An Evaporation System for Film Deposition Using Electron Beam Sources

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Abstract. EBPVD (electron beam physical vapor deposition) technique offers independence and freedom in control of microstructure and composition of the coating via manipulation of controlling process parameters such as pressure level, substrate temperature, gas content (in case of reactive evaporation), power (voltage, current) and evaporant composition. The process based on the above technique allows the production of films from a wide range of materials such as, metallic, dielectrics and semiconductors with relatively low deposition time. Though commercial coaters are available with transverse electron guns, their parameters are not negotiable. The design issues are not addressed in any literature. Some of the design issues and construction of an evaporation system will be presented in this paper. The evaporation system will be described in three parts, which consist of gun chamber, substrate chamber and specific accessories. The specific accessories correspond to substrate heater, substrate rotation, substrate holder maneuverability (heightwise), ion cleaning, film thickness monitor, crucible indexing and upstream/downstream pressure controller. Also the design issues related to the power source, which will energize the guns, will be presented in this paper.

1. Introduction
Electron beam physical vapor deposition (EBPVD) technology has infused a lot of confidence in developing many new coatings. The unique features and flexibility of EBPVD arises due to its controllability in variation of structure and composition of processed materials, low contamination and high packing density in deposits. Thus multilayer metallic/ceramic (oxide, nitride etc) coating can be easily formed using EBPVD. The led us to design and construct an evaporation system where metallic, dielectric and reactive coatings can be performed with desired quality. Reactive coatings need to be carried out at lower pressure in the range 1x10^-3 mbar to 1x10^-4 mbar. Therefore, the work chamber needs to be isolated from the gun chamber. The present work presents the design and construction of an evaporation system with electron beam sources for vacuum film deposition. Section 2 describes the evaporation system and some of the design issues. Section 3 deals with some experimental results. Section 4 concludes the paper.

2. Evaporation System
The evaporation system is described in two parts namely, evaporation chamber and chamber accessories. Evaporation chamber comprises of gun chamber and substrate chamber. These two chambers have been isolated through a bifurcation plate on which there are two beam emergence opening. It is a dual-gun system. Each emergence opening relates to each gun and it has to be
optimally sized so that the differential vacuum shall be maintained and the beam will come out of the opening unhindered. Chamber accessories correspond to film thickness and rate monitor, radiant substrate heater, ion cleaning system, gas feeding system, rotary substrate holder, upstream/downstream pressure controller, crucible shutter and crucible indexing. An overview of the evaporation system is shown in the Figure 1.

Figure 1: 15 kW dual electron gun based evaporation system

2.1. Evaporation Chamber
The evaporation chamber is a box type chamber of 750x750x1000mm dimension. The chamber is double walled and water cooled on all sides except the bottom plate. Through an isolation valve the hot water supply line is connected to the same water inlet for chamber baking purpose. All the feedthroughs for crucible water and gun power source are provided on the bottom plate. The mounting arrangement for substrate holder and the radiant heater assembly is from the top plate. The chamber has front opening door. This chamber has been divided with the help of a bifurcation plate into a gun chamber of dimension 750x750x250 and a substrate chamber of 750x750x750 maintaining a differential vacuum between the chambers. The enclosure for the gun chamber is not connected with the main chamber enclosure.

2.2. Chamber Accessories
In Figure 2 the chamber accessories are shown.
2.2.1. Electron Beam Source

Two guns, each with 10 kV, 15 kW rating, have been designed for electron beam source. The gun is mounted below the crucible. The filament is made of tungsten in helical shape. The beam is generated by thermionic emission from the filament and accelerated by the anode. The electron gun is immersed in ExB field with the help of extended permanent magnetic field. Therefore, the beam is bent by 270° and falls on the crucible. The desired magnetic field is achieved by Nd-Fe-B permanent magnet with suitable magnetic shunts. The magnetic field at filament tip is about 35 Gauss. The filament is floated at –10 kV. Electromagnets have been used to position the beam at the desired location and to sweep the beam across the evaporant surface by changing magnetic field. The electromagnets are placed in longitudinal and lateral direction around the beam emergence opening. By sweeping the beam over the evaporant surface, not only the evaporation rate is maximized, the uniformity in coating thickness can also be controlled.

