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High-Temperature Acoustic Loss in Bulk AlN Piezoelectric Resonators

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Summary:

Aluminum nitride (AlN) single crystals are grown by physical vapor transport under varying conditions to achieve samples that exhibit a wide range of doping concentrations for carbon, oxygen and silicon. Accordingly, properties such as electrical conductivity and acoustic loss vary significantly. Beside structural quality and essential point defects, the electrical conductivity, thermal expansion, elastic constants and acoustic losses are determined up to 900°C. Special attention is paid to the correlation of acoustic losses and electrical conductivity, as they are crucial application-relevant parameters. For example, the losses in crystals with low dopant concentration ratios of oxygen to carbon ([O]/[C] ≤ 1) are found to be determined by the electrical conductivity above about 650°C. The lowest overall losses are observed in AlN with lowest concentration of oxygen impurities.

Keywords: aluminum nitride, high temperature, piezoelectric resonator, acoustic loss.

Motivation

Single crystalline aluminum nitride (AlN) shows attractive properties if used for piezoelectric sensors at temperatures above 500°C. The predominant covalent bonds in the material result in high thermal stability and low losses of piezoelectric resonators thereby enabling new applications like resonant pressure and temperature sensors for turbines and engines.

To take advantage of these properties, high quality bulk crystals are required. Presently, they are provided by a very low number of commercial suppliers which limits the options for users to get crystals with tailored materials properties. Therefore, (1) the growth of crystals that exhibit a wide range of properties such as electrical conductivity, (2) the determination of electrical and acoustic properties and (3) their correlations are the focus of this work.

Samples and methods

AlN single crystals are grown by physical vapor transport under varying conditions resulting, in particular, in dopant concentration ratios of oxygen to carbon ranging from [O]/[C] = 0.4 to 4.0. Differently oriented crystal plates are cut and polished to enable piezoelectrically excitation of length-thickness extension, thickness extension and thickness-shear vibrations. The resonance spectra are acquired by resonant piezoelectric spectroscopy [1]. Details on the AlN growth, sample preparation and electrode deposition can be found in [2,3].

Results

The electrical conductivity of the AlN samples at 900°C ranges from 10^{-5} to 10^{-2} S/m and shows activation energies of about 2 eV in the temperature range from 650 to 900°C. The highest value of about 2.2 eV results for [O]/[C] = 1.

The resonance spectra show the expected pattern and are clearly evident even at 900 °C (Fig. 1). A nearly linear decrease of the resonance frequency *f* is observed with increasing temperature (Fig. 2).

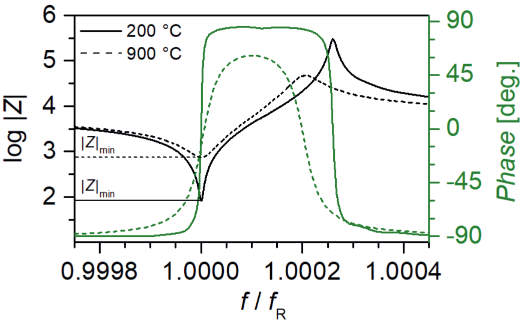

Fig. 1. Resonance spectra of a m-cut sample operated in thickness-shear mode at 200 and 900°C (f_R: f at room temperature).

The acoustic losses, as expressed e.g. by the inverse Q-factor, are of particular importance for piezoelectric resonators since they determine the accuracy of the frequency measurement. The overall loss results from the following contributions (Fig. 3):

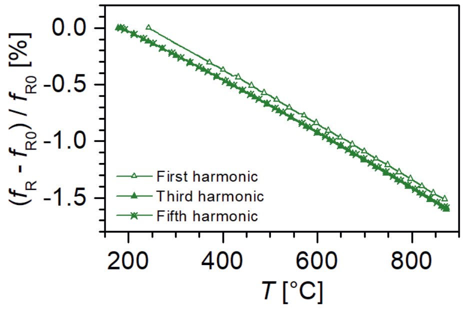

Fig. 2. Resonance frequency of a m-cut sample operated in thickness-shear mode as a function of temperature.

- Intrinsic phonon-phonon interaction
  In the temperature range of interest, i.e. well above room temperature, this loss mechanism shows a low temperature dependence [4]. Since the intrinsic phonon-phonon interaction is generally low and the total losses increase strongly with temperature, this contribution is practically negligible in the present samples.
- Anelastic relaxation of point defects
  At low and medium temperatures, high contributions are observed in oxygen dominated AlN samples (Q_{a1}^{-1} and Q_{a2}^{-1} in Fig. 3).

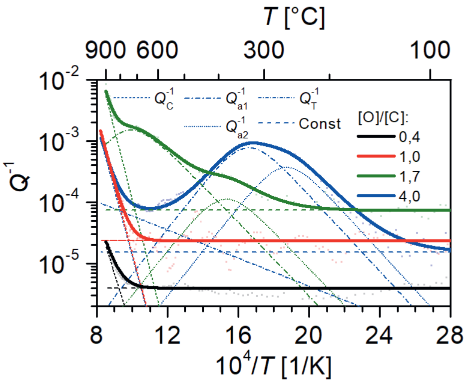

Fig. 3. Contributions to the electromechanical losses in AlN single crystals with different dopant concentrations (details see text).

- Electrical conductivity
  The piezoelectric effect couples the mechanical and electrical systems on a microscopic level. The corresponding mechanical losses is caused by the relaxation of charge carriers and dominates in AlN with high C- or O-concentrations at temperatures of about 650-900°C (Q_C^{-1} in Fig. 3). This statement results directly from the conversion of the electrical conductivity into mechanical losses [3].
- Temperature dependent background and contributions from sample support
  For AlN samples with higher oxygen content ([O]/[C] = 4.0 and 1.7) the background is relatively high and determines the total losses below about 250°C. For AlN with low oxygen content ([O]/[C] = 1.0 and 0.4) the losses are very low (< 3×10^{-5}) [3].

Further, the long-term stability of ALN at high temperatures (900°C) and low oxygen partial pressures (10^{-17} bar) is investigated. Within 22 days, the resonance frequency decreases by only 0.36%. The losses are low and remain virtually unchanged.

Finally, the losses in AlN are compared with those of other high temperature stable piezoelectric crystals using the product of Q-factor and resonance frequency. Above about 500°C, AlN exhibit lower losses than LGS ($La_3Ga_5SiO_{14}$). In contrast, AlN generally shows slightly higher losses than CTGS ($Ca_3TaGa_3Si_2O_{14}$) [5].

Conclusions

The modeling of the temperature dependent acoustic losses in the AlN crystals allows an assignment of domonating loss contributions. In AlN with an oxygen content lower or comparable to that of carbon, the electrical conductivity is the main loss contribution at temperatures above 650°C.

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