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SPM observation of nano-dots induced by slow highly charged ions

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Abstract

We have observed nano-dots on a highly oriented pyrolytic graphite (HOPG) surface produced by highly charged ion impacts with a scanning probe microscope. In order to clarify the role of potential and kinetic energies in surface modification, we have measured the kinetic energy and incident ion charge dependences of the dot size. The results showed that the potential energy or the incident ion charge has strong influence on the surface modification rather than the kinetic energy.

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1. Introduction

Collisions of slow highly charged ions (HCIs) with surfaces have received great attention in recent years and have been extensively studied with various methods, such as scanning probe microscopy, secondary particle observation, photon spectroscopy, and so on (for these studies, for example, see [1] and references therein). Through previous observations with an scanning probe microscope (SPM), it has been shown that a single HCI impact can induce surface modification. However, the mechanism for inducing such modification is not known, and further systematic investigations are necessary.

We have been studying the surface modification through observations with a scanning probe microscope (SPM) in both scanning tunneling

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microscope (STM) and atomic force microscope (AFM) modes. STM observation gives information on the electronic density of states, while AFM observation directly gives topographic surface structure. Thus, in order to understand the physical properties of the HCI-induced nano-dots, it is important to make observations in both modes. Up to now, we have made observations for highly oriented pyrolytic graphite (HOPG). In similar studies done by other groups [2,3], formation of protrusions at impact sites was reported with a height of ~0.5 nm and a diameter of several nm in the STM observation, but such a structure has never been observed with an AFM. Consequently, it was concluded by them that the protrusion observed in the STM mode is not topographic surface modification but changes in the electronic density of states. However, in our previous observation for 138 keV Xe^{46+} impacted HOPG, nano-dots were observed also in the AFM mode [4]. Our observation clearly gave the evidence that the nano-dot corresponds to the topographical change on the surface at least for the kinetic energy and the incident ion charge studied. The discrepancy between our and the previous results could be due to the difference(s) in one or more of the following items:

1. the potential energy or the charge state of the incident ion,
2. the kinetic energy of the incident ion,
3. AFM mode (contact or non-contact).

We considered that the larger potential energy or larger kinetic energy (or both) induced larger surface modification which is easily observable in AFM observation. However, the relative importance between them remained unclear. In order to clarify the role of potential and kinetic energies, we have measured the dot size and height as functions of incident charge state and impact energy in this study.

2. Experiments

We have been using two ion sources, a high-T_C superconductor EBIS [5] and the Tokyo-EBIT [6] depending on the charge state used. The former can produce relatively intense but relatively low charged ions, and was used for charge states of up to 40+. On the other hand, the latter can produce highly charged but relatively low intensity ion beam and was used for charge states higher than 40+. HOPG cleaved in the air with adhesive tape was irradiated with HCIs from one of those ion sources. The extraction voltage of HCIs was 2–4 kV. When a kinetic energy lower than $2 \times q$ keV was needed, the ions extracted with an extraction voltage of 2–4 kV were decelerated just before the target. After irradiation, the HOPG sample was exposed to air, transported and set on a sample holder of the ultra high vacuum SPM.

The SPM used is JEOL JSPM-4500A, which can be operated in both the STM and AFM modes [4]. In the present study, however, all the measurements have been done only in the constant current STM mode, in which a mechanically prepared Pt/Ir tip was used.

3. Results and discussion

Fig. 1 shows a typical STM image for the HCI irradiated HOPG surface. Our previous observation [4] confirmed that this dot structure corresponds to topographical surface deformation. However, since the kinetic energy of the incident HCI was rather large (138 keV), we could not specify which is more effective for the surface deformation between the kinetic and potential energies. Thus, in this study, we have studied the kinetic energy and the incident ion charge dependences of the dot size and height.

Fig. 2 shows the kinetic energy dependence of the dot size and height, which contains the present results and the previous results by Minniti et al. [7]. In order to obtain the present results, more than 20 dots were sampled with the STM mode for each kinetic energy. The error bars in the figure represent the standard deviations. As seen in the figure, it seems that there is no kinetic energy dependence even though the kinetic energy range is as wide as about 1–300 keV. The incident ion charge dependence of the dot size and height is plotted in Fig. 3 which contains the present results and the previ-

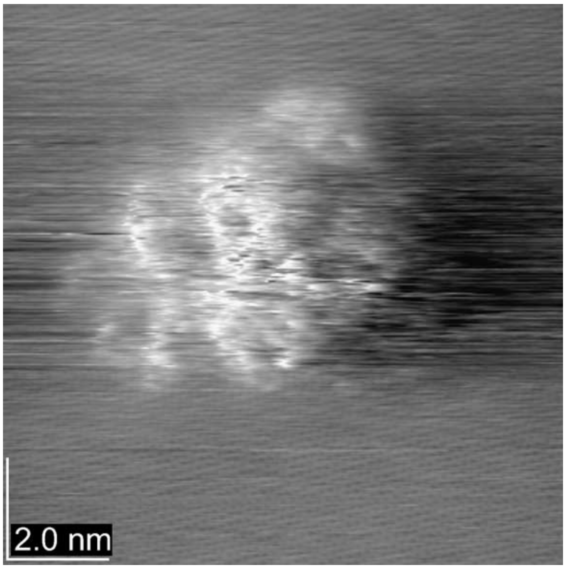

Fig. 1. A typical STM image of the HCI impacted site on HOPG, which was obtained for 138 keV Xe^{46+} incident ion.

