3D Field Ion Microscopy for Characterization of Radiation Damage in Fusion Related Materials

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In the leading approach for the design of a fusion reactor, the plasma is confined magnetically inside a device called ‘Tokamak’. Prospective materials to construct this device must withstand extremely high temperature and radiation dose conditions. The divertor plates within the Tokamak remove heat and impurities and are a particularly challenging component to design. Tungsten, the element with the highest melting point, is a leading candidate for this role. Hence, an extensive, atomic scale investigation of tungsten behavior under extreme and cyclic conditions is critical to determine its suitability as a material for plasma facing components and their operational lifetime. Especially challenging, even for advanced microscopy techniques, is the detection of nanoscale damage to the crystal lattice. The formation of dislocations, nano-voids, clustering effects, self-interstitials and transmutation damage requires atomic-scale characterization and correlation to changes in mechanical properties of the irradiated material.

Here we present a technique for the atomic-scale study of irradiated tungsten utilizing field ion microscopy (FIM). Conventionally, FIM is a 2D imaging technique since only the surface of the needle-shaped specimen is imaged. However, by sufficiently increasing the voltage applied on the tip during imaging, it is possible to field evaporate constituent surface atoms from the specimen. This enables FIM to operate in a mode such that the surface of the specimen is continually evolving as the next layer of atoms is progressively uncovered. The result of this procedure is a series of 2D FIM images that can be tomographically stacked to create a highly resolved 3D view of the crystal lattice [1], [2]. FIM-based 3D reconstruction has the potential to significantly exceed the resolution of atom probe analysis as it is not subject to the detection efficiency limitations of atom probe.

To initially develop a 3D atom-by-atom reconstruction procedure, a pure tungsten specimen was imaged, and subject to an increasingly high voltage throughout the measurement for continuous evaporation of atomic planes as the radius of the specimen increased. The 3D reconstruction of three (222) planes is presented in Figure 1. Each of the planes appears in a set of time ordered FIM images as seen in Figure 1a-1c, demonstrating the evaporation process of the first plane to be reconstructed. The XY coordinates of the atoms are then identified on each of the 2D images, while the Z coordinates are calculated via the sequence of evaporation and assumed knowledge of the plane spacings in tungsten. This information is constructed into a 3D view of these planes in the crystal lattice (figure 1d), where each atom is accounted for.

An alternative method of 3DFIM has also been explored. To study radiation damage, ion-irradiated tungsten specimens were used. Figure 2b is a FIM image of the (110) pole of an irradiated tungsten specimen, and is shown in comparison to the same pole in an un-irradiated tungsten specimen on figure 2a. The spiral shape in 2b, replacing the concentric rings in 2a indicates a radiation induced dislocation in the irradiated sample [3]. The radius of the specimen can be estimated from the 2D image by calibrating known crystallographic angles to distances between the poles in the image. The image is put on a sphere, and atoms are identified using their intensity contrast to produce the 3D view in 2c.
References:


Figure 1. (a)-(c): Time ordered FIM images of atoms within a set of (222) planes during evaporation. (d): Tomographic reconstruction of three (222) planes, all evaporated in the same way as shown in (a)-(c).

Figure 2. (110) pole in (a) pure W needle, (b) irradiated W needle. The spiral in (b) replacing the concentric rings in (a) indicates a dislocation. (c) 3D view of the dislocation. Atoms are identified by intensity contrast. The 2D FIM image is placed on a sphere (representing the shape of the needle). Sphere radius can be estimated from the 2D image.