The Photoelectric Work Functions of the 211 and 310 Planes of Tungsten

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The work functions of a 211 and a 310 plane on one tungsten crystal were determined using Fowler's method. Since the time necessary thoroughly to outgas the crystal would have been very great, the photocurrents characteristics of the clean surfaces were determined from data obtained soon after the crystal was flashed at about 2200°C. The work function of the 211 plane was found to be 4.50 volts and that for the 310 plane to be 4.35 volts.

SEVERAL experiments[1–5] with copper and zinc crystals have shown the dependence of the photoelectric work function on the crystal structure of the surface, but because of the high vapor pressure and low melting point of both copper and zinc the crystals could not have been heated at high temperatures and therefore may not have been well outgassed. The purpose of this experiment was to study a crystal which could be heated at high temperatures without damage.

APPARATUS

The crystal about eleven mm long with a hexagonal cross section of about 3 mm diameter had six natural faces, two 211 planes, two 310 planes, and two "mixture" planes.

The experimental tube evolved in several steps from a simple tube in which the crystal was mounted on a vertical shaft in a collecting cylinder. It was heated by electron bombardment from a filament mounted inside the cylinder. After several months of outgassing, it was found necessary to isolate the bombarding region from the region where photoelectric measurements were made because the high potential (2000 volts) necessary for bombardment polarized and charged the Pyrex walls of the tube to the extent that the amplifier was unsteady and photocurrent measurements impossible for at least a week after the potential was removed. When the tube was heated at about 400°C the amplifier became steady in a very short time due to the increased conductivity of the glass.

In the final tube shown in Fig. 1 the crystal A was so mounted on a vertical shaft that it could be placed in the molybdenum collecting cylinder B and rotated magnetically to permit photoelectric measurements on any one of the faces of the crystal, or it could be lifted into the molybdenum cylinder C where it was heated by electron bombardment from the tungsten filament D. The bombarding potential was applied to the filament and cylinder to allow the crystal and mounting assembly to remain at ground potential, thus preventing polarization of the Pyrex below the bombarding region. A grounded platinum guard ring E fused to the inner wall of the tube prevented surface leakage along the tube. A bottom in the cylinder C prevented space charge leakage into the lower region of the tube. The hole through which the crystal entered the cylinder was covered by a platinum coated molybdenum disk mounted on the shaft which supported the crystal. The soft iron ring F moved along molybdenum wire guides on the Pyrex tube which supported the crystal mounting. These wire guides were found necessary, for when the ring was allowed to slide on the Pyrex the amplifier was very unsteady for several days after the crystal was lowered.

Two complete Pyrex vacuum systems, each consisting of two liquid-air traps in series (the ones nearest the tube were cooled only after the major part of the outgassing had been completed) and a water-cooled mercury diffusion pump were connected in parallel to the tube. One system had a bore of $1\frac{1}{4}''$ and the other $1''$. A forepump was connected through a liquid air trap to the mercury pumps. The pressure was measured with an ionization gauge.

* The junior author who was a research assistant to the late Dr. C. E. Mendenhall completed the experiment and wrote this report.

[1] J. H. Dillon, Phys. Rev. **38**, 408 (1931).
[2] E. G. Linder, Phys. Rev. **30**, 649 (1927).
[3] A. Nitzche, Ann. d. Physik **5**, 14, 463 (1932).
[4] B. A. Rose, Phys. Rev. **44**, 585 (1933).
[5] N. Underwood, Phys. Rev. **47**, 502 (1935).

The light source was a water-cooled quartz capillary mercury arc[6] used with a Leiss double prism quartz monochromator. The monochromator, arc, and auxiliary lenses were mounted on a heavy cast iron base provided with two lateral crossed motions and a rotation about a vertical axis so that the light could be thrown either onto the crystal surface for photocurrent measurement or onto the receiver of a vacuum thermopile. The quartz window on the thermopile was identical to that on the photoelectric tube, thus the optical paths were as nearly as possible identical. Thermopile readings were made with a Kipp type Zc galvanometer at a scale distance of three meters. The sensitivity of the thermopile was determined after each set of observations by radiation from a pyrometer lamp which had been calibrated by comparison with a standard lamp.

The photocurrents were measured with a modification of the Barth[7] circuit using a Western Electric D96,475 tube. The tube and high resistances were mounted in the evacuated brass chamber *H* (Fig. 1) which also enclosed the seal connection to the collecting cylinder; thus the entire photocurrent lead was in a vacuum. The high resistances and a ground lead were mounted on a clear Bakelite block inside the vacuum chamber in such a way that an externally controlled contact arm could shunt the tube with any one of the resistances or the ground lead. The ratios of the resistances were determined several times during the experiment by comparing the deflections produced with the tube shunted by each resistance when one face of the crystal was illuminated by light of the same wave-length and intensity. Since these ratios remained constant the absolute values of the resistances were probably constant. The voltage sensitivity of the amplifier (140,000 mm/volt maximum) was measured after each set of photocurrent measurements.

