is that the individual atomic moments remain nearly constant throughout. Thus, the Fe moment remains within 10% of 2.8 μ_B in both the Pd-Fe and Ni-Fe systems over a concentration range for which the average number of electrons per atom varies from 10–9. A similar property may be ascribed to the other atoms with characteristic moment values of 1.8 μ_B per Co, 0.6 μ_B per Ni and 0.4 μ_B per Pd. This atomic character of the moments in these face-centered cubic systems may well be explained by a partially localized-partially itinerant model. In this model the splitting of the d wave functions of t_{2g} and e_g symmetry is accomplished not by a true crystal field effect, but rather by the overlap properties in this crystal structure of the two types of wave functions. The strongly overlapping t_{2g} functions are assumed to form a conventional band, and the fractional moments are attributed to exchange splitting in that band. The e_g type functions do not overlap appreciably in this crystal structure, and are assumed to remain localized. The electronic configurations e_g^2, e_g^3, and e_g^4 are then associated with integral moments of 2, 1, and 0 μ_B in Fe, Co, and Ni. These discrete moments associated with the e_g levels along with the partial moments from the t_{2g} band, which is similar for all of these atoms, are then responsible for the intrinsic atomic moments.

In the concentrated Pd-Fe and Pd-Co alloys the Pd moment remains nearly constant at 0.4 μ_B per atom, while in the dilute alloys this moment apparently assumes somewhat smaller values. It was mentioned in an earlier section that, in the dilute alloys, the Pd moment probably varies with distance from the Fe impurity atoms and that these apparent moments should be regarded as average values. Unfortunately, these data do not permit the evaluation of this Pd moment variation.

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Effect of Elevated Temperatures on Sputtering Yields*

C. E. CARLSTON, G. D. MAGNUSON, A. COMEAUX, AND P. MAHADEVAN
Space Science Laboratory, General Dynamics/Convair, San Diego, California
(Received 2 December 1964)

A study was made of the effect of elevated temperatures on the sputtering yields of polycrystalline and single-crystal metals. The temperature range extended from 350 to 1000°K. The yield determinations were made by standard weight-loss techniques. The bombarding ions were Ar^+ with energies 2, 5, and 10 keV. The face-centered-cubic polycrystalline Cu and Al targets showed essentially no change in yield with temperature. This is to be contrasted with the polycrystalline body-centered-cubic targets Mo, W, and Ta which showed linear increases in yield of 26, 28, and 39%, respectively. A Mo(100) crystal face showed no change in yield over the temperature range, but a Mo(110) face showed a 12% increase in yield. On the other hand, a Cu(110) crystal showed no change in yield with temperature, while a Cu(111) face showed a decrease in yield of 24, 12, and 16% at 2, 5, and 10 keV, respectively.

INTRODUCTION

SOME measurements of sputtering yields have been made at elevated target temperatures. Almén and Bruce measured the sputtering yields of Ni, Pt, and Ag between 300 and 900°K when bombarded with 45-keV Kr^+ ions.[1] They found that Ag had a constant sputtering yield S in atoms/ion, whereas Ni and Pt showed a monotonic decrease in S of about 30% over the temperature range of their experiments. Measurements[2] using 20-keV Ar^+ ions bombarding polycrystalline Cu showed a slight increase of about 10% over the temperature range 300 to 600°K. Measurements[3] of 3-keV N_2^+ ions bombarding polycrystalline Cu showed an approximate 15% decrease in sputtering yield over the temperature range 330 to 750°K. Wehner[4] has reported that the yields he has measured for polycrystalline materials bombarded by low-energy Hg^+ ions change less than 15% over the temperature range 300 to 700°K.

At the other extreme of temperature there have recently been some measurements[2] made of Cu single crystals bombarded by 20-keV Ar^+ and Ne^+ ions at various temperatures between 30 and 320°K.

Various theoretical models have been proposed for the effect of temperature on the sputtering process. Two main lines of reasoning have been followed: annealing of the defects created by the bombardment, and disruption of focused collision sequences. Increased annealing of defects is expected as the target temperature is raised. This would tend to increase the sputtering

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[1] O. Almén and G. Bruce, Nucl. Instr. Methods **11**, 257 (1961).

