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Elastic stiffness and ultrasonic attenuation of superconductor MgB₂ at low temperatures

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Temperature dependencies of elastic constants and ultrasonic attenuation of a polycrystalline MgB₂ showing high-T_c superconductivity are reported. An electromagnetic acoustic resonance method detected the specimen’s resonance frequencies, from which we derived the elastic constants for nonporous MgB₂ using micromechanics calculation. The bulk and shear moduli extrapolated to 0 K are determined to be 96.6 GPa and 74.2 GPa, respectively, which gives the Debye temperature Θ_D=819 K and the coupling constant λ̃≈0.76–0.89 with McMillan formula. In the temperature behavior of ultrasonic attenuation, two anomalous peaks are observed near 30 K.

The remarkable discovery of intermetallic superconductor MgB₂ with a high T_c of 39 K (Ref. 1) has triggered related extensive studies to elucidate the mechanism of its superconductivity. A significant boron isotope effect implies that MgB₂ is a phonon-mediated superconductor. The ab initio calculations,¹² tunneling-spectroscopy studies,⁴⁵¹ nuclear spin-lattice relaxation,⁶ and photoemission measurements⁷ have concluded that MgB₂ is a conventional s-wave superconductor of “strong” or “intermediate” electron-phonon coupling, although an essential uncertainty still remains in whether MgB₂ is a multiple-gap⁸–¹¹ or anisotropic-gap⁴¹³ superconductor.

The elastic constants are important parameters for knowing the Debye temperature and the electron-phonon coupling constant in a phonon-mediated superconductor. Several related studies appeared: first-principles calculations predicted the single-crystal elastic constants;¹⁴,¹⁵ x-ray measurements under high pressure gave the isothermal bulk modulus;¹⁶ the flexural resonant method gave Young’s modulus;¹⁷ and other results were given in sound-velocity measurements.¹⁸ However, these are inconsistent with each other. Also the temperature dependence has not been systematically measured yet.

Here we have examined the elastic and anelastic properties of MgB₂ through the ultrasonic characteristics. This paper presents the temperature dependence of elastic constants of nonporous MgB₂ deduced using a micromechanics model, the temperature behavior of ultrasonic attenuation, and observation of two anomalous attenuation peaks below 30 K.

A sample was prepared from commercially available powder by pseudo-HIP sintering at 1273 K for 12 h (referring to the method described in Ref. 1), and we checked that T_c of the sample was about 39 K by an eddy-current method. The x-ray-diffraction spectrum indicated that the sample included a very small amount of MgO. The sample was machined into a rectangular parallelepiped, measuring 5.125(x₁)×3.940(x₂)×2.349(x₃) mm³, where xᵢ denotes the coordinate axis of the specimen. The mass density is 2301 kg/m³, 87.7% of the theoretical value.

The resonance frequencies for all vibration modes (dilation, torsion, shear, and flexure modes) were measured by the resonant ultrasound spectroscopy (RUS) method at room temperature. Subsequently, each resonance frequency was identified with the electromagnetic acoustic resonance (EMAR) method, which can excite the specific vibration group through the Lorentz-force mechanism. This noncontact technique is quite sensitive to the ultrasonic attenuation and can measure accurately the internal (intrinsic) friction.

At low temperatures, we used only the EMAR measurement and focused on the two vibration groups: B₂g (shear modes around the x₁ axis) and A₁g (dilatation modes). The ultrasonic attenuation was measured by the free-decay method, and the attenuation coefficient α was determined by fitting exp(−αf) to the measured ring-down with time. The normalized attenuation coefficient (internal friction) is obtained by Q°⁻¹=α/πf.

In the RUS procedure, the elastic constants are determined by comparing the measured and calculated resonance

![Graphical representation](image-url)

FIG. 1. EMAR resonance spectrum at room temperature (upper), the resonance peak of the B₂g-2 mode (lower left), and the free decay at this resonance frequency (lower right). Underlined modes were used for determination of the elastic constants.

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Here, \( \lambda \) is the mean atomic volume, and \( \gamma_1 \) and \( \gamma_2 \) are the isotropic elastic constants of the compound. The present elastic constants at 0 K yield the lattice parameters, as naturally predicted from its low bond strength is predicted to be stronger than those of the other compounds. The present study indicates that the elastic property of MgB\(_2\) is similar to that of ZrB\(_2\) (rather than TiB\(_2\)) in terms of both axial ratio and sound velocity \( \sqrt{B/\rho} \). The elastic stiffness of MgB\(_2\) is not particularly large among these compounds, as naturally predicted from its low condensation. From the above viewpoints, the present elastic constants are more reliable and reasonable.

