

Photoelectric and Thermionic Properties of Nickel*

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The photoelectric and thermionic properties of spectroscopically pure nickel were studied through a wide range of temperatures including the Curie temperature, 350°C. The samples were studied after having been subjected to long outgassing processes. A marked change occurs in the slope of the temperature-photoelectric current curves at the Curie temperature. This change is accounted for by an increase in the work function and a change in the probability factor α . The work function of carefully outgassed nickel was found to be 5.05 ± 0.05 electron volts below 623°K. At this temperature the work function increases becoming 5.20 ± 0.05 electron volts at 1108°K. A work function of 5.24 electron volts was determined thermionically at temperatures of 1150°K and above.

I. INTRODUCTION

PHOTOELECTRIC and thermionic properties of several¹⁻⁴ metals have been studied with emphasis on changes associated with crystallographic transformations and/or Curie points. This paper is a report of a similar study on nickel through a wide range of temperatures, including the Curie point. It is generally agreed in the case of nickel that at the magnetic transformation temperature, 350°C, no crystallographic transformation occurs.

II. APPARATUS AND METHOD

The experimental tube was similar to that used by the author in the study of tantalum.⁵ The tube was specially designed for measurements on both photoelectric and thermionic properties, a guard ring being so placed that end effects were eliminated. The sample in the form of a strip, 0.03 millimeters thick, 4 millimeters wide and 14 centimeters long, was suspended as a loop inside a molybdenum collecting cylinder. The spectroscopically pure (at least 99.99 percent) nickel from which the filaments were fabricated was supplied by Adam Hilger.

For photoelectric observations, radiation from a quartz mercury arc was dispersed by a Bausch and Lomb quartz monochromator and fell onto the sample through a thin quartz window and a hole in the collecting cylinder. Relative intensities of the spectral lines were obtained from the response of a bismuth-silver vacuum thermopile. Temperatures at and above 1100°K were determined by means of an optical pyrometer of the disappearing-filament type focused on the sample through a thin optically flat Pyrex window and a hole in the cylinder. Black-body temperatures were corrected for the emissivity of nickel according to the data of Wahlin and Wright.⁶ Lower temperatures

were determined graphically by interpolation between room temperatures and temperatures in the optical pyrometer range.

For most of the work the vacuum system consisted of a silicone-fluid three-stage water-cooled diffusion pump, a liquid-air trap, and a Welch Duo-seal mechanical pump. Several runs were made with a water-cooled mercury diffusion pump substituted for the silicone-fluid pump. Pressures were determined with a type VG-1A ionization manometer.

Photoelectric and thermionic currents were measured by a current amplifier utilizing a Western Electric D-96475 tubes. Current sensitivity of a wide range could be obtained by changing the fixed high resistor in the circuit.

The outgassing process to which each sample was subjected varied only slightly. In general, after the installation of the sample, the entire tube and ionization gauge were baked at 500°C for several days. During the last two or three days of this interval, the filament was heated by a conduction current at temperatures which were slowly increased to 900°C. At the end of this period the furnaces were removed and the filament

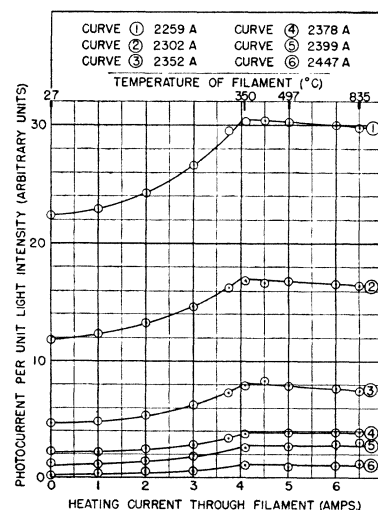


FIG. 1. Variation of photocurrent with temperature.

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¹ A. B. Cardwell, Proc. Nat. Acad. Sci. **14**, 438 (1928).

² A. Goetz, Phys. Rev. **33**, 373 (1929).

³ A. B. Cardwell, Phys. Rev. **38**, 2033 (1931).

⁴ H. B. Wahlin, Phys. Rev. **61**, 509 (1942).

⁵ A. B. Cardwell, Phys. Rev. **38**, 2041 (1931).

⁶ H. B. Wahlin and R. Wright, J. App. Phys. **13**, 40 (1942).

