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Energy Spectra of Secondary Electrons from Mo and W for Low Primary Energies

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Measurements have been made of the energy spectra of secondary electrons from molybdenum and tungsten using primary voltages, V_p, from 0 to 100 volts. A 127° electrostatic analyzer was used having an experimentally determined resolution of one percent. Primary electrons were decelerated to the required energy while approaching the target. The target was cleaned before each measurement by heating above 2000°K for one second. Measurement of the energy spectrum could be completed before formation of the first monolayer of contamination on the target surface. For V_p above 20 volts, the observed energy spectra, each consisting of a low-energy maximum and a peak of elastically reflected primary electrons, were almost independent of V_p. For V_p below 20 volts, the low-energy maximum became increasingly smaller and narrower and moved upward in energy by approximately 2 volts. For V_p below about 5 volts, reflected primaries remained but secondaries were absent. Similar but not identical results were obtained for molybdenum and tungsten targets.

INTRODUCTION

THE general shape of the energy spectrum of secondary electrons from metal targets is known to be largely independent of the energy of the primary electrons.[1] For primary voltages between 20 and 2000 volts or higher, the energy spectrum of secondary electrons comprises two principal features: the large low-energy peak with its maximum in the neighborhood of two or three volts, and a second narrow peak due to the elastic reflection of primary electrons. The work described here is a study of the change in shape of the spectrum of secondary electron energies as the primary energy is decreased below 20 electron volts. Targets of molybdenum and tungsten were used because these offer the advantage of being more easily cleaned than most other metals.

A number of experimental studies of secondary emission at low primary energies have been reported. Farnsworth[2] demonstrated that the secondary emission yield from a nickel target depended on the cleaning process employed and concluded from measurements of the retarding potential type that only elastic reflection of primary electrons occurred for primary energies below 10 electron volts. Bruining[3] measured the coefficient of elastic reflection of electrons from surfaces of Ag, Ba, and BaO and found it to increase by a factor greater than two as the primary voltage was lowered from 25 to approximately three volts. Gimpel and Richardson[4] observed the yield and energy distribution of secondary electrons from a spherical copper target outgassed at 1000°C and placed at the center of a spherical collector. For primary voltages below 10 volts they observed the total yield to remain constant at about 0.25 and the current being measured to consist almost entirely of elastically reflected primary electrons. Meyers[5] measured the yield and energy distribution from copper and silver films in a vacuum of 10^{-8} mm of Hg using a plane target mounted at the center of a spherical collector. Values of yield differed from that mentioned above but again it was found that only primary reflection occurred below 10 volts.

Three major difficulties are present in measurements made with low primary energies. The first is the problem of obtaining primary electrons at the low voltages desired. This is most easily accomplished by operating the electron gun at a higher voltage and causing the primary electrons to be decelerated as they approach the target. If the target is small in size, the velocity of the primary electrons will drop toward the final value only when they are relatively near the target. The second difficulty is related to the first: it is the general problem of obtaining sufficient secondary current to measure conveniently. In this regard, a high primary current density is necessary to compensate for the low secondary yield at low primary energies and, in the work reported here, to compensate for the fact that only a fraction of the total emission entered the energy analyzer. The third problem is the necessity of having a very clean target surface. At low primary energies, since production of secondaries occurs very near the surface and since the elastic reflection of primary electrons is a significant factor, freedom from contamination of the target surface is more important than is generally the case at higher primary energies.

APPARATUS

The apparatus used for these measurements has been described before[6] so that a brief description will suffice here. In Fig. 1 the system is shown schematically. It consisted of an experimental tube containing electron gun, target, and 127-degree electrostatic analyzer, and

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[1] H. Bruining, *Physics and Applications of Secondary Electron Emission* (McGraw-Hill Book Company, Inc., New York, 1954), p. 104.

[2] H. E. Farnsworth, Phys. Rev. **20**, 358 (1922).

