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Photoelectric Work Function from Analysis of Emission in an Accelerating Field

PAUL E. CARROLL
The Carborundum Company, Niagara, Falls, New York

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The photoelectric work function can be determined by analysis of monochromatic photoelectric emission in an accelerating field. A plot of *I vs* $E^{\frac{1}{2}}$ gives a straight line for incident light a few tenths of an ev from the threshold. The ratio of the zero-field intercept to the slope of this line is directly proportional to $h(\nu-\nu_0)$ and is independent of the intensity of the incident light. The work function can be determined from this ratio for both metallic and semiconducting emitters. A graphical method is developed for eliminating the dependence of the determination on the field factor and the parameter, m, and the dielectric constant, k_e, in the emission equation for semiconductors. The work function of Te is determined by the present method from data of Apker, Taft, and Dickey. The value obtained, 4.78 ev, is in good agreement with their determination.

I. INTRODUCTION

THE present paper shows how photoelectric work functions can be obtained by analysis of the monochromatic photoelectric emission in an accelerating field. This method has several advantages. It is not necessary to normalize the emission current to unit light intensity as is required in a Fowler[1] plot of photoemission as a function of the energy of incident light. Since the temperature of the emitter is held constant, the temperature variation of the work function would not contribute as it could in the DuBridge[2] method of studying photoemission as a function of the temperature of the emitter. The present method is applicable to both metallic and semiconducting emitters.

II. THEORY

In 1941 Guth and Mullin[3] developed the theory for monochromatic photoelectric emission in an accelerating field. The Guth-Mullin theory applied the mirror image lowering of the work function to Fowler's[1] equation for emission as a function of temperature of the emitter and energy of incident light. The development was analogous to the Schottky[4] effect for thermionic emission. Their result is:

$$I \propto \frac{4\pi m k^2 T^2}{h^3}\left\{\frac{\pi^2}{6}+\frac{\delta^2}{2}-\left[\epsilon^{-\delta}-\frac{\epsilon^{-2\delta}}{2^2}+\frac{\epsilon^{-3\delta}}{3^2}\cdots\right]\right\} \quad \text{for} \quad \delta \geq 0, \qquad (1)$$

where $\delta=(h\nu-\phi')/kT$ contains the field-dependent work function, $\phi'=h\nu_0-e^{\frac{3}{2}}E^{\frac{1}{2}}$, h is Planck's constant, k Boltzmann's constant, m the mass of the electron, T the temperature in degrees Kelvin, $h\nu$ the energy of incident light, $h\nu_0$ the threshold energy of the emitter equals ϕ the work function, e the charge on the electron, and E the applied field at the surface of the emitter.

When $\delta \gg 0$, which occurs for $h(\nu-\nu_0)>0.3$ ev at room temperature, the exponential terms in (1) can be neglected and one obtains:

$$I \propto \frac{4\pi m}{h^3}\left\{\frac{[\pi k T]^2}{6}+\frac{[h(\nu-\nu_0)]^2}{2} +h(\nu-\nu_0)e^{\frac{3}{2}}E^{\frac{1}{2}}+\frac{e^3 E}{2}\right\}+\cdots. \qquad (2)$$

For low fields the term $e^3E/2$ would be negligible by comparison with the other terms, and since room temperature is assumed, the term $(\pi kT)^2/6$ will also be negligible. One then has:

$$I \propto \frac{4\pi m}{h^3}\left\{\frac{[h(\nu-\nu_0)]^2}{2}+h(\nu-\nu_0)e^{\frac{3}{2}}E^{\frac{1}{2}}\right\}+\cdots. \qquad (3)$$

Relation (3) is the basis for the present method for determining work functions. If the monochromatic photoelectric emission is plotted as a function of $E^{\frac{1}{2}}$, a straight line is obtained. The slope of this line is proportional to $e^{\frac{3}{2}}h(\nu-\nu_0)$ and the zero-field intercept of the line is proportional to $[h(\nu-\nu_0)]^2/2$.

The relations (1), (2), and (3) are written as proportionalities because the magnitude of the photoemission will depend on the intensity of the light shone on the emitter in addition to the other dependencies indicated. Both the slope and the zero-field intercept of the straight line plot of *I vs* $E^{\frac{1}{2}}$ are proportional to the light intensity. If one takes the ratio of zero-field intercept, I_0, to the slope of the line, $S=(dI/dE^{\frac{1}{2}})$, the dependence on light intensity is eliminated and one obtains:

$$I_0/S=\tfrac{1}{2}h(\nu-\nu_0)/e^{\frac{3}{2}}. \qquad (4)$$

With a knowledge of the energy of incident light, $h\nu$, the work function, $h\nu_0$, can be determined according to this equation.

One obtains a similar equation if, in place of Fowler's[1] equation as a starting point, one uses the relation derived for a semiconductor by Apker, Taft, and Dickey[5]:

$$I \propto [h\nu-\phi]^{(m+2)}, \qquad (5)$$

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[1] R. H. Fowler, Phys. Rev. 38, 45 (1931).

[2] L. A. DuBridge, Phys. Rev. 39, 108 (1932).

[3] E. Guth and C. J. Mullin, Phys. Rev. 59, 867 (1941).

[4] W. Schottky, Physik. Z. 15, 872 (1914).

