occur on the outer spiral which may reflect the hexagonal BiMn structure. This is not a surface effect since the light is scattered from beneath any surface coating or disturbance due to polishing.

The light which is scattered perpendicularly from these surfaces appears to be elliptically polarized. We have had difficulty in measuring the amount of rotation and the degree of ellipticity due to the small width of the domains when observed down the c_0 axis. A small rotation of the mica plate in the Bausch and Lomb elliptical compensator will reverse the domain intensities observed.

The primary reason for the ease in observation of the domains is thought to be the high resistivity of BiMn, 424 micro-ohm cm, as reported by Kondo.[4] The lower number of conduction electrons would permit deeper penetration into the region of magnetization and thus permit a greater total rotation of the plane of polarization as has been observed in studies of thin-magnetic films.

We are indebted to Miss Jean Hurd for the metallographic preparation and pictures shown here.

[4] K. Kondo, J. Phys. Soc. Japan **5**, 307 (1950).

PHYSICAL REVIEW VOLUME 96, NUMBER 6 DECEMBER 15, 1954

Fermi Level in Amorphous Antimony Films

E. TAFT AND L. APKER
General Electric Research Laboratory, Schenectady, New York
(Received September 2, 1954)

Films of antimony were deposited by evaporation on interchangeable emitters in concentric-sphere, retarding-potential phototubes. Below thicknesses of about 300 A, they behaved as semiconductors. The Fermi level lay about 0.1 ev above the occupied band. They converted irreversibly to the normal crystalline metallic form at 200°C or somewhat higher. The results are consistent with previous measurements on the electrical resistance and optical transmission of thin antimony films; they indicate that the semiconducting form is amorphous. Analogies with the behavior of arsenic are mentioned.

AN amorphous form of antimony has been recognized for many years.[1] It is especially common in very thin evaporated films, and it is stable in this form considerably above room temperature. The electrical resistivity[2] and optical absorption[1] of this material indicate that it is a semiconductor.

The present paper supports this view and discusses a direct photoelectric determination of the Fermi level relative to the occupied band of electron energy states. The approach was identical with that used in previous work on amorphous arsenic.[3] Two separate concentric sphere phototubes were used. Results were duplicated with antimony films deposited on substrates of nickel and of crystalline Ge.

Figure 1 shows the current-voltage characteristics for the photoemission from films of antimony deposited on substrates held near room temperature. If the films were below about 300A in thickness, they showed a behavior quite typical of a semiconductor (curve 2). Above this thickness, they were clearly normal crystalline antimony, and showed the photoelectric behavior typical of this poor metal (curve 1).[4] Further, films about 50 a.u. in thickness underwent a transition from semiconducting to metallic behavior upon heating to 200°C or thereabouts for a few minutes.

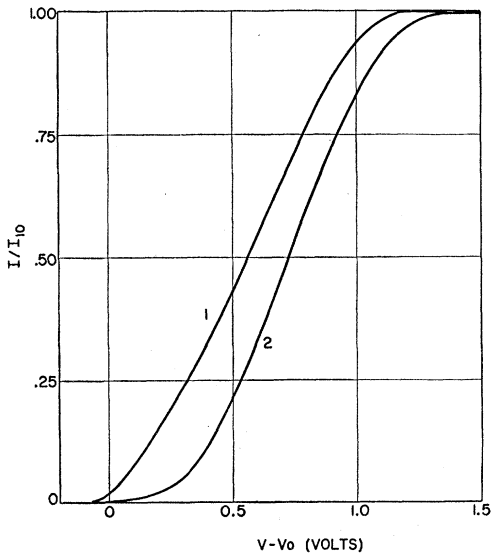

FIG. 1. Current-voltage characteristics for photoemission from antimony films in concentric-sphere phototube at $h\nu = 5.80$ ev. Currents are normalized at a collector potential $V = 10$ v. Abscissas are given relative to the 0°K stopping potential V_0 of an ideal metal, a voltage corresponding to the common Fermi level of all the interchangeable emitters. Curve 1 is for crystalline antimony; curve 2 is for the semiconducting amorphous variety.

