Energy transfer to a tungsten lattice by ion bombardment

Harold F. Winters and Donald Horne
IBM Research Laboratory, San Jose, California 95193
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The energy transferred to a tungsten lattice under bombardment by noble-gas and nitrogen ions has been measured for energies between 25 and 600 eV. A linear relationship was found between the energy transferred and the initial kinetic energy over the entire range for Xe^+ and Kr^+ and between 150 and 600 eV for N_2^+ and 75 to 600 eV for He^+. A nonlinear relationship was found for Ne^+ and Ar^+ over most of the energy range. The fractional energy transferred was found to be between 0.4 and 0.6 for all gases measured. It is shown that the experimental data can be qualitatively explained on the basis of the binary-collision model.

I. INTRODUCTION

In an ion-solid collision, the amount of energy transferred to the lattice (E_{tot}) is an important parameter in such diverse fields as sputtering, radiation damage, the kinetic ejection of electrons, gas incorporation into thin films, and ion pumping. Nevertheless, there has to our knowledge only been two sets of measurements. One involved the bombardment of several targets with 30–70-keV ions[1] and the other bombardment of molybdenum with noble-gas ions whose energy was between 300 and 900 eV.[2]

The experiments reported in this paper had a threefold motivation: (i) to determine whether it was probable that E_{tot} would influence the functional dependence of the sputtering yield on ion energy, (ii) to determine whether the characteristics of energy transfer could be described at least qualitatively on the basis of the binary-collision model, and (iii) to determine whether reflected energetic neutrals were as important as previously assumed for gas incorporation into sputtered films.[3] It will be shown that the answer to all of these questions is in the affirmative.

II. EXPERIMENTAL: DESCRIPTION

The energy-transfer experiments described in this paper are conceptually simple. The experimental tube is shown in Fig. 1 and a schematic diagram of the control electronics is shown in Fig. 2. Two tungsten filaments were made part of a bridge circuit. A small 10-kHz reference signal was applied to the bridge and its imbalance detected by a lock-in amplifier. The resistance and thus the temperature of the bombarded filament was maintained constant by using the signal developed across the bridge to control a feedback circuit which provided dc heating current. The dc current was measured by determining the voltage between points A and B (see Fig. 2).

When energy is supplied to the filament by the impinging ions, the dc current is decreased in a manner so as to keep the temperature constant. Figure 3 shows the heating current both with and without ion bombardment for energies of 100 and 150 eV. This heating current is subsequently squared and then averaged electronically to obtain the final data. Figure 4 shows a block diagram of the apparatus.

The constant temperature feature eliminates many errors because the energy conducted away through the filament support rods, the energy radiated, and the energy loss due to gas surface interactions is independent of whether the filament is being bombarded or not. Since the energy losses are constant, the decrease in power due to i^2R heating is exactly equivalent to the power contributed by ion bombardment. A sensitivity of about 1 μW has been obtained using this technique. The ion current to the bombarded filament is measured, hence the energy input per ion can be determined.

Tubes similar to the one shown in Fig. 1 have been described previously and only a brief description will be given here.[4] Two 0.005-in. spiral tungsten wires (F_1, F_2) whose lengths were 22 cm were mounted symmetrically with respect to the electron beam. The wires were terminated at each end by a straight portion whose length was 0.8 cm. This part of the wire was placed through a 4-mm hole in a metal guard ring and then connected to the filament support rods. The guard ring was biased to prevent bombardment near the filament ends. The filament used as a standard (see Fig. 2) was shielded so that it did not collect any ions. It should be noted that previous experiments on gas sputtering indicate that bombardment is relatively uniform in this geometry.[5] Standard ultrahigh vacuum techniques were employed and have been previously described.[4]

Electrons are accelerated from the indirectly heated cathode F_e into region V and collected at electrode H. Electrode K was typically held 5 V positive, and electrodes J and L held 5 V negative with respect to C through H. This arrangement provides a small drawing out field for ions without

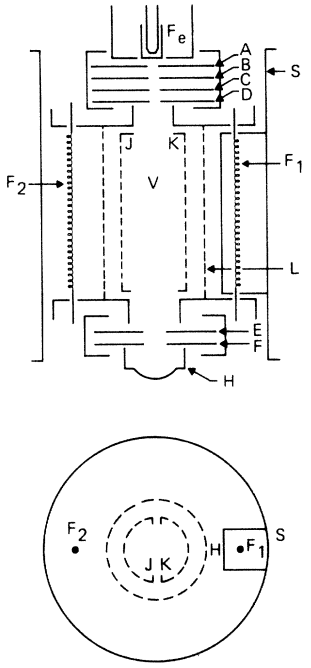

FIG. 1. Schematic diagram of experimental tube. F_1 is the standard filament which was shielded from the ions.

drastically altering their energy distribution. Retarding potential measurements indicate that the energy spread of ions arriving at electrode S was about 5 eV. A magnetic field of 100–200 G was used to focus the emitted electrons.

