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DISLOCATION AMPLITUDE DEPENDENT ULTRASOUND ABSORPTION IN NORMAL AND SUPERCONDUCTING LEAD CONTAINING DIVERSE VALENCY IMPURITIES

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Abstract. - Amplitude dependence of ultrasonic absorption $\omega(\varepsilon_c)$ has been studied in lead single crystals containing one of the following impurities: Tl, Sn, Bi, Cd, Sb. Critical amplitude of the beginning of $\varepsilon_c$ dependence on $\omega$ increased in the going from Tl to Sb in the above impurity series. At s-n transition $\varepsilon_c$ increased by 25 to 35%. The characteristic stress level values of dislocation unpinning from impurities were obtained and their change at the superconducting transition was identified. With the aim to define contributions of different physical nature to the total value of interaction between dislocations and impurity atoms an approach for experimental data treatment is offered and the quantitative information of these contributions is obtained. The change of $\omega$ at n-s transition is explained by the variation of dislocation loops, $L_N^*$, overdamping degree leading to the increase in internal friction. Mechanical properties of a real crystal depend on concentration of impurity atoms along the dislocation line and on its energy of interaction $U$ with these atoms. The full $U$ value is determined by some contributions of different physical nature. Separation of individual contributions may be accomplished by the study of amplitude dependent internal friction since it is due to the process of dislocation unpinning. To establish the role of some types of interactions investigations and analysis of amplitude dependent internal friction were carried out in Pb containing impurities differing first of all in valency under conditions (a rather high frequency $\omega$ and low temperature range) when it is expected that the process of dislocation unpinning will be athermal. The next aim was to clear the mechanism that is responsible for the change in high frequency amplitude dependent internal friction at the superconducting transition.

Measurements were carried out using the ultrasonic pulse method at a frequency of 7.5 kHz in Pb single crystals containing one of the following impurities: Tl, Sn, Bi, Cd, Sb, which was introduced in an equal amount of $3 \times 10^3$ at.%. All single crystals were of the same orientation. Direction of the sound wave propagation coincided with the crystallographic direction [100]. For each type of impurity measurements were carried out on five identical samples prepared of one.
single crystal.

The \( \mathcal{L}(\varepsilon_0) \) dependences were investigated in the n- and s-state at 4.2 K (Figs. 1a and b). The averaged \( \varepsilon_c \) values and corresponding critical stresses \( \mathcal{C}_c \) in n- and s-states are given in Table 1. The \( \mathcal{L}(\varepsilon_0) \) dependence is determined by the process of pinning center surmounting by dislocation. Lack of the influence of temperature change by a factor of 2.5 (from 1.3 to 4.2 K) in the n-state observed experimentally indicates the athermal character of unpinning. This enables to analyze data in the frame of Granato-Lücke athermal theory [1]. The \( \mathcal{L}(\varepsilon_0) \) dependencies were presented in Granato-Lücke coordinates. The straight line slopes in those coordinates are proportional to the characteristic stress level \( \Gamma \). Table 1 presents the averaged \( \Gamma \) values in n- and s-states. At the successive consideration in the frames of string model \( \Gamma \) turns to be [2] equal to

\[
\Gamma = \frac{2f_b}{b l_c}
\]

where \( f_b \) is the maximum binding force between the dislocation and the pinning center, \( b \) is the Burgers vector, \( l_c \) is the mean length of dislocation segment.

Dislocational structure, which is responsible for the appearance of hysteresis losses while measuring by ultrasonic pulse method in the helium temperature range is formed during the sample deformation by a quartz cell because of difference in their linear expansion coefficients. In this case \( l_c \) is determined by [2].

![Fig. 1: \( \varepsilon_0 \) dependence of \( \mathcal{L} \) in Pb containing different impurities at 4.2 K. a - n-state, b - s-state.](image)

- Pb+Tl; • - Pb+Sn; ○ - Pb+Bi; ▲ - Pb+Cd; ● - Pb+Sb.
\[ l_c = \left( \frac{U_o}{U_b} \right)^{1/3} \frac{2b}{c^{2/3}} \]  \tag{2}

Here \( U_b \) is the binding energy between the dislocation and impurity atom, \( U_o = Gb^3/2 \) is the elastic energy of dislocation of \( b \) length, \( G \) is the shear modulus. Taking into account that \( U_c \sim l_c^{-1} \), (2) may be verified through experimental data on \( c \) dependence of \( U_c \). For \( \text{Pb+Sb} \) results in \( \log \log \) coordinates fall on a straight line with a slope of 2/3, thus confirming (2).

From the Peierls-Nabarro model it follows that \( f_b = \frac{3\sqrt{3}U_b}{8d} \) where \( d \) is the halfwidth of dislocation line and is equal to \( b \). Substituting expressions for \( l_c \) and \( f_b \) into (1) a ratio is obtained which connects \( \Gamma \) with the binding energy

\[ \Gamma = \Gamma_o \left( \frac{|U_b|}{U_o} \right)^{4/3} \]  \tag{3}

where \( \Gamma_o = 3\sqrt{3}Gc^2/3/16 \), that at the \( c \) selected and \( \text{Pb} \) gives 604.3 g/mm².

