The Materials Science *of* Thin Films

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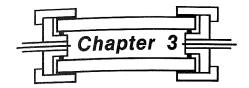London   Sydney   Tokyo   Toronto

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Chapter 3

Physical Vapor Deposition

3.1. INTRODUCTION

In this chapter we focus on evaporation and sputtering, two of the most important methods for depositing thin films. The objective of these deposition processes is to controllably transfer atoms from a source to a substrate where film formation and growth proceed atomistically. In evaporation, atoms are removed from the source by thermal means, whereas in sputtering they are dislodged from solid target (source) surfaces through impact of gaseous ions. The earliest experimentation in both of these deposition techniques can apparently be traced to the same decade of the nineteenth century. In 1852, Grove (Ref. 1) observed metal deposits sputtered from the cathode of a glow discharge. Five years later Faraday (Ref. 2), experimenting with exploding fuselike metal wires in an inert atmosphere, produced evaporated thin films. Advances in the development of vacuum-pumping equipment and the fabrication of suitable Joule heating sources, first made from platinum and then tungsten wire, spurred the progress of evaporation technology. Scientific interest in the phenomenon of evaporation and the properties of thin metal films was soon followed by industrial production of optical components such as mirrors, beam splitters, and, later, antireflection coatings. Simultaneously,

sputtering was used as early as 1877 to coat mirrors. Later applications included the coating of flimsy fabrics with Au and the deposition of metal films on wax masters of phonograph records prior to thickening. Up until the late 1960s, evaporation clearly surpassed sputtering as the preferred film deposition technique. Higher deposition rates, better vacuum, and, thus, cleaner environments for film formation and growth, and general applicability to all classes of materials were some of the reasons for the ascendancy of evaporation methods. However, films used for magnetic and microelectronic applications necessitated the use of alloys, with stringent stoichiometry limits, which had to conformally cover and adhere well to substrate surfaces. These demands plus the introduction of radio frequency (RF), bias, and magnetron variants, which extended the capabilities of sputtering, and the availability of high-purity targets and working gases, helped to promote the popularity of sputter deposition. Today the decision of whether to evaporate or sputter films in particular applications is not always obvious and has fostered a lively competition between these methods. In other cases, features of both have been forged into hybrid processes.

Physical vapor deposition (PVD), the term that includes both evaporation and sputtering, and chemical vapor deposition (CVD), together with all of their variant and hybrid processes, are the basic film deposition methods treated in this book. Some factors that distinguish PVD from CVD are:

1. Reliance on solid or molten sources
2. Physical mechanisms (evaporation or collisional impact) by which source atoms enter the gas phase
3. Reduced pressure environment through which the gaseous species are transported
4. General absence of chemical reactions in the gas phase and at the substrate surface (reactive PVD processes are exceptions)

The remainder of the chapter is divided into the following sections:

3.2. The Physics and Chemistry of Evaporation
3.3. Film Thickness Uniformity and Purity
3.4. Evaporation Hardware and Techniques
3.5. Glow Discharges and Plasmas
3.6. Sputtering
3.7. Sputtering Processes
3.8. Hybrid and Modified PVD Processes

Additional excellent reading material on the subject can be found in Refs. 3–6. The book by Chapman is particularly recommended for its entertaining

and very readable presentation of the many aspects relating to phenomena in rarefied gases, glow discharges, and sputtering.

3.2. THE PHYSICS AND CHEMISTRY OF EVAPORATION

3.2.1. Evaporation Rate

Early attempts to quantitatively interpret evaporation phenomena are connected with the names of Hertz, Knudsen, and, later, Langmuir (Ref. 3). Based on experimentation on the evaporation of mercury, Hertz, in 1882, observed that evaporation rates were:

1. Not limited by insufficient heat supplied to the surface of the molten evaporant
2. Proportional to the difference between the equilibrium pressure P_e of Hg at the given temperature and the hydrostatic pressure P_h acting on the evaporant.

Hertz concluded that a liquid has a specific ability to evaporate at a given temperature. Furthermore, the maximum evaporation rate is attained when the number of vapor molecules emitted corresponds to that required to exert the equilibrium vapor pressure while none return. These ideas led to the basic equation for the rate of evaporation from both liquid and solid surfaces, namely,

$$\Phi_e = \frac{\alpha_e N_A (P_e - P_h)}{\sqrt{2\pi MRT}}, \tag{3-1}$$

where Φ_e is the evaporation flux in number of atoms (or molecules) per unit area per unit time, and α_e is the coefficient of evaporation, which has a value between 0 and 1. When $\alpha_e = 1$ and P_h is zero, the maximum evaporation rate is realized. By analogy with Eq. 2-9, an expression for the maximum value of Φ_e is

$$\Phi_e = 3.513 \times 10^{22} \frac{P_e}{\sqrt{MT}} \text{ molecules/cm}^2\text{-sec.} \tag{3-2}$$

When P_e is expressed in torr, a useful variant of this formula is

$$\Gamma_e = 5.834 \times 10^{-2} \sqrt{M/T}\, P_e \text{ g/cm}^2\text{-sec,} \tag{3-3}$$

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