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CYCLOTRON RESONANCE EFFECTS IN ZINC

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(Received March 12, 1959)

We have observed cyclotron resonance effects in single-crystal samples of zinc at about 1.3°K and at both 24 000 Mc/sec and 72 000 Mc/sec. We have done the experiment both with the magnetic field along a twofold and along a sixfold axis.

The experiments were done by using the same technique used previously in experiments on bismuth[1,2] and graphite.[3] The crystallographically oriented plane surface of a disk sample was made to form part of the wall of a microwave cavity in an area where circularly polarized radiation was incident upon it. In the experiments on zinc, the sensitivity of the experiment was increased by making the sample form a larger part of the cavity end-wall than in the earlier work. As a result, the two circular polarizations in the radiation incident on the sample have a ratio as low as 7.5 in some cases, but this does not seem to have led to vital difficulties.

Single-crystal boules of zinc were grown in a stream of hydrogen at atmospheric pressure by pulling a seed from a melt formed from New Jersey Zinc Company's "super-purity" zinc. Disks with at least one plane, carefully oriented surface were cut from these, some with the plane surface normal to a twofold axis, ⟨10·0⟩, so that a sixfold axis was in the surface, and some with the plane surface normal to a sixfold axis in which case twofold axes were in the plane. The data in the figures are from two samples, both cut from a crystal in which the dc resistance ratio $R(300°K)/R(4.2°K)$ was about 9000.

For each sample type, experiments were done both with the field in the plane of the sample and normal to it. When the field was in the plane of the sample, the behavior observed was like that predicted by Azbel' and Kaner[4] and observed by others in tin, lead and copper.[5] Data taken under these conditions at 24 000 Mc/sec showed the appropriate frequency dependence and generally confirmed those taken at 72 000 Mc/sec but were not as good, and only the latter are presented.

Figure 1 shows data taken with the field in the sample plane and along a sixfold axis. The data

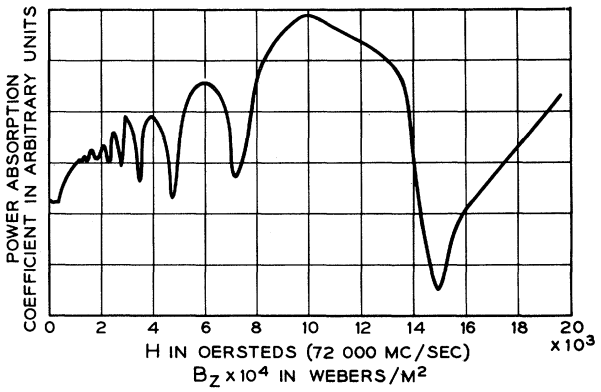

FIG. 1. Cyclotron resonance data at 72 000 Mc/sec and 1.3°K for zinc with magnetic field in sample plane and along a sixfold axis.

below one kilogauss do not constitute a well-resolved signal, but they do indicate the presence of a carrier of cyclotron mass less than $0.015m_0$. This part of the data agrees qualitatively with de Haas-van Alphen data,[6] which give a cyclotron mass of $0.005m_0$ for carrier motions about this axis. The high-field region in Fig. 1 shows a well-resolved signal of the type predicted by Azbel' and Kaner which is from another carrier. These data fit reasonably well the behavior of $R(H)/R(0)$ derived from the formula given by Azbel' and Kaner[4] for $Z(H)/Z(0)$ using a mass of $0.55m_0 \pm 5\%$, an $\omega\tau$ of about 20, and a phase of $e^{-i\pi/3}$ in $Z(0)$. This signal also has the characteristic predicted by Azbel' and Kaner that it disappears unless the field is within about one degree of the sample surface. The fit to the theory is not perfect, but the misfit probably arises primarily from imperfect tracking of the cavity and signal oscillator frequencies, so that the signal partly reflects the surface reactance as well as the surface resistance.

