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FOR MORE INFORMATION
Hua Zhou or Randall Headrick, Department of Physics, University of Vermont
hzhou@uvm.edu; rheadrick@uvm.edu

Wavelength Tunability of Ion-Bombardment-Induced Ripples on Sapphire

H. Zhou[1], Y. Wang[1], L. Zhou[1], R.L. Headrick[1], A.S. Özcan[2], Y. Wang[2], G. Özaydin[2], K.F. Ludwig, Jr.[2], and D.P. Siddons[3]

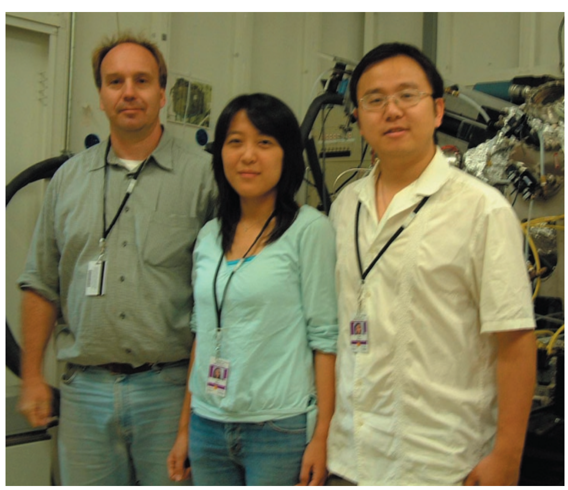
[1]Department of Physics, University of Vermont; [2]Department of Physics, Boston University; [3]National Synchrotron Light Source, Brookhaven National Laboratory

A study of ripple formation on sapphire surfaces by low-energy ion bombardment is presented. Surface characterization by in-situ synchrotron grazing incidence small angle x-ray scattering and ex-situ atomic force microscopy is performed. We find that the wavelength can be varied over a remarkably wide range by changing the ion incidence angle. The ion induced viscous flow smoothing mechanism follows the general trends of the ripple wavelength at low temperature and incidence angles larger than 30 . In this model, relaxation is confined to a few-nm thick damaged surface layer. However, strong smoothing is inferred from the observed ripple wavelength near normal incidence.

Energetic particle bombardment on surfaces is known to produce highly correlated arrays of one-dimensional (ripples or wires) and zero-dimensional (dot) structures at the submicron or nanometer-length scale by a self-organization process. This phenomenon has demonstrated the potential to tailor not only surface morphology but also related surface properties, such as optical blue shift due to quantum confinement of dots and magnetic anisotropy induced by rippled structures. We have recently investigated the kinetics of ion-bombardment-induced ripple formation on sapphire surfaces, in particular, smoothing mechanisms in the self-organization process.

Real-time monitoring of sapphire surface evolution upon ion bombardment are carried out in a versatile in-situ surface x-ray facility installed at NSLS beamline X21 end station. A schematic diagram of the experiment is shown in **Figure 1**. A grazing incidence geometry is employed for small angle x-ray scattering (so-called GISAXS), allowing for an enhancement of the near surface scattered intensity with respect to the bulk one. In this work, a detector scan of α_f with a fixed α_i near the critical angle for total external reflection is performed to obtain 2D-GISAXS. The constraint of $\alpha_f \geq 0.3°$ avoids the specular reflected x-rays and maximizes the sensitivity to off-specular diffuse scattering patterns. The 2D scans can be approximately assumed to be Q_z vs. Q_x reciprocal map since Q_y is very small in this case.

Figure 2 shows real-time GISAXS intensities plotted versus parallel component of scattering momentum transfer Q_x at a constant vertical component $Q_z = 0.92\ nm^{-1}$. Scans are shown at 10-minute intervals during 45° off-normal incidence 500 eV Ar^+ bombardment. At time t = 0, the initial roughness of the sapphire surface only produces a single peak in the diffuse scattering (circles). Two satellite peaks, resulting from lateral correlated roughness become visible after 10 minutes. The ripple wavelength, $\ell = 2\pi/\Delta Q$, remains almost constant during ion irradiation, but the peak intensity continues to increase as a result of an increase in ripple amplitude. It is also clear that the two satellite peaks develop in an unequal way as irradiation proceeds, which can be attributed to the onset of nonlinear effects of ion beam erosion.