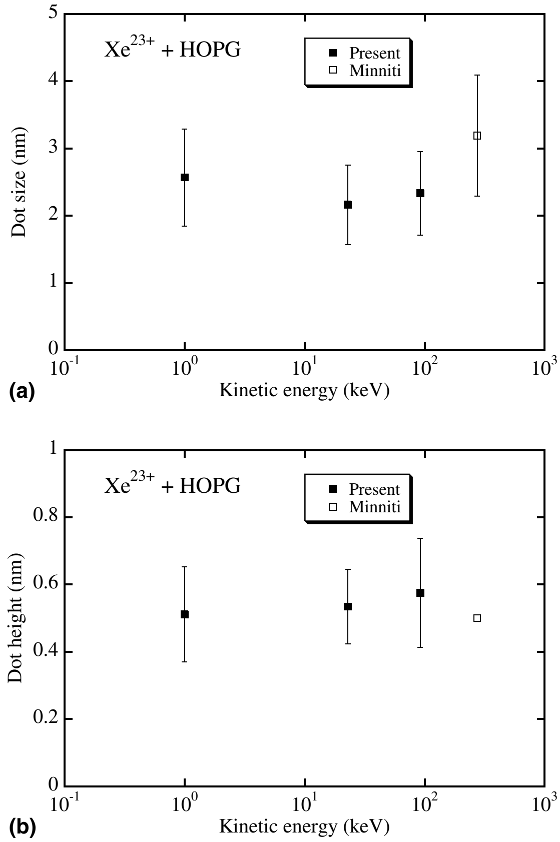

Fig. 2. The kinetic energy dependence of (a) dot size and (b) dot height for Xe^{23+} incident ion. The error bars represent the standard deviations.

ous results by several groups [7,2,8]. Although the height seems to be less sensitive to the charge, the dot size shows strong charge dependence as seen in the figure. Consequently, it should be concluded that the potential energy or the incident ion charge has more direct and strong influence on the nano-dot formation rather than the kinetic energy at least for the kinetic energy range studied.

Up to now, a number of observations have been made for ion-induced defects on HOPG, and several mechanisms for the production of the defects have been proposed [2,7–11]. From our previous observation [4], we found that the protrusions observed with an STM correspond to topographical modification at least for the case where ions with very high charge states such as 46+ are used. For the cause of such surface deformation, it was found from the present results that the simple collision cascade does not play an important role because the height and size of the dot do not show significant impact energy dependence. Thus, it can be concluded that the nano-dots were produced by electronic interactions between incident HCIs and HOPG. Up to now, several electronic processes have been proposed (for example, see [7] and references therein). However, unfortunately, we can not pick one out of them only from the present results.

As well as HOPG, mica has also been well investigated with an SPM up to now. In the previous measurements [12,13], protrusion-like dots were observed also on a mica surface. According to their observations, the dot size and height on mica show similar behaviour as those on HOPG, i.e. the dot size is insensitive to the kinetic energy but shows strong dependence on the incident ion charge, and the dot height is less sensitive to both the kinetic energy and the incident ion charge. These similarities are very interesting because it is considered that the surface modification mechanism should be essentially different between these materials due to the difference in the physical properties such as conductivity. The similarity in

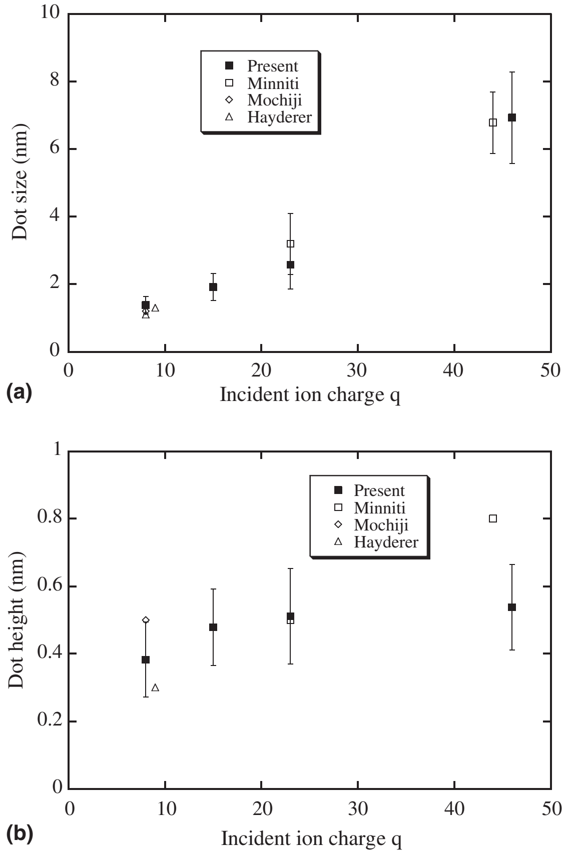

Fig. 3. The incident ion charge dependence of (a) dot size and (b) dot height. For $q < 10$, the incident ions are Ar, while for $q > 10$ the incident ions are Xe. Although the kinetic energies of the incident ions are not the same, it can be considered that the dot size and height are insensitive to the kinetic energy (see text and Fig. 2). The error bars represent the standard deviations only for the present result.

a layered structure may have something to do with the similarities in the kinetic energy and incident charge dependences.

For further understanding, systematic studies are still ongoing for the kinematic energy and incident ion charge dependences of the dot size with both STM and AFM. In addition, it will be important to investigate targets with various conductivity and various structures. Although HOPG and mica surfaces are stable even in the air atmosphere, material surfaces are not stable in general so that the sample should be handled only in the ultra high vacuum. Consequently, we have built a system for in situ observation by connecting the compact HCI source, high-T_C EBIS, and the SPM. This in situ system allows us to study target dependence. We expect that these studies will clarify the surface modification mechanism.

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