[2] J. M. Fluitt, C. Snoek, and J. Kistemaker, Physica **30**, 144 (1964).

[3] T. W. Snouse and M. Bader, *Transactions of the Second International Vacuum Congress* (Pergamon Press, Inc., New York, 1962), Vol. 1, p. 271.

[4] G. K. Wehner, Phys. Rev. **108**, 35 (1957).

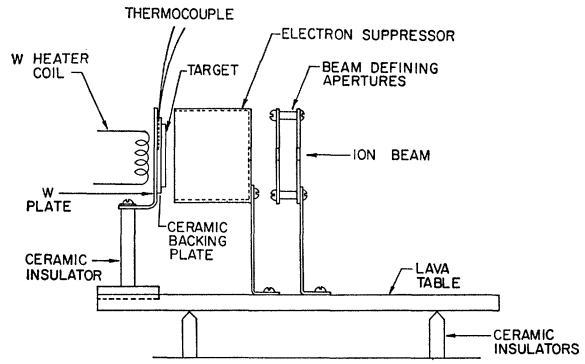

FIG. 1. Target arrangement for the temperature-effect study.

rate since annealing would augment the Silsbee[5,6] chaining mechanism. Conversely, an increase in temperature would also result in a diminishing of the average length of a focusing collision sequence due to increased lattice vibration, hence resulting in a decrease of the sputtering yield.

Due to the wide variation in results of presently available data on the effect of temperature on sputtering yields, and the relative scarcity of such data, it was deemed worthwhile to obtain further information about temperature effects on sputtering. The research reported in this paper was carried out for this purpose.

APPARATUS

The apparatus is the same as has been used before in previously reported sputtering research.[7] The target arrangement for the temperature effects study is shown in Fig. 1. A positively biased 0.025-in.-diam W filament, suspended directly behind the target, was used to heat the target radiantly to the appropriate temperature. The target was clamped to a W plate which was clamped to a high-temperature insulating standoff. The W plate served not only to support the target but also to shield the target from W evaporated from the filament.

To prevent the possibility of diffusion of the metals at high temperatures a ceramic disk about $\frac{1}{16}$ in. thick was placed between the target and the W mounting plate. The ceramic disk had a small hole drilled in its center to allow a Chromel-Alumel thermocouple to be placed in direct contact with the back of the target. The thermocouple wires were led out between the W mounting plate and the ceramic disk allowing an inch or so of the thermocouple wires to be exposed to high temperature. This reduced the heat conduction away from the thermocouple junction and resulted in a more accurate indication of the temperature. The thermocouple emf was measured by standard millivolt-potentiometric methods. At the highest temperatures attained in this work (1000°K) thermal emf's were small enough to be negligible, being less than 100 μV.

The potentiometer circuit was capable of reading to ± 10 μV. The precision in reading the temperature was thus about ± 1°C. The temperature would usually show a long-period fluctuation of about ± 3°C at high temperatures so the precision of the temperatures given here is taken to be that figure. The thermocouple was calibrated with an optical pyrometer and was found to be correct in absolute value to within ± 20°C.

EXPERIMENTAL PROCEDURE

The beam-current densities employed in this work ranged from about 50 μA/cm^2 at 2 keV to about 450 μA/cm^2 at 10 keV. The background pressure in the system with the target at temperature and before admitting gas to the source was less than or equal to 2×10^{-7} Torr. The bombardment ratio of Ar^+ ions to ambient-background gas atoms thus varied from about 3.8 to 350, at 2 and 10 keV, respectively. These favorable ratios assured that the sputtering measurements were made on monatomically clean surfaces (surfaces with at most a small fraction of a monolayer contaminant) since all yields measured were greater than unity.[7,8]

The secondary electron suppressor was maintained at a potential of about 150 V negative with respect to the target. Electrons emitted by the W filament were prevented from going to the target by biasing the filament about 100 V positive with respect to the target. Sputtering yields were determined by standard weight loss techniques. Target preparation, weight-loss measurement, and total-charge determination were described in a previous paper.[7]

