EFFECT OF THERMAL VIBRATIONS OF THE CRYSTAL LATTICE ON THE ANISOTROPY OF SPUTTERING COEFFICIENTS AND ION-ELECTRON EMISSION OF SINGLE CRYSTALS

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EFFECT OF THERMAL VIBRATIONS OF THE CRYSTAL LATTICE ON THE ANISOTROPY OF SPUTTERING COEFFICIENTS AND ION-ELECTRON EMISSION OF SINGLE CRYSTALS

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1. It is known (see, for example, ([1])) that sputtering is a cascade process which begins when an incident ion collides with an atom of the target and transfers to it part of its kinetic energy. If the transferred energy is sufficiently large, the target atom (in this case it is called a primary displaced atom) leaves the site it occupies and begins to move in the crystal lattice, producing other displaced atoms along its path. Some of the displaced atoms reach the surface and leave the target. This sputtering mechanism is called diffusional.

There is also another sputtering mechanism—the focusing mechanism. According to this mechanism, the energy released in the collision of the ion with a target atom is carried to the target surface by sequences of focused collisions—focusons. In this case the sputtering event occurs if the transported energy exceeds the binding energy of a surface atom. The question of the role of both mechanisms in the sputtering process has not yet been resolved and continues to be debated ([2], [3]). Useful information can be obtained from a comparative experimental study of the temperature dependences of sputtering and ion-electron emission of single crystals. The results of some experiments of this kind are given below.

2. The targets used were the (110) and (111) faces of a copper crystal and polycrystalline copper. Irradiation was carried out with argon ions of energy 30 keV. The method for determining the sputtering and emission coefficients was the same as in ([4], [5]). At high temperatures the experiments are complicated by the fact that, simultaneously with sputtering, evaporation of the target material occurs. To take this into account, the measurements were carried out as follows. The target was heated at the required temperature for a certain time, after which the weight loss due

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

to evaporation was measured. During the same time the heated target was irradiated and the total weight loss of the target, due to both evaporation and sputtering, was determined. Finally, the target was heated once more and the weight loss due to evaporation was again determined. As the working value of the weight loss due to evaporation, the half-sum of the losses during the first and second heating without irradiation was taken. In this way it was possible to take into account the fact that the weight loss due to evaporation depends on the microstructure of the target surface, which changes during ion bombardment ([1]).

3. The results obtained are presented in Figs. 1-3. Figure 1 shows the dependences of the sputtering coefficients S and ion-electron emission γ on the angle of incidence φ for a target whose section plane is close to the (111) face (making an angle of 6° with it). The target was rotated about the [112] axis; the angles were measured from the normal to the target surface. The target temperature was 150°C. It can be seen that the dependences $S(\varphi)$

and $\gamma(\varphi)$ have the usual character: as the angle of incidence of the ions increases the coefficients increase and pass through minima when the ion beam becomes parallel to low-index crystallographic axes ($\sim 6°$—axis [111], 18°—axis [123], 34.5° —axis [021]). It is also seen that the anisotropy of the sputtering coefficient is greater than the anisotropy of the ion-electron emission coefficient (as a measure of the anisotropy, the ratio was taken of the difference of the coefficients at the maximum at $\sim 25.5°$ and the neighboring minimum at $\sim 18°$ to their half-sum). For several fixed angles of incidence of the ions on the target, which are marked by Roman numerals, the dependences of the coefficients S and γ on the target temperature were studied.

Fig. 1

It turned out (Fig. 2) that at all the angles of incidence studied the sputtering coefficient decreases as the target temperature is raised to 750–850°C; however, the rate of decrease dS/dT is different for the different cases. The smallest decrease (about 6% in the interval 300–750°C) occurred at the minimum at $-6°$; the largest (about 33%)—at the maximum at $\sim 27.5°$. At target temperatures above approximately 850°, even a small increase in the target temperature leads to a sharp increase in S (we note that this effect was found by Nelson ([6]) on polycrystalline targets).

Fig. 3

Figure 3: Fig. 3

Fig. 2. The numerals correspond to the designations in Fig. 1. a–S, b–γ

The ion-electron emission coefficient upon heating the target either changes almost not at all (for example, at $\varphi = 18^\circ$), or decreases (for example,

at $\varphi = 27.5^\circ$, but considerably more slowly than the sputtering coefficient. No increase in γ is observed at $T > 850^\circ$. Let us also note that, at all the temperatures studied, the anisotropy of S remains greater than the anisotropy of γ.

