

## THIN FILMS 2010 ONE-DAY SHORT COURSE ON

### Thin Film Nucleation, Growth, and Microstructural Evolution

**Instructor: Professor Joe Greene**  
**(Editor-in-Chief, *Thin Solid Films*)**  
**University of Illinois**

Date: 11 July 2010 (Sunday)



#### Course Objectives

- Understand the primary experimental variables and surface reaction paths controlling nucleation/growth kinetics and microstructural evolution during vapor-phase deposition.
- Develop an appreciation of the advantages/disadvantages of competing growth techniques.
- Learn how to better design film growth processes.

#### Course Description

Thin-film technology is pervasive in many applications, including microelectronics, optics, magnetics, hard and corrosion resistant coatings, micromechanics, etc. Progress in each of these areas depends upon the ability to selectively and controllably deposit thin films (thickness ranging from tens of angstroms to micrometers) with specified physical properties. This, in turn, requires control -- often at the atomic level -- of film microstructure and microchemistry.

Essential fundamental aspects, as well as the technology, of thin-film nucleation and growth from the vapor phase (evaporation, MBE, sputtering, and CVD) are discussed in detail and highlighted with "real" examples. The course begins with an introduction on substrate surfaces: structure, reconstruction, and adsorption/desorption kinetics. Nucleation processes are treated in detail using insights obtained from both in situ (RHEED, LEED, STM, AES, EELS, etc.) and post-deposition (TEM and AFM) analyses. The primary modes of nucleation include 2D (step flow, layer-by-layer, and 2D multilayer), 3D, and Stranski-Krastanov. The fundamental limits of epitaxy will be discussed.

Experimental results and simulations are used to illustrate processes controlling 3D nucleation kinetics, island coalescence, clustering, secondary nucleation, column formation, preferred orientation, and microstructure evolution. The effects of low-energy ion-irradiation during deposition, as used in sputtering and plasma-CVD, will be discussed with examples. The course concludes with a detailed discussion of the origins, mechanisms, and control strategies, of intrinsic and extrinsic stresses in thin films.

#### Course Content

The course provides an understanding of:

- the role of the substrate in mediating growth kinetics
- the nucleation process
- film growth modes
- epitaxy
- the development, and control, of film stress (strain engineering)
- nucleation and growth of strain-mediated self-organized structures
- polycrystalline film growth, texture, and microstructure evolution
- structure-zone models of film microstructure
- the role of low-energy ion/surface interactions during film growth
- the relationship between film growth parameters and film properties

#### Who Should Attend?

Scientists and engineers involved in deposition, characterization, or manufacturing/marketing of thin film deposition equipment. Research students working on thin film science and technology.

#### Instructor:

Joe Greene, Editor-in-Chief of *Thin Solid Films*, the D. B. Willett Professor of Materials Science and Physics, University of Illinois, and Past Director of the Frederick Seitz Materials Research Laboratory.

#### Course Materials:

Course notes with extensive reference lists will be provided.

# Outlines: Thin Film Nucleation, Growth, and Microstructural Evolution

## Chapter 1. Introduction: surface structure and processes

- a. surface energies: measurements and role in film growth
- b. surface structure: examples of reconstruction and relaxation
- c. terrace-step-kink structure: examples (STM)
  1. step-edge barrier and 2D kinetic roughening
  2. corner barrier and 1D kinetic roughening

## Chapter 2. Nucleation

- a. nanotechnology
- b. thermodynamics of nucleation (a simple stability problem): examples
  1. models
  2. wetting angle: examples (TEM, STM, AFM)
- c. kinetics of nucleation: examples (STM)
- d. early stages of film growth (experiment and simulation): examples

## Chapter 3. 2D step flow and layer-by-layer growth

- a. introduction: Si on Si(001), a case study (STM)
- b. 2D step flow
  1. definition and requirements
  2. possible to achieve?
  3. role of buffer layers: examples
  4. experimental observations using He atom, x-ray, and RHEED oscillations
- c. layer-by-layer growth
  1. definition and requirements
  2. possible to achieve?
  3. experimental observations using He atom, x-ray, and RHEED oscillations

## Chapter 4. 2D multilayer growth

- a. experimental observations: STM vs RHEED oscillations
- b. simulations vs experimental observations
- c. low-temperature epitaxy: fundamental limits
  1. critical epitaxial temperature  $T_{\text{epi}}$  vs critical thickness  $t_{\text{epi}}$
- d. techniques for increasing  $t_{\text{epi}}$ 
  1. surfactants: examples (STM and RHEED oscillations)
  2. hyperthermal beams: examples (XTEM)

## Chapter 5. Heteroepitaxy and the role of strain

- a. elastic strain energy
- b. edge, screw, and mixed dislocations: TEM, XTEM, & LEEM videos
- c. relaxation mechanisms: elastic vs misfit disloc and surface energies
  1. Misfit dislocations, critical thickness: examples
  2. Surface roughening, islanding, S-K growth: examples
- d. quantum dots: examples (STM, XTEM)
  1. nucleation and self-limiting growth of quantum dots: examples (STM)
- e. quantum wires: examples (STM)

