Dislocation scattering and charge transport in copper

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Galvanomagnetic measurements have been carried out on plastically deformed single-crystal copper specimens. Effective small-angle scattering of the conduction electrons has been found. Point and extended defects, generated for small degrees of low-temperature plastic deformation, change the form of the magnetoresistance both for the open and closed electron trajectories. The scattering of electrons becomes predominantly isotropic for relatively large densities of deformation defects.

The problem of the influence of extended defects of the crystal structure on the kinetic coefficients of copper is being studied extremely actively at present. It is generally accepted that the main contribution to the additional dislocation electrical resistivity at T = 4.2°K comes from large-angle scattering by the cores of extended defects.[1] However, as has been shown,[2,3] the temperature dependence of the thermal conductivity for small deformations in the range $T \leqslant 4.2$°K is not linear, and the thermal conductivity varies nonmonotonically with the change in deformation. In addition, calculation of the dislocation density from the increase in the thermal resistivity gives a value several orders of magnitude greater than is found by other, more direct, methods. These features are associated with the scattering of electrons by quasilocal dislocation modes, by elastic strain fields and by the so-called flutter effect. It was shown by Gantmakher and Kulesko,[4] who studied the temperature dependence of the additional dislocation electrical resistivity, that this dependence has a step form in the temperature range T = 30–90°K for different means and degrees of deformation.

As is well known, when there are certain singularities at the Fermi surface (FS) which lead to a rapid change in the electron distribution function in momentum space, the effectiveness of small-angle collisions can increase appreciably.[5] The dependence of the magnetoresistance on temperature and other characteristics of the scattering parameters, and also on the orientation and magnitude of the magnetic field, when the asymptotic dependence is reached, is determined by the scattering mechanisms.[6] Thummes and Kötzler[7] studied the effect of a longitudinal magnetic field on the temperature dependent part of the resistance of copper whiskers. It was established that the influence of deformation, as also of a magnetic field, is to increase the region of the quadratic temperature dependence of resistance from 1.5 to 2.3°K. These features are associated with the marked anisotropy of the relaxation time of electrons at the FS, i.e., the effect of dislocations and of a magnetic field is of the same nature.[8]

In the present work we present the results of a study

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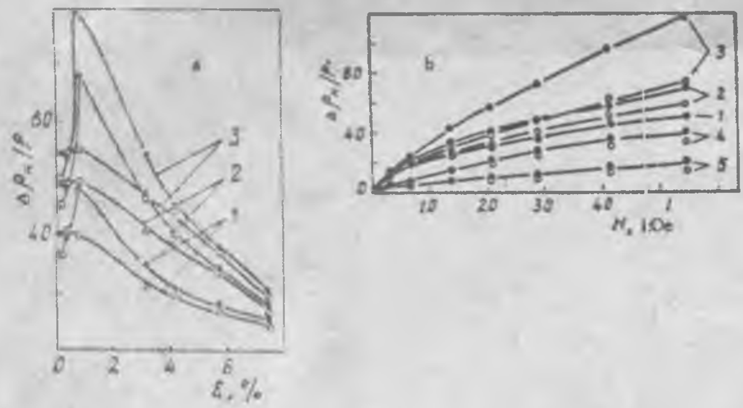

FIG. 1. The dependence of the transverse magnetoresistance $\Delta\rho_H/\rho$ of the Cu-1 series of specimens (a) on the degree of deformation, (1) H = 20, 2) 40, 3) 55 kOe) and (b) on magnetic field, (1) $\varepsilon = 0$, 2) 0.2, 3) 0.8, 4) 5.8, 6) 7.4%); ○, and ●) are results for specimens before and after annealing.

of the effect of low-temperature plastic deformation of copper single-crystals on their electron transport in a transverse magnetic field. The series of specimens Cu-1 and Cu-2 used in the experiments underwent many stepwise deformations at liquid helium temperature. After each loading the specimens were held at T = 100°K for an hour with a subsequent slow cooling.[4] The axis of the Cu-1 specimens coincided with the threefold symmetry axis, while for the Cu-2 series it was with the fourfold axis. The orientation of the magnetic field strength vector H for Cu-1 led to the existence of only closed orbits, while for Cu-2 there was a layer of open trajectories. The resistances were recorded at T = 4.2°K in the magnetic field of a UIS-1 helium cryostat immediately after the cold deformation and the subsequent annealing-out of vacancies.

