# AN INTRODUCTION TO PHYSICAL VAPOR DEPOSITION (PVD) PROCESSES

Donald M. Mattox

Consultant, IP Industries & Technical Director - SVC

For AESF SUR/FIN '92

## ABSTRACT

Physical Vapor Deposition (PVD) processes are atomistic deposition processes in which material vaporized from a source is transported in the form of a vapor through a vacuum or low pressure gas environment to the substrate where it condenses and film growth takes place. PVD processes may be used to deposit films of compound materials by the reaction of depositing material with the ambient gas environment or with a co-deposited material. The three basic PVD techniques are: vacuum evaporation, which uses thermal evaporation as a source of depositing atoms, sputter deposition, which used physical sputtering as the source of depositing atoms, and ion plating which uses concurrent ion bombardment during deposition to modify the film growth.

## INTRODUCTION

Physical Vapor Deposition (PVD) processes are atomistic deposition processes in which material vaporized from a source is transported in the form of a vapor through a vacuum or low pressure gas environment to the substrate where it condenses. PVD processes may be used to deposit films of compound materials by the reaction of depositing material with the ambient gas environment or with a co-deposited material. The three basic PVD techniques are: vacuum evaporation, which uses thermal evaporation as a source of depositing atoms, sputter deposition, which uses physical sputtering as the source of depositing atoms, and ion plating which uses concurrent ion bombardment during deposition to modify the film growth and properties. A fourth technique which can be considered to be a type of ion plating is Ion Beam Assisted Deposition (IBAD) which uses concurrent bombardment from an "ion gun" in vacuum to modify the film growth and properties. The various PVD techniques are shown in Figure 1. Typically, PVD processes are used to deposit films with thicknesses in the range of a few nanometers* to thousands of nanometers; however they can be used to form multilayer coatings, very thick deposits and freestanding structures.

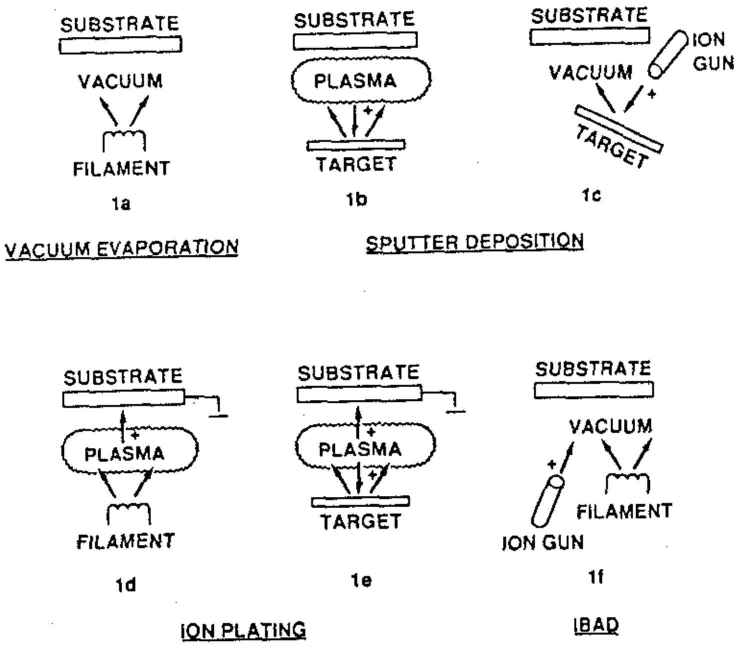

**Figure 1:** PVD processing techniques: 1a) vacuum evaporation, 1b) sputter deposition in a plasma environment, 1c) sputter deposition in a vacuum, 1d) ion plating in a plasma environment with a thermal evaporation source, 1e) ion plating in a plasma environment with a sputtering source and 1f) Ion Beam Assisted Deposition (IBAD) in a vacuum environment with a thermal evaporation source and ion bombardment from an ion gun.

---

* 1 nanometer (nm) = $10^{-9}$ meters = 10 Angstroms (A) = $10^{-3}$ microns = 0.04 microinches.