Under our experimental conditions, it was demonstrated that the measured values for the energy transferred per incident ion were independent of

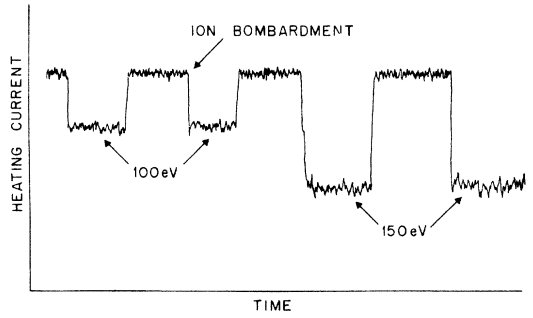

FIG. 3. Heating current vs time. The sharp drop in the heating current occurs when ion bombardment is initiated.

electron energy, the initial dc heating current, and the bombarding ion current. Figure 5 shows the energy transfer as a function of ion current for the noble gases at 300 eV.

Figure 6 shows the energy input as a function of pressure for Kr. The data for the other noble gases were similar. The slight pressure dependence is due to charge exchange which occurs in the region between electrodes S and L. In order to obtain enough ions, we were forced to operate in a pressure region where charge exchange was important. For this reason, the data were taken as a function of pressure and then extrapolated to zero.

The experiment was conducted under conditions where all of the secondary electrons leaving the tungsten wire were collected by the surrounding electrodes. This was demonstrated by heating the tungsten wire until thermionic emission occurred and then showing that the emission was independent

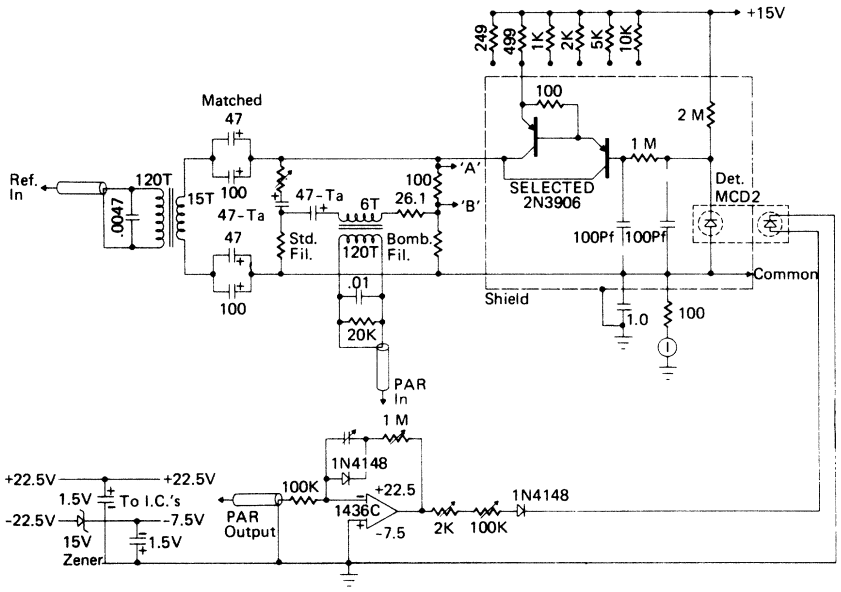

FIG. 2. Schematic of control electronics. Transformers wound on Ferroxcube Toroid K300-502/3E with No. 24 wire, 2N3906's selected for high beta at 100-μA collector current.

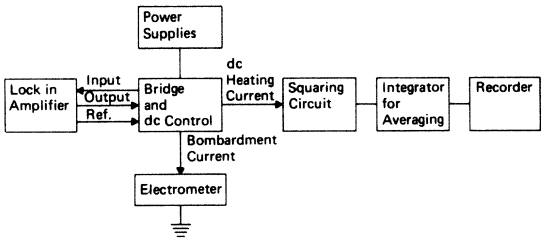

FIG. 4. Block diagram of electronics.

of magnetic field and applied bias voltage. Consequently, the well-known secondary-electron coefficients found in the literature[6] could be used to determine the actual number of bombarding ions.

One of the important parameters which is only determined within limits in these experiments is the angle of incidence of the bombarding ions. The energy transfer should be a fairly strong function of this parameter, as has been demonstrated by Oechsner and Andersen.[1,2] In order to determine the extent of this problem, sputtering-yield measurements were made on tungsten and compared with similar measurements for normally incident ions found in the literature.[7,8] This measurement was made by weighing the spiral wires both before and after bombardment. The data of Table I show that both the absolute magnitude and the energy dependence of the sputtering yields are equal to those found in the literature. Oechsner has recently shown, that for 1-keV Ar^+, changing the angle of incidence from 0° to 30° causes ~12% increase in the sputtering yield.[9] Since our yield measurements are within 12% of those obtained for normal incidence, we believe that on the average our angle of incidence is $< 30° - 40°$.

The sensitivity of energy transfer to angle of incidence may be greater than that of the sputtering yield in which case our measurements might be somewhat smaller than would be obtained at normal incidence.