The Debye temperature \( \Theta_D \) is an important quantity to estimate the electron-phonon coupling constant \( \lambda \), which is proportional to the mean sound velocity \( v_m \),

\[
\Theta_D = \left( \frac{h}{k_B} \sqrt{\frac{3}{4\pi\Omega}} \right) v_m, \quad \frac{3}{v_m^3} = 1 + \frac{2}{v_j^3} + \frac{2}{v_s^3},
\]

where \( h/k_B \) has the usual meaning in quantum mechanics, \( \Omega \) is the mean atomic volume, and \( v_j \) and \( v_s \) are the isotropic sound velocities given by \( (B + 4G/3)/\rho \)\(^{1/2}\) and \( (G/\rho)\)^{1/2}, respectively. The present elastic constants at 0 K yield \( \Theta_D = 819 \) K. According to the McMillan formula,\(^26\) the critical temperature \( T_c \) is expressed using \( \Theta_D \), \( \lambda \), and the Coulomb pseudopotential \( \mu^* \) as
The square of frequency corresponds to the elastic constant (owing to the light component elements) contributes to its high $T_c$.

As seen in Fig. 2, a clear internal-friction peak appears at about 180 K, where the curvature of the resonance frequency changes and a slight modulus variation appears. A similar peak was first reported by Cordero et al.$^{27}$ their peak temperature was located within 70–120 K, being different from our measurement, which is probably attributed to the difference in the frequency ranges used in both measurements (we used $\sim 1$ MHz, while they used 5–73 kHz). Thus, this large peak at about 180 K, showing a frequency dependence, can be a relaxation type like a Bordoni peak and not related to the superconductivity. In our measurement, since the large peak was located at relatively high temperature (180 K), the ultrasonic attenuation at the low-temperature region near $T_c$ was possible to be studied, without being obscured by the large peak.

Figure 3 (upper part) shows the square of the resonance frequency and the internal friction of mode $B_{2g^2}-2$ near $T_c$. The square of frequency corresponds to the elastic constant representative for the resonance vibration. Obviously, the slope of the $f^2$ curve decreases below $T_c$, which indicates that the elastic softening occurs with the superconducting transition. However, the degree of softening is much less than in monoatomic superconductors$^{27}$ and the A15 superconductors. Less softening means that the lattice still remains stiff below $T_c$, which results in the high Debye frequency.

It is noticeable that two very sharp attenuation peaks appear both in mode $B_{2g^2}-2$ and in mode $B_{2g^2}-3$ below 30 K, see Fig. 3. However, peak 2 is clearly shifted in temperature between $B_{2g^2}-2$ and $B_{2g^2}-3$. A third peak marked $T_c$ appears in mode $B_{2g^2}-2$, but is absent in $B_{2g^2}-3$. These findings make it difficult to interpret our results at this stage. Currently we are investigating the possibility that the peaks are linked to the superconducting state. At the same time we have to exclude effects due to sample porosity.

In conclusion, we have examined the elastic property and ultrasonic attenuation behavior of the high-$T_c$ intermetallic superconductor MgB$_2$. The salient results are summarized as follows:

(i) The elastic constants are determined to be $B = 96.6$ and $G = 74.2$ GPa at 0 K through the micromechanics calculation. The bulk modulus $B$ is smaller than the previous reports. However, the presented value is more reliable and reasonable in terms of both the axial ratio of the AlB$_2$ structure and its low condensation.

(ii) The elastic constants determined in this work yield the Debye temperature $\Theta_D = 819$ K and the intermediate coupling constant $\lambda = 0.76$–0.89 with the isotropic McMillan formula.

(iii) In the temperature behavior of ultrasonic attenuation, two anomalous peaks were observed.

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\[
T_c = \frac{\Theta_D}{1.45} \exp \left[ -\frac{1.04(1 + \lambda)}{\lambda - \mu^*(1 + 0.62\lambda)} \right].
\]

$T_c = 39$ K requires $\lambda \approx 0.76$–0.89 with the conventional values of $\mu^* = 0.05$–0.1; MgB$_2$ is thus within the intermediate-coupling regime. Nevertheless, the high Debye temperature $\Theta_D$ contributes to its high $T_c$. $T_c \approx 5$ H. Schmidt


25 H. Inui, K. Tanaka, and S. Otani (private communication).