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Inelastic scattering of electrons by dislocations in aluminum

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The temperature dependence of the electrical resistance ρ_d due to the presence of dislocations is measured in aluminum samples of various purities. In pure samples the dependence is a step-like function. The introduction of $\approx 0.1\%$ of impurities suppresses the growth of ρ_d. This effect of the additional resistance, on the temperature dependence which corresponds to an increase in the impurity concentration in the dislocation cores, may be due to a change in the scattering of the electrons by quasi-local defect modes.

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A pronounced increase, over a comparatively narrow temperature range, of the additional electrical resistance $\rho_d(T)$ due to dislocations introduced in a crystal, has been observed in a series of metals: Cu, Ag, Au, Mo, Zn.[1–3] The increase in $\rho_d(T)$ turned out to be dependent on the length of the dislocation sections free of pinning points. The quantity $r_{max}=[\rho_d(T_{max})-\rho_d(0)]/\rho_d(0)$ decreased with increase in the density of intersection point of the dislocation lines. The $r(T)$ dependence was studied in detail in samples of Cu and Mo having different dislocation structures; no effect of the presence of impurities on r_{max} was observed. However, for both these metals, the concentration of contaminant atoms along the linear defects was unknown. The distance between the impurity atoms located on the dislocation lines could be significantly greater than the mean distance between the dislocation interactions, and this, as a result, determined the growth of r. The fact that one has managed to create in pure samples a structure with a high number of dislocations indicates the stability of the structure, independent of the dislocation pinning by the impurity atoms.

It is therefore desirable to carry out similar measurements of $\rho_d(T)$ in a metal in which the stable arrangement of the dislocations (after plastic deformation) depends very strongly on the presence of impurity atoms. Aluminum satisfies such requirements completely, since there is a high probability in it at room temperature of displacement of the dislocations under the action of internal stresses.

The plastic deformation of pure polycrystalline aluminum generates the formation of a cellular dislocation structure with very thin walls of the cells.[4] In aluminum containing ~0.1% impurities, a cellular structure is also developed, but with a significantly greater mean density of dislocations after approximately the same deformation. The difference in the mean density of dislocations is brought about by the fact that, in migrating, the dislocations are fixed at many points by foreign atoms, the high concentration of which in this case determines the length of the free dislocation segment L. The effect of a decrease in L_c on the temperature dependence of $\rho_d(T)$ was investigated in samples of Al of various purity.

EXPERIMENT

The measurements of the electric resistance were carried out by the potentiometric method. The sample preparation is similar to that described in Ref. 2.

The samples were plates of polycrystals or single crystals of aluminum with cross sections of (3–4) $\times$ (0.2–0.5) mm, length 80–90 mm. The distance between the potential leads was 40 mm. The quantity ρ_d was determined as

$$\rho_d(T)=\left[\frac{R(T)}{R_{st}(273\,\mathrm{K})}-\frac{R_{st}(T)}{R_{st}(273\,\mathrm{K})}\right]\rho(273\,K), \qquad (1)$$

R and R_{st} are the resistance of the sample and the standard, $\rho(273\ \mathrm{K})$ is the resistivity of Al. We used $\rho(273\ \mathrm{K})=2.5\times10^{-6}$ ohm-cm and $\rho(372\ \mathrm{K})=2.64\times10^{-6}$ ohm-cm for the pure and "dirty" Al, respectively.

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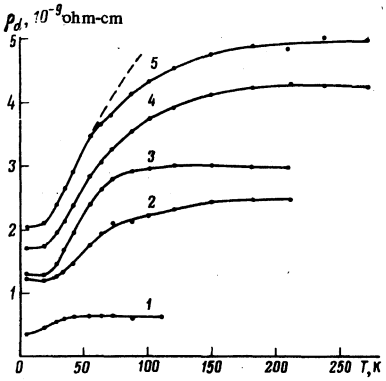

FIG. 1. Curves $\rho_d(T)$ for pure aluminum: γ: 1) 6500, 2) 3000, 3) 5500, 4) 5000, 5) 5000. Degree of deformation: single crystal 2) 30%, polycrystals: 3) 18%, 4) 22%, 5) 32%. The portion of the dependence $\Delta\rho_d \sim A_2 e^{-\xi/kT}$ above 60 K is shown by the dashed line, at $\xi = 7.35\times10^{-3}$ eV, $A_2 = 7\times10^{-9}$ ohm-cm. Curve 1 is the dependence $\Delta\rho(T)$ of undeformed fine-grained Al. The size of most of the grains was 50–70 μ, individual crystals up to 300 μ.

