Fine structure in the energy and angular distributions of the secondary-ion emission of implanted argon

A. A. Kosyachkov, V. T. Cherepin, and S. M. Chichkan'
Institute of Metal Physics, Academy of Sciences of the Ukrainian SSR

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Fine structure has been detected in the energy and angular distributions of the emission of secondary ions of argon implanted in a Mo(100) surface. The distributions have two maxima, which correspond to two states of the argon atoms in the lattice of the single crystal.

The development of diagnostic methods for studying the state of an inert gas which has been implanted by ion bombardment in a solid surface is an important step forward in research on the radiation stability of substances and toward improving the technology for using ion beams to alter the microstructure of surfaces. The secondary-ion emission which accompanies sputtering of a surface is widely used for a concentration analysis of the implanted atoms.[1] Unfortunately, the mass spectra of the secondary-ion emission of a chemically inert gas cannot tell us the state of the gas; for example, they cannot tell us whether the implanted substance is in the form of individual atoms or in the form of microbubbles which have formed near the surface of the substance under study. It may be that information of this sort is contained in the energy and angular distributions of the secondary-ion emission of an inert gas. These distributions could be measured by the method of secondary-ion mass spectrometry with high energy and angular resolution; this method is presently in the development stage. So far, there have been no such studies. On the other hand, it has recently been found[2] that the fine structure in the energy distributions of the implanted and simultaneously sputtered neutral argon atoms reflects the state of the argon atoms in a silicon lattice.

In this letter we report a study of the sensitivity of secondary-ion emission to the state of the inert gas which has been carried out with the help of an ultrahigh-vacuum spectrometric complex with a high energy resolution (0.1 eV), a high spatial resolution (8.6×10^{-3} sr), and a high mass-spectrum resolution ($1M$) (Ref. 3). As the test object we used the (100) face of a molybdenum single crystal; an implantation and a simultaneous sputtering of this phase were carried out with 6-keV argon ions at an ion current density of 2×10^{-4} A/cm^2. The geometry of the study was varied by varying the polar angles of the bombardment (α) and of the ion emission (θ); both angles were reckoned from the normal in the (010) plane, which was perpendicular to the Mo(100) surface. The measurements were carried out in a field-free space under conditions corresponding to a stabilization of the secondary-ion emission of argon, which set in at bombardment doses on the order of 10^{17}–10^{18} at/cm^2. The absolute values of the energies, on the other hand, may turn out to be too high, since they were measured within the constant but unknown contact potential difference between the

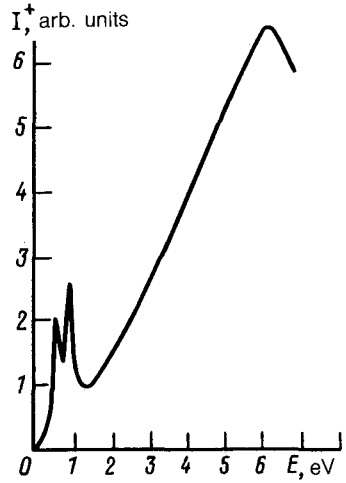

FIG. 1. Energy distribution of secondary-ion emission with $\alpha = 45°$ and $\theta = 46°$.

bombarded surface of the sample and the surface of the secondary-ion analyzer. Figure 1 shows the energy spectrum of the secondary ions before mass separation. The mass-spectrometric analysis of these ions revealed that the high-energy peak with a maximum at $E_m = 6.1$ eV corresponds to monatomic and polyatomic secondary molybdenum ions, while two peaks, at $E_m = 0.5$ eV and $E_m = 0.8$ eV, correspond to the emission of secondary argon ions. The results in Fig. 1 thus confirm the suggestion that there is an energy fine structure in the secondary-ion emission of implanted argon. It was found that the structure of the energy spectrum corresponds to two characteristic distributions of the secondary ions in emission direction. It can be seen from Fig. 2 that the energies of the maxima and the angular distributions of the secondary argon ions depend on the direction of the implantation and sputtering of the surface by the molybdenum, characterized by the angle α.

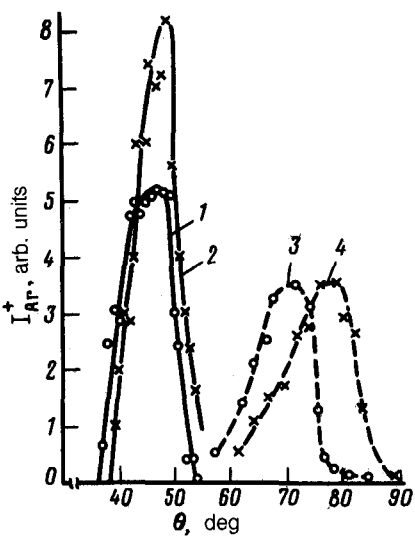

FIG. 2. Polar distributions of the secondary-ion emission of argon. Solid lines: $\alpha = 45°$. Dashed lines: $\alpha = 0°$. E_m: 1—0.5; 2—0.8; 3—0.4; 4—1.2 eV.

The presence of two peaks in the energy and angular distributions of the secondary-ion emission is evidence that the atoms of the implanted argon are present in two distinct states in the molybdenum lattice. These energy features of the secondary-ion emission have certain aspects in common with the energy distributions of the neutral argon atoms which were measured in Ref. 2. In both cases, the energy splitting of the maxima is a few tenths of an electron volt, and the magnitude of the splitting varies with the energy position of the maximum, depending on the implantation conditions. These conditions were varied by varying the temperature of the silicon sample[2] or by varying the geometry of the bombardment of the molybdenum surface (Fig. 2). Van Veen *et al.*[2] interpret the fine structure in the E distributions of the neutral argon atoms as corresponding to an ion-stimulated desorption of atoms of the implanted gas, which are diffusing to the silicon surface (the lower-energy peak), and the appearance of argon-filled microbubbles during the sputtering of the silicon surface (the higher-energy peak). The results of an electron-microscopy study of the state of inert gases implanted in the surfaces of molybdenum and other metals, which was carried out in Ref. 4, also confirms the presence of microbubbles, with an internal pressure sufficient in some cases for the crystallization of the inert gas into a solid phase.

Consequently, the energy fine structure observed in the secondary-ion emission in the present experiments results from a difference between the energy states of the argon atoms which are present at the molybdenum surface in the form of single atoms and in the form of microbubble formations. Recalling the uncertainty regarding the measurement of the absolute values of E_m, which we mentioned at the beginning of this letter, we see that the relative positions of these peaks, i.e., the difference between the energies of the maxima of the E distributions, contain information about the difference between the potential energies of the argon atoms in the two states. On the basis of the conclusions reached in Ref. 2 and the data in Figs. 1 and 2 of the present paper, we can conclude that the average potential energy per argon atom in a microbubble is at least a few tenths of an electron volt. This conclusion is evidence of a significant pressure in these microbubbles; this pressure may lead to a crystallization of the argon in a solid phase.

The anomalously narrow angular distribution of the emission of the secondary ions of implanted argon which was seen in these experiments, and which is not typical of secondary-ion emission, also corresponds to these arguments. Specifically, an ion-stimulated desorption is characterized by a sharp spatial directionality.[5] The focusing effect of the lattice stress in molybdenum would also act on the argon atoms present at a high pressure in microbubbles when these bubbles are opened up on the side of the surface being sputtered.

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