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Spatial control of thin-film thickness through fundamental system design and analysis

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ABSTRACT

Thin-film nonuniformity is a fundamental, systematic error present in optical coating systems which leads to limitations on substrate sizes, reductions in capacity, poorer production yield, and other associated issues. Fundamental system design principles, based on source distribution and substrate mounting/motion profiles, can provide significant control over thin-film uniformity. Such an approach greatly improves the overall deposition performance, enabling deposition systems to provide both uniform and prescribed non-uniform film thickness profiles very accurately.

INTRODUCTION

The subject of uniform and intentionally non-uniform thin-film deposition has been considered for many years,[1-3] with the fundamental approach largely unchanged. The deposition source distribution must be characterized, the source(s) placed appropriately in the coating chamber, and the substrate position and/or motion profile must be optimized in order to best distribute the coating over the desired optic aperture.

The degree of precision and, by extension, attention to detail largely determine the expected performance of a coating system configuration. Placement of sources may be optimized for a general source, or specific to a coating material with a defined deposition process. Substrate rotation may be approximated to perfectly average the deposition with a given motion profile over infinite time, or real-world deposition times, deposition-rate fluctuations, and motion systems can be considered.

In this work, the current state of thin-film uniformity modeling and optimization is reviewed. Deposition source placement and basics of symmetry are considered, together with substrate rotation and the concerns of planetary rotation construction. Highly uniform performance is possible when the system design and fabrication is adequately addressed.

DEPOSITION SOURCES

Deposition sources can be broadly characterized based on a radiation/illumination approach, with a surface source description being the primary source type. This approach allows the thickness distribution from a deposition source to be characterized as a function of the departure angle from the surface, as given by:

$$t(\theta) \propto \frac{cos\theta}{r^2} \quad , \qquad (1)$$

where θ is the departure angle from the deposition source, and r is the distance from the source to the substrate (or detector). Point sources can be characterized without an angular dependence, since flux is equal in all directions. This yields a characterization of

$$t(\theta) \propto \frac{1}{r^2} \quad . \qquad (2)$$

The distribution of real sources can then be quantified using a combination of the two expressions, based on the actual geometry. As shown in Fig. 1 below, a traditional electron-beam melt, crucible of material under a filament, or a near-circular resistance source boat can be described as a surface source. Meanwhile, a boat with extended length, a cylindrical coil filament, or a cylindrical magnetron incorporates surface-source distribution in 1 direction, while behaving as a pseudo-point source in the other direction.

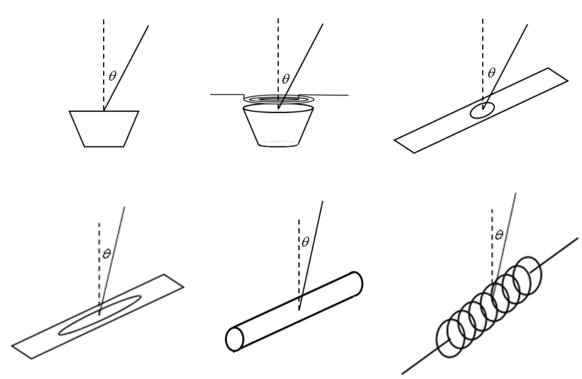

Figure 1 – Shapes of deposition sources and the influence on the distribution profile. The top row are nominally surface sources with circular symmetry. The elongated sources in the bottom row exhibit point-source-like behavior about the long axis, while exhibiting an additional cosine dependence along the length of the source.

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More-complex approaches are required to adequately describe the distribution from planar sputtering targets, particularly due to the spatial variations in flux from differences in the plasma, magnetic field, ion-beam shape, or other features. As a first approximation, an extended deposition source such as a sputtering target can be described as the integration over the target surface of the cosine distribution.[4] Since large-area sources can be viewed as integrations or summations of a series of smaller sources, source placement for extended sources can be determined using the relative distribution of the various source positions.

