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Influence of dislocation microstructure on low temperature magnetoresistance in copper single- and polycrystals

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ABSTRACT

Angular and field dependent transverse magnetoresistance (TMR) have been studied in copper single- and polycrystals containing different density and distribution of dislocations. In the open-orbit orientation, the quadratic variation of TMR with the applied magnetic field changes to the quasi-linear dependence, as the density of dislocations increases. In the closed-orbit orientations, TMR shows a linear dependence with the magnetic field, the slope of the characteristic decreases with increasing the density of dislocations. The signatures of closed and extended orbits are preserved until the very high dislocation densities stored in the single crystals. The analysis of the Kohler's plots indicates that in the open-orbit orientation TMR violates Kohler's rule, but in the closed-orbit orientation Kohler's rule is obeyed. The results suggest that at low dislocation density, the magneto-transport of electrons is strongly anisotropic and is dominated by small-angle scattering, irrespective of the distribution of dislocations. In the crystals with higher densities of dislocations containing dislocation walls and cells, the electron transport is dominated by a high-angle scattering process. The magnetoresistance data are consistent with the two-band model and support the theory that the dislocation-induced relaxation time is anisotropic due to the non-sphericity of the Fermi surface. In the spherical portion of the Fermi surface the scattering is isotropic, associated with the constant relaxation time. Strongly anisotropic scattering in the aspherical portion of the Fermi surface is associated with a much smaller relaxation time.

1. Introduction

The galvanomagnetic properties of materials including Hall and magnetoresistance (MR) depend strongly on the character of the Fermi surface and the way electrons move on the Fermi surface under the influence of the applied magnetic field [1]. In metals, conduction electrons undergo scattering on different constituents of material microstructure, including impurities and lattice imperfections such as vacancies, interstitials, dislocations, stacking faults and grain boundaries. Progress has been made over the years in understanding the scattering of conduction electrons on impurities and point defects, but a description of electron transport in the presence of lattice dislocations has encountered difficulties related to understanding the nature of electron-dislocation collisions [2], the details of the scattering process [3–5] and the corresponding relaxation times for the complex dislocation network that is stored in a material [2, 6, 7].

For uncompensated metals, the semiclassical transport theory of Lifshitz and co-workers [8] predicts a quadratic variation of TMR with the applied field in open or long extended orbit orientation and a saturating behaviour in closed-orbit orientation. A saturating TMR has never been observed experimentally in simple metals and instead a linear increase of TMR with the magnetic field has commonly been reported in the literature. The discrepancy has triggered a debate in the research community that the linear variation of TMR with the field arises either from intrinsic [9–13] or from extrinsic [14–18] properties of metals. It has been pointed out that the dislocation substructure may exert an important effect on MR and contribute to the peculiarities of MR behaviour observed in deformed materials [19]. Recent measurements of TMR in compensated metals indicate that dislocations influence the field and temperature dependence of TMR and these properties depend on the type of dislocation distribution in the materials [20]. It has been argued that in some metals with a closed Fermi surface, such as tungsten and molybdenum, the change in the character of the electron orbits resulting from electron-dislocation collisions, known as dislocation breakdown, are responsible for some of TMR responses [21]. The theoretical arguments indicate that in noble metals the dislocation-induced scattering is strongly anisotropic [22]. This may lead to the peculiar galvanomagnetic phenomena in the uncompensated metals with an open Fermi surface, but the topic has not been explored sufficiently.

In the present paper we report the experimental studies of the TMR of copper single- and polycrystals containing different density and distribution of dislocations introduced to the samples by tensile deformation. The objective of this work is to examine the effect of dislocation microstructure on magnetoresistance of copper, to understand the mechanism of electron scattering on dislocations and to characterize

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the behaviour of TMR corresponding to different electron orbits. Copper has been selected for these studies because its Fermi surface provides easy access to various open and closed electron orbits in a magnetic field, and also because the type and the properties of dislocation substructure have been well documented in the literature. In the next Sections 1.1 and 1.2, we give an overview of the electron orbits and the electron transport properties in copper. The experimental procedure and the experimental results, which include orientation dependence of TMR, measurements of field dependent TMR and Kohler plot analysis for copper single- and polycrystals with different dislocation content are presented in Sections 2 and 3 respectively. Discussion and conclusions are given in Sections 4 and 5.

1.1. Electron orbits in copper

In the presence of a magnetic field conduction electrons move in the helical trajectories along the direction of the applied magnetic field $\vec{B}$. The corresponding motion of electrons in the *k*-space occurs in the plane orbit determined by the intersection of the Fermi surface with the momentum plane normal to the direction of the applied magnetic field. The Fermi surface of copper provides a spectrum of open, extended and closed orbits; the properties of these orbits have been well documented in the literature [23–25].

Fig. 1 shows, after Klauder and co-workers [23], the [110] stereographic projection indicating the crystallographic orientations in which the different types of electron orbits are observed in a copper single crystal in *k*-space. The principal symmetry directions ⟨100⟩, ⟨110⟩ and ⟨111⟩ parallel to the applied magnetic field correspond to the orientation of closed orbits. These include ⟨100⟩ belly and rosette orbits, ⟨110⟩ dogbone orbit and ⟨111⟩ belly and neck orbits. ⟨100⟩ and ⟨111⟩ belly orbits are nearly circular approximating the spherical shape of the free electron Fermi surface, with the radius $k_F = (3\pi^2 n_e)^{1/3}$, where n_e is the density of free electrons. For Cu, the radius of the belly orbit is about $k_F \approx 1.6 \times 10^{10}/m$. ⟨111⟩ neck orbits arise due to the presence of {111} Brillouin zone energy gap. They have a cylindrical shape and are the smallest closed orbits in copper, about one-fifth of the size of the belly

