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INDUCED BY HIGH-ENERGY HEAVY IONS**

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HIGH-RESOLUTION MICROSCOPY OF LATENT TRACKS INDUCED BY HIGH-ENERGY HEAVY IONS

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Abstract

On its way through a solid, an energetic heavy ion deposits an enormous amount of kinetic energy per unit path length during an extremely short time interval. The energy transfer induces very fast primary processes which can cause, depending on the specific solid properties, damages ranging from point defects to a total amorphization in the case of crystalline material within a long, thin cylinder-shaped volume along the ion trajectory. Details of size, shape, and morphology of the ion tracks, though representing the final stage of the damage creation, store indirect information about the not simultaneously observable very rapid primary processes. We present images and additional information on the properties of ion tracks in germanium monosulfide, highly oriented pyrolytic graphite, and muscovite mica achieved with transmission electron-, scanning tunneling-, and scanning force-microscopy.

1. Introduction

In numerous insulating or semi-conducting materials an energetic heavy ion creates a zone characterized by a considerable alteration of the original structure along its trajectory. A uranium ion, to take an extreme example, accelerated to a kinetic energy of 11.6 MeV/nucleon, has an energy typical of ion beams provided by the Universal Linear Accelerator UNILAC of GSI. This ion travels along the first tens of microns of its trajectory in a solid with a velocity of about 15% of the velocity of light. At such a velocity, the ion loses its energy mainly by interaction with the electrons of the solid and deposits energy amounts on the order of 30 keV/nm. Assuming a lattice constant of a third of a nm along the ion path, the ion is successively transferring about 10 keV per lattice plane in time intervals of $7 \cdot 10^{-18}$ seconds. This illustrates that the ion passage creates extreme conditions initiating dramatic, very rapidly developing primary processes which cannot be observed directly. However, the details of size, form, and internal structure of the ion track, though representing the final stage of damage creation, contain indirect information about these processes.

Depending upon the radiation sensitivity of the material, the changes range from the occurrence of point defects via, e.g., separate clusters of an atomic component of the solid to continuous damage trails (usually called latent tracks), in which the crystal is fully amorphized. It should be emphasized that a comprehensive understanding of the processes underlying ion track creation can be achieved only on a long-term basis by collecting data from many different materials and accompanying experimental findings

with gradually refined modeling. For this purpose, latent tracks have been tackled by numerous groups with a variety of methods: scattering of neutrons and X-rays, or infrared spectroscopy derive the signal from an interaction with a large number of ion tracks. To provide access also to single, individual tracks, these methods were complemented by transmission electron microscopy (TEM), scanning tunneling microscopy (STM), and scanning force microscopy (SFM). The latter techniques are capable of characterizing the objects under study with subnanometer resolution.

This article gives an overview of our results on latent tracks in three different kinds of layered crystals, namely germanium monosulfide, highly oriented pyrolytic graphite, and muscovite mica, obtained by means of TEM as well as STM and SFM. The materials chosen all possess a layered structure that can be easily cleaved parallel to the layers. They are especially sensitive to high-energy ion irradiation, i.e., they store latent tracks with a clear signature. In particular, HOPG and mica are well suited for imaging with STM and SFM, providing atomic resolution even under ambient conditions. Besides presenting images of single track cross sections, we report on subtle track-related effects, such as lattice strain centers, periodic changes of the electron density, and altered friction and surface hardness on a nanometer scale. All samples under study were irradiated with high-energy heavy ions at the UNILAC, which can accelerate ions of all elements throughout the periodic table up to kinetic energies of about 14 MeV/u.

2. Transmission Electron Microscopy

2.1. GENERAL REMARKS

Transmission electron microscopy is capable of visualizing the atomic columns of a crystalline lattice and nanometer-sized objects embedded in a lattice. Therefore, TEM was already being applied in the late fifties and early sixties to fission fragment tracks in mica (Silk and Barnes, 1959; Bonfiglioli *et al.*, 1961; Price and Walker, 1962; See also Fleischer *et al.*, 1975; section 1.2.2), which are objects on a nanometer scale. However, since latent ion tracks tend to fade under the influence of an energetic electron beam, the method was pushed into the background for a longer period of time. In the late eighties, TEM of latent ion tracks was taken up again and applied successfully to a variety of crystalline materials such as yttrium-iron-garnet and others (Fuchs *et al.*, 1987; Houpert *et al.*, 1988; Houpert *et al.*, 1989; Studer *et al.*, 1989). A comprehensive TEM study on tracks in zirkon in 1990 (Bursill and Braunshausen, 1990) was followed by first measurements on heavy ion tracks in germanium sulfide (Vetter *et al.*, 1992; Vetter and Scholz, 1993; Scholz *et al.*, 1993). Recent TEM investigations on latent tracks in high- T_c superconducting crystals should also be mentioned (Wiesner *et al.*, 1996; Yan *et al.*, 1996). The results on GeS having grown significantly since 1993 are briefly summarized in the following section.

