Ion induced grain rotation – a general phenomenon?

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Various amorphous materials show the so-called ion hammering effect [1]. It is supposed that this effect is driven by shear stress relaxation during the transient, fluid state of the ion track while the surrounding solid matrix responds perfectly elastically [1]. Ion hammering was also invoked to explain ion-beam-induced nanostructuring of NiO and other metal oxides [2,3]. But online X-ray diffraction of NiO indicated the absence of any amorphous material. Rather, the observed shear deformation is probably the result of grain boundary motion and grain rotation. In fact, when ion beam and specimen normal subtend an angle $\alpha \geq 20°$, single crystalline NiO rapidly transforms into nanocrystallites with diameters around 30 nm and the nanocrystals rotate. Their tilt is easily detectable as a change of the lattice orientation Ω and increases with ion fluence Φt [4,5].

To test if the observation for NiO is a more general material response, we exposed single crystals of NiO, MgO, UO_2, and LiF to 709-MeV Au ions. The irradiations were performed at the M2-beamline of the UNILAC using a scanned beam. The irradiation chamber is equipped with a 4-circle X-ray diffractometer (Seifert 3003TT, see fig. 1). The samples had a typical size of 0.5-1 cm^2 and a thickness of 0.5 to 1 mm. The information depth of the X-rays is larger than the ion range so that the unirradiated sample part serves as reference. The irradiation temperature was kept below 80°C. The irradiation angle α was 45°.

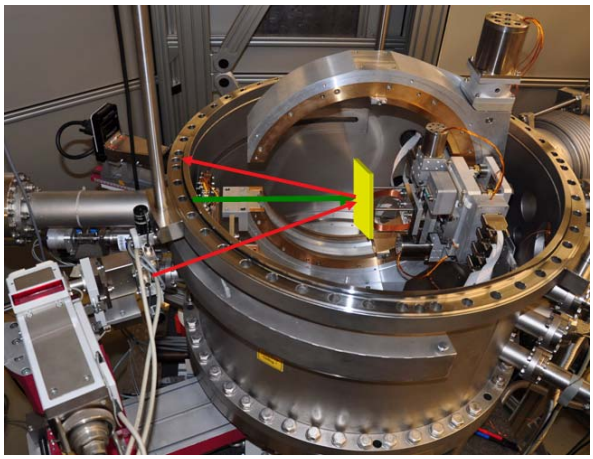

Figure 1: In-situ XRD setup at beamline M2 (M-branch, UNILAC). The green arrow indicates the ion beam (here at $\alpha = 0°$). The red arrows indicate the incident and diffracted X-ray beam.

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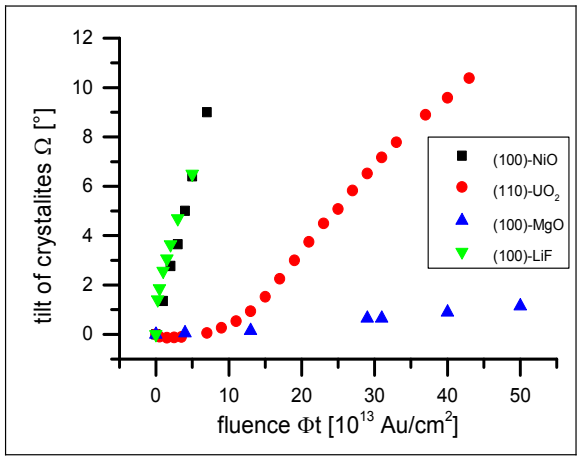

Figure 2: Lattice tilt Ω vs. ion fluence for irradiation with Au ions under $\alpha = 45°$. The beam energy was 945 MeV (NiO, UO_2, and MgO) and 709 MeV (LiF).

All four materials exhibit grain rotation (figure 2). There is no indication of amorphization and the crystals stay mechanically intact. In the case of MgO, the effect of grain rotation is rather weak compared to the other crystals. Grain rotation of UO_2 shows a non-linear evolution and a kind of incubation fluence of $\sim 7\times10^{13}$ ions/cm^2. Above this value, the rotation rate $d\Omega/d\Phi t$ gradually increases followed by a constant rotation rate above $\sim 3\times10^{14}$ ions/cm^2. A similar behaviour was also found for ω-titanium [4]. Grain rotation is nearly reversible if the rotation axis coincides with a high-symmetry crystal axis. Changing α from +45° to -45° reverses the sign but leaves the magnitude of the rotation rate almost unchanged [5]. When the rotation axis is not a crystal axis of high symmetry, additional crystallite tilts occur which destroy gradually the memory on the original orientation of the single crystal and are the starting point for the formation of a polycrystal.

Our results give evidence that grain rotation seems to be a rather common phenomenon in non-amorphizing materials. The basic mechanism is not yet clear, but it is probably linked to loop punching in the immediate surroundings of the extremely hot and thus over pressurized ion tracks.

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