[1] Hans Murman, Z. Physik **54**, 741 (1929); for discussions, see H. Krebs, *Semiconducting Materials*, H. K. Henisch, editor (Butterworths Scientific Publications, Ltd., London, 1950); F. S. Moss, *Photoconductivity in the Elements* (Academic Press, Inc., New York, 1952); an example of recent work is Julius Cohn, J. Appl. Phys. **25**, 798 (1954).
[2] R. Suhrmann and W. Berndt, Z. Physik **115**, 17 (1940).
[3] E. Taft and L. Apker, Phys. Rev. **75**, 1181 (1949).
[4] Apker, Taft, and Dickey, Phys. Rev. **76**, 270 (1949).

One concludes that the thin, semiconducting antimony films were behaving quite like the genuinely amorphous form of the element recognized by previous workers.[5] The data in Fig. 1 indicate that the Fermi level in this semiconductor lies above the occupied band of electron energy states by an amount of order 0.1 ev. This may be seen more clearly in Fig. 2, which shows the energy distributions of the photoelectrons from the amorphous as well as from the crystalline form of antimony. The amorphous variety displays the

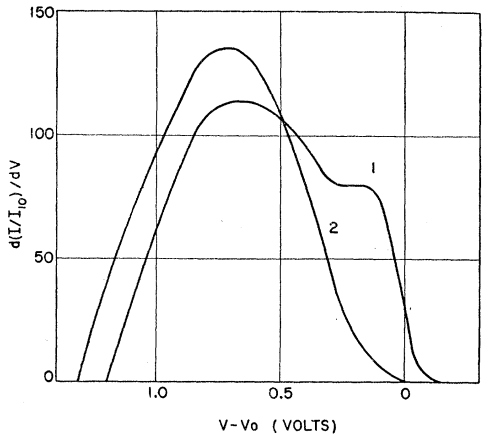

FIG. 2. Normalized energy distributions obtained by differentiation of curves in Fig. 1. Abscissa is reversed from Fig. 1 in order that energies increase toward the right. Note the sparsity of electrons originating just below the Fermi level in amorphous films (curve 2) and the plateau which appears in this region when the material is crystallized (curve 1).

pronounced sparsity of high-energy electrons expected from the energy structure mentioned above.

The Fermi level determination given here is consistent with observations in the literature on resistivity and optical properties.

Independent evidence for these views appears in the spectral distributions of the photoelectric yield as shown in Fig. 3. Although the saturation points on the current-voltage characteristics of Fig. 1 show that the work

[5] J. A. Prins, Nature **131**, 760 (1933).

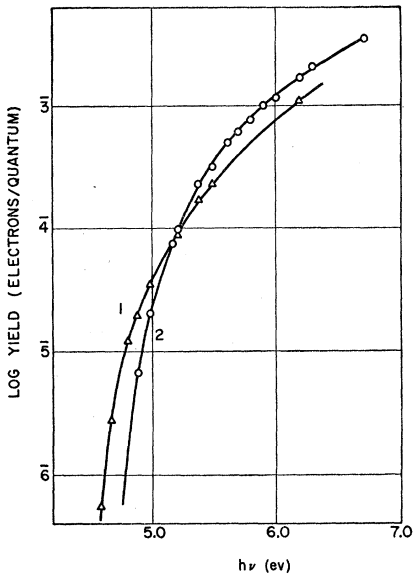

FIG. 3. Spectral distribution of the photoelectric yield from antimony films. Note higher threshold for amorphous material even though the work function determined from saturation point in Fig. 1 is lower than for crystalline film.

function of amorphous antimony is lower than that of the crystalline material (4.49 ev *vs* 4.60), the photoelectric threshold of the amorphous form is higher—a behavior consistent with a scarcity of occupied energy states just below the Fermi level.

Amorphous antimony is similar to amorphous arsenic, except that the forbidden energy zone is smaller in the former, as one would expect. Crystallization of these materials gives rise to a characteristic structure in the energy distribution of the photoelectrons and in the deduced energy level spectrum of the solid.[3,4] Levels lying 1 ev or thereabouts below the Fermi level are not much affected in density. Between the edge of the occupied band of the semiconductor and the Fermi level, however, a relatively low but clearly discernable group of occupied energy levels appears on crystallization. It is this group, of course, which is responsible for the characteristic poorly metallic behavior of these crystals.