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Mechanical losses in low loss materials studied by Cryogenic Resonant Acoustic spectroscopy of bulk materials (CRA spectroscopy)

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Abstract. Mechanical losses of crystalline silicon and calcium fluoride have been analyzed in the temperature range from 5 to 300 K by our novel mechanical spectroscopy method, cryogenic resonant acoustic spectroscopy of bulk materials (CRA spectrocopy). The focus lies on the interpretation of the measured data according to phonon-phonon interactions and defect induced losses in consideration of the excited mode shape.

1. Introduction

Low mechanical loss materials are demanded in instruments with extraordinary precision to decrease their thermal noise as mechanical losses and thermal noise are linked [1]. For instance, low loss materials like crystalline silicon, sapphire, calcium fluoride and quartz are candidates for the optical components of future cryogenic interferometric gravitational wave detectors [2]. Due to the anisotropy of the crystals and the search for an optimal operating temperature of the detectors systematic measurements of the mechanical losses have to be performed. Therefore, our novel mechanical spectroscopy method, cryogenic resonant acoustic spectroscopy of bulk materials (CRA spectrocopy), was applied in the temperature range from 5 to 300 K. Instead of the small losses in the detection band, the reciprocals of the losses at the resonant frequencies, the mechanical quality factors Q, have been measured. Following the test of our method on the fairly well-known material crystalline quartz [3], results on silicon and calcium fluoride are presented. For details on the measuring setup and method see references [4] and [5].

2. Results on crystalline silicon (100)

The sample was of cylindrical shape, 76.2 mm in diameter and 12 mm thick. The reciprocals of the measured Q factors, corresponding to the mechanical loss at the particular resonant frequency and temperature, of two selected modes have been plotted in Figs. 1 a) and b). According to the superposition principle of mechanical losses, the total damping curve has been decomposed into contributions (displayed by coloured lines and roman numerals, respectively)

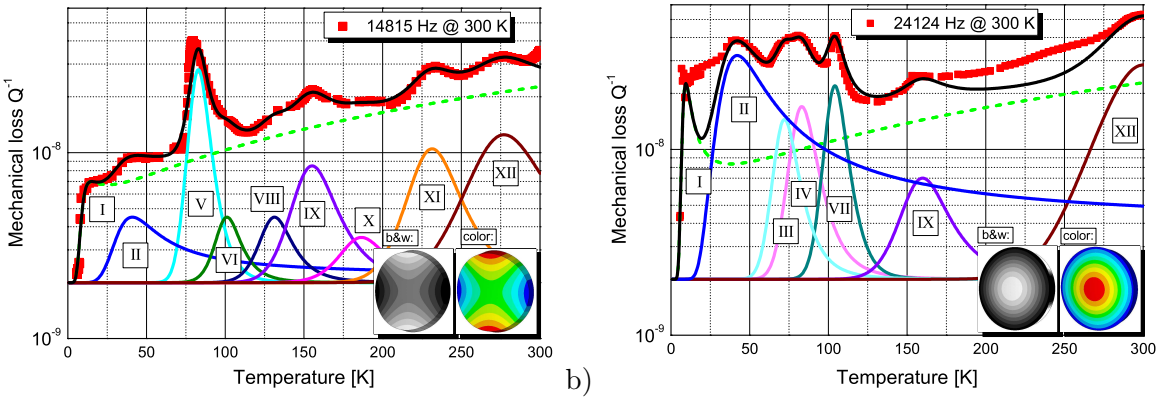

Figure 1. (color online) Loss vs. temperature gained by Q measurements on a silicon sample. Red squares: reciprocals of measured Q factors. For fit parameters see text. The excited mode shape is shown as a contour plot of the displacement in direction of the cylinder axis. Red and blue denote max. displacement (in B&W: black and white), green minimum.