## VACUUM EVAPORATION

Vacuum evaporation is a PVD process in which material from a thermal vaporization source reaches the substrate without collision in the gas phase (1). This means that there is no scattering during transport and the trajectory of the vaporized material is "line-of-sight". The vacuum environment also provides the ability to reduce gaseous contamination in the system to a very low level. Typically vacuum evaporation takes place in the pressure range of $10^{-5}$ Torr ** to $10^{-9}$ Torr depending on the level of gaseous contamination that can be tolerated. Figure 1a depicts a simple vacuum evaporation arrangement.

### Evaporation and sublimation

The vapor pressure of materials is very dependent on the temperature. Materials that have a high vapor pressure over the solid, such as chromium, sublime. If the material must be molten before the vapor pressure is substantial the material evaporates. Materials that have a high vapor pressure at a relatively low temperature may be vaporized from a resistively heated source such as a filament or boat. For more refractory materials, the material is vaporized using a focused electron beam source. In either case the area of vaporization is rather small resembling approximating a "point source". When vaporizing large amounts of material the source may be replenished using wire or pellet feeds to keep the level of the evaporant constant.

In most cases evaporation of alloys of materials results in a change in composition since the alloying materials usually have differing vapor pressures and thus evaporate at differing rates. In some cases the alloy composition can be retained using "flash evaporation" techniques where small amounts of material are completely evaporated. In the case of evaporation of compounds the composition of the deposited material often differs from that of the starting material because of decomposition and loss of a portion of the more gaseous material i.e. oxygen from an oxide. Thus substoichiometric oxides are normally deposited by vacuum evaporation.

### Other vaporization sources

In addition to evaporation and sublimation,other specialized vaporization techniques may be used in a vacuum. Arc vaporization is used to vaporize electrically conductive materials in a high-current low-voltage electric arc. This technique produces high vaporization rates with a high percentage of the atomic vapor being ionized. These ions are accelerated away from the arc and achieve a kinetic energy much higher than thermal energy. In the arc vaporization process molten globules are formed which deposit along with the atomic species. These globules are often detrimental to the properties of the deposit and various techniques are used to try to eliminate them. Laser vaporization (laser ablation) is used to vaporize compound materials and has found particular application in the deposition of high quality high transition temperature (high $T_c$) superconductor oxides.

### Thickness and surface coverage

Since the thermal evaporation is from a point source and the flux has a cosine distribution around the normal to the surface the distribution of the deposited material is determined by

---

** Atmospheric pressure = 760 Torr. 1 Torr (mm mercury) = $10^3$ milliTorr (mTorr). 1 mTorr = 7.5 Pascals (Pa) = 1 micron the source-substrate distance, the angle of the substrate-source trajectory with the surface normal, and the angle of the substrate normal with the depositing flux. In order to increase the deposition uniformity the substrate is generally held in a moving fixture that randomizes the position and orientation of the substrate relative to the source during deposition. Another approach is to use multiple sources to produce an apparent large area evaporation source, although this approach makes thickness uniformity control more difficult.

The ability of vacuum evaporation to cover a surface depends on the surface topography. If the surface is smooth surface coverage will be good. However if the surface is not smooth, geometrical shadowing will prevent good surface coverage. Surface coverage can be improved by randomizing the deposition direction using fixturing that is moveable.

### Advantages and disadvantages of vacuum evaporation

Some advantages of vacuum evaporation are:

- high purity materials can be deposited from high purity source material
- source of material to be deposited may be a solid in any form and purity
- line-of-sight trajectories and "point sources" allow the use of masks to define areas of deposition
- deposition monitoring and control are relatively easy

Some disadvantages of vacuum evaporation are:

- many alloy compositions and compounds can only be deposited with difficulty
- line-of-sight and point sources result in poor surface coverage on complex surfaces
- line-of-sight trajectories and point sources result in poor film thickness uniformity over large areas
- film properties depend on the "angle-of-incidence" of the flux of the depositing material
- fixturing with movement capability is necessary to improve surface coverage and thickness uniformity
- few processing variables are available for film property control
- substrate preparation is important to resulting film properties
- source material utilization may be poor
- high radiant heat loads may exist in the system
- the liquid source material may move thus changing the source configuration

### Some applications of vacuum evaporation

Vacuum evaporation is widely used to form optical interference coatings, mirror coatings, decorative coatings, permeation barrier films on flexible packaging materials, electrically conducting films, and corrosion protective coatings.