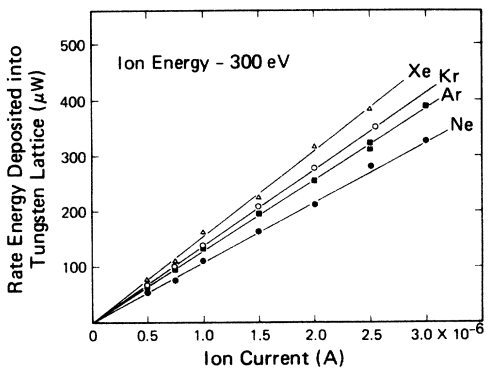

FIG. 5. Rate of energy deposition vs ion current. The data are not corrected for pressure or secondary-electron emission.

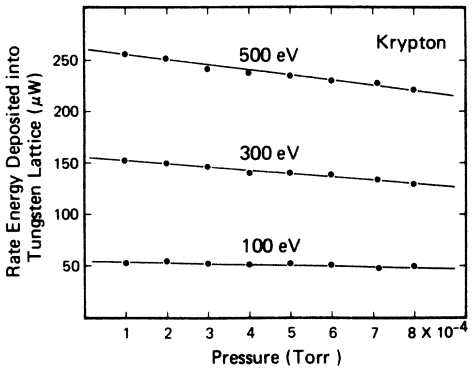

FIG. 6. Rate of energy deposition vs pressure.

III. DISCUSSION AND RESULTS

A. Experimental results

Figures 7 and 8 show the energy transferred to the tungsten lattice as a function of the initial kinetic energy. The relationship is linear for Kr and Xe over the entire range and is linear for all the noble gases below 100 eV with the exception of helium. The results for N_2 and He show curvature at low energies and become linear at high energies. The opposite result is observed for Ne and Ar.

Figure 9 shows the absolute magnitude of the ratio of the energy transferred to the lattice divided by the total energy of the ion as a function of kinetic energy. The data have been extrapolated to zero pressure and corrected for secondary emission. The values for all the noble gases are between 0.4 and 0.6. Moreover, in a subsequent section it will be shown that the fractional part of the kinetic energy transferred to the lattice is mass dependent where the largest energy transfer occurs when $\alpha = 4m_1m_2/(m_1+m_2)^2$ is largest.

In the following portions of this paper we will attempt to explain (a) the absolute magnitude and mass dependence of energy transfer and (b) why a linear relationship between energy transfer and kinetic energy is observed for Kr and Xe and a nonlinear one for He, Ne, and Ar.

B. Background and assumptions

The binary-collision model assumes that an energetic ion interacting with a solid loses its energy in a series of elastic collisions where each collision involves only two particles. This approximation has been used extensively in theories involving sputtering, radiation damage, and the penetration of ions into solids (range theory).[10] Experimental

TABLE I. Comparison of sputtering yields.

Ion energy (eV)	Neon		Argon		Krypton		Xenon	
	This work	Wehner	This work	Wehner	This work	Wehner	This work	Wehner
150	0.06	0.07	0.14	0.18	0.20	0.20	0.24	0.20
300	0.18	0.17	0.39	0.40	0.57	0.58	0.67	0.60
500	0.25	0.27			0.91	0.92	1.12	1.02

verification for its validity has been most clearly demonstrated for ion scattering from surfaces where, for example, the energy loss of scattered He^+ and Ne^+ is accurately predicted for initial energies down to at least 100 eV.[11,12] For some of the other noble gases the data are more ambiguous and it has been suggested by Heiland *et al.* that for the scattering of heavy ions below 1 keV the binary-collision approximation is insufficient.[13] A similar conclusion was drawn by Gay and Harrison from their results with a computer simulation of the scattering of Cu atoms by a copper lattice.[14] On the other hand, Karpuzov and Yurasova have recently simulated reflection of 50–500-eV argon ions from a copper crystal and concluded that ion reflection is adequately described by the binary-collision model.[15] For the purposes of this paper we will assume that the binary approximation is valid and compare our experimental results with expressions derived from this assumption.

For calculations presented in this section assumptions are made (i) about the differential cross section for energy transfer, (ii) that the material is randomly oriented, and (iii) that the binary-collision approximation is valid.

The interaction potential from which the probability of a given energy transfer is derived is not accurately known for the low-energy region of interest in this paper. Furthermore, the nature of the potential functions is usually such that severe approximations are required for a solution in closed form. A hard-sphere potential has been used extensively in the past for interactions in the low-energy range (see Ref. 9 for a discussion of this subject). For a similar energy range, Sigmund has suggested a differential cross section where the probability of transferring energy between T and $T+dT$ to a target atom is given by

$$d\sigma = \tfrac{1}{2}\pi\lambda_0 a^2 (dT/T) \ . \qquad (1)$$

This results from a power-law approximation to the Born-Mayer potential.[16] λ_0 and a are constants for which Sigmund suggests values of 24 and 0.219 Å, respectively. Robinson has derived by numeri-

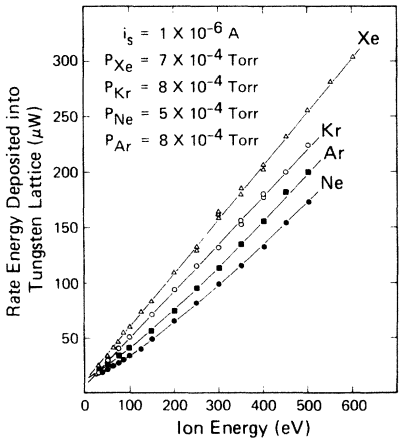

FIG. 7. Rate of energy deposition vs the initial kinetic energy of the ions. The data have not been corrected for secondary emission or pressure. i_s is the bombarding-ion current.

