MULTIPLE CONNECTIVITY OF THE FERMI SURFACE OF NICKEL FROM ITS MAGNETORESISTANCE ANISOTROPY

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We have obtained clear evidence from the anisotropy of the magnetoresistance of a nickel single crystal that its Fermi surface is multiply connected and may have the topology of the well-known Pippard model for copper.[1] This is the first direct experimental information about the electronic band structure of a ferromagnetic metal.

The resistance ratio, $R_{295°K}/R_{4.2°K}$, of the single-crystal sample was 2700, and its long axis, which defines the current direction, was within 2° from the ⟨110⟩ symmetry axis. The sample was mounted so that it could be continuously tilted from a vertical to a horizontal position. The magnetoresistance in a field of 18 kG was measured as a function of the field direction in the horizontal plane as the tilt angle φ was changed in increments of 5° from 0° (vertical) to 90°. For some field directions the magnetoresistance was measured as a function of the field strength.

The anisotropy of the transverse magnetoresistance for the field in the (110) plane is illustrated in Fig. 1(a). It is characterized by deep minima centered on the major symmetry axes. As the sample axis is tilted to make an arbitrary angle φ with the axis of rotation of the field, these minima disappear. But their "shoulders" remain in the form of peaks in the magnetoresistance, which move away from the symmetry axes as illustrated for $\varphi = 15°$ in Fig. 1(b).

The positions of the peaks as φ is changed from 0° to 90° are represented on a stereogram in Fig. 2, and are seen to form "ridges" of magnetoresistance near the sets of planes {100}, {110}, and {111}. For an arbitrary field direction the magnetoresistance saturates at high fields [Fig. 3(a)], while for a field direction producing a peak it increases faster than linearly with field [Fig. 3(b)].

The saturation of the magnetoresistance for arbitrary field directions shows that nickel behaves like an uncompensated metal for which $\omega_c \tau > 1$ at the highest fields H, ω_c being the cyclotron frequency (eH/m^*c) of carriers of effective mass m^*, and τ the carrier relaxation time. The great-circle "ridges" of magnetoresistance indicate sets of open cyclotron orbits on the Fermi surface in the [100], [110], and [111] directions,[2] since such orbits lead to a nonsaturating magnetoresistance for all current directions having a component in the open-orbit direction in reciprocal space.[3]

The behavior we observe in nickel is very similar to that observed in copper by Klauder and Kunzler,[4] who show that it is consistent with the Fermi surface proposed by Pippard.[1] The surface

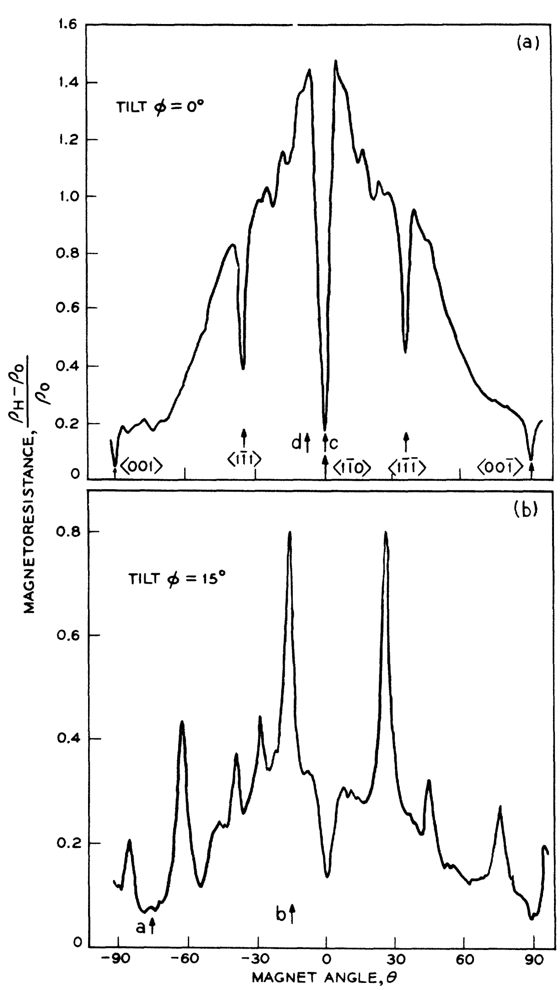

FIG. 1. Anisotropy of the magnetoresistance of nickel at a temperature 4.2°K in a magnetic field 18 kG, which is rotated about a direction making an angle φ with the ⟨110⟩ axis of the sample in the tilt plane at ~25° to the (001) plane. The vertical arrows indicate the field directions for which the field dependence of the magnetoresistance is shown in Fig. 3.