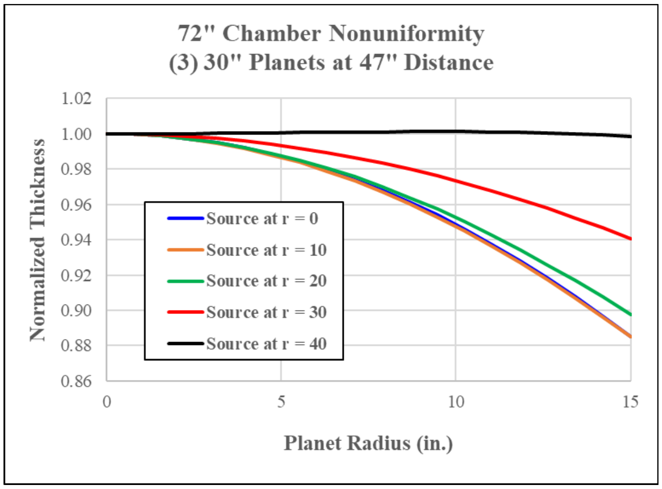

Figure 2 – Distribution from a theoretical electron-beam evaporation source (surface source) in a planetary rotation system. The uniformity improves significantly for source placements near the perimeter. Extended sources should be placed such that there is an averaging effect over acceptable distribution regions, likely resulting in the source being placed tangentially in the system, rather than radially.

SUBSTRATE MOTION SYSTEMS

The primary purpose of a substrate motion system is to provide improved thin-film uniformity. As such, the benefits of each type of substrate motion must be weighed relative to that goal, and inherent limitations of a given configuration should be carefully evaluated to determine if the use is justified.

The most basic motion system for optical coating is simple rotation about a vertical axis at chamber center, with the deposition source(s) placed on the chamber floor. The source-to-substrate distance *h* and radial placement *r*, together with the precise source distribution, determine the thickness distribution of the coating over the substrate fixture. The fixture can be sectioned for smaller substrates, domed to improve the distribution over the fixture, or formed in a pyramidal shape, with a series of planar sections holding parts to be coated at an inclined angle. The various types of simple rotation are summarized in Fig **3**. It is apparent that the flat fixture has the least capacity, but with the potential for the greatest size optic to be coated. The dome and the pyramid both present opportunities for greater capacity, but typically with a deviation from the symmetry imposed by the fixture; the dome assumes sufficiently negligible deviation of the optic surface from the perfect symmetry of concave optics matching the dome curvature, while the pyramid is based around a cone formed by rotating the centerline of a section about chamber center. As a result, such fixtures have inherent, systematic film nonuniformity that should be quantified and addressed in the process development.

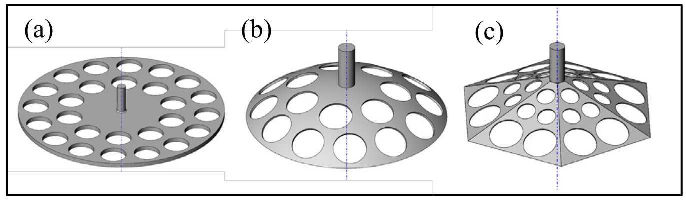

Figure 3 – Substrate motion systems primarily involve rotary motion for coatings deposited using batch processing. (a) Single-axis planar rotation is the simplest form, providing reasonable capacity for low-curvature optics. Substrates with significant curvature should be centered on the rotary axis. (b) Domed single-axis rotation attempts to better match the distribution from the source while providing somewhat greater substrate capacity; departure of the substrate shape from the concave profile of the dome result in systematic nonuniformities that cannot be corrected. (c) Pyramidal single-axis rotation can lead to significant departure from a symmetrical cone shape, resulting in large, uncorrectable nonuniformities.

Planetary rotation systems involve the use of dual-axis motion, in order to both rotate and revolve a substrate holder about chamber center. In general, the substrate holder, or planet, moves in a plane with a stationary and rolling gear coupled to induce the second degree of motion. As detailed in prior work[5], the chosen gears should have no common factors, with a non-integer solar gear: planet gear ratio of the order of 3 - 5, and no near-repetitions for 10+ revolutions. The path of a point in planetary motion can be tracked over multiple revolutions to confirm the system is appropriately geared. As shown in Fig. 4a, the gear ratio may be used to achieve an evenly distributed sampling of the vapor plume in the coating chamber, while Fig 4b demonstrates how a minor gearing change can poorly sample the chamber spatially (modeled for the same number of revolutions). Proper selection of planetary gears is critical for uniform distribution of an optical coating, with any near-repetitions of the planetary gearing potentially patterning the deposited film.thickness.[5] The rotation must also be constructed to limit angular planet error, planet height error, and tilt of the overall rotation fixture[6]; errors in planetary fabrication can lead to significant issues in the realized film distribution, with substantial impact on the overall system performance.

