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Temperature Dependence of the Characteristic Energy Loss of Electrons in Aluminum[*]

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The change in the 15-ev characteristic energy loss suffered by 15-kev electrons passing through a thin film of aluminum has been measured as a function of temperature from 4.2°K to 518°K. It is found that above room temperature the energy loss change agrees, within experimental error, with the change expected due to decreased electron density resulting from expansion of the lattice. However, below room temperature the energy loss change is much greater than expected on the above basis. It was also found that the half-widths of both the energy loss and the zero loss lines increased with decreasing temperature while the ratio of these two remained constant.

INTRODUCTION

THE change in the characteristic energy loss of electrons[1] passing through a thin film of aluminum as the temperature of the film is increased has recently been measured by Meyer.[2] His results, for a range of temperature from room temperature to 400°C, indicate that a small change of the energy loss may occur. On the other hand, an earlier measurement by Watanabe[3] from room temperature to 617°C did not show any change in the energy loss although he states that the expected magnitude is too small to be detected with his analyzer.

The present work was undertaken to remeasure the change in energy loss of electrons in thin films of aluminum as the temperature of the aluminum film is increased, and also to extend these measurements to temperatures below room temperature.

APPARATUS AND EXPERIMENTAL METHOD

The scattering chamber is a cylinder 32 cm in diameter and 28 cm high. The specimen mount is suspended from the top cover plate so that the specimen is on the axis of the cylinder. The electron gun and analyzer were aligned along the diameter of the chamber. The distance from the anode of the gun to the specimen is 35 cm and from the specimen to the analyzer 9.5 cm.

The analyzer used for these measurements is of the retarding potential type, using a guarded Faraday cage. This is shown in Fig. 1. The outer electrode is held at ground potential and has an aperture of 0.874 cm. Since the specimen is 9.5 cm from this aperture, the acceptance angle of the analyzer is approximately $5\frac{1}{4}$ degrees. The guard electrode is 0.95 cm from the first and is at the cathode potential of 15 kev. It has an aperture of 0.952 cm. To keep the field across these large apertures as uniform as possible it was necessary to cover them with a wire mesh of 0.8 mm spacing. These first two electrodes form a lens which focuses the incoming electrons into the Faraday cage which follows the second electrode. It is also between these electrodes that the retarding potential is applied. The Faraday cage is placed 0.158 cm behind the second electrode, and has an aperture of 1.02 cm. All the metal parts are gold-plated to reduce contact potential effects, and the inside of the Faraday cage is coated with carbon to reduce secondary electron production.

To eliminate the necessity of graphically differentiating the integral curve resulting from retarding potential measurements, a method of electrical differentiation was developed. This has been described in another paper.[4] Linear differential curves of the energy loss spectra were directly recorded.

Since we wished to measure the energy losses both above room temperature and below room temperature, it was found convenient to have two separate arrangements for these two regions. In the case of the high-temperature measurements, the specimen holder was mounted on the end of a small oven wound with several turns of Nichrome wire. An iron-constantan thermocouple was attached directly to the specimen holder

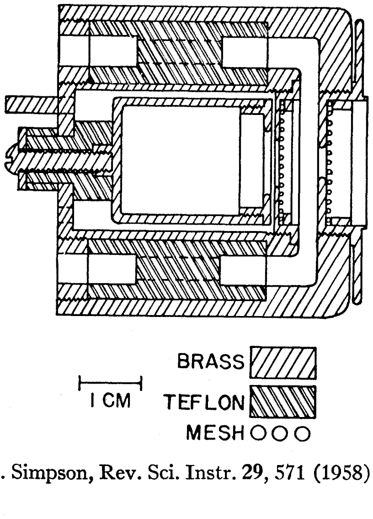

FIG. 1. Retarding potential analyzer. The electrons to be measured enter from the right side. The outer shield is at ground potential, and the guard electrode and Faraday cage are at cathode potential.

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[1] Marton, Leder, and Mendlowitz, *Advances in Electronics and Electron Physics* (Academic Press, Inc., New York, 1955), Vol. 7, p. 185.

[2] G. Meyer, Z. Physik **148**, 61 (1957).

[3] H. Watanabe, J. Phys. Soc. Japan **11**, 112 (1956).

