ACOUSTIC DAMPING IN LANGATATE AS A FUNCTION OF TEMPERATURE, FREQUENCY, AND MECHANICAL CONTACT

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Abstract – Resonant acoustic damping in plano-convex (trapped-mode) langatate ($La_3Ga_{5.5}Ta_{0.5}O_{14}$) disks was measured at frequencies from 2 MHz to 18 MHz and temperatures from 130 K to 450 K. A broad anelastic relaxation peak was observed in the temperature dependence of the damping, and this peak extends into the ambient temperature range. Measurements and theoretical calculations of the vibrational trapping efficiency indicate that external damping was not significant for measured overtones above the fundamental. For some modes, relatively narrow peaks in the temperature dependence of the loss were observed, and these are attributed to coupling with other modes.

I. INTRODUCTION

Interest in langatate ($La_3Ga_{5.5}Ta_{0.5}O_{14}$), langasite ($La_3Ga_{5.5}SiO_{14}$), and langanite ($La_3Ga_{5.5}Nb_{0.5}O_{14}$) for electronic oscillator and filter applications has been motivated in part by the potential of these piezoelectric crystals for providing values of *Q* that are higher than those of quartz. To date, the reported values of the product of *Q* and the frequency *f* for langatate are the highest among this group of materials [1,2]. However, *Qf* is found to vary significantly between specimens, even when crystals are taken from the same boule.

The fundamental limit of *Q* in a perfect piezoelectric crystal is determined by phonon-phonon interactions (the Akhieser mechanism [3]), neglecting the thermoelastic loss, which is two to three orders of magnitude smaller in quartz [4]. In imperfect crystals, the dominant contributions to the loss can arise from extended or point defects in the bulk or from defects localized near the surface.

The identification of dominant sources of internal loss is critical to the development of langatate for electronic applications, just as it was to the development of synthetic quartz. Only limited information about loss mechanisms can be obtained from an analysis of the frequency dependence of Q^{-1} at room temperature. To obtain a more complete picture, measurements of Q^{-1} as a function of temperature were performed in this study. Supplemental tests also were performed to determine whether the mechanical support of specimens significantly affected the *Q*.

II. SPECIMEN PREPARATION

Specimens of langatate were fabricated in the form of unplated plano-convex Y-cut disks (blanks) with a diameter of 14 mm. The spherical surface had a radius of 265 mm (2 diopter). The thickness at the center was 0.68 mm, which provided a fundamental trapped-mode frequency near 2 MHz. The methods of cutting, lapping, polishing, and cleaning the specimens are described by Smythe *et al.* [1]. Final cleaning also was performed with acetone followed by ethanol.

III. MEASUREMENT METHODS

Acoustic-resonance measurements at room temperature were performed using time-domain and frequency-domain techniques. At temperatures above and below ambient, only time-domain measurements were performed. With both measurement techniques, direct piezoelectric coupling to resonant vibrations was employed with noncontacting planar electrodes on opposite sides of the specimen.

For the time-domain measurements, specimens were supported on three sapphire spheres. The spacing of the electrodes was 2.75 mm. A sinusoidal tone burst was used to drive the electrodes at a frequency close to a resonance. Q^{-1} was determined from the exponential decay of the amplitude calculated from the components of the signal that were in phase and out of phase with the reference driving sinusoid.

Time-domain measurements at room temperature were made in a roughing vacuum of 27±3 Pa. Measurements as a function of ramped temperature were performed in a turbo-pumped chamber with a continuous flow of oxygen-free helium at ~1.3 Pa, which provided thermal exchange.

For measurements in the frequency domain, specimens were supported at their edges with a Teflon ring, and the electrode spacing was 1.27 mm. Swept-frequency transmission measurements were performed with an RF vector network analyzer. A hybrid network was used to eliminate the effect of static fixture capacitance. The unloaded Q was calculated from the 3 dB bandwidth of each resonance peak and the measured insertion loss at the maximum of transmission. These measurements were performed at a pressure of 13 Pa.

III. RESULTS

Measurements of Q^{-1} of seven specimens at room temperature are presented in Table 1. The uncertainties indicated for time-domain values are based on systematic changes arising from repositioning of the specimens (for example, from removal and reinsertion in the sample chamber) or systematic changes as a function of time.

For the three highest-frequency modes, values of Q^{-1} obtained with the two techniques agree within 10 %, with the exception of the fifth overtones of specimens LGT4 and LGT7. The agreement between the two techniques is not as good for the third overtone (differing by 10-22 %) and is relatively poor for the fundamental mode (differing by 24-56 %).

The highest value of Qf from Table 1 is 2.0×10^{13} Hz for the 7th overtone of specimen LGT17. This is significantly below the highest value (2.9×10^{13} Hz) reported by Smythe *et al.* [1].