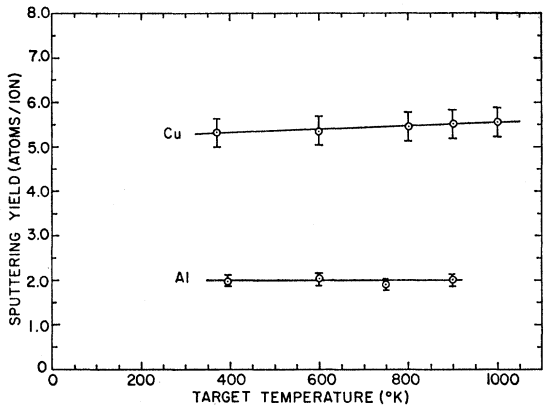

FIG. 2. The sputtering yields of polycrystalline Cu and Al bombarded at normal incidence by 5-keV Ar^+ ions as a function of target temperature. The Cu curve is drawn through the points and exhibits a 4.7% increase over the temperature range 350 to 1000°K. Since this increase is less than the maximum expected experimental uncertainty it is probably not significant.

[5] R. H. Silsbee, J. Appl. Phys. **28**, 1246 (1957).
[6] G. Leibfried, J. Appl. Phys. **30**, 1388 (1959); **31**, 117 (1960).
[7] G. D. Magnuson and C. E. Carlston, J. Appl. Phys. **34**, 3267 (1963).
[8] As further evidence of target cleanliness see: G. D. Magnuson and C. E. Carlston, Phys. Rev. **129**, 2403, 2409 (1963).

At 1000°K, the vapor pressure of all the target materials was low enough that essentially no evaporation would occur. However, it was thought advisable to check whether degassing of the target would occur, resulting in a weight loss, or contamination would occur, resulting in a weight gain. Therefore, prior to sputtering, the targets were weighed, mounted in the vacuum system and held at 1000°K for 4 h. In all cases no weight change was detectable.

The maximum expected uncertainty in the yields was at most ±8% at 2 keV and ±6% in all other cases. The reproducibility of the yield determinations was better than ±4%.

RESULTS

All the data reported in this paper were taken using Ar^+ ions as the bombarding particle. The energy was 5 keV for all targets. The only exception to this was the Cu(111) crystal for which measurements were made at 2, 5, and 10 keV. The temperature range was from room temperature to 1000°K. Because of the power input to the target from the beam (~0.5 W) the room-temperature point varied from about 350 to about 400°K.

Face-Centered-Cubic Metals

a. Polycrystalline

The polycrystalline fcc metals that were studied were pure (99.99%) Al and oxygen-free high-conductivity Cu. The yields of these metals as a function of temperature are shown in Fig. 2. As can be seen the yields of polycrystalline Cu and Al were independent of target temperature. Although the Cu data tend to show a slight increase in yield of about 4.7%, this is less than the expected uncertainty and hence is not significant.

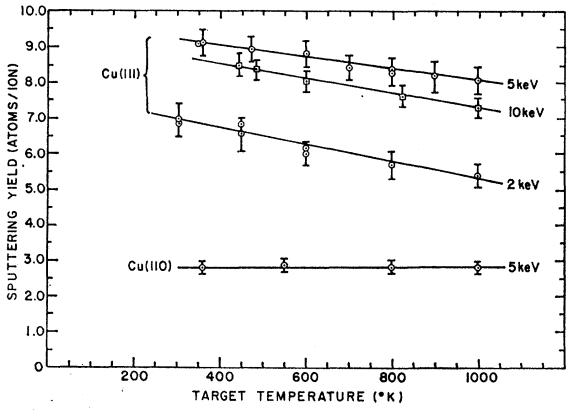

FIG. 3. The sputtering yields of two copper single crystals bombarded at normal incidence by Ar^+ ions as a function of target temperature. The Cu(111) crystal was bombarded at 2, 5, and 10 keV and the yield showed decreases of 24, 12, and 16%, respectively. The yield of the Cu(110) face showed no dependence on the temperature.

