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MAGNETIC FOCUSING OF ELECTRONS IN COPPER SINGLE CRYSTALS

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Abstract.- Magnetic focusing of electrons in metal single crystals can be studied by injecting and detecting electrons via point-contacts. Experiments performed on copper single crystals show clearly internal reflections at the surface. The observed reluctance of the detected voltage to respond to changes in the injected current can be understood on the basis of inductive effects and explains the failure of attempted AC measurements.

In recent years it has been demonstrated that it is possible to observe magnetic focusing of electrons inside single crystals of metals and semi-metals by means of point-contacts $1/4$. One point-contact ("the emitter, $E$") is used to inject electrons into the metal crystal with energies slightly above the Fermi-level. At a second point-contact ("the collector, $C$") located at a distance $d$ from the emitter, shorter than the mean free path $\langle \bar{\ell} \rangle$ of the charge carriers - a voltage can be registered when the injected electrons are focused onto it.

Electrons can be focused either longitudinally or transversally. In the first case $1,2/$ the emitter and the collector are placed on opposite sides of a thin slab of the metal crystal and the connecting line $E-C$ between them is parallel with the magnetic field. In the transversal focusing $3,4/$ experiments the contacts are on the same face of a single crystal and the magnetic field is perpendicular to the connecting line $E-C$. Electrons are injected by the emitter in all directions. Yet there are two reasons why focusing nevertheless takes place. The number of electrons entering the crystal under an angle $\theta$ with respect to the normal on the crystal face is proportional to $\cos \theta$. Thus most electrons moving in the plane through $E$ and $C$ and perpendicular to the magnetic field enter the crystal in a direction perpendicular to the surface.

Secondly electrons entering the crystal under small $\theta$ angles will all be focused on practically the same spot by the magnetic field. No electron-whatsoever its $\theta$ value is- can reach the crystal surface beyond this area of high electron density. This results in an asymmetric peak-shape with the steeper edge on the high field side of the peak. If an electron or hole collides with a crystal boundary it can be specularly reflected to a degree dependent on the quality of the crystal surface. In transversal focusing experiments signals are therefore registered not only in a magnetic field which focuses electrons directly from the emitter to the collector, but also in field-strengths which are integral multiples of the direct focusing field. We now report details about transverse focusing experiments in copper.

Point-contacts were made using copper wires (cross section $10^{-5}$ m) which were electrolytically sharpened. The $(110)$ face of the crystal was chemically polished. The resistances of the point-contacts were generally between 0.25 and 10 ohm. Emitter-currents were between 50 and 150 mA. Such high current densities didn't visibly affect the quality of the point-contacts. A representative spectrum is shown in figure 1. The distance between emitter and collector was about $9 \times 10^{-5}$ m. In the spectrum of figure 1 the direct focusing and three reflections can be seen. For this orientation of the crystal and contacts with respect to the magnetic field $(B/||11\bar{1}||)\) contacts on $(110)$, $E-C(B)$ the electrons can move over both neck and belly orbits but only the belly orbits could be observed.

In such a magnetic field that focusing from emitter to collector takes place, the travelling time of an electron from emitter to collector is...
extremely short ($\approx 10^{-10}$ s.).

Fig. 1: Focusing of electrons in a single crystal of copper. The small peak at about -1.6 kGauss possibly represents a hole orbit (T=4.2 K).

It would be anticipated that any change in current through the emitter would result in an instantaneous response at the collector. However, experiments show that there is a delay of about 30 seconds before the response on a change in the emitter-current is completed (see figure 2a).

Our experiments indicate that the time-constant is independent of the size of the crystal but that smaller distances between emitter and collector lead to shorter response times. In contrast with this slow response the underlying background signal is extremely fast (figure 2b). The background signal possibly has the nature of a Hall potential.

Also when the direction of the magnetic field is reversed a response to changes in the emitter-current (figure 2c). This change in the signal during the change in the emitter-current and the subsequent slow decay to the original background level reflects the rearrangement of currents in the crystal when the emitter doesn't inject enough electrons any more to feed the existing current loops. The slowness of the response make AC-measurements of AC-modulated DC-measurements impossible for the copper system. The reason for this strikingly slow response is most likely the inductive time constant, $\tau_I$, of the current loops in the crystal. The extremely low resistance of the pure copper crystal can lead to high L/R values. A similar time-constant has been observed for the decay of eddy currents in metals of comparable purity /5/. Samples with higher specific resistances such as bismuth have been studied successfully with AC-techniques /6/.

References