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Electrical resistance of an elastically bent thin metal wire in a magnetic field

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If the mean free path of charge carriers is sufficiently large compared to sample dimensions, the resistance of a straight wire increases as it is elastically bent. We have studied this effect in Bi, Sn, and Zn in the presence of a magnetic field and find that for magnetic fields perpendicular to the plane containing the bent sample, the resistance is not changed by reversal of sample current or magnetic-field direction. These results are discussed in connection with a classical theoretical model of charge carriers which predicts that such a change would occur. As the magnetic field is increased the bending effect decreases and at sufficiently large fields it vanishes. This result reinforces our interpretation that the bending effect is caused by enhanced surface scattering due to the change in sample geometry.

I. INTRODUCTION

We have reported previously that an elastically bent metal whisker has more electrical resistance than the same whisker when straight.[1] Because this bending effect increases as the temperature decreases, increases as the whisker diameter decreases, and is large in materials which are known to have long electron mean free paths, it is reasonable to interpret the effect as being due to enhanced surface scattering of electrons due to the bent whisker shape. An experimental result is illustrated in Fig. 1. The conduction electrons have mean free paths (in the bulk material) much greater than the whisker diameter and about equal to the whisker length. Electrons directed along the whisker length would travel their mean path except for the bend which causes them to hit the surface. Calculations based on this interpretation gave qualitative agreement with experiment which, under the circumstances, is as good as one could expect.

Recently Berger[2] has discussed the motion of charged particles in a ring with a magnetic field parallel to the ring's axis. Under a set of "widely accepted" classical assumptions too lengthly to repeat here "it is predicted that a current will flow around the ring", although such a current would represent a violation of the second law of thermodynamics. Another way to state this fundamental violation is that this current would be a diamagnetic response of the charged particles to the applied magnetic field and such a response, according to Van Leeuwen's theorem, "does not exist in classical physics".[3] Nevertheless, under the assumptions above, Berger has suggested that the effective resistance of a whisker bent in a circular arc in a magnetic field would change if the whisker current were reserved, being lower for that current direction which results in the cyclotron orbit curving along the whisker.

Partly because of Berger's encouragement and partly because of our own interest in testing the mean-free-path interpretation of the bending effect we have done some experiments on the bending resistance, this time in a magnetic field.

II. EXPERIMENTAL DETAILS

The details of our resistance measurement techniques may be found elsewhere.[4] Briefly each whisker had two current leads and two potential leads, the current was held constant to one part in 10^5 and the sample voltage was monitored with a resolution of 0.1 μV. System noise was less than 50 nV.

The magnetic fields were produced by Helmholtz coils wound with superconducting wire. Coil constants (two pairs were used) were calculated from the dimensions of each turn on the coils and were 9.19 and 10.95 mT/A. The field was uniform over the

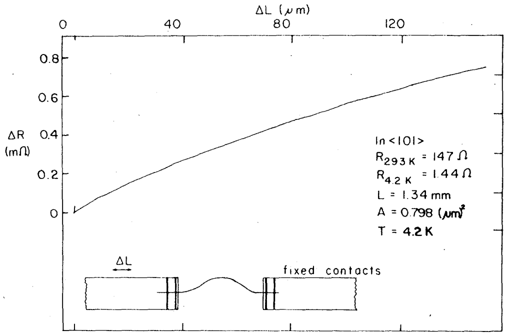

FIG. 1. Change in resistance of a whisker as it is bent into a sinusoidal curve. The sharp rise in resistance after the whisker is straight is the normal piezoresistance. The motion of the movable contact inward from the just straight position is ΔL.

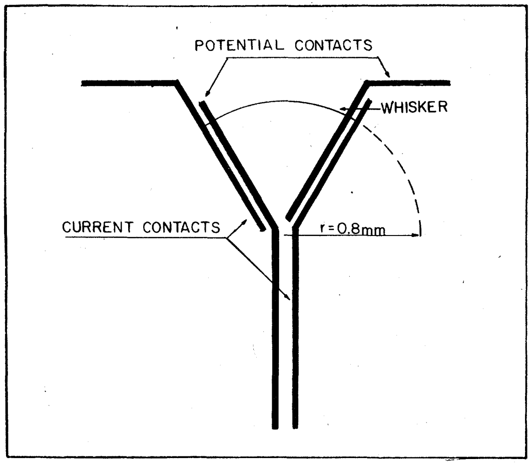

FIG. 2. Sample mount for whiskers bent into a circular arc. The copper cladding of a circuit board was etched away except for the heavy lines which formed the electrical leads to the whisker.

sample volume to within one part in 75.