[4] L. B. Leder and J. A. Simpson, Rev. Sci. Instr. **29**, 571 (1958).

close to the specimen surface. For the low-temperature measurements a double Dewar system was used.[5] The specimen was mounted at the bottom of the inner, liquid helium, Dewar, and the temperature was "monitored" with a carbon resistor thermometer.[6] We use the term "monitored" because the thermometer was not absolutely calibrated, but was used only to observe that no temperature change occurred during the course of measurement. It is therefore possible that the temperatures given in the results are somewhat lower than the actual specimen temperature. For the measurements at liquid nitrogen temperature both Dewars were filled with liquid nitrogen while for the measurements at liquid helium temperature the outer Dewar contained liquid nitrogen and the inner one liquid helium.

The aluminum foils were prepared by vacuum evaporation onto a collodion film mounted on a glass slide. No particular care was taken to maintain uniformity of thickness other than to evaporate the individual films under the same conditions each time. The films were calculated to be of the order of several hundred angstroms thick. After evaporation, the films were removed by first immersing the slides in ether to dissolve the collodion, and then floating them off on water. They were then picked up on the appropriate specimen holder containing several 0.033-cm holes.

The incident electrons had an energy of 15 kev, and the beam current, measured after passing the electrons through one of the empty apertures in the specimen holder, was of the order of 5×10^{-8} amp.

RESULTS

To ensure the accuracy of the measurements, the retarding potential batteries were measured with a potentiometer before and after a run at each temperature; and the energy loss at room temperature was also measured before and after the set of runs at elevated temperatures and the set of runs at low temperatures. The specimens used in the low-temperature measurements were prepared in a separate evaporation from those used in the high-temperature measurements. With the films made for the high-temperature run, the energy loss at room temperature was found to be $15.3_3\pm0.1_4$ ev both before and after increasing the temperature whereas with the second batch of films the characteristic loss was measured as $15.0_4\pm0.0_9$ both before and after decreasing the specimen temperature. This inconsistency in the energy loss from one evaporation to another is one which has been observed by other investigators as well and has not as yet been completely explained. However, the results of our measurements are not affected since they are internally consistent.

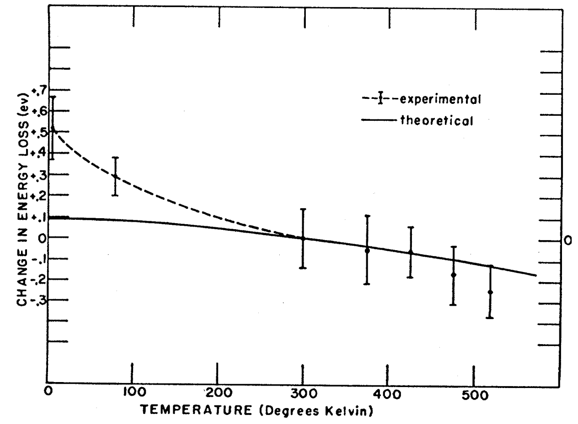

FIG. 2. Temperature dependence of the characteristic energy loss of 15-kev electrons in Al. The theoretical curve shows the change expected due to thermal expansion.

In Table I are collected the data for the energy loss measurements using 15-kev primary electrons. In the first column are given the temperatures in degrees Kelvin, and in the second column the change in the energy loss with its standard deviation. In the third column we have shown the number of measurements made at each temperature. These results are plotted on Fig. 2. In the low-temperature region we have drawn a dashed line joining the room temperature, liquid nitrogen temperature, and liquid helium temperature points.

TABLE I. Variation of the characteristic energy loss of 15-kev electrons in aluminum as a function of temperature. The energy loss changes are with reference to the energy loss at room temperature. The errors shown are standard deviations.

Temp. (°K)	ΔE_f (ev)	No. meas.
~4.2	$+0.5_2\pm0.1_5$	29
78	$+0.2_9\pm0.0_9$	76
300	0	38
374	$-0.0_5\pm0.1_6$	20
425	$-0.0_6\pm0.1_2$	18
475	$-0.1_7\pm0.1_4$	50
518	$-0.2_4\pm0.1_3$	20

From these measurements we also obtained the change in half-width of both the zero loss line and the characteristic loss line from room temperature to liquid helium temperature. This is shown in Table II. It was found that as the temperature of the aluminum specimen was decreased, the half-width increased for both lines. However, the ratio of the half-widths remained constant at a value of 1.6. The rather large deviations in the values of E_f are a result of the fact that this line is weak and is in the noise region.

