Some Photoelectric Properties of Evaporated Bismuth Films

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Some photoelectric properties of bismuth films deposited on glass by evaporation in high vacuum are investigated. It is shown that the photoelectric emission and threshold wave-length increase with film thickness to a limiting value. DuBridge's method, in which the photoelectric currents are measured at a single incident frequency and variable temperature, was employed in the threshold determinations and an excellent fit of the observed data to the theoretical curves is always obtained for the temperature range $-53.8°C$ to $24.4°C$ but not for higher temperatures. The maximum threshold wave-length for the bismuth films as determined by the present work is between 2564 and 2600A. The minimum measured threshold wave-length, corresponding to a glass surface thinly spattered with bismuth, is between 2443 and 2506A. Films subject to possible gas contamination and films more carefully protected from such contamination show little difference. Two sets of data, analyzed by Cashman's method, give values of n, the exponent of T in the photoelectric emission equation equal to 2.039 and 2.052.

THIS paper describes experiments on the photoelectric emission for monochromatic illumination of bismuth films of varying thickness deposited on glass by evaporation in high vacuum. Threshold determinations were made by a method due to DuBridge,[1] in which the temperature variation of the photoelectric emission of the films at a single incident frequency is measured.

Early work[2–4] on the variation of the photoelectric emission from pure metals with film thickness was generally carried out with gas contaminated surfaces and some of the discrepancies in the results are probably assignable to the presence of occluded gases. More recently Ives and Johnsrud[5] and Roller[6] and his coworkers have experimented on the photoelectric emission from films of carefully outgassed rubidium and mercury, respectively. In the present work the bismuth films were deposited under carefully controlled conditions so that gas contamination, although possibly present to some extent in the preliminary experiments, was minimized as much as possible in the final determinations.

APPARATUS. PROCEDURE

The photoelectric tube used is shown in Fig. 1. A fused quartz window W is joined with a graded seal to the main Pyrex tube. A is a conical copper anode open at each end and carries a hinged nickel flap F which can be operated externally with a magnet. When a film is deposited the flap is placed in the "up" position (as in Fig. 1) to prevent condensation on the window; when measurements are made the flap is put "down" to allow the radiation entering W to pass through A to the metallic film deposited on the glass face B. A small casting of 99.8 percent C.P. bismuth is held in the rectangular molybdenum trough M supported by two lead-in wires which carry the heating current. T is a chromel-alumel thermocouple (No. 28 B. & S. gauge wires) embedded in the lower central region of B. Two 12-mil tungsten wires are also embedded in B to make electrical contact with the deposited film. These four wires are ground flat with the glass face.

The photoelectric currents were measured with a Compton electrometer shunted by an S. S. White resistor of 5.5×10^9 ohms. The sensitivity was usually about 3×10^{-13} amp./mm. The electrometer was calibrated after each set of readings and the deflections were corrected for nonlinearity of the scale.

An Hanovia SC-2537 quartz low pressure mercury arc operating from a 5000-volt transformer was used as a source of monochromatic radiation. A variable series resistance was em-

[1] L. A. DuBridge, Phys. Rev. **39**, 108 (1932).
[2] S. Werner, Dissertation, Upsala (1913).
[3] K. T. Compton and L. W. Ross, Phys. Rev. **9**, 559 (1917); **13**, 374 (1919).
[4] O. Stuhlman, Phys. Rev. **13**, 109 (1919); **20**, 65 (1922).
[5] H. E. Ives and A. L. Johnsrud, Astrophys. J. **62**, 309 (1925).
[6] D. Roller, W. H. Jordan and C. S. Woodward, Phys. Rev. **38**, 396 (1931).