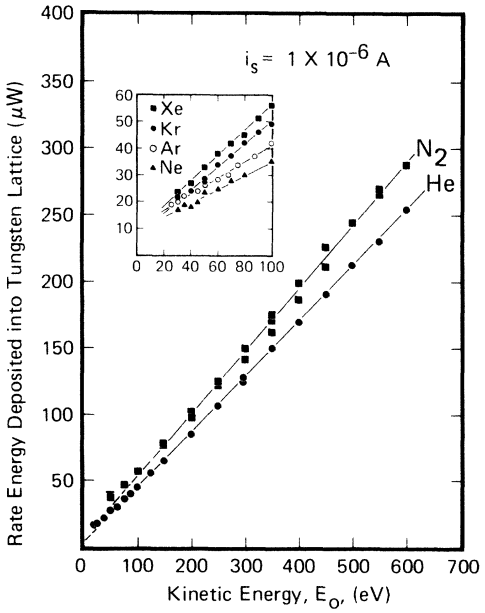

FIG. 8. Rate of energy deposition vs the initial kinetic energy of the ions. The data have not been corrected for secondary emission or pressure. i_s is the bombarding-ion current.

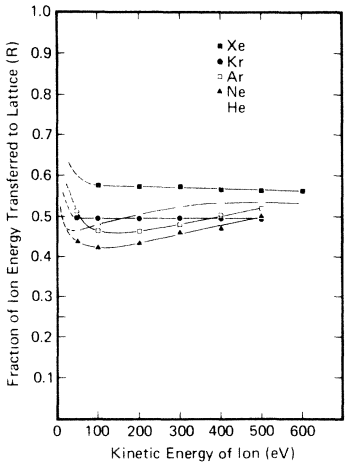

FIG. 9. Fraction of energy transferred to lattice vs initial kinetic energy. The data have been corrected for secondary emission and to zero pressure, $R = E_{\text{tot}}/E_0 + E_I$.

cal Firsov inversion the exact potential corresponding to this type of cross section and shown that it varies exponentially for small separations but falls more rapidly at large distances.[17]

It is evident the total cross section $\int_0^\infty d\sigma$ is infinite, hence, for our purpose it will be cut off at a lower limit $\alpha\Delta(E_0)$, where Δ can be made arbitrarily small. This is equivalent to neglecting small-angle scattering. For this cross section

$$g(E_0, E_1)\,dE_1 = (E_0 - E_1)^{-1}\,dE_1 \Big/ \int_{(1-\alpha)E_0}^{(1-\alpha\Delta)E_0} \frac{dE_1}{(E_0 - E_1)}$$

$$= (E_0 - E_1)^{-1}\,dE_1 / \ln(1/\Delta)\ . \qquad (2)$$

Note that by definition, $T = E_0 - E_1$. Calculations will be made using the potential suggested by Sigmund although the arguments would be identical for the hard-sphere potential.

C. Probability distribution function

Let $G(E_0, E_n)$ be the probability distribution function for finding primaries of initial energy E_0 between energies of E_n and $E_n + dE_n$ after n collisions [see Eq. (2) for $g(E_0, E_1)$], then[18]

$$G(E_0, E_{n+1}) = \int\int\int g(E_0, E_1) \times g(E_1, E_2)\ldots g(E_n, E_{n+1})\,dE_1\,dE_2\ldots dE_n$$

$$= \int G(E_0, E_n)\,g(E_n, E_{n+1})\,dE_n\ . \qquad (3)$$

The average energy of the primary ion after $n+1$ collisions is given by

$$\langle E_{n+1}\rangle = \int G(E_0, E_n) \times \left[\int E_{n+1} g(E_n, E_{n+1})\,dE_{n+1}\right] dE_n\ , \qquad (4)$$

where, of course, $g(E_n, E_{n+1})$ has the same functional form as $g(E_0, E_1)$. For both the hard-sphere and power-law approximations the term in the brackets is given by a function of α times E_n, i.e., $f(\alpha)E_n$. Therefore,

$$\langle E_{n+1}\rangle = f(\alpha)\int E_n\,G(E_0, E_n)\,dE_n = f(\alpha)\,\langle E_n\rangle = [f(\alpha)]^{n+1}E_0\ . \qquad (5)$$

Consequently, the average kinetic energy transferred to the lattice after $n+1$ collisions is given by

$$E^t_{n+1} = E_0\{1 - [f(\alpha)]^{n+1}\}\ , \qquad (6)$$

where the superscript t indicates energy transferred. For the power-law approximation,

$$f(\alpha) = \left(1 - \frac{\alpha(1-\Delta)}{\ln(1/\Delta)}\right). \qquad (7)$$

It should be noted that Eq. (6) contains no adjustable parameters. The quantity $\langle E_n\rangle/E_0$ is plotted as a function of the number of collisions, n, in Fig. 10 for several values of α.

