satisfactory, the theoretical areas are systematically smaller than the corresponding experimental ones. Both holes and electrons are similarly affected; so a simple change of the Fermi level is not sufficient to correct all the areas.

There are four important effects which determine the energy bands in a transition metal.[16] These are the *d* bandwidth, hybridization, *s*-*d* shifts, and the spin-orbit coupling. Of these the spin-orbit coupling and *s*-*d* shifts are the most important, since the *d* bandwidth and hybridization seem to vary little between various calculations. Thus, to bring the calculations into agreement with the experimental data, it appears likely that corrections in the *s*-*d* shift and spin-orbit coupling in addition to an adjustment of the Fermi level will be required.

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IDEAL FLUX-FLOW RESISTANCE IN A TYPE-II SUPERCONDUCTING ALLOY

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In an ideal type-II superconductor, between the fields H_{c1} and H_{c2}, a regular lattice of current vortices or "fluxoids" is formed. If a current I is applied at right angles to the applied field $\vec{H}$ in an ideal, defect-free superconductor, it is thought that the fluxoid lattice undergoes a translational motion at a uniform velocity in a direction mutually orthogonal to both I and $\vec{H}$.[1] The fluxoid motion gives rise to an electric field which is observed as a resistive voltage drop, V, in the direction parallel to I. This is the so-called "flux-flow" resistivity.[2,3] Theoretically, one expects the ideal behavior to be Ohmic, i.e., $V=IR$, where R depends only on H.[4,5] In real superconductors, one generally observes nonlinear I-vs-V curves and (equivalently) noncurrent-independent R-vs-H curves.

The deviation from the "ideal" linear behavior has been the subject of much discussion[2,6-8] and some controversy,[9,10] though the popular view appears to be that the departure from linearity is due to interactions with the surface and with volume defects (e.g., dislocations). These "pinning" forces are particularly effective at low values of I where the electromagnetic forces on the fluxoid are relatively small.

The purpose of this Letter is to report recent experiments in which we have been able to achieve linear V-vs-I and current-independent R-vs-H behavior and in which we find that this "ideal" resistivity is in excellent agreement with predictions of the recent microscopic theory[4,5] over a large variation of the dc current. The depinning of the fluxoids is achieved by superimposing on the transverse dc magnetic field a small longitudinal oscillatory field.[11]

The experiments reported here were performed on foils of In + 1.5 at.% Bi, approximately 3 $\times 1 \times 0.02$ cm^3 which were chrome plated to quench the surface currents.[12] A foil was clamped between two flat surfaces in a four-probe sample holder immersed in liquid helium. The probe could be rotated so as to allow the dc magnetic field to be parallel or perpendicular to the plane of the foil. The dc current was always in the direction of the longest dimension of the foil, perpendicular to H. The oscillatory field, $H^{\rm osc}$, was supplied by a long (6-cm) one-layer solenoid in the long (current) direction of the sample.

A combination of Figs. 1 and 2 is required to illustrate our results. In Fig. 1 we show actual recorder plots of the resistive voltage as a function of applied dc field H for several values of the dc current I. Curves 1-3 are taken with the oscillatory field $H^{\rm osc}$ set to zero;

