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Low-Field de Haas–van Alphen Effect in Copper*

A. S. JOSEPH
North American Aviation Science Center, Canoga Park, California

AND

A. C. THORSEN
Atomics International Division of North American Aviation, Inc., Canoga Park, California

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The de Haas–van Alphen effect has been observed in a copper single crystal by means of a null-deflection torsion balance technique. Detailed measurements have been carried out which provide an accurate determination of the topology of the Fermi surface necks in copper. Effective mass values are found to be in excellent agreement with cyclotron resonance results. Unusual behavior observed in the angular dependence of the amplitude of the oscillatory torque is attributed to the spin-splitting factor in the theoretical expression for the magnetization.

I. INTRODUCTION

THE first observation of the de Haas–van Alphen effect in copper by Shoenberg was accomplished by means of an impulsive field technique. His detailed results[1] confirmed the model of the Fermi surface proposed by Pippard,[2] and demonstrated conclusively that the Fermi surface deviates from sphericity and is multiply connected along the ⟨111⟩ directions, forming "necks" at the hexagonal faces of the Brillouin zone. The precise size and shape of the necks, however, could not be ascertained with pulsed magnetic fields. In this paper we report on detailed low-field measurements of the de Haas–van Alphen (dHvA) effect in copper resulting in accurate determinations of the neck topography and the associated effective masses. In addition, we report on what we believe to be the first unequivocal observation of the vanishing of the amplitude of the dHvA oscillations due to the zero value of the spin-splitting factor for $m^*=0.5m_0$ (and $g=2$).

II. EXPERIMENTAL

The measurements reported herein were made with a torsion balance apparatus which has been described in detail in a previous publication.[3] Magnetic fields up to 40 kG were supplied by a 22-in. Varian magnet, and were measured to within 0.1% with a rotating coil probe. The magnetic fields were swept automatically at the slow rate of ≈200–400 G/min to reduce the effects of eddy currents in the sample. The copper single crystal, supplied by K. R. Garr of Atomics International, was grown by the Bridgeman technique from a 99.999% pure rod purchased from the American Smelting and Refining Company. A suitable sample was spark cut in the form of a 0.1-in.-diam ×0.15-in.-long cylinder and was mounted so that the $[1\bar{1}0]$ axis was along the axis of suspension. The magnetic field could thus be rotated in the $(1\bar{1}0)$ plane of the crystal and was oriented in this plane to within 1°.

III. RESULTS AND DISCUSSION

The values of the period of the dHvA oscillations arising from extremal orbits around the necks are shown in Fig. 1. The period has a maximum value of 4.64×10^{-8} G^{-1} along the [111] axis (≈12% greater than that reported in Ref. 1) corresponding to a minimum cross-sectional area of 2.06×10^{15} cm^{-2}. As the field is rotated away from the [111] direction the period decreases and can be determined over an angular range of approximately 48°. To within the experimental accuracy, the data can be represented by the expression

$$\frac{P(\theta)}{P(0)}=\frac{m^*(0)}{m^*(\theta)}=\cos\theta\left(1-\frac{m_t}{m_l}\tan^2\theta\right)^{1/2}, \qquad (1)$$

with $m_t/m_l=2.55\pm0.10$, indicating that the shape of

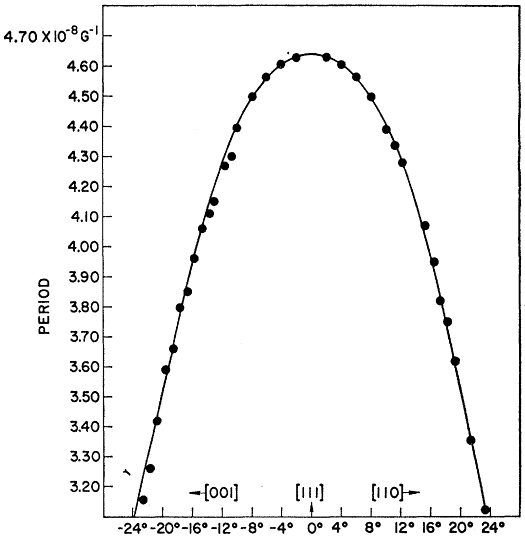

FIG. 1. de Haas-van Alphen period in copper versus orientation in the $(1\bar{1}0)$ plane. The solid line is a plot of Eq. (1) with the parameter $m_t/m_l=2.55$.