[3] H. Bruining, Physica **5**, 913 (1938).

[4] I. Gimpel and O. Richardson, Proc. Roy. Soc. (London) **A182**, 17 (1943).

[5] H. P. Myers, Proc. Roy. Soc. (London) **A215**, 329 (1952).

[6] G. A. Harrower, Phys. Rev. **102**, 340 (1956).

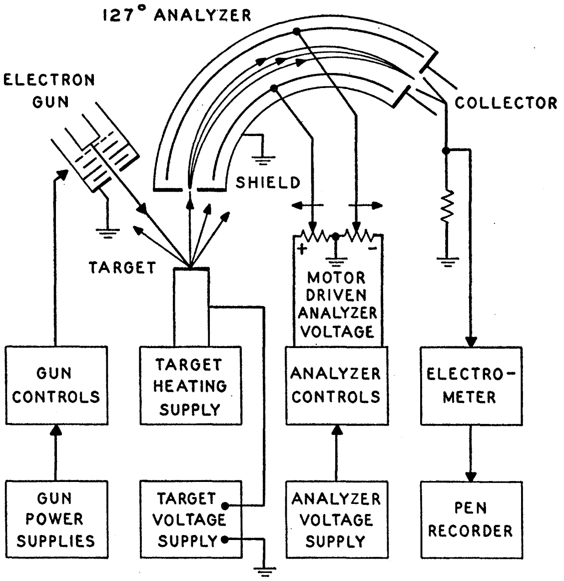

FIG. 1. Schematic diagram of the apparatus used, showing the components of the experimental tube—electron gun, target, and analyzer, and the associated electric circuits. The target was surrounded by a shield held at ground potential (not shown here). During the course of a series of measurements the final anode of the gun, the analyzer shield, and the target shield were at ground potential; the target was held at a fixed voltage so that the field in front of the target was constant; primary electrons struck the target with energy corresponding to the voltage between the cathode of the gun and the target, this primary energy being varied by varying the cathode potential.

the associated power supplies, amplifiers, and a pen recorder. Primary electrons struck the target at 45 degrees and secondaries were observed at 90 degrees to the target surface. The required low primary energies were obtained by operating both the cathode of the electron gun and the target, negative with respect to ground, the anode of the gun and the analyzer being at ground potential. The voltage between target and analyzer was fixed at 20 volts for Mo and 100 volts for W, these values being chosen somewhat arbitrarily. The fixed voltage between target and analyzer caused the observed energy spectra to be shifted by that amount. This served to compensate partially for the variation of the analyzer's sensitivity with energy.[6] The voltage applied to the cathode of the gun was varied to give the primary electrons the desired energy at the target surface. Measurements were corrected for contact potential differences. The voltages applied to the deflecting plates of the 127-degree analyzer were motor-driven and synchronized with the pen recorder so that energy spectra were recorded automatically.

The target was in the form of a ribbon, being 0.125 inch wide and 0.0015 inch thick, and was cleaned by passing a current through it. The cleaning procedure consisted of two stages—first, prolonged preliminary heating (about 15 hours at temperatures of 2000°K for Mo and 2600°K for W) and secondly, a brief heat treatment before each measurement (one or two seconds at 1900°K for Mo and 2400°K for W). The results produced by this second brief heat treatment can be seen in Fig. 2, where pressure in the vacuum system is plotted as ordinate and time as abscissa. Following a one-second flash, the pressure dropped below the normal level because the clean target surface acted as a pump adsorbing gas readily until the first monolayer of contamination had been accumulated. The monolayer adsorption time is inversely proportional to the pressure, being approximately one second at a pressure of 10^{-6} mm of Hg. In the work reported here the target was flashed before each energy spectrum was recorded and the vacuum was subsequently near 5×10^{-10} mm of Hg. Observations like the one shown in Fig. 2, which were made continually, showed that each measurement was completed before a small fraction of a monolayer of contamination had formed on the target surface.