The derivation of Eqs. (4)–(7) assumes that none of the bombarding ions have been reflected from the surface which clearly does not coincide with the experimental conditions. However, in the following section it will be shown that Eq. (6) can be used to interpret the results in an approximate way.

The deflection angle (θ) in the c.m. system is given by Eq. (8) for the power-law approximation,[16] where p is the impact parameter:

$$\theta_{PL} = 2\sin^{-1}(\exp - p^2/\lambda_0 a^2)\ . \qquad (8)$$

θ is independent of E_0. The scattering angle for the first collision determines the point of impact for the second collision where θ is again independent of E_0. Reasoning of this type indicates that the trajectories of the particles and therefore the number of collisions suffered by each particle prior

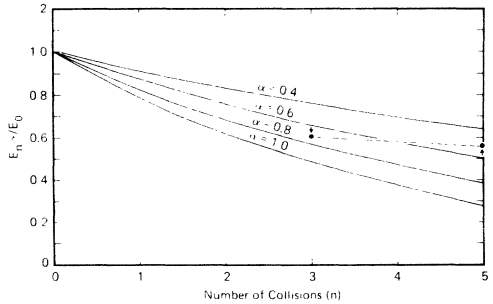

FIG. 10. Ratio of average energy of primary particles/initial kinetic energy as a function of the number of collisions. The dashed curve schematically represents the average energy of backscattered particles/initial kinetic energy as a function of n; $\Delta = 0.01$.

to backscattering are not functions of E_0 for the potential used in this section. Since θ is independent of E_0 at every collision, so is the fractional amount of energy transferred given by

$$T/T_m = \sin^2 \tfrac{1}{2}\theta \ .$$

T_m is the maximum possible energy transfer. This leads to the very important conclusion that the average kinetic energy transferred to the lattice is a linear function of E_0, i.e.,

$$E_{av} = kE_0 \ , \tag{9}$$

where k is a constant. This can be written

$$E_{av} = a_n\{1 - [f(\alpha)]^n\}E_0 \ , \tag{10}$$

where

$$a_n = k/\{1 - [f(\alpha)]^n\} \ .$$

To estimate the magnitude of a_n, additional insight into low-energy scattering processes is needed. Kornelsen has measured the trapping probabilities for noble-gas ions on tungsten and found that in the low-energy range, dependent on the gas, the trapping probabilities were very small, i.e., most of the ions were reflected from the surface as neutrals.[19] It is reasonable to believe that the lack of trapping implies that energetic particles are not penetrating the lattice. This interpretation is consistent with the computer simulated results of Pryde *et al.*[20] This being the case, the scattering process involves only a few collisions with atoms on the immediate surface. A second consequence is that one expects a laboratory angle greater than 90° to lead to reflection. This will not necessarily be the case when the ion has penetrated the lattice. The assumption that scattering at low energies involves only a few collisions with atoms on the immediate surface is crucial to the conclusions drawn in the following sections of this paper.

Forward scattering is known to be highly probable and therefore most particles will have at least two collisions. The average fractional energy transferred to a tungsten atom in one collision (T/T_m) is 0.215 for $\alpha = 0.35$ and $\Delta = 0.01$. This yields a c.m. scattering angle of ~ 56° and a laboratory angle of 50°. For $\alpha = 1$ and $\Delta = 0.01$ the respective angles are ~ 56° and 27°, respectively. The choice of $\Delta = 0.01$ is an implicit assumption that scattering events where the c.m. scattering angle is less than ~ 12° are unimportant. Because of the small laboratory angles it is expected that the average ion will suffer more than two collisions before being backscattered. On the other hand, it is difficult to visualize a sequence of collisions which would result in the average particle suffering more than four or five collisions in the absence of lattice penetration. However, if $m_1 > m_2$ then the laboratory angles would be small and lattice penetration should become much more probable which in turn should lead to a large number of collisions.

Let r be chosen so that very few particles are backscattered before the rth collision and let q be chosen so that most particles are backscattered at or before the qth collision. If all particles were backscattered at the nth collision then from Eq. (5) $(E_0 - E_{av}) = \langle E_n \rangle$. Therefore since most particles are backscattered between the rth and qth collision we have

$$\langle E_r \rangle > (E_0 - E_{av}) > \langle E_q \rangle$$

and

$$E_r^t < E_{av} < E_q^t \ . \tag{11}$$

The substitution of Eqs. (6) and (10) into Eq. (11) followed by some algebraic manipulation yields

$$\frac{1 - [f(\alpha)]^r}{1 - [f(\alpha)]^n} < a_n < \frac{1 - [f(\alpha)]^q}{1 - [f(\alpha)]^n} \ . \tag{12}$$

If n is chosen midway between r and q then a_n is a constant of order unity when q is a reasonably small integer.