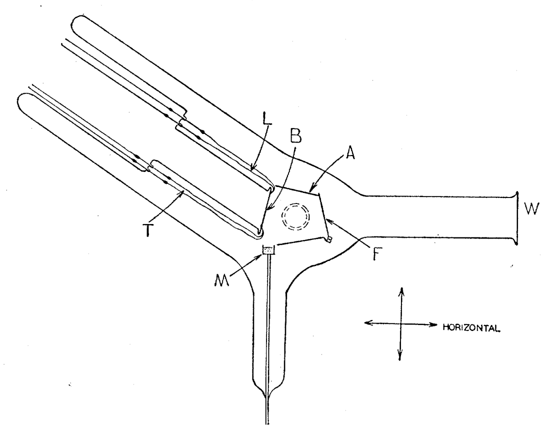

FIG. 1. Side cross-sectional view of photoelectric cell.

ployed to maintain a constant primary current. The arc radiation was focused on the bismuth films with a quartz lens of focal length 1.81 in. (for the 2536.5A line). The arc, used without filters or monochromator, is a rather pure source of monochromatic light of wave-length 2536.5A. Maddock's data[7] indicate that 90 percent of the total radiant output of this type of lamp is in this line. If Parmley's value[8] for the photoelectric threshold of bismuth (2835A) is assumed to be correct[9] the effect of lines above this wave-length can be neglected. If such lines are eliminated from Maddock's table of intensities[7] more than 99 percent of the energy of the remaining wave-lengths listed is in the 2536.5 line. Since Maddock measured the chief lines only (he lists 15 lines between 2400 and 2600A) this percentage purity is probably slightly too high. Maddock's data were experimentally confirmed during the progress of the present work.

The photoelectric cell was outgassed, by vigorous heating with a Bunsen flame, before depositing each of the bismuth films. During this outgassing the bismuth also was given some heat treatment by carefully heating the molybdenum trough M. To prevent the condensation of bismuth evaporated during this procedure on the glass face B, a resistance heater was inserted in the reentrant tube directly behind B. The photoelectric cell remained connected to the vacuum pumps throughout the experiments. A stopcock was used to close off the tube from the pumps when these were not operating. A trap, permanently packed with a slush of dry ice and acetone, was included between the tube and stopcock to prevent contamination of the bismuth film by stopcock grease vapors.

EXPERIMENTS. RESULTS

To study the variation of the photoelectric emission with film thickness, the bismuth was evaporated onto the glass face B by passing a constant electric current through M for times totaling 2 to 3 hours. The evaporation process was interrupted during the measurements. Because of the geometry of the cell the film was not of uniform thickness but was thicker at the bottom than at the top. The incident beam of light stopped down to a diameter of about 2 mm was focused on the film at different regions between the top and bottom by moving the focusing lens along a micrometer scale. Fig. 2 shows a typical set of curves obtained. The six curves are for six settings of the micrometer and are numbered in order from the thicker to the thinner part of the film. The data of Fig. 2 were not obtained in one continuous run but during experiments spread over a period of 14 days.

Measurements of the temperature variation of the photoelectric emission were made from time to time (indicated by the arrows along the abscissa of Fig. 2) while the film was in the process of formation. A mixture of dry ice and acetone

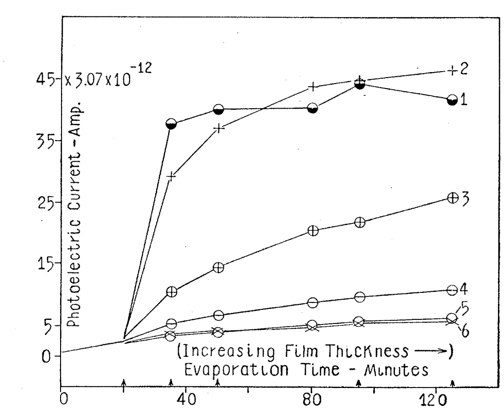

FIG. 2. Curves showing variation of photoelectric emission of gas contaminated bismuth with film thickness. The six curves are for different regions of the film.