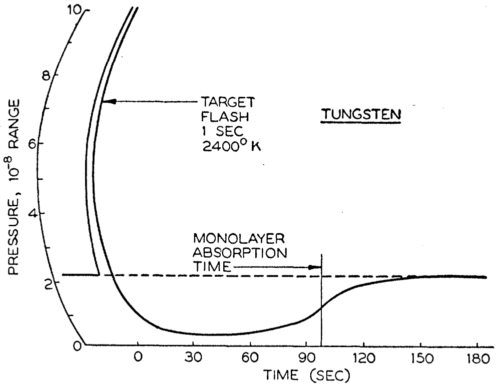

FIG. 2. Pressure in the vacuum system *versus* time following flashing the target. The interval of abnormally low pressure is used to determine the time required for a single monolayer of contamination to accumulate on the target surface. This record was made for display purposes only; actual measurements were taken at much lower pressures and with much longer monolayer adsorption times.

MEASUREMENTS

Energy spectra were recorded for both Mo and W for primary voltages, V_p, between zero and 100 volts, taken at one-volt intervals below 20 volts and at five-volt intervals above 20 volts. Figure 3 provides a representative selection of measured curves for Mo and Fig. 4 does the same for W. In both figures it will be noticed that it was convenient to use more than one scale of electron energy in electron volts on the horizontal axes. Further, it must be emphasized that the vertical heights of these energy spectra were set arbitrarily and curves recorded for different primary voltages cannot be compared with regard to relative heights. This results from the fact that the apparatus did not afford a means of measuring accurately the primary current striking the target.

Several general observations can be made concerning the shape of the energy spectra displayed in Fig. 3 and

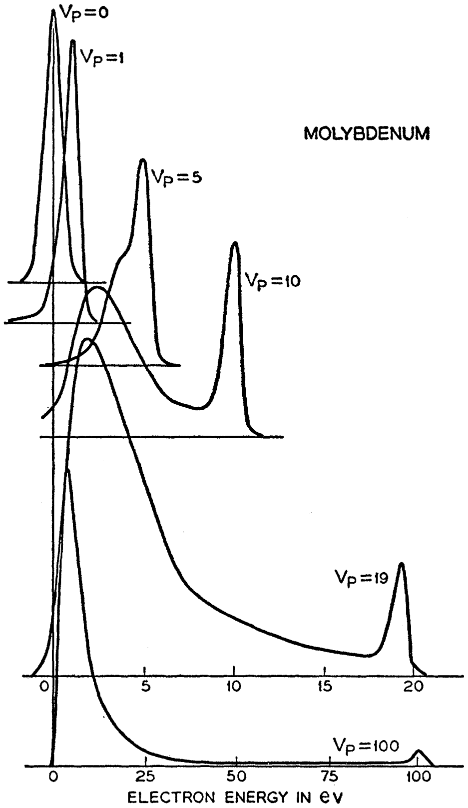

FIG. 3. A representative selection of the energy spectra of secondary and reflected primary electrons from a Mo target for values of primary voltage V_p as indicated. The ordinate is proportional to the number of electrons per unit energy interval and the abscissa is the energy in electron volts of the electrons as they leave the target surface.

