Effect of Oxygen on the Magnetoresistance of Copper

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To determine the influence of physical and/or chemical impurities on the high field magnetoresistance of copper, measurements were made of the effect on specimen properties of work hardening and the presence of O_2 in the atmosphere used for annealing. A Kohler plot of the transverse magnetoresistance for all specimens gave a single smooth curve. The plot for the longitudinal magnetoresistance of any one specimen as the concentration of defects was increased between successive measurements, also gave a smooth curve. However, the saturation value of the longitudinal magnetoresistance was markedly affected by annealing in an atmosphere containing O_2. The zero field ratio of transverse to longitudinal magnetoresistance was found to be quite insensitive to work hardening and the presence of O_2 in the annealing atmosphere.

PREVIOUS measurement[1] of the magnetoresistance of polycrystalline copper specimens gave various saturation values for the longitudinal magnetoresistance even though the transverse magnetoresistance of the same specimens obeyed Kohler's rule. To determine the extent to which physical and/or chemical impurities might influence the saturation value of the longitudinal magnetoresistance, a study has been made of the effect on specimen properties of work hardening and the presence of O_2 in the atmosphere used for annealing.

Recently it has been shown that the presence of oxygen in the annealing atmosphere will decrease the residual resistivity of copper.[2] The oxygen absorbed into the copper is not only effective in neutralizing certain existing impurities. but when present in excess contributes new scattering centers so that the residual conductivity passes through a maximum as the specimens are annealed in atmospheres containing progressively larger concentrations of O_2.[3] To determine the influence of this absorbed oxygen on magnetoresistance, specimens were prepared throughout the range of the conductivity maximum and the magnetoresistance of each specimen was measured. Finally, the influence of physical defects was determined by progressively work hardening (bending) the specimens between subsequent measurements of the magnetoresistance.

As might be expected,[4] a Kohler plot of the transverse magnetoresistance for all specimens gave a single smooth curve. However, as shown in Fig. 1, the longitudinal magnetoresistance is affected markedly by the presence of O_2 in the annealing atmosphere.

The saturation value of longitudinal magnetoresistance increases from $\Delta R/R\sim 1$ for specimens annealed at very low oxygen concentrations (Curve I) to $\Delta R/R\sim 2$ for specimens annealed to produce the conductivity maximum (Curve III). Intermediate values (Curves II) occur only during the transition from Curve I to Curve III. It is significant that excessive concentrations of O_2 in the annealing atmosphere do not cause the saturation value of the longitudinal magnetoresistance to rise above $\Delta R/R\sim 2$. The data of Curve III includes samples doped with O_2 to beyond the conductivity maximum and showing degradation of the low-temperature conductivity by as much as a factor or two. Work hardening of the specimens has little effect on the saturation value. Curves I and III contain data on specimens worked sufficiently to change the zero field residual conductivity by as much as that induced by the absorption of oxygen producing the separation of the curves.

All specimens displayed a linear relationship be-

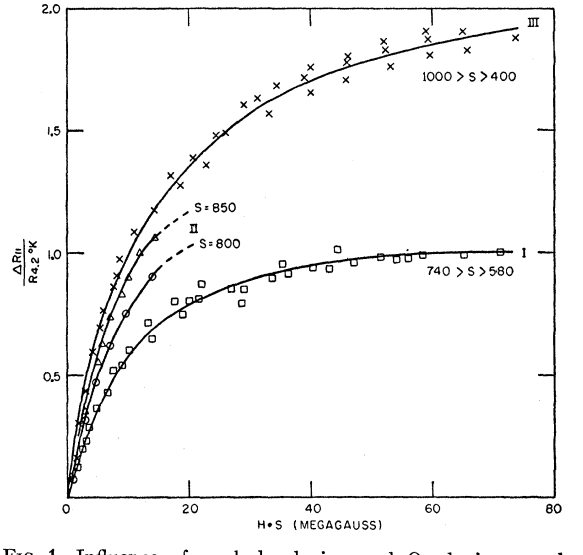

FIG. 1. Influence of work hardening and O_2 doping on the longitudinal magnetoresistance (ΔR_{11}) of polycrystalline samples. The resistance ratio $S=R_{273°K}/R_{4.2°K}$ is given as an index of the low-temperature resistivity. Curve I contains data from three specimens prepared at very low oxygen concentrations with subsequent work hardening to reduce S over the range 740–580. Curves II are for two samples prepared with increasing O_2 doping, but insufficient to produce the conductivity maximum. Curve III contains data from samples prepared at O_2 dopings yielding specimens at and beyond the conductivity maximum with subsequent work hardening to reduce S over the range 1000–400.

