Photoconduction in Anodic Ta_2O_5

L. APKER AND E. A. TAFT
General Electric Research Laboratory, Schenectady, New York

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Interference phenomena in films of anodic Ta_2O_5 show that fundamental optical absorption occurs for $h\nu > 4.6$ ev. The resultant photoconduction between electrolyte and tantalum substrate shows a quantum yield near 0.5 when the field in the film is of order 10^7 volts/cm.

WE have observed photoconduction in thin films of Ta_2O_5 formed by anodizing Ta metal sheet in the well-known manner.[1] The electrolyte was 0.1 normal citric acid buffered to *p*H5 with sodium citrate, a solution transparent in the ultraviolet to $h\nu \sim 5$ ev. Thus radiation penetrated the liquid to the oxidized Ta plate. The film thickness was roughly 15A per volt of forming potential applied between the Ta and a Pt cathode,[2] the field in the Ta_2O_5 film being of order 10^7 volts/cm.

Figure 1 shows the behavior of the photoconduction at $h\nu = 4.89$ ev with incident radiation fluxes near 10^{14} quanta/sec. As indicated by the solid curve, photocurrents increased with increasing forming potential up to ~10 volts (and hence with increasing film thickness up to ~150A). The full forming potential was applied during these photoconduction measurements. Above 10 volts, the photoconductive yield remained practically constant near 0.5 electron/incident quantum. At a fixed film thickness (and hence, in the range below a fixed forming potential), the photoconduction was proportional to the applied voltage as shown by dashed lines of Fig. 1.

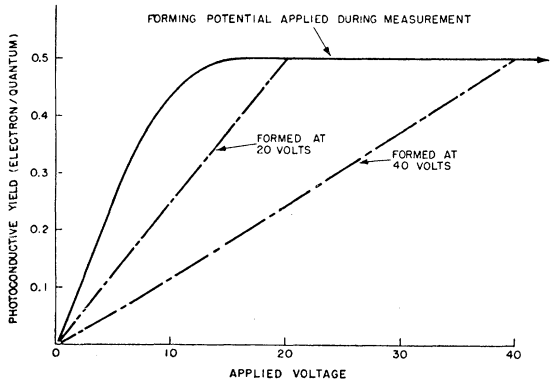

FIG. 1. General behavior of photoconduction in anodic Ta_2O_5 film with radiation levels near 10^{14} quanta/sec cm^2 at $h\nu = 4.89$ ev. With full forming potentials applied, data follow solid line; experimental deviations were of order 20 percent. Data in range below two typical fixed forming potentials are dashed; deviations from these lines were less serious. Hysteresis at very low voltage is ignored.

(At very small voltages deviations appeared. Small but measurable currents could still be drawn at zero applied voltage. In fact, a retarding voltage (Ta−, Pt+) of ~1 volt was necessary to stop the photoconduction. The same was true for a very small leakage current driven by chemical action. Some hysteresis was evident in this region.)

This relatively efficient photoconduction was observed only for photon energies $> h\nu \sim 4.6$ ev. Measurements of the reflecting power of anodic Ta_2O_5 films of various thicknesses on bright Ta substrates showed that interference effects typical of a transparent film were prominent for $h\nu < 4.6$ ev. These abruptly ceased at 4.6 ev. Beyond this point, the reflecting power exhibited only the slow variation typical of first-surface reflection from an opaque film. One concludes that the fundamental absorption edge of anodic Ta_2O_5 is close to 4.6 ev and that this absorption is responsible for the observed photoconduction. Further, the absorption constant for $h\nu > 4.6$ ev exceeds 10^5 cm^{-1}. At $h\nu = 4.89$ ev, most of the radiation that enters a film thicker than about 150A is absorbed. Thus, the absorption and the photoconductive quantum yield does not change with forming voltage above 10 volts. Below this value, the film is too thin to absorb all of the entering radiation, and the photoconduction decreases with decreasing forming voltage.

