SURFACE DEFORMATION PRODUCED BY ION BOMBARDMENT

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Methods and results are given for the change in shape of a homogenous and isotropic body in response to ion bombardment. Possible errors are indicated in the method of measuring [1] the erosion rate as a function of angle of incidence of the ion beam.

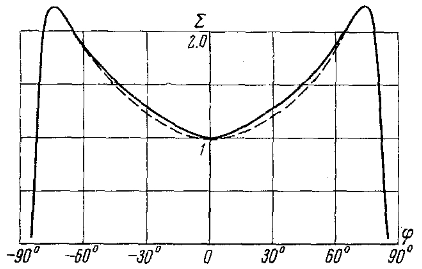

Fig. 1

The rate of mass removal is defined by the sputtering factor S (atom/ion). Experimental results indicate that S varies substantially with the angle of incidence φ for polycrystalline materials and for energies on the order of 1 keV. Figure 1 shows a typical $\Sigma(\varphi) = S(\varphi)/S(0)$ relation for 6 keV Ar^+ ions on copper. An ion beam uniform in direction, energy, and density will thus produce a change in surface shape.

An ion beam (density j_0 ion/cm^2-sec) moves in the negative direction of the y-axis (Fig. 2) and strikes a body whose shape is initially described by $y_0(x)$. The practical j_0 in cathode sputtering are such that the motion of the ions is of free-molecular type, so we need not consider the difference between the actual case and the planar one. The rate of erosion along the normal at P is given for a known $S(\varphi)$ by

$$W_n = -\frac{j_0 \cos\varphi\, S(\varphi)}{N_0} = -\frac{j_0 S_0}{N_0}\sum(\varphi)\cos\varphi \quad (S_0 = S(0)),$$

in which N_0 (atom/cm^3) is the atomic density of the material and φ is the angle between the normal at P and the y-axis. Then the rate of erosion along the y-axis is

$$W_y = \frac{W_n}{\cos\varphi} = -\frac{j_0 S_0}{N_0}\sum(\varphi), \tag{1}$$

$$y(x, \tau) = y_0(x) + \int_0^\tau W_y(x, \tau)\, d\tau, \tag{2}$$

in which τ is time. We substitute (1) into (2) and differentiate with respect to time to get

$$\frac{\partial y}{\partial \tau} = -\frac{j_0 S_0}{N_0}\sum(\varphi). \tag{3}$$

It is desirable to have Σ as a function of $\tan\varphi$, i.e., $\partial y/\partial x$. Differentiation with respect to x then gives

$$\frac{\partial^2 y}{\partial\tau\,\partial x} = -\frac{j_0 S_0}{N_0}\frac{\partial\Sigma}{\partial(\partial y/\partial x)}\frac{\partial^2 y}{\partial x^2}.$$

Substitution reduces this nonlinear differential equation of hyperbolic type to the form

$$\frac{\partial f}{\partial t} = -\frac{\partial\Sigma}{\partial f}\frac{\partial f}{\partial x} \qquad \left(t = \frac{\tau j_0 S_0}{N_0},\ f = \frac{\partial y}{\partial x}\right). \tag{4}$$

We know $\Sigma(\varphi)$, and hence $\Sigma(f)$, so (4) may be put as

$$\frac{\partial f}{\partial t} = \xi(f)\frac{\partial f}{\partial x} \qquad \left(\xi(f) = -\frac{\partial\Sigma}{\partial f}\right). \tag{5}$$

The initial condition is

$$f(x, 0) = \frac{\partial y_0}{\partial x} = F(x), \tag{6}$$

and the solution satisfying this may be put as

$$V(x,t,f) = f - F[x + t\xi(f)] = 0. \tag{7}$$

In fact

$$\frac{\partial V}{\partial f} = 1 - F't\frac{\partial\xi}{\partial f}, \quad \frac{\partial V}{\partial x} = -F', \quad \frac{\partial V}{\partial t} = -F'\xi(f),$$

and then

$$\frac{\partial f}{\partial t} = \frac{\partial V/\partial t}{\partial V/\partial f} = \frac{-F'\xi(f)}{1 - F't\,\partial\xi/\partial f},$$

$$\xi(f)\frac{\partial f}{\partial x} = \xi(f)\frac{\partial V/\partial x}{\partial V/\partial f} = \frac{-F'\xi(f)}{1 - F't\partial\xi/\partial f} = \frac{\partial f}{\partial t}.$$

Figure 3 shows the forms of $\Sigma(f)$ and $\xi(f)$ for the $\Sigma(\varphi)$ of Fig. 1.

Existing data on $S(\varphi)$ do not allow us to determine the form of $\xi(f)$ for $f \to 0$ with adequate precision.

If we assume that $\Sigma(\varphi) \sim (\cos\varphi)^{-1}$ [2] for small φ, then $\xi(f) \to 0$ as $f \to 0$. The observed $\Sigma(f)$ is closely fitted by $\exp\{a|f| - bf^2\}$, and in that case $\xi(0)$ is finite but has two values. Figure 3 shows $\Sigma(f)$ and $\xi(f)$ for the case where $\partial S/\partial\varphi = 0$ when $\varphi = 0$ ($\Sigma(\varphi) \sim (\cos\varphi)^{-1}$ for small φ).

