Some Like 'em HOT

A brief account of some new developments reported at a symposium on the subject of hot electrons in thin films

By ***R. Smoluchowski***

THE ordeal of attending meetings and conferences four or more days long, packed with the "confetti" of several parallel sessions of contributed or invited papers and other ceremonial or not-so-ceremonial sessions, has prompted the search for other solutions. One of the most welcome developments in this search is the growing number of *one-day* symposia organized for a limited audience interested in specialized subject matter. While these occasions do not in any way substitute for the more formidable events, they give at least an opportunity for the assembled fraternity to talk shop down to the minutest experimental or theoretical details. Even the excellent *Physical Review Letters* do not substitute for the attractiveness of a sizzling bit of information fresh from the laboratory, a scratch pad, or a computer.

As one of a series of such symposia, the Philco Scientific Laboratory, which is located outside of Philadelphia, organized, on February 28th, a Symposium on "Hot Electrons in Thin Films". This subject is "hot" in more ways than one: first, the behavior of electrons of energy considerably higher than the Fermi energy is of great theoretical interest and involves the use of some of the most sophisticated theoretical tools; second, the field has just been opened by experimentalists giving some very interesting results; and thirdly, there is a pious, or impious, hope among some industrial physicists that a "hot" device of dazzling amplificatory or energy-converting properties may be developed in this way.

The meeting was opened by Donald G. Fink, director of the Philco Scientific Laboratory, and it was co-chaired by Carlo V. Bocciarelli and Joseph R. Feldmeier, associate directors of the Laboratory. After a minimum of introductory preliminaria the first paper (entitled "A Review of Recent Investigations") was given by Pierre Aigrain of the Ecole Normale Supérieure in Paris. With his customary Gallic clarity and eloquence Prof. Aigrain described how hot electrons can be produced by high electric fields, a technique which is naturally limited to nonmetals, or by injection of electrons by tunneling through an insulating layer, or finally by an internal photoelectric effect. The hot electrons can either emerge into vacuum by crossing the surface barrier or they are sorted out by crossing a similar potential barrier between a metal and a semiconductor. While in principle all these methods are simple, in practice many spurious effects such as secondary emission caused by localized surface potential differences, film defects, etc., complicate the measurements and their interpretation considerably. Prof. Aigrain gave also a brief derivation of the electron distribution function which can be obtained under certain simplifying assumptions. Gold, the metal most frequently used in these investigations, has obvious experimental advantages but it has the drawback that the conducting $6s$ band overlaps the dense $5d$ band, and thus the scattering cross section of electrons may depend upon their interaction with electrons

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in both bands. Aigrain pointed out that if the insulating layer through which the electrons have to tunnel has local thin areas, then the adjoining gold layer becomes overheated and evaporates preferentially. This may lead to a considerable overestimation of the range of hot electrons in metals, a quantity which is of paramount experimental and theoretical interest.

John Quinn of the RCA Laboratories and the University of Pennsylvania undertook the formidable task of leading the predominantly experimentally inclined audience into the never-never land of calculating the "Range of Excited Electron in Metals" using all the tricks and diagrams of the many-body technique. In particular, he considered an electron in metal, excited to an energy above the Fermi energy, and the problem of calculating its range—that is, the distance before it loses an appreciable fraction of its energy. Specifically, it is assumed that even one collison lowers the energy of the electron to such an extent that the chances of its emerging from the metal are essentially nil. It is thus necessary to calculate the probability that a state of a given initial energy decays in a certain time to a particularly lower energy. This is done for a somewhat unrealistic model of a high-density degenerate gas, taking into account individual collisions as well as creation of plasmons. The general characteristics of the energy dependence of the range will be, however, quite similar to those of real metals. It appears that the range depends very strongly on the initial energy and it drops from several hundreds of atomic spacings for small excitations (i.e., close to the Fermi energy) down to 10 to 20 atomic spacings for excitations of the order of several volts. The results are in very good agreement with experiments made on gold and aluminum.

