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Challenges in PVD technique (Thin film formation by thermal evaporation)

Dr. Pelluri Rahi
Ex. Assistant Professor, Cardinal Malula University,
Kinshasa – D R Congo

ABSTRACT
Among the outstanding achievements of Science and Technology in the 21st century, thin films occupy by right a major position. The earliest first Thin Film was made by Faraday paved the way for the development of Thin-film Technology. Today, Thin Film and Thin Film Systems find wide use in many fields of Science and Technology. They are employed in Electronic Systems, Communication Systems, Computer Technology, Navigation Equipment's, Robotics, Instrumentation and Controlling Systems and in Complicated Technological Process etc., due to the specific properties of the low dimensional materials.

Keyword: VLSI, GSI, PVD, Thermal Evaporation, Point Source, Knudsen's Assumption.

1. INTRODUCTION

The master applications of thin films save time in the development of microelectronics, optical coatings and integrated optics, thin film superconductivity and quantum engineering, surface science, engineering and technology, micromagnetism, metallurgical coatings and amorphous materials is shot into prominence. The frontiers pivoting thin films such as

- Exciting phenomena of micro-science assisted with low dimensional (i.e., Micro and Nano) materials.
- The industrial applications of micro science and micro technology for the development of synthetic materials for VLSI/GSI communication, informatics and solar energy conversion etc., - with decreasing size of active electronic components a higher packing density, higher speed performance and low cost are obtained., at the same time –
- The investigation of physical characteristics of these low-dimensional materials – now a part of textbook literature.

Dimensions as low as, 200A^0 has been delineated by Lithography. However, the lower limit of deposition is measured by the resist – radiation interaction characteristics. The techniques of ion sources and laser beam are in experimental stages at present.

2. The principle techniques of the deposition of solid thin films

The principle techniques of the deposition of solid thin films have been classified as:

- Physical Vapours Deposition (PVD)
- Chemical Vapour Deposition (CVD)
- Electro Chemical Deposition (ECD)
- Solution growth Deposition of Electrolysis (SGD)
- Micro Lithographic Technology (MLT)

3. PVD Technique

In general thin films are made by physical Vapour Depositing Techniques i.e., the vapour stream obtained by proper heating the material in a high vacuum and inert atmospheres exposed to the cooled substrate over which the molecules of the vapour must condense on their first impact. Now the exciting frontier is that the deposit should follow a specified thickness distribution over the substrate surface.

4. History

Solid materials get vaporized when heated to sufficient temperatures. When these vapours condense on cooler substrates thin film are formed. The first evaporated film was obtained by Faraday by passing high currents through a metal wire in an inert atmosphere. This attributes the possibility of vacuum evaporation into the scientific world. The deposition by thermal evaporation is the simple, convenient process and is a predominant method at present.

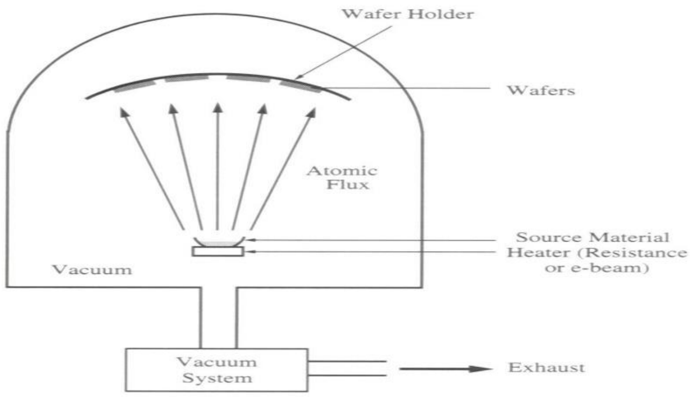
The pivotal role of the thin film science with its challenging frontiers in the modern day technology requires several types of solid thin films on either metallic or non-metallic supports for a variety of applications. All the deposition techniques have been distinguished by the nature of the depositing source, the nature of the substrate, the required film – structure, thickness, and distribution etc., in the forgoing topics some of the well-established PVD techniques will be discussed in detail.