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[1] D. Shoenberg, Phil. Trans. Roy. Soc. London A255, 85 (1962).

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

[3] A. S. Joseph and W. L. Gordon, Phys. Rev. 126, 489 (1962).

the neck closely approximates the form of a hyperboloid of one sheet, and is hence similar to that of nickel.[4] In the above equation, θ is the angle measured from the [111] axis in the (1$\bar{1}$0) plane, and m_t and m_l are the transverse and longitudinal effective masses.

At several angles the effective mass was determined from the temperature dependence of the amplitude of the oscillations. These results are shown in Fig. 2 and are compared with Eq. (1), indicated by the solid line. The theoretical curve was normalized to the value $m^*(13°)=0.5m_0$ at $\theta=\pm 13°$ for reasons to be discussed below. The data indicate a value of effective mass along the [111] axis of $0.45m_0 \pm 3\%$. These results are in excellent agreement with the masses determined by Koch, Stradling, and Kip[5] by means of cyclotron resonance.

In Fig. 3 the amplitude of the oscillatory torque is plotted as a function of θ for a constant magnetic field. At $\theta=0$, this amplitude vanishes as is always the case for an extremum in the magnitude of the period. The torque amplitude increases initially with θ, passes through a maximum and goes to zero at $\theta=\pm 13° \pm 1°$. For larger angles the amplitude again increases and then decreases, finally vanishing at $\theta \approx \pm 24°$. We attribute the vanishing of the amplitude at $\theta \approx \pm 13°$ to the effect of spin-splitting of the Landau levels. This effect is manifested in a cosine multiplicative factor in the theoretical expression for the magnetization. The factor can be expressed as $\cos[\pi g m^*/2m_0]$, where g is the spectroscopic splitting factor, and m^* is the effective mass. It was introduced by Sondheimer and Wilson[6] and Dingle[7] for the case when m^* differs from m_0, and is given above in the generalized form derived by Cohen and Blount.[8] If the reasonable assumption that $g=2$ is made, then the amplitude should vanish when $m^*=0.5\ m_0$. Our experimental mass values do indeed approach this value for $\theta \approx \pm 13°$, evidencing remarkable agreement with the theory.

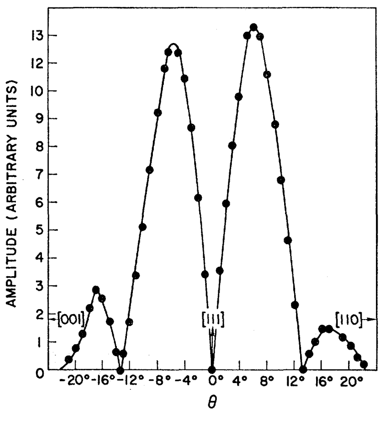

FIG. 3. Amplitude of the oscillatory torque at constant magnetic field (in arbitrary units) versus orientation in the (1$\bar{1}$0) plane.

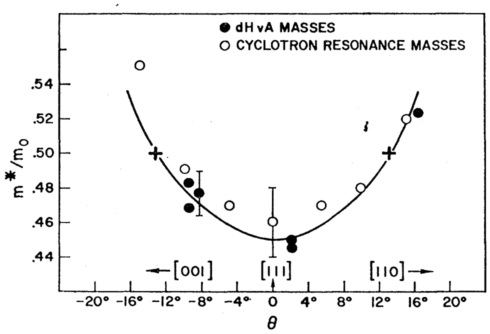

FIG. 2. Effective masses in copper versus orientation in the (1$\bar{1}$0) plane. Open circles are data of Koch, Stradling, and Kip (Ref. 5), found by cyclotron resonance. The solid curve is a plot of Eq. (1) normalized to a value $m^*=0.5\ m_0$ at the points denoted by crosses.

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[5] J. F. Koch, R. A. Stradling, and A. F. Kip, Phys. Rev. **133**, A240 (1964).

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[7] R. B. Dingle, Proc. Roy. Soc. (London) **A211**, 500 (1952).

[8] M. Cohen and E. I. Blount, Phil. Mag. **5**, 115 (1960).