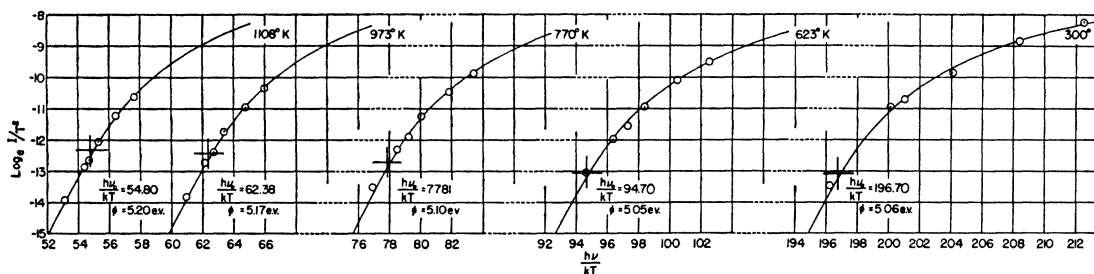


FIG. 2. Analysis of photoelectric observations by Fowler's method.

further heated at temperatures which were finally increased to 1200°C. At intervals the collecting cylinder was heated by high-frequency induction to a cherry-red temperature. After approximately 1500 hours of heat treatment, the photoelectric and thermionic properties of the sample became stable. Pressures varying from 2 to 8×10^{-8} mm of mercury were obtained with the filament at the high temperature.

III. PHOTOELECTRIC RESULTS

Data for the photoelectric and thermionic properties which are presented in this paper were taken after the sample had gone through the entire outgassing process and thus after it had reached a stable condition. Therefore, it is hoped that the results obtained represent the properties of pure "gas-free" nickel.

Figure 1 is a sample curve showing the photoemission as a function of current through the filament at the time observations were made. The temperatures corresponding to four heating currents have been indicated. It is obvious that these curves do not follow the variation of photocurrent with temperature for various wave-lengths required for a given metal by Fowler's theory.^{7, 8}

It was thought that the discontinuous change in slope of the photoemission-temperature curve (Fig. 1) at 623°K might possibly be a direct result of the change in the reflectivity of the nickel surface. To obtain information on this point, the photocurrent produced from the collecting cylinder by radiation reflected from the nickel strip was measured as a function of the filament temperature. Since the radiation from the monochromator was carefully focused onto the filament, such a curve was readily obtainable by reversing the accelerating potential between the filament and the cylinder. No appreciable change in the reflectivity with temperature could be detected. This is in agreement with the work of Weil,⁹ who found no change in the reflectivity in the region of the Curie point.

The data were analyzed by the method of Fowler.⁷ Sample curves of the photoelectric data for five temperatures (one below, one at, and three above the Curie point) are shown in Fig. 2. In each case the origin of

the theoretical Fowler curve, which brings the experimental curve into coincidence with the theoretical curve, is indicated on the curve. Work functions were computed from the horizontal shifts ($h\nu_0/kT$). Fowler plots of data taken at temperatures between 623°K (Curie temperature) and 1108°K give work functions which gradually increase from 5.06 to 5.20 electron volts. Photoelectric data above 1108°K could not be obtained because of the magnitude of the thermionic emission.

It should be noted that the vertical shifts required to bring the curves into coincidence with the theoretical curves are not the same for all temperatures. Since the photocurrent in all cases was measured in the same units, the different vertical shifts correspond to changes in the probability factor α in the Fowler theory as the sample passes through the Curie temperature. Since α is thought to vary as $n^{-4/3}$ (n being the number density of free electrons), the implication is clear. The variation in α for a metal due to change in density with temperature is not only smaller than that indicated for nickel but also in the opposite direction.

No high degree of accuracy is claimed for the magnitude of the vertical shift. Bringing the curves into coincidence is hardly as sensitive to a vertical shift as to a horizontal shift. However, best fits for data taken on the several samples studied were obtained with the vertical shifts indicated.

The change in the slope of the photoemission-temperature curve (Fig. 1) which occurs at the Curie point and which indicates both a change in α and the work function is an interesting characteristic associated with the discontinuities of electrical conductivity, thermal expansion, and secondary electron emission observed for nickel by Masumoto¹⁰ and Hayakawa.¹¹ It also throws some additional light on the changes in the thermionic and/or photoelectric properties which have been observed for iron,^{1, 4} tin,² and cobalt³ as these metals pass through temperatures at which crystallographic and/or magnetic properties change.