Figure 3 I shows the temperature dependences of the sputtering and emission coefficients for the (110) face irradiated along the normal to its surface. When the target is heated, both S and γ increase (by approximately 20% in the temperature range 300–800° C). We did not investigate the higher-temperature region, since, owing to the small sputtering coefficient of the (110) face at these temperatures, the weight loss due to evaporation exceeds the weight loss caused by sputtering, and the accuracy of the experiment becomes low.

Fig. 3

Figure 3 II presents analogous dependences obtained when a polycrystalline target was irradiated with ions at an angle of 30°. It turned out that the sputtering coefficient in the temperature range 300–800° C and the emission coefficient in the temperature range 300–900° C do not depend on temperature.

A summary of the results obtained is given in Fig. 4. For convenience in comparing data referring to different targets and different angles of incidence, all the curves have been normalized: the coefficient values at 300° C were taken as unity. It is easy to see that, when the target is heated, the sputtering and emission coefficients may, generally speaking, increase, remain unchanged, or decrease (cf. (8)). It is also evident that the behavior of S and γ may be either the same or different.

4. Let us now turn to a discussion of the results obtained. When the target is heated, a number of processes occur, each of which may, generally speaking, influence sputtering and electron emission. These include a change in the transparency of the crystal, caused by an increase in the amplitude of the thermal vibrations of the lattice, annealing of defects, a change in the binding energy of atoms, etc. Since, within the framework of existing theories of sputtering and emission, it is impossible to take all these effects into account, it was of interest to compare the data obtained with the results of an idealized calculation that takes into account only one temperature effect–the change in crystal transparency (cf. (7)). The calculation was performed in the Einstein approximation, without allowance for correlations; estimates showed that including them does not substantially affect

the results but greatly complicates the calculations. The calculation was carried out for the same angles of incidence as in the experiment, with the exception of curve III. This curve was calculated for the maximum at $\varphi = 10^\circ$, whereas the experimental data refer to a somewhat larger angle ($\sim 12^\circ$, see Fig. 1). It turned out that the calculated dependences $S(T)$ and $\gamma(T)$ are linear functions of temperature, which is confirmed by experiment.* The calculated and experimental dependences of the electron-emission coefficients practically coincide, whereas the experimental values of the sputtering coefficients lie below the calculated ones. Nevertheless, in the case of sputtering as well, the calculation correctly reflects the differences in the character of the temperature dependences of the sputtering coefficients at different angles of ion incidence on the target. All the calculated dependences are, as it were, shifted relative to the experimental experimental ones, and to make them coincide it is sufficient to rotate the calculated curves clockwise by a certain angle (about 20°).

From a comparison of the calculated and experimental temperature dependences of the sputtering and emission coefficients it follows, first of all, that the assumption underlying the calculation—that thermal vibrations of the crystal lattice affect only the transparency of the crystal, but do not affect the escape of secondary particles (or the transport of energy to the target surface)—is justified for electron emission and unjustified for sputtering. From the standpoint of focusing concepts this result is quite natural: it is well known (see, for example, (1)) that the path length of focusons and, consequently, the depth from which they can carry energy decreases with increasing target temperature. Therefore the character of the temperature dependence of the sputtering coefficient is determined by the competition of two processes: an increase in the probability of collision of the ion with a target atom, which leads to an increase in the number of focusons formed, and a decrease in the focuson path length. In those cases where the first process predominates—for example, for the face (110), which is the most transparent in the absence of thermal vibrations—an increase in the sputtering coefficient occurs. In those cases where thermal vibrations practically do not change the transparency of the crystal, as occurs for the face (111) (see (5)), the second process predominates, and the sputtering coefficient decreases.

Fig. 4. *I*—experimental dependences $S/S(300)$: 1—face (110); 2—polycrystal; 3—face (111), curve *I*; 4—the same, curve *III*; 5—the same, curve *II*; 6—the same, curve *V*; 7—the same, curve *IV*. *II*—calculated dependences $S/S(300)$: 1—face (110), 2—face (111), first minimum; 3—face (111), second and third minima; 4—face (111), first maximum; 5—face (111), second maximum. *III*—experimental (solid lines) and calculated (dashed lines) dependences $\gamma/\gamma(300)$: 1—face (110); 2—face (111), curve *III*; 3—face (111), curve *IV*.

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* Contrary to the conclusion of the theoretical work (9) on the independence of the anisotropy of the sputtering coefficient of single crystals from temperature.

The experimental data show, moreover, that the role of those factors which should increase the values of the sputtering coefficients at the maxima (for example, annealing of defects, which increases the focuson path length) is apparently small.

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