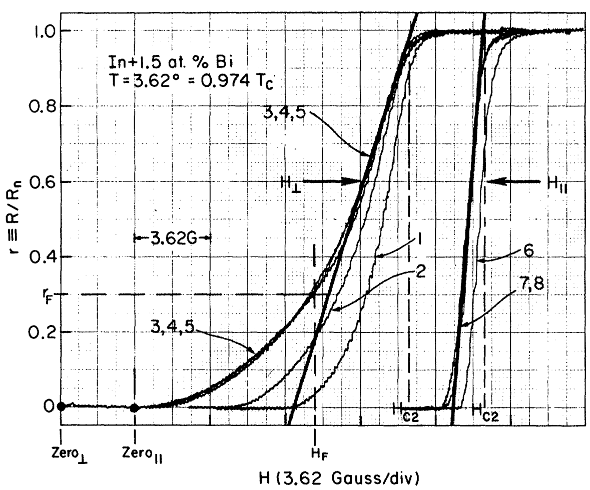

FIG. 1. Photograph of an actual recorder tracing of the resistance as a function of applied dc field perpendicular to the foil (curves 1-5) and parallel to the foil (6-8). For curves 1 and 2 the dc current density is 2.3 and 5 A cm^{-2}, respectively, with no oscillatory magnetic field. Curves 3-5 ($J = 2.3$, 5.0, and 23.0 A cm^{-2}, respectively) obtain when the oscillatory field is set at the plateau threshold value $H_T^{\rm osc}$ (see Fig. 2) and are thought to correspond to the ideal $r(H)$ curve. Curves 6-8 illustrate the same effect in parallel field. (Note the displaced origin.) Curve 6: $J = 5$ A cm^{-2}, $H^{\rm osc} = 0$. Curves 7, 8: $J = 5.23$ A cm^{-2}; $H^{\rm osc} = H_T^{\rm osc}$. The straight lines drawn through the curves near H_{c2} are predicted by the microscopic theory (Ref. 5) for free flux flow. The ideal $r(H)$ curve obtains also for much lower current densities than these but the display is complicated by low-level "spurious" emf's which, unlike r, change sign with reversal of field, and must be subtracted out.

in this case, the resistive voltage is a function of current, approaching the supposed free-flow values as the current increases. This is equivalent to the observation that the V-I curves become linear at high current densities. In Fig. 2 we plot the resistive voltage as a function of the rms amplitude of the oscillatory field, $H^{\rm osc}$, for several values of current and at a fixed value of $H_{\rm dc}$ indicated by H_F in Fig. 1. For a given current, as $H^{\rm osc}$ is increased the resistive voltage rises rapidly to a definite plateau region before finally increasing again as the strength of the oscillatory field begins to drive the sample normal. The plateau resistance is found to be independent of current density over a wide range of values, and to depend only on the applied dc field. Returning to Fig. 1, it is seen that with $H^{\rm osc}$ set at a value within the plateau region, the resistance follows a current-independent[13] curve which we associate with the ideal flux-flow resistivity. Another way of describing the foregoing is in terms of V-I curves, Fig. 3. Again with H set at a fixed value H_F, the $H^{\rm osc} = 0$ curve has the usual appearance, characterized by a minimum onset current I_p at which voltage first appears, a curved region, and finally the usual linear region. As $H^{\rm osc}$ is increased from zero, the zero-voltage intercept of the straight-line region I_F approaches zero, and finally the resistance is perfectly Ohmic with a straight-line V-I curve passing through the origin. The corresponding value of $H^{\rm osc}$ agrees with the

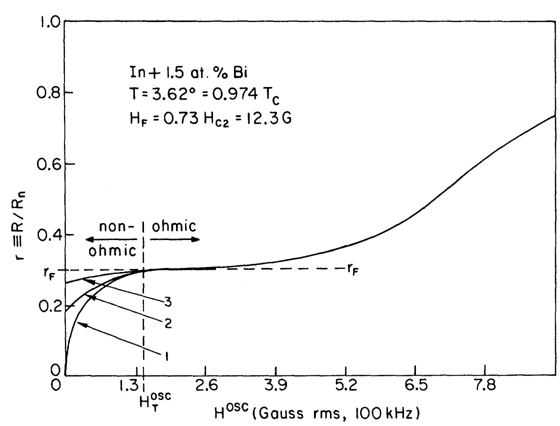

FIG. 2. The resistance as a function of the rms amplitude of the oscillatory magnetic field $H^{\rm osc}$ at 100 kHz for constant dc field $H = H_F$ (see Fig. 1). The plateau region corresponds to the "ideal" flux-flow resistance curve $r(H)$ shown in Fig. 1. For $H^{\rm osc} > H_T^{\rm osc}$, the V-I curves are "Ohmic," i.e., $V = IR$. Curves 1-3 are for $J = 2.3$, 5.0, and 15.0 A cm^{-2}, respectively.