Power supply used for the gun has low charge storage to ensure the occasional surge due to the breakdown of filament anode gap does not affect the electronic circuits. Such high voltage breakdown adversely affects the evaporation rate. To ensure that the deposition rate does not get affected, specialised electronic circuits have been used to reduce the potential at the cathode for a short length of time if flashover occurs. Sufficient protections have been incorporated so that the high voltage surges get bypass routes without affecting the control circuits.

The crucible is made of copper and it is water cooled and the molten evaporant is maintained inside to avoid contamination. The crucible assembly provides a turret type of source of evaporated material. The top copper hearth contains four pockets. The schematic of the gun crucible assembly is shown in the Figure 3.

2.2.2. Film thickness and rate monitor

The thickness monitor is based on a quartz crystal oscillator connected to a deposition controller module from Maxtek MDC-360C. The quartz crystal sensor is mounted in such a manner it is kept close to the substrate with proper tooling factor. The deposition controller provides the final thickness of the film and also the deposition rate. Through the deposition controller one can control the desired...
thickness using a programmable power ramp. When the desired thickness is achieved the shutter operation is performed through the deposition controller. In case of multi-layer coating the position control is activated through programming in the deposition controller thereby achieving the final composite thickness of the coating.

Figure 3: Gun crucible assembly schematic.

2.2.3. **Substrate heater**

This is a coil type heater integral with the substrate holder. It is in serpentine fashion with molybdenum tubular heater and is mounted behind the dome shaped substrate holder. The heater is supplied by 32 V, 6 kW power. The temperature range is controllable upto 600°C through a PID controller. The temperature is measured by a thermocouple wire fixed in the top base of the heater. Actual temperature on the substrate has been calibrated by mounting the thermocouple on the substrate. Heat shield is provided along the periphery of the substrate holder dome.

2.2.4. **Ion cleaning system**

Before carrying out the coating operation, the in-situ cleaning of the substrates are done through glow discharge using ion cleaning module. In order to avoid vapor shadow effect a sector bar has been mounted at the far end from the vapor source. A power source of 5 kV, 1A (variable) is used for glow discharge cleaning. The cleaning is done at 5x10^-2 mbar. This pressure is controlled through a downstream pressure controller by adjusting motorised throttle valve position and purging Argon gas into the substrate chamber.

2.2.5. **Gas feeding system**

During reactive coating, desired reactive gas is purged into the substrate chamber. Using an upstream pressure controller MKS-647B and mass flow controller MKS-1179A, desired pressure in the range of 10^-3 mbar to 10^-4 mbar can be controlled in the substrate chamber while maintaining the gun chamber pressure better than 5x 10^-5 mbar. A capacitance manometer senses the pressure of the substrate chamber to control using pressure controller.
2.2.6. Rotary substrate holder

A dome shaped rotary substrate holder is used for holding the substrate on which the coating is performed. The substrate holder rotates around a central shaft in the controllable range 1-5 rpm. The substrate holder, ion cleaning module and the substrate heater are an integral assembly. This assembly can be moved up/down over the height between the vapor source and the substrate holder in the range 300-500mm.

2.2.7. Upstream/downstream pressure controller

One capacitance manometer MKS-627B senses the pressure. If the requirement of pressure control is for ion cleaning purpose, the downstream operation takes place. In this case Argon gas of set flow is purged in the substrate chamber and the pressure is controlled through motorised throttle valve, which is at the roughing line. In case of reactive coating which is carried out at lower vacuum, the upstream pressure controller operates by adjusting the flow of desired gas.

2.2.8. Crucible assembly

The water-cooled copper crucible is designed to handle the beam power to be dissipated. The top copper hearth contains four pockets which is encased at the bottom by circular stainless steel flange. The cooling is done through the annular region. There is a cover plate on the top, which keeps only one pocket open at a time. The crucible assembly rotates by motor drive through an indexing mechanism to select the desired pocket in case of multilayer coating. Crucible shutter is placed above the vapor source. This is closed during the initial operation when there is a chance of material sputtering and also when the desired thickness is achieved by sensing through film thickness monitor. The shutter is operated pneumatically.

2.2.9. Vacuum system

The details of the vacuum system for the gun chamber and the substrate chamber have been narrated in another paper.