Fig. 4. Beginning with the case of $V_p=100$, each spectrum consists of a large low-energy maximum near two or three volts and a small peak of elastically reflected electrons at the primary voltage. This description applied equally well to all cases in which V_p is greater than 20 volts. The spectrum recorded with $V_p=20$ shows the low-energy maximum still located at the same energy but the peak of the elastically reflected primary electrons has become more prominent. As V_p is decreased further, the reflected primary electrons become increasingly more prominent and the low-energy end of the distribution changes considerably. At $V_p=10$, it can be seen that the low-energy maximum has begun to move upward in energy. As V_p is decreased below 10 volts, the low-energy maximum continues to move upward in energy but becomes steadily smaller until it finally disappears. The lowest primary voltages for which secondary electrons are seen to provide a discernable low-energy maximum are $V_p=5$ for Mo and $V_p=7$ for W. Below these primary voltages, the measured energy spectra consist simply of a peak of elastically reflected primary electrons with some spreading on the low-energy side indicating the presence of some inelastic scattering. This effect is seen in the cases shown for $V_p=1$ in Fig. 3 and Fig. 4. Finally, when $V_p=0$ elastic reflection of primary electrons still occurs but the curve is symmetric about the vertical axis, as would be expected, since inelastic scattering is impossible. The width of the curves taken at $V_p=0$ is due mainly to the finite resolution of the analyzer but also to a small spread in primary energy. It was found that if the gun voltage was lowered a small fraction of a volt below the case shown for $V_p=0$, the current of primary electrons entering the analyzer increased greatly—presumably because primary electrons no longer struck the target but were reflected by the retarding electric field in front of the target.

Three of the principal features concerning the shape of the energy distribution for primary energies below 20 volts are illustrated in Figs. 5, 6, and 7. In Fig. 5 the ratio of the height of the low-energy maximum to the height of the reflected primary peak is plotted against primary voltage. For both Mo and W, this

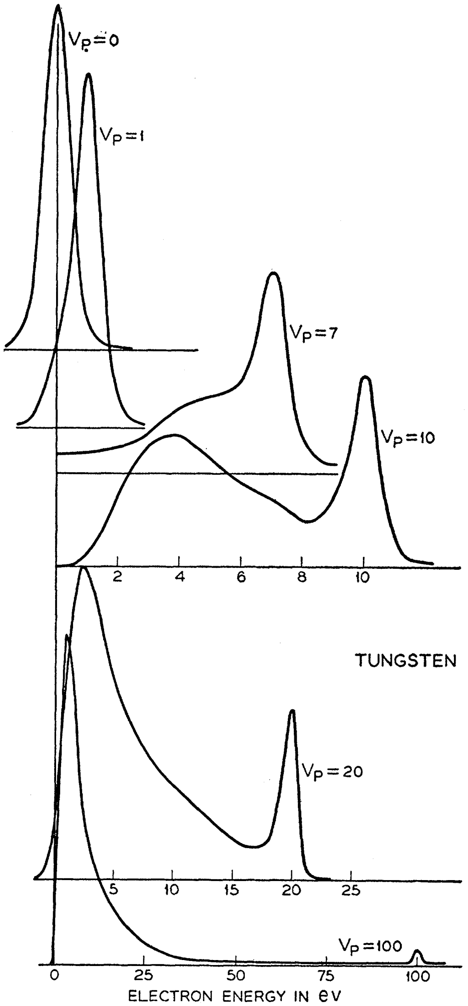

FIG. 4. Measurements for W. See caption for Fig. 3.

ratio drops from approximately three at $V_p=20$ volts to zero at $V_p=5$ volts. Figure 6 shows the change in energy of the low-energy maximum of the energy distribution of secondary electrons plotted against primary voltage. Above $V_p=17$ volts, the position of the low-energy maximum is independent of primary voltage and is in the neighborhood of two or three electron volts. Its absolute position could not be determined with as good accuracy as changes in that position. Below $V_p=17$ volts the position of the low-energy maximum shifts upward in energy, by 2.2 electron volts for Mo and 1.6 electron volts for W. In Fig. 7 the half-width of the low-energy maximum in electron volts, that is, the width at half the maximum height, is plotted against primary voltage. This was done after subtracting the underlying background presumed due to the inelastic scattering of primary electrons. The half-width for *W* remains constant at about 4.5 electron volts while in the case of Mo it decreases from five to two electron volts as the primary voltage is lowered from twenty to five volts.