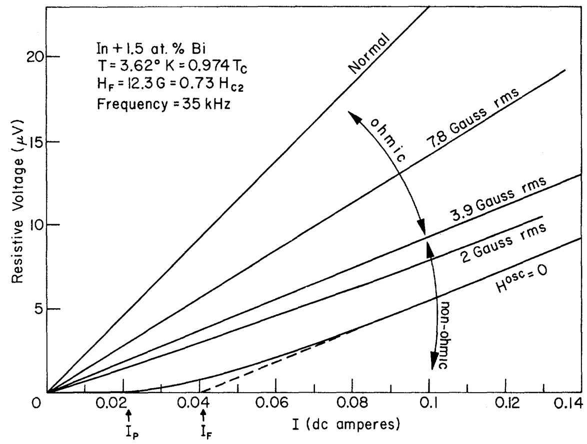

FIG. 3. The resistive voltage versus dc current at constant dc field $H=H_F$ (see Fig. 1). The resistance first becomes Ohmic when H^{osc} attains a value corresponding to the plateau thresold H_T^{osc} at 35 kHz as determined by a curve similar to that of Fig. 2. Cross-sectional area of the sample is 0.02 cm^2.

35-kHz value of H_T^{osc} as defined by a curve similar to that of Fig. 2. (The frequency dependence of H_T^{osc} will be discussed below.) For all higher values of H^{osc} the resistance is Ohmic until the sample is normal. It is interesting to note that the onset current I_p goes to zero for very small values of H^{osc}. This corresponds to the very steep rise of the curves of Fig. 2 for low values of current.

Recently, from microscopic considerations Schmid[4] and Caroli and Maki[5] have derived an expression for the ideal flux-flow resistance. The resistance appropriate to the dirty limit is given by

$$r(H) \equiv R/R_n = 1 + 4\kappa_1^2(0)4\pi M(H)/H_{c2}, \qquad (1)$$

where R_n is the normal-state resistance, M is the magnetization, and $\kappa_1(0) \equiv H_{c2}(0)/\sqrt{2}H_c(0)$ is the Ginzburg-Landau parameter at zero temperature. Near $H=H_{c2}$, the magnetization is given by[14]

$$4\pi M(H) = -(H_{c2}-H)/[(2\kappa_2^2-1)\beta+n], \qquad (2)$$

where κ_2 is the temperature-dependent parameter introduced by Maki,[15] β is expected to be 1.16, $n=1$ when H is perpendicular to the foil, and $n=0$ when the field is parallel. Thus near H_{c2}, the quantity r as a function of the reduced field H/H_{c2} is expected to be linear with a slope

$$S \equiv H_{c2}(dr/dH)_{c2} = 4\kappa_1^2(0)/[(2\kappa_2^2-1)\beta+n]. \qquad (3)$$

To compare with experiment, since all data were taken at $T/T_c \approx 1$, we have used $\kappa_2(T)=\kappa$ and $\kappa_1(0)=1.2\kappa$ (as prescribed by dirty-limit theory),[15] where $\kappa \equiv \kappa_1(T_c)=\kappa_2(T_c)$. In a previous experimental study,[16] the value of κ for In + 1.5 at.% Bi was found to be 0.77 ± 0.01. Using this value, we find $S_\perp = 2.8$ and $S_\parallel = 16$. Straight lines corresponding to these slopes are shown drawn through the experimental curves in Fig. 1. The agreement is evidently satisfactory. Moreover, H_{c2} as thus determined is in good agreement with magnetization measurements.[16] In the course of the experiments our usual procedure was simply to draw a straight line fitted visually to the experimental curves and thus determine an experimental slope. In more than two dozen such observations, at temperatures between $t=0.80$ and $t=0.975$, the experimental slope never exceeded 3.0 nor was less than 2.65 for the perpendicular case. In this same range, the theoretical value given by Eq. (3), using the dirty-limit temperature dependence, decreases from about 2.8 to 2.7. We thus find that the resistivity of the microscopic theory and the experimental Ohmic resistivity resulting from application of the oscillatory perturbation are in agreement to within better than 10% for all observations of this study.

