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Electron absorption of ultrasound in plastically deformed tungsten

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Abstract. The absorption of longitudinal and transverse ultrasound in plastically deformed single crystals of tungsten was measured as a function of temperature. The maximum in the temperature dependence of the electron absorption was found to be more pronounced in deformed specimens. The electron absorption of longitudinal waves decreases in a magnetic field as the degree of plastic deformation is raised. The results are interpreted, allowing for intersheet scattering of electrons in hot spots of the Fermi surface.

The effect of dislocations on the parameters of ultrasonic waves is of great interest and has been the subject of numerous studies. However, only a few papers [1, 2] deal with ultrasound frequencies of several dozens of megahertz. This range of frequencies is specific in that, apart from the direct contribution of dislocations, conduction electrons start to contribute greatly to ultrasound absorption at low temperatures. An earlier study of ultrasound absorption in plastically deformed single crystals of tungsten [3] showed that dislocations have a considerable effect on the electron absorption of ultrasonic waves and its temperature dependence.

Of special importance for the kinetic effects at low temperatures is the non-equilibrium addition to the electron distribution function. If the addition is anisotropic on the Fermi surface (FS), the effectiveness of small-angle scattering is enhanced. Local features of the FS will play an important role. These are the so-called hot spots, i.e. parts of the FS where the gap between two sheets is minimal. The scattering of electrons on dislocations gives rise to the process of intersheet transfer from the region of hot spots. If the FS zones that are effective with respect to ultrasound absorption pass through hot spots, where the electron scattering rate is much higher than in the rest of the FS, the electron absorption changes considerably. Especially strong changes occur at low temperatures, where ultrasound absorption can decrease several-fold.

This paper considers the effect that dislocation scattering of electrons has on the absorption of longitudinal and transverse ultrasound. Special attention is attached to analysis of the situation taking place on the application of a high magnetic field. Following the concept due to Pippard [4, 5] about the influence of small-angle scattering of electrons upon the kinetic characteristics of a metal [6, 7], we shall interpret the experimental results in terms of a simple model which is in qualitative agreement with experiment. The discussion will take into account features specific to the real FS of tungsten.

The experiments were carried out on a single crystal of pure tungsten, which was grown using the electron-beam zone-melting method. The residual resistance ratio was 62 000. Specimens were cut out of the single crystal. They were approximately cylindrical in shape

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and measured 9 mm in diameter and 5.8 mm in height. The end faces of the specimens were ground until the required degree of planeness and parallelism was achieved, with subsequent electropolishing. The dislocation density of the parent single crystal was 10^4 cm^{-2}.

Two specimens were plastically deformed to 0.6% and 1.2% at room temperature by compression along the cylinder axis ([100] axis of the crystal). One specimen was not subject to plastic deformation. Ultrasound measurements were performed 3–5 months after deformation.

The measurements were made on the ultrasound frequencies of 42–171 MHz with both longitudinal and transverse waves propagating along the [100] axis of the crystal. All the experiments were conducted at low amplitudes of elastic displacement. A superconducting solenoid was used to produce a magnetic field of up to 50 kOe. Temperature measurements were performed under conditions of continuous heating at a rate of 0.4 K min^{-1} or lower within 4.2–100 K.

The temperature dependence of ultrasound absorption was studied earlier using single crystals of tungsten with a low dislocation density [8,9]. It was found that the temperature dependence of transverse waves exhibits a maximum. Some measurement results for plastically deformed specimens are depicted in figure 1. The figure gives the relative absorption $\Delta\alpha_l$ of longitudinal waves and the relative absorption transverse $\Delta\alpha_t$ of waves as functions of temperature. The results of measurements made in a 40 kOe magnetic field are shown as broken curves. The magnetic field was applied parallel to the direction of the wavevector q and the [100] axis of the crystal. Figure 1 presents the variation in the ultrasound absorption coefficient $\Delta\alpha$ with reference to the initial value, which is taken to be absorption in the given specimen at $T = 4.2$ K without a magnetic field.