Figure 2 shows data taken with the field in the sample plane and along a twofold axis. Here we

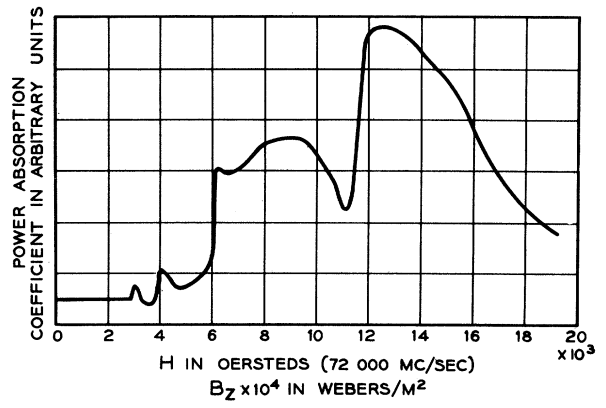

FIG. 2. Cyclotron resonance data at 72 000 Mc/sec and 1.3°K for zinc with magnetic field in sample plane and along a twofold axis.

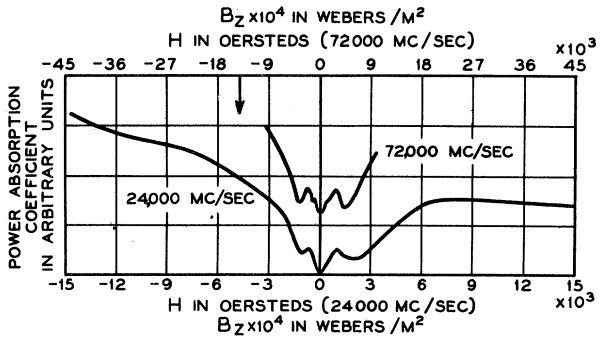

FIG. 3. Cyclotron resonance observations at 72 000 Mc/sec and 24 000 Mc/sec at 1.3°K on zinc with magnetic field normal to sample plane and along a sixfold axis. Field scales are adjusted so that cyclotron fields for both curves are on the same vertical line. The cyclotron field deduced from the data in Fig. 1 is shown by an arrow. Electrons resonate on the negative-field side of the figure, holes on the positive-field side.

were unable to detect a signal from the very-low-mass carrier apparent from the de Haas-van Alphen data,[6] but a signal is observed in the higher field region. The signal here fits fairly well the behavior of $R(H)/R(0)$ derived from the formula given by Azbel' and Kaner for $Z(H)/Z(0)$ using a mass of $0.43m_0 \pm 10\%$, an $\omega\tau$ of about 10, and a phase of $e^{i\pi/3}$ in $Z(0)$; it will be noted that the phase in $Z(0)$ is different for this curve than for that in Fig. 1. Here again as in Fig. 1, and presumably for the same reasons, the fit to the theoretical curve is not perfect, and in particular the curve has an extra bump in the field range between 7 and 11 kilogauss. The signal in Fig. 2 did not change drastically until the field was rotated more than 5 degrees out of the plane of the sample.

Figure 3 shows data taken at both experimental frequencies with the magnetic field normal to the sample plane and along a sixfold axis. Caution must be used in interpreting these data because they are observed under anomalous skin effect conditions and no theory of the shape of the curve is now available, but they are important because they are a basis for distinguishing effects due to holes from those due to electrons. Furthermore, they do correspond broadly to what might be expected from the data in Fig. 1, which is taken with the magnetic field along the same crystal direction, i.e., low-field structure from a very-low-mass carrier and broad variations at higher fields from the higher-mass carrier. There are indications from the differences in behavior for magnetic fields of the two signs that the carrier with mass $0.55m_0$ (as determined from the data in Fig. 1) is an electron.