It was thought that both the above effects might be caused by positive-ion currents formed by the electrons in front of the analyzer[7] since these ions could conceivably enter the Faraday cage and be collected. This

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[5] E. Hoerl and L. Marton, Rev. Sci. Instr. (to be published).

[6] J. R. Clement and E. H. Quinell, Rev. Sci. Instr. 23, 213 (1952).

[7] This was suggested by Dr. J. A. Simpson of our laboratory.

would cause an error voltage to appear on the 10^9-ohm resistor in the input of the preamplifier, which would add to the retarding potential. This error voltage would be dependent on both the electron current and the chamber pressure (the addition of liquid nitrogen reduced the pressure in the chamber from 2.5×10^{-5} mm Hg to 2.8×10^{-6} mm Hg while the addition of liquid helium to the center Dewar reduced the pressure to 6×10^{-7} mm Hg). To test this we again measured the energy loss and the half-widths at room temperature, and then filled only the outer Dewar with liquid nitrogen. This had the effect of reducing the pressure in the chamber to the same extent as during the liquid nitrogen temperature measurements but kept the specimen at room temperature. It was found that under these circumstances no significant change in the energy loss or in the half-width occurred. We believe that this test effectively ruled out the effects of ions. The results are given in Table III. It will be noted in this table that there is a small variation from the half-widths and ratio shown in Table II. It is not known whether this is real or due only to the statistical variation of the measurements. The measurements shown in Table II were made with foils prepared at a different time from those shown in Table III. This may, therefore, indicate some effect due to thickness variation or oxidation.

TABLE II. Change in the half-width of the zero loss and characteristic loss lines as a function of temperature below room temperature. E_0 is the zero line and E_f the loss line. The errors shown are standard deviations.

	Half-width (ev)			
Temp. (°K)	E_0	E_f	E_f/E_0	No. meas.
300	1.7±0.1	2.7±0.3	1.6±0.2	12
78	1.9±0.1	3.1±0.2	1.6±0.1	14
∼4.2	2.5±0.2	4.0±0.9	1.6±0.4	11

TABLE III. The energy loss and the half-widths of the zero loss and energy loss lines measured as a function of chamber pressure. The errors shown are standard deviations.

		Half-width (ev)			
Pressure (mm Hg)	Energy loss E_f (ev)	E_0	E_f	E_f/E_0	No. meas·
2.5×10^{-5}	$15.2_3\pm0.0_9$	1.5±0.0	2.9±0.5	1.9±0.3	30
2.8×10^{-6}	$15.2_5\pm0.3_4$	1.6±0.1	2.8±0.5	1.8±0.3	22

DISCUSSION

Both Meyer[2] and Watanabe[3] assumed that the only way in which the energy loss could change with temperature was through the change in electron density due to the thermal expansion of the specimen. Such a change would have the following form

$$E_f=E_i(1-\tfrac{3}{2}\alpha\Delta T),$$

where E_i is the energy loss at temperature T, E_f is the energy loss at temperature $T+\Delta T$, α is the thermal coefficient of expansion, and ΔT is the change in temperature. In Fig. 2 we have plotted the change in energy loss expected from this equation. This is shown as the solid line. The coefficients of thermal expansion used to plot this curve were taken, for the low-temperature region, from the work of Bijl and Pullan[8] and for the high-temperature region from the work of Wilson.[9] Since in both these articles only the differential thermal expansion coefficients were given, it was necessary to integrate them numerically in order to obtain values referred to room temperature.

It is seen that for temperatures above room temperature, the experimental results fit this theoretical curve within the limits of accuracy of the measurements. The significant result of these measurements occurs below room temperature where we find a surprisingly large deviation from the change expected due to the thermal expansion coefficient. Some effect other than the change in the density of electrons is apparently affecting the energy loss at low temperatures, and one possible explanation may be the change in the dielectric constant of the metal (and, therefore, in the electrical conductivity). We are now investigating this equation, and also plan to extend the measurements to other metals.

ACKNOWLEDGMENTS

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[8] D. Bijl and H. Pullan, Physica 21, 285 (1955).

[9] A. J. C. Wilson, Proc. Phys. Soc. (London) 54, 487 (1942).