2.2. SOLID-STATE PROPERTIES, ION IRRADIATION, AND SAMPLE PREPARATION OF GERMANIUM MONOSULFIDE

Germanium monosulfide (GeS) is a semiconducting IV-VI compound that crystallizes in an orthorhombic structure with the lattice parameters $a=0.43$ nm, $b=1.047$ nm and $c=0.364$ nm. It consists of layers in the (010) plane and can be cleaved easily parallel to these layers by pulling off a thin sheet with the help of adhesive tape. Alternatively, the

definition $b=0.364$ nm and $c=1.047$ nm is also used in the works cited (Grandke and Ley, 1977; Láznicka, 1975), the plane of the layers being denoted with (001). Concerning the details of the solid-state properties and the crystal growth procedures of GeS, the reader is referred to the following works and further references therein (Grandke and Ley, 1977; Láznicka, 1975; Stanchev and Vodenicharov, 1975; Schönherr and Stetter, 1975).

The samples were irradiated with different heavy-ion species with the kinetic energies ranging from about 5.6 to 13.5 MeV/u. The fluences were typically on the order of 1 to $5 \cdot 10^{10}$ ions/cm², large enough to guarantee a facile and fast detection, but still sufficiently small to avoid overlapping of the tracks. The ion beam direction was perpendicular to the (010) basal plane. In some cases, after ion irradiation, GeS flakes were further thinned by means of low-energy ion bombardment (typical parameters, sufficiently low to avoid undesired sample modifications, are: Ar⁺, 5 keV, 1 mA) to become suitable for TEM imaging.

2.3. RESULTS AND DISCUSSION

Images were produced with high-resolution transmission electron microscopes (JEOL and Philips). The micrograph of Figure 1 shows the latent tracks of Au-ions with a primary energy of 11.4 MeV/u.

Figure 1. Cross sections of gold ion tracks in GeS imaged by TEM.

The cross sections of the tracks appear as elliptical areas embedded in an undamaged environment. Since the number of tracks per unit area corresponds to the applied ion fluence, they originate without any doubt from the passage of heavy ions. The ellipses are oriented with their long axes parallel to the direction of the lattice constant c . Figure 2 shows a high-resolution image of the cross section of a track caused by a single uranium ion.

Figure 2. TEM micrograph of a latent track in GeS caused by a single 5.6 MeV/u uranium ion (Vetter *et al.*, 1992).

Each of the dots of the surroundings represents an atomic column perpendicular to the (010) image plane, whereas the material within the track looks completely disordered. This loss of atomic order clearly indicates that the solid has changed into an amorphous phase along the ion trajectory. The amorphized material fills a long and thin volume with the shape of an elliptical cylinder. The amorphous and crystalline phases are separated by a remarkably sharp interface.

Figure 3. TEM image of zinc ion tracks serving as pinning centers for migrating dislocations in GeS.

The track is surrounded by four symmetrically arranged strain centers that have a preferred orientation. Furthermore, the latent tracks serve as pinning centers for migrating dislocations (for details see Scholz *et al.*, 1993). The phenomenon of dislocation pinning is impressively illustrated in Figure 3, showing a sample irradiated with 11.4 MeV/n zinc ions. Furthermore, the latent tracks serve as pinning centers for migrating dislocations (for details see Scholz *et al.*, 1993). The phenomenon of dislocation pinning is impressively illustrated in Figure 3, showing a sample irradiated with 11.4 MeV/n zinc ions. Aiming at a quantitative characterization of the ion tracks in GeS, the sizes of the long and short axes of the elliptical cross sections were evaluated for eight different ion species, each species corresponding also to another value of energy loss. Penetration depth and energy loss were calculated with the TRIM (Transport of Ions in Matter) computer code (Ziegler *et al.*, 1985). Mean values of the axes as a function of ion energy loss are plotted in Figure 4.

