per micrograph) was determined, and this variance was then used to calculate the expected fraction $f(n)$ on the assumption that the distribution of dislocations obeyed a Poisson distribution. The goodness of fit was then checked using the standard χ^2 test (e.g., Parratt[57]). For example, the distribution for the specimens pulsed to 878°C (see Fig. 6) had a probability of less than 10^{-3} of fitting a Poisson distribution. The main reason for the poorness of the fit is that the measured distribution had a higher fraction of plates with low n values than the calculated Poisson distribution. This result is hardly surprising, since we would expect the dislocations in highly deformed and recrystallized metals to be non-randomly distributed.

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ACKNOWLEDGMENTS

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Electron Emission from Tungsten under Proton Bombardment*

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The yield of electrons from clean polycrystalline tungsten under bombardment by protons at normal incidence has been measured as a function of proton energy in the range 50 to 225 keV. The maximum value of the yield is 1.65 ± 0.03 electrons per proton at a proton energy of 125 keV. The tungsten surface was cleaned by flash heating a tungsten ribbon to 2400°K in a vacuum chamber in which the total pressure was about 2×10^{-10} Torr. The yield was measured with the surface at room temperature, about two minutes after the surface was cleaned, while the time for a monolayer of residual gases to form on the surface was greater than two hours.

INTRODUCTION

ELECTRON emission from solids under ion bombardment can supply information about the surface and bulk properties of solids,[1] and is an important phenomenon in gas discharges and in the measurement of ion currents.

The specification of the surface condition of the target during the measurement of γ, the electron yield per incident ion, is of prime importance, since the presence of absorbed gases may strongly influence the observed value.[2] Hagstrum,[3] and Propst and Luscher[4] have demonstrated the effects of monolayer adsorption on electron ejection from tungsten under bombardment by low-energy ions. Large[5] has measured γ for flashed tungsten targets bombarded by protons in the energy range 10 to 140 keV. In his experiments the residual pressure was about 10^{-8} Torr, and the time to obtain a measurement of γ was of the order of the monolayer coverage time.

In the present work γ was measured with an experimental accuracy of 1%. The residual pressure was about 10^{-10} Torr, and measurements were obtained within a time after flash-cleaning that was less than 2% of the observed time for a monolayer of gas to form on the target. At the time of the measurement, the tungsten surface was covered by no more than a few percent of a monolayer of gas. The electron yield γ was observed to depend on surface coverage by adsorbed gas at less than monolayer coverage.

APPARATUS

The essential components of the apparatus are shown in Fig. 1. The energy of the proton beam was determined by measuring the accelerating voltage on the Cockcroft-Walton accelerator to an accuracy of 0.2%. The proton beam entered the measurement chamber through a 0.30-in.-diam canal of length $\frac{3}{8}$ in., which permitted differential pumping between accelerator and chamber. The beam passed through three apertures of diameters $\frac{1}{16}$, $\frac{3}{16}$, and $\frac{1}{8}$ in., respectively, in the plates marked A, B, and C in Fig. 1. Plate A was grounded and restricted the beam size; plate B was biased 600 V negative to repel stray electrons; and plate C was part of the electrode that collected the secondary currents emitted from the target. The targets were

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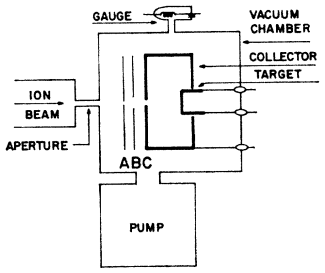

FIG. 1. Experimental arrangement.

0.001-in.-thick tungsten ribbons measuring $\frac{3}{16}\times 1$ in. which extended inside the cylindrical collector electrode.

The vacuum system consisted of a stainless steel chamber, a 125-liter/second sputter-ion pump, and an ionization gauge to measure the system pressure. The chamber was baked at 450°C and the pump at 300°C for 16 h and allowed to cool for 24 h. The residual pressure produced was less than 2×10^{-10} Torr.

The Bayard-Alpert ionization gauge used to measure the system pressure was modified to include a modulator electrode[6] and was mounted inside a 1.5-in.-diam stainless steel envelope cooled by external water coils and shielded against stray magnetic fields. Regulated dc voltage supplies provided grid bias and filament power, and the collector wire was biased to a negative voltage by a battery to prevent collection of electrons from the filament. The fast-response electrometer and oscillographic recorder used to record the pressure during desorption had a characteristic response time of less than 10 msec.

