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Intensity distributions of reflected surface channeling protons scattered on surfaces of electron-bombarded alkali halide crystals

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ABSTRACT

We have examined the surface-channeling of 550 keV protons on electron-bombarded KBr(001) surfaces at grazing incidence. On the surface, electron-stimulated desorption (ESD) resulting from the irradiation of 5 keV electrons changes the surface morphology. In order to investigate the change of the surface morphology, the luminous intensity distributions observed on a fluorescent screen (scattering patterns) of the reflected protons under the surface-channeling conditions are measured. Normalized specular intensity of the protons oscillates, and the results of computer simulations show that the period of the intensity oscillation agrees with the period of layer-by-layer desorption. The measured period of the oscillation is comparable to the simulated one, i.e., the period of the desorption, however, the measured amplitude of the oscillation is weak. This shows that the layer-by-layer desorption of the experimental surface is observed but is not as remarkable as that of the perfect surface introduced in the simulation.

1. Introduction

Electron-stimulated desorption (ESD) resulting from irradiation of electrons changes the morphology of the surfaces of insulators or semiconductors. Especially remarkable change for alkali halide surfaces due to the ESD is known. Many rectangular pits with steps of monolayer height are induced, and the desorption yield oscillates with a period of layer-by-layer removal of the surface [1]. Non-contact atomic force microscopes (NC-AFM's) in ultrahigh vacuum systems have greatly developed in the past twenty years allowing changes of the surface morphology induced by ESD of the alkali halide crystal to be effectively investigated. On the other hand, prior to the studies using NC-AFM, the change of the morphology of NaCl(001) surface by photon stimulated desorption (PSD) was studied by Höche et al. [2]. In order to investigate the change of morphology, they used He atom scattering (HAS) technique. The measured specular intensity of the scattered He with UV exposure shows oscillatory structure, which indicates the layer-by-layer desorption [2]. Recently, the fast atom scattering combined with diffraction method is again noticed with studies of an alkali halide surface as a new method for structure analysis [3]. These glancing angle scattering techniques are non-destructive and convenient to analyze surfaces which are easily damaged by charged particles.

We have studied the scattering of MeV protons from electron irradiated alkali halide surfaces [4–7]. Intensity distributions of protons scattered from the surfaces at the glancing angle incidence have been observed using a solid state detector or a spectrometer. In the present study, decreasing the electron fluence compared with these studies, the intensity of the specularly scattered protons (specular intensity) were measured simply as a function of the electron fluence ranging a few layers removal by the ESD (a few tens $\times 10^{13}\ \mathrm{cm}^{-2}$). The measured intensity is then compared with that calculated by a computer simulation. This experiment is expected to be a new method to examine the layer-by-layer desorption of the surface. The experimental device used is simple. We are able to measure easily with a very popular device (digital camera) without using any special device for particle detector.

2. Experimental

We carried out the experiments using an ultrahigh vacuum (UHV) system consisting of the scattering chamber equipped with an electron gun connected to a 15° beam-line of the tandem Van de Graaff accelerator at Nara Women's University. A single crystal of KBr was cleaved parallel to the (001) plane in air and was immediately mounted on a holder of 4-axis gonio-meter in the scattering chamber. The cleaved surface of KBr(001) was cleaned by baking the chamber for 20 h, followed by heating the sample holder up to 520 K for an hour, and keeping it at 420 K during measurements [5–7].

Fig. 1 shows the experimental arrangement. The base pressure in this system was below 10^{-7} Pa. The sample surface ($20 \times 25\ \mathrm{mm}^2$) was irradiated by 5 keV electrons at a 45° incidence angle. The vertically long electron beam was deflected and scanned

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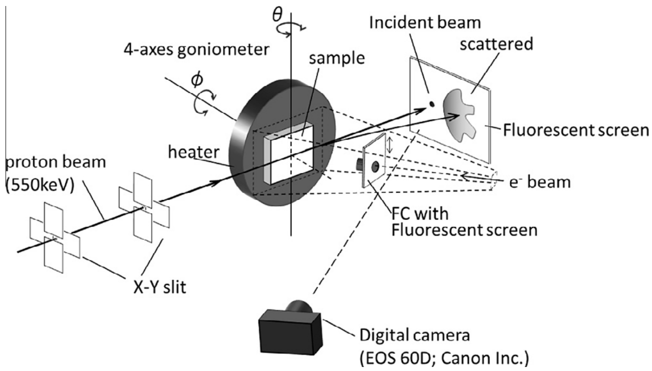

Fig. 1. Schematic overview of the experimental setup.

horizontally on the sample surface. The electron beam monitored by a Faraday cup (FC) with a secondary electron suppressor was 0.01–0.1 μA/cm^2.

The 550 keV proton beam from the accelerator was collimated to be 0.2×0.2 mm^2 by two sets of XY-slits and incident on the surface with the angle of incidence, θ_i, less than 10 mrad. The incident beam current of protons was not more than 50 pA. Observing the fluorescent screen during the sample approach to the beam, we have estimated that more than half of these protons miss the surface or impinge on the (1 0 0) side plane. The azimuthal angle (φ_i) of the incident beam direction was along one of the major axes on the surface (the [1 0 0] or [1 1 0] crystallographic directions).