Though the mechanism of depinning by the oscillatory field is obscure, the following observations may be of interest. Below about 10 kHz the resistivity no longer exhibits a plateau region because H_T^{osc} becomes comparable with H_{c2}. As the frequency increases, H_T^{osc} decreases.[17] To within experimental error we find $H_T^{osc} \propto \omega^{-\frac{1}{2}}$ between 10 and 150 kHz. As the temperature is lowered, H_T^{osc} increases, being roughly twice as large at $t=0.80$ as at $t=0.975$. In the presence of the depinning field, the resistive voltage has a relatively high noise content suggesting possibly incoherent motion of the vortices, i.e., a stochastic distortion of the vortex lattice superimposed on the average flow velocity.

In summary, we observe that the good agreement between the measured resistivity in the presence of H_T^{osc} and the calculated resistivity from the microscopic theory is consistent with the conclusions that (a) the theory correctly predicts the free flux-flow resistance, (b) the oscillating longitudinal field effectively depins the fluxoid lattice, and (c) the ideal V-I curves are linear, and deviations from this behavior should be regarded as arising from vortex pinning rather than being a feature of ideal flux flow.

We would like to thank J. Curnow and D. H. Leslie for their technical assistance.

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[12]Experiments performed on nonplated samples yielded the same general results qualitatively. For low-current values, the bare-sample transition curves are broadened owing to surface conduction, making quantitative interpretation of the data difficult. There was no evident indication, however, that the depinning threshold was different between the bare and plated samples.

[13]We have varied I over more than two orders of magnitude. There is no evidence of a lower limit but the upper limit appears to be where the current appreciably changes the field distribution.

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MAGNETO-OSCILLATORY EXCITATION SPECTRA OF SHALLOW ACCEPTOR IMPURITIES IN InSb AND Ge

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The effect of a magnetic field on the excitation spectra of impurities in semiconductors has been the subject of considerable theoretical and experimental interest. In general, this interest has been directed either to the high-field regime $\gamma \gg 1$, or the low-field regime $\gamma \ll 1$, where the field parameter $\gamma \equiv \frac{1}{2}\hbar\omega_c/\text{Ry}^*$ is the ratio of the zero-point energy in a magnetic field to the effective Rydberg energy, Ry*, of the impurity atom, and ω_c is the cyclotron resonance frequency multiplied by 2π. The present Letter describes an experimental study of acceptor impurity excitations in InSb and Ge that involves simultaneously the high-field and low-field regimes. In addition to yielding information concerning the acceptor impurity states, the experiments provide a useful means of studying the valence-band structure in a magnetic field.

The absorption due to shallow acceptor impurities in InSb and Ge has been measured in magnetic fields up to 100 kG, at temperatures near 4.2°K. The spectral regions of interest extended upward in energy from the ionization energies of the impurities. Impurity-induced photoconductivity has also been observed; however, this work will be described in detail elsewhere. Acceptor concentrations were in the range 10^{14}-10^{15} cm^{-3}. At the higher fields, measurements were made with a grating spectrometer designed for use with the Naval Research Laboratory Bitter-type magnets. Additional spectra were obtained at lower fields by means of an interferometric spectrometer and superconducting solenoid.

Typical transmission spectra for Cd-doped InSb are shown in Fig. 1. The transmission minima were observed with equal strength in the Voigt and Faraday orientations, and in the Voigt orientation with the electric field of the radiation parallel or perpendicular to the ap-

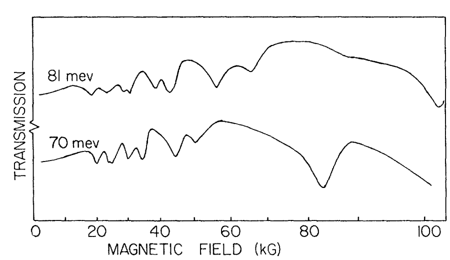

FIG. 1. Transmission spectra obtained at two fixed photon energies for Cd-doped InSb at 4.2°K, using a monochrometer and Bitter-type magnet. The sample was in the Voigt orientation, with the electric field of the radiation parallel to the applied magnetic field.