Effect of pressure on ultrasonic attenuation in Ce monopnictides at low temperatures

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The ultrasonic properties can be used as non-destructive techniques for the detection and characterization of a material's properties not only after the production but during processing as well [1–3]. Ultrasonic absorption and velocity at different temperatures and pressures are mainly determined by elastic behaviour, electrical resistivity and thermal conductivity.

Extensive studies on ultrasonic absorption and velocity have been made theoretically and experimentally in a variety of solids over a wide temperature range [4]. In the low temperature region in metals, the most important factor contributing to ultrasonic absorption is the electron-phonon interaction.

In the literature there is no report on the estimation of pressure contribution to the ultrasonic absorption in semimetallic compounds at low temperatures. The present paper calculate this contribution.

In recent years, there has been considerable interest in the study of mechanical properties of rare-earth compounds. Among them, the Ce monopnictides (CeX: X = P, As, Sb and Bi) have received focused attention on their highly unusual electrical and magnetic behaviour arising from their extremely low carrier concentration. In CeP and CeAs the carrier number is only about 0.1% per Ce atom, whereas in CeSb and CeBi, the carrier number is a few percent per Ce atom [5]. In addition to the low carrier concentration, the position and the width of 4*f* level with respect to the Fermi level, the crystalline field effects, the Coulomb repulsion between the 4*f* electrons in opposite spin state and the magnetic interaction between the 4*f* electrons on different sites give rise to the great diversity of physical properties observed in these compounds.

We determine the quantitative contribution of pressure to the ultrasonic absorption in CeP and CeSb at low temperatures.

Athough semimetallics have low charge carrier concentrations we employ the theory, which was originally formulated for pure metals [6] after considering the electron-phonon interaction. The electron-phonon interaction in CeP and Cesb has been determined by utilizing the electrical resistivity and elastic parameters. The basic idea is that in the normal state, a lattice vibration can communicate energy to the electron gas.

The ultrasonic absorption coefficient (α) due to shear and compressional viscosities ofs the lattice at lower temperature are [6].

$$\alpha_{\text{long}} = \frac{2\pi^2 f^2}{\rho V_l^3}\left(\frac{4}{3}\eta_e + \chi\right) \tag{1}$$

$$\alpha_{\text{shear}} = \frac{2\pi^2 f^2}{\rho V_s^3}\eta_e \tag{2}$$

$$\eta_e = \frac{9 \times 10^{11}\hbar^2(3\pi^2 N)^{\frac{2}{3}}}{5e^2 R} \tag{3}$$

Where η_e is the electronic viscosity, V_l is the velocity of longitudinal ultrasonic wave, V_s is the velocity of shear ultrasonic wave, f is frequency of wave, χ is compressional viscosity, ρ is density, R is electrical resistivity, N is electronic density, $\hbar$ is Planck's constant divided by 2π.

V_l and V_s are directly related to second order elastic constants C_{IJ}, as

$$V_l = \sqrt{\frac{C_{11}}{\rho}} \quad \text{and} \quad V_s = \sqrt{\frac{C_{44}}{\rho}}$$

We have computed the temperature dependence of second order elastic constants (SOEC) (C_{11}, C_{12}, C_{44}) for the evaluation of ultrasonic velocities. All the evaluations of SOEC were made using the method described by Mori and Hiki [7].

The calculated values of SOEC are presented in Tables I–II and the ultrasonic velocities are presented in Tables III–IV Figs 1–4, show the variation of ultrasonic absorption (α/f^2) with temperature in CeP and CeSb for longitudinal and shear waves at different pressures.

It is obvious from the Equations1–3 that ultrasonic absorption (α/f^2) is inversely proportional to resistivity (R).

A perusal of Figs 1–4 reveals that the ultrasonic absorption decreases with the temperature for all the applied pressures and tends to approach a limiting value at high temperatures. This behaviour is similar to pure metals [8] and it correlates with the low electrical resistivity [9] seen in CeP and CeSb at ≅5 K for all the pressures. The ultrasonic absorption due to electron-phonon interaction is significant only upto 50 K at every pressure. In CeP at 10 K, the ultrasonic absorption for longitudinal and shear waves is not significant at

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0022-2461
DOI: 10.1007/s10853-005-4397-y

TABLE I Calculated second order elastic constants (SOEC) (10^{10} N/m^2) of CeP at temperature range 2—80 K

Temperature (K)	C_{11}	C_{12}	C_{44}
2	4.486	1.205	1.237
5	4.487	1.205	1.237
10	4.486	1.205	1.237
20	4.486	1.205	1.237
30	4.486	1.203	1.237
40	4.488	1.199	1.237
50	4.491	1.194	1.237
60	4.497	1.188	1.237
70	4.505	1.182	1.238
80	4.515	1.175	1.238