5. Types of PVD Techniques

The film is formed by atoms directly migrated to the substrate from the source through vacuum/gas phase

- Evaporation
    - Thermal Evaporation
    - E – beam Evaporation
- Sputtering
    - DC Sputtering
    - DC Magnetron Sputtering
    - RF Sputtering
- Reactive PVD

6. Thermal Evaporation



Typical Diagram of Evaporating System

Thermal evaporation is a simple and is a convenient process to evaporate and to condense a wide range of materials in a vacuum on a cooler substrate surface. So, it is one of the versatile techniques of PVD at present.

In thermal evaporation, the material to be evaporated is in any available form i.e., powder, solid or liquid should be supported on a chemically inert source. The source is the heated to sufficient temperature by either resistive or R.F heating techniques. The vapour stream thus created having the desired pressure of $\leq$ 0.1 Tor is allowed to condense on a cooler substrate. Elaborate work has been carried out in a high vacuum ambient, to minimize the interaction between required gas and the surface of the growing film. In high vacuum i.e., $\leq$ 0.00001 Tor, the mean free path between collisions of the vapour atoms with the residual gas atoms becomes large enough. So, that the unscattered vapour beam arrives at the substrate. In other wards most of the emitted vapour atoms emerge in a striated line path and deposited over the substrate surface. In a vacuum evaporator, the normal separation between the source and the substrate at an optimum stream pressure should be 10 to 50 cm of Hg. A low vacuum has an additional affect that, there will be a reduction of impurities in the deposit and more ever in a vacuum, the materials will boil at low temperatures. In the case of most of the materials, it is ranging from 1000 ^{0}C to 2000 ^{0}C. However, the requirement of the source material is that it should not react with the evaporate material and hence a negligible vapour at the deposition temperature.

CIMS' Sharon Thermal Evaporator

7. Vapour Sources

The versatile Thin-Film Technology with its frontiers in the modern day technology requires that the required coating should follow a specified thickness over the surfaces of either metallic or non-metallic substrate for a variety of applications. The specified distribution has been distinguished by the nature of the depositing source, the nature of the substrate, the arrangement of the vapour source or sources relative to the surface. It must be also take into account the mode of the evaporation from the source viz., whether the vapour stream distributes uniformly in all directions or in any proffered directions. In this chapter, some of the well-established vapour sources will be discussed in detail.

Anyhow the choice of the design of any particular source should have been the limiting factors related to the evaporating material i.e., its – nature (granules, powder, wire or sheet), evaporation behavior – whether it wets or chemically react with heater material or volatilizes. Whether may be the vapour source, we shell assumes that the evaporation takes place according to the Knudsen's cosine law. The validity of the assumptions to be made in order to characterize the vapour sources classifies as follows:

7.1 Point Source

Foil Dimple Boat

It is assumed that the emission carried out by a small sphere having a uniform surface temperature with a small diameter in comparison with the separation from the receiving surface, the evaporation should take place uniformly in all directions. Such a source is called point source.

In Practice the electron beam evaporation technique, the technique of laser beam and ion sources approximate to the point source. Under limited practical conditions, the hairpin and conical basket sources are realized as point sources.

7.1 Extended Source

Cr Coated Tungsten Rod

According to Knudsen's assumptions the evaporation from a small cylinder of small diameter compared with the other distances having uniform temperature is assumed to takes place uniformly at the low pressures. Such an emitting cylinder is called as extended source.

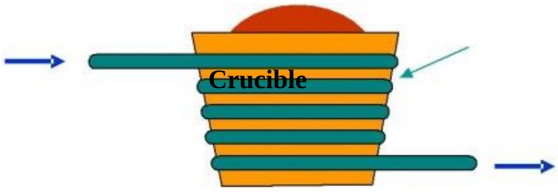
In practice it is found that the extended sources should have directional properties i.e., the evaporation in any particular direction is limited by the cosine of the emission angle. In general foil sources of considerable width approximate to this.

8. Limitations of the Source

However, Contamination Problem with Thermal Evaporation Container material also evaporates, which contaminates the deposited film, in practice the postulates of one source should be carried out as the limiting condition of the other one. As we discussed in the early, we shall have three general conditions irrespective the type of the source viz.,

1. The evaporation carried out at a low pressure usually $\leq$ 0.1 mm of Hg. to avoid the scattering of vapour molecules during the bombardment with the ambient molecules.
2. The vapour pressure should be low in order to increase mean free path between collisions of the vapour molecules.
3. The vapour stream must condense on the substrate on the first impact which is usually at high temperature above 1000 ^{0}C
4. .