## SPUTTER DEPOSITION

Sputter deposition is the deposition of particles vaporized from a surface by the physical sputtering process (2). This PVD process is sometimes called just sputtering i.e. "sputtered films of --". Figure 1b and 1c show sputter deposition configurations.

### Physical sputtering

Physical sputtering is a non-thermal vaporization process where surface atoms of a solid sputtering "target" are physically ejected by momentum transfer from an massive energetic bombarding particle. Usually the energetic particle is an ion accelerated from a gaseous plasma. Electrically conducting materials may be sputtered in a direct current (DC) diode plasma configuration. Dielectric materials must be sputtered using a radio frequency (rf) sustained plasma. In the magnetron sputtering configuration a magnetic field is utilized to contain the plasma-generating electrons and produce a high plasma density near the target surface thereby increasing the sputtering rate. There are many sputtering configurations and often the sputter erosion pattern from the target is non-uniform requiring movable fixturing to obtain a uniform deposition over a substrate surface.

Sputter deposition may be performed in a vacuum using an ion gun or in a low pressure (<5 mTorr) plasma where the sputtered particles and reflected high energy neutral particles do not suffer gas phase collisions between the target and the substrate. Sputtering may also be performed in a higher pressure (5-30 mTorr) where energetic particles from the sputtering target are thermalized by gas phase collisions before they reach the substrate surface. The properties of the sputter deposited films depend strongly on the sputtering conditions.

### Sputtering targets

The sputtering target is a solid surface and sputtering can be attained over a large area of a surface. Solid targets provide a long-lived vaporization source with rather constant and reproducible vaporization rates. Fabrication of large-area sputtering targets is often costly and the material utilization of the target is poor.

### Reactive sputter deposition

By using a reactive gas in the plasma,the deposited material may be made to react to form a compound material. The reaction is promoted by "plasma activation" of the reactive species.

### Advantages and disadvantages of sputter deposition

Some advantages of sputter deposition are:

- elements, alloys and compounds may be sputtered and deposited
- the sputtering target provides a stable, long-lived vaporization source
- the solid sputtering target may be mounted in any orientation
- in some configurations the sputtering target provides a large-area vaporization source that can be of any shape
- in some configurations the sputtering source may be a defined shape such as a line or a rod
- in some configurations reactive deposition may be easily accomplished because the reactive species are "activated" in a plasma (i.e. "reactive sputter deposition")

Some disadvantages of sputter deposition are:

- sputtering rates are low compared to those that can be attained in thermal evaporation
- in many configurations the deposition flux distribution is non-uniform requiring fixturing to randomize the position of the substrates in order to obtain films of uniform thickness
- film properties depend on the "angle-of-incidence" of the flux of depositing material
- sputtering targets are often expensive and material utilization may be poor
- most of the energy incident on the sputtering target turns into heat which must be removed

- in some configurations gaseous contamination is not easily removed from the system and gaseous contaminants are "activated" in the plasma thus making film contamination more of a problem than in vacuum evaporation
- in some configurations radiation and energetic particle bombardment from the plasma or sputtering target may change the film properties in an uncontrolled manner

### Some applications of sputter deposition

Sputter deposition is widely used to deposit thin film metallization on semiconductor material, coatings on architectural glass, reflective coatings on compact discs, magnetic films, dry film lubricants and decorative coatings.

## ION PLATING

Ion plating utilizes concurrent or periodic energetic particle bombardment of the depositing film to modify and control the composition and properties of the depositing film (3). Ion plating may be done in a plasma environment where ions for bombardment are extracted from the plasma or it may be done in a vacuum environment where ions for bombardment are formed in a separate "ion gun". The latter ion plating configuration is often called Ion Beam Assisted Deposition (IBAD) (4). Figure 1d and 1e show ion plating in a plasma environment. Figure 1f shows ion plating in a vacuum environment or IBAD.

