On Erosion Mechanisms of the Solid Surface under the Treatment with Submicrosecond Ion Beams

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An analysis of erosion mechanisms of the solid surface under the treatment with submicrosecond ion beams in the power range $W = 10^6 \ldots 5 \cdot 10^9$ W/cm^2 is made on a base of our calculations and scientific literature data. Sputtering and evaporation have been examined. A flow of atoms leaving the surface is divided on two partial components. One of them is caused by sputtering and another by evaporation. Proportion of these components is determined by surface thermodynamic state which depends on power and duration of radiation.

It's possible to fix three ranges of the beam power density in an exhibition of erosion mechanisms. Below $W \sim (1 \ldots 5) \cdot 10^6$ W/cm^2 the atomic flow from the surface produced by sputtering is dominate. An erosion ratio doesn't exceed some tens of units. At $W \sim (0.5 \ldots 1) \cdot 10^8$ W/cm^2 and above the erosion is connected with intensive evaporation. The erosion ratio is in range $10^4 \ldots 10^5$ atoms/ion.

The range $W \sim 5 \cdot 10^6 \ldots 5 \cdot 10^7$ W/cm^2 is studied insufficiently. We suppose that the contributions of sputtering and evaporation into the atomic flow from the surface may be commensurable here. Under these conditions the total erosion ratio is less on orders then in the case of intensive evaporation around an temperature of boiling point.

1. Introduction

The proportion between partial fractions of atoms sputtered by fast particles and evaporated under radiation heating is uninvestigated problem in study of surface erosion mechanisms.

To make an estimation of the proportion of these processes intensities we separate the atoms flow leaving surface on two partial components: the fast component (caused by collision processes) and heat one (caused by evaporation). Accordingly the total erosion ratio D is equal to a sum of the sputtering ratio S and evaporation one Q ($D = S + Q$).

When ion beams and plasma influencing the solid surface sputtering takes place at any energies of accelerated particles (more precise starting with E_{Sh} which has order some electronvolts) and at any ion flow intensity [1]. Moreover, the numerous results of investigations display (for example [2]) that intensity of sputtering exceeds evaporation one essentially at the surface temperature $T_S < T_{melt}$ (T_{melt} – the melting temperature). In contrast, the evaporation appears and develops as the surface temperature T_S caused by radiation heating increases. At the surface temperatures around the boiling point T_b the intensity of evaporation exceeds one of sputtering on some orders [3]. In contrast to sputtering the evaporation intensity doesn't depend on the particle nature at first hand, but on a shape and quantity characteristics of a liberated energy space and time function produced by irradiation flow near the surface.

In this paper we present the analysis of submicrosecond ion beam influence and heating caused by it on surface erosion mechanisms and on the intensity of atomic flows away from the surface.

2. Sputtering

Ion sputtering of substance has been studied well at the close by indoor temperatures. The sputtering ratios for numerous ion-target combinations have been obtained experimentally. The sputtering models have been produced: from simple semi-empirical formulas up to complicated computer models simulating the atomic collisions processes. At the ion energy values about hundreds keV found sputtering ratios don't exceed some tens of units [1].

The investigations show that at $T_S < 0.7 T_{melt}$ the sputtering ratio depends on temperature slightly. But at higher temperature sharp exponential rise begins. At the approaching T_{melt} the $S(T)$ value may exceed the $S(300)$ on two orders [2]. This effect is explained, firstly, by weakening of atomic binding with lattice because of increasing a heat oscillations amplitude, and secondly, by an elevation of the temperature in a region of thermal spikes created within atomic collision cascades [2].

Unfortunately, we didn't succeed in finding in scientific literature the trusty systematic data about sputtering ratios of various materials at relatively high temperatures ($T > 0.7\ T_{melt}$). Perhaps, this phenomenon hasn't got the strict mathematical foundation yet.