The deformation and field dependences of the magnetoresistence $\Delta\rho_H/\rho$ of Cu-1 specimens are shown in Fig. 1, where $\Delta\rho_H/\rho = (\rho_H - \rho)/\rho$, ρ_H and ρ are the resistances in a magnetic field and in its absence. As can be seen from Fig. 1a, the magnetoresistance depends nonmonotonically on the deformation even for the unannealed state, and has a maximum for a deformation ~0.8%, the magnitude of which grows sharply with the annealing of vacancies. The field dependence $\Delta\rho_H/\rho$ is characterized by the fact that while its form is close to saturation for the initial state, then for small deformations ($\varepsilon \sim 0.8\%$) the magnetic field dependence of the magnetoresistance is stronger both in the annealed state and without annealing. The magnetoresistance grows much more slowly with increasing field for relatively large deformations ($\varepsilon \sim 7\%$), while the magnitude of the magnetoresistance before and after annealing differ insignificantly. It has been shown by Gurzhi and Kopeliovich[6] that the effective relaxation times determining the electrical resistivity in high magnetic fields $\tau^{\infty}_{\text{eff}}$ and in zero magnetic field τ^{0}_{eff} can differ from one another appreciably and in view of this, the regions of strong and weak magnetic fields are separated by a region of intermediate magnetic fields (RIMF). This is associated with the fact that in the absence of a field the conductivity is, to an appreciable extent, determined by the time for diffusion across the FS, while in strong magnetic fields under the given conditions the time for umklapp processes becomes important, $\tau_U \ll \tau_F$. A RIMF occurs for $T > T_p$, where T_p is some characteristic temperature determined from the ratio $T_p/T_0 < 10^{-1}$; $T_0 \approx \Delta pS$ (Δp is the minimum distance between the Fermi surfaces in the extended zone scheme, S is the velocity of sound). For the given orientation, when only closed orbits occur, T_0 corresponds to 60°K. The temperature T = 4.2°K thus corresponds entirely to the RIMF in which umklapp processes can lead to effectively open trajectories and the resistance can depend on magnetic field not only as H^{-2}, but also as H^0 and H^{-1}. The corresponding component of the resistivity tensor should then increase with increasing magnetic field. The experimentally observed dependence $\rho_H \sim H^n$ with $n < 1$ is evidently produced by the collision integral also having a contribution due to structural defects which scatter isotropically, thus the experimental observation of the Peierls damping of the resistivity is not possible.

The field and deformation dependences of the magnetoresistance of the Cu-2 specimens are shown in Fig. 2. It is characteristic that the power of the field de-

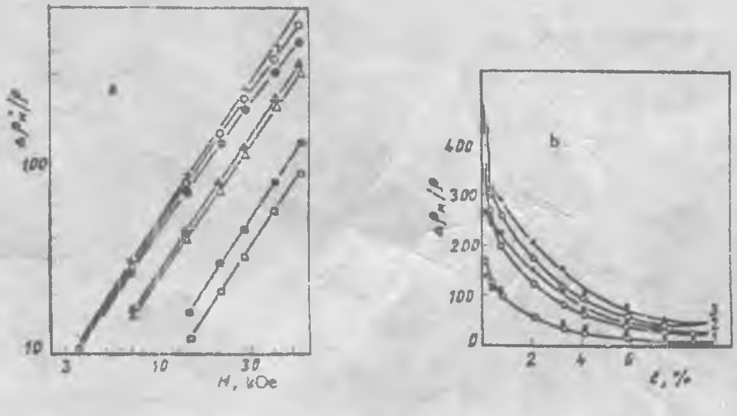

FIG. 2. The dependence of the magnetoresistance of the Cu-2 series of specimens: a) on magnetic field for different deformation defect densities: ×) $\varepsilon = 0$, ○, ●) 0.2, △, ▲) 0.5, □, ■) 7%; b) on the degree of deformation for different values of H, kOe: 1) 20; 2) 40; 3) 55 (the open and dark symbols are results for specimens before and after annealing, respectively).

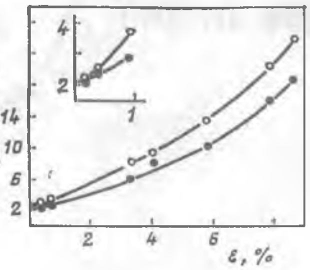

FIG. 3. A typical dependence of the resistivity ρ on the degree of deformation ε after cold deformation (○) and after annealing at 100°C (●). The inset shows the small deformation region.

pendence $\Delta\rho_H/\rho$ for the initial state ($\varepsilon = 0$) remains constant over the whole range of magnetic fields, while in the weakly deformed state it decreases in strong fields. This feature is reinforced on annealing the vacancies. At higher degrees of deformation ($\varepsilon = 4\%$) the power law increases again to the original level for the whole range of values of H.

The dependence of the magnetoresistance $\Delta\rho_H/\rho$ on deformation shows a reduction with an increasing concentration of structural defects (Fig. 2b). For large deformations the magnetoresistance in the annealed state is higher than before the anneal, which correlates with the Kohler law, since the resistivity in the annealed state is less, while for small deformations the reverse relation holds. The characteristic deformation dependence of the resistivity is shown in Fig. 3. The nonlinear nature of the $\rho(\varepsilon)$ relation is evidence of the nonlinear growth in deformation defects.

