OVERVIEW

The Ion Beam Sputtering (IBS) process is known to produce the lowest scatter and lowest loss optical thin films. IBS films have numerous, significant advantages including: Near bulk density, highly repeatable and fully automated process control, very low absorption and scatter, and high laser damage thresholds. Additionally, IBS is an energetic deposition process, which leads to dense film morphology and improved film adhesion.1, 2

Because of these advantages, Ion Beam Sputtering is the coating technology of choice for precise, robust optical thin film coatings, such as very high-reflectors (T < 20ppm), steep filters, polarizers, and dichroic beam splitters. With suitable process controls and modeling tools, the inherent stability and repeatability of the IBS process lends itself to applications with difficult coating thickness control requirements, such as large optics with stringent uniformity requirements.

Because IBS process pressures (~ 10E-4 Torr) are lower than those of other coating technologies, such as electron beam evaporation and magnetron sputtering, we are able to develop deterministic mathematical models based on the (largely) ballistic trajectories of coating material as it forms the film on the substrate. Such models allow us to leverage the inherent precision of the IBS process and achieve coating thickness control on the order of a monolayer of material in certain circumstances.

In this paper we discuss the development and application of PPC’s VirtualChamber™ which is a sophisticated three dimensional mathematical model of the IBS deposition process. When coupled with shadow masking techniques, we utilize VirtualChamber™ to achieve precision spatial control of the IBS deposition process. We discuss the underlying assumptions of the model, which utilizes computational geometry algorithms to calculate the effects of the shadow masks, analogous to calculating highlights and shadows in a computer graphics animation. The shadow masks, developed using VirtualChamber™, are fabricated using CNC machining, a process facilitated in a production setting by synchronizing the coordinate systems of VirtualChamber™ with those of the CAD software being employed.

Finally, we outline three applications of VirtualChamber to precision manufacturing challenges drawn from PPC’s production and R&D work.

THE ION BEAM SPUTTERING PROCESS AND THE THREE DIMENSIONAL MODEL

*FIGURE 1* shows a simplified sketch of the IBS process, which takes place within a high vacuum chamber. A beam of ions (typically Argon) is produced by the Ion Source and is accelerated towards a sputtering target. Material (e.g. Ta) is sputtered off of the target and combines with the reactive gas (e.g. O2) to form a stoichiometric film (e.g. Ta2O5) at the substrate. In general the net deposition plume in the region of the substrate is highly non-uniform. In practice, one achieves coating uniformity by a combination of substrate rotation and shadow masking techniques.

PPC’s VirtualChamber™ (shown in *FIGURE 2*) has excellent agreement with experiment because it is a semi-empirical model which utilizes calibration data and captures essential real-world coating chamber attributes:

- The sputtering target is an extended emitter, and our film deposition occurs in the near field regime of this emitter. Each point on the substrate “sees” deposition over an extended range of angles θ.
- The sputter yield depends on ejection angle θ'.”
- The intensity from a given dA’ (surface area element in the target plane) along a given
The instantaneous deposition rate can be calculated for an arbitrary position within the coating chamber. The coating thickness is then calculated as the path integral substrate of the deposition rate equation.

A common planar substrate fixturing system is a planetary (dual) rotation system. The required coating thickness is achieved in this case with the use of a shadow mask which selectively blocks the coating material for a fraction of the substrates’ orbits.

In this case, the uniformity mask is often shaped like a willow tree leaf, as shown in FIGURE 4. We note that the three dimensional model is helpful, but not essential to solve this problem. The uniformity mask contour can also be determined by iterative empirical techniques and 2-d approximations well known to coating manufacturers.
When solving more challenging problems, such as coating uniformity inside steeply curved surfaces, the three dimensional VirtualChamber™ model becomes an enabling tool. In FIGURE 5 we show a deep concave lens where the radius of curvature is on the order of the diameter of the lens. In this configuration, and in the absence of any corrective mask, the coating is thicker in the center of the lens than it is at the edge of the lens, which is due to two competing effects: The center of the lens is further from the sputter source than the edge of the lens, which makes the coating at the center of the lens comparatively thinner, however the average incident angle of the coating material at the edge of the lens is relatively greater, which makes the coating at the edge of the lens relatively thinner.

The net effect is calculated in VirtualChamber™ and is shown in FIGURE 5 (bottom). In the case of a 2.54cm diameter lens, with a 10cm radius of curvature, the net coating shift is on the order of 0.5%. Depending on application and customer specifications, even this relatively small level of coating non-uniformity may require correction with the use of precision shadow masks, developed in VirtualChamber™. For an example optical coating such as an anti-reflective coating at 633nm, the total coating thickness is on the order of 200nm. Therefore our model is giving predictions on the order of 0.5nm, which is at the level of a monolayer in average coating thickness.

In FIGURE 6 we show a more extreme case of a deep concave surface, which is a tangent ogive missile nose cone, positioned within a coating chamber and is configured for coating the interior dome surface. In this case there are more significant challenges, such as the presence of glancing incidence coating trajectories relative to the steeply curved surface, as well as the fact that the dome shape ‘self- shadows’ some of the coating trajectories.

To address these challenges, we utilize PPC’s VirtualChamber to calculate the 3-d effects of the shadow masks, and of dome self shadowing by incorporating computer graphics algorithms analogous to those used for calculating highlights in a computer generated animation, as illustrated in FIGURE 7.
FIGURE 7. (top) An example coating ray being deposited on the interior dome surface. (bottom) An example of dome self-shadowing: The coating ray is blocked by the dome’s exterior. This ray is ‘self-shadowed’ and does not contribute to the interior coating thickness.

In the case of the tangent ogive dome we calculate the ratefield at the interior surface of a 3-d ogive curve as shown in FIGURE 8. The resultant ratefield can be specified conveniently by the Z/Phi coordinates (i.e. cylindrical coordinates) along the interior dome surface.

VirtualChamber™ allows us to optimize the configuration of the dome within the coating chamber, and provides a tool for developing the shadow masking required to achieve the customer’s thickness profile specifications. The contours of the shadow masks are conveniently exported to CAD software, such as SolidWorks, for detailing and subsequent machining, a process greatly facilitated by synchronization of the coordinate systems of VirtualChamber™ with those of the CAD model.

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REFERENCES