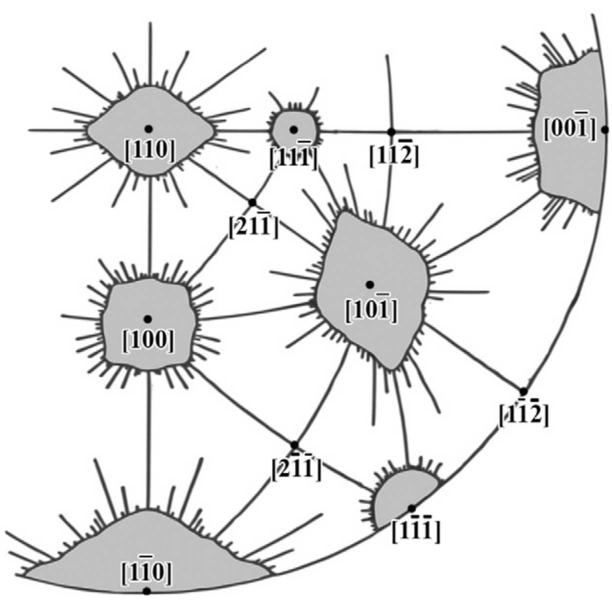

Fig. 1. Stereographic representation of the orientation of electron orbits in copper. The open orbits occur for the magnetic field $\vec{B}$ along the direction coinciding with the lines or within the shaded areas of the stereographic projection, except the high symmetry directions ⟨100⟩, ⟨110⟩ and ⟨111⟩ indicated by black dots. The empty areas and the principal symmetry directions ⟨100⟩, ⟨110⟩ and ⟨111⟩ correspond to the regions of extended and closed orbits respectively, for which the resistivity saturates. Redrawn from Ref. [23].

orbits. ⟨100⟩ rosette and ⟨110⟩ dogbone hole orbits are formed from bellies and necks of the Fermi surface in adjacent zones. The rosette and dogbone orbits are about half the area of the ⟨100⟩ belly orbit.

The principal symmetry directions ⟨100⟩, ⟨110⟩ and ⟨111⟩ are surrounded by wide solid angles and orientations within the shaded areas in Fig. 1 coinciding with the occurrence of open orbits of various order. The principal open orbits associated with the highest magnetoresistance (magnetoresistance ridges [23]) are observed a few degrees off the exact ⟨100⟩, ⟨110⟩ and ⟨111⟩ orientations. The combination of the principal open orbits in various crystal orientations give rise to the occurrence of higher order open orbits associated with somewhat lower magnetoresistance values. The higher order open orbits are observed in the close proximity of ⟨113⟩, ⟨133⟩, ⟨112⟩, ⟨122⟩, ⟨115⟩, ⟨155⟩, ⟨335⟩, ⟨355⟩, ⟨223⟩, ⟨233⟩, ⟨012⟩, ⟨013⟩, ⟨015⟩,⟨023⟩, ⟨035⟩ and ⟨123⟩ directions [23].

The empty areas of the stereographic projection correspond to the orientations of the extended orbits in copper. The whisker lines along the commensurate directions in Fig. 1, represent a spectrum of orientations where the periodic open orbits are guarded by the highly extended orbits. The spikes are more numerous in the neighbourhood of the shaded areas and eventually become infinitively close converging into the principal open orbits ⟨100⟩, ⟨110⟩ and ⟨111⟩ within the shaded areas in Fig. 1 [23].

1.2. Overview of electron-dislocation scattering in metals

Since dislocation theory became well-established in the early 1950s [26], the electron-dislocation scattering and its effect on the electrical properties of metals have attracted considerable research interest [27–43]. Terwilliger and Higgins [34], Coleridge and Watts [44] and Chang and Higgins [4] carried out the pioneering measurements of the de Hass–van Alphen (dHvA) effect in coper single crystals containing different densities of dislocations and contributed important results towards understanding the nature of electron-dislocation collisions in dHvA experiments. The theory of the scattering of conduction electrons on lattice dislocations in metals has been critically reviewed by Watts, based on the analysis of electrical resistivity and de Hass–van Alphen measurement data available in the literature [7]. These results suggest that in the absence of the magnetic field conduction electrons undergo high-angle scattering on regions of large atomic displacements close to the dislocation core, with the radius of the scattering cross-section approximately equal to the Burgers vector of the dislocation [4, 7]. The change of the momentum during scattering events gives rise to the electrical resistivity [7]. The de Haas–van Alphen effect, on the other hand, is sensitive to both high and low-angle scattering and the effect is dominated by the electron scattering from long-range strain fields of dislocations rather than dislocation core regions [7]. In de Haas–van Alphen measurements the electrons are scattered mostly in the forward direction and the radius of the dHvA scattering cross-section is about 2000*b*, where $b = 0.256$ nm is the Burgers vector of ordinary dislocations in copper [4, 7].

In uncompensated metals the TMR is expected to show a quadratic dependence with applied magnetic field in open orbit crystal orientations, whereas it should exhibit a saturating magnetoresistance at high magnetic fields in closed orbit orientations [8]. Experimental studies of the magnetoresistance of various metals reveal that the results do not conform to the theory. For example, early studies by Kapitza [45] showed that polycrystalline wires of Cu, Ag and Au exhibit a linear dependence of TMR with the magnetic field, which was subsequently interpreted as the average response from the randomly distributed open-orbit crystallites in a polycrystalline wire [46]. In subsequent studies of the MR effect, Garland et al. [47], Babiskin et al. [48] and Kesternich et al. [49] observed similar linear variation of the TMR with the magnetic field in metals with closed Fermi surfaces such as K, Al and In. The explanation of this discrepancy has led to a debate in the literature that the observed MR behaviour is an intrinsic property of the