### Source of depositing species

The depositing material may be created either by evaporation, sputtering, or arc vaporization. The energetic particles used for bombardment are usually ions of inert or reactive gas, ions of the depositing material ("film ions") or ions of the reacting gaseous materials (e.g. oxygen or nitrogen).

### Source of bias potential

Generally positive ions are accelerated to the depositing material due to a negative potential on the surface. This potential may be applied from an external source or be due to a "self-bias" on the surface. For electrical conductors such as metals, TiN, etc the applied potential may be DC. However if the film material is an insulator the applied potential must be rf in order to prevent a surface charge buildup which will cause the bombardment to cease. A self-bias can be caused to appear on the surface of a dielectric or electrically floating conductive surface by continuously bombarding the surface by high energy electrons.

### Reactive ion plating

By using a reactive gas in the plasma the deposited material may be made to react to form a compound material. The reaction is promoted by "plasma activation" of the reactive species and the concurrent bombardment of the depositing material i.e. "bombardment enhanced chemical reaction". Materials such as TiN and $SiO_2$ are routinely deposited by reactive ion plating.

### Film properties

The concurrent bombardment can be used to modify and control the properties of the depositing material. The most common film properties that are modified include: residual film stress, density of the deposited material and composition (stoichiometry) of deposited compound materials.

### Surface coverage

Concurrent bombardment results in sputtering and redeposition of materials on surfaces that have a complex morphology. This effect, along with gas scattering at higher plasma pressures, can be used to give good surface coverage on complex surfaces such as ones having roughness or which have been patterned to form vias, metallization patterns, etc,

### Other sources of concurrent bombardment

Concurrent bombardment of the depositing film can occur without a bias on the surface of the depositing material. For example, bombardment by the reflected high energy neutrals in low pressure sputter deposition and the ions accelerated away from the arc in vacuum arc evaporation can modify the film properties. Ion guns can be used to accelerate ions into a field-free deposition chamber.

### Advantages and disadvantages of ion plating

Some advantages of ion plating are:

- in situ sputter cleaning of substrate surface
- surface coverage may be improved over vacuum evaporation and sputter deposition due to gas scattering and "sputtering/redeposition" effects
- bombardment may be used to modify film properties such as adhesion, density, residual film stress, optical properties, etc.
- film properties are less dependent on the "angle-of-incidence" of the flux of depositing material than with sputter deposition and vacuum evaporation due to gas scattering and "sputtering/redeposition" effects
- bombardment may be used to improve the chemical composition of the film material by "bombardment enhanced chemical reactions" and sputtering of un-reacted species from the growing film
- in some configurations the plasma may be used to activate reactive species, and create new chemical species that are more readily adsorbed and to aid in the reactive deposition process ("reactive ion plating")

Some disadvantages of ion plating are:

- there are many processing variables to control
- it is often difficult to obtain uniform ion bombardment over the substrate surface leading to film property variation over the surface
- substrate heating can be excessive
- under some conditions the bombarding gas may be incorporated into the growing film
- under some conditions excessive residual compressive film stress may be generated

### Some applications of ion plating

Ion plating is used to deposit hard coatings on surfaces, adherent coatings on surfaces, optical coatings with high densities, and conformal coatings on complex surfaces.

## SUMMARY

There are a variety of PVD techniques, each with many variations. Each of these deposition options has advantages and disadvantages. The choice of technique to be used to accomplish a specific coating task depends on a number of factors that must be evaluated for each situation.

## REFERENCES

1. "Film Formation Methods" Chapter 6 in Coatings on Glass H.K. Pulker, Thin Film Science and Technology Series #6, Elsevier 1984
2. "Sputter Deposition Processes" Robert Parsons, Chapter II-4 in Thin Film Processes II, edited by John L. Vossen and Werner Kern, Academic Press 1991
3. "Ion Plating", Donald M. Mattox, Chapter 13, in Handbook of Plasma Processing Technology: Fundamentals, Etching, Deposition and Surface Interactions, edited by S.M. Rossnagel, J.J. Cuomo and W.D. Westwood, Noyes Publications, 1990
4. F.A. Smidt "Use of ion beam assisted deposition to modify the microstructure and properties of thin films" International Materials Reviews 35(2) 61, 1990