PLASMA- AND ION-BEAM ASSISTED PHYSICAL VAPOR DEPOSITION: PROCESSES AND MATERIALS

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1. INTRODUCTION

Physical vapor deposition (PVD) includes any thin film process involving the deposition of physically generated atoms or molecules onto a substrate in a vacuum environment. Evaporation, sputtering, and ion plating, the fundamental PVD processes, are characterized by the physical mechanism by which the vapor flux is generated. Modification of these basic processes (e.g., by addition of an ion beam) accounts for the apparent numerous PVD processes in the literature. In spite of minor processing variations, PVD processes have many common features including: (1) a high vacuum system with low impurity gas levels and with the ability to input controlled flow rates or partial pressures of one or more working gases; (2) a coating material source(s) with a well-controlled and often monitored vapor flux; and (3) a substrate mounting assembly which controls substrate temperature and distance/orientation to the coating source. Plasma and ion-beam assisted PVD processes are derived from the fundamental evaporation, sputtering, and ion plating processes through, for example, incorporation of a bias voltage to create a glow discharge.

PVD processes are used to deposit thin films for purposes such as microelectronics circuit fabrication, control of light reflectance and absorption, corrosion and oxidation mitigation, decorative coatings, and tribology. PVD fabricated materials include: metals, ceramic compounds, including superconductor thin films; composites; and semiconductors, including layered superlattice structures. Suitable substrates range from metals to ceramics to polymers. Nearly every imaginable industry from automotive to textiles to microelectronics actively utilizes PVD technologies in their products and manufacturing processes. Recently developed ion assisted PVD technologies which are rapidly finding applications include ion plating (a plasma-assisted process), activated reactive evaporation, and ion-beam assisted molecular beam epitaxy. These processes offer possible advantages in film adhesion, microstructure, chemistry, and mechanical/electrical properties.

Bombardment of a PVD film with energetic particles (ions and/or neutrals) prior to and during film deposition can dramatically and beneficially alter the structure, chemistry, and physical properties of the film and the film/substrate interface. Applications of plasma-assisted and ion beam-assisted thin film PVD processes are increasing in areas such as microelectronics and aerospace where improved performance requirements are continually being placed upon materials. Energetic particle bombardment during film growth has also been found to enhance formation of new materials and alloys, such as compound semiconductors, whose metastable microstructures result in unique physical properties.
The objectives of this paper are to review (1) the processes (equipment and operation) for plasma and ion-beam assisted PVD and (2) the structure, chemistry and physical properties of films deposited with these processes. Discussion will include ceramic (nitride and oxide), metallic (elemental and layered), and compound semiconductor films deposited onto metallic and ceramic substrates. Topics to be discussed include the effects of energetic particle bombardment on film characteristics such as: porosity; residual stresses; film nucleation, growth, and preferred orientation; and, adhesion, including chemical mixing and compound formation at the film/substrate interface. Emphasis will be placed on the microstructural (analysis with SEM and cross-section TEM) and microchemical (analysis with EDX, Auger, and SIMS) effects of energetic particle bombardment. For additional in-depth discussions on PVD and related topics, the reader is directed to references (1-6) [note especially the extensive and detailed discussions of PVD deposition processes and materials by J. A. Thornton in references (4 and 5)].

2. EVAPORATION

Evaporation is a process involving the heating of a source material to a sufficiently high temperature, usually in a high vacuum, so that atoms or molecules are liberated from the source, move through the vacuum with little scattering and low average kinetic energies, and deposit onto a substrate (7,8). A basic evaporation system consists of a vacuum chamber, a vacuum pumping system capable of achieving high vacuum, a gas inlet system for chamber venting, an evaporation source(s), and a specimen holder. Vacuum technology is a common and essential feature for all PVD processes and the reader is directed to Glang, Holmwood, and Kurtz (9) for a thorough review.

2.1. Equipment and operation

Processing is done inside a vacuum chamber which may range in size and shape from a small glass bell jar to a room-sized cube. Fixturing is required inside the vacuum chamber for supporting and positioning the substrates during film deposition. This fixturing may be a simple stationary rod or plate or it may utilize motion along one or more axes to enhance coating thickness uniformity over complex-shaped substrate surfaces. Substrate fixturing systems often incorporate heating and cooling capabilities because temperature is a key parameter in controlling substrate cleanliness and film adhesion, residual stress, and microstructure. If a bias voltage is to be applied to the substrate for plasma assisted deposition, electrical connections and shielding requirements can make the fixturing quite complex.

2.2. Vacuum system. Straight evaporation is typically done in a high vacuum environment so the need for gas introduction into the chamber is limited mainly to initial pump-down cycles where introduction of an inert gas serves to purge the chamber of unwanted gases. Depending on purity requirements the inert gas may need to be further purified of reactive gases such as oxygen, nitrogen, or water vapor prior to introduction into the chamber by passing it through a heated titanium sponge system. To understand how residual gases affect the film microstructure and properties, it is important to know the composition of the residual gases in the vacuum chamber during deposition. This is done with a residual gas analyzer (RGA) which is simply a mass spectrometer designed to measure ion current as a function of atomic mass (9). Because RGA's require vacuums of \(10^{-2}\) Pa or less to operate, auxiliary pumping and valving may be required when analyzing the gas compositions of poor vacuums often found in plasma-assisted deposition systems.

The vacuum pumping system must be capable of producing a high vacuum of approximately \(10^{-3}\) Pa (\(7.5 \times 10^{-6}\) Torr or \(7.5 \times 10^{-3}\) \(\mu\)m) or better and this