TABLE II Calculated second order elastic constants (SOEC) (10^{10} N/m^2) of CeSb at Temperature range 2–80 K

Temperature (K)	C_{11}	C_{12}	C_{44}
2	3.746	0.848	0.865
5	3.746	0.848	0.865
10	3.746	0.848	0.865
20	3.746	0.847	0.865
30	3.749	0.842	0.866
40	3.755	0.836	0.866
50	3.765	0.830	0.866
60	3.766	0.823	0.866
70	3.788	0.816	0.867
80	3.80	0.809	0.867

TABLE III Ultrasonic velocity V_l for longitudinal wave, V_S for shear wave and density (ρ) of CeP at temperature range 2–80 K

Temperature (K)	V_l (10^3 m/s)	V_S (10^3 m/s)	ρ (10^3 Kg/m^3)
2	2.845	1.493	5.543
5	2.845	1.494	5.543
10	2.845	1.494	5.543
20	2.845	1.494	5.543
30	2.845	1.494	5.543
40	2.846	1.494	5.542
50	2.847	1.494	5.541
60	2.849	1.494	5.540
70	2.852	1.495	5.539
80	2.855	1.495	5.538

TABLE IV Ultrasonic velocity V_l for longitudinal wave, V_S for shear wave and density (ρ) of CeSb at temperature range 2–80 K

Temperature (K)	V_l (10^3 m/s)	V_S (10^3 m/s)	ρ (10^3 kg/m^3)
2	2.375	1.142	6.639
5	2.375	1.142	6.639
10	2.375	1.142	6.639
20	2.375	1.142	6.639
30	2.376	1.142	6.639
40	2.378	1.142	6.638
50	2.382	1.142	6.637
60	2.385	1.142	6.636
70	2.389	1.143	6.635
80	2.393	1.143	6.634

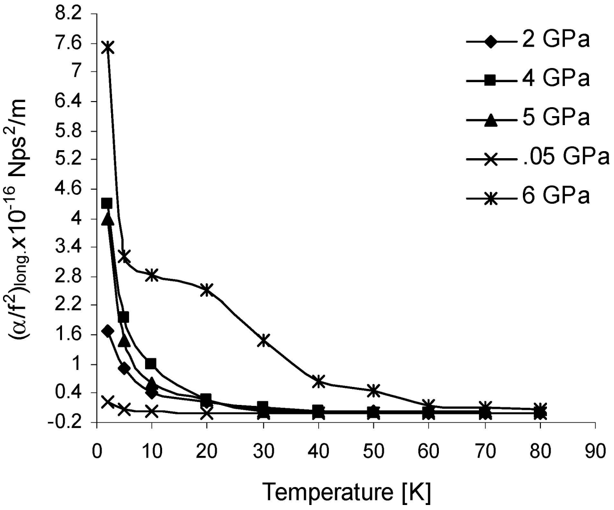

Figure 1 $(\alpha/f^2)_{\text{long.}}$ vs. temperature of CeP.

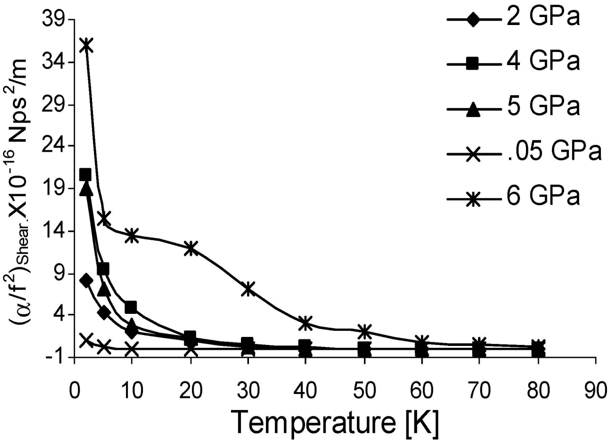

Figure 2 $(\alpha/f^2)_{\text{Shear.}}$ vs. temperature of CeP.