The standards—polycrystalline plates with flat grains of diameter 2–4 mm—were annealed in vacuum of 1×10^{-5} Torr at 550 °C for an hour. After measurement of $R(T)$ of the deformed sample, the latter was annealed under the same conditions, so that recrystallization was completed in it. The resistance of this annealed sample is denoted in Eq. (1) by $R^*(273\text{ K})$. The deformation was achieved by rolling. To remove vacancies formed before the measurements, the samples were aged at room temperature for days.

Since $\rho_d(T)$ is the very small difference of two quantities that are rapidly increasing with temperature, six samples were placed in the thermostat in each experiment, of which 2 or 3 were standards. It was possible to estimate the error in the measurement by comparing the temperature behavior for the different standards. In very deformed polycrystals of pure aluminum, the error in measurement of $\rho_d(T)$ was less than 10% of $\rho_{d\,max}$ at 273 K and 5% at 80 K.

About 20 samples of polycrystals and monocrystals were measured. The degree of deformation was varied from 10 to 40%. The purity, i.e., the ratio of the resistance of the annealed bulk samples, $\gamma = R(273\text{ K})/R(4.2\text{ K})$, amounted to 15,000, 6000 and 19 for the polycrystals and 3000 and 1500 for the monocrystals.

In all the samples with low impurity content, the dependence of $\rho_d(T)$ has the shape of a step (Fig. 1, samples 2–5). The temperature range of the basic change of $\rho_d(T)$ is 20–100 K. The height of the step lay within the limits $r_{max} = 1-1.8$. The effect of the impurities at low concentration was insignificant. For example, the single crystal with $\gamma = 1500$ and $\rho_d(4.2\text{ K}) = 16\times10^{-10}$ ohm-cm had $r_{max} = 1.5$—larger than in the crystal 2, for which $\gamma = 3000$, $r_{max} = 1$.

The $\rho_d(T)$ dependence of the samples of dirty Al was quite different. After small deformation (Fig. 2), the values of r_{max} in samples 1 and 2 was <0.1, while in samples 3 and 4, we have $r_{max} < 0.05$. Thus, the presence of about 0.1 at.% of impurities practically suppressed the growth of $\rho_d(T)$.[1)]

DISCUSSION

It was determined from a comparison of $r(T)$ of samples of Al and Mo [2] having different cellular structure after deformation that the form of the dependence of $\rho_d(T)$ on the temperature is connected with the peculiarities of electron scattering by the same dislocations.

Thus, in the two samples of Mo,[2] which differ greatly in "purity" (sample 3, $\gamma = 22$, sample 4, $\gamma = 1000$), r_{max} was 0.32 and 0.4, respectively, while in the dirty Al, the growth of ρ_d was suppressed. The basic difference for the dislocations in Al is that the pressure of ≈ 0.1 at.% impurity sharply reduced (but to some finite value) the length of the free portion of the dislocation and as a result, the growth of $\rho_d(T)$ with temperature was not observed.

Two probable reasons were pointed out in Ref. 2 for the growth of ρ_d. One is connected with the appearance upon elevation of the temperature of a new scattering channel from the local modes of oscillations; according to the other, the increase in the scattering cross section is brought about by the filling of the electron levels localized on the dislocations. The results of measurements in Al apparently allow us to express a preference for the first of these.

An attempt can be made to estimate the free path length of the segment of dislocations in dirty Al. Starting out from a concentration of impurities ~ 0.1 at.%, the mean distance between the foreign atoms is equal to approximately ten times the atomic spacing, which gives the lower limit of the value of L_c. Measurements of the internal friction in Al [5] give $L_c \approx 10^{-5}$ cm. The most probable value of L_c should lie between these limits.