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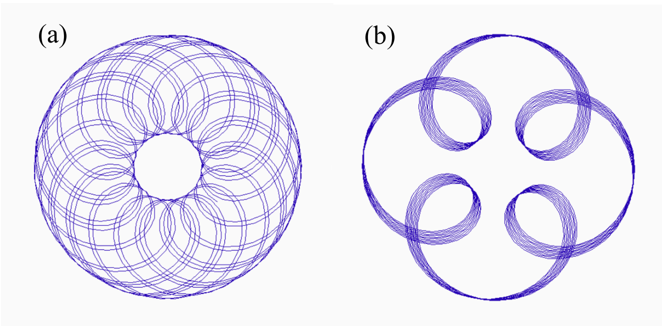

Figure 4 – Tracking of a point undergoing planetary rotation shows the impact of gear ratio selection. (a) A solar:planet gear ratio of 277:65 yields a pattern in the vacuum chamber that is relatively evenly distributed, while (b) a ratio of 277:69 leads to paths through the chamber that concentrate in one area. Uniform motion and sampling of the vapor plume leads to a more uniform deposition process.

Planetary rotation concepts can be used for curved optics of various types, including traditional lenses, parabolics, hyperboloids, cones, and other more complex surfaces. Since a properly constructed planetary rotation will exhibit axial symmetry about the planet center, large substrates with significant deviations from planar should be mounted in a symmetrical manner with the rotation motion. Smaller substrates, which may not be practical to coat in this manner, may require more-advanced motion profiles such as the use of tilted planets.[7]

Planetary motion concepts have been extended beyond the traditional design in order to attain other goals. The use of a counter-rotating planetary[8] increases the capacity for large, oblong optics which cross chamber center by 100% (2 substrates versus 1 per deposition). The VPT *Gyro* rotation[9] enabled uniform deposition on large-aperture substrates approaching the size of the coating chamber. The recent development of the VI *Lunar Rotation*[10] provides precise control of uniformity over mid-sized, steeply curved substrates as shown in Fig. 5.

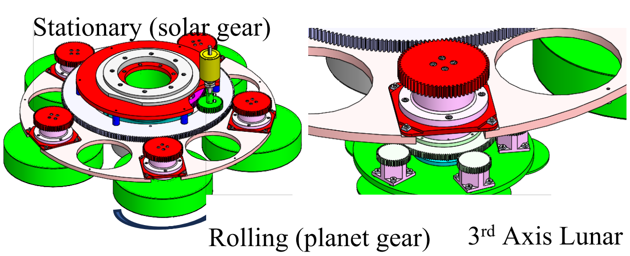

Figure 5 – The Vacuum Innovations' *Lunar Rotation* accessory implements axially symmetric coating for multiple mid-sized optics in place of a standard planet in the planetary rotation system. By implementing a 3rd axis of rotary motion, each substrate can be coated in an axially symmetric manner with precise uniformity control.

Other substrate motion systems are commonly used for other deposition methods, including:

1. Scanning system – linear motion of the substates past one or more deposition sources. This is particularly well suited for high-throughput sputtering systems,
2. Drum coating – array the sources along a line inside, outside, or on both sides of a rotating cylindrical substrate holder, enabling deposition on one or both sides of many substrates.

Care must be taken to ensure that the principles of symmetry, deposition angles/distances, and curvatures are appropriately addressed. For example, deposition with a drum coater can lead to large nonuniformities for wide substrates, since the substrate is then deviating significantly from the symmetry of the cylindrical substrate holder.

UNIFORMITY

A fundamental evolution in the understanding of thin-film uniformity has been strongly influenced by computerized approaches to calculation; past work[11] has often relied on integration over a substrate path, as well as over the extent of a source. Planetary rotation systems have been assumed to sample regions of the vapor plume in a continuous, infinite fashion, rather than imposing deposition-time limitations together with discrete, gearing-induced paths through the vapor flux.

Numerous corrections have been evaluated to the traditional models of deposition uniformity, with varying impact on the practical deposition of optical coatings. The impact of the discrete nature of planetary gearing was documented by Baumeister,[12] with the understanding that the number of teeth on the planet and solar gears should have no common factors, as this would reduce the number of potential paths through the vapor plume by that number. The impact of gearing choices and approaches to mitigate the negative impacts on film distribution were significantly extended,[5] based largely on the available measurements using high-resolution uniformity mapping.

There are some key issues to incorporate in the overall understanding of thin-film nonuniformity:

1. Different source materials, and the condition of the source (size, sweep, shape, depletion, form, etc.), impact the film distribution. Therefore, multilayer coatings will typically have differing film distribution for different layers.
2. The uniformity parameter of interest is optical thickness, however materials will usually exhibit differences in refractive indices over the extent of the substrate holder and throughout the coating chamber. Coating uniformity is often a compromise of offsetting changes in film thickness and refractive index, such that the optical thickness remains approximately constant.

