Strain Fields Around the Tracks of High-Energy Ions in Quartz

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Motivation—Ion beam treatments modify the properties of materials, usually producing little change in dimensions, <~1 µm. However, irradiation of amorphous films by high energy ions can change lateral film dimensions by 10's of percent. Models based on local expansion of rapidly heated material along the ion path (called a "thermal spike") are being developed to explain the phenomenon. The expansion is modeled as straining the matrix around molten track centerline, which is the microscopic basis for the lateral expansion. Amorphous SiO_2 (a-SiO_2) is a widely studied prototype material that is being understood with the models. While latent ion tracks can be identified in a-SiO_2 by transmission electron microscopy (TEM), strain is not readily detected in amorphous materials. Thus, a critical part of the models has not been experimentally verified.

Accomplishment—We have examined the tracks of 374 MeV $^{197}Au^{26+}$ and 241 MeV $^{127}I^{18+}$ in α-quartz with TEM. Quartz has the same SiO_2 composition but has a hexagonal crystal structure. These high-energy ions transfer large amounts of energy to electrons along their tracks, 24 and 19 keV/nm, respectively, which are sufficient to produce melting and form amorphous latent track centerlines. We have found strain fields around the tracks with symmetry and lateral extent like those expected when amorphous SiO_2 is fitted with the model.

The high-energy ions were produced with the tandem accelerator and sent into the radio-frequency quadrupole booster in Sandia's Ion Beam Materials Research Laboratory to increase their energies to 1.9 MeV/amu. Thinned quartz specimens were irradiated and examined by TEM with low beam intensities to minimize damage. Higher ion fluxes were obtained for $^{127}I^{18+}$ beams to produce a dense array of tracks as seen in Fig. 1. Tracks are more readily identi-fied by tilting the specimen to view their projected length, as shown. The oscillatory contrast along the track is due to the strain in the matrix around the amorphous centerline. Figure 2a shows a $^{197}Au^{26+}$ track with the strain extending radially 16 nm beyond the amorphous centerline, which is 4 nm in radius. Radial strain is expected to extend several times the centerline radius from the expansion model.

The strain contrast changed in images taken with other diffraction conditions. Whereas in Fig. 2a the diffraction vector has a component orthogonal to the track projection, Fig. 2b was obtained with the diffraction vector parallel to the projection. In this case, the contrast does not extend as far outward and is also present along the centerline. When considered within TEM contrast theory, these differences are consistent with radial strain around the track centerline. Our findings with several diffraction vectors taken together imply cylindrical symmetry around the centerline for the radial strain, as assumed in the expansion model.

Significance—Energy transfer to electrons, track melting, and elastic response of the matrix are similar in quartz and a-SiO_2, however the amorphous phase expands less on melting. Nonetheless, finding strain fields with the expected properties in such a closely related crystalline phase provides an additional experimental basis for confidence in the modeling of the expansion of a-SiO_2. Amorphous track centers had been found in quartz, but strain around them was not reported.

Sponsors for various phases of this work include: Laboratory Directed Research & Development

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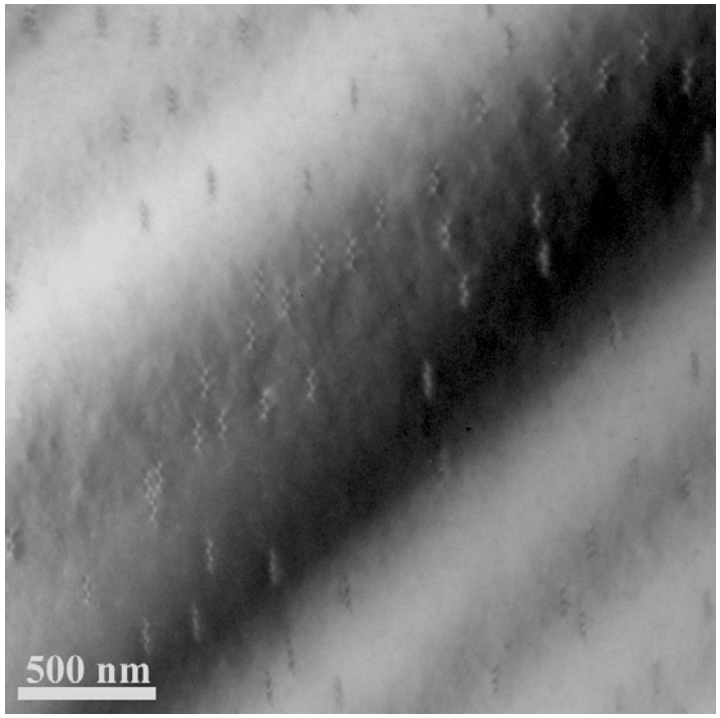

Figure 1. Bright-field TEM image of 241 MeV ^{127}I tracks in α-quartz, obtained at 300 kV using **g** = (11-20) diffraction conditions with the specimen tilted 13º from normal. (Our thanks to P. Kotula, 1822, for assistance with images taken at 300 kV.)

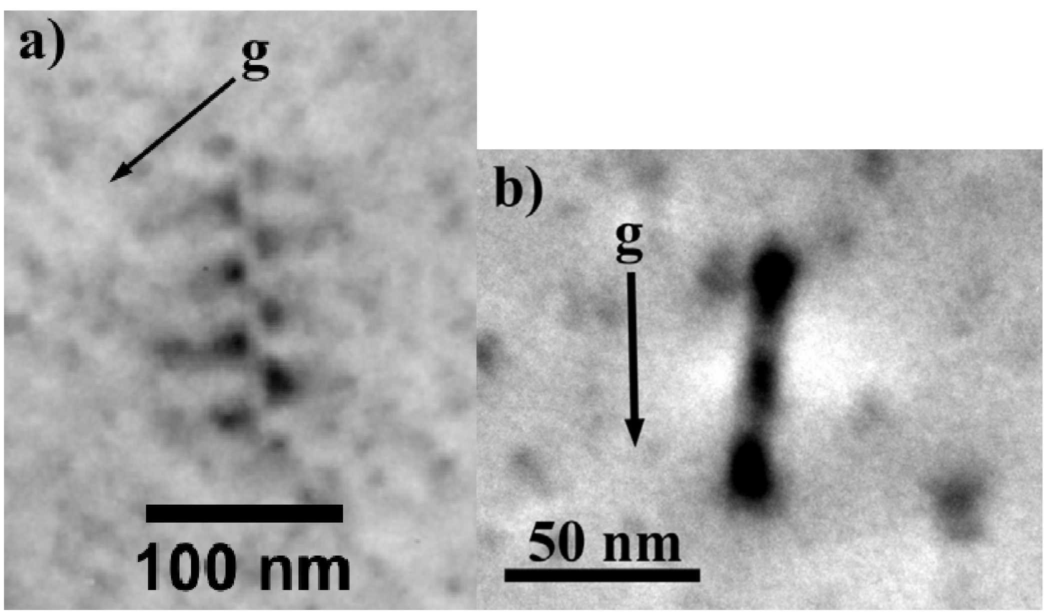

Figure 2. a) Bright-field TEM image of 374 MeV Au track in α-quartz, obtained at 200 kV with **g** = (1-100) diffraction conditions and the specimen tilted 35°. b) Bright-field image of 374 MeV Au track, obtained at 200 kV but with the diffraction vector parallel to projected track length. Note the 2x enlargement of b); the lateral width of contrast in b) is therefore narrower than that in a). In addition, the contrast in b) lies along the track centerline whereas that in a) has a clear centerline.