Figure 4. Long and short axes of elliptical latent tracks in GeS as a function of energy loss (standard errors of the data points are ± 0.5 nm).

During the past two decades, the functional dependence of track properties on essential parameters of projectile, solid, and projectile-solid interaction has been the subject of an enormous amount of theoretical work (See, e.g., Katz, 1978; Meftah *et al.*, 1994; and ref. therein). Thus, a sound understanding of the track diameter-versus-energy loss curve will require a detailed comparison of these data with the predictions of available theoretical concepts, such as the so-called thermal-spike model (Meftah *et al.*, 1994; Toulemonde *et al.*, 1992).

3. Scanning Probe Microscopy

3.1. SCANNING TUNNELING MICROSCOPY OF ION TRACKS IN HIGHLY ORIENTED PYROLYTIC GRAPHITE

Highly oriented pyrolytic graphite (HOPG) is a layered crystal consisting of parallel lattice planes with hexagonal ordering of the carbon atoms. The material exhibits a high electric and thermal conductivity within the lattice planes. Since only van der Waals forces are acting between adjacent lattice planes, a much smaller conductivity exists along the normal of the planes, i.e., parallel to the c-axis of the crystal. As a consequence, the HOPG can be cleaved easily parallel to the planes by pulling off a thin surface layer by means of an adhesive tape. In this way, a fresh non-contaminated surface can be created, which is atomically flat over hundreds of nanometers.

During the past decade, damage features in HOPG produced by ion irradiation were studied with STM by a number of working groups (Porte *et al.*, 1989; Coratger *et al.*, 1990; Porte *et al.*, 1991; Kemmer *et al.*, 1992; Bouffard *et al.*, 1993; Yan *et al.*, 1994). We performed studies on HOPG samples irradiated with 15 MeV/u Au²⁴⁺ ions (Kemmer *et al.*, 1992). For most samples, the direction of irradiation was parallel to the c-axis, and in a few cases almost at grazing incidence. In some cases, prior to STM imaging, a surface layer having a thickness of typically several microns was pulled off. For the given initial kinetic energy of 15 MeV/u the ions have a penetration depth of more than 100 μm . Due to the large ion energy, the damage trails in the interior of the crystal, whose cross sections become accessible by the cleavage, are caused exclusively by electronic energy loss.

An STM image containing the cross section of an ion track is shown in Figure 5 (from Probst *et al.*, 1993).

Figure 5. STM image (9.9 nm^2) of a single heavy-ion track in HOPG (Probst *et al.*, 1993).

It is obvious that the crystalline order has been destroyed within the track, whereas the intact surroundings appear with atomic resolution. Interestingly, small hillocks occur at the site of the track cross sections on a freshly cleaved surface. This finding is in agreement with results reported by Porte *et al.* (1989, 1991) and Coratger *et al.* (1990)

for low-energy ions. We interpret the occurrence of hillocks by the release of stress, built up by dislocations of atoms from the track core to the periphery. Wave-like structures of vertical, parallel and equidistant straight lines, starting from both sides of the disordered region are also visible in Fig. 5. The line pattern has a periodicity of 4 Å and an orientation of $\approx 30^\circ$ with respect to the HOPG lattice (as indicated by the black bars in Figure 5). We tentatively interpret these oscillations, which occurred repeatedly in our micrographs, as periodic density changes of the two-dimensional electron gas in the hexagonal graphite lattice plane, caused by the scattering of Bloch waves at the ion-induced localized lattice defect (Mizes and Foster, 1989; Probst *et al.*, 1993). Similar features in ion-irradiated HOPG were reported by Porte *et al.* (1989), Bouffard *et al.* (1993) and Yan *et al.* (1994).