It is clear that a substantial change in $\xi(f)$ does not produce a deviation in $\Sigma(f)$ exceeding the experimental error.

This method has been used to determine the change in shape for some simple surfaces; the broken line for $\xi(f)$ in Fig. 3 was used. The solution does not take account of transfer between parts of the surface, so it applies, strictly speaking to convex surfaces. Figures 4 and 5 show successive forms for bodies of initial shape $y_0 = \cos x$ and $y_0 = 4\cos x$; it is clear that the bombardment has a leveling action.

The effects of $\xi(f)$ for small f on the change of shape were considered via a hemisphere on the end of a cylinder, $y_0 = (1 - x^2)^{1/2}$, with both of the $\xi(f)$ of Fig. 3 (Fig. 6). The results for $\partial S/\partial\varphi = 0$ at $\varphi = 0$ do not differ from those for $\partial S/\partial\varphi \neq 0$ at $\varphi = 0$ within the errors of the calculation; the surface tends to become conical with $\lim|f| = 3.5$ for $t \to \infty$, which corresponds to the f at which $\xi(f) = 0$, i.e., to maximum erosion (Σ_{max}). Figure 7 shows the shape change from $y_0 = \cos x$ after exposure at $\varphi_0 = 40°$ to the x-axis; ridges analogous to those observed [3] are formed.

Wehner [1] deduced $S(\varphi)$ from the erosion of a spherical model on the assumption that the surface at a given x did not vary greatly in φ during bombardment, so $\Sigma(\varphi) \sim \Delta y(\varphi)/\Delta y(0)$. Wehner [1] did not give the precise j_0 used, so it is not possible to determine the characteristic reduced times t; but he states that j_0 was on the order of 1

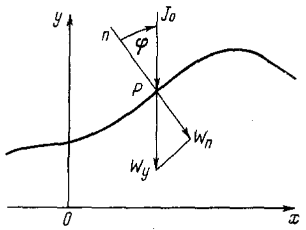

Fig. 2

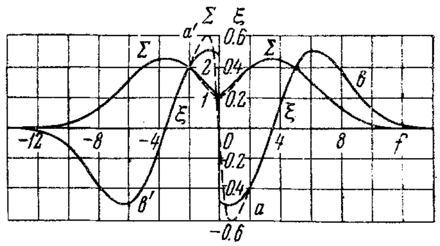

Fig. 3

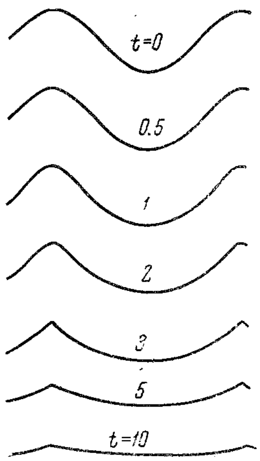

Fig. 4

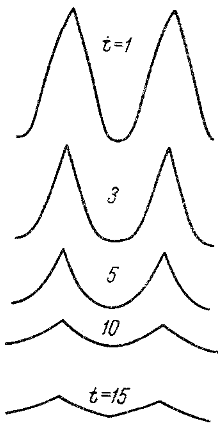

Fig. 5

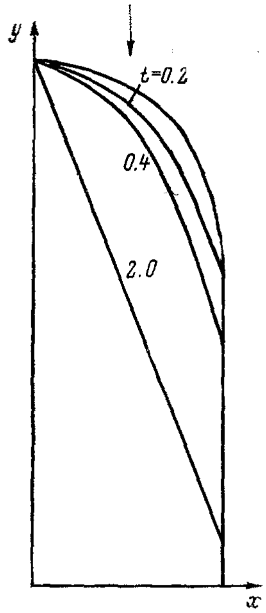

Fig. 6

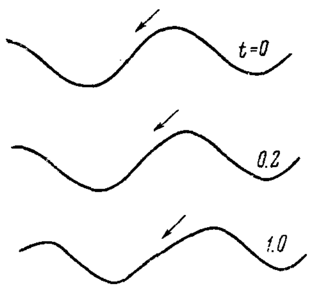

Fig. 7

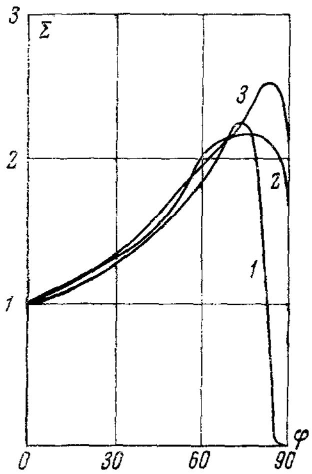

Fig. 8

mA/cm^2, so we may take t as 0.2–0.4. Figure 8 compares the $\Sigma(\varphi)$ used in the calculation on the hemisphere, curve 1, with curves 2 and 3 obtained by processing the surface forms by Wehner's method [1] for t of 0.2 and 0.4. It is clear that this processing gives an error in $\Sigma(\varphi)$ and in the estimate of the corresponding to Σ_{max}.

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