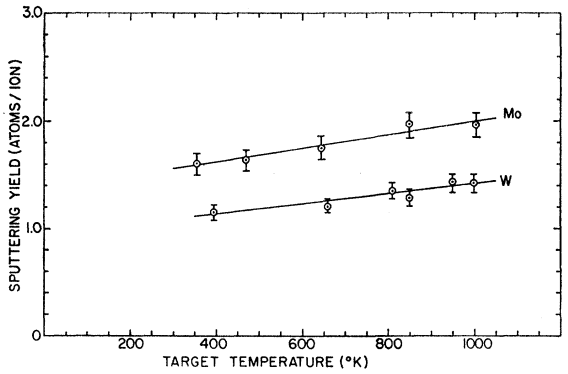

FIG. 4. The sputtering yields of polycrystalline Mo and W bombarded at normal incidence by 5-keV Ar^+ ions as a function of target temperature. The increase in yield was 26% and 28% for Mo and W, respectively, over the temperature range 350 to 1000°K.

b. Single Crystal

Two single-crystal planes were investigated, the Cu(110) and the Cu(111). Of the three low-index planes, these represent the extremes in sputtering yields and denseness of atomic packing.[7,9] The yields of these planes as a function of target temperature are shown in Fig. 3. Note that the Cu(110) yield is independent of temperature, similar to the polycrystalline behavior, but that the Cu(111) yield decreases with increasing temperature. Since 5 keV is less than the energy (~7 keV) at which the yield is a maximum for this plane,[7] it was decided to determine if the temperature behavior was different at an energy above the maximum and an energy considerably less than the maximum. Thus, Fig. 3 also includes the yield of the Cu(111) plane as a function of temperature at 2 and 10 keV. As can be seen, the behavior is similar at all three energies. However, the percentage decrease seems to be greatest for the lowest yield. The yields decrease by 24, 12, and 16% over the temperature range investigated at 2, 5, and 10 keV, respectively.

Body-Centered-Cubic Metals

a. Polycrystalline

The polycrystalline bcc metals that were studied were Mo, Ta, and W. The results are shown in Figs. 4 and 5. All three metals showed a linear increase in yield with increasing target temperature. The increases were 26, 28, and 39% for Mo, W, and Ta, respectively. On the other hand, although the data are not included, a type-304 stainless-steel target showed no variation in yield with temperature.

b. Single Crystals

Figure 6 shows the yields of the two planes of Mo studied, the Mo(110) and Mo(100) planes. The yield

[9] P. K. Rol, J. M. Fluit, and J. Kistemaker, Physica **26**, 1009 (1960).

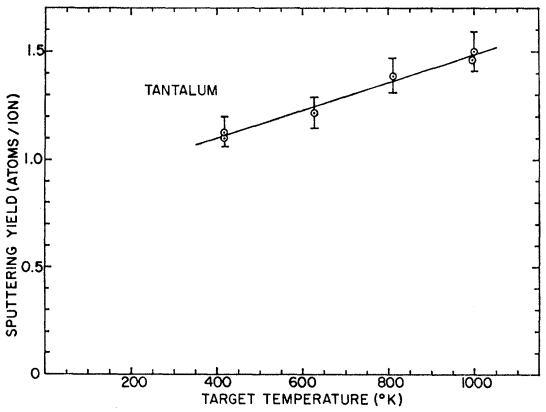

FIG. 5. The sputtering yield of polycrystalline Ta bombarded at normal incidence by 5-keV Ar^+ ions as a function of temperature. The yield shows a 39% increase over the temperature range 350 to 1000°K.

of the Mo(100) face was independent of temperature but the yield of the Mo(110) face showed a 12% increase over the temperature range investigated. Again, as in the case of the Cu single crystals, the yield of the most opaque plane shows a dependence on target temperature. However, the effect is reversed from that of Cu.

DISCUSSION

Various authors have investigated the effect of target temperature on the sputtering process,[1–4] and various theoretical models have been proposed to account for the results.[2,10,11] The most probable explanation of the effect of target temperature on the sputtering process lies in the effect of temperature on Silsbee[5] "chains." Annealing at elevated temperatures of the defects introduced into a lattice by ion bombardment could be expected to increase sputtering rates. This would occur since the energy transmitted along a chain in a focusing sequence can be scattered out of the chain by lattice defects. Annealing, by tending to restore the crystallinity of the lattice, would thus lengthen the mean free path of the collision sequence thereby increasing the probability that a surface atom will receive enough energy to escape the binding force of the lattice. However, it seems doubtful that build up of lattice displacements could occur since it is known from quenching[12] and radiation-damage studies[13] that interstitials and vacancies are quite mobile even at the low-temperature end of the temperature range investigated here.[14] Thus, it would appear that the annealing of defects cannot explain any change observed in sputtering yields since rapid annealing occurs over the entire temperature range investigated. The presence of single crystal deposit spot patterns at room temperature would also seem to substantiate the view that the lattice is not disrupted to any great extent.