It has been shown by Gurzhi and Kopeliovich[9] that when openness occurs, a RIMF appears as the magnetic field vector approaches the boundary of the two-dimensional open region on the stereographic projection under the condition

$$\tau_F\beta^2 < \omega_c^{-1} < \tau_F, \qquad (1)$$

and occurs in the angular interval $|\varphi| < (\omega_c\tau_F)^{-0.5}$, $\beta = T/\Theta$ (Θ is the Debye temperature, ω_c is the cyclotron frequency, φ is the angle measured from the boundary of the two-dimensional open region). For copper with residual resistivity $\sim 2\cdot 10^{-10}$ Ω·cm and a value $\beta \simeq 0.01$ at $T = 4.2°K$, Eq. (1) really holds in a magnetic field $H \simeq 50$ kOe, then $\varphi \simeq 5°$ and almost spans the two-dimensional region of openness. Following Gurzhi and Kopeliovich,[9] it can be considered that the conductivity as a function of magnetic field is proportional to $(\omega_c^2\tau F)^{-0.5}$, and corresponding to this, the resistivity should grow with an increase in magnetic field with an exponent equal to 1.5.

The results of the experiments thus show that small deformations affect the scattering cross section for scattering of conduction electrons very weakly for electron transport in zero magnetic field, which agrees with the proposition that the main contribution to electrical resistivity comes from large-angle scattering of electrons. The magnetoresistance, however, is very sensitive to small densities of deformation defects, and there are then also anomalies in the behavior of the magnetoresistance in the presence of vacancies. This fact is evidence of the partially small-angle nature of the scattering of electrons by point defects. After annealing of vacancies, the change in the behavior of the magnetoresistance is extremely large, i.e., the small-angle character of the scattering by quasilocal phonon modes and by strain fields, which is unimportant in zero magnetic field, is more clearly revealed due to the effective screening of the cores of extended defects.

At large deformations, when the density of the defects introduced is high, electron scattering is predominantly isotropic, the role of strain fields decreases, both as a result of the reduction in the distance between dislocations and in view of the fact that the dislocation structure has a more sharply defined looped character; the dislocations are locked up inside the specimen and do not emerge at the surface. The elastic strain fields then decrease with distance according to a cubic law,[10] and the short-range potentials of the cores of extended defects then play the leading part. At small deformations, the increase in anisotropy is produced both by the capture by dislocations formed during the low-temperature deformation, of impurity atoms scattering isotropically to a first approximation[11] and by a contribution to the collision integral from small-angle scattering by the extended defects introduced,[12] the elastic strain fields of which are of longer range then closed dislocation loops.

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NOTATION

Here Θ is the Debye temperature, ρ is the electrical resistivity, ρ_H is the resistivity in a magnetic field, $\Delta\rho_H/\rho$ is the magnetoresistance, ω_c is the Larmor frequency, ε is the degree of deformation, τ^0_{eff} is the effective relaxation time in zero magnetic field, τ_F is the diffusion relaxation time, τ_U is the effective umklapp process relaxation time, τ^∞_{eff} is the effective relaxation time in a high magnetic field.

[1] R. A. Brown, Can. J. Phys. 19, 766 (1982).

[2] A. O. Fedotov, L. P. Mezhov-Deglin, and A. Yu. Kasumov, Fiz. Tverd. Tela (Leningrad) 23, 311 (1981) [Sov. Phys. Solid State 23, 177 (1981)].

[3] A. O. Fedotov and L. P. Mezhov-Deglin, Fiz. Tverd. Tela (Leningrad) 24, 207 (1982) [Sov. Phys. Solid State 24, 114 (1982)].

[4] V. F. Gantmakher and G. I. Kulesko, Zh. Eksp. Teor. Fiz. 67, 2335 (1974) [Sov. Phys. JETP 40, 1158 (1974)].

[5] A. B. Pippard, Proc. R. Soc. London Ser. A305, 291 (1968).

[6] R. N. Gurzhi and A. I. Kopeliovich, Zh. Eksp. Teor. Fiz. 67, 2307 (1974) [Sov. Phys. JETP 40, 1144 (1974)].

[7] G. Thummes and J. Kötzler, Phys. Rev. B31, 2535 (1975).

[8] M. Kaveh and N. Wiser, J. Phys. F13, 1207 (1983).

[9] R. N. Gurzhi and A. I. Kopeliovich, Proc. 19th All-Union Conf. on Low-temperature Physics, Minsk (1976), p. 148.

[10] A. M. Kosevich, The Principles of the Mechanics of a Crystal Lattice [in Russian], Nauka, Moscow (1972).

[11] A. Yu. Kasumov and V. N. Matveev, Fiz. Tverd. Tela (Leningrad) 18, 3724 (1976) [Sov. Phys. Solid State 18, 2172 (1976)].

[12] A. Yu. Kasumov, Ch. V. Kopetskii, L. S. Kokhanchik, and V. N. Matveev, Fiz. Tverd. Tela (Leningrad) 23, 271 (1981) [Sov. Phys. Solid State 23, 151 (1981)].

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