Figure 4 shows data taken at both experimental frequencies with the magnetic field normal to the sample plane and along a twofold axis. Here again, anomalous skin effect conditions prevail, but two comments may be made. First, the unresolved structure at low fields indicates the presence of a very-low-mass carrier, presumably the one observed in de Haas-van Alphen experiments.[6] Second, on the negative field side the curve indicates that as the field increases the surface impedance is almost independent of

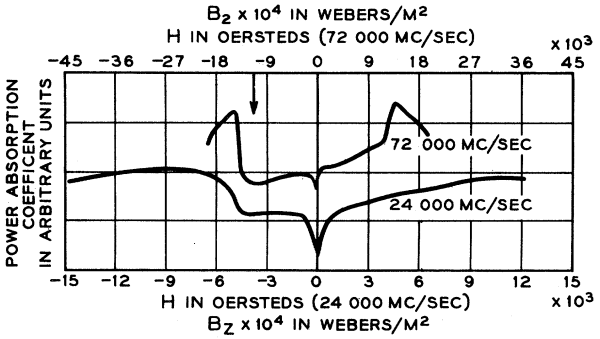

FIG. 4. Cyclotron resonance observations at 72 000 Mc/sec and 24 000 Mc/sec at 1.3°K on zinc with magnetic field normal to sample surface and along a twofold axis. Field scales are adjusted so that cyclotron fields for both curves are on the same vertical line. The cyclotron field deduced from the data in Fig. 2 is shown by an arrow. Electrons resonate on the negative-field side of the figure, holes on the positive-field side.

field until after the resonance of the high-mass carrier shown by the data in Fig. 2 is passed. It seems likely that this lack of change is a result of anomalous skin effect conditions, and that the sharp rise observed at a field just above the resonance represents at least partial emergence from the anomalous skin effect region.[7] This occurs for the sign of field corresponding to electron resonance, and indicates that the carrier of mass $0.43m_0$ observed in Fig. 2 is an electron.

We wish to thank B. B. Cetlin for help in sample preparation, W. H. Richards for growing zinc crystals, and D. F. Gibbons for a residual resistance measurement.

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DIRECT OBSERVATION OF ANTIPARALLEL DOMAINS DURING POLARIZATION REVERSAL IN SINGLE-CRYSTAL BARIUM TITANATE

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(Received March 13, 1959)

This communication describes a new and better method than others previously reported for the continuous, direct observation of the antiparallel ferroelectric domain structure in $BaTiO_3$ during polarization reversal. This method has been applied to both liquid- and metal-electroded crystals and some of the more interesting results concerning domain growth and domain-wall motion in metal-electroded crystals are given.

The study of the domain dynamics of polarization reversal in c-domain $BaTiO_3$ crystal plates has been rather severely hampered due to the difficulty experienced in trying to observe directly the antiparallel domains in question.[1] Under conditions where the applied electric field is either parallel or antiparallel to the spontaneous polarization in $BaTiO_3$, it has generally been considered that domains of opposite polarization cannot be discerned by direct optical observation. Several investigators[2-4] have observed directly the antiparallel domain configuration during polarization reversal; however, in each case it was necessary to subject the $BaTiO_3$ samples to a "perturbing" electric field applied in a direction normal to the spontaneous polarization. This field rotates the optic axes of the antiparallel domains by small amounts, in opposite directions, so that with the appropriate experimental arrangement, one can discern the antiparallel domain structure. Some of the experimental results of these investigations seem to be in conflict with other work in which the perturbing electric field was omitted. However, it is difficult to interpret some of the results obtained by direct observation, as mentioned above, in terms of polarization reversal in the usual sense where the only applied field is one parallel to the ferroelectric axis.

Two other methods which have frequently been employed to observe a stationary antiparallel domain pattern in $BaTiO_3$ are the acid etch technique[5] and the electrostatically charged powder technique.[6] Unfortunately, although very valuable, these latter two techniques are not suitable for a continuous direct observation of the antiparallel domain configuration during polarization reversal. The ideal method for the study of domain dynamics is, of course, one in which the field is applied parallel to the ferroelectric axis and the domain configuration observed continuously through transparent, or semitransparent, electrodes. The authors have found that this is indeed possible.

In the course of experiments on the electric field dependence of 180° domain-wall velocity in $BaTiO_3$, it was noted that occasionally one could differentiate antiparallel domains without recourse to any of the aforementioned techniques. That is, portions of the antiparallel domain configuration of liquid-electroded samples[7] which were partially reversed with fields of the order of a thousand volts per centimeter and then washed in water to remove the electrolyte, were sometimes visible when the sample was mounted