Determination of the electron absorption is a challenging task; it was solved qualitatively following the method described in [10]. The expected trend of the curve of temperature versus non-electron absorption is shown as a thin curve in figure 1. The electron absorptions at low temperatures are denoted as α_l and α_t, and in a magnetic field as α_l^H and α_t^H.

The non-electron absorption is due to the interaction of ultrasound with dislocations and thermal phonons. The dislocation density of deformed specimens is much higher and therefore the temperature dependence of non-electron absorption is steeper in these specimens. The electron absorption becomes significant at temperatures lower than 50 K.

In the absence of a magnetic field the electron absorption of longitudinal ultrasound in the undeformed specimen decreases monotonically as the temperature is raised. In all the other cases, first a maximum and then a decrease in electron absorption is observed. The relative magnitude of the maximum, which shows the degree to which the electron absorption drops at low temperatures, rises as the plastic deformation is enhanced. Lowering of the electron absorption shows up more clearly for longitudinal waves than for transverse waves. Absorption of a longitudinal wave decreases most in deformed specimens exposed to a high magnetic field. Figure 1 gives data only for the specimen deformed to $\epsilon = 0.6\%$ but for the specimen with $\epsilon = 1.2\%$ these trends are still more conspicuous. This is illustrated by table 1 which lists the ratios α_l^H/α_l and α_t^H/α_t calculated from the experimental dependencies, as well as the ratios of the coefficients α_l and α_l^H to their maximum values.

Two features should be noted. First, for the longitudinal ultrasound the ratio of the absorption coefficient in the magnetic field to that without the field decreases, while for transverse waves the same ratio does not show this tendency. Secondly, at low temperatures the longitudinal wave absorption coefficient decreases compared with the maximum value. It is worthwhile noting that the decrease takes place both in the magnetic field and without the field but in the former case the decrease is much greater.

The first phenomenon was attributed [3] to the passage of the effective orbits through

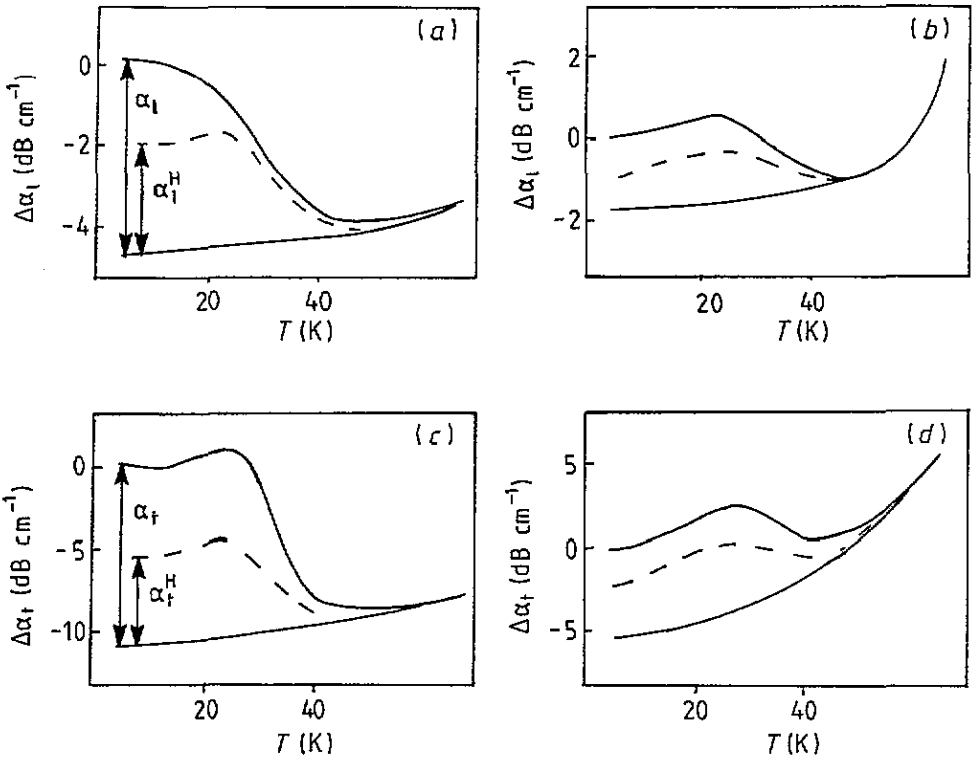

Figure 1. Temperature dependence of ultrasound absorption in tungsten: (*a*), (*b*) longitudinal waves, $f = 59$ MHz; (*c*), (*d*) transverse waves, $f = 168$ MHz; (*a*), (*c*) undeformed crystal; (*b*), (*d*) crystal deformed to 0.6%.