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tween the applied field ($H\cdot S$) and the ratio of the transverse magnetoresistance to the longitudinal magnetoresistance ($\Delta R\perp/\Delta R_{11}$). In this relationship $\Delta R\perp/\Delta R_{11}=A+B(H\cdot S)$, changes in O_2 doping and work hardening had little effect on the zero field intercept A which remained relatively constant about $\Delta R\perp/\Delta R_{11}\sim 2$. The slope ($B$) is also independent of work hardening, but decreases with O_2 doping and reaches a minimum value for the conditions of Curve III. This decrease can be inferred from Fig. 1, since the Kohler plot of the transverse magnetoresistance is the same for all samples.

Thus, the longitudinal magnetoresistance of copper, as well as the low-temperature conductivity, is sensitive to the presence of impurity induced effects and due regard for their possible presence must be given in any interpretation of data. For polycrystalline copper, the saturation value of the longitudinal magnetoresistance for the pure metal appears to lie between $1>\Delta R_{11}/R_{4.2°K}>0$.

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Cascade Capture of Electrons in Solids

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Enormous capture cross sections in the range 10^{-15} cm^2 to 10^{-12} cm^2 have been observed for a wide variety of Coulomb attractive centers in Si and Ge, some involving binding energies many times the Debye energy. Whereas multiphonon transitions to the ground state yield cross sections five to ten orders of magnitude too small, capture into excited states of large radius followed by a cascade of one-phonon transitions leads to cross sections of the right order of magnitude. The initial capturing event is likely to involve an optical phonon or an intervalley collision in the room temperature range, but the acoustic phonon contribution will predominate at low temperatures.

Subsequent collisions may eject the electron or cause it to increase its binding energy. The "sticking probability," or probability of eventual capture into the ground state, becomes significant for binding energies of order kT. As the temperature is reduced capture into orbits of larger radius becomes effective, and, at least for the acoustic phonon case the cross section increases rapidly with decreasing temperature, and with decreasing electron energy. The large cross sections 10^{-17} cm^2 to 10^{-15} cm^2 found for neutral centers can be explained on a similar basis, the attractive potential in this case being provided by the large polarizability of the neutral center.

1. INTRODUCTION[1]

Traps and Recombination Centers

THE pioneer work of Shockley and Read[2] and Hall[3] suggested that the recombination of electrons and holes in solids could best be understood in terms of the successive capture of an electron and hole at a localized site ("recombination center") in the crystal. Indeed Burton, Hall, Morin, and Severiens[4] showed that Cu and Ni impurities in germanium behaved as recombination centers at room temperature, whereas Shulman and Wyluda[5] showed that at lower temperatures Cu behaves as a trap.

The distinction between a trap and a recombination center is therefore a quantitative rather than a qualitative one. For the sake of definiteness we shall adopt the following picture: A minority carrier is captured at a center. If the carrier lives a mean lifetime in the captured state and is ejected (e.g., thermally), we may regard the center as a trap. If, however, before thermal ejection can occur, a majority carrier is trapped, recombination will have taken place, and the center may be regarded as a recombination center. Which role a center will play depends then on the concentration of majority carriers and on the relative cross section for capture of minority and majority carriers.

Perhaps the simplest picture to adopt is as follows: Centers that are singly charged and attractive to minority carriers are likely to act as recombination centers since the cross section for the subsequent neutral capture of a majority carrier may only be one order of magnitude lower than the minority carrier cross section, but the number of majority carriers may be sufficiently large that recombination will occur before ejection. Centers that are doubly charged and attractive to minority carriers are likely to act as traps. They will possess a large cross section for the minority carrier, but after capture will be repulsive to the majority carrier. The repulsion can reduce the cross section by many orders of magnitude so that ejection of the trapped minority carrier will be much more likely than recombination.

[1] A detailed summary of the results contained in this paper was presented by M. Lax at the *Proceedings of the International Conference on Semiconductors, Rochester, 1958* [J. Phys. Chem. Solids **8**, 66 (1959)]. Our choice of mechanism and partial results were presented to the American Physical Society: M. Lax, Bull. Am. Phys. Soc. **1**, 128 (1956); **2**, 147 (1957).
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