SURFACE TREATMENT

The tungsten surface was cleaned by the flash filament method,[7] in which a high current is passed through the tungsten ribbon to rapidly raise it to a temperature sufficient to drive off all adsorbed contaminants. Reproducible yield measurements were obtained only after extended heating and flashing of the target ribbon in ultrahigh vacuum. Recently, Stern[8] found that his tungsten samples could be freed of carbon contamination only by heating the surface in an oxygen atmosphere. In the present expreiments, the yield values were unchanged after one ribbon was heated to 2000°K for 8 h at an oxygen pressure of 10^{-4} Torr, about 200 times the exposure sufficient to clean Stern's samples. From this result we conclude that carbon contamination of the tungsten surface was a negligible factor in our measurement. The manufacturer's analysis supplied with the tungsten ribbons showed 99.95% tungsten minimum and 0.008% carbon maximum.

A constant voltage (6.0 V dc) applied to the target terminals produced a temperature of 2400°K, measured with an optical pyrometer, within 0.2 sec after application. The ribbon was held at that temperature for an additional 0.1 sec to allow the desorbed gases to be pumped out of the system. A typical profile of system pressure during desorption is shown in Fig. 2. The temperature variation was calculated from the measured current through the ribbon and the known resistivity of tungsten as a function of temperature. The ribbon cooled to near room temperature in about 1.5 min. All of the adsorbed gas is driven off the surface by the flash to 2400°K, so that the quantity of gas desorbed is equal to the amount on the surface just prior to the flash. The quantity of gas desorbed is proportional to the integral of the desorption profile, Fig. 2.[9] Since the shape of the desorption profile did not vary with surface coverage, the height of the curve is proportional to its integral for any surface coverage. Therefore, the maximum pressure rise upon desorption is proportional to the amount of gas adsorbed on the surface. The maximum pressure rise during desorption is shown as a function of time after cleaning the surface in Fig. 3. The amount of gas adsorbed saturated in about two hours at the residual pressure of about 2×10^{-10} Torr with the beam on the target. This saturation time is taken to be the monolayer-formation time.

A more convenient method of obtaining the monolayer-formation time is shown in Fig. 4, a record of the pressure in the vacuum chamber after flash-cleaning the target. Adsorption of gas on the clean ribbon caused the pressure to decrease about 30% below the residual pressure. As the sites on the ribbon available for adsorption became saturated, the pressure rose again to the residual value. The time at which the pressure is midway between its minimum and residual values, indicated by T_m, is about 2 h, which corresponds to the saturation time (or monolayer-formation time) observed in Fig. 3. The optimum flash duration and interval between cleaning flashes were determined by observing this pumping action of the ribbon. About five desorption

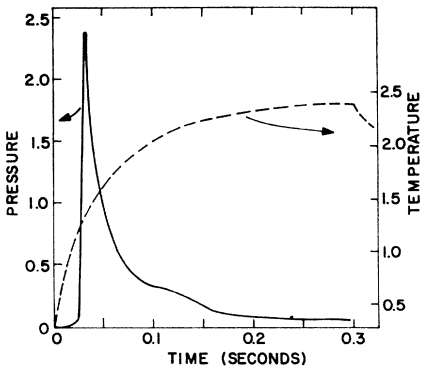

FIG. 2. Typical desorption profile. System pressure (solid curve, units of 10^{-7} Torr) and ribbon temperature (dashed curve, units of 1000°K) during desorption of gas from the tungsten ribbon. Voltage is applied across the ribbon at time=0 for a period of 0.3 sec. Gases were adsorbed on the ribbon for 10 min prior to this desorption, at a pressure of 2×10^{-10} Torr.