[7] A. J. Maddock, Proc. Phys. Soc. **48**, 57 (1936).
[8] T. J. Parmley, Phys. Rev. **30**, 656 (1927).
[9] According to the results of the present paper the threshold wave-length for the bismuth films was never greater than 2600A.

was placed in the reentrant tube directly behind the glass face B and the photoelectric current at each of the six micrometer settings was observed as the film warmed up to room temperature; the exact temperature was measured with the thermocouple. The data obtained were analyzed by the graphical method of DuBridge.[1] Typical results are shown in Figs. 3 and 4, the data for which were obtained after 95 minutes of evaporating time. The theoretical curves were plotted from the values given in DuBridge's paper. The fit of the experimental points to the theoretical curves is seen to be excellent. Values of the threshold wave-length and photoelectric work function, directly obtained for each of the six micrometer settings from the process of fitting the corresponding experimental points to the theoretical curves,[10] are recorded on the figures. It is to be noted that, in general, the threshold wave-length increases with the film thickness. These experiments were repeated a number of times with fresh films deposited after removing the previous film by heating the supporting glass face with an electric heater.

The above experiments were also repeated in a modified form to obtain a corresponding set of data in one continuous run thus decreasing the chance of gas contamination of the film. The modified experiments were performed with the light always focused on a fixed region of the film. Results are shown in Figs. 5 and 6, the three

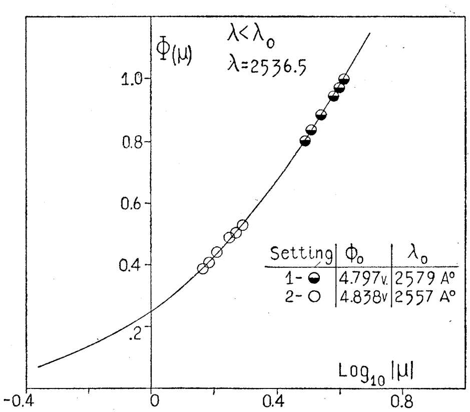

FIG. 3. Positive branch of DuBridge plot of data obtained after 95 minutes evaporating time for the bismuth film of Fig. 2.

[10] See reference 1 for complete details.

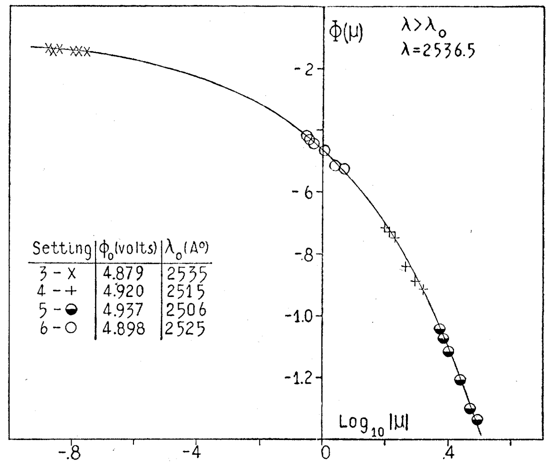

FIG. 4. Negative branch of DuBridge plot for same group of data as Fig. 3.

curves shown were obtained with three bismuth films deposited in the order in which the curves are numbered. It can be seen that the maximum photoelectric current attained and also the rate at which this maximum current was established, decreased with each successive film. These differences are probably due to changes in the rate at which the bismuth was evaporated and in the direction of the vapor stream, both caused by the gradual depletion of the bismuth in the trough. The arrows on the curves of Fig. 5 indicate the points at which temperature effect runs were made. Fig. 6 is the result of the DuBridge analysis of the temperature effect data of curve 1, Fig. 5. The four sets of points of Fig. 6, labeled A, B, C and D, correspond to the four lettered points on curve 1 of Fig. 5. The necessary negative portion of the theoretical curve is included as an inset in Fig. 6. Again the fit of the experimental points to the theoretical curves is excellent. There is again a shift of the threshold wave-length toward the red with increasing film thickness.

