THIN FILM TECHNOLOGY: AN INTRODUCTION TO DEPOSITION TECHNIQUES AND OVERVIEW

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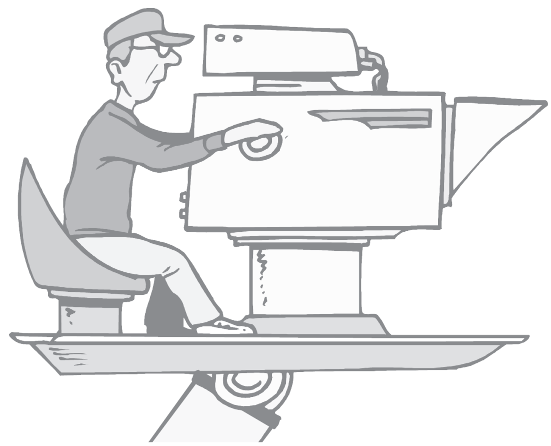
1 - Introduction



Thin Film Deposition technology can well be regarded as the major key to the creation of devices such as computers, since microelectronic solid-state devices are all based on material structures created by the deposition techniques. Excellent stability and accuracy together with a level of reliability (which is not economically feasible with other technologies) of the electronic components and devices is the hallmark of thin film technology.

Electronic engineers have continuously demanded films of improved quality and sophistication for solid-state devices, requiring a rapid evolution of deposition technology. Equipment manufacturers have made successful efforts to meet the requirements for improved and more economical deposition systems and for in situ process monitors and controls for measuring film parameters. The improved understanding of the physics and chemistry of films, surfaces, interfaces, and microstructures made possible by the remarkable advances in analytical instrumentation during the past twenty years. A better fundamental understanding of materials leads to expanded applications and new designs of devices that incorporate these materials. A good example of the crucial importance of deposition technology is the fabrication of semiconductor devices, an industry that is totally dependent on the formation of thin solid films of a variety of materials by deposition from the gas, vapor, liquid, or solid phase.

2 - Thin Film Deposition Techniques

A solid material is said to be in thin film form when it is grown as a thin layer on a solid substrate by controlled condensation of the individual atomic, molecular, or ionic species either by physical process or ultra chemical reactions. There are many dozens of deposition techniques for material formation [1-4]. Since, the concern here is with thin-film deposition methods for forming layers in the thickness range of a few nano-meters to about ten micrometers, the task of classifying the techniques is made simpler by limiting the number of techniques to be considered.

Basically, thin-film deposition techniques are either purely physical, such as evaporative methods, or purely chemical, such as gas- and liquid-phase chemical processes. A considerable number of processes that are based on glow discharges and reactive sputtering combine both physical and chemical reactions; these overlapping processes can be categorized as physical-chemical methods. A brief introduction to the deposition techniques where thin-film deposition techniques are grouped together according to evaporative, glow discharge, gas-phase chemical, and liquid-phase chemical processes is mentioned in the following table:

CLASSIFICATION OF THIN-FILM DEPOSITON TECHNOLOGIES

A] Evaporative Methods

- Vacuum Evaporation
- Conventional vacuum evaporation
- Electron-beam evaporation
- Molecular-beam epitaxy (MBE)
- Reactive evaporation

B] Glow-Discharge Processes

- Sputtering
- Diode sputtering
- Reactive sputtering
- Bias sputtering (ion plating)
- Magnetron sputtering
- Ion beam deposition
- Ion beam sputter deposition
- Reactive ion plating
- Cluster beam deposition (CBD)
- Plasma Processes
- Plasma-enhanced CVD
- Plasma oxidation
- Plasma anodization
- Plasma polymerization
- Plasma nitridation
- Plasma reduction
- Microwave ECR plasma CVD
- Cathodic arc deposition

C] Gas-Phase Chemical Processes

- Chemical Vapor Deposition (CVD)
- CVD epitaxy
- Atmospheric-pressure CVD (APCVD)
- Low-pressure CVD (LPCVD)
- Metal-organic CVD (MOCVD)
- Photo-enhanced CVD (PHCVD)
- Laser-induced CVD (PCVD)
- Electron-enhanced CVD
- Thermal Forming Processes
- Thermal oxidation
- Thermal nitridation
- Thermal polymerization
- Ion implantation