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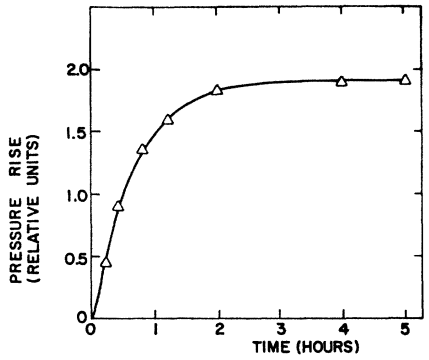

FIG. 3. Maximum pressure rise during desorption, which is proportional to quantity of gas adsorbed, versus exposure time of tungsten surface to residual gases at a pressure of 2.0×10^{-10} Torr.

flashes of duration 0.3 sec, spaced at 5-min intervals, were found to produce the maximum monolayer formation time. The proton current was about 1×10^{-9} A so that the target surface was undisturbed by sputtering or heating due to the incident ion beam.

YIELD MEASUREMENT

The currents to the target and to the collector were measured simultaneously and recorded continuously as functions of time. The target was at ground potential. The collector potential could be varied between -600 and $+600$ V by batteries. Figure 5 shows a typical curve of the ratio of collector current to incident proton current as a function of collector potential. The ratio saturates at a positive voltage at which all the secondary electrons reach the collector. In this case

$$\gamma'=I_c/I_b=I_c/(I_t-I_c) \qquad (1)$$

where I_c, I_b, I_t are the magnitudes of the collector, proton beam, and target currents, respectively.

The ratio also saturates at a negative voltage at which all electrons are suppressed and return to the target. In

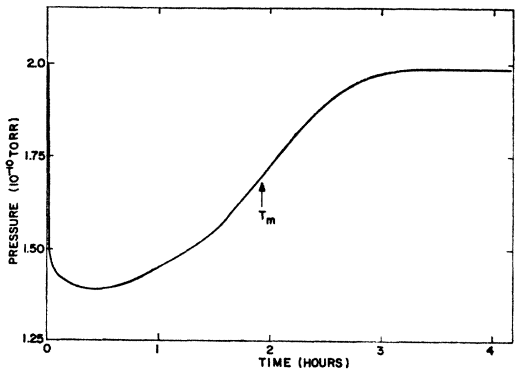

FIG. 4. System pressure versus time after a cleaning flash, illustrating the pumping action of the clean ribbon. T_m is the time at which the adsorption rate is reduced by one-half, which corresponds to the monolayer-formation time. The zero of the pressure scale is suppressed.

that case

$$R'=I_c/I_b=I_c/(I_t+I_c). \qquad (2)$$

The positive current to the collector in case (2) is due to protons reflected from the target to the collector. Protons reflected by a single collision in the target will have essentially the same energy as the incident protons, whereas a reflected proton that has undergone multiple scattering in the target will be degraded in energy. At the bias voltages used in the measurement of γ', most of the reflected protons will have sufficient energy to reach the collector. Thus, in case (1) the collector current is the algebraic sum of the electron current from the target and the current of reflected protons. Therefore

$$\gamma'=\gamma-R \qquad (I)$$

where γ is the average yield of electrons from the target per incident proton and R is the fraction of protons reflected from the target.

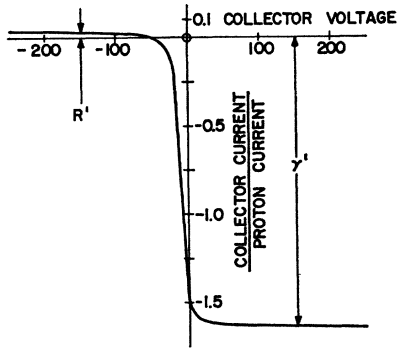

FIG. 5. The ratio of collector current to incident-proton current as a function of collector voltage, for a target at ground potential. Saturation values γ' and R' are discussed in the text. Proton energy = 100 keV.

In case (2) the reflected protons release secondary electrons from the collector which flow to the target, thus increasing the apparent positive current to the collector. In that case

$$R'=(1+\gamma_c)R, \qquad (II)$$

where γ_c is the effective electron yield from the collector per reflected proton that strikes it. The value of the electron emission coefficient is

$$\gamma=\gamma'+R'/(1+\gamma_c).$$

Since R' is only a few percent of γ', the reflected protons introduce only a small uncertainty in γ. An estimate of γ_c was obtained from measurements on a gas covered tantalum surface similar to that used for the collector, and from an estimate of the distributions in energy and angle of the reflected protons. In this case γ_c is estimated to be about 2, so we define

$$\gamma=\gamma'+R'/3. \qquad (III)$$

This estimate introduces an error of no more than one percent in the value of γ.