Table 1. The ratios α_l^H/α_l, α_t^H/α_t, α_l/α_l^{max} and $\alpha_l^H/\alpha_l^{H,max}$.

Plastic deformation ϵ(%)	α_l^H/α_l	α_t^H/α_t	α_l/α_l^{max}	$\alpha_l^H/\alpha_l^{H,max}$
0	0.49	0.49	—	0.8
0.6	0.37	0.61	0.8	0.43
1.2	0.3	0.52	0.65	0.2

hot spots of the FS with an intensive intersheet scattering of electrons. We shall use these results in the discussion below. To account for the other phenomenon, a simple model is constructed, which makes it possible to calculate the electron absorption of longitudinal ultrasound.

Let us calculate the electron absorption of ultrasound allowing for anisotropic scattering. In the case of longitudinal waves in a compensated metal the main contribution is due to the mechanism which is connected with deformation of the FS by elastic displacements of the wave. Compute the contribution made to absorption by a spherical sheet of the FS of radius R, which is separated from the other sheets by a narrow gap (figure 2). Parts of the FS sheet adjacent to the clearances are modelled by the sheet regions limited by plane sectors with the expansion angle $2\theta_0$. We shall assume that in the shaded parts the electron collision rate is ν_r, while in the rest of the sheet it is ν. Without a magnetic field the contribution to

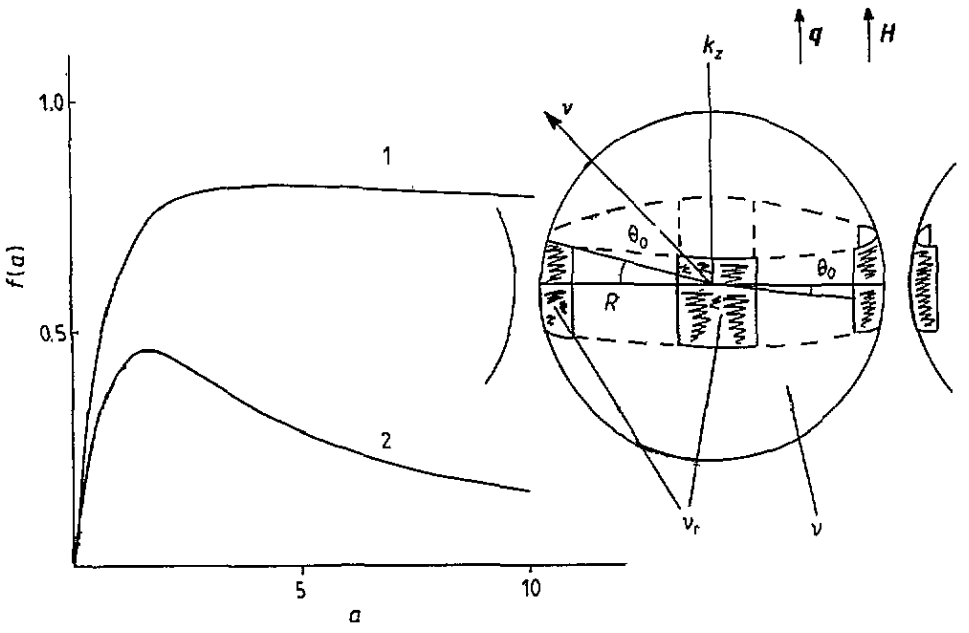

Figure 2. Calculated ql-dependence of the contribution made by deformation to absorption of longitudinal waves in a spherical sheet of the FS with $\theta_0 = 0.4$ and $a_d = 0.01$.

