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STM study of ion tracks created in GaAs by GeV Xe ion irradiation

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Abstract

Defect structures in p-type GaAs bulk crystals irradiated with 3.54 GeV Xe³¹⁺ ions were studied by scanning tunneling microscopy (STM) and scanning tunneling spectroscopy (STS). STM images of the cleavage (1 1 0) surfaces revealed the fine structure of a single ion track that consists of a long straight linear defect of ~5 nm in diameter sheathed with a thin fringe in bright contrast. Unexpectedly, the surrounding region was observed to be irregular in contrast to atomically resolved images in non-irradiated regions. The local density of states measured by STS indicates that the tracks are amorphous whereas the sheath and the surrounding sites retain crystalline structures. Some of the defect contrasts can be explained as due to the shift of the Fermi level and the variation of the LDOS in the energy bands. Though the tracks and the surrounding regions were unaffected by STM observations and STS measurements under mild imaging conditions (tunneling current < 1 nA), we found that the contrasts of the tracks are 'erased' when we scan the tracks with the STM tip at tunneling current greater than 2 nA. These facts strongly suggest that the defects introduced by GeV Xe ion irradiation are recovered by atomic motion enhanced by injection of tunneling current.

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1. Introduction

Energetic ion irradiation, a technique for modifying the structures of solids and hence the physical properties, has a feature that the spatial extent of the modified area can be controlled by varying the species, the charge state, and the kinetic energy of the ions. It is known that irradiation

of swift heavy ions generate linear defects called tracks. Although direct observations of individual ion tracks have been performed in some solids by optical microscopy [1], transmission electron microscopy [2] and scanning force microscopy [3], the knowledge of the microscopic structures of individual ion tracks and of the associated electronic states is still quite limited.

In this paper, the structures and the electronic states of individual tracks created in GaAs by 3.54 GeV Xe³¹⁺ ion irradiation were investigated by scanning tunneling microscopy (STM) with a nano-scale resolution. STM combined with

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scanning tunneling spectroscopy (STS) is especially suitable for such studies because it can provide direct information of the local electronic states associated with the defect structures imaged with an extremely high spatial resolution. Furthermore, current injection from the STM tip sometimes causes an atomic motion or reactions that can be detected in situ in the STM observations [4–8]. We actually found also in the present samples the recovery of the ion tracks on injection of tunneling electrons from the STM tip.

2. Experimental

The samples used were Zn doped p-type GaAs bulk crystals (hole density, $p \sim 10^{18} \text{ cm}^{-3}$) irradiated at normal incidence to the (001) surface with 3.54 GeV Xe³¹⁺ ions up to a dose of $2.5 \times 10^{11} - 5 \times 10^{11} \text{ cm}^{-2}$ at RIKEN ring cyclotron. After irradiation, clean cross-sectional (110) sample surfaces were prepared by cleaving in an ultrahigh vacuum STM chamber (base pressure $< 2 \times 10^{-8}$ Pa) to investigate the defect features created along the ion trajectories. The (110) surfaces were probed with a mechanically sharpened Pt–Ir tip under various conditions of sample bias voltage (V_s) and tunneling current (I_t). The structural features were examined in the constant-current STM images obtained at $V_s = +2.1$ V and $I_t = 0.1$ nA, and the electronic properties were investigated by STS measurements of the local current–voltage (I – V) relation from which the approximate local density of states (LDOS) was deduced by calculating $(dI/dV)/(I/V)$. All experiments were performed at room temperature.

3. Results and discussions

Fig. 1(a) shows a typical STM image of a long straight linear defect observed in a cleavage (110) surface of a sample under the imaging condition of $V_s = +2.1$ V and $I_t = 0.1$ nA. These types of defects were found only within a depth of 1 μm on the irradiated side of the surface and never on the opposite side, hence they are tracks definitely produced by individual ions. Commonly, each