For the experiments in which the whisker was mounted in a circular arc, a printed circuit board was etched to leave the pattern shown in Fig. 2. The exposed fiberglass was scraped away so that the whisker did not touch the board. The whisker was mounted on the contacts in coincidence with a circular arc of radius 0.794 mm ($\frac{1}{32}$ inch) scribed on the eyepiece reticle of a microscope.

For the experiments in which the distance between whisker ends was varied the whiskers were mounted on a quartz puller described elsewhere.[4]

All experiments reported here were done at 4.2 K with the sample either immersed in liquid or gaseous helium. The temperature was measured with a germanium resistance thermometer.

III. EFFECT OF REVERSING THE SAMPLE CURRENT AND THE MAGNETIC-FIELD DIRECTION

The sample was of Bi. It was about 1 mm in length between potential leads and was mounted in a circular arc of radius 0.8 mm. The magnetic field was applied parallel to the axis of the circular arc. The sample resistance was 1916 Ω at room temperature and 656.2 Ω at 4.2 K. Figure 3 shows a recorded tracing of sample voltage versus magnetic field for both forward and reverse directions of the field. On this scale there is no observable difference between forward and reverse field directions. Higher resolution readings were taken pointwise and show that the difference in sample voltage upon reversing the magnetic field never exceeds 7 μV out of ~8000 μV. They also show that reversal of sample current produces voltage differences no greater than 2 μV and that reversal of both magnetic field and sample current (which should produce no effect) produces sample voltage changes as great as 6 μV. We therefore conclude that within this precision there is no effect on the sample resistance due to either reversing the sample current in a fixed magnetic field or reversing the magnetic field with fixed current.

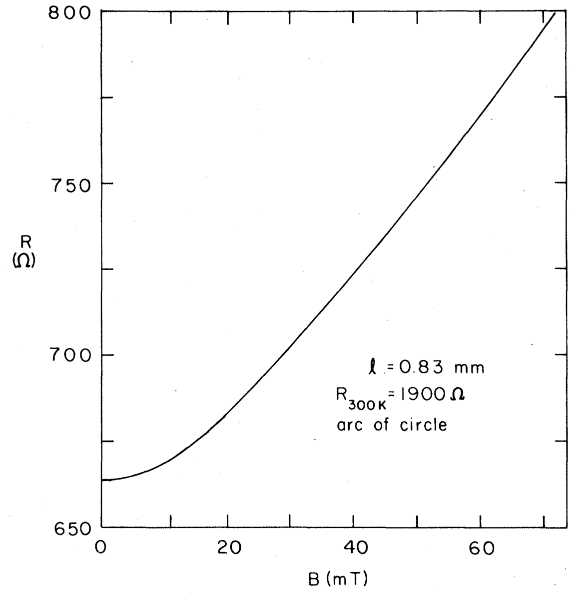

FIG. 3. Change in resistance at 4.2 K of a Bi whisker mounted in a circular arc of radius 0.8 mm as a function of the magnetic field perpendicular to the circle. The whisker length is ℓ; its resistance at temperature T was R_T; its cross-sectional area is A and its crystallographic orientation is ⟨101⟩. Although the whisker cross section is not usually a simple geometric shape, the width is approximately the square root of the cross-sectional area. The sample current was 10.0 μA.