D] Liquid-Phase Chemical Techniques

- Electro Processes
- Electroplating
- Electroless plating
- Electrolytic anodization
- Chemical reduction plating
- Chemical displacement plating
- Electrophoretic deposition
- Mechanical Techniques
- Spray pyrolysis
- Spray-on techniques
- Spin-on techniques
- Liquid phase epitaxy

2.1 - Evaporative Techniques

Thermal Evaporation or Vacuum Evaporation technique is that one of the oldest techniques used for depositing thin films [1,3], which is still widely used in the laboratories and in industries for depositing metals and metal alloys. The following sequential basic steps take place: (i) a vapor is generated by boiling or subliming a source material, (ii) the vapor is transported from the source to the substrate, and (iii) the vapor is condensed to a solid film on the substrate surface. Although this deposition technique is deceptively simple in principle, but for the better results, the skilled practitioner must be well versed in vacuum physics, material science, mechanical and electrical engineering, as well as in elements of thermodynamics, kinetic theory of gases, surface mobility, and condensation phenomena. Evaporants cover an extraordinary range of varying chemical reactivity and vapor pressures. This variety leads to a large diversity of source components including resistance-heated filaments, electron beams; crucibles heated by conduction, radiation, or rf-induction; arcs, exploding wires, and lasers. Additional complications include source-container interactions, requirements for high vacuum, precise substrate motion (to ensure uniformity) and the need for process monitoring and control.

2.2 - Glow-Discharge Techniques

The electrode and gas-phase phenomena in various kinds of glow discharges (especially rf- discharges) represent a rich source of processes used to deposit and etch thin films. Creative expansion of these phenomena has resulted in the development of many useful processes for film deposition (as well as etching), as listed in Table 1. The most basic and well-known of these processes is sputtering,[1-3] the ejection of surface atoms from an electrode surface by momentum transfer from bombarding ions to surface atoms. From this definition, sputtering is clearly an etching process, and is, in fact, used as such for surface cleaning and for pattern formation. Since sputtering produces a vapor of electrode material, it is also (and more frequently) used as a method of film deposition similar to evaporative deposition. Sputter deposition has become a generic name for a variety of processes.

2.3 - Gas-Phase Chemical Processes

Methods of film formation by purely chemical processes in the gas or vapor phases include chemical vapor deposition and thermal oxidation. Chemical vapor deposition (CVD)[1-2] is a materials synthesis process whereby constituents of the vapor phase react chemically near or on a substrate surface to form a solid product. The deposition technology has become one of the most important means for creating thin films and coatings of a very large variety of materials essential to advanced technology, particularly solid-state electronics where some of the most sophisticated purity and composition requirements must be met. The main feature of CVD is its versatility for synthesizing both simple and complex compounds with relative ease at generally low temperatures. Both chemical composition and physical structure can be tailored by control of the reaction chemistry and deposition conditions. Fundamental principles of CVD encompass an interdisciplinary range of gas-phase reaction chemistry, thermodynamics, kinetics, transport mechanisms, film growth phenomena, and reactor engineering.

2.4 - Liquid-Phase Chemical Formation

The growth of inorganic thin films from liquid phases by chemical reactions is accomplished primarily by electrochemical processes (which include anodization and electroplating), and by chemical deposition processes (which include reduction plating, electroless plating, conversion coating, and displacement deposition). A number of extensive reviews[1-3] of these film formation processes discuss theory and practice. Another class of film forming methods from the liquid phase is based on chemically reacting films that have been deposited by mechanical techniques.[1,3] Finally, liquid phase epitaxy[4] is still being used for growing a number of single-crystal semiconductors.

3.0 - Criteria for the Selection of a Deposition

Technology For Specific Applications

The selection of a specific technology for the deposition of thin films can be based on a variety of considerations. A multitude of thin films of different materials can be deposited for a large variety of applications; hence, no general guidelines can be given of what the most suitable deposition technology should be. In selecting an appropriate deposition technology for a specific application, several criteria have to be considered.