The maximum and minimum values of the threshold wave-length and the work function for the three curves in Fig. 5 are listed in Table I together with the same quantities taken from Figs. 3 and 4.

SUBSIDIARY EXPERIMENTS AND RESULTS

1. Since the threshold wave-length of the bismuth films studied shifts from below 2536.5A

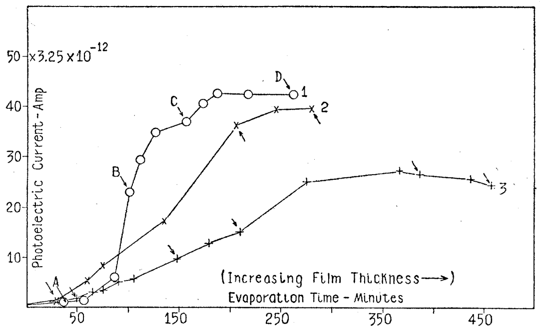

FIG. 5. Variation of photoelectric emission with film thickness for bismuth protected from gas contamination. The three curves are for three successively deposited films.

to above this value, some of the temperature effect measurements chanced to be made when the threshold was close to 2536.5A. Such data can be analyzed by Cashman's method[11] to yield values of the exponent n of the absolute temperature in the photoelectric emission equation. Two sets of data so analyzed appear in Table II.

2. In the experiments on the temperature variation of the photoelectric emission of the bismuth films the temperature was varied between $-53.8°C$ and $24.4°C$. Data obtained in this range could be fitted excellently in all cases to the theoretical curve. Data obtained at higher temperatures, with an electric heater inside the

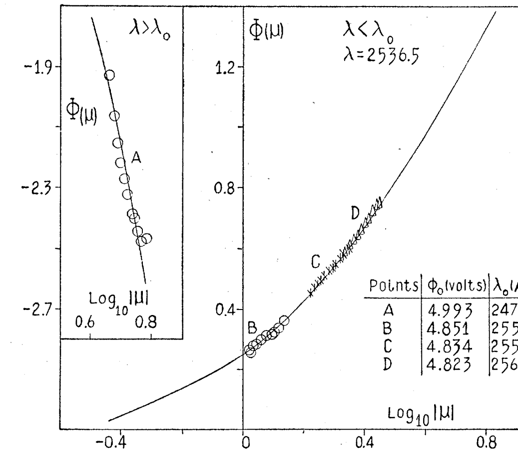

FIG. 6. DuBridge plot of data of curve 1 of Fig. 5.

reentrant tube, were not reproducible and did not fit the theoretical curve. Apparently the structure or gas content of the films changes rapidly above room temperature. As is emphasized by DuBridge[1] his method of analysis cannot be applied to surfaces which suffer any changes with temperature.

3. To check the results of Maddock[7] on the purity of the arc radiation the light from the SC-2537 lamp was passed through a Hilger quartz monochromator, with collimator and telescope slits set at 0.012 in. and 0.015 in., respectively, and the photoelectric emission of a bismuth film was measured for various monochromator drum

TABLE I. *Maximum and minimum values of photoelectric threshold and work function for bismuth films.*

Gas Contaminated Film (Figs. 3 and 4)	Threshold Wave-Length (A) Minimum	Threshold Wave-Length (A) Maximum	Work Function (volts) Maximum	Work Function (volts) Minimum
	2506	2579	4.937	4.797
Films protected from gas contamination (Fig. 5)				
Curve 1	2478	2565*	4.993	4.823*
Curve 2	2461	2566	5.026	4.820
Curve 3	2443	2600	5.063	4.758

* Possibly affected by gas contamination.

TABLE II. *Values of n and corresponding photoelectric data for two gas contaminated bismuth films.*

n	Threshold Wave-Length (A)	Work Function (volts)
2.039	2535*	4.879*
2.052	2534.9	4.880

* Data from Fig. 4, setting 3.