3.2. SCANNING FORCE MICROSCOPY OF ION-IRRADIATED MUSCOVITE MICA

3.2.1. Introductory Notes

Muscovite mica is an insulating, layered crystalline silicate. Similar to HOPG, it can be cleaved easily parallel to its layers, always splitting between the two neighbouring SiO_4 -hexagonal lattice planes. It was early recognized that mica is very sensitive to irradiation with energetic heavy ions. Over several decades, ion tracks in mica have therefore been investigated with a variety of methods. Transmission electron microscopy (Silk and Barnes, 1959; Bonfiglioli *et al.*, 1961; Price and Walker, 1962) and X-ray (Dartyge and Lambert, 1974; Dartyge *et al.*, 1981; Albrecht *et al.*, 1985; Albrecht *et al.*, 1986) and neutron scattering (Albrecht *et al.*, 1985) were followed more recently by SFM (Thibaudau *et al.*, 1991; Bouffard *et al.*, 1993; Hagen *et al.*, 1994; Ackermann *et al.*, 1995; Daya *et al.*, 1995a; Daya *et al.*, 1995b; Ackermann *et al.*, 1996; Daya *et al.*, 1996). The latter technique was also applied to study the unperturbed structure of the SiO_4 -planes (Erlandsson *et al.*, 1988; Marti *et al.*, 1990; Sharp *et al.*, 1993). It should be mentioned once more that ion tracks represent objects of very limited size, having diameters of only several nanometers. They are thus not only of interest concerning the analysis of radiation-induced damage features, but are suitable also for the study of friction and elasticity on a nanometer scale.

Samples of mica were irradiated with heavy ions at right angles to the SiO_4 -layers. Choosing several ion species with different kinetic energies, a set of data on ion-track diameters versus electronic energy loss could be achieved. The relevant properties of the ion beams applied to mica are listed in Table 1.

Ion Species	Total Energy [GeV]	Energy Loss [keV/nm]	Penetration Depth [μm]
Krypton	0.50	11.8 ± 0.6	47
Xenon	1.47	16.9 ± 1.5	90
Gold	2.64	25.6 ± 1.2	110
Lead	2.37	27.4 ± 1.0	95
Uranium	2.76	31.0 ± 0.6	100

Table 1: Relevant properties of the ion beams applied to mica (Ackermann *et al.*, 1996)

Similar to our work on GeS, the values of energy loss and penetration depth were calculated with TRIM (Ziegler *et al.*, 1985). The measurements were performed with

two homebuilt scanning force microscopes (SFM). These microscopes acquire simultaneously the vertical bending (for topographic imaging) and the torsion (for lateral-force imaging) of the force-sensing cantilever. For this purpose, we apply the common technique of reflecting the beam of a laser diode at the cantilever's backside and monitoring its movements on a quadrant photodiode.

3.2.2 Lateral-Force Microscopy

The ion energy loss as a function of the penetration depth possesses a broad plateau starting at the target surface. Therefore, a mica sample can be cleaved several times by pulling off a sheet with a thickness of a few microns, before the plateau is exceeded. This cleaving procedure provides a fresh surface free of contaminations and suitable for SFM imaging.

The SFM mode of operation, called lateral-force imaging, records the torsion of the force-sensing cantilever around its long symmetry axis and is particularly sensitive to friction. As reported in a previous study (Hagen *et al.*, 1994), the ion tracks are amorphous zones whose cross sections exhibit a significantly higher friction coefficient than the surrounding intact lattice plane.

Figure 6a. Lateral-force image ($95 \times 95 \text{ nm}^2$) of uranium ion tracks in mica.
 b. Line scan through the image from A to B with a left (F_l) and a right (F_r) foot defining the limits of the track diameter.

For the sake of thoroughness, it should be noted that the level of the track cross sections coincided completely with the cleaved surface planes, showing neither hillocks nor craters. Fig. 6a displays the lateral-force image of Au-ion tracks. Each impinging ion created a latent track.

The diameter of an individual track was evaluated by determining a left and a right foot of the line profile as illustrated in Fig. 6b. Mean track diameters for the different ion species were obtained by fitting the diameter distributions with a Gaussian curve. In Figure 7, our result is compared with data from small-angle x-ray and neutron scattering (Albrecht *et al.*, 1985; Albrecht *et al.*, 1986) and from topographic scanning force microscopy (Thibaudau *et al.*, 1991; Bouffard *et al.*, 1993).

Figure 7. Diameters of latent tracks in mica as a function of energy loss.
 (•) Our lateral-force SFM measurements (Ackermann *et al.*, 1996)
 (o) SFM (Thibaudau *et al.*, 1991; Bouffard *et al.*, 1993)
 (+) X-ray and neutron scattering (Albrecht *et al.*, 1985; Albrecht *et al.*, 1986)

Partial agreement and discrepancies among the three data sets are clearly visible. Further information about the acquisition and evaluation of the data compiled in Fig. 7 can be found in Ackermann *et al.* (1996).