9. Point Source



It is assumed that the emission carried out by a small sphere having a uniform surface temperature with a small diameter in comparison with the separation from the receiving surface, the evaporation should take place uniformly in all directions. Such a source is called point source.

9.1 Evaporation of the mass from a Point Source

Consider a small sphere of negligible dimensions with respect to all other length dimensions, evaporating material uniformly in all directions at a rate of' gr./sec. such a source is called as a point source.

Let 'dm' be the mass evaporated through a solid angleω' in any direction in unit time. Mathematically it can be expressed as,

$$dm = m \frac{d\omega}{4\pi}$$

Let 'ds' be any small area over the substrate surface inclined at an angle 'θ' with the evaporation direction. Then we have,

$$d\omega = \frac{ds\ Cos\theta}{R^2}$$

So that, the mass growth rate of the deposition over the substrate surface is given by,

$$dm = m \frac{ds\ Cos\theta}{4\pi R^2}$$

If 'ρ' be the density of the evaporating material in gr/c.c and' be the growth rate of the film thickness, then the volume growth rate and hence the mass growth rate of the deposition over the considered surface is given by,

$$dv = t.ds$$

$$dm = t.ds.\rho$$

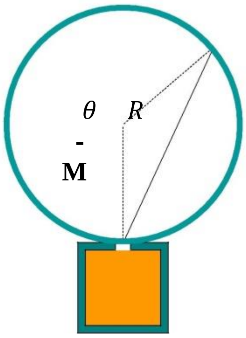
Therefore the growth rate of the film thickness over the surface is given by,

$$t = \frac{m\ Cos\theta}{4\pi\rho R^2}$$

On eliminating the time element by substituting "M" gr to be the total mass evaporated instead of mass growth rate' gr/cc and "T" cm be the total thickness of the deposited film over the substrate surface instead of the deposited film over the substrate surface instead of growth rate of the film thickness -'t' cm/sec. We have,

$$T = \frac{M\,Cos\theta}{4\pi\rho R^2}$$

9.1.1 Evaporation of the mass from a Point Source on to the Spherical Substrate



Consider the evaporation from a point source situated at the center of a spherical substrate. Since, $\cos\theta = 1$ for a spherical substrate surface, the expression for the thickness of the deposit collected at any point inside the surface of the substrate is,

$$T = \frac{M}{4\pi\rho R^2}$$

Let "V" be the volume of the material to be evaporated and is to be deposited over the substrate, (since $V = \frac{M}{\rho}$)

$$T = \frac{V}{4\pi R^2}$$

9.1.1. (A) Distribution of the mass over the Spherical Substrate

So that, the evaporation from a point source situated at the center of the spherical substrate forms a uniform coating over it following inverse square law.

Finally, the film over the substrate surface is limited by

1.
2. The volume of the material is to be evaporated "V"
3. The normal separation between the surface of the substrate and the source "R"

i.e., $T \propto \frac{1}{R^2}$

& $T \propto \frac{M}{\rho}$ (or) V

Where, $\frac{1}{4\pi}$ is the dimension less quantity and is the constant of proportionality. However the substrate must be cooled in order to condense the evaporated molecules on their first impact with the surface.

9.1.1. (B) Example: Gold Plating over a Spherical Substrate

Let us suppose 10 grams of gold is to be plated over a spherical substrate of radius 100 cm and is situated around the point source located at its center.

Substance used for the formation of thin film is:		**Gold**
Mass of the evaporating material in grams is	:	10
Density of the evaporating material in gr/cc is	:	19.3
Normal separation b/n source and substrate in cm is	:	100
Evaporating rate of the material in gr/sec is	:	0.01
The volume of the material is to be evaporated in c.c is:		0.518
Total time required for the evaporation in sec. is	:	1000
Thickness of the gold film so formed over the substrate in ^{0}A is	:	**0.041215**

So that thin film of uniform thickness is forming over the spherical substrate.