It's advisable to divide on two groups the atomic flows away from the surface on sputtering:

(1) recoiled atoms with energy which exceeds much the energy of substance sublimation U_0. As a rule, these atoms are sputtered by mechanisms of direct knocking out or at the beginning of displacement cascades. Yield of such atoms S_{DK} must depends weakly on the sample temperature;

(2) atoms with energy $\leq U_0$ (usually they are sputtered by the thermal spikes mechanism). As overcoming of surface potential barrier U_0 is impotent for such atoms the base temperature of sample as an addition to the atom energy must influence the sputtering ratio S_{TS}. Sputtering due to the mechanism of thermal spikes may be described as activation evaporation by an expression

$$S_{TS} = A(T)\exp\left(-\frac{U_0}{kT}\right). \qquad (1)$$

Here T is the temperature in the thermal spike, k is Boltzmann's constant.

Factor A is defined by material properties, by the spikes' size and lifetime. In the paper [5] it's exhibited that $A(T)$ may be presented as $A_0 T^{3/2}$.

The thermal spikes' temperature is added of the initial target temperature T_0 and a temperature increment ΔT caused by cascade processes ($\Delta T \sim 0,1\ldots$ 10 eV [1]). So, the total sputtering ratio is

$$S(T) = S_{DK} + S_{TS}(T) = S_{DK} +$$
$$+ A_0(T_0 + \Delta T)^{3/2}\exp\left(-\frac{U_0}{k(T_0 + \Delta T)}\right). \qquad (2)$$

Unfortunately, we haven't found information about values of factors S_{DK}, A_0 and ΔT. To check presented expressions we took an experimental dependence $S(T)$ from [6] and approximated it with (2). We found the approximation factors S_{DK}, A_0 and ΔT by the least squares method. The results shown in Fig. 1 confirm right of the assumed correlations.
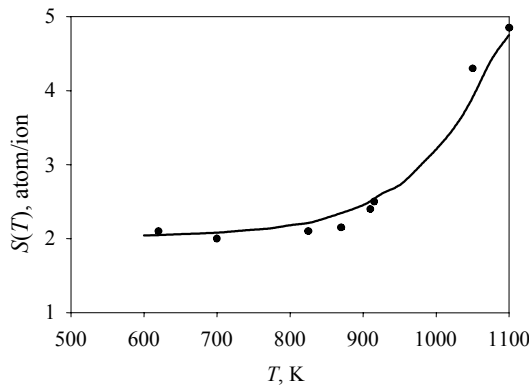

Fig. 1. Temperature dependence of the sputtering ratio when polycrystal copper being irradiated by argon ions with initial energy 400 eV. Points – experiment [6], solid line – approximation by formula (2), where $S_{DK} = 2$, $A_0 = 419$ K$^{-3/2}$, $\Delta T = 1095$ K

3. Evaporation

With increasing power density W surface warming up is elevated and the atomic flow caused by evaporation is strengthened [3]. At the beginning the atoms are taken away by action of the heat activation mechanism. Near the surface the average molecules' heat energy is less then evaporation heat and in the result of fluctuations only single particles get the sufficient energy to leave the target. The erosion ratio due to evaporation Q may be presented by means of an evaporation front velocity [7]:

$$v_f = \overline{c}\left(\frac{3}{4\pi}\right)^{1/3}\exp\left(-\frac{\lambda M}{RT_0}\right), \qquad (3)$$

where λ is specific evaporation heat at 0 K per mass unit, M – atomic weight of substance, R – gas constant, $\overline{c}$ – average sound speed.

The surface temperature T_0 is defined by solving a heat conductivity equation with v_f.

At the temperatures around boiling the molecules from thin layer of target are evaporated unconditionally. The evaporation process without activation is realized because average energy of molecules near the surface of substance overtops the evaporation heat. A layer of vapor arises in front of the surface. It influences the evaporation kinetics substantially, so its effect must be taken into account. Use of equation (3) which is correct only at evaporation into vacuum is wrong for calculation of v_f under these conditions.