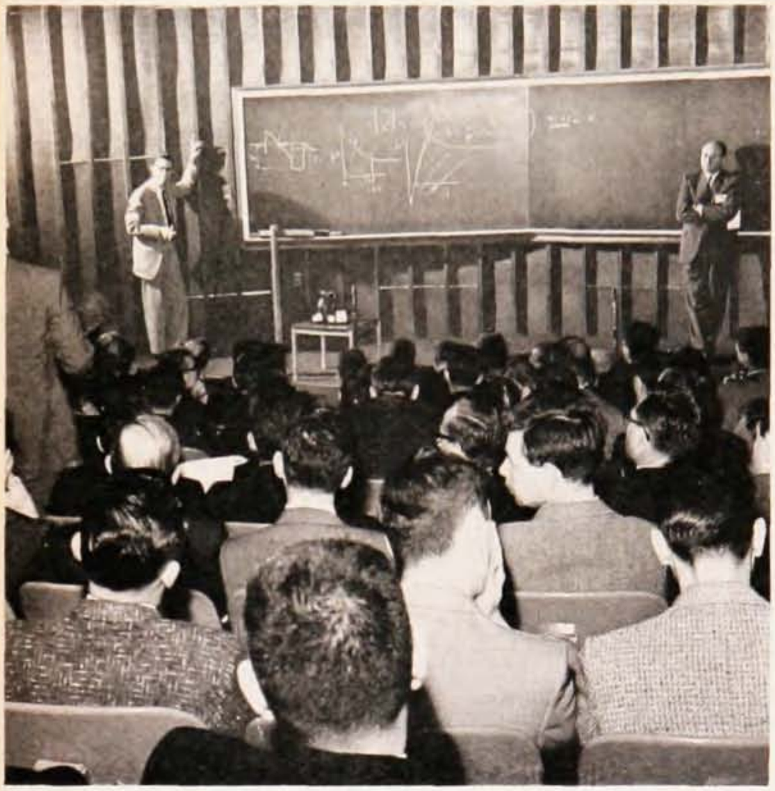
A set of very elegant experiments on "not so hot" electrons made by W. G. Spitzer and C. R. Crowell of the Bell Telephone Laboratories was described by the first author in a paper entitled "Electron Attenuation Length in Metals". The author pointed out that photoelectrons can emerge from a metal only if their excitation exceeds the work function which is of the order of several volts. On the other hand, they need to be excited only to 0.5 or 0.8 ev above the Fermi energy in order to cross into an appropriate semiconductor. The photoelectric response of such a metal (Au, Ag, Cu, Pd) and semiconductor (n-type silicon) sandwich is controlled by the absorption length of the photons and by the electron range. Particularly good results are obtained in that wavelength range where the absorption is approximately constant. Considerable difficulty was caused by various surface contaminations of the less noble metals. For an excitation energy of 1 ev the attenuation lengths for Au, Ag, Pd, and Cu are 740, 440, 170, and about 145A respectively. It is somewhat surprising that these experimental values, which are actually average displacements in a kind of ballistic random walk, are so close to the theoretical


Pierre R. Aigrain


Gerald Lucovsky


John J. Quinn


William G. Spitzer



Comment from the audience. The lecturer is Carver A. Mead and the chairman, J. R. Feldmeier.

range calculated along the path of the electron in the previous paper.

C. A. Mead of the California Institute of Technology, in a paper entitled "Tunnel Emission", described the most recent in his series of experiments in which a layer of beryllium is covered with a thin layer of silicon monoxide, which in turn is covered with gold. The electrons from Be tunnel through SiO into Au and escape into the vacuum. A voltage applied between the two metals controls the rate of tunneling. The voltage necessary to obtain a given tunnel current at liquid-nitrogen temperature is about four times as high as at 500°K. Since the work functions themselves are essentially independent of temperature it seems that other phenomena must play a role. The possibility of ionic effects in the insulator, which can be anodized, was mentioned. Another possibility is the occurrence of a Schottky thermionic emission which, according to some authors, is responsible for nearly all the observed current at temperatures higher than about 200°K. Prof. Mead spent considerable time discussing the various experimental difficulties and pitfalls and called for great caution in attempting to interpret experimental data on the basis of too idealized models.

A series of elegant experiments on "Photoelectric Effects in Thin Films", in particular on metal-oxide-metal sandwiches, was described by G. Lucovsky of the host institution. A relationship was shown to exist between the dark current-voltage characteristic and the open circuit photovoltage. Also, the photovoltage and photocurrent were found to be polarity sensitive with respect to the direction of the incident light. The independence of the current-voltage characteristic on temperature indicated an absence of a Schottky emission. The possibility of a Fröhlich-type dielectric breakdown at high temperatures was discussed. Another interesting effect seems to be the evidence for a diffusion of metallic ions from the metal into oxide. The smaller the atomic radius the lower the resistance. It was pointed out that there is a possibility of using the photo-emissive effect in a solar-energy converter.

The final paper, "Active Devices—Recent Experimental Results", by James P. Spratt and Ruth F. Schwarz, also of the Philco Scientific Laboratory, was presented by the first author. He showed that the present experimental evidence indicates the feasibility of hot-electron solid-state devices. The structure is similar to that used by Mead, with best results obtained with aluminum rather than gold. An additional effect occurs when the metallic emitter layer gets in direct contact with the semiconducting collector. The voltage existing between the base and the emitter creates very high fields at the edge of the oxide layer. These "edge effects" lead to field emission which depends upon various geometrical factors. Here, as in all other experiments, much difficulty arises from film imperfections and other technical problems.

The general impression of the symposium is that while both theory and experiment leave much to be desired, or rather much to be done, certain important strides, both in the direction of an understanding of the behavior of hot electrons and in the direction of constructing a perhaps useful device, have been made. The most obvious outstanding problems seem to be the extension of the present theory to cases where the various simplifying assumptions are not valid and to the calculation of time-dependent distribution functions of initially hot electrons. On the experimental side, the most perplexing difficulties seem to arise from the many secondary effects such as Schottky emission, secondary emission, ionic motion in the insulator, film imperfection, etc. Unraveling of these problems will be an interesting though arduous undertaking.

A word of praise is due to the host laboratory for a very expert organization and smooth operation of the symposium. In spite of leisurely discussion periods, the guests were able to leave in plenty of time to dodge the five o'clock traffic and some even reached their homes the same day.