# ELECTRICAL RESISTIVITY MINIMUM OF IRON, COPPER, LUTECIUM AND THULIUM FILMS FORMED BY LOW TEMPERATURE CONDENSATION

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The temperature dependence of electrical resistivity is studied in Fe, Cu, Lu, and Tu films formed by metal vapor deposition on a backing cooled by liquid helium. In all freshly condensed films an electrical resistivity minimum is observed in the region 4°–25°K. The temperature at the minimum depends on the thickness of the film and the anneal temperature. High temperature anneals usually cause the disappearance of the resistance minimum in the thickest films. It is suggested that a new characteristic of conduction electron scattering is present in highly distorted metal lattices.

THE temperature dependence of the electrical resistivity of many metals exhibits a minimum point at low temperatures.[1-3] This effect has been attributed to the scattering of conduction electrons on local magnetic moments formed by small impurities.[4-6]

In the present work we have observed an electrical resistance minimum in iron, copper, lutecium, and thulium films formed by high-vacuum metal vapor condensation on a glass backing cooled by liquid helium. The first results of our investigation of lutecium have been reported in[7]. The technique used to produce the films has been described in[8-10]. We took additional precautions against contamination of the condensed films. As a preliminary step the first portion of the metal was evaporated without exposing the surface of the backing. The thickness of the metal film was determined from its electrical resistance in an annealed state.

We investigated the temperature dependence of electrical resistance in condensed metal films of different thicknesses in the temperature range from ~30° to ~1.5°K, both immediately following their condensation and after annealing at different temperatures. The maximum anneal temperature was ~650°K.

Freshly condensed films of the given metals, of different thicknesses, exhibit a minimum point of the electrical resistance, while bulk samples of the same metals have no minimum point down to ~1.5°K.

In iron, thulium, and lutecium the temperature at the minimum depends on the film thickness and on the anneal temperature following condensation. A lowering of the temperature at the minimum accompanies higher anneal temperatures, as is shown in Fig. 1 for an ~50-A iron film. Curves 1, 2, and 3 were plotted after annealing at 35°, 200°, and 600°K, respectively.

In copper no appreciable temperature shift of the minimum is observed after the anneal (Fig. 2). Curves 1 and 2 were plotted after annealing at ~30° and 650°K, respectively. The minimum is appreciably lowered by the annealing process.

The temperature at the minimum is lowered for thicker films of all the investigated metals in the freshly condensed state. Figure 3 shows the temperature dependence of $\Delta\rho = \rho - \rho_{\min}$ for two freshly con-

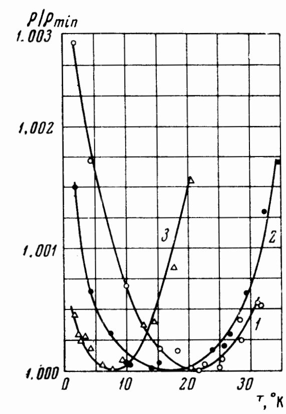


FIG. 1

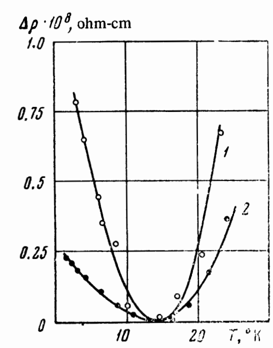


FIG. 2

FIG. 1. Temperature dependence of $\rho/\rho_{\min}$ for a ~ 50-Å iron film. ($\rho$ is the resistivity of the film; $\rho_{\min}$ is its resistivity at the temperature for the minimum.) Curve 1 was plotted following an anneal at 35°; curve 2, at 200°; curve 3, at 600°K.

FIG. 2. Minimum of the electrical resistivity ($\Delta\rho = \rho - \rho_{\min}$) for an ~ 900-Å thick copper film. Curve 1 was plotted following an anneal at 40°; curve 2, at 650°K.

densed copper films ~200 and ~3000 A thick (curves 1 and 2, respectively).

The considerable lowering of the minimum in thicker films and the absence of a minimum in the bulk metal led us to expect that the minimum would disappear in the thickest layers following an anneal. Indeed, in iron films thicker than 200 Å the minimum disappears after a high-temperature anneal; the anneal temperature required for this result increases with the film thickness. Curve 2 of Fig. 4 shows that the minimum disappears for an ~600-Å iron film that has been annealed at ~650°K. For thulium films ~8000 Å thick the resistance minimum disappears after an anneal at room temperature. For the thinnest films of the investigated metals a resistance minimum is still observed following anneals at the highest temperatures that were possible under the experimental conditions.

Unlike the cases of the other metals, all the very thick copper films (up to ~3500 Å) exhibited a minimum after an anneal at ~650°K. However, copper films con-

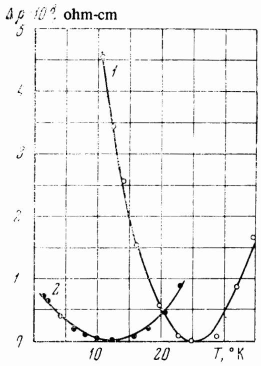


FIG. 3

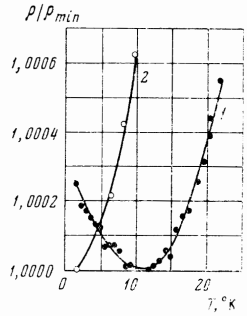


FIG. 4

FIG. 3. Temperature dependence of $\Delta\rho$ for copper films ~ 200 Å thick (curve 1) and 3000 Å thick (curve 2) annealed at ~ 35°K.

FIG. 4. Temperature dependence of $\rho/\rho_{min}$ for an ~ 600-Å iron film annealed at 1) ~ 25°, 2) 650°K.

densed on a glass backing heated to ~550°K in a vacuum of ~5 × $10^{-6}$ Torr do not exhibit a minimum.

The absence of a resistivity minimum in the bulk metal and in some annealed films shows that the presence of a minimum cannot result from impurities. Support for this conclusion is found in the fact that, for example, a magnetic field as high as 25 000 Oe does not affect the temperature at the minimum in lutecium.[6] However, for gold the minimum caused by an impurity has been found to vanish in a magnetic field of ~8 000 Oe.[11]

In control measurements metal films were formed by condensation on a glass backing that had been heated to remove adsorbed gas. No appreciable change was observed in the behavior of the electrical resistance minimum. We thus have evidence that gas adsorbed on the backing does not affect the minimum and cannot be the cause of its appearance. It is also evident that the minimum cannot be associated with noncompactness ("island" structure) of the film. This conclusion follows from the fact that the resistivity of an annealed metal film is identical with the resistivity of the bulk metal, and from electron microscope studies of metal films.

It should be noted that not all metal films formed by low temperature condensation exhibit a minimum point of their electrical resistivity. No minimum is observed even for extremely thin indium and aluminum films (i.e., under the most favorable conditions for the given effect).

The observed effects can be summarized as follows:

1. Some metals exhibit a minimum point of electrical resistivity in films formed by condensation on a cold backing, but not in their bulk state.
2. The minimum is observed at higher temperatures for thinner films.
3. The temperature at the minimum is usually lowered by an anneal; the extent of the decrease is enhanced in thicker films. High-temperature annealing leads to disappearance of the minimum point.
4. No minimum point is observed for films formed by condensation on a hot backing (~550°K in the case of copper).

The scattering of conduction electrons in a highly distorted metal lattice has therefore revealed a new characteristic consisting in the appearance of a minimum point of electrical resistivity for some metal films condensed under extreme nonequilibrium conditions.


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