At ion beam power density W below 10^9 W/cm^2 all substance may be divided on two clearly defined phases. It's correct to consider evaporation as superficial and produced by heat processes mainly. The problem of heat spread and development of evaporation is described by the system of expressions including a heat conductivity equation and appropriate boundary conditions which take into account the influence of produced vapors on the surface. We named it as bi-phase model of evaporation [3].

At $W > 10^9$ W/cm^2 ion beams make vapor with internal energy overtopping evaporation heat [3]. Main part of beam energy absorbed by substance turns into kinetic energy of target material atoms. It's incorrect to neglect the interaction of vapor molecules. The clearly defined boundary between phases is vanished and smooth passage from normal substance density to zero is observed. Superficial character of evaporation passes into volume one. Hydrodynamic scattering of substance takes place. Under these conditions the system of continuous medium and wide-range substance state equations must be used to calculate the thermodynamic parameters of target matter. We named it as hydrodynamic model of evaporation [3].

It's evidently that various regimes of evaporation may be realized practically in dependence on input power density W and duration of radiation. They pass from one type to another.

At sufficient high values of W the surface temperatures laying over boiling point T_b may appear. The energy dissipation process has extremely nonequiliblium character [3].

Within the 0,1 ... 2 MeV bombarding ions energy range the calculations reveal some quality difference

between evaporation produced by heavy and middle ions on the one hand and light ions on another.

The features of solid erosion due to evaporation under radiation by heavy and middle ion pulse beams are defined by following conditions: 1) ion projective path in substance with energy below 2 MeV doesn't exceed 1…2 μm; 2) energy liberation function maximum is on the surface. Even at the temperatures somewhat exceed the boiling point evaporation has superficial character and develops according to the mechanism without activation. So, we used the bi-phase model of evaporation [3] to calculate evaporated substance quantity when treating samples with pulsed beams of heavy and middle ions.

The dependence of surface erosion ratio due to evaporation Q on current density j of carbon ions nanosecond duration beam is shown on Fig. 2. Within the 50…100 A/cm^2 (which corresponds to $W \sim (0.5…1) \cdot 10^8$ W/cm^2) boiling starts. It's accompanied with intensive evaporation. Within this W range the component Q gets values around 10^4 atom/ion. The further increment of the ion flow power density results in rising of the value Q up to 10^5 atom/ion, whereupon decrease follows. On increment of the heavy and middle ions beam current density a maximal attainable thickness of evaporated layer may exceed a projective path depth of accelerated particles in substance not more than 20% [3]. This fact is due to the energy liberation function of heavy and middle ions passing through the substance has shape near-by rectangular. Besides, metal vapors absorb significant portion of the beam energy keeping under its spread into condensed component of target. As with elevation of initial ions energy the value of their liberation energy on the very surface rises (at least within the 0.1…2 MeV range), so the erosion ratio rises too.
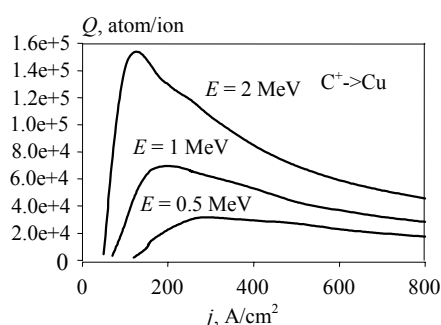

Fig. 2. The evaporation ratio Q dependence on current density for the copper sample irradiated by the carbon ion beam with pulse duration 120 ns and various initial energy of ions