On the other hand, the charge of the impurity is screened at about an atomic length and consequently should not significantly change the probability of electron capture by the free segments of the dislocations. It can again be noted that about the same impurity content in molybdenum did not influence the growth of ρ_d. It would be legitimate to assume that the presence in the core of the dislocations of a large number of atoms with

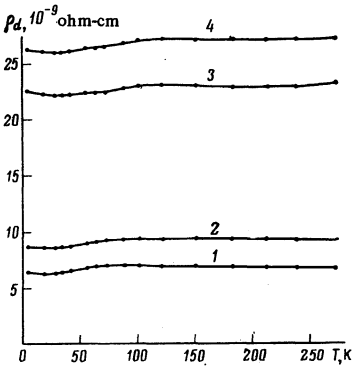

FIG. 2. Curves $\rho_d(T)$ for dirty aluminum; $\gamma = 19$. Degree of deformation: 1) 10%, 2) 15%, 3) 30%, 4) 40%.

a mass different from the mass of the atoms in the host lattice or of intersection points of the dislocations affects the local vibrations in the dislocation cores.

The lattice dynamics in the presence of linear defects has been considered with the use of various models.[6-8] From the very general representations of the excitation in the dislocation cores comes the possibility of the existence of an additional branch of the spectrum of vibrations localized near the defects and separated by a gap from the corresponding branch of the unexcited crystal.[6] The fundamental contribution to the change in the electrical resistance in this case should be made by the scattering from the high-frequency vibrations. Phonons with small quasimomentum are ineffective. By assuming the scattering to be isotropic, the dependence of $r(T)$ was approximated in Ref. 2 by the expression

$$r(T)\sim A_1\xi e^{\xi}(e^{\xi}-1)^{-2}, \qquad (2)$$

where $\xi=\hbar\omega/kT$, k is Boltzmann's constant. Equation (2) gives a good description of the low-temperature portion of the curves. For example, for sample 5, Fig. 1, the calculated curve at $\hbar\omega=7.35\times10^{-3}$ eV and $A_1=1.315$ is close to the experimental below 60 K. However, beginning with $\xi\approx1$, i.e., above 90 K, r increases linearly with temperature. At the same time, the experimental curves in this region reach saturation. Below 60 K, the curves can be represented with practically the same accuracy with the aid of the simple expression

$$r(T)\sim A_2e^{-\varepsilon/kT}. \qquad (3)$$

The energy ε, calculated according to Eqs. (2) or (3), lay within the limits $5\times10^{-3}=1\times10^{-2}$ eV for different samples.

The strong effect of the dislocations on the temperature dependence of the electrical resitance in the temperature range 30–100 K can evidently be due to the difference in the limiting frequencies of the local vibrations and the vibrations of the basic lattice. Actually, in the quantity $\rho(T)=\rho_i(T)+\rho_d(0)+\Delta\rho_d(T)$, where $\rho_i(T)$ is the resistance of the entire crystal, the components $\rho_i(T)$ and $\Delta\rho_d(T)$ are determined by the number of excited phonons of the corresponding branches of the spectrum. In spite of the fact that the quantity of atoms in the dislocation cores is extremely small in comparison with the total number of atoms (less than 10^{-4} in strongly deformed metal), near 50 K the value of $\Delta\rho_d(T)$ in Cu and Mo reaches 10% of $\rho_i(T)$ and 5% of $\rho_i(T)$ in Al near 35 K.

The problem of the spectrum of lattice vibrations in the presence of two-dimensional defects, for example, grain boundaries, is very similar.[6] There is similarity also in the temperature dependence of the additional electrical resistance. In Fig. 1, curve 1 is the dependence of $\Delta\rho(T)$ of finely crystalline aluminum. The growth of the additional resistance was measured with an error of 20% at 50 K. An increase of $\Delta\rho$ of fine-grained polycrystalline aluminum by 20% at 77 K was also observed in Ref. 9. This increase is in comparison with the resistance at 4.2 K.

Thus, the growth of ρ_d with increase in the temperature can be connected with the appearance of a new scattering channel by the quasilocal modes of dislocations. The concentration of impurity atoms, located along the dislocations, appears in aluminum as an additional parameter, which allows an effect on the dynamics of the lattice near linear defects.

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