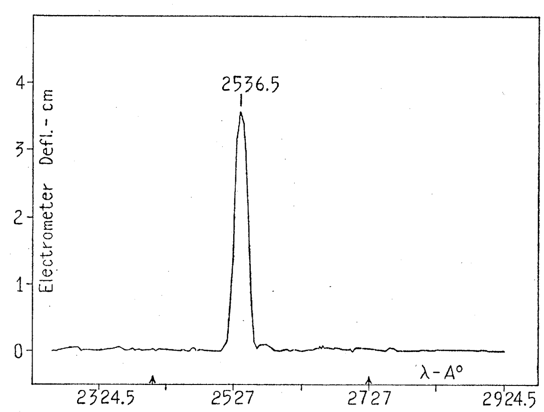

FIG. 7. Test of the purity of the radiation used. Curve shows response of a bismuth film to the radiation from the low pressure arc. Ordinates are proportional to the photoelectric currents from the film. Abscissae are monochromator drum settings. The curve was drawn through 83 plotted points. Electrometer sensitivity = 15,000 mm/volt, approximately.

[11] R. J. Cashman, Phys. Rev. 52, 512 (1937).

settings. Fig. 7 shows a typical curve which confirms Maddock's data and is definite evidence that practically all of the photoelectric emission of the bismuth film is due to this line.

Conclusions

1. The curves of Figs. 2 to 6 indicate that the photoelectric emission and the threshold wave-length of bismuth films increase with increasing film thickness until a limiting value is attained.

2. The maximum and minimum values of the threshold wave-length for the four films, given in Table I, are in substantial agreement despite the fact that the first film was "gas contaminated" to a much greater degree than were the other three. It also should be noted that the four maximum threshold wave-lengths do not correspond to films of equal thickness. The minimum values of the threshold wave-lengths obtained are for extremely thin films, barely visible.

The author wishes finally, to express his thanks to the physics department of the University of Pennsylvania for the loan of the Hilger monochromator and to Dr. C. B. Bazzoni of the same laboratories for helpful suggestions and discussions while the work was in progress.

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Reflection of Sound

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The losses in the reflection of sound on solids are investigated. The heat conduction of the solid disturbs the temperature distribution in the gas and sets up a temperature wave. The fact that the pressure in the gas near the wall is no longer in phase with the density results in a heating of the gas on the wall. The effect amounts to a few percent for a million cycles. The scattering of the molecules on the wall, the scattering of the sound waves by uneven places, the effect of adsorption are also investigated. They become important only at higher frequencies.

I. Introduction

It has been customary to state that the reflection of a sound wave by a smooth solid wall is almost complete. In support of this it is argued that because of the very large density and hardness of the wall the amplitude of the sound wave propagated into it will be small.

A few years ago, however, measurements by J. C. Hubbard gave ultrasonic reflection coefficients lower than expected and R. W. Curtis[1] reported reflection coefficients as low as 70 percent for 1000 kc in air on brass. The present investigation was undertaken at that time to look for a theoretical explanation for this result. It turned out that the theory leads to losses of a few percent, but that it was impossible to account for losses as high as 30 percent. Recent measurements[2] and computations of Alleman, done under Professor J. C. Hubbard, which include a modification of interferometer theory to take account of the effect discussed in this paper show good agreement of his own and previous measurements with the theory presented here.

To understand how the loss in reflection discussed here arises attention must first be drawn to the periodic temperature variations in the gas due to adiabatic expansion and compression. At the contact with the wall, the heat conduction of which is usually very much greater than that of the gas, heat will be alternately drained and put back into the gas, setting up a "temperature wave" in the solid in addition to the mechanical wave, which was alone considered before. The effect increases with frequency, because with shorter wave-length the temperature gradient increases.[3]

[1] R. W. Curtis, Diss. 1934, Phys. Rev. **46**, 811 (1934).
[2] R. Alleman, to be published.
[3] K. F. Herzfeld and F. O. Rice, Phys. Rev. **31**, 691 (1928).