absorption under consideration is [11]

$$\alpha_l = \frac{2q^2}{\pi h^2 \rho s_l} \operatorname{Re}\left(\int |m_c| \, dk_z \int_0^{2\pi} \frac{\Lambda^2 \, d\theta}{\nu + i(q \cdot v - \omega)} \right). \tag{1}$$

Here $\omega = 2\pi f$ is the circular wave frequency, m_c the cyclotron mass of an electron, Λ the component Λ_{33} of the deformation potential tensor, which is further considered as isotropic on the FS sheet and ρ the metal density. Limiting ourselves to the case of a weak time dispersion $\omega/\nu < 1$, we have in accord with [3]

$$\begin{aligned} \alpha_l &= 8R|m_c|\Lambda^2 f(a)/h^2 \rho s_l v \\ f(a) &= \tan^{-1} a - (4\theta_0/\pi)[\tan^{-1}(ak_0/R) - \tan^{-1}(a_r k_0/R)]. \end{aligned} \tag{2}$$

The following designations are used in (2): $a = qv\tau$, $a_r = qv\tau_r$, $\tau = 1/\nu$ and $\tau_r = 1/\nu_r$. The quantity $k_0 = R \sin\theta_0$ determines the dimensions of the FS parts with the collision rate ν_r. The value of the parameter a_r depends on the intensity of electron scattering processes, including that involving transfer of an electron to another sheet of the FS. The parameter a_r introduces the degree of plastic deformation or dislocation density into the expression for ultrasound absorption. The absorption coefficient as a function of temperature is determined by the dependence of the function f on the parameters a and a_r.

If the dislocation scattering processes are taken to be independent of other scattering processes, one may assume that $\nu_r = \nu + \nu_d$, where ν_d is the electron–dislocation collision rate, at which an electron is transferred to another sheet of the FS. Curve 1 in figure 2 shows the function f versus the parameter a for $\theta_0 = 0.4$ and $a_d = 0.01$. As is seen from the figure, the absorption coefficient is a maximum when $a \simeq 4$. The relative magnitude of

the maximum is small: $f_{max}/f(a = 15) = 1.03$. The maximum appears only when the hot spot is sufficiently large and the umklapp processes intensive.

In a sufficiently high magnetic field, when $\omega_c > qv_{max}$ and $q \| H$, equation (1) is replaced by the following expression for the longitudinal ultrasound absorption coefficient [11]:

$$\alpha_l^H = \frac{2q^2}{\pi h^2 \rho s_l} \operatorname{Re}\left(\int |m_c| dk_z \int_0^{2\pi} \frac{\tilde{\Lambda}^2 \, d\theta}{\tilde{\nu} + i(q \cdot v - \omega)} \right). \tag{3}$$

Here $\tilde{\Lambda}$ and $\tilde{\nu}$ mean that the quantities Λ and ν are averaged over the cyclotron orbit in the magnetic field. Instead of (2), we have

$$\begin{aligned} \alpha_l^H &= 8R|m_c|\tilde{\Lambda}^2 \tilde{f}(a)/h^2 \rho s_l v \\ \tilde{f}(a) &= \tan^{-1} a - \tan^{-1}(ak_0/R) + \tan^{-1}(a_r k_0/R). \end{aligned} \tag{4}$$

The function $\tilde{f}(a)$ calculated in terms of the model adopted is given by curve 2 in figure 2. As is seen, the maximum on the temperature dependence of the absorption coefficient is more pronounced in the magnetic field. This effect of the magnetic field is associated with changes in the character of electron movement [12].

When no magnetic field is applied, an electron should diffuse on the FS and reach hot spots, which act as sinks. In the region of a spot a sheet-to-sheet transfer of the electron occurs and, as a consequence, the electron is removed from the FS region which is effective with respect to ultrasound absorption at $a > 1$. In a sufficiently high magnetic field, when $\omega_c \tau > 1$, the electron moves regularly on the FS and the movement is faster than diffusion. Hence, an electron, which enters the zone shown in figure 2, is rapidly transported to the shaded area and can be transferred to another sheet of the FS as a result of collision with a dislocation. The electron kinematics are analogous to the concept proposed by Pippard [4] to describe the longitudinal magnetoresistance of a metal by small-angle scattering of electrons.