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3. Consideration of non-physical extremes (i.e. infinite rotation, perfect deposition rates, source distribution with perfect symmetry) may help inform ideal system uniformity, but limitations must also be used to understand expected performance. This will limit the allowed error due to nonuniformity to a much greater degree.

VAPOR MASKING

In treating the deposition of a coating as a radiation source, the vapor path can be considered as a line-of-sight characteristic. This permits the use of shadow masks to alter the distribution, by blocking regions with excessive flux in order to balance against those with too little flux.

Mask mounts should be precise and provide accurate placement of the mask with respect to its theoretical/designed position. The system should be built such that removal for maintenance activities still allows the mask to be re-installed in the same location. Since the purpose of a mask is to cast a shadow in the deposition vapor on the substrates, the configuration is much more stable if the mask is as close as possible to the substrates, since the shadow moves less as a function of the source position, which necessarily varies due to electron-beam sweep or material depletion.

Uniformity mask profiles are intended to smoothly reduce the concentration of flux in some regions of the deposition, while maintaining maximum flux in others in order to optimize the efficiency of the deposition process. Optimal deposition performance will be achieved if the transition is smooth, with no sharp discontinuities in the deposited film thickness; as a result, the mask profile should be a continuous, smoothly varying profile throughout the deposition region. If the mask must stop or start within the coated aperture of the substrate, the transition in shape should smoothly approach zero width and/or the width of the mask mount.

Uniformity masks can also be used to induce intentional nonuniformity in deposited films. Non-uniform thickness profiles have been used to compensate film stress,[13] yield graded film profiles, and even provide steps in physical thickness on the substrate surface.[14] Masks have been used to correct surface flatness of substrates[15] and can potentially be used to realize layer-by-layer nonuniform coating performance, given the ability to change masks *in situ*.

CONCEPTS IN SYSTEM DESIGN

These concepts can be used in a systematic approach for the design and optimization of a coating system, in order to yield a high-performance, prescribed thickness distribution over substrates of various shapes and sizes. As shown previously for a 54-in. coating system, configurations for the use of ≤ 3 large planets perform better if the sources are arrayed near the chamber walls; while there is a significant penalty for source efficiency, the improved uniformity and control make such a sacrifice worthwhile.[6] Conversely, sources should be located near chamber center for larger numbers of small planets, describing an annular region nearer the chamber walls. Examples of such source configurations are shown in Fig. **6**.

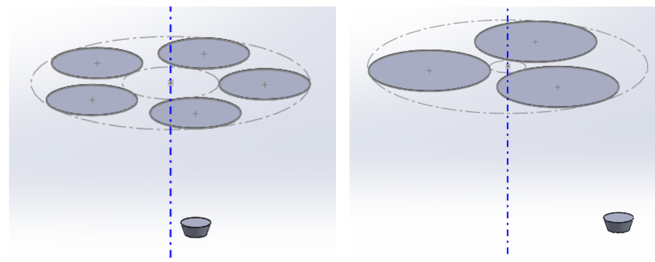

Figure 6 – Standard planetary rotation leads to the planets describing an annular region throughout their motion. (a) Larger quantities of smaller planets create a narrower annulus, leaving a central region unused in the chamber; sources near chamber center are preferred for efficient, uniform distribution. (b) Fewer large planets leave more of the chamber unused near the outside of the chamber; thin-film uniformity is improved (though with reduced efficiency) if the sources are located near the perimeter.

The relative benefits of any configuration should be established based on the types of coatings to be deposited. Complex coatings requiring precise control of layer thicknesses cannot be deposited successfully without the appropriate care in system configuration. There will likely be a cost in substrate-loading and material-usage efficiency, and there may be impacts based on realized refractive indices and other factors, but the system must be configured in a manner to achieve optimal control of film properties in order to achieve the highest performance coatings.

CONCLUSIONS

A quantitative, analytical approach to thin-film thickness distribution enables the construction of high-performance coating systems. Careful characterization of the source distribution based on its geometry, deposition material, and coating process can yield a well-defined flux distribution for use in modeling the overall film-thickness profile. Establishment of geometrical symmetry within the system for source placement and substrate mounting/motion profiles is essential for the precise deposition of multilayer, multi-material coatings, since the materials often make use of multiple, spatially separated deposition sources. Substrate motion must properly consider numerous details, including:

- the accuracy of mounting and fixture motion
- the discrete nature of geared motion

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- the finite nature of layers with respect to rotation speeds
- the harmonic nature of substrate motion, and its potential to beat with other oscillatory aspects of the deposition process

These aspects of system design are particularly important when addressing complex, large-aperture coating requirements for optical systems for aerospace, defense, and laser applications.

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