Nanoscale Morphology Evolution Under Ion Irradiation

Abstract

The use of ion beam's great promise in materials processing is its ability to perform direct patterning of materials surfaces and pattern identical one- and two-dimensional arrays of nanoscale surface features ("ripples" and "dots") sometimes termed "structural transfer". The concept that ion bombardment can cause surface morphology evolution during ion irradiation at energies low enough that the principal phenomena are sputter erosion and Harper erosion (see sub-section on Harper erosion) has been well known for decades. However, the role of sputter erosion in ion-induced surface modification has only recently been re-discussed. The purpose of this study is to explore the synergy between ion bombardment and sputter erosion as it relates to a profound physical and chemical alteration of materials surfaces. In this study, the methodology of ion bombardment is applied to the understanding of materials surfaces and is able to identify the behavior for each spatial frequency. This is a direct measurement of the partial differential equation governing morphological evolution. We have confirmed our attention to the linear regime of exponential amplification and nonlinear regime will be experimentally accessible when our new system comes online.

Irradiation-Induced Nanoscale Pattern Formation

Theoretical

We have developed a new theoretical framework for predicting the governing partial differential equation for surface evolution from the accumulation of topographic responses to individual ion impacts. The local regime (the "crafter function") can be obtained by experiment (e.g., 5MeV simulation) or modeling (e.g., Molecular Dynamics [MD]). Among the many ions we were able to explore, a single crater is found over many craters that matters. The theory exposes a separation in length scale between the topographic change due to the sputtering effect and the thermal effects. We have considered the effect of impact energy on the crater function and the spatial frequency. The theory describes, without any free parameters, the 3 coefficients in Eq. (1) is one for each independent spatial dimension, a constant from the crater function. A flat surface is stable of both 3D and 2D positive 2D, it is negative the surface is unstable. Prior to this work, the best models for the 3 coefficients contained adjustable parameters, and in many cases there was no way to reliably estimate the magnitude of those parameters.

A Parameter-Free Theory

Central surface response

- Irradiation flux
- spin-up yield vs. slope A
- Unique class of partial differential equation (PDE) without adjustable parameters

Norris’s Theory: Abbreviated Math

\[ \hat{\nu} = \frac{\nu}{v_0} \]

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Input parameters:

- Irradiation flux
- Spin-up yield vs. slope A
- Unique class of partial differential equation (PDE) without adjustable parameters

Moment Form

- Multidimensional correlated impacts
- Surface evolution more rapidly than flat crater function
- More information may be obtained from nonlinear responses

| Parameter-Free Theory vs. Experiment | | Parameter-Free Theory vs. Experiment | | Parameter-Free Theory vs. Experiment | | Parameter-Free Theory vs. Experiment |
|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| Linear regime                       | Nonlinear regime                   | Linear regime                       | Nonlinear regime                   | Linear regime                       |
| Influence of irradiation flux on surface evolution | Influence of irradiation flux on surface evolution | Influence of irradiation flux on surface evolution | Influence of irradiation flux on surface evolution | Influence of irradiation flux on surface evolution |

Implications for Fusion Reactor Walls

- Novel behavior based on accelerated ion bombardment
- Observation of non-local effects, e.g., spatio-temporal superposition
- Influence of ion energy on crater function

Impact on reactor wall design

- New multi-scale architecture can potentially over come ion bombardment challenges
- Novel behavior based on accelerated ion bombardment

Outlook

- Important advances towards materials processing and patterning
- Implications for fusion reactor walls
- Novel behavior based on accelerated ion bombardment

Experimental

In a collaboration with Karl May & Uwe Chen to measure the linear dispersion relation in situ in real time using Grazing Incidence Small Angle X-Ray Scattering (GISAXS) at the National Synchrotron Light Source at Brookhaven National Laboratory, we measure the real-time diffusivity-disentangled intensity corresponding to topographic correlations at the sample surface. We observe its amplification into ripples or ripples into ultrasmooth surfaces and are able to identify the behavior for each spatial frequency. This is a direct measurement of the partial differential equation governing morphological evolution. We have confirmed our attention to the linear regime of exponential amplification and nonlinear regime will be experimentally accessible when our new system comes online.

- IMD (Ion Bombardment Setup)
- Phase Diagram for S(n) Ripping Logic (n is the number of ripples)
- Linear dispersion relation

- Direct Measurement of Linear Dispersion Relation

- Ion Impact-Induced Mass Redistribution: Design of linear STABILITY & INSTABILITY