[5] Apker, Taft, and Dickey, Phys. Rev. 74, 1462 (1948).

where m is a parameter >0. Applying the mirror-image lowering of the work function for an insulator of dielectric constant k_e, one obtains to the same degree of approximation as (3) above:

$$I \propto [h(\nu-\nu_0)]^{(m+2)} + (m+2)\left[\frac{k_e-1}{k_e+1}\right]^{\frac{1}{2}} e^{\frac{3}{2}} E^{\frac{1}{2}} [h(\nu-\nu_0)]^{(m+1)} + \cdots. \quad (6)$$

This relation predicts a linear variation of I *vs* $E^{\frac{1}{2}}$ for monochromatic photoelectric emission from a semiconductor. In this case the ratio of zero-field intercept, I_0, to the slope, S, gives:

$$I_0/S = \frac{h(\nu-\nu_0)}{(m+2)e^{\frac{3}{2}}}\left[\frac{k_e+1}{k_e-1}\right]^{\frac{1}{2}}. \quad (7)$$

The work function can be determined from this equation for a semiconducting emitter if the parameter, m, and the dielectric constant, k_e, are known. The dependence on intensity of incident light has been eliminated in Eq. (7) as it has been in Eq. (4) for a metallic emitter.

Equations (4) and (7) will depend on the determination of the field strength at the surface of the emitter since the values for slope are taken from a plot of I *vs* $E^{\frac{1}{2}}$. This dependence on the field determination can be eliminated. Two or more plots of I *vs* $V^{\frac{1}{2}}$, where V is the applied voltage, are needed at a different energy of incident light for each plot. The zero-field intercept, I_0, and the slope, $S_V = (dI/dV^{\frac{1}{2}})$, are determined for each plot. Ratios, I_0/S_V, plotted as a function of the energy of incident light, $h\nu$, should give a straight line. Where this line intercepts the axis of zero ratio, $I_0/S_V = 0$, the work function, $h\nu_0$, is obtained.

One can also eliminate the dependence on the parameter, m, and the dielectric constant, k_e, in the same manner. In Eq. (7) an unknown field factor, K, where $E = KV$, can be combined with the unknown factor $(m+2)[(k_e-1)/(k_e+1)]$. Then it can be seen from Eq. (7) that the same method applies. Two or more plots of photoelectric emission, I *vs* $V^{\frac{1}{2}}$, are needed at separate energies of incident light for each plot. The ratios, I_0/S_V, are plotted as a function of the energy of incident light, $h\nu$. Extrapolation of the line, I_0/S_V *vs* $h\nu$, to the axis, $I_0/S_V = 0$, gives the work function, $h\nu_0$.

III. TEST OF THE THEORY

Apker, Taft, and Dickey[5] have presented data which can be evaluated by this method. Their Fig. 7 shows photoelectric emission in an accelerating field for Te plotted as a function of $V^{\frac{1}{2}}$ for two separate energies of incident light. Figure 1 in the present paper shows a plot of I_0/S_V *vs* $h\nu$ for their data. The intercept of the line obtained from these two points gives $h\nu_0 = 4.78$ ev. Apker, Taft, and Dickey report values from 4.76 to 4.83 for their Te surfaces.

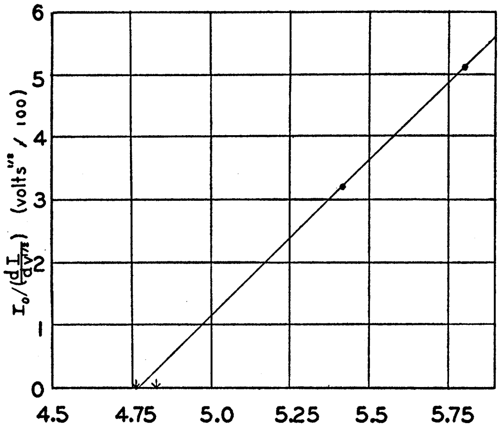

FIG. 1. I_0/S_V *vs* $h\nu$. Extrapolation of the line to the axis, $I_0/S_V = 0$, gives the work function, 4.78 ev. I_0, S_V, and $h\nu$ are taken from Apker, Taft, and Dickey's[5] Fig. 7 which shows a plot of I *vs* $V^{\frac{1}{2}}$ for photoelectric emission from Te at two separate energies of incident light. Apker *et al.* report values from 4.76 to 4.83 (shown by arrows) for Te surfaces.

Carroll and Coomes[6] have also reported data on BaO analyzed according to Eq. (7). Nine determinations of the work function were made for a single cathode and they ranged in value from 1.99 to 2.01 ev.

IV. CONCLUSIONS

The graphical method described for obtaining work functions from the analysis of monochromatic photoelectric emission in an accelerating field has been shown to be quite versatile. For emission from a metal, one needs only data on I *vs* $E^{\frac{1}{2}}$ for incident light at one energy, providing $h\nu - h\nu_0 > 0.3$ ev. The method has a self-contained means of eliminating dependence of emission on the intensity of the incident light. Thus it is unnecessary that the intensity be determined. If the field factor, K, is not known, then two or more plots of I *vs* $V^{\frac{1}{2}}$ for different energies of incident light will determine the work function for either metallic or semiconducting emitters. Since the work function is determined at a fixed temperature of the emitter, it should be a method useful in determining the temperature dependence of the work function.[7]

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[6] P. E. Carroll and E. A. Coomes, Phys. Rev. **85**, 389 (1952).

[7] Careful attention should be paid to the approximations of Eqs. (3) and (6) when extreme sensitivities are required such as in the determination of the temperature dependence of the work function.