The small photocurrent drawn at zero applied voltage may be classed as a kind of photovoltaic or Becquerel effect. We may safely assume that there is a gradient in chemical composition as we progress from Ta to electrolyte in the Ta_2O_5 film.[3] The oxide should become less *n*-type (or more *p*-type) in this same direction. An electrostatic field is thus present, and the energy of an electron at the bottom of the conduction band increases from the Ta side to the electrolyte side of the film. Charges freed by the absorption of light will thus migrate even when no voltage is applied externally, and a photocurrent results. This current will only be stopped when an external voltage is applied in the retarding direction and is sufficient to level the bottom of the

[1] A. Guntherschulze and H. Betz, *Electrolytic Condensers* (M. Krayn, Berlin, 1947).
[2] D. A. Vermilyea, private communication. The value given in reference 1 is apparently too small.
[3] H. E. Haring, J. Electrochem. Soc. **99**, 30 (1952) and references cited there.

conduction band. This naive model neglects, of course, such possibly important influences as electronic work functions and other surface properties at the interfaces. Nevertheless, it is useful in correlating some of the main features of the film behavior.

The linear variation of photocurrent with voltage below the forming potential is of interest, particularly since the leakage current is very nonlinear. The situation appears somewhat similar to that in thin semiconductor films in vacuum.[4]

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Multiple Scattering of Fast Protons in Photographic Emulsions*†

MARTIN J. BERGER‡
Department of Physics and Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
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Measurements have been made of the multiple Coulomb scattering of protons with energies of 337±1 Mev and 218±2 Mev in Ilford G-5 emulsions. A total of 261 tracks with a combined length of 130.4 cm were analyzed by the determination of the lateral multiple scattering deflections according to the "coordinate method." The results are summarized in terms of the customary scattering factors which, for a given cell length, indicate the proportionality of the average multiple scattering deflection to the quantity "charge/momentum×velocity" of the scattered particle. Scattering factors are given for cell lengths of 250, 500, 750, and 1000 microns. These results are compared with the predictions of various theories of multiple scattering, including those of Moliere, Snyder, and Scott, as well as a proposed extension of the theory of Goudsmit and Saunderson, which has the advantage of being directly and conveniently applicable to the analysis of lateral multiple scattering deflections. The predicted theoretical scattering factors are in fair agreement with the experimental values, but slightly larger; the discrepancies are either within, or just outside of, the limits of the experimental error (3–6 percent).

I. INTRODUCTION

THE energy of charged particles can be determined by the measurement of the deflections of their tracks in photographic plates caused by multiple scattering, i.e., frequent and predominantly small-angle Coulomb scattering. This method has been developed by various investigators in the course of cosmic ray research[1–5] and has more recently been applied to fast electrons from nuclear reactions and from accelerators.[6,7] It was the purpose of this investigation to determine the multiple scattering of artificially accelerated high energy protons. A preliminary account of some of the results of the experiment has been presented in a previous communication.[8] Measurements of the multiple scattering of fast protons under controlled conditions have also been reported by Gottstein *et al.*[9]

The evidence presented here is based on the analysis of the lateral multiple scattering deflections that occurred in 130.4 cm of track of protons with energies of 337±1 Mev and 218±2 Mev in Ilford G-5 emulsions that had been exposed to the external beam of the 184-in. Berkeley cyclotron.[10] Since the energy of this beam is known with an accuracy of 0.3 percent, the multiple scattering calibration was thus freed of the error introduced by the uncertainty of the particle energy that occurs with cosmic-ray particles whose energies must be determined by grain counts or range measurements, or with fast electrons which may suffer considerable radiative energy loss.

II. ANALYSIS OF THE TRACKS

The method of determining the multiple scattering from the deflections of the tracks is illustrated by Fig. 1. The heavy winding curve represents a track of a particle passing successively through points P_1, P_2, and P_3, as projected onto a plane parallel to the surface of the emulsion. Point P_2 divides the portion of track shown

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† Based on a doctoral dissertation submitted to the University of Chicago.
‡ Now Postdoctoral Fellow in statistics and physics, University of Chicago, Chicago, Illinois.
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[8] Berger, Lord, and Schein, Phys. Rev. **83**, 850 (1951).
[9] Gottstein, Menon, Mulvey, O'Ceallaigh, and Rochat, Phil. Mag. **42**, 708 (1951).
[10] The plate exposures were obtained through the courtesy of Professors E. O. Lawrence and W. Barkas of the Radiation Laboratory of the University of California.