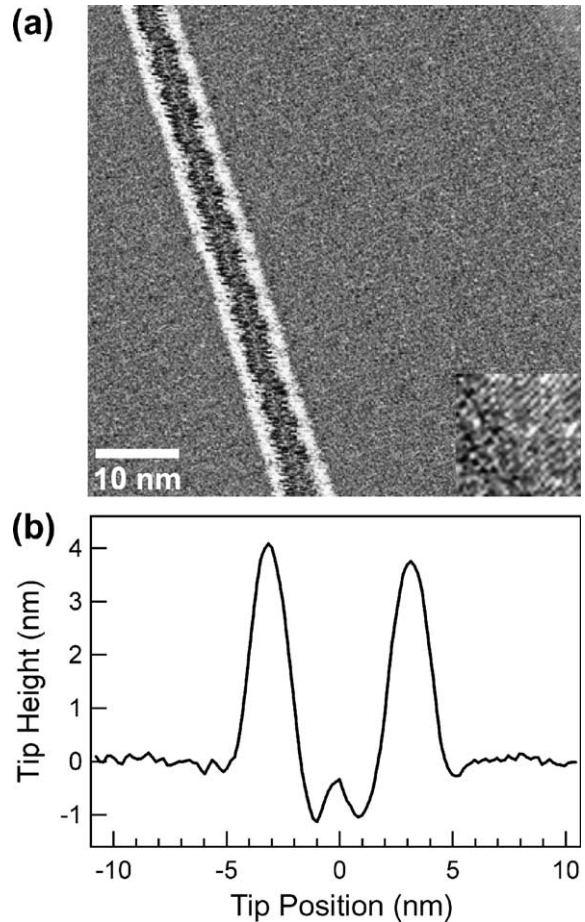


Fig. 1. (a) A typical STM image ($V_s = +2.1$ V, $I_t = 100$ pA) of a cross-sectional (110) cleavage surface of p-GaAs irradiated with 3.54 GeV Xe ions at room temperature. (b) The average line profile of the tip height across an ion track. The ion track of ~ 5 nm in diameter observed in dark contrast is sheathed with a thin fringe of ~ 2 nm in width in bright contrast. The effects of a single ion spread around the ion track creating an extended region where we could not see such lattice contrasts as clearly observed at the upper right corner in (a) which is zoomed in the inset.

track imaged in dark contrast is sheathed with a thin fringe in bright contrast. One may also notice a bright thin line running along the core of the track. Fig. 1(b) shows the average line profile of the tip height (giving the contrast in constant-current images) plotted across the track. The width of the track in dark contrast is ~ 5 nm, and the thickness of the bright sheath is ~ 2 nm in average.

The tracks in dark contrast appear quite disordered, which is consistent with previous TEM observations of amorphous tracks of 5–8 nm in diameter formed in heavy ion irradiated GaAs [2]. However, the TEM image of the region outside the track appeared crystalline whereas the STM image exhibits no crystalline features extending over a distance of 40 nm from the track. Note the atomically resolved image beyond the disordered region, indicating that the non-crystalline contrasts are not due to the poor resolution of the tip. Thus, our results indicate that the impact effect of an ion is not confined to the track but extends to a much larger volume.

The origin of the fringe contrasts of the sheath is judged to be not the surface corrugation from the reasons as follows: (i) if it were the projection formed by cleaving, reverse contrasts or dark fringes would be found in some other places on the symmetrically cleaved non-polar (110) surface, which was never observed in experiments and (ii) if it were the distortion due to the relaxation of the stress around the ion track, the magnitude of it would be very small because it spread only ~ 2 nm horizontally as shown in Fig. 1(b), but for which the height of up to ~ 4 nm is too large. Therefore, we have to attribute the main cause of the contrast to a spatial variation of the electronic states. Fig. 2 shows the spectra of LDOS deduced from the I - V relations measured at characteristic sites around the track. The energy zero in each spectrum indicates the Fermi level at the surface. At sites where atomic rows are observed, the spectrum ('P' in Fig. 2) shows features characteristic of p-type GaAs perfect crystals, the bandgap of ~ 1.4 eV and the Fermi level being located near the valence band top. At the track in dark contrast ('T' in Fig. 2), however, the bandgap is considerably reduced. This is consistent with the well-known fact of band-tailing induced by amorphization of semiconductor crystals [9,10]. In contrast, at the bright fringe ('F') and the outskirts of the track ('O'), such reduction of the bandgap is not observed. This means that these regions retain the crystalline structures although they exhibit no crystalline contrasts in the STM images. The spectra at F sites and O sites differ, from the perfect sites ('P') and from each other, in the relative position of the

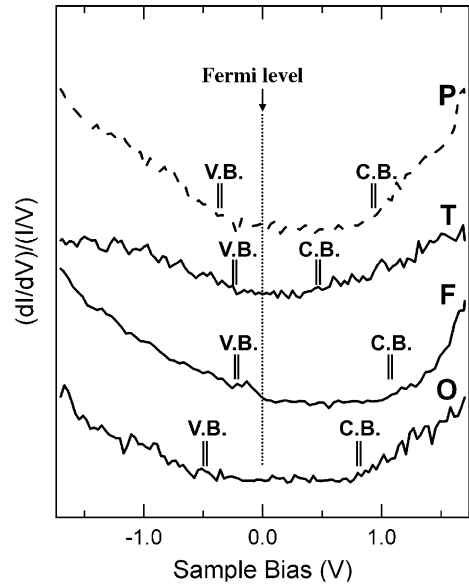


Fig. 2. LDOS deduced from I - V relations measured at characteristic sites around the track. The spectrum labeled 'P' shows one typically obtained at sites where atomic lattice images are observed. Spectra inside the dark track, at the bright fringe, and at the outskirts of the track are also shown as 'T', 'F' and 'O', respectively. The vertical double lines with letters V.B. and C.B. indicate the positions of the valence band top and the conduction band bottom, respectively.