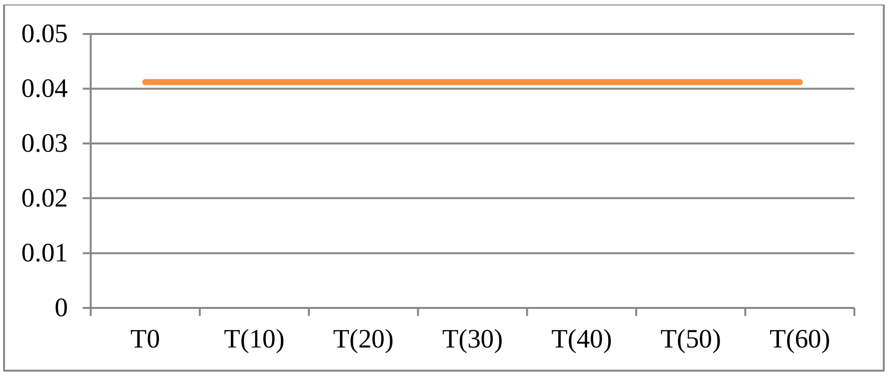


Chart 1. Thickness of the gold plating over spherical substrate from 0^0 to 60^0 from the center w.r.t to source

9.1.2 Evaporation of the mass from a Point Source onto the Plane Substrate

Consider the evaporation from a point source situated normally at a distance "R" below the center of a plane substrate. The thickness of the deposition at a point "o" which is just above the source is

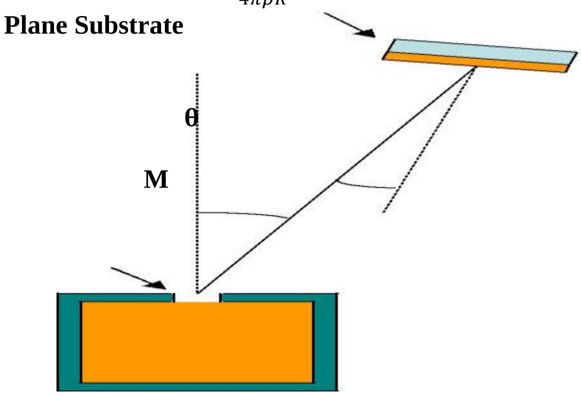
$$T_o = \frac{M}{4\pi\rho R^2}$$

And that for any point "P" at an angle θ to the normal vapour stream and at a distance "D" from the source is

$$T_\theta = \frac{M \cos\theta}{4\pi\rho D^2}$$

Since, D cos $\theta = R$, On implementing for D in the above expression., we get,

$$T_\theta = \frac{M \cos^3\theta}{4\pi\rho R^2}$$



So that, the thickness of the deposition is varying from the point just above the source to its edges. The relative variation of the thickness from the center of the substrate 'O' to the point 'P' at an angle θ to the normal joining the source and the center over the substrate surface is given by,

$$T_\theta / T_0 = \cos^3\theta$$

9.1.1. (A) Distribution of the mass over the Plane Substrate

So that, the evaporation from a point source situated bellow the center of the plane substrate forms a non-uniform coating over it following the inverse square law and cosine law.

Finally, the thickness of the film at a point over the substrate surface is limited by

1. The volume of the material is to be evaporated "V"
2. The normal separation between the surface of the substrate and the source "R"
3. The cube of Cos angle θ

i.e., $T \propto \frac{1}{R^2}$

& $T \propto \frac{M}{\rho}$ (or) V

& $T \propto \cos^3\theta$

Where the thickness of the film decreases rapidly by a factor $\cos^3\theta$ form the center of the substrate to its edges, as a result a non – uniform deposition is forming over the surface of the substrate. However the, substrate must be cooled in order to condense the evaporated molecules on their first impact with the surface.