The choice of values for r and q is somewhat arbitrary at best and in the case of the power-law potential depends on the cutoff energy Δ. However, if r is chosen so that an ion suffering an average energy loss at each collision has a total laboratory angle less than 90° and if q is chosen so that the total angle is substantially greater than 90°, then much of the ambiguity disappears. Based on these arguments it is expected that $p = 2$ and $q = 5$ are reasonable estimates which suggest a value of $n \cong 4$. Even in extreme cases for the power-law potential with $\Delta = 0.01$, it is not expected that the choice of $n = 4$ and $a_n \cong 1$ will introduce an error greater than ~ 50%.

It should be noted that n and hence a_n are in reality functions of α, however, in light of the arbitrariness already involved in the choice of n it is not believed that attempting to determine this dependence would substantially improve the accuracy of the estimate given in this paper.

Let $\gamma_1 E_I$ be the amount of energy derived from the ionization potential which is transferred to the lattice and let $\gamma_2 E_a$ be the sorption energy transferred to the lattice. The term sorption energy is used to mean the interaction energy due to chemical binding forces. γ_2 is the probability that an incident ion will be sorbed. The total average energy transferred to the lattice is then given by

$$E_{tot} = a_4\{1 - [f(\alpha)]^4\}E_0 + \gamma_1 E_I + \gamma_2 E_a - E_S \ . \tag{13}$$

E_S is the energy carried away by sputtered particles and the kinetic energy is obtained from Eq. (10). It should be noted that the quantities calcu-

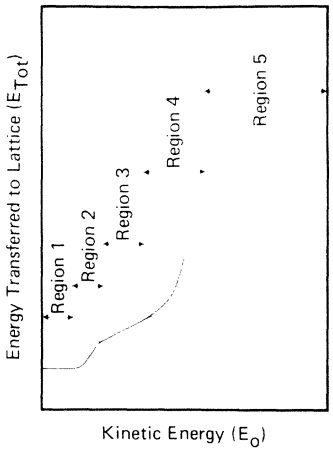

FIG. 11. Schematic illustration of the functional relationship between the energy transferred to the lattice and the initial energy.

lated in this paper are closely related to the quantity defined as sputtering efficiency where the crucial paper is that of Sigmund.[21] E_S will be small compared to E_{tot} and $E_a \sim 0$ for the noble gases and is constant for the active gases. Therefore, the last two terms in Eq. (13) can be considered for our purposes independent of E_0.

Most of the excitation energy E_I is transferred to the lattice but some is carried away by secondary electrons and reflected neutrals. The fact that some fraction of E_I can become part of the kinetic energy of a reflected neutral is illustrated by the following example. Consider an ion initially at rest which approaches the surface as the result of the image potential. It may have a kinetic energy of 1–3 eV when the neutralization reaction occurs and by analogy with the previous discussion some of it will not be transferred to the lattice.

Since the energy distribution of secondary electrons is relatively independent of E_0 and the fraction of E_I carried away by neutrals small,[6] and by analogy with the data of Fig. 7 approximately constant, we can safely assume that $(\gamma_2 E_a + \gamma_1 E_I - E_S)$ is only a slowly varying function of E_0 and therefore for our purposes considered constant. Therefore

$$E_{tot} = a_4\{1 - [f(\alpha)]^4\}E_0 + k \ , \qquad (14)$$

where k is a new constant and $a_4 \sim 1$. Equation (14) is the expression which will be used to interpret the experimental data.

We are now in a position to schematically illustrate the predictions of the model (see Fig. 11). For values of E_0 in the eV range, the effective mass of the target atom may be large, i.e., $\alpha \ll 4m_1m_2/(m_1+m_2)^2$ and therefore $E_{tot} \cong k$. This is called region 1 in Fig. 11. The effective-mass concept will be discussed in more detail in a later section. At higher energies a region is expected where there is little lattice penetration and $\alpha = 4m_1m_2/(m_1+m_2)^2$. From Eq. (14) we expect a linear relationship between E_{tot} and E_0 with an intercept at k. This is designated region 3. At very high energies most particles are trapped in the lattice and we expect a linear relationship with a slope close to unity.[21] Region 4 is a transition where lattice penetration becomes important and the average number of collisions suffered by a particle is continually increasing. Region 2 is another transition which goes from a value of E_0 where lattice binding forces are important to a value where the binary approximation is valid.

In reality region 4 may consist of a series of linear segments because of the various energies where the two body interaction can be described by a power-law potential, the sputtering efficiency is independent of energy.[21] This probably accounts for the linearity of helium and nitrogen for energies between 100 and 500 eV (see Fig. 8).

