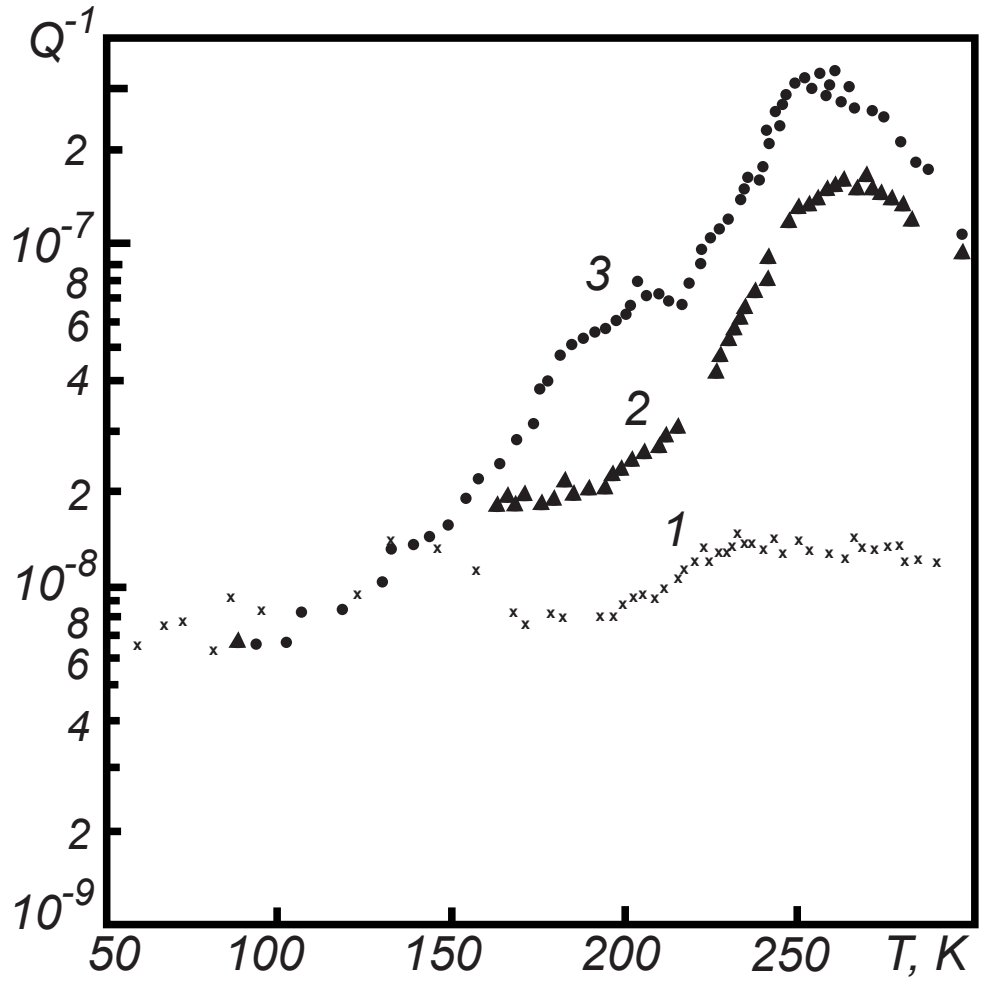
Real crystals have defects in the crystal lattice: vacancies, impurities, dislocations and so on. They are sources of various dissipation processes.

Main feature of sapphire: high values of the Peierls' potentials in the crystal lattice. Hence motion of defects is embarrassed but is not eliminated.

Figures show examples of damping in sapphire resonators associated with impurities of Cr_2O_3 and dislocations.