The above-considered model of a spherical sheet of the FS illustrates the rule applicable to an actual metal too. If the orbits, which are effective for ultrasound absorption at $a > 1$, pass through the regions of an intensive scattering, i.e. hot spots on the FS, one might expect the absorption coefficient to drop at low temperatures as the temperature is decreased. The drop will be more pronounced in a magnetic field.

Now we turn to consideration of the tungsten FS orbits which are effective in ultrasound absorption (figure 3). These are the orbits, where $q \cdot v - \omega = 0$, i.e. the orbits close to extremum orbits. At $a > 1$, for transverse ultrasound, the effective orbits pass through the neck and knob of the sheet Γ3e (orbits σ and π according to the notation in [13]), and orbits ρ_2 on ellipsoids N4h. Central orbits of the sheets Γ3e and H4h do not participate in absorption as their deformation potential components Λ_{13} and Λ_{23} are zero. Only orbits with $\tilde{\Lambda}_{13}^2 \neq 0$ and $\tilde{\Lambda}_{23}^2 \neq 0$ are effective in a magnetic field. These are ρ_2 orbits located on hole ellipsoids. As is seen, the orbits, which are effective in the absorption of transverse waves, do not pass through hot spots.

Opposite to transverse ultrasound, in the case of longitudinal waves the central orbits passing through the centre of the jack Γ3e and that of the octahedron H4h are absorption effective. The orbits τ and ν remain effective in a magnetic field too, as $\tilde{\Lambda}_{33} \neq 0$ in these orbits. Thus, the consideration of the tungsten FS permits explanation of the specific features of ultrasound absorption in tungsten crystals with a large number of dislocations.

Scattering on thermal phonons can play the same role as dislocation scattering. A study of the galvanomagnetic properties of tungsten revealed a relationship testifying to the umklapp processes in hot spots [14].

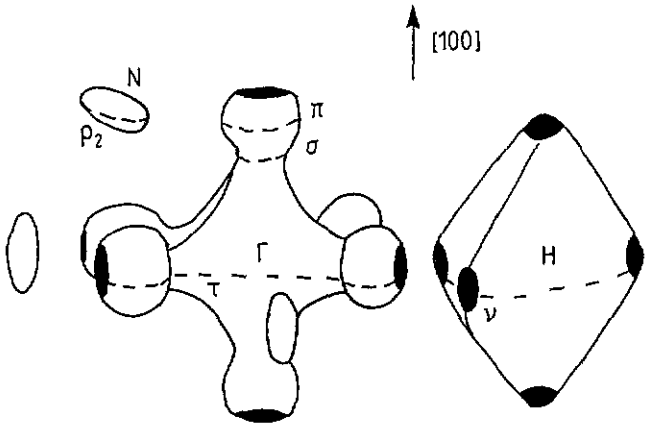

Figure 3. A schematic representation of the tungsten FS showing the orbits effective for ultrasound absorption. The hot spots with intersheet scattering of electrons are shown as black regions.

The experimental data cited by us on the electron absorption of ultrasound were explained proceeding from anisotropic scattering of electrons on dislocations and changes in movement of electrons when a magnetic field is applied. No assumption as to the dependence of the electron scattering probability on the magnetic field was needed. An examination of the specimen deformed to $\epsilon = 1.2\%$ showed that at $f = 162$ MHz the longitudinal ultrasound absorption did not depend on the magnetic field in the range 8–35 kOe and then decreased at fields of 40–50 kOe. The undeformed specimen did not reveal such behaviour of absorption. The theory [11] does not predict in a first approximation the dependence of the longitudinal ultrasound absorption on the magnetic field intensity when $\omega_c > q v_{max}$ and $q \| H$. The decrease in the absorption coefficient, a fact which disagrees with the model used here, can be attributed to the field dependence of the relaxation time. This problem requires further investigations.

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