Authors (from left): Randall Headrick, Lan Zhou, and Hua Zhou

Ex-situ AFM images in **Figure 3** display surface morphologies obtained at different angles of incidence for ion sputtered sapphire. Off-normal incidence at 25° produces only micron-scale ripples, which are readily visible in the large-scale image [**Figure 3(b)**]. An ultra-smooth surface is obtained surprisingly at small length scale [**Figure**

3(a)]. In contrast, 55° and 65° incidence, shown in **Figure 3(c) and 3(e)**, produce a well-ordered nanorippled surface with the wave vector parallel to the projection of the incoming ion beams along the surface. Grazing ion incidence at 75° switches the orientation of the ripple wave vector perpendicularly. Fully developed ripples are observed, with an unusual rod-like structure, as shown in **Figures 3(g) and 3(h)**.

The ion-induced viscous flow smoothing mechanism can explain the behaviors of observed ripple wavelength at low temperature and middle-range angles of incidence. Strong smoothing near normal incidence is suggested to be the result of ion-bombardment-induced effective downhill currents along the surface.

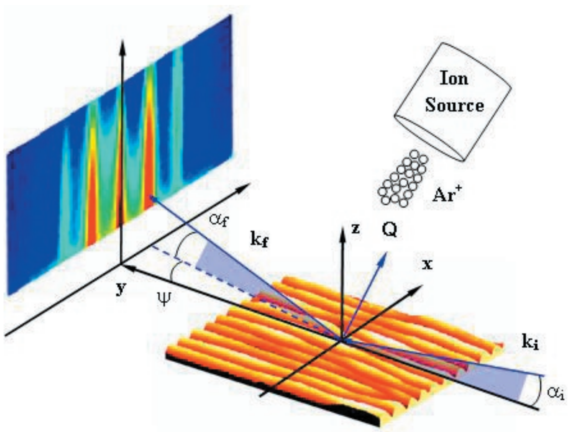


Figure 1. *Schematic diagram of the experiment. z-axis: sample normal. y-axis: the incident x-ray beam. k_i and k_f : the incident and scattered wave vectors, respectively. Glancing angle: $\alpha_i = 0.2°$, $\alpha_f \geq 0.3°$; in-plane (x-y plane) angle: $-1° \leq \psi \leq 1°$. The incoming Ar^+ ions bombard at an incident angle with respect to the surface normal.*

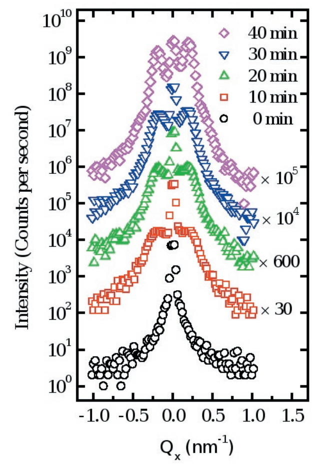


Figure 2. *Time-resolved GISAXS measurements indicate the increase of the lateral correlations on a sapphire surface during ion exposure. The ion exposure was paused during the scans. The curves are shifted for clarity.*

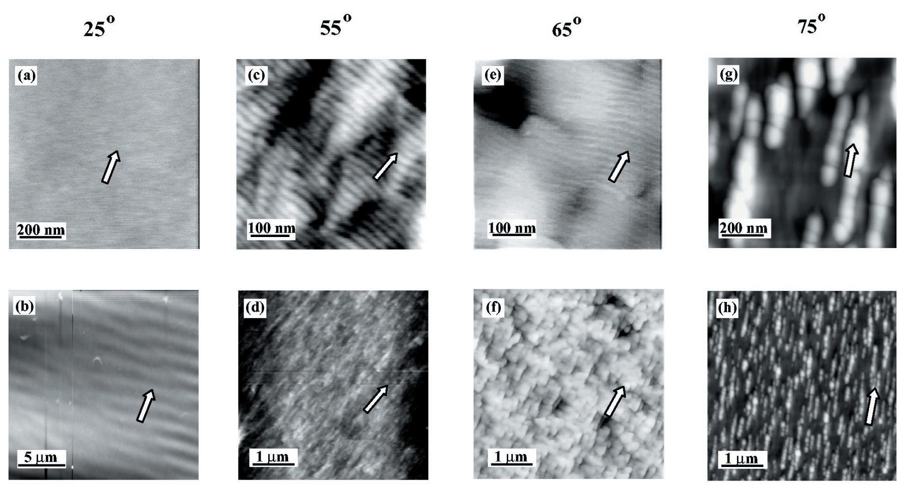


Figure 3. *AFM images of surface morphology at different angles of incidence. Two different image sizes are shown for each angle of incidence. The white arrow indicates the projection of the ion beam direction along the surface. The progression of ripple orientation and wavelength can be seen in this sequence of images.*