The foregoing remarks are certainly valid for the fcc metals studied, Cu and Al. Some question remains, however, concerning the annealing of defects in the bcc metals. Here the situation is not so clear cut, since the activation energy for recovery in the bcc metals is greater than for the fcc metals. Kinchin and Thompson[15] have investigated the dimensional and lattice-parameter increases in Mo after neutron bombardment at 30°C. They believe that interstitials are present up to a temperature of 200°C. Gray[16] has observed the lattice expansion in Mo after fast neutron bombardment at 35°C and believes that interstitials are present up to 800°C. Since the bcc metals usually have high-temperature melting points the important factor here might be the high melting temperature rather than crystal group. If annealing of the lattice defects in a bcc crystal does not occur until higher temperatures are reached one would expect an increase in yield with increasing target temperature as was observed in this research for the bcc metals investigated.

Increasing the target temperature can also lead to an increase in the energy loss per collision in a Silsbee chain due to the increased scattering at larger amplitudes of vibration of the lattice atoms, and hence lead to a reduction in the range of a collision sequence. Excellent calculations of the range of focused collision sequences taking into account increased lattice vibrations have recently been published.[10,11] This reduction in range would have the effect of decreasing the sputtering yield with increasing temperature. In the work reported here, a decrease in yield was observed only for the Cu(111) crystal. It would seem that a decrease

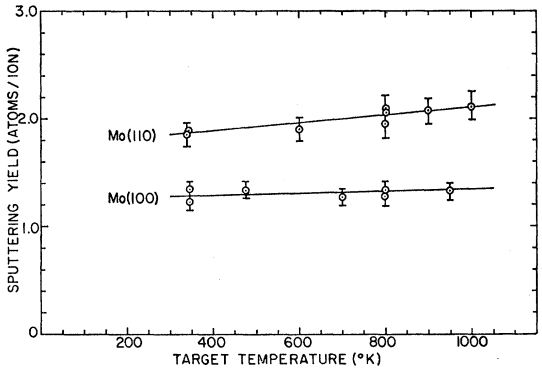

FIG. 6. The sputtering yields of two Mo single crystals bombarded at normal incidence by 5-keV Ar^+ ions as a function of target temperature. The Mo(100) crystal yield was independent of temperature but the Mo(110) crystal showed a 12% increase in yield over the temperature range 350 to 1000°K.

[10] R. S. Nelson, M. W. Thompson, and H. Montgomery, Phil. Mag. **7**, 1385 (1962).
[11] J. B. Sanders and J. M. Fluitt, Physica **30**, 129 (1964).
[12] J. E. Bauerle and J. S. Koehler, Phys. Rev. **107**, 1493 (1957); M. Doyama and J. S. Koehler, Phys. Rev. **127**, 21 (1962).
[13] G. D. Magnuson, W. Palmer, and J. S. Koehler, Phys. Rev. **109**, 1990 (1958).
[14] H. B. Huntington, Am. J. Phys. **32**, 775 (1964).
[15] G. H. Kinchin and M. W. Thompson, J. Nucl. Energy **6**, 275 (1958).
[16] D. L. Gray, Atomic Energy Commission Report HW-57903 1958 (unpublished).

in yield should also have been observed in the Cu(110) crystal unless a competing process, tending to increase the yield, is operative and effectively cancels the decrease in yield due to the shortening of the focused collision sequence with temperature. In the case of the Cu(111) crystal this implies that the shortening of focused collision sequences is the predominant effect.