3. Experimental Results

After the system was constructed, individual module has been tested. First the vacuum testing has been done. The pressure of the gun chamber was 3x10^{-6} mbar and substrate chamber was 1.1x10^{-5} mbar. The major thrust of this system design was to maintain a good differential vacuum and beam shall fall on the crucible through the beam emergence opening without heating the surrounding. This has been found quite satisfactory through experimentation. The following table shows how much gas flow can be purged and what effect it will have on gun chamber pressure and substrate chamber pressure. We have dealt with two kinds of gases.

| Sr.No. | Gun chamber pressure (mbar) | Substrate chamber pressure (mbar) | Oxygen flow rate (sccm) | Nitrogen flow rate (sccm) |
|--------|-----------------------------|----------------------------------|-------------------------|--------------------------|
| 1      | 6.1x10^{-6}                 | 9.1x10^{-5}                      | 0                       | 2.49                     |
| 2      | 8.0x10^{-6}                 | 9.1x10^{-5}                      | 0                       | 5.70                     |
| 3      | 1.0x10^{-5}                 | 9.1x10^{-5}                      | 0                       | 9.73                     |
| 4      | 1.5x10^{-5}                 | 9.1x10^{-5}                      | 0                       | 13.80                    |
| 5      | 1.7x10^{-5}                 | 9.1x10^{-5}                      | 5.88                    | 11.62                    |
| 6      | 1.9x10^{-5}                 | 9.1x10^{-5}                      | 7.07                    | 12.52                    |
| 7      | 2.5x10^{-5}                 | 2.5x10^{-3}                      | 10.07                   | 14.48                    |
| 8      | 3.2x10^{-5}                 | 2.8x10^{-3}                      | 12.23                   | 17.12                    |

Table1: Differential vacuum data.

It shows that the gun can work reliably with extensive gas purging in the substrate chamber as per desired coating.
Now next experiment was to find beam trajectory so that the optimum beam emergence opening could be found and whether the beam falls on the crucible pocket (25 mm diameter) reliably at varying acceleration voltage. Since the radius of the bent beam changes with change in acceleration voltage, local electromagnetic field has been controlled to get the beam on the center of the crucible. In this regard a look up table below has been prepared so that one can set the electromagnetic field before drawing the beam on the crucible avoiding any damage to the crucible housing. This experiment has been carried out at low power. In the figure 4, it shows that the beam emerges from 18mmx15mm opening and falls on the crucible. In the Figure 5, trials at 7kV, 8kV, 9 kV and 10 kV are shown and they are at the center of the crucible. The parameters for these trials are tabulated in the Table 2.

Figure 4: Electron beam emerges from the right slot and falls on the crucible left.

Figure 5: Four samples showing beam impinging (about 5 mm dia) at the center of the crucibles corresponding to various acceleration voltages.
| Sr. No. | Acceleration voltage (kV) | Beam current (mA) | Longitudinal deflection current (A) | Lateral deflection current (A) |
|---------|---------------------------|-------------------|-----------------------------------|-------------------------------|
| 1       | 7                         | 165               | -0.20                             | -0.09                         |
| 2       | 8                         | 130               | 0.28                              | 0.08                          |
| 3       | 9                         | 160               | 0.64                              | 0.24                          |
| 4       | 10                        | 160               | 0.86                              | 0.46                          |

Table 2: Electromagnetic deflection parameters for beam to fall on the crucible center at different acceleration voltages.

4. Conclusion
In this work the design and construction of an evaporation system with electron beam sources for vacuum film deposition has been presented. The emphasis was on deposition of reactive evaporation. The scope for EBPVD is enormous. One can achieve desired coating using this system. The major design challenge for reactive coating using differential pumping has been met in this system. The experiment that has been carried out on this system for optimum electron beam trajectory will help reduce the system down time.

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6. References
[1] S. Schiller, U. Heisig and S. Panzer, “Electron Beam Technology”, John Wiley & Sons, New York, 1982.
[2] V. Hamza and G. S. Kins, IEEE Trans. On Electron Devices, p195,1967
[3] F. S. De Vicente, E. A. A Rubo, M. Siu Li, Revista Brasileira de Aplicacoes de Vacuo, v.23,n.1, 11-16, 2004
[4] Michael Gevelber, Bing Xu and Douglas Smith, “Improved rate control for electron beam evaporation and evaluation of optical performance improvements”, Applied Optics, 45, 7, March 2006.
[5] J. Singh and D. E. Wolfe,” Review - Nano and macro-structured component fabrication by electron beam –physical vapor deposition (EBPVD)”, Journal of Materials Science 40, 2005. More references