9.1.1. (B) Example: Gold Plating over a Plane Substrate

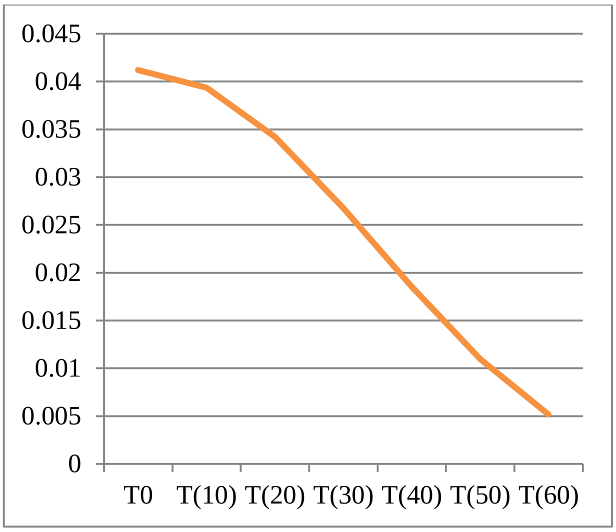
Let us suppose 10 grams of gold is to be plated over a plane substrate of 10 X 10 cm^2 in size and is situated above the point source (located normally bellow the center of the plane substrate) at a normal separation of 100 cm.

Substance used for the formation of thin film is	:	**Gold**
Mass of the evaporating material in grams is	:	10
Density of the evaporating material in gr/cc is	:	19.3
Normal separation b/n source and substrate in cm is	:	100
Evaporating rate of the material in gr/sec is	:	0.01
The volume of the material is to be evaporated in c.c is	:	0.518
Total time required for the evaporation in sec. is	:	1000

Thickness of the gold film so formed over the surface of the plane substrate in ^{0}A is

The thickness of the film decreases rapidly by a factor $cos^3\theta$ form the center of the substrate to its edges, as a result a non – uniform deposition is forming over the surface of the substrate as shown in the chart 2.

Example: at the center of the substrate 0.041215 ^{0}A while at 60^0 w.r.t. source it is 0.005166 ^{0}A



θ	Thickness of the film in ^{0}A	T/T_0
0^0	0.041215	1
10^0	0.039367	0.955157
20^0	0.034206	0.82993
30^0	0.026782	0.649818
40^0	0.018544	0.449934
50^0	0.010963	0.266005
60^0	0.005166	0.125345

Chart 2. Thickness of the gold plating over spherical substrate from 0^0 to 60^0 from the center w.r.t to source

10. Challenges in PVD - Techniques

The challenging and more exciting frontier in PVD is that the deposit should fallow a specified thickness distribution over the substrate surface, i.e., it may need to be uniform or non-uniform over a plane or curved substrate surface as required. But the distribution of solid film over the substrate surface is limited by the source-receiver geometry and the emission characteristics of the source, viz., the shape of the receiving surface, the arrangement of the vapour source or sources relative to the receiving surface and evaporation takes place uniformly or non-uniformly in all directions or if there are any preferred directions.

11. CONCLUSION

O'Brien and Russell deposited evaporated coatings of continuously varying density onto a plane receiver by interrupting the vapour stream with a rotating sector disc, whose profile was cut in the form of Archimedes spiral. The source must be sufficiently far from the receiver to provide a uniform film with the disc removed. The disc should be moved at a constant speed of 60 rpm and the evaporation rate is adjusted so that 2 or 3 minutes is required to form a deposit. The total number of vapour atoms striking any given zone on the plate will be directly proportional to the distance of the zone from the origin of the wedge. So that the optical density measured along the radius of the plate should be linear. O'Brien found that aluminum wedges above a critical thickness exhibited a uniform change of optical density for wavelengths between 2200A0 to 6000A0.

Strong has used a rotator sector plate for providing graded aluminum deposition on a spherical surface so as to produce parabolic coatings.

"Our most exciting pivotal emerging is the design of a shutter introduced in between the source and the receiver rotating with uniform speed So that its profile covers the source to form a required solid thin film over a required substrate surface. For this we considered all the possible measures of solid distribution and thickness over the substrate surface, viz., source – receiver geometry and characteristics of the considered vapour source etc., such proposal will be discussed in detail in the foregoing papers".

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BIOGRAPHIES

- *Author name is Dr. Pelluri Rahi Ex- Assistant Professor in Cardinal Malula University – Kinshasa, Democratic Republic Congo PH: +91 9550870695.*
  E-mail: pellurirahi@gmail.com
- *Holds M.Sc{Tech} Instrumentation from Andhra University in 1991*
- *Having 26 Years of Lecturing experience in both Physics & Instrumentation and currently pursuing second Ph.D. program in electric engineering in Process Control at Hindustan University - Chennai, India.*