Two other interpretations regarding the effects of thermal vibration of lattice atoms should be mentioned. An oscillating atom in the lattice has a higher probability of being found at the end points of its travel than at the center. The effect of thermal oscillations thus is such that lower lying atoms, which were previously shielded from bombarding ions by surface atoms, become more and more exposed as the amplitude of vibration increases. The net result would be an increase in the probability of collision between an ion and a lattice atom and an increase in the sputtering yield.[7,9,17] This effect may not be small since according to Menzel-Kopp and Menzel,[18,19] amplitudes of vibration of surface atoms of Cu and Ag are roughly five times as great as for atoms in the interior of the metal.

The other effect attributable to increased lattice vibration is the decrease in effective binding energy of the surface atoms with increasing target temperature. Increased vibration is of course accompanied by an increased average energy of the surface atoms. Therefore, surface atoms need receive a proportionally smaller amount of energy in a collision to be ejected from the surface. This too would tend to increase the sputtering rate. The effect of binding energy on sputtering thresholds, for example, has been considered by Harrison and Magnuson.[20]

The effect of temperature on the channeling process[21,22] would be similar to the effect on focused collision sequences. That is, the increased vibration would result in a decrease of the distance an atom could travel in a channel of the crystal, resulting in a decrease in the sputtering yield.

The changes in yields reported here are generally quite small, in some cases not much larger than the maximum expected experimental uncertainty. However, the effect is a very real one and in view of the variant behavior of different crystal planes warrants further theoretical and experimental investigation.

[17] A. L. Southern, W. R. Willis, and M. T. Robinson, J. Appl. Phys. **34**, 153 (1963).
[18] Chr. Menzel-Kopp and E. Menzel, Z. Physik **142**, 245 (1955).
[19] Chr. Menzel-Kopp and E. Menzel, Z. Physik **144**, 538 (1956).
[20] D. E. Harrison and G. D. Magnuson, Phys. Rev. **122**, 1421 (1961).
[21] M. T. Robinson and O. S. Oen, Appl. Phys. Letters **2**, 30 (1963); O. S. Oen and M. T. Robinson, *ibid.* **2**, 83 (1963); M. T. Robinson, D. K. Holmes, and O. S. Oen, Bull. Am. Phys. Soc. **7**, 171 (1962); M. T. Robinson and O. S. Oen, *ibid.* **8**, 195 (1963).
[22] J. A. Davies, J. Friesen, and J. D. McIntyre, Can. J. Chem. **38**, 1526 (1960); J. A. Davies, J. D. McIntyre, R. L. Cushing, and M. Lounsbury, *ibid.* **38**, 1535 (1960); J. A. Davies and G. A. Sims, *ibid.* **39**, 601 (1961); J. A. Davies, J. D. McIntyre, and G. A. Sims, *ibid.* **40**, 1605 (1962); J. A. Davies, F. Brown, and M. McCargo, *ibid.* **41**, 829 (1963); F. Brown and J. A. Davies, *ibid.* **41**, 844 (1963).

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Motion of a Frenkel–Kontorowa Dislocation in a One-Dimensional Crystal*

W. ATKINSON AND N. CABRERA
Department of Physics, University of Virginia, Charlottesville, Virginia
(Received 4 December 1964)

An analytic solution is given for the equations of a linearized Frenkel–Kontorowa one-dimensional dislocation. It is shown that the motion of the defect with velocity v excites lattice vibrations with k given by $\omega(k)=vk$, where $\omega(k)$ is the dispersion of the lattice waves. At high velocity there is only one k excited (in one dimension) appearing at the back of the defect, so that the frictional force is very small, one order of magnitude smaller than the Peierls force. At low velocities, however, there are many waves excited appearing both ahead and behind the moving defect, and the frictional force increases to the point of making steady-state nonthermally activated motion impossible.

1. INTRODUCTION

THE motion of singularities in a lattice, whether foreign particles or imperfections of the lattice, remains as yet a rather mysterious subject.

First of all, there is the low-velocity motion, under a small applied force, which is described by assuming that the energy received by the singularity during an elementary jump is dissipated rapidly into the solid in the form of lattice waves. The motion has then to be thermally activated in so far as every elementary jump has to be independently excited. There is no question that this assumption appears to fit many of the experimental conditions; however, to our knowledge, no simple justification has been given for the fact that lattice waves are capable of rapidly dissipating the energy under these conditions.

Secondly, and more important to us, is the question

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