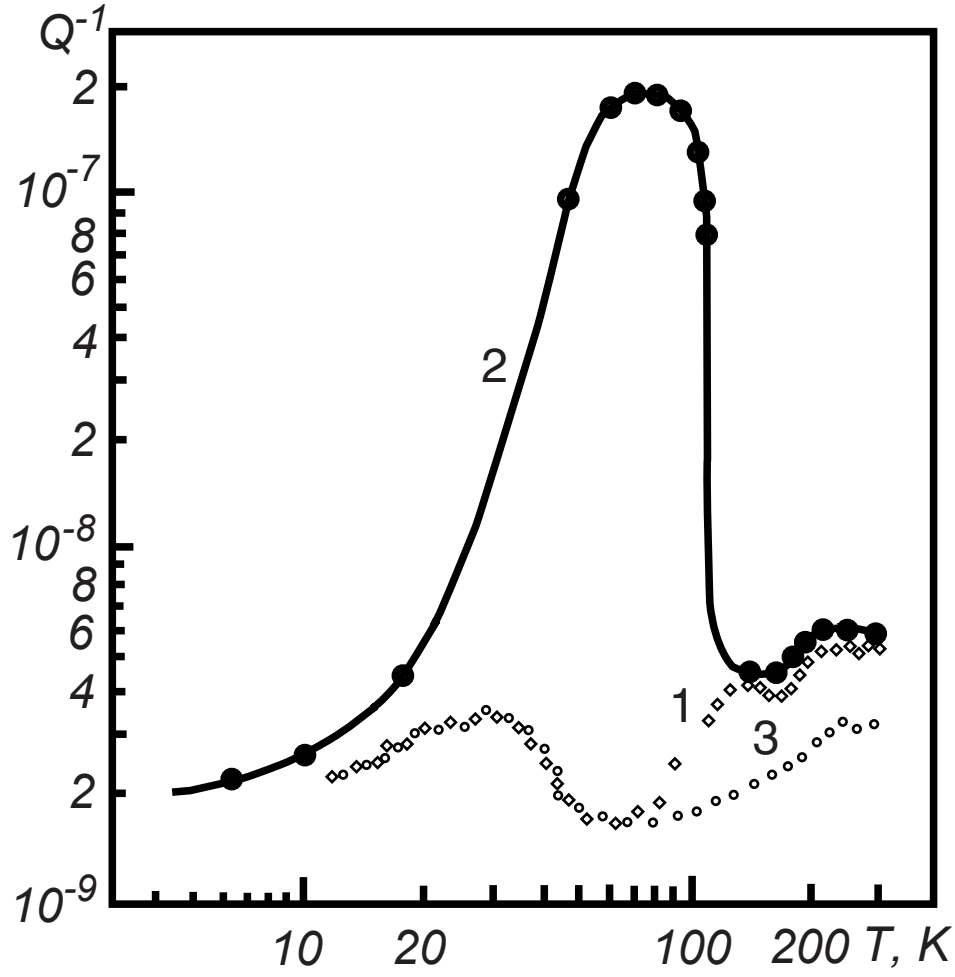
These losses can be excluded for pure sapphire crystals annealed in vacuum at high temperature (if it is necessary).

DAMPING IN SAPPHIRE ASSOCIATED WITH IMPURITY OF Cr_2O_3



Curve 1 – pure sapphire;
Curve 2 – sapphire with 0.1% Cr_2O_3 f=17.3 kHz;
Curve 3 – sapphire with 0.2% Cr_2O_3 f=13.9 kHz;

DISLOCATION DAMPING IN SAPPHIRE



Curve 1 – before spalling; Curve 2 – after spalling;
Curve 3 – after high-temperature (1960 ^{o}C) annealing

INTERNAL LOSSES IN SAPPHIRE

Ideal crystals (without defects)

Fundamental dissipation mechanism caused by the principle anharmonicity (nonlinearity) of a crystal lattice. Deformation of the crystal changes phonon frequencies and thereby perturbs the phonon distribution function away from its equilibrium Planck form. The process of restoring thermal equilibrium to the phonon gas is accompanied by dissipation of the elastic energy.

$$Q^{-1}_{ph-ph} = \frac{\sum C_i T_i \left(\gamma_i^2 - \bar{\gamma}_i^2 \right)}{\rho \upsilon^2} \frac{\omega \tau^*_{ph}}{1 + \left(\omega \tau^*_{ph} \right)^2}$$

where

$\gamma_i = -\dfrac{\partial \nu_i / \partial \xi}{\nu_i}$ – Grunisen's coefficients;

$\tau^*_{ph} = 3k / C\upsilon^2_D$ – phonon relaxation time;