IV. DISAPPEARANCE OF BENDING EFFECT AS THE MAGNETIC FIELD IS INCREASED

In these experiments the samples were mounted straight on a whisker puller device such that the distance between whisker ends could be made less than the whisker length. This causes the whisker to be bent elastically and reversibly into a sinusoidal shape. The magnetic field was then applied perpendicular to the plane defined by the bent whisker. This field direction was set visually at room temperature but could be determined most sensitively at 4.2 K by observing the symmetry of the bending effect as a function of angle in a relatively small field. Measurements were made at the symmetry point. The current was occasionally reversed and no effect was noted within a precision of about 1%. The whisker resistance was plotted as a function of the change in

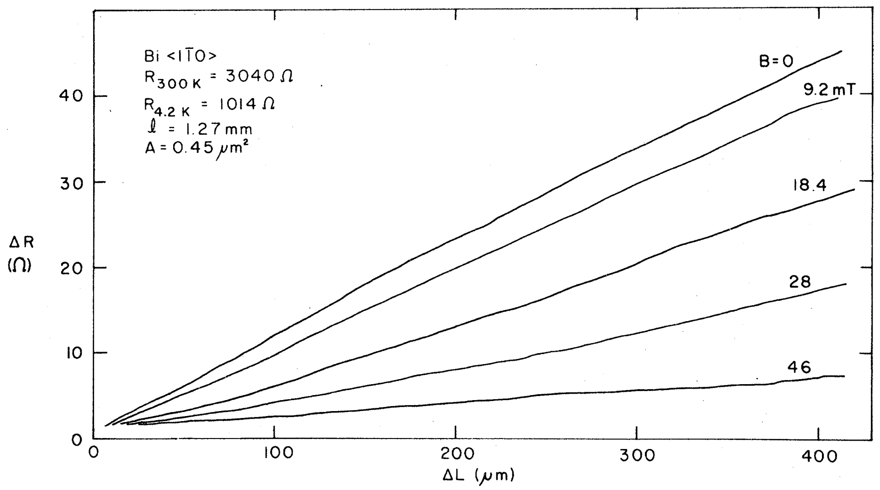

FIG. 4. Change in resistance of a Bi whisker as it is bent in a sinusoidal curve. The motion of the movable contact from the just straight position is given by ΔL. The magnetic field perpendicular to the plane of the whisker is a parameter. The sample current was 1.00 μA.

distance between whisker ends with the magnetic field a parameter. Plots of the data are in Figs. 4 – 6.

V. OTHER EXPERIMENTS

In addition to the experiments already discussed we mounted several Bi and Sn whiskers on a puller in a tight helix of one turn with axis parallel to the pulling axis. A magnetic field was then applied along the axis of the helix. By extending the distance between the puller's grips the pitch angle of the helix was increased while its radius was decreased such as to conserve the length of the whisker itself. Crystals mounted in this way indeed showed the bending effect in zero field. In nonzero field there was no resistance change due either to reversing the sample current or the field direction, as in earlier experiments.

Some samples were mounted in a circular arc on the puller. Changing the distance between whisker's ends distorted the sample from a circular arc. A magnetic field was applied perpendicular to the plane defined by the bent whisker. Except for Bi nothing special occurred at any value of the field as the whisker was caused to pass through a circular arc. In the case of Bi one sample showed a maximum resis-

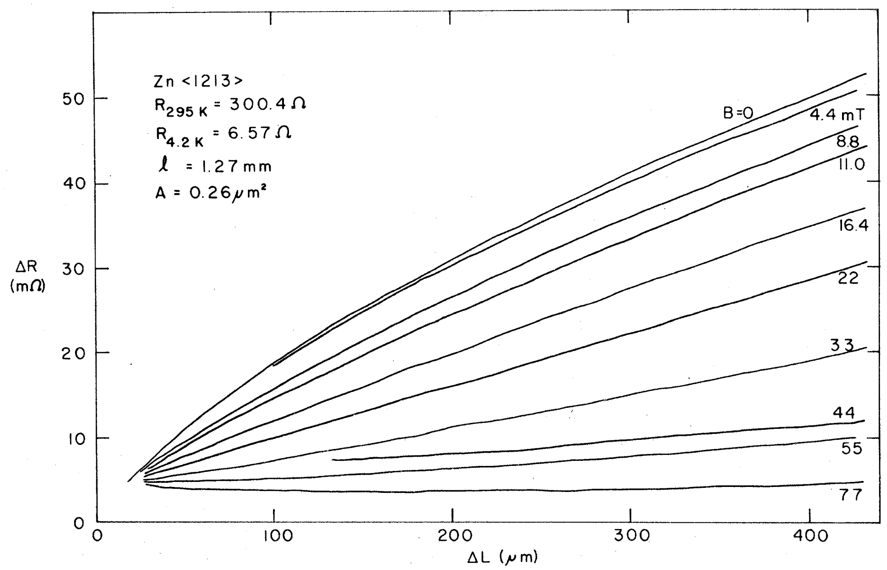

FIG. 5. Change in resistance of a Zn whisker with bending, as in Fig. 4. The sample current was 1.00 μA.