An appearance of substance hydrodynamic scattering is characteristically for the case of treatment with light ions of 1 MeV and more initial energy and the enough power density of radiating flow. Our calculations by means of the hydrodynamic model of evaporation displayed [3] that in this case the erosion ratio may get $(1…5) \cdot 10^5$ atom/ion (Fig. 3).
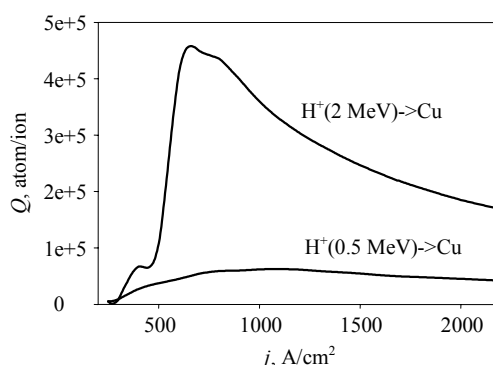

Fig. 3. The evaporation ratio Q dependence on current density for the copper sample irradiated by proton beam with 120 ns duration and various initial proton energy

In Fig. 4 calculated dependence of the copper surface erosion ratio Q caused by evaporation on pulse duration τ at equal carbon ion initial energy ($E = 1$ MeV) and the equal density of energy flow ($F = 30$ J/cm^2) is presented. Decreasing of the Q with rising of beam pulse duration is observed. It's connected with growth of heat outflow due to thermal conductivity into target depth during radiation pulse. This fact indicates that at pulse radiation regimes when very nonequilibrium temperatures fields are formed the erosion component Q caused by evaporation depends on pulse duration of the essence. According to our calculations the pulse nanosecond duration beams are the most effective for removal of atoms from the surface.
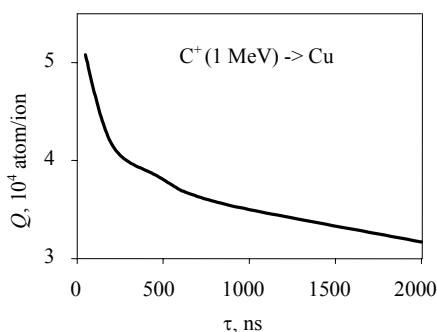

Fig. 4. The evaporation ratio Q on pulse duration when the copper sample being irradiated by carbon ion beam. The initial energy E and energy flow density F are fixed ($E = 1$ MeV, $F = 30$ J/cm^2)

The calculations carried out by us display that to get the high erosion ratios for technologies of micro-relief being made on the surface it can use effectively the continuous ion beams. To the effect they have to be focused till sizes $\sim 20…100$ μm, making current density on a level with 20…60 A/cm^2, and their scanning on the sample surface with velocity about 2…20 m/s must be provided. Under these conditions erosion ratios due to evaporation on a level with $10^3…10^4$ atoms/ion are achievable for metals.

4. Conclusions

On the treatment with submicrosecond ion beams within the $10^6...5 \cdot 10^9$ W/cm^2 power density W the surface erosion includes both sputtering and evaporation. The intensity of these processes depends on the surface temperature T_S caused by radiation warming up. T_S is determined by the beam power density and radiation duration. In proportion to increasing W evaporation passes over three stages: activation evaporation, evaporation process without activation and hydrodynamic scattering of substance.

At W below $(1...5) \cdot 10^6$ W/cm^2 the main mechanism of erosion is sputtering. The erosion ratio doesn't overtop some tens of units. At $W \geq (0.5...1) \cdot 10^8$ W/cm^2 erosion is connected with evaporation of atoms away from surface as a result of its warming up by beam particles up to the temperatures near boiling point and higher. The erosion ratio is within the range $10^4...10^5$ atoms/ion (at $E \leq 2$ MeV).

Within the $5 \cdot 10^6...5 \cdot 10^7$ W/cm^2 range of W evaporation by the activation mechanism takes place. On the samples surface the temperatures up to melting point and more are achieved. So, the spattered atomic flow away from the surface may be rather intensive. Within this range of the power density an estimation of atomic flows proportion caused by sputtering and evaporation hasn't been made at present. Since sputtering may occur from the layer of nanometer thickness [8], so it seems the total erosion ratio D to be less on orders within this W range than under regimes producing intensive surface evaporation around the temperature of boiling point.

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