## Chapter 6. 3-D polycrystalline growth and microstructure evolution

- a. nucleation: examples (TEM)
- b. coalescence: examples (TEM and STM videos)
  1. complete vs incomplete: examples (STM)
- c. coarsening: examples (TEM and STM videos)
- d. grain boundary energies
- e. grain growth: examples (TEM)
- f. structure-zone models: experiment vs computer simulations

## Chapter 7. Film stress and texture evolution

- a. thermal stress: examples
- b. stress measurement: examples
- c. tensile stress mechanisms: examples (TEM, XTEM)
- d. ion-induced stress: examples
- e. compressive stress mechanisms: examples (XTEM)
- f. stress in superlattices and multiplayer systems
- g. texture evolution: examples (AFM, XTEM, simulation)

## Short Biography of Professor J.E. Greene

**Joe Greene** is the D.B. Willett Professor of Materials Science and Physics at the University of Illinois and the Tage Erlander Professor of Materials Physics at Linköping University, Sweden. The focus of his research has been the development of an atomic-level understanding of adatom/surface interactions during the dynamic process of vapor-phase crystal growth in order to controllably manipulate nanochemistry, nanostructure, and, hence, physical properties. His work has involved nanotechnology and film growth by all forms of sputter deposition, solid and gas-source MBE, UHV-CVD, MOCVD, and ALE. Joe has published more than 500 papers and review articles, 22 book chapters, and co-edited 4 books in the general areas of crystal growth, thin-film physics, and surface science. In particular, he has used energetic accelerated condensing species and UV photochemistry for probing as well as stimulating surface reactions that do not proceed thermally. Joe has presented over 400 invited talks and 70 Plenary Lectures at international meetings.

He is currently Editor-in-Chief of *Thin Solid Films* and past Editor of *CRC Critical Reviews in Solid State and Materials Sciences*. He is active in the AVS where he has served on the Trustees, twice as a member of the Board of Directors, as President of the society in 1989, and is currently Secretary. He has also Chaired the AVS Thin Film and Advanced Surface Engineering Divisions, the IUVSTA Education Committee, and served on the Governing Board of the American Institute of Physics and the Executive Committee of the APS Division of Materials Physics. He is currently the US representative to the International Union of Vacuum Science and Techniques and is serving on the Executive Committee of the ASIED.

### **A partial list of major awards includes:**

- the John Thornton Award (1991) from the AVS for "outstanding research in thin films"
- the Tage Erlander Award (1991) from the Swedish Natural Science Research Council for "contributions to the physics and chemistry of thin films,"
- Senior University of Illinois Scholar (1991) for "distinction as a member of the faculty"
- Honorary Doctor of Science in Materials Physics (1992) from Linköping Univ. (Sweden)
- Fellow of the American Vacuum Society (1993) for "outstanding research in thin film science with emphasis on the use of ion/surface interactions and photo-induced reactions to controllably alter film nucleation and growth kinetics"
- Technical Excellence Award from the Semiconductor Research Corporation (SRC) for "outstanding research contributions in the development of low-energy accelerated-ion doping during MBE Si and Si<sub>1-x</sub>Ge<sub>x</sub> film growth" (1994)
- 1996 DOE Award for Sustained Outstanding Research on "growth of new metastable nitride-based ceramic alloys, superlattices, and multilayers with enhanced properties"
- 1998 David Adler Award in Materials Physics from the American Physical Society for "outstanding research and lecturing on the physics and chemistry of thin films"
- 1998 Aristotle Award from SRC for "career achievement in outstanding graduate student teaching in its broadest sense; including innovation in student advising, instilling students with a love and respect for science, teaching students to carry out research at the highest level, contributing to student maturation and professional development, and continuing to impact student careers following graduation"
- Fellow of the American Physical Society (1998) for "original contributions to the experimental development, modeling, and understanding of Si, Ge, and Si<sub>1-x</sub>Ge<sub>x</sub> atomic-layer epitaxy and gas-source molecular-beam epitaxy"
- AVS Distinguished Lecturer (1998-present)
- First D.B. Willett Professor of Engineering Science (1999), University of Illinois
- David Turnbull Award, Materials Research Society (1999), for "contributions to the use of non-thermal methods in the growth of thin films and the engineering of their phase, composition and microstructure; and for excellence in teaching and writing"
- Sustained research "Extending the Science of Transition Metal Nitrides" cited by the Department of Energy in 2001 as one of the most important scientific accomplishments in the last 25 years
- 2001 International Scientist of the Year for "contributions to thin film science," International Biographical Center, Cambridge, UK.
- Elected to the European Academy of Science, 2002.
- Elected to the US National Academy of Engineering in 2003 for "pioneering studies in the synthesis and characterization of epitaxial and highly ordered polycrystalline materials."