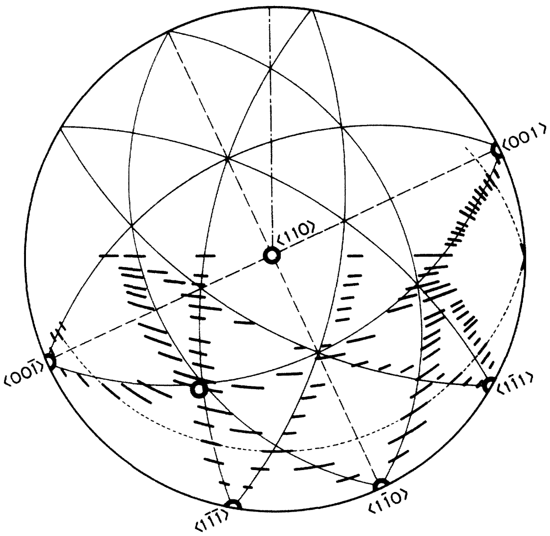

FIG. 2. Stereographic projection of the magnetoresistance data for nickel. The peaks are represented by heavy bars, which indicate their angular widths, and the minima centered on the symmetry axes by circles. The great-circle "ridges" of magnetoresistance are shown by solid lines. The field directions for which the open-orbit direction is perpendicular to the current direction so that no peak in the magnetoresistance is observed are shown by dashed lines, and the great circle $\varphi = 15°$ by dotted lines. The current direction is along the ⟨110⟩ axis, and the tilt plane is shown by the dash-dot line.

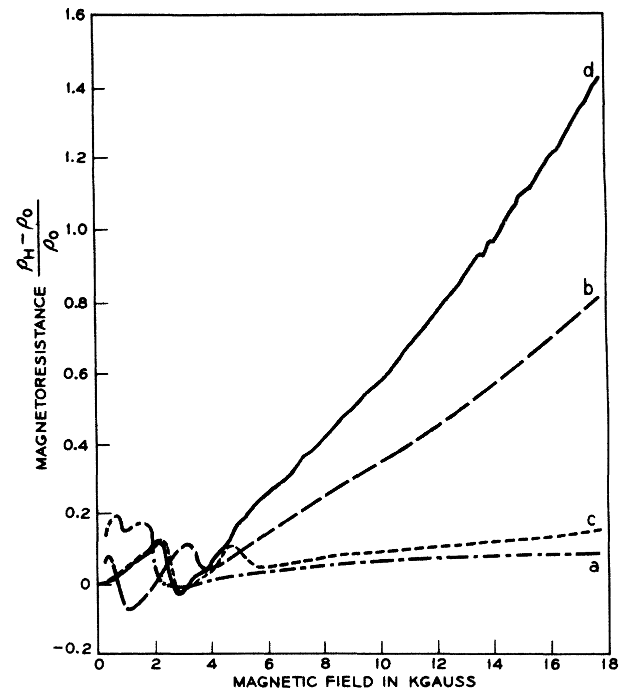

FIG. 3. Field dependence of the magnetoresistance of nickel at a temperature 4.2°K. The angles φ and θ refer to the sample orientation and field direction as described in Fig. 1: (a) $\varphi = 15°$, $\theta = -78°$; (b) $\varphi = 15°$, $\theta = -16°$; (c) $\varphi = 0°$, $\theta = 0°$; (d) $\varphi = 0°$, $\theta = -6°$.

intersects the {111} faces of the Brillouin zone to form "arms" in the [111] directions between neighboring zones. Similar behavior is also observed in gold[5] and silver.[6] The tertiary and higher order open orbits observed in copper[4] have not been detected in nickel, but their absence is not surprising since the magnetoresistance even for the primary [111] and secondary [100] and [110] peaks is small.

The smallness of the magnetoresistance, and the fact that is does not achieve the ideal quadratic field dependence associated with open orbits,[3] indicate that $\omega_c\tau$ is still only of order unity for a field of 18 kG even in this fairly high-purity sample. This conclusion is consistent with the high room-temperature resistivity of nickel, which is a factor 4 greater than that of copper, so that even with a resistance ratio of 2700 the mobility at 4.2°K is still relatively low.

The minima on the magnetoresistance rotation curve for $\varphi = 0°$ [see Figs. 1(a) and 2] are due to the vanishingly small number of open orbits when the field is directed along the major symmetry axes. The field dependence approaches the expected saturation at a minimum [Fig. 3(c)], while for neighboring field directions the open orbits along the ⟨110⟩ axis produce a field dependence more rapid than linear [Fig. 3(d)].[7] When the field passes near a symmetry axis for $\varphi \neq 0$, the magnetoresistance exhibits a central dip with a surrounding rim formed in the two-dimensional region of open orbits,[8] analogous to the "volcano-like" behavior observed in copper.[4]

The close similarity between the topology of the Fermi surface of nickel and that of the noble metals suggests that the electronic band structure of nickel comprises a multiply connected surface of high-mobility electrons, the *s* band, and of an equal number of low-mobility holes, the *d* band.[9] Presumably nickel would exhibit the magnetoresistance behavior of a compensated metal if one could achieve the "high-field" region where $\omega_c\tau > 1$ for all carriers, since it has an even number of electrons (ten) outside the last closed shell.[10]

Preliminary measurements of the Hall voltage for field directions where there are no open orbits give a number of electrons per atom 0.82 ± 0.05, but this estimate is subject to modification due to the possibility of appreciable d-band conduction. For field directions giving rise to open orbits, a small transverse-even voltage is also observed as expected.[11]

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[1]A. B. Pippard, Phil. Trans. Roy. Soc. London A250, 325 (1957).