The scattered protons from the sample surface hit the fluorescent screen, whose surface normal was parallel to the beam direction. A few tens of photographs of the luminous intensity distribution appearing on the fluorescent screen were taken with a digital camera (EOS 60D; Canon Inc.). The scattering intensity distribution map was plotted by adding up the green RGB values of each individual pixel (0.44×0.55 mrad^2) using these photographs. Change of the intensity distributions with increasing irradiation fluence of electrons was expressed by the normalized specular intensity, i.e., the intensity at the specular position divided by the total intensity of the scattered protons.

3. Results and discussion

3.1. Experimental results

Fig. 2 shows an example of the measured scattering patterns. The shadows indicated by dotted lines are the blocking lines on the comparatively broad scattering pattern due to protons reflected from the subsurface layers [5–7]. The intensity profile containing the incident and scattered beams along the direction normal to the crystal surface is inserted on the top of the figure. The width of the distribution of the scattered beam was broader than that previously measured by a movable solid state detector with a pin-hole slit and reported [4]. The first reason for the broadening is that the incident beam size is rather large. In order to obtain higher brightness on the fluorescent screen, the incident beam current on the sample has been increased at the sacrifice of the collimation of the incident beam. The larger beam size provides a broad target position for scattering along the beam line. The second reason is that the linearity of the light intensity emitted from the fluorescent screen has not been guaranteed. Since the light intensity showing the incident beam might be saturated, the light intensity may be a sublinear function of the yield of protons.

The intensity at the position of the peak of the scattering angle $\theta = 2\theta_i$, i.e., specular intensity, as a function of the electron beam fluence is plotted in Fig. 3 by circles. The shown specular

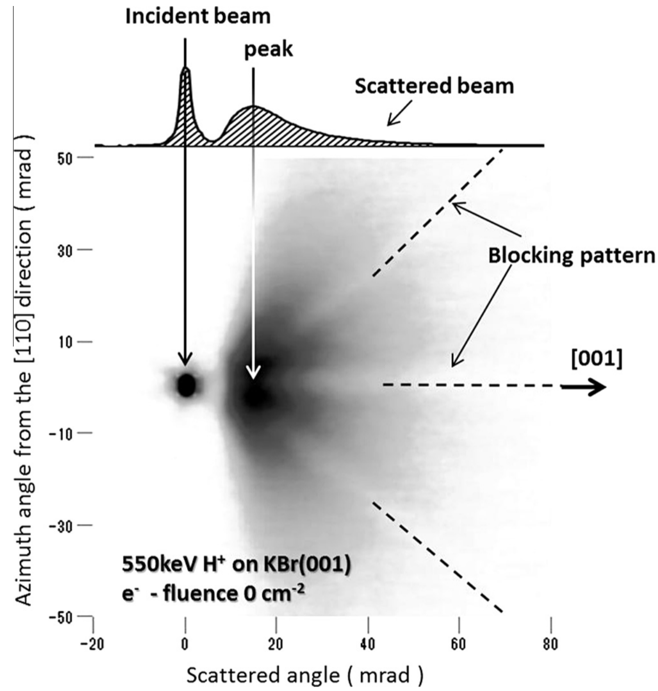

Fig. 2. An example of the observed scattering patterns. The section-profile in the scattering plane along the [0 0 1] direction is shown on the figure. The size of one pixel corresponds to the angular width of 0.44×0.55 mrad^2 along the φ and θ directions, respectively.

intensities were normalized ones. In order to be careful to the change of condition of incident beam angle, this experiment was carried out under the surface channeling conditions. When channeling conditions are satisfied, blocking lines are located suitably in scattering patterns as shown in Fig. 2. If one of conditions such as azimuthal angle of incident beam is changed, blocking lines move in the pattern. Fig. 3(a) and (b) show for the [1 0 0] and [1 1 0] channeling incidence, respectively. Solid lines drawn in these figures are added to guide for the eye. For both channeling conditions, the specular intensity oscillates with electron irradiation for a few periods. These periods are 6×10^{13} cm^{-2} for the [1 0 0] incidence and was 7.5×10^{13} cm^{-2} for the [1 1 0] incidence, respectively. Although the data in the fluence range between 3×10^{14}–3×10^{15} cm^{-2} are not shown in Fig. 3, both oscillations disappear and become constants.

3.2. Computer simulation

A set of the model surfaces was obtained by a sub-module program code of the computer simulation as follows: The model surfaces were prepared by referring the experimental results presented by Kolodziej et al. [8]. Their sample was KBr(0 0 1), and the temperature of the sample was 410 K. When the surface was irradiated by means of a 1 keV electron beam, the surface atoms were desorbed in layer-by-layer mode. The desorbed atom yields show oscillatory structure corresponding to the removal of several monolayers in the layer-by-layer mode. In our simulation using the sub-module, the period of the oscillation of the yields of desorbed atoms has been fitted to their experimental results by several fitting parameters. Fig. 4(a) shows the calculated oscillating behavior of yields of the desorbed atoms with one that measured by Kolodziej et al. [8]. More detail of the procedure can be found in Ref. [9,10].

Examples of the morphologies obtained by the sub-module are shown in Figs. 4(b)–(d). Many rectangular pits having edges along <1 0 0> direction are observed in these figures which are similar to