RELAXATION PEAK	FREQUENCY @ 300 K (Hz)	T_{peak} (K)	Δ_0 ($\times 10^{-10}$)	τ_0 (s) ($\times 10^{-15}$)	E_a (meV)	$d(\vartheta, f_r)$
I (light green)	14815	15	7.8	92×10^{7}	2.5	ϑ
II (blue)	14815	40	50	3.8×10^{8}	12	1
V (cyan)	14815	83	520	35	140	1
VI (dark green)	14815	100	50	12×10^{2}	140	1
VIII (dark blue)	14815	131	50	12×10^{2}	185	1
IX (violet)	14815	155	130	25×10^{2}	205	1
X (magenta)	14815	185	30	2×10^{3}	250	1
XI (orange)	14815	230	170	20	402	1
XII (brown)	14815	278	210	14×10^{2}	380	1

Table 1. Fit parameters of the relax. peaks in Fig. 1 a). The background loss is max. 2×10^{-9}.

RELAXATION PEAK	FREQUENCY @ 300 K (Hz)	T_{peak} (K)	Δ_0 ($\times 10^{-10}$)	τ_0 (s) ($\times 10^{-15}$)	E_a (meV)	$d(\vartheta, f_r)$
I (light green)	24124	9	45	9×10^{7}	3.3	ϑ
II (blue)	24124	41	600	2×10^{8}	12.7	1
III (light cyan)	24124	72	250	9×10^{3}	84	1
IV (light magenta)	24124	83	300	5×10^{3}	101	1
VII (dark cyan)	24124	104	400	1	203	1
IX (violet)	24124	160	100	30×10^{2}	200	1
XII (brown)	24124		530	28×10^{2}	380	1

Table 2. Fit parameters of the relax. peaks in Fig. 1 b). The background loss is max. 2×10^{-9}.

due to single anelastic processes of different origin. The loss ϕ caused by a single relaxation process with small relaxation strength Δ at frequency f has been modelled by [6]

$$\phi = \Delta\, 2\pi\, f\, \tau / \left(1 + (2\pi\, f\, \tau)^2\right), \quad \Delta = \Delta_0\, d\,(\vartheta, f_r)\,, \tag{1}$$

where τ is the relaxation time, Δ_0 is a dimensionless coupling strength and $d\,(\vartheta, f_r)$ is in general a dimensionless function of reduced temperature ϑ and frequency f_r. The maximum damping

occurs when $2\pi f\tau = 1$. In Q measurements f is the resonant frequency specified by the material, sample geometry and temperature T, whereas τ is characteristic for the loss process and depends on T. The relaxation strength may vary with f and T and furthermore depends on the excited mode shape. Therefore, one aim is to extrapolate the relaxation strength in the off-resonant region by performing systematic Q measurements. The relaxation time was assumed to follow an Arrhenius-like law [6]

$$\tau = \tau_0 \, exp\,(E_a/k_B\,T)\,, \tag{2}$$

with the relaxation constant τ_0, activation energy E_a, and Boltzmann constant k_B. The parameters of the fitted relaxation peaks are arranged in Tabs. 1 and 2, respectively.
The mechanical losses are dominated over the whole temperature range by dissipation processes assigned to interactions of the acoustic waves with thermal phonons (peak I, dashed lines in Figs. 1 a) and b)). Landau and Rumer [7] developed a theoretical description for the lower temperature region of the peak ($2\pi f\tau > 1$) whereas Akhieser [8] treated the higher temperature region ($2\pi f\tau < 1$). Nevertheless, the 'phonon-peak' is well approx. by assuming Δ proportional to T and τ according to Eq. 2. For the mode in Fig. 1 a) the result is better than for that in Fig. 1 b). The quality of the description of the phonon-phonon interactions is of outstanding relevancy as the quality of the fit of the remaining relax. peaks strongly depends on it.
Several parameters of the remaining peaks have been related to formerly observed reorientation processes. Lam and Douglass [9] reported an activation energy of E_a=0.14 eV and relaxation constants of τ_0= 7.2×10^{-12}s resp. τ_0=4.7×10^{-12}s in loss measurements which could be assigned to vibrations of Si-O-Si complexes by IR measurements on oxygen-doped silicon. The peak VI in Fig. 1a) shows similar parameters. Lam and Douglass further related the parameters E_a=0.20 eV and τ_0=8.64×10^{-13}s to the vacancy-oxygen (VO) complex. At that time Watkins and Corbett [10] had already observed by ESR that different kinds of redistribution can take place in a VO center. An electronic redistribution is related to the mentioned parameters above. A defect reorientation is characterized by E_a=0.38 eV and a relaxation time of τ_0=2×10^{-13}s which had been also observed by Berry [11]. In the damping curves of both modes peak IX and XII might be of that origin. Coutinho et al. [12] investigated a hydrogen atom jumping between two Si dangling bonds in vacancy-oxygen-hydrogen complexes (VOH and VOH_2 defects) with E_a=0.18 eV. The related relaxation constant reported by Johannesen et al. [13] is τ_0=1.1×10^{-12}s. Peak VIII in Fig. 1 a) is probably caused by this defect. As the VO as well as the VOH complex anneals out at 573 K, such a treatment might decrease the damping in the corresponding temperature regions. According to the attenuation measurements of Pomerantz [14] the sample is presumably doped with phosphor (peak II). Regarding the relaxation strengths the dependence on mode shape is especially visible in the low temperature region.