[2]No correction has been applied for anisotropic demagnetization, which would still have an appreciable effect at an applied field of 18 kG for this sample of length 14 mm and diameter 2.3 mm. This effect and slight misorientation of the sample are sufficient to explain the deviation by a few degrees of many of the peaks from exact coincidence with the symmetry planes.

[3]I. M. Lifshitz, M. Ia. Azbel', and M. I. Kaganov, J. Exptl. Theoret. Phys. (U.S.S.R.) 31, 63 (1956) [translation: Soviet Phys. – JETP 4, 41 (1957)].

[4]J. R. Klauder and J. E. Kunzler, Proceedings of the International Conference on the Fermi Surface (John Wiley & Sons, Inc., New York, 1960), p. 125.

[5]Yu. P. Gaidukov, J. Exptl. Theoret. Phys. (U.S.S.R.) 37, 1281 (1959) [translation: Soviet Phys. – JETP 10, 913 (1960)].

[6]N. E. Alekseevskii and Yu. P. Gaidukov, J. Exptl. Theoret. Phys. (U.S.S.R.) 42, 69 (1961) [translation: Soviet Phys. – JETP 15, 49 (1962)].

[7]The unusual behavior in all the field-dependence curves at fields ≲6 kG, roughly the saturation field intensity of nickel, is presumably associated with the magnetocrystalline anisotropy energy.

[8]I. M. Lifshitz and V. G. Peschanskii, J. Exptl. Theoret. Phys. (U.S.S.R.) 35, 1251 (1958) [translation: Soviet Phys. – JETP 8, 875 (1959)].

[9]By slight modification of the nickel band structure calculated by J. G. Hanus (Massachusetts Institute of Technology Solid-State and Molecular Theory Group, Quarterly Progress Report No. 44, 1962), this topology can be made consistent with 0.5 $d\downarrow$ holes, 0.3 $s\uparrow$ electrons, and 0.2 $s\downarrow$ electrons yielding a net unpaired spin of 0.6 Bohr magnetons and the gyromagnetic ratio $g \simeq 2.0$. The slight modifications are that relative to the $d\downarrow$ band, the $s\uparrow$ and $s\downarrow$ bands are lowered by 0.03 ry and the $d\uparrow$ band is lowered by 0.05 ry. To give roughly the observed contact area at the symmetry point, L, of the Brillouin zone one requires $E_F - L_2' \sim 0.015$ ry [J. C. Phillips (private communication)].

[10]E. Fawcett, Phys. Rev. Letters 7, 370 (1961).

[11]J. R. Klauder and J. E. Kunzler, Phys. Rev. Letters 6, 179 (1961).

MAGNETOSTATIC HIGHER MODE RESONANCE IN A PARAMAGNET

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The study of paramagnetic resonance absorption in copper potassium chloride,[1,2] $K_2CuCl_4 \cdot 2H_2O$, has been extended to a temperature region down to 1.5°K. When the static magnetic field is applied along the [001] direction, all the copper ions in the unit cell become equivalent, though the unit cell contains two inequivalent copper ions, and only a single peak can be observed even at the highest frequency.

In our case the specimens used were ground to have approximately ellipsoidal shapes. At $\lambda = 1.30$ cm the linewidth was observed to be about 30 Oe at about 3°K; however, when the temperature was lowered it decreased to about 17 Oe at 1.5°K and the resonance field shifted toward the low field side by about 60 Oe. In addition, several small subsidiary peaks appear at the central part of the main peak. An example of the recorder traces observed at $T = 1.68$°K and at $\lambda = 1.30$ cm is shown in Fig. 1, in which the main peak is labeled m.

The splitting, δH_i, of the ith peak measured from the main peak increases with decreasing temperature; however, the ratio, $\delta H_i/\delta H_j$, of the splitting of the ith to the jth peak is constant with temperature. The origin of these small peaks was concluded to be the magnetostatic higher mode of oscillation in the paramagnet expected by Geschwind.[3] The main peak is due to the uniform precession of the moments within the specimen which corresponds to the Kittel mode in ferromagnetic resonance.[4] In this temperature region and at the resonance field (about 8 kOe), the total magnetization of the specimen may reach about half of its saturation value, so the effect of the demagnetization field cannot be neglected.

Walker discussed modes of oscillation of a ferromagnetic spheroid having an isotropic g tensor and calculated the resonance conditions for some