Effects of Mechanical Contact

The relatively large variations in the measured Q^{-1} at 2 MHz in Table 1 are consistent with a lack of effective vibrational trapping of this mode. Theoretical calculations indicate that the relative amplitude of vibrations near the edges of a specimen is orders of magnitude higher for the fundamental mode than for overtones 3 through 9.

Information on the degree of trapping also was pursued experimentally by measuring the effects of additional mechanical contact introduced near the edges of the specimen. A Buna-N rubber O-ring with outer and inner diameters of 12.7 mm and 9.0 mm

Table 1: $Q^{-1}\times10^{6}$ of seven langatate specimens at room temperature measured with time-domain and frequency-domain techniques. Frequency-domain measurements are in parentheses.

Specimen	Overtone index; Frequency				
	1; 2 MHz	3; 6 MHz	5; 10 MHz	7; 14 MHz	9; 18 MHz
LGT4	0.87±0.05	0.863±0.013	1.2±0.2 (2.18)	1.49±0.04	2.34±0.03
LGT5	4.6±1.0 (2.96)	0.95±0.04 (1.10)	0.94±0.01 (0.889)	1.17±0.02 (1.10)	1.53±0.03 (1.45)
LGT7	5.7±0.9	1.48±0.1	1.30±0.05 (1.46)	1.66±0.06	2.03±0.08
LGT9	0.95±0.1 (1.18)	1.23±0.2 (1.36)	1.03±0.01 (0.983)	1.26±0.01 (1.18)	1.54±0.02 (1.42)
LGT11	0.42±0.02 (0.691)	0.63±0.02 (0.727)	0.58±0.01 (0.613)	0.74±0.02 (0.818)	1.53±0.03 (1.52)
LGT14	0.78±0.01	1.25±0.06	3.86±0.05 (3.82)	3.83±0.24	41.1±12.4
LGT17	0.54±0.04 (0.850)	0.63±0.07 (0.499)	0.56±0.01 (0.551)	0.68±0.01 (0.677)	1.15±0.03 (1.16)

was placed on the top surface of the specimen. Figure 1 shows typical results for Q^{-1} with and without the O-ring present. Contact with the O-ring resulted in an increase in damping of the fundamental mode (consistent with a lack of trapping) but had no significant effect on the other modes. These results and those of Table 1 indicate that the measurements of Q^{-1} at 2 MHz are unreliable on an absolute basis.

Frequency Dependence at Room Temperature

Since the above results show that mechanical contact near the edge has an insignificant effect on the Q^{-1} of overtones 3, 5, 7, and 9, the frequency dependence of these modes apparently provides information on the internal damping mechanisms. The intrinsic Akhieser loss is proportional to frequency in the megahertz range [3]. The values of Q^{-1} do not show this overall frequency dependence (see the line proportional to f in Fig. 1), although most of the values for overtones 5, 7, and 9 show a dependence that is not greatly different from linear ($\sim f^{0.8}$). Therefore, internal mechanisms other than the Akheiser mechanism contribute significantly to the loss, at least for some of the modes. It may be noted that this statement also is true with respect to values of Q^{-1} for langatate previously reported by Smythe *et al.* [1].

Temperature Dependence

Measurements of the Q^{-1} of LGT7 and LGT17 were performed as a function of temperature from 130 K to 450 K to provide additional information on the physical sources of damping. As shown in Fig. 2, Q^{-1} of LGT7 has a broad peak that shifts systematically to higher temperatures at higher frequencies. Anomalous narrower peaks also are present, except for the 5th overtone (9.86 MHz). Q^{-1} of the 3rd overtone (not shown) has a continuous series of narrow peaks versus temperature.

The general form of the broad peak in Fig. 2 is characteristic of an anelastic defect relaxation. For a single relaxation time τ, the anelastic loss is given by

$$Q^{-1} = \Delta_0 \frac{\omega\tau}{1+\omega^2\tau^2}, \qquad (1)$$

where ω is equal to $2\pi f$ and Δ_0 is proportional to the concentration of defects and inverse temperature [5]. For point defects, τ usually has an Arrhenius

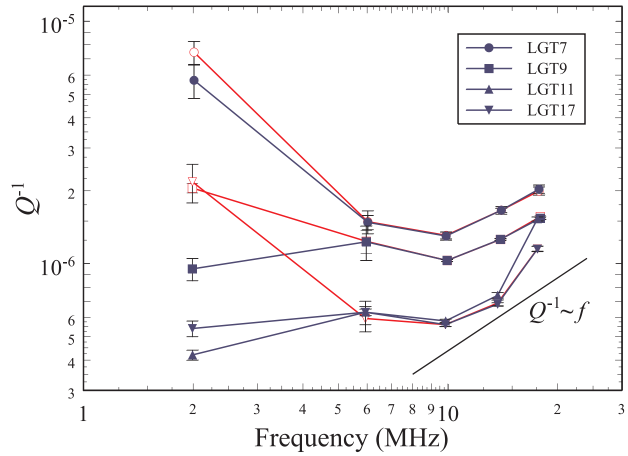

Figure 1: Q^{-1} of specimens with and without an O-ring resting on the upper surface. Filled symbols in the legend are for the measurements without the O-ring. Open symbols with the same shapes are used for measurements with the O-ring.