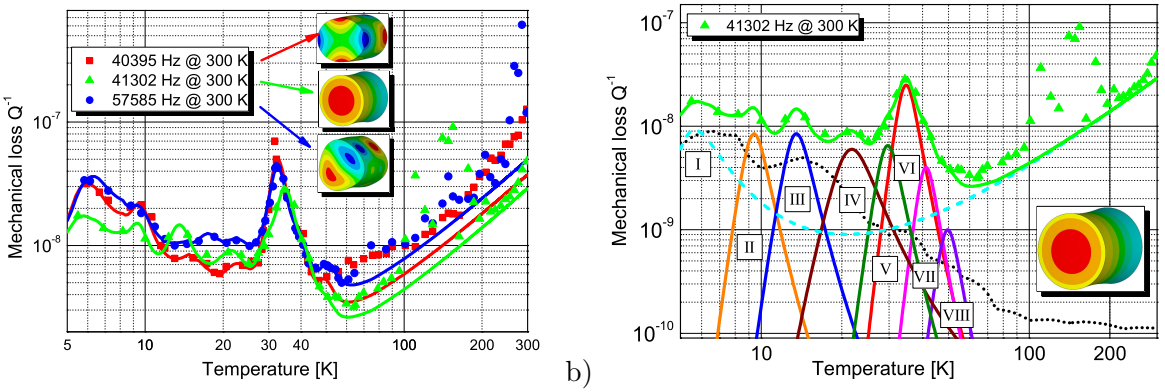

Figure 2. (color online) Losses gained from Q measurements on CaF_2 sample (details in text).

RELAXATION PEAK	T_{peak} (K)	Δ_0 ($\times 10^{-10}$)	τ_0 (s) ($\times 10^{-13}$)	E_a (meV)	$d(\vartheta, f_r)$
I (cyan)	5	6	1.9×10^4	3.6	ϑ^2
II (orange)	9	170	30	11.4	1
III (blue)	13	170	1×10^2	15	1
IV (brown)	21	120	1×10^4	15.5	1
V (dark green)	29	130	20	37	1
VI (red)	34	500	3	49	1
VII (magenta)	41	80	1	62	1
VIII (violet)	49	20	3	70	1

Table 3. Fit parameters of the damping peaks shown in Fig. 2 b).

3. Results on crystalline calcium fluoride (100)

Examining the mechanical losses of the selected modes of a sample made of CaF_2 (cylindrical shape, 75 mm in diameter, 75 mm thick) in Fig. 2 a) the variation with mode shape is far less existent as for silicon. Peaks with the same characteristic parameters appear in all damping curves except very narrow loss peaks above 100 K due to coupling of the substrate motion to the suspension [15]. Therefore, the results on one mode have been examplarily plotted in Fig. 2 b) with corresponding fitting parameters in Tab. 3. In the low temperature range the mechanical losses are dominated by thermoelastic damping (dotted line in Fig. 2b)) [16]

$$\phi_{te} = \kappa\, T\, \alpha^2\, \rho\, 2\pi\, f / \left(9\, C^2\right), \tag{3}$$

with the thermal conductivity κ, the volume thermal expansion coefficient α, density ρ and specific heat C. Hence, the 'phonon-peak' is less visible. The damping at higher temperatures offers an orientation for fitting. According to it, the relaxation strength has been modelled to be proportional to T^2. An investigation of the losses below 5 K where the thermoelastic damping decreases would be helpful for a better determination of the shape of the maximum. A further interpretation of the damping peaks according to their characteristic parameters is in progress.

Acknowledgments

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