In the frames of Peierls-Nabarro model \( U_b \) between the dislocation and an impurity atom located just in its slip plane is defined by

\[ |U_b| = H |\eta_{tot}| \]  \tag{4}

where \( H = 3kV_h(1-2\nu)/(2\pi)(1-\nu) \), \( \nu \) is the Poisson's ratio, \( k \) is the modulus of dilatation, \( V_h \) is the volume of matrix atom. In the case of lead \( H_{\text{Pb}} = 1.45 \) eV. The dimensionless parameter introduced here

\[ \eta_{tot} = \eta_1 + \alpha Z + \beta \eta_1 Z - \gamma Z^2 \]  \tag{5}

characterizes the "power" of point defect taking into account its charge. Here \( \eta_1 = 1/a \) da/dc is the factor of dimensional inconsistency, \( Z \) is the relative valency of matrix and impurity, \( \alpha \), \( \beta \) and \( \gamma \) are constants characterizing (respectively) first order electrostatic interaction, electrodimensional interaction and second order electrical interaction between the dislocation and impurity atom. Formula (3) rewritten as

\[ |U_b| = U_o (\Gamma/\Gamma_o)^{3/4} \]  \tag{6}

allows, proceeding from the experimental data on \( \Gamma \), to determine \( |U_b| \) directly. Table 2 gives the \( |U_b| \) values found in this way.

For two impurities in one matrix the \( |U_b| \) ratio can be determined with greater accuracy
\[ \frac{|U_b^1|}{|U_b^2|} = \frac{\eta_{\text{tot}}^1}{\eta_{\text{tot}}^2} = \left( \frac{\Gamma_1}{\Gamma_2} \right)^{3/4} \quad (7) \]

since it does not depend on theoretical estimations of \( U_o \) and \( \Gamma_o \).

Taking Sn as a standard impurity atom for which \( Z = 0 \) and thus \( |\eta_{\text{tot}}| = |\eta| = 0.071 \), and using the experimental \( \Gamma^s_0 \) values \( \eta_{\text{tot}} \)

Table 1

<table>
<thead>
<tr>
<th>Impurity</th>
<th>( \eta )</th>
<th>( \eta_{\text{tot}} )</th>
<th>( U_b )</th>
<th>( U_b ) el</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb+Tl</td>
<td>0.36</td>
<td>0.31</td>
<td>0.68</td>
<td>3.31</td>
</tr>
<tr>
<td>Pb+Sn</td>
<td>0.48</td>
<td>0.37</td>
<td>1.05</td>
<td>15.0</td>
</tr>
<tr>
<td>Pb+Bi</td>
<td>1.31</td>
<td>0.95</td>
<td>2.41</td>
<td>27.3</td>
</tr>
<tr>
<td>Pb+Cd</td>
<td>2.71</td>
<td>1.39</td>
<td>5.35</td>
<td>48.0</td>
</tr>
<tr>
<td>Pb+Sb</td>
<td>2.14</td>
<td>1.58</td>
<td>4.47</td>
<td>57.4</td>
</tr>
</tbody>
</table>

can be determined by (7) for the rest impurities (see Table 2). Knowing the experimental values of \( |U_b| \) and \( |\eta_{\text{tot}}| \) we can find \( \eta_{\text{exp}} = 1.32 \) eV by (4), that being only by 10\% different from \( \eta_{\text{theor}} = 1.45 \) eV.

Assuming in (5) \( Z = 0 \) we obtain the elastic constituent of full binding energy

\[ |U_b \text{ el}| = H \eta \quad (8) \]

Knowing \( \eta_{\text{exp}} \) and \( \eta \) one obtains the more accurate (experimental) \( |U_b \text{ el}| \) value for all the impurity atoms (Table 2). From the comparison of \( |U_b \text{ el}| \) with \( |U_b| \) one can conclude about the relative contribution of electrostatic interaction to the total binding energy between the impurity atoms and dislocations.

It follows from Table 2, that the electrostatic interaction can
be not only of the same order of magnitude as the elastic one, but, as for example in the case of Sb, greatly exceed it.

The relative change of $U_b$ in lead at $n$-$s$ transition does not exceed several per cent\(^2\), that being essentially less than the relative change of maximum binding force $f_{bn} \approx 30\%$ required for the explanation of the experimental results obtained. Therefore an alternative mechanism is considered,— effect of the electron viscosity decrease at the transition to $s$-state on the process of pinning centers surmounting by dislocations under high-frequency amplitude dependent internal friction.

The main result of this study is the conclusion about the essential influence of dislocation loops, $L_N$, overdamping level on the amplitude dependent losses values. The overdamping level is determined by the relationship between the length, $L_N$, and the characteristic length $L_d = 2\sqrt{C/B\omega}$, where $C$ is the line tension coefficient and $B$ is the damping coefficient. At $L_N \gg L_d$ dislocational hysteresis is principally of dynamic character and the internal friction is described by the expression

$$Q^{-1} = Q_0^{-1} \frac{12\pi C}{L_N B\omega}$$

where $Q^{-1}$ is the value of amplitude dependent internal friction with no viscosity. At the transition to $s$-state the loop overdamping level decreases and, as a consequence, the amplitude dependent losses increase. This effect is of a great enough value to explain the internal friction changes at the transition to $s$-state observed experimentally.

References