3.2.3. Force-Modulation Microscopy

Force-modulation microscopy, which was introduced some years ago (Maivald *et al.*, 1991; Radmacher *et al.*, 1992; Overney *et al.*, 1994; Heuberger *et al.*, 1994), allows for the imaging of surface properties, e.g., hardness or elasticity, on a nanometer scale. Recently, our group applied this method for the first time to heavy-ion tracks (Ackermann *et al.*, 1995; Neumann *et al.*, 1996). The microscope was operated in the modulation mode by varying the sample position periodically normal to its surface. The modulation was driven with a piezo crystal at 3 kHz by the reference frequency of a lock-in amplifier, keeping constant an average loading force between the force-sensing

tip and the sample via a feedback circuit. Periodic variations of the sample position result in a deformation of the sample surface and a vertical cantilever deflection. This deflection is enlarged (reduced) if the sensor probes a harder (softer) surface area, as illustrated in Fig. 8.

The lock-in filtered signal, derived from the cantilever deflection while scanning the sample, provides a map of the surface hardness. A force-modulation micrograph is shown in Fig. 9.

Figure 8. The cantilever deflection δz_c as a function of surface elasticity, driven by a sample modulation of constant amplitude δz_s .

Figure 9. Force-modulation image of Au-ion irradiated mica ($170 \times 170 \text{ nm}^2$), acquired by lock-in filtered detection of the cantilever deflection (Neumann *et al.*, 1996). The cross sections of ion tracks are areas of reduced surface elasticity as is indicated by the lower brightness. Their slightly elliptical shape originates from the creep of the scanner piezo counter to the direction of slow scanning (from top to bottom). The error bars of the average track diameters cover this effect.

Mean track diameters were extracted from the images, applying a similar evaluation procedure as for the lateral-force results. Both data sets are plotted in Fig. 10, demonstrating good agreement within the ± 2 nm vertical error bars. From this, we conclude that the changes of friction and surface hardness are both caused by the amorphization.

Figure 10. Latent-track diameters in mica versus ion-energy loss (Neumann *et al.*, 1996).

(o) Force modulation measurements of our group

(•) Lateral-force microscopy (Hagen *et al.*, 1994; Ackermann *et al.*, 1996)

The vertical error bars of all data points are ± 2 nm, but have been omitted in all cases where a mutual overlap would occur.

3.2.4. Force Microscopy in an Ultrahigh Vacuum

The SFM studies described in the previous sections were performed under ambient conditions, where the presence of adsorbates such as a thin film of water and hydrocarbons hamper the reproducibility of quantitative measurements, e.g., of the friction coefficient. Therefore, after ion irradiation, mica samples were transferred into an ultrahigh-vacuum (UHV) chamber, housing a homebuilt scanning force microscope. The optical arrangement, which monitors the deflection of the force sensor, uses movable mirrors driven by inertial sliding mechanisms similar to the setup reported by Howald *et al.* (1993). Our microscope and the UHV system are described in detail in: Ackermann (1994), Sedlacek (1995), Wörtge *et al.* (1994). While baking the UHV chamber for nearly three days, the temperature was restricted to a maximum value of 120 °C to avoid damaging the semiconductor devices (an IR-laser diode and a four-segmented photodiode) of the optical detection system. For this reason, the vacuum obtained was limited to about $1\text{--}2 \cdot 10^{-9}$ mb, but nevertheless, guaranteed a significant reduction of undesired adsorbates. We used a commercial bar-shaped cantilever with a pyramidal tip at its free end, consisting of amorphous Si_3N_4 and having a bending and a torsion spring constant of $k=0.215$ N/m and $k=8.4 \cdot 10^{-10}$ Nm/rad, respectively.

Other than the mica studies described in the previous sections, the following measurements were performed on the original sample surface, as it had been exposed to ion irradiation (Ackermann, 1997). The direction of fast scanning, in the following denoted with y , was perpendicular to the long axis of the sensor bar. Four simultaneously acquired images of the damage caused by the impact of a 11.4 MeV/u uranium ion are shown in Figure 11.

Figure 11. SFM images ($45 \times 45 \text{ nm}^2$) of a latent uranium ion track in mica, measured under UHV conditions (Ackermann *et al.*, 1997). (a) and (b) are topographic images, whereas (c) and (d) represent the torsion of the cantilever. The fast scanning motion (along y) occurred in the vertical direction.