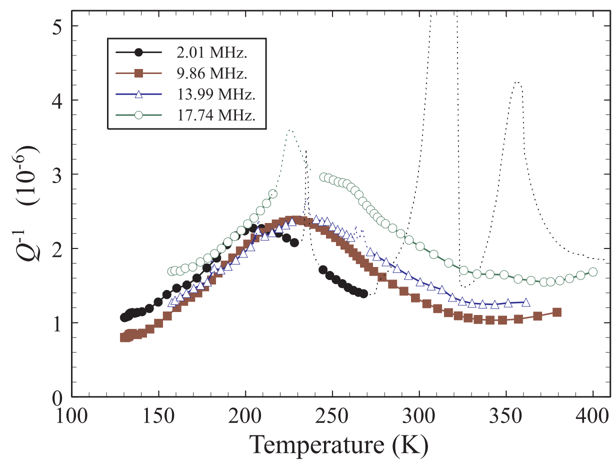

Figure 2: Q^{-1} versus temperature in specimen LGT7. Anomalous peaks are plotted with dotted lines.

dependence on temperature T:

$$\tau = \tau_0 \exp(U/kT), \qquad (2)$$

where τ_0 is a constant, U is the activation energy, and k is Boltzmann's constant. The widths of the peaks in Fig. 2 actually suggest some distribution of relaxation times, but this complication is not considered here.

Using Eq. (2), a least-squares fit of the peak positions obtained from measurements of Q^{-1} of LGT7 versus temperature yields a τ_0 of 6.2×10^{-14} s and a U of 0.25±0.03 eV. These values are typical of anelastic relaxations of point defects

At temperatures well above the peak, $\omega\tau$ is significantly less than 1. Therefore, from Eq. (1), the anelastic contribution to Q^{-1} at ambient temperatures is approximately proportional to ω (close to the frequency dependence of the Akhieser loss).

Figure 3 shows Q^{-1} of the 5th and 7th overtones of LGT17 versus temperature. The loss is lower than that of LGT7 and shows no clear relaxation peak. However, the fact that the ratio of Q^{-1} for the 13.66 MHz and 9.82 MHz modes decreases at lower temperatures suggests that a peak is present (see Eq. (1) and Fig. 2). Any peak will be superimposed on an Akhieser loss, which decreases at low temperatures. The increase in Q^{-1} above ~350 K for both LGT7 and LGT17 (Figs. 2 and 3) is consistent with the high-temperature loss previously reported for langatate cylinders at lower resonant frequencies [6].

Q^{-1} of the 1st, 3rd, and 9th overtones of LGT17 (not shown) has numerous peaks as a function of temperature. Such peaks, and similar ones observed for LGT7, apparently correspond to the phenomenon of activity dips, which is encountered in the design of electronic resonators and arises from coupling between modes [7]. At least for some specimens, the anomalous peaks affect the apparent frequency dependence shown in Fig. 1. For example, the high relative value of Q^{-1} for the 9th overtone of LGT17 arises from the presence of a relatively narrow peak in this mode near room temperature.

IV. Conclusions

Measurements of Q^{-1} of langatate as a function of temperature have revealed an anelastic effect that could not be identified in measurements performed only at room temperature. This effect is consistent with a point-defect relaxation. In the ambient temperature range, the frequency dependence of the anelastic loss is approximately the same as that of the intrinsic phonon-phonon loss. Because of anomalous peaks in the temperature dependence of Q^{-1} of some modes, the frequency dependence at any single temperature provides little information regarding physical mechanisms.

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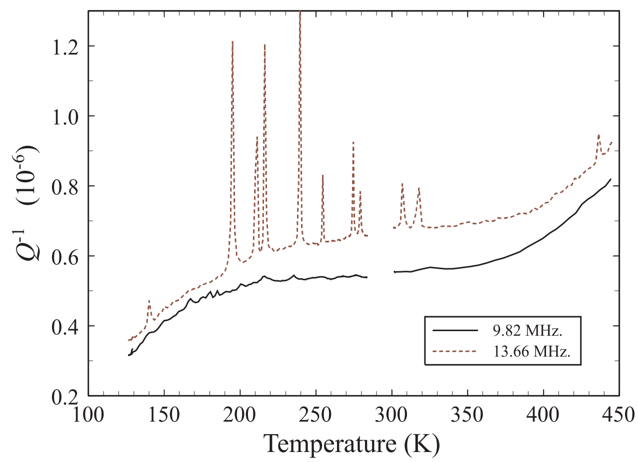

Figure 3: Q^{-1} versus temperature in specimen LGT17

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