surface Fermi level with respect to the band edge and in the magnitude of the LDOS in the energy bands. It is likely that defects introduced by irradiation form electronic levels that alter the LDOS and the position of the Fermi level. Therefore, the fringe contrast and the irregular contrast in the surrounding in the STM images are considered to be due to such variations of electronic states due to some irradiation defects.

As long as the tunneling current I_t was smaller than 1 nA, the contrast of the tracks remained unchanged during STM observations and STS measurements. However, we found that the tracks change the contrasts when we increase the tunneling current above 2 nA. Fig. 3 shows an STM image of a track a part of which has been 'erased' by scanning the stripe area with a tip at $I_t = 2$ nA for 5 s. A subtle change in the contrast is discernible also at the outskirts of the track. These facts indicate that the amorphous structures in the track and defects in the sheath and the surround-

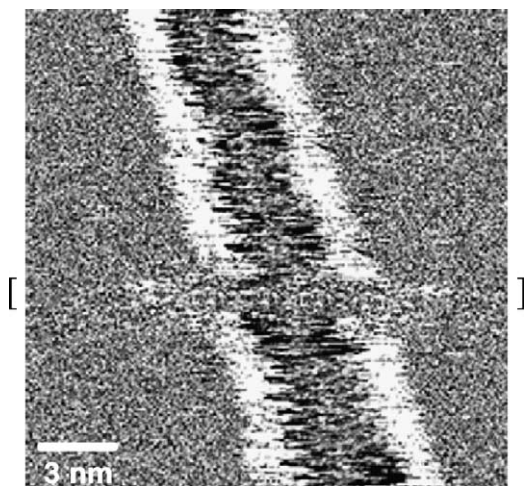


Fig. 3. An STM image of a track scanned with an STM tip over the area indicated with [] marks at $I_t = 2$ nA for 5 s. In the scanned area, both track and bright fringe are almost erased while the change in the outskirts is subtle.

ing are recovered by the injection of tunneling current. Our recent studies showed that injection of tunneling electrons in energies as low as several eV induces atomic motion and reactions on surfaces of non-metals, hopping motion of chlorine atoms on Si (111)-(7 × 7) surfaces [8] and polymerization and decomposition of C₆₀ clusters deposited on substrates [7], which are all interpreted as due to electronic-excitation-induced effects. Jencic et al. [11] reported a similar recovery of tracks in GaAs by the effect of irradiation of electrons in energies smaller than 100 keV, well below the threshold for the displacement damage. A noteworthy fact in their results is that the recovery rate increases with decreasing electron energy, which is a feature expected from an electronic excitation effect of energetic electron irradiation on thin films. These facts strongly suggest that electronically enhanced atomic motion induced by electron injection is the cause of the recovery of tracks on STM probing.

Recently, such effects of electronic excitations on solid reactions have attracted a great deal of attention as a novel approach for controlling the properties of materials [12]. Iwase et al. [13] reported that electronic excitations caused by irradiation of swift heavy ions induce non-thermal

effects even in metals. Although the mechanism is not known at present for the formation of the present defective regions extending around the ion tracks and the thin linear structure along the core of the tracks detected in STM images, electronic excitations might be responsible for the creation of the unexpected structures. The elucidation of the microscopic mechanism is subject to further studies.

4. Conclusions

Individual ion tracks in p-GaAs crystals irradiated with 3.54 GeV Xe ions were studied by STM and STS with nano-scale spatial resolution. The STM plan-view images of a single ion track revealed a fine structure of the track consisting of a straight linear rod of ~5 nm in diameter in dark (but bright at its core) contrast that is sheathed with a bright fringe of ~2 nm in thickness and further surrounded by an irregular region extending over a distance of ~40 nm from the track. STS measurements suggest that the tracks in dark contrast are amorphous but the sheath and the surrounding retain crystalline structures though heavily disordered. Some of the contrasts can be interpreted by the spatial variation of the electronic states regarding the position of the Fermi level and the LDOS of the energy bands probably modified by irradiation defects. These facts indicate that the effects of an ion passage in GaAs crystals are not confined to the track but extend to a much larger volume. It was also found that the tracks are erased by probing with an STM tip at tunneling current larger than 2 nA. This phenomenon can be explained by electronically enhanced atomic motion that brings about the recovery of the disordered structures.

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