3.1 - Thin-Film Applications

In considering the different applications of deposited thin films, [3-4] the following generic categories can be identified-

Electronic Components. The fabrication of electronic components, especially solid-state devices and microelectronic integrated circuits, have undoubtedly found the widest and most demanding applications for thin film depositions. These films typically consist of semiconductor materials, dielectric and insulating materials, and metal or refractory metal silicide conductors.

Electronic Displays: Electronic displays are used for interfacing electronic equipment with human operators. Different components and device structures are required, such as: Liquid-crystal displays, Light-emitting diodes (LEDs), Electroluminescent displays, Plasma and fluorescent displays & Electrochromic displays. The fabrication of these displays requires conductive films, transparent and conductive films, luminescent or fluorescent films as well as dielectric and insulating layers.

Optical Coatings: Optical coatings are applied for antireflection purposes, as interference filters on solar panels, as plate glass infrared solar reflectors, and for laser optics. In the fabrication of filter optics, thin films with refractive index gradients are deposited on preforms from which the optical fibers are drawn. These coatings require dielectric materials with precisely defined indices of refraction and absorption coefficients. Laser optics require metal reflective coatings which can withstand high radiation intensities without degradation. Infrared reflecting coatings are applied to filament lamps to increase the luminous flux intensity.

Magnetic Films for Data Storage: Thin films of magnetic materials have found wide commercial applications for data storage in computers and control systems. The substrates can be metal, glass or plastic polymeric materials. Thin film deposition processes for magnetic materials and for materials with a high degree of hardness are required.

Optical Data Storage Devices: Thin films are finding increasing commercial use for optical data storage devices in compact disks and computer memory applications. Processes for the deposition of organic polymer materials as storage media and as protective overcoats are required for this technology.

Antistatic Coatings: Thin films of conductive or semiconductive materials are deposited to provide protection from electrostatic discharges.

Hard Surface Coatings: Thin film coatings of carbides, silicides, nitrides, and borides are finding increased uses to improve the wear characteristics of metal surfaces for tools, bearings, and machine parts. Of particularly great current interest are films of diamond-like carbon because of this material's heat dissipation properties, electrical insulation, hardness, and resistance to high-temperature and high-energy radiation.

3.2 - Material Characteristics

The desired material characteristics of the deposited films[3-4] will be, in most cases, the decisive factor for the selection of a preferred deposition technology. In many, if not most, instances the characteristics of a thin film can be quite different from the bulk material properties, since thin films have a large surface area to bulk volume ratio. In addition, the morphology, structure, physical and chemical characteristics of the thin film can also be quite different from those of the bulk materials. The surface and/or interface properties of the substrate can drastically influence thin film characteristics due to surface contamination, nucleation effects, surface mobility, chemical surface reactions, adsorbed gases, catalytic or inhibitory effects on film growth, surface topography, and crystallographic orientation, and stress effects due to thermal expansion mismatch.

3.3 - Process Technology

As discussed before, a wide variety of process technologies are available for the deposition of thin films. The technologies differ to a large degree in their physical and chemical principles of operation and in the commercially available types of equipment. Each process technology has been pursued or developed because it has unique advantages over others. However, each process technology has its limitations. In order to optimize the desired film characteristics, a good understanding of the advantages and restrictions applicable to each technology is necessary. The desired film thickness is closely related to the deposition or formation rates, since economical considerations determine, to a large degree, the selection of the most appropriate deposition technology. Thin films cover a thickness range from about 1 nm to several micrometers, or from film mono-layer to thickness approaching bulk material characteristics.

Of increasing importance is the particle density associated with the deposited film. Particles originating from the equipment, the substrate, the environment, or from the reactant materials supplied to the deposition equipment can impose serious limitations to the utility of a deposition process or the equipment used. This is especially true for the fabrication of high-density microelectronic devices where the particle size can be equal to or exceed the minimum device dimensions. Deposition processes for very-large-scale integrated (VLSI) circuits require, or will require in the near future, particle densities of less than 0.1 per cm^2 for particles down to 0.2 µm in diameter.