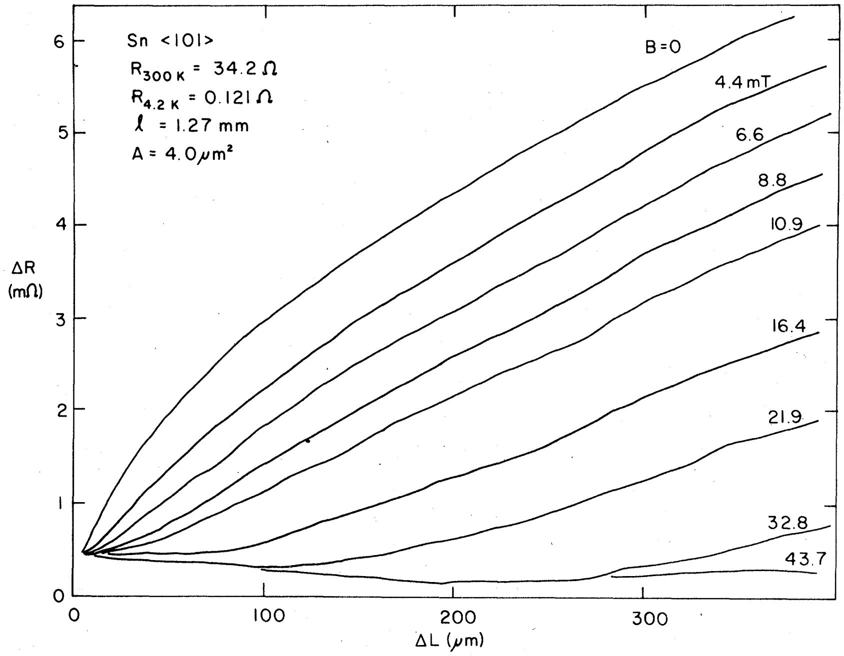

FIG. 6. Change in resistance of a Sn whisker with bending, as in Fig. 4. The sample current was 100 μA.

tance as a function of distance between whisker's ends while a different orientation Bi whisker showed a minimum at this position. These particular results for Bi appear to be associated with the stress induced in the whisker since they persisted even to room temperature. Sn and Zn showed no such behavior nor anything singular about the position of a circular arc.

VI. CONCLUSIONS

As predicted by the second law of thermodynamics there is no decrease in resistance of a sample bent into a circular arc in a magnetic field parallel to the axis of the arc.

Of course the path of the charge carriers in real space is not usually circular, nor do all carriers have the same path. There are, however, nearly circular orbits in Bi and for some carriers in Sn and Zn. In any case, one might expect an effect when the radius of curvature of a sample matched the radius of curvature of an extremal orbit in which many carriers would participate.

An estimate of the cyclotron radii may be made from known electronic properties. The cyclotron radius, r_c, is given by $r_c = A/B$, where A is a constant and B is the applied magnetic field. For Bi, depending on the location of the carriers on the Fermi surface and the orientation of B with respect to the crystal lattice, $3\times10^{-5} \leq A \lesssim 3\times10^{-7}$ m T.[5] Thus, at a field of 30 mT, $10^{-3} \lesssim r_c \lesssim 10^{-5}$ m. Most of the carriers in Sn and Zn have cyclotron radii in this range also. This is just the range of radii and magnetic fields used in these experiments, i.e., the magnetic field was swept through values such that cyclotron radii in this range would have matched the whisker radii. If any anomaly is present when the cyclotron radius matches the whisker's bend radius its effect on resistance is less than our ability to detect.

Second, the disappearance of the bending effect in sufficiently large magnetic fields reinforces our belief that the bending effect is due to enhanced surface scattering in the bent crystal. For magnetic fields such that the cyclotron radii of charge carriers are small compared to the bend radius and the mean free path, charge carriers would collide with the surface before traveling their mean paths whether the sample were bent or not. This would result in increased resistance of the sample but this resistance would be insensitive to sample bending, as was found in our experiments.

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