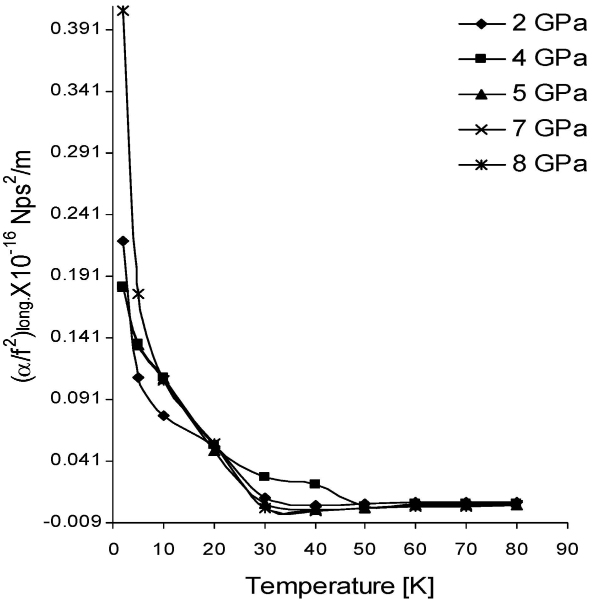

Figure 3 $(\alpha/f^2)_{\text{long.}}$ vs. temperature of CeSb.

ambient pressure (≅0.05 GPa) and it correlates with a sharp pointed peak of resistivity [9] at ≅10 K, which is caused by the antiferromagnetic phase transition. The resistivity passes through a minimum at about 23 K, a broad maximum $T = T_{\max}$ around 80 K and then decreases with increasing temperature, showing a typi-

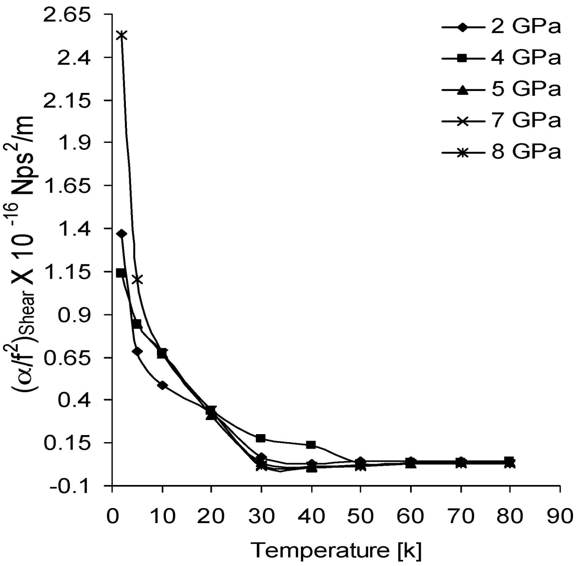

Figure 4 $(\alpha/f^2)_{\text{Shear.}}$ vs. temperature of CeSP.

cal magnetic dense Kondo (MK) behaviour [9]. Thus at ambient pressure, ultrasonic absorption (α/f^2) is not significant in CeP even at very low temperature (≅10 K)

In Fig. 1, the ultrasonic absorption $(\alpha/f^2)_{\text{long.}}$ in CeP for longitudinal wave at 6 Gpa increases with decrease in the temperature. This behaviour correlates with the temperature dependence of the resistivity in CeP. A sudden fall of (α/f^2) at ≅5 K is expected as the T_H magnetic transition temperature is found to approach zero at 6 GPa [9]. A similar behaviour of $(\alpha/f^2)_{\text{shear}}$ is also found for the shear wave attenuation (Fig. 2).

The anomalous decrease in $(\alpha/f^2)_{\text{long.}}$ and $(\alpha/f^2)_{\text{shear}}$ in CeP starting from 20 K at 2 Gpa, 4 Gpa and 5 GPa is direct consequence of sudden anomalous increase in resistivity of CeP at these pressures. The temperature dependence of (α/f^2) in CeSb for the longitudinal and the shear waves at all the pressures is mostly due to the anomalous temperature dependent resistivity of CeSb under different pressures [9]. The observed nearly constant values of (α/f^2) is seen presently above 50 K in CeP and CeSb. This arises from a similar behavior observed in the electrical resistivity of these compounds.

A perusal of Figs 3 and 4 reveals on abrupt increase in ultrasonic absorption at 35 K at 4 Gpa. This is also caused by a similar behaviour in electrical resistivity.

We conclude the investigation with the following important observations:

- Normal trend of temperature dependence of ultrasonic absorption in CeP and CeSb at different pressure is similar to that seen in for pure metals.
- Some characteristic features in the temperature dependence of (α/f^2) in CeP and CeSb at some pressures are due to the maximum magnetic transition temperature and anomalous temperature dependent resistivity of the semimetals.
- At all pressures the elastic constants do not affect the temperature dependence of ultrasonic absorption in CeP and CeSb.
- Our theoretical approach seems to be valid for the ultrasonic characterization of CeP and CeSb semimetallic compounds having lower carrier concentrations at low temperatures and pressures.

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Received 17 December 2003
and accepted 16 February 2005