IV. THERMIONIC EMISSION

Data for determining the thermionic constants were taken on one sample, and the saturation value of the

⁷ R. H. Fowler, Phys. Rev. **38**, 45 (1931).

⁸ L. A. DuBridge, *New Theories of the Photoelectric Effect* (Hermann & Cie, Paris, 1935).

⁹ R. Weil, Nature **158**, 672 (1946).

¹⁰ H. Masumoto, Sci. Rep. Tohoku Univ. **15**, 449 (1926).

¹¹ K. Hayakawa, Sci. Rep. Tohoku Univ. **22**, 934 (1933).

thermionic emission was determined as a function of the temperature. A Richardson plot of these data gave an average value for the work function of 5.24 electron volts. Consistent values for A were not obtained, but its value appeared to be in the neighborhood of 50.

The value of the photoelectric work function, 5.05 ± 0.05 electron volts obtained below the Curie temperature agrees well with the value, 5.01 electron volts, obtained photoelectrically at room temperature by Glasoe.¹² The photoelectric work function of 5.20 ± 0.05 electron volts determined at 1108°K is slightly lower than the value 5.24 electron volts determined thermionically at temperatures of 1150°K and

¹² G. N. Glasoe, *Phys. Rev.* **38**, 1490 (1931).

above. This indicates that the photoelectric work function might further increase slightly with temperature before reaching a constant value, and thus before giving a typical Fowler variation of photocurrent with temperature. The above values are higher than the thermionic value 5.03 electron volts determined by Fox and Bowie¹³ and 4.61 electron volts reported by Wahlin.⁴

V. ACKNOWLEDGMENT

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¹³ G. W. Fox and R. M. Bowie, *Phys. Rev.* **44**, 345 (1933).

Breakdown of Ionic Crystals by Electron Avalanches*

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In gases at moderate pressures breakdown occurs when the avalanche produced by a primary electron regenerates with certainty a new starting electron (Townsend condition). In ionic crystals the breakdown strength appears to be determined by the probability of exciting lattice vibrations, without reference to the electron supply. The theory as formulated to date predicts an increase of the breakdown strength with temperature. Confirming our previous results we find for both d.c. and a.c. an increase followed by a decrease. By extending our experiments to transient voltages of rise times down to 10^{-8} sec., and by adopting evaporated metal electrodes and various kinds of irradiation, the influence of field emission and of space charges on the breakdown strength and on the scatter of the breakdown values has been investigated. The occurrence of directional breakdown paths seems to be connected with the Brillouin zones of the crystal structure as the outcome either of electron diffraction or of collisions between electrons and directed lattice vibrations. The possibility of using crystals as Geiger counters is briefly discussed.

INTRODUCTION

WHILE the sequence of events leading to electric breakdown in gases is today fairly well understood, in the case of solids basic questions are still asked concerning the mechanisms causing the destruction of these dielectrics. This lag in advance is partly due to the experimental difficulties of handling very high field strengths and partly inherent in the complexities of the solid state. In solids, electrons and ions do not lead a transitory existence as in gases, but appear as stable building stones of the structure in various forms of bonding. They may be mobilized under a variety of conditions, but remain, even in motion, strongly coupled to their surroundings. Space is at a premium; reaction products, once formed, are left behind as localized debris instead of being swept out in short order. Hence breakdown may occur in various ways: by thermal activation of charge carriers or by chemical decomposition, by dendrite formation or electron trapping,

and finally, when these types of destruction are avoided, by electronic impact ionization.¹

This last form of electronic breakdown has been of special interest to us for a number of years² because it holds the key to the development of a "physics of high field strength." It is the purpose of the present paper to re-assess the situation in the light of new evidence.

The major part of our experiments up to the present has been carried out with alkali halide single crystals since they may be grown and handled with ease, form a variety of compounds of cubic structure, and have been investigated in much detail at lower field strength, especially by Pohl and his co-workers.³

1. ORIGIN OF THE STARTING ELECTRONS

Statistical considerations as well as experimental evidence show that the concentration of conducting electrons in these crystals is negligible at room tem-

¹ A. von Hippel, *J. App. Phys.* **8**, 815 (1937).

² A. von Hippel, *Trans. Faraday Soc.* **42**, 78 (1946).

³ R. W. Pohl, *Physik. Zeits.* **39**, 36 (1938).

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