Preface

The RHEED (reflection high-energy electron diffraction) technique has been used extensively in epitaxial thin film growth worldwide for many years. In particular, the reflection mode has been routinely used for monitoring the layer-by-layer epitaxial growth of thin films for three decades. Several books have been published containing RHEED in the title in the past two decades. All of them discuss the principle and applications of RHEED in the reflection mode for epitaxial film growth. However, when thin films deviate from a single crystal structure and surfaces are not smooth, which occur often in film growth, the conventional RHEED reflection mode may not give useful information. In this monograph, we present new aspects of RHEED in the transmission mode that can be used to monitor the texture evolution of thin films and nanostructures. We introduce the principles and applications of a new technique called RHEED pole figure. This technique opens up new possibilities of studying not only single crystalline films, but also textured films (polycrystalline, fiber, and biaxial) and nanostructures. Experimentally, the technique does not require an extensive modification of the existing RHEED setup. The only major modification is to include a substrate rotation scheme (a capability most existing RHEED equipment may already have), which allows one to rotate the substrate around an axis normal to the substrate and to collect RHEED diffraction patterns at various azimuthal angles to construct the pole figures. Just as in a conventional RHEED setup, the working distance between the incident electrons and the sample is large (typically over 20 cm) and will allow *in situ* monitoring of the growth of thin films and nanostructures.

Traditionally, the most widely used method for thin film texture characterization is x-ray diffraction, specifically, the x-ray pole figure technique. There are several major advantages of the RHEED pole technique compared to the x-ray pole figure technique when one deals with the texture of very thin films and with the growth front of thick films.

1. The scattering cross section for electrons is orders of magnitude higher than that of x-ray. This feature allows the texture of ultra-thin films and nanostructures to be characterized at ease using the RHEED pole technique in a common laboratory setting. For x-ray, one would require a very high-intensity source such as the ones produced at synchrotron radiation facilities in order to gather sufficient diffracted intensity for the construction of an x-ray pole figure.

2. The mean free path of RHEED electrons in solid materials is a few nanometers, but for x-ray it is a few microns. This short mean-free path of electrons allows one to monitor the growth front texture of a thicker film using the RHEED pole figure technique without interference from the bulk of the film and the substrate. For x-ray, the pole figure constructed from a thicker film is the average texture of the entire thickness and also may include the diffracted intensity signal from the substrate if the substrate is of a similar material.
3. Typically the wavevector **k** or radius of the Ewald sphere in RHEED is one order of magnitude larger than that of x-ray, and the Ewald sphere is almost like a plane. The flat phosphor screen that displays the RHEED patterns allows one to construct the χ-scan from the center of the pole (0°) to nearly the edge of the pole (90°). In contrast, because of the smaller x-ray wave vector **k**, the finite-size area detector typically used in x-ray detection can only cover the χ angle from 0 to 30°, and the sample has to be tilted at least twice to cover the entire 90° χ angles. This makes RHEED pole figure data acquisition much easier and faster.

After a general introduction of electron diffraction (Chap. 1), the monograph covers a basic description of crystal lattice and reciprocal lattice (Chap. 2), followed by the fundamental principles of kinematic diffraction (Chap. 3). In Chap. 4, we discuss the principles of the RHEED reflection mode and the application of the technique in layer-by-layer growth and two-dimension ordering models. Basic x-ray instrumentation, including sources and detectors, and x-ray pole figure analysis are covered in Chap. 5. In Chap. 6, the RHEED transmission mode and the characteristics of thin film textures, including fiber and biaxial textures, are discussed. The main focus of this monograph, RHEED pole figure construction and analysis, is introduced in this chapter. Detailed RHEED pole figure instrumentation and instrument response function are covered in Chap. 7. In Chap. 8, the origins of various types of films, including epitaxial films, fiber texture, and biaxial texture are discussed and their connection to the structure zone model is explored. Examples of texture control through the shadowing effect during physical vapor deposition are summarized in Chap. 9. In Chap. 10, applications of RHEED pole figure, in particular, examples of time evolution of texture formation in film growth by shadowing, are given. Chapter 10 also includes a discussion of possible future improvements of RHEED pole figure instrumentation, including energy-filter RHEED pole figure to improve the instrument response function. Appendix A gives detailed operational procedures for RHEED pole figure construction and source codes for readers who are interested in implementing the RHEED pole figure technique. Appendix B contains RHEED pattern simulation codes for textured films.

Films and nanostructured materials covered in this monograph include metals, semiconductors, and thin insulators. This monograph can be used by academic researchers as a reference and by industrial scientists working in the areas of electronic and optoelectronic materials, semiconductor processing, nanotechnology, memory, photovoltaic and solar cell materials, and high T_c superconductor materials.

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