D. Comparison of model with experiment

Figures 7 and 8 show the experimental relationship between the energy transferred to the lattice and the initial energy of the bombarding ions. Let us first focus our attention on Xe and Kr where we find a linear relationship between E_{tot} and E_0 for $25 < E_0 < 600$ eV which implies that the measurements are all made in region 2 (see Fig. 11). The strict linearity is in good agreement with Eq. (14).

When lattice penetration becomes significant the average number of collisions suffered by an impinging ion will increase substantially, and furthermore, backscattering may not lead to reflection and hence the average energy transfer should increase. This is precisely what is observed for He, Ne, Ar, and N_2 in Figs. 7 and 8. There is a linear relationship corresponding to region 3 at low energies and behavior corresponding to region 4 at higher energies. The regions where curvature is greatest corresponds to values of E_0 where Kornelsen has found large changes in sticking probabilities.[19] It should be noted that the sticking

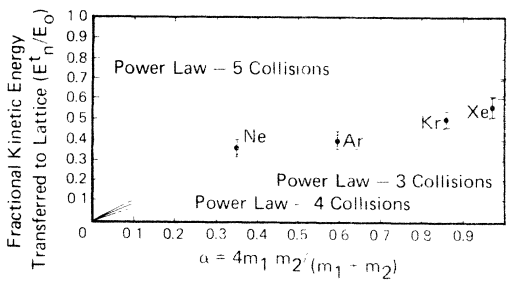

FIG. 12. Fractional kinetic energy transferred to the lattice as a function of α. The solid lines are calculations based on Eq. (10). The experimental points have been corrected for secondary emission and to zero pressure $a_n = 1$.

probabilities of Kr and Xe are small over the entire energy range, hence the linear relationship. It should also be noted that we are going from a region of no penetration to a region of penetration which shows that the assumption that θ is independent of E_0 is not completely correct.

Figure 8 shows the power input as a function of E_0 for $E_0 < 100$ eV. There are three conclusions one can draw from these data: (a) There is for all gases except helium a linear relationship as expected between E_{tot} and E_0; (b) there is no conclusive evidence for a transition region like region 2 in Fig. 11; and (c) the intercept for most of the curves is between 8 and 15 eV. The intercepts should approximate the fraction of the ionization energy transferred to the lattice, i.e., $\gamma_1 E_I$. These values appear to be a bit lower than one might expect; however, the uncertainty in the experimental values for E_0 are of such a magnitude that we hesitate to draw this conclusion. More work is needed to clarify this point.

The quantity E_n^t/E_0 from Eq. (6) is shown as a function of α in Fig. 12. The experimental values were obtained from the initial slope (region 2) of experimental curves similar to those shown in Fig. 8 but corrected to zero pressure. The data for helium are not plotted since penetration is believed to be a problem over the entire energy range.[22] It is clear from this figure that the experimental values for energy transfer are about the magnitude expected assuming the binary model.

Both Eq. (14) and the experimental results (see Fig. 12) indicate that energy transfer increases with increasing α. On the other hand the experimental values do not increase as fast as one would expect. A straightforward interpretation of the data shown in Fig. 12 suggests that neon has on the average more collisions than Xe. The opposite result is intuitively expected since lighter mass particles are more easily backscattered.

Smith and Carter have simulated on a computer the backscattering of Kr^+ from tungsten.[23] Their calculated values for energy transfer appear to be higher than our values. The reason for the discrepancy is not clear.

E. Miscellaneous experimental results

1. Effect of radiation damage

Helium is not expected to produce displacement of tungsten atoms until $E_0 > 400$ eV. Therefore the following experiments were undertaken. The energy transferred for He ($E_0 < 400$ eV) was measured on a freshly annealed wire. The wire was then bombarded with 1×10^{16} 300-eV Ar^+ ions which should have produced displacements in the tungsten lattice and allowed some argon to be trapped. The energy transfer for He was again measured and found to be the same as the previous measurement thus indicating that radiation damage does not produce gross changes in the amount of transferred energy.

2. Effect of nitrogen adsorption

Energy-transfer measurements for He were made with both the presence and absence of an adsorbed monolayer of nitrogen (5×10^{14} atom/cm^2). The results were the same in both cases. In another experiment the tungsten was bombarded with 600-eV N_2^+ until a layer of altered chemical composition was formed where the nitrogen concentration was (8×10^{15} atom/cm^2).[24] The energy transfer for Ne and Xe was measured and found to agree with the results for clean tungsten. We suspect that there should be a change due to these sorbed layers but that it was probably small and hidden by our experimental error.

F. Implications for binary-collision model

When the energy of the incident ion is low there will be considerable interaction between this ion and target atoms other than the one considered to be struck, i.e., the assumption of a series of binary collisions is no longer valid and a model for collective interactions is needed. Arifov[25] and Gurvich[26] have considered this problem in detail and their work has been summarized by Carter.[9] They conclude that the collective interaction can be approximated by solving a two-body problem where the effective mass of the target atom increases as E_0 decreases. At low energies the target begins to act as a macromolecule rather than a collection of isolated atoms. This being the case the fractional kinetic energy transferred to the lattice should decrease. This effect should be greater for the heavier noble gases since they have a larger radius and are moving slower. Our data give no indication of a change in collision mode down to 25 eV for Kr and Xe (see Fig. 7). This at least suggests that the binary approximation is valid down to this energy which also agrees with the computer simulated results of Karpuzov *et al.*[15]

G. Comments on average energy of particles backscattered at nth collision

Let $\bar{V}_n$ be the average energy of particles backscattered during the nth collision and $\bar{V}_n'$ be the average energy of those who have suffered n collisions without being backscattered. It will be assumed that no particles are backscattered during the first two collisions and that all particles have been backscattered after five collisions.