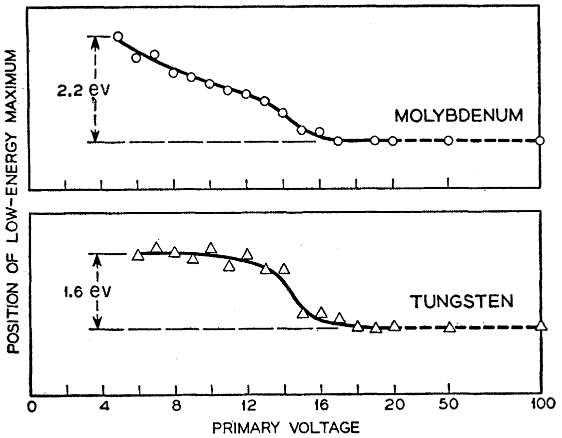

Fig. 6. The change in position of the low-energy maximum occurring for primary voltages below 20 volts. For both metals, above 20 volts the position of the low-energy maximum remains constant at about 2 electron volts.

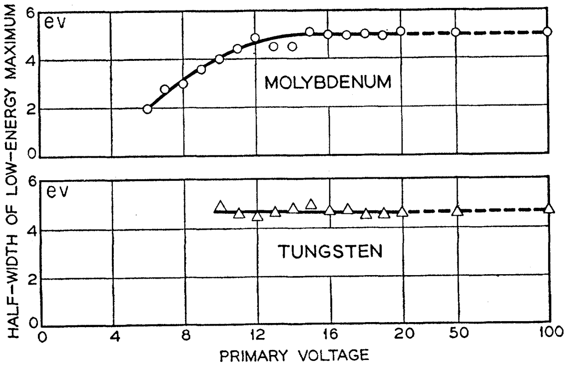

Fig. 7. The width at half the maximum height of the low-energy maximum plotted against primary voltage.

DISCUSSION

It is evident from these measurements that the shape of the energy distribution, although essentially constant for primary energies above 20 electron volts, changes considerably in going to lower primary energies. The most obvious change is the decrease in the number of secondaries being produced as shown in Fig. 5. Presumably fewer secondaries are produced at lower V_p simply because less energy is available. Concerning the position of the low-energy maximum, two extreme cases can be considered. The first and more commonly observed case is that with V_p greater than 20 volts. Here the production of secondaries results from a cascade process as described theoretically by Wolff.[7] In this process, electrons which have received energy from the primaries, scatter repeatedly before reaching the surface, each electron giving up about half its energy, on the average, at each scattering. Wolff has shown that the position of the low-energy maximum of the energy spectrum should be independent of primary energy so long as this energy is sufficient that primary electrons penetrate the target to a depth which allows the secondaries produced to undergo several scatterings before reaching the surface. The second extreme case

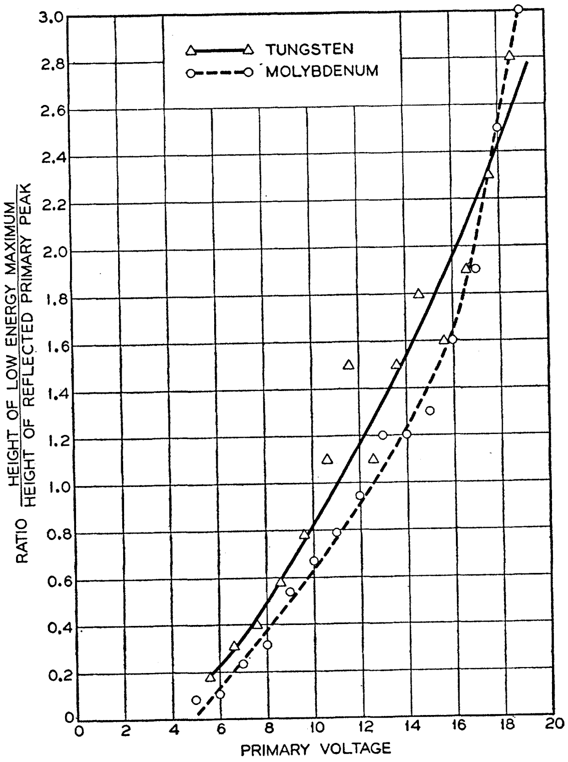

Fig. 5. The ratio of the height of the low-energy maximum to the height of the reflected primary peak plotted against primary voltage for Mo and W.