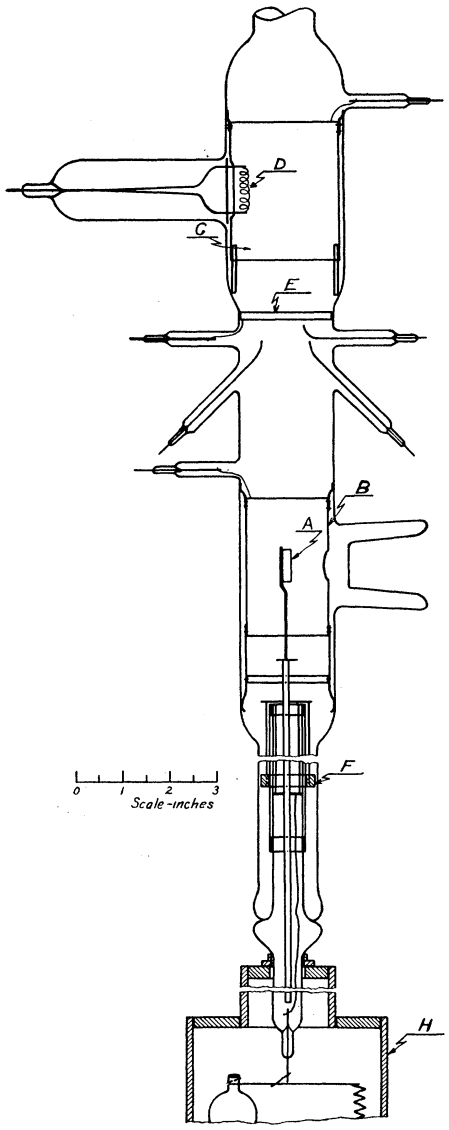

FIG. 1. Diagram of experimental tube.

PROCEDURE

Because of difficulties in the construction of the photoelectric tube, the tube has been rebuilt five times. The following procedure described in detail was the treatment since the tube was last rebuilt, but is characteristic of the procedure throughout the experiment. The crystal had been heated for a total of more than 20,000 hours at temperatures above 1000°C prior to the last rebuild.

Before the tube was assembled the last time, an x-ray comparison of the heated crystal with a half of the original crystal which had not been heated showed that it had not been damaged by the heat treatment. The authors are indebted

[6] F. Daniels, and L. J. Heidt, J. Am. Chem. Soc. **54**, 2381 (1932).
[7] G. Barth, Zeits. f. Physik **87**, 399 (1934).

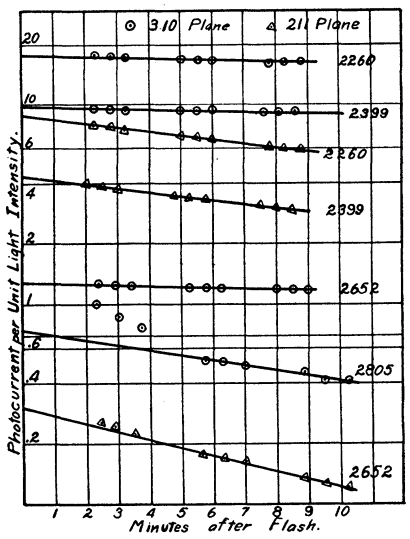

FIG. 2. Monochromatic fatigue curves for the two crystal planes.

to Dr. J. D. Hanawalt of the Dow Chemical Company for this comparison.

The two cylinders and the crystal mounting assembly were heated to bright red in auxiliary vacuum systems until pressures less than 5×10^{-7} mm were attained with the parts heated. They were then quickly transferred to the photoelectric tube and connected to the main system. The tube was baked at 450°C until a pressure of 2×10^{-8} mm was obtained with the tube hot; this required about five weeks. During this period the remaining parts of the vacuum system were heated with a hand torch. The crystal was then placed in the cylinder *C* and bombarded. The temperature was increased at such a rate that the pressure never exceeded 10^{-7} mm. After heating the crystal for three months the pressure was 2×10^{-8} mm with the crystal at about 1500°C. When it was heated continuously at higher temperatures the tube became sufficiently warm that danger of alkali contamination from the Pyrex became appreciable. The crystal was then flashed at 2200°C for 7 seconds once per minute for 1500 hours by a motor driven switch. The temperature of the crystal between flashes was about 1400°C. The pressure remained less than 3×10^{-8} mm during the flash. During the last 1500 hours' outgassing the collecting cylinder was heated very rapidly to a cherry red with an induction furnace. Since the cylinder was supported by legs in contact with the tube, it could be heated only for a very short time and then allowed to cool before another flashing.