Particles which have suffered large energy losses are more likely to be backscattered than those with small losses, therefore from Eq. (5)

$$\overline{V}_3 < \langle E_3 \rangle < \overline{V}_3' \ . \tag{15}$$

Since predominantly low-energy particles will be backscattered during the next two collisions and since all remaining particles are backscattered during the fifth collision,

$$\langle E_5 \rangle < \overline{V}_5' = \overline{V}_5 \ . \tag{16}$$

Equations (15) and (16) show that the function $\overline{V}_n/E_0$ changes more slowly than $\langle E_n \rangle/E_0$. This is illustrated schematically by the dashed curve in Fig. 10. This illustration suggests that the average energy of backscattered particles is a very weak function of n and could conceivably increase as n increases.

IV. CONCLUSIONS

In fields such as sputtering where the transfer of kinetic energy from the ion to the lattice is important, investigators must be aware of the fact that a substantial fraction of the kinetic energy is carried away by neutrals backscattered from the surface. Furthermore, the relationship between the initial energy of the ion and the energy transferred to the lattice may be nonlinear. Whereas our data only extend to 600 eV, we expect this conclusion to be valid to several thousand eV since Kornelson has shown that the sticking probabilities are substantially less than unity up to this energy range.[19]

A binary-collision model which assumes a sequence of two-body collisions and uses very simple potentials adequately describes the gross features of the experimental data on energy transfer to a tungsten lattice for ion energies between 25 and 600 eV. The absolute magnitude of energy transfer, the functional relationship between E_{tot}/E_0 and α, the linear relationship between E_{tot} and E_0 for Xe^+ and Kr^+, and the effect of lattice penetration are in qualitative agreement with the predictions of this model.

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[1]H. H. Andersen, Radiat. Eff. 3, 51 (1970); H. H. Andersen, Radiat. Eff. 7, 179 (1971).
[2]H. Oechsner and W. R. Gesang, Phys. Lett. 37A, 235 (1972).
[3]H. F. Winters and Eric Kay, J. Appl. Phys. 38, 3928 (1967).
[4]H. F. Winters and D. E. Horne, Surf. Sci. 24, 587 (1971).
[5]H. F. Winters, J. Vac. Sci. Tech. 8, 17 (1971).
[6]H. D. Hagstrum, Phys. Rev. 104, 317 (1956).
[7]G. K. Wehner, General Mills Rept. No. 2309, July 15, 1962.
[8]R. V. Stuart and G. K. Wehner, J. Appl. Phys. 32, 365 (1961).
[9]H. Oechsner, Z. Phys. 261, 37 (1973).
[10]For a review of these subjects see G. Carter and J. S. Colligon, *Ion Bombardment of Solids* (American Elsevier, New York, 1968).
[11]E. Taglauer and W. Heiland, Surf. Sci. 33, 27 (1972).
[12]D. Smith, Surf. Sci. 25, 171 (1970).
[13]W. Heiland, H. G. Schaffler, and E. Taglauer, Surf. Sci. 35, 381 (1973).
[14]W. L. Gay and D. E. Harrison, Phys. Rev. 135, A1780 (1964).
[15]P. S. Karpuzov and V. E. Yurasova, Phys. Status Solidi B 47, 41 (1971).
[16]Peter Sigmund, Phys. Rev. 184, 37 (1969).
[17]M. T. Robinson, *Atomic Collision Phenomena in Solids* (North Holland, Amsterdam, 1970), p. 66.
[18]See Ref. 9, p. 107; and D. K. Holmes and G. Leibfried, J. Appl. Phys. 31, 1046 (1960).
[19]E. V. Kornelsen, Can. J. Phys. 42, 364 (1964).
[20]M. Pryde, A. G. Smith, and G. Carter, J. Phys. D 4, 1681 (1971).
[21]P. Sigmund, Can. J. Phys. 46, 455 (1968).
[22]E. V. Kornelsen, Can. J. Phys. 48, 2812 (1970).
[23]A. G. Smith and G. Carter, Radiat. Eff. 12, 63 (1972).
[24]H. F. Winters, J. Appl. Phys. 43, 4810 (1972).
[25]U. A. Arifov, *The Interaction of Atomic Particles With the Surface of a Metal* (Tashkent University, Uzbekhistan, 1961).
[26]L. G. Gurvich, Izv. Akad. Nauk S. S. R. 26, 1418 (1962) [Bull. Acad. Sci. 26, 1443 (1962)].