The micrographs (a) and (b) were obtained by detection of the vertical bending of the sensor during back and forth scanning and represent the topography, i.e., the spatial shape of the sample surface. Since reversing the scanning direction does not change the vertical bending, images (a) and (b) have a similar appearance. When penetrating the mica surface, the uranium ion created a small hillock roughly 2 nanometers high and with a diameter of about 20 nm. This is in contrast to the absolutely flat cross sections of the ion tracks on freshly cleaved mica surfaces, observed with a SFM in air. The micrographs (c) and (d) were also acquired while scanning back and forth, however, by monitoring the torsion of the cantilever around its long axis. These lateral-force images contain information on topography and friction. They exhibit a different contrast, since the friction force changes its sign when reversing the scanning direction and, therefore, the fraction of contrast caused by friction is reversed.

According to a model presented in: Grafström *et al.* (1993), Grafström *et al.* (1994), the lateral force F_y , directed along the y -axis and effecting the cantilever torsion, can be expressed as:

$$F_y = - (F_L + F_A) \cdot (s_y \pm \mu) \quad (1)$$

for scanning along $\pm y$. Here, F_L and F_A are the external loading force and the inherent adhesion force; μ denotes the dynamic friction coefficient; and $s_y = \partial s(x,y)/\partial y$ represents the partial derivative of the surface topography $s(x,y)$ with respect to the y -direction. The equation expresses the fact that the topography-induced contrast (s_y) does not depend upon the scanning direction, whereas the friction-induced contrast (μ) reverses its sign. In conclusion, the sum and difference of the torsion micrographs (a) and (b) provide a deconvolution into the pure topography- and friction-induced parts of the total contrast. The sum and difference images are given in Figure 12.

Figure 12. Sum (a) and difference (b) of the images (c) and (d) in Figure 11 (Ackermann *et al.*, 1997). The sum maps the derivative (i.e. the slope) of the topography along the y -direction. The difference represents the pure tribologic contrast. (c) Numerical y -derivative of the image (a) in Figure 11

It should be pointed out, once again, that Figure 12a displays the slope of the topography in the y -direction, rather than the topography itself. The intact mica lattice with zero slope around the damage zone appears as a homogeneously gray background. Areas brighter or darker than this background indicate a positive or negative slope and represent the hillock. This interpretation can be examined by comparing Figure 12a with Figure 12c, which maps the numerical y -derivative of the topographic image in Figure 11a. The agreement of the two images is very satisfying. Figure 12b, containing the pure tribological contrast shows a friction increase (indicated by the higher brightness) on the hillock in comparison with the surrounding mica lattice. This finding is in accordance with previous SFM results on cleaved mica in air, manifesting amorphization of the crystalline lattice along the ion trajectory accompanied by higher friction within the disordered zones.

4. Conclusions

Latent tracks induced by energetic heavy ions in the layered crystals GeS, HOPG, and muscovite mica have been imaged with very high resolution using TEM, STM, and SFM. The micrographs visualize the tracks as disordered regions embedded in an almost intact crystalline environment. For GeS, they further revealed a sharp interface between the amorphous and the crystalline phases; a strict orientation of the elliptical cross sections with respect to the anisotropic lattice; symmetrically distributed and oriented strain centers around the tracks; and a pinning of migrating dislocations at the tracks. The sizes of the track cross sections were evaluated as a function of the ion energy loss. Latent ion tracks on the surface of freshly cleaved HOPG samples were identified by STM as tiny amorphous hillocks. We interpret the occurrence of hillocks by the release of stress along the ion trajectory. In addition, wave-like superstructures of parallel and equidistant lines were found, originating from a track and reaching quite far into the unperturbed lattice. They probably represent density oscillations of the conduction electrons due to scattering at the track.

The study of ion tracks in mica by force microscopy provided a data set of track diameters versus energy loss, similar to the results for GeS. It should be pointed out that in both cases our compilations of latent-track data intend to contribute to the experimental basis indispensable for the modeling of track creation processes. Moreover, the track cross sections were used as objects for studies of surface properties on a nanometer scale. By operating the force microscope in different dedicated imaging modes, an increased friction and a reduced elasticity could be demonstrated within the track areas. Finally, first SFM measurements of tracks in mica were performed under UHV conditions. They are considered to be a first step towards in-situ SFM investigations in an UHV chamber flanged to an ion beam line at GSI.

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