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[7] P. A. Wolff, Phys. Rev. **95**, 56 (1954).

may be considered to occur when the primary energy is so low that if the primary shares its energy with a second electron, neither electron will have sufficient energy to escape from the target. It was previously pointed out in the discussion of Fig. 3 and Fig. 4 that this occurs for Mo when V_p is less than 5 volts and for W when V_p is less than 7 volts. Only elastic reflection of primary electrons occurs for V_p values lower than these. Between these two extreme cases lies a transitional region which appears from the experiment to be about 10 or 12 volts wide in terms of V_p. The transition is evident in Figs. 5, 6, and 7. In this region it is possible for the primary to undergo a small number of scatterings—probably one or two—and still retain sufficient energy to be able to escape. For V_p greater than 20 volts, statistical theories can be applied but for lower V_p values, single processes must be considered and appropriate theoretical treatment is not available at the present time.

ACKNOWLEDGMENTS

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Multiple Ferromagnetic Resonance in Ferrite Spheres

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Ferromagnetic resonance experiments have been performed on single crystal spheres of manganese and manganese-zinc ferrites placed in field configurations having large gradients in the rf magnetic field at the sample site. Five major and several minor resonant absorptions are observed extending over a region of 700 oersteds at room temperature. The line spacings are essentially independent of sphere size. The absorptions are shown to be attributable to modes of precession of the bulk magnetization of the sample which are more complicated than the spatially uniform precession contemplated by the usual ferromagnetic resonance theory. The lowest order modes are identified and their dynamical properties shown to be consistent with the prediction of an idealized magnetically-coupled-oscillator model.

INTRODUCTION

THE phenomenon of ferromagnetic resonance has been much used as a tool for the investigation of the magnetic properties of ferrite materials. The variation with crystallographic orientation of the field required for resonance yields the crystalline magnetic anisotropy constants. The field for resonance corrected for anisotropy effects gives the magnetic *g* factor. Perhaps most important, the half-width of the resonance in ω or in H may be interpreted according to the theory of Bloembergen[1] or of Landau and Lifshitz[2] to give the characteristic relaxation time of the magnetic system.

Two problems pertaining to this last property have for several years puzzled investigators using conventional ferromagnetic resonance techniques: First, why is it an experimental fact that the resonant absorption is often far from symmetric in shape and may even exhibit clearly defined secondary maxima, especially for larger sample sizes? Second, why are the relaxation times inferred from the line widths so short?

The answer to the first question is contained in the work reported here. Higher modes of ferromagnetic resonance, in which the precessional phase varies from point to point within the sample, are shown to exist and to have fields for resonance in general different from the Kittel value.[3] The "distorted" line shapes and "spurious" secondary maxima may be explained as caused by the accidental excitation of the higher modes of resonance.

Though the answer to the second question is far from contained in the work below, some strong clues are present. Coupling of the ferromagnetic resonance mode of uniform precessional phase to nearly degenerate modes of much higher order may be of great significance in the relaxation process.

APPARATUS

The experimental apparatus used for the resonant absorption measurements is similar in many respects to the recording system described by Tinkham, Solt, Davis, and Strandberg.[4] The system consists of two

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[1] N. Bloembergen, Phys. Rev. **78**, 572 (1950).

[2] L. Landau and E. Lifshitz, Physik. Z. Sowjetunion **8**, 153 (1935).

[3] C. Kittel, Phys. Rev. **73**, 155 (1948).

[4] Strandberg, Tinkham, Solt, and Davis, Rev. Sci. Instr. **27**, 596 (1956).