3.4 - Thin-Film Manufacturing Equipment

The equipment for the deposition of thin films can be classified into three basic categories:

- Thin-film deposition equipment for device research and development.
- Prototype equipment for the study of new or established deposition processes.
- Thin-film production equipment for device manufacturing.

The automation of deposition equipment is making rapid progress. Automated deposition systems provide automatic loading and unloading, process sequencing, and control of variables, such as reactor pressure, gas flows, and substrate temperature. In addition, diagnostic capabilities for detecting and analyzing equipment failures, maintenance requirements, and process integrity are being incorporated. Equipment communication of process parameters, failure modes and product status with upstream host computers as well as remote process recipe generation is becoming increasingly available for modern deposition equipment.

4.0 - Summary and Perspective for the Future

The importance of thin-film deposition technology in modern fabrication processes is well known. Thin-film deposition technologies have been outlined and classified into four major generic categories: (*i*) evaporative methods, (*ii*) glow-discharge processes, (*iii*) gas-phase chemical processes, and (*iv*) liquid-phase chemical film formation techniques. A variety of different thin-film deposition technologies and equipment is available from which a selection can be made. It is possible to a large degree to tailor the deposition process to the specific needs, based on-

- Physical and chemical material characteristics
- Specific applications
- Advantages and limitations in process technology
- Manufacturing technology and equipment

The fabrication processes established for semiconductor devices during the last two decades have provided an important stimulus for the development of new thin-film materials, processes and equipment. It can be expected that this trend will continue for the decade. The current trends in deposition technology for the fabrication of semiconductor devices are characterized by-

- A shift to larger substrate sizes
- Automation in substrate handling and process controls
- Reduction in particle and metal contamination
- Improvements in equipment reliability and ease of service and maintenance
- Lower process temperatures
- Improvements in film uniformity

- Reduced in-process damage (due to high voltage, radiation, particle bombardment, electrostatics, etc.)

The number of deposition steps in the fabrication sequence of integrated circuits is expected to increase with the advent of more complex circuits. Less complex devices, such as those introduced a decade ago, typically NMOS and CMOS integrated circuits, have required only three deposition steps for inorganic film deposition, whereas more advanced devices such as high-performance VLSI silicon integrated circuits, now require 8 to 11 deposition steps. With increasing demands for cost reductions in the manufacturing of integrated circuits, cost effective, high-volume manufacturing equipment for all deposition processes will be required.

Complex high-density integrated circuits face increased limitations in interconnecting the numerous components on a chip. Optical interconnection schemes are under development which can reduce this problem considerably. This trend will lead to new technologies combining opto-electronic device technology with the existing semiconductor process technologies. Thin-film deposition techniques will most likely play an important role for the fabrication of these interconnections. This overview of the important processes and techniques used industrially for forming thin films indicates the extremely powerful and versatile arsenal of methods that is now available to the technologist. Coatings can be prepared that can meet a very wide range of requirements for specific industrial or scientific applications. While remarkable advances in thin-film technology have been made, there are still areas in which the technology is leading science. This is particularly true for photo-induced, ion-assisted, and plasma-enhanced processes; these areas should provide fertile ground for future research.

References

1. Maissel, L. I., and Clang, R., (eds.), *Handbook of Thin Film Technology*, McGraw-Hill, New York (1970)
2. Vossen, J. L., and Kern, W., (eds.), *Thin Film Processes*, Academic Press, New York (1978)
3. Bunshah, R. F., (ed), Deposition Technologies for Films and Coatings: *Developments and Applications*, Noyes Publications, Park Ridge, NJ (1982)
4. Ghandhi, S. K., *VLSI Fabrication Principles*, John Wiley & Sons, New York (1983)

••• Clearly Define the Person You Want to Be •••

Who exactly do you want to be? What kind of person do you want to be? What are your personal ideals? Whom do you admire? What are their special traits that you would make your own?

It's time to stop being vague. If you wish to be an extraordinary person, if you wish to be wise, then you should explicitly identify the kind of person you aspire to become. If you have a daybook, write down who you're trying to be, so that you can refer to this self-definition. Precisely describe the demeanor you want to adopt so that you may preserve it when you are by yourself or with other people.