The currents were measured with vibrating-capacitor electrometers connected to a dual-pen chart recorder. Controls for zero suppression and scale expansion on the recorder allowed magnification of small variations in current signal. The electrometer-recorder system was calibrated by applying a known voltage, measured with a differential voltmeter, to a calibrated resistance in series with the electrometer input. The input resistance of the electrometer was a negligible fraction of the calibrating resistance (less than 0.1%). The measurement accuracy of this method was better than 0.5% for currents in the 10^{-9} A range used in the γ determination.

PROCEDURE

For each target ribbon the system was baked out and the target flashed to 2400°K until a reproducible desorption profile (Fig. 2) was obtained. One of the targets was later heated in oxygen as described above. The accelerator was adjusted to the selected proton energy and beam current, and the target was cleaned and the monolayer time determined. At each proton energy the target cleaning cycle was repeated several times, and the target and collector currents were recorded for several minutes following each cleaning cycle.

RESULTS

A typical record of γ' is shown as a function of time after cleaning the target in Fig. 6. The initial decrease in γ' occurred while electrometer transients introduced by the flash were decaying, and while the target and electrode assemblies were cooling. The constant value between two and four minutes was consistently reproducible and was taken as the clean-surface value. A further decrease in γ' due to adsorption of residual gases became apparent about 4 min after cleaning. This monotonic decrease with surface coverage was observed at all proton energies. As a typical case, for protons of energy 100 keV, γ' decreased from 1.63 for the clean surface to 1.50 for the surface covered by a monolayer of residual gases, while R' did not vary.

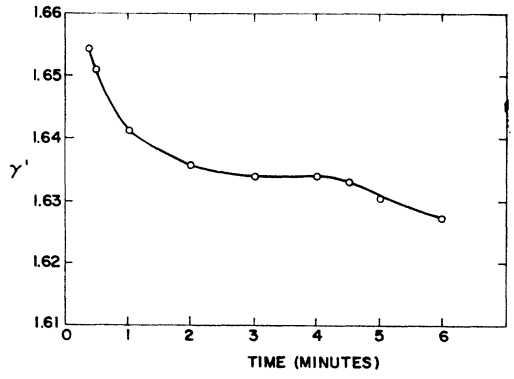

FIG. 6. Variation of γ' with time after cleaning of tungsten surface at a pressure of 2.0×10^{-10} Torr. Proton energy = 100 keV. The zero of the γ' scale is suppressed.

TABLE I. Observed values of γ' and R', the saturation values shown in Fig. 5 and analyzed in Eqs. (I) and (II); and the yield (γ) of secondary electrons per incident proton derived from Eq. (III).

Proton energy (keV)	γ'	R'	γ
50	1.52	0.054	1.54
75	1.61	0.039	1.62
100	1.63	0.029	1.64
125	1.64	0.023	1.65
150	1.63	0.018	1.64
175	1.60	0.015	1.61
200	1.56	0.012	1.56
225	1.53	0.009	1.53

The observed values of γ' and R', and the derived values of γ, are listed in Table I. The values shown are averages obtained for three target ribbons. The maximum variation from these values for any one ribbon was less than 2% for γ' and 5% for R'.

DISCUSSION

While there is no quantitative theory directly applicable to the present experiment, a qualitative understanding of the results is afforded by a theory due to Sternglass,[10] whose conclusions are summarized here. Although free electrons are produced all along the path of the proton in the metal, only those produced in a thin layer near the surface of the metal can reach the surface and be emitted. The depth of this escape zone is only a few atomic layers, which is a small fraction of the proton range in the metal. Thus, the proton energy is essentially unchanged in passing through the escape zone. In addition, neither the depth of the zone, nor the fraction of the free electrons emitted from the escape zone, is strongly dependent on the proton energy. In this view, the observed γ, and its variation with proton energy, is proportional to the cross section for free-electron production in tungsten by protons. This view is given added credence by the fact that the differential energy-loss cross sections for protons in metals exhibit maxima near the maximum of γ observed here, 125 keV.[11] The variation of γ as gas is adsorbed on the tungsten surface may be due to the difference between the cross section for free-electron production in the gas and in tungsten, or may be caused by a change in work function of the surface, since the work function determines the transmission of free electrons from the metal to the vacuum.

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