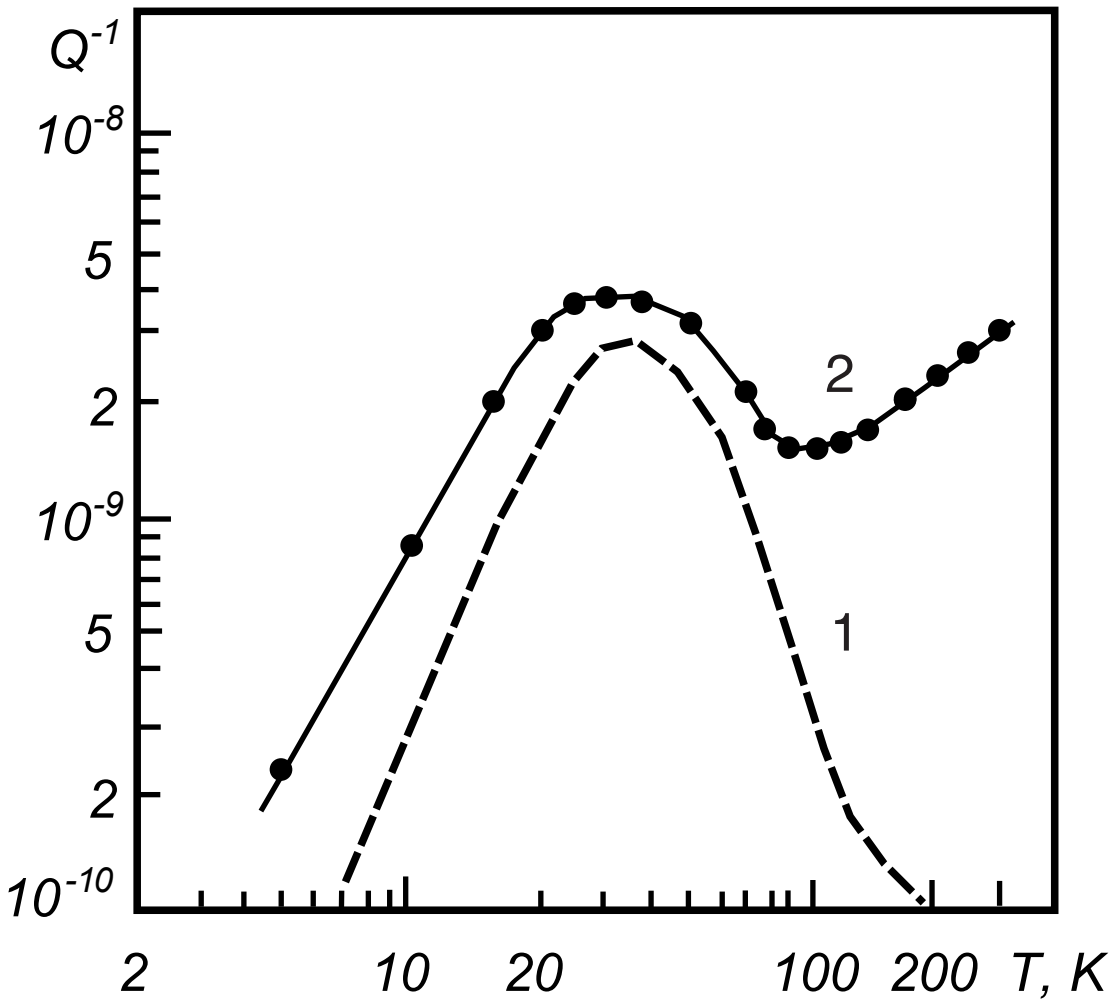
ρ – the density of sapphire, υ – the sound velocity;

C – the heat capacity per unit volume of the i-th phonon mode in the crystal; k – the thermal conductivity.

- Q^{-1}_{ph-ph} – is proportional to ω for frequencies $< \tau^{*\,-1}_{ph}$.

Loss associated with the surface and leakage in to the support are likely responsible for the damping in sapphire resonators measured at the room temperature.

FUNDAMENTAL DISSIPATION IN SAPPHIRE DUE TO PHONON-PHONON INTERACTIONS (AKHIEZER'S MECHANISM)



Curve 1 – calculated

Curve 2 – measured

SAPPHIRE TEST MASSES

Thermal noise and dissipation at the frequency range 10 Hz – 1 kHz is important for LIGO.

V. B. Braginsky, M. L. Gorodetsky, and S. P. Vyatchanin have shown that thermoelastic noise associated with thermoelastic dissipation in sapphire plays a key role.

*V. B. Braginsky, M. L. Gorodetsky, and S. P. Vyatchanin, Phys. Lett. A **264**, 1 (1999)*

This result was made more precise for finite test mass by Yu. T. Liu and K. S. Thorne.

*Yu. T. Liu and K. S. Thorne, Phys. Rev. D **62**, 122002 (2000)*

Now these groups analyze the possibility to reduce thermoelastic noise in the mirrors changing shape and size of beam and mirror.