An unreasonably long time would have been required to outgas the entire crystal to the same extent that thin strip filaments could be outgassed, since the crystal was many times thicker than filaments which must be heated for at least 1000 hours. However, since the photoelectric effect is a surface phenomenon, it seemed reasonable to measure the photocurrent which would be emitted by the clean surface by extrapolating to zero time the curve obtained by plotting the log of the photocurrent per unit light intensity emitted by the surface as a function of the time after the crystal had been flashed at 2200°C. The long wave limit at absolute zero of each surface was obtained by plotting these extrapolated values in Fowler[8] coordinates and fitting the experimental and theoretical curves in the usual way.

RESULTS

In Fig. 2 the log of the photocurrent per unit light intensity emitted when each of the two crystal surfaces was illuminated by light having the wave-lengths indicated is plotted as a function of the time after the crystal was flashed. These curves show that the higher work function plane (211) points represented by Δ fatigues more rapidly than the other plane (310) points repre-

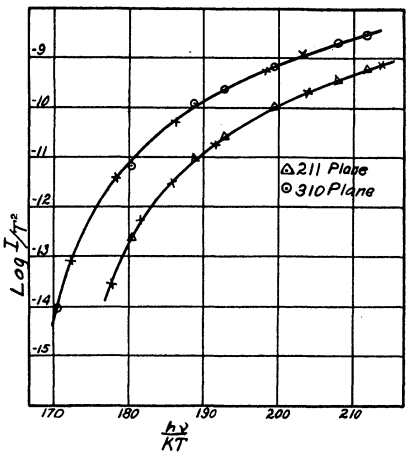

FIG. 3. Photocurrents plotted in Fowler coordinates. The crosses are Fowler theoretical values; the other points are experimental values.

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

sented by circles. As the wave-length of the exciting light approaches the long wave limit of the surface, the experimental points for the first few minutes after the flash deviate to a greater extent from the straight lines determined by the later points. This deviation is undoubtedly due to the fact that the crystal had not cooled to room temperature when the first measurements were made.

In Fig. 3 the extrapolated values of the photocurrents per unit light intensity are plotted in Fowler coordinates. The curves are the shifted theoretical curves, while the points are experimental. The long wave limit at absolute zero was 2840A for the 310 plane and 2740A for the 211 plane. These correspond to 4.35 and 4.50 volts, respectively.

Although the experimental points shown in Fig. 2 for both planes fit the theoretical curve very well, the experimental points for the 211 plane taken four hours after flashing do not fit the Fowler curve, while points obtained at the same time for the 310 plane do fit the curve as shown in Fig. 4. The long wave limit for the 310 plane as given by this curve is 2660A, which corresponds to 4.64 volts, an increase of about 0.3 volt.

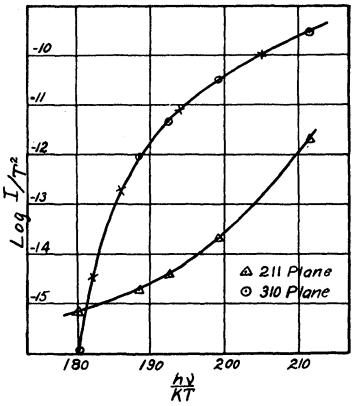

FIG. 4. Fowler plot of the photocurrents taken four hours after the crystal was flashed. The crosses are Fowler theoretical values; the other points are experimental.

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On the Calculation of Errors

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An exact analysis is developed for the calculation of erratic experimental errors. Methods of calculation which have been used are examined and criticized. The analysis developed here is applied to the specific case of the determination of erratic errors resulting from disturbances in a galvanometer system. The formulae here obained reduce, in a second approximation, to the formulae obtained by Zernicke. It is shown that these approximate formulae are too inexact to be used in cases in which the number of observations is small. The exact formulae and more accurate approximations are worked out in detail.

IN conducting experimental investigations it is desirable to be able to use the data obtained to calculate the errors in the measurements which result from erratic disturbances or changes occurring during the course of the experiment. The purpose of this paper is to indicate the general procedure which must be followed in using the data to arrive at the most exact expression for the average resultant error. This problem has been attacked by Zernicke[1] and his method has been reviewed by Barnes and Silverman[2] but owing to a lack of generality in their treatment, resulting from unnecessarily stringent conditions imposed by their statistical assumptions, their results are only approximations to the more exact calculations and may, under

[1] F. Zernicke, Zeits. f. Physik **79**, 516 (1932).
[2] Barnes and Silverman, Rev. Mod. Phys. **6**, 185 (1934).