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UNDERDAMPED DISLOCATION RESONANCE IN Cu

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Abstract Measurements of dislocation dependent attenuation ($\alpha_D$) in Cu and Al are obscured at temperatures below 50 K by the attenuation due to electron-phonon interactions ($\alpha_E$). This paper presents the measurements on Al and Cu single crystals in which $\alpha_E$ is eliminated by using a magnetic field $H \perp \mathbf{q}$ perpendicular to the direction of propagation of the acoustic waves. Underdamped resonance peak in $\alpha_D$ was obtained at 4.2 K in a slightly deformed Cu sample. The results are discussed in the framework of the Granato-Lucke theory.

Introduction At low temperatures, the total measured attenuation $\alpha$ of acoustic waves in pure single crystals of Cu has three components:

$$\alpha = \alpha_B + \alpha_D + \alpha_E$$  \hspace{1cm} (1)

where $\alpha_B$ is a background attenuation, $\alpha_D$ is the dislocation attenuation, and $\alpha_E$ is the attenuation due to the electron-phonon interactions. In pure single crystals of Cu, the component $\alpha_B$ becomes significant at temperatures below 50 K, and increases linearly with the conductivity according to Pippard's Law [1] when the temperature decreases. In order to see the dislocation resonance behavior at low temperature (4.2 K) the electron-phonon contribution to the total attenuation of ultrasonic waves must be somehow eliminated. It was already done in lead by D. Read [2], R. B. Schwarz, R. D. Isaac and A. V. Granato [3] by using the superconducting property of this metal. In this paper a magnetic field perpendicular to the direction of propagation of ultrasonic waves was applied, and the field at which the electron-phonon interactions in Cu samples became negligible was experimentally evaluated for each frequency. Underdamped dislocation resonance was seen at liquid helium temperatures for a pure copper sample with relatively long loop lengths. The magnetic field effects are discussed and compared with results found by Morse [1].

Theory The effect of magnetic field on ultrasonic attenuation depends on the value of $q \cdot l$, when $q$ is the wave vector of the ultrasonic wave and $l$ is the mean free path of electrons in the sample [1]. When the value of $q_l$ is equal or less than unity, the attenuation decreases monotonically as the field increases. When the magnetic field is perpendicular to both the particle velocity and the propagation direction the ratio of the attenuation to the zero field attenuation is found to be:

$$\frac{\alpha(H)}{\alpha(0)} = \frac{1}{1+(2\omega_c \tau)^2}$$  \hspace{1cm} (2)

where $\tau$ is the relaxation time in the absence of the field, and $\omega_c$, the cyclotron frequency,

$$\omega_c = \frac{eH}{mc}$$  \hspace{1cm} (3)

where $e$ is the electronic charge, $m$ the mass, and $c$ the velocity of light. These equations have been confirmed by Morse et al. (1958) on Cu single crystals and the results are shown in Fig. 1.
Experimental Procedure. Two pure single crystal copper samples were cut in a $<\text{Ill}>$ direction, with a crystallographic orientation better than 2 degrees. The samples were lapped, etched and annealed and later irradiated in a Co$^{60}$ source with a dose of 30 MRad. This irradiation was sufficient to pin the dislocation loops in order to obtain the background attenuation at room temperature. One of the Cu samples was deformed up to 1% by uniaxial compression. The second sample remained undeformed, but the resulting deformation due to the thermal stresses of cooling in a sample holder was evaluated after the low temperature experiment and found to be 0.1%. The samples were mounted in a cryostat containing a superconducting magnet. A Matec 6600 system with an attenuation recorder were used to monitor the attenuation changes as a function of frequency at constant temperature equal to 4.2 K. For each measured frequency; 10; 30, 50, 70, 90, 110, 130 and 150 MHz the attenuation as a function of increasing magnetic field was recorded, and the results are presented in Fig. 2.

A 4-methyl-1-pentane bond was applied over liquid nitrogen temperature. This procedure does not produce an undesirable contribution to the total dislocation attenuation.

Results. Figure 2 presents the total ultrasonic attenuation as a function of the increasing magnetic field for different frequencies. At zero field the total measured ultrasonic attenuation has the highest value for all measured frequencies except for 150 MHz. In this case, $q\xi$ becomes greater than unity, and small oscillations in the range between 0 to 5 Kgauss are seen. This is the experimental limit of the application of Eq. (2), which was formulated for $q\xi < 1$. But the character of the changes of the ultrasonic attenuation for increasing magnetic field is the same. In all experiments the applied magnetic field reduces the ultrasonic attenuation to a constant low value compared to the zero field case. Above 8.6 Kgauss, the attenuation for all measured frequencies is not affected by a further increase of the field, this means, according to Eq. (2) that the electron-phonon interaction is eliminated by the field. Figure 3 presents the dislocation attenuation $\alpha_0$ as a function of frequency at constant magnetic field $H = 8.6$ Kgauss at 4.2 K on a double logarithmic scale.

The dislocation attenuation has been converted to a logarithmic decrement. The result obtained for 10 MHz deviates from other points but a correction for the background attenuation (dotted line) should be made. It is seen that the points obtained for two lowest frequencies 10 and 30 MHz should be brought down to lower values of the logarithmic decrement.
Fig. 2 Attenuation versus magnetic field for different frequencies. Slightly deformed Cu sample, $\varepsilon = 0.1\%$; $T = 4.2$ K.

Fig. 3 Underdamped dislocation resonance in Cu at 4.2 K in presence of the constant magnetic field $H = 8.6$ KGauss. Circles are experimental points.
The frequency dependence found in Fig. 3 is too steep for an overdamped resonance, but is consistent with that expected for an underdamped resonance. Similar results were found for Al.

**Discussion** Using the experimentally obtained resonance frequency $f_0 \sim 150$ MHz one can estimate the average loop length $L$ of the dislocations using the theory of Granato-Lucke

$$f_0 \sim \frac{v}{2L} = 150 \text{ MHz}$$

where $v_s$ is the shear wave velocity. This gives $L \sim 10^{-3}$ cm. Knowing $L$, one can estimate the critical dislocation viscous drag constant $B_c$ at $T = 4.2$ K from

$$B_c = 2/\pi \cdot \frac{v_s}{L}$$

where $A$ is the dislocation mass per unit length and $k$ is the restoring force

$$k = \frac{12 \cdot C}{L^2} = \frac{6 \cdot Gb^2}{L^2},$$

where $G$ is the elastic shear modulus and $b$ is the Burger's vector.

$$B_L = 4\sqrt{3} \cdot A \cdot v_s = 1.2 \times 10^{-8}$$

Taking $L \sim 10^{-3}$ cm

$$B \sim 10^{-5} \text{ in cgs units}$$

These are reasonable values, [4] and show that even relatively long loop lengths can be underdamped at low enough temperatures.

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**References**

1. Physical Acoustics.