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High-volume, cost-effective uniform deposition for flat and curved optical surfaces

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Introduction

Many coating applications require excellent uniformity with respect to their physical properties. These can include thickness, refractive index, optical thickness, and resistivity among others. There are well-known methods for achieving this uniformity for substrates with flat surfaces, including evaporation, ion beam sputtering, and planar magnetron sputtering. These physical vapor deposition (PVD) methods all have their own advantages and tradeoffs, but all require masking or complex motion (or both) and none of them are capable of coating curved surfaces with similar uniformities. By using inverted cylindrical magnetron (ICM) technology, almost all of the drawbacks can be overcome, masks are eliminated, and similar results are obtainable on both flat and curved surfaces. This opens up many new thin film coating applications, especially for high-volume curved surfaces such as curved mirrors and ball lenses for Photonic Integrated Circuits, rod lenses for LiDAR, and EUV/lithography/instrumentation precision optics and domes for aerospace and defense applications.

A comparison of these methods is shown in Table 1. Evaporation, both thermal and e-beam, is a well-known method for obtaining highly uniform flat films. Films with thickness uniformity specifications below +/-0.5% are readily achievable. This is done through dual rotation substrate motion (e.g. "planetary" motion) into and out of the deposition plume, and subtractive masking of the deposition plume to shape the deposition profile. Multiple planets are used, so the plume is always depositing on substrates as they rotate in and out of the deposition zone. This is inherently a batch processing solution, with long wait times for pumpdown/vent. It is not very scalable or compatible with standard automation, so it remains relatively labor intensive and results can be limited by the skill of the operators. This is not particularly compatible with high-volume manufacturing requirements.

Ion beam sputtering (IBS) can also achieve excellent uniformities. This is done by rastering the substrate through a relatively small monoenergetic deposition beam. Only a small area is coated at a time, so the effective deposition rate is inherently low. Planetary motion and substrate tilting can be used to optimize uniformity. IBS can be compatible with standard semiconductor automation, but the main drawbacks are the equipment expense and deposition rate. The deposition rate is low enough that adding automation does not provide much benefit to throughput or labor reduction.

Planar magnetron sputtering is also used to produce highly uniform films. This is typically done by a combination of subtractive masking, and restricting the deposition zone to a small highly uniform section. The smaller the section, the better the uniformity. Magnetron sputtering is generally very repeatable and compatible with standard semiconductor automation, so it is well suited for high-volume manufacturing, but small useable areas limit its overall productivity for highly uniform optical films.

Curved surfaces present special challenges. In general, due to different deposition angles at different points along the curved surface, a thicker or thinner film will be deposited. Complex, slow substrate motion is required to counter this effect, and in practice is little used. CVD methods are applicable to curved surfaces, but the material sets available are limited, and many of the precursors are hazardous chemicals. For coating facilities not already set up to mitigate these chemicals, this can be a very expensive solution.

Table 1. Overview of standard thin film PVD techniques

Process	Material	Uniformity	Impurity	Film Quality, Density & Adhesion, Stress	Deposition Rate	Temperature	Directionality	Scalability	Cost / Complexity
Thermal resistive evaporation	Low melting point, typically metals	Poor, excellent w/ planetary & masks	High	Poor, improved w/ ion assist, moderate stress	< 50 A/s	50° – 100°C	Good	Limited at reduced utilization & deposition rate	Very low
E-beam evaporation	Metals & dielectrics	Poor, excellent w/ planetary & masks	Low	Poor, improved w/ ion assist, moderate stress	< 100 A/s	50° – 100°C	Good	Limited at reduced utilization & deposition rate	Moderate / moderate complexity
Planar magnetron sputtering	Metals & dielectrics	Good, improvement difficult & costly	Low	Very good, moderate to high stress	Metals: < 100 A/s, dielectrics: 1 – 10 A/s	200°C Typically requires cooling	Low, improved w/ system geometry	High w/ automation	High / moderate complexity
Ion beam sputtering	Metals & dielectrics	Excellent	Very low	Excellent, high stress	1 – 2 A/s	Low	Excellent, controlled	Low	Very high cost & complexity
Inverted cylindrical magnetron sputtering	**Metals & dielectrics**	**Excellent**	**Low**	**Very good, moderate to high stress**	**Metals: < 100 A/s, dielectrics: 1 – 10 A/s**	**200°C Typically requires cooling**	**Low, improved w/ system geometry**	**High w/ automation**	**High / moderate complexity**

Technology selection considerations • Capex • Yield • Throughput • Film Quality

With ICM sputtering, the advantages of planar magnetron sputtering (repeatability, scalability, large number of coating materials available) are maintained, while the weaknesses (low productivity for high uniformity, inability to coat curved optics) are overcome. With ICM, instead of sputtering down or up, these cathodes sputter from the inside of the cylinder with the substrate sitting in the center, so the sputtering direction is completely inverted. The substrate position can be adjusted and rotated in a conventional dual planetary motion to achieve excellent uniformity on substrates with curved surfaces or 3D shapes.

System Description

The ICM Cathode

The results shown below were produced using systems with one or more inverted cylindrical magnetron (ICM) cathodes. Each cathode has two electrodes that are driven with mid-frequency AC power, as shown in **Figure 1**.

ICM cathodes are available in a number of sizes, depending on application requirements. For optical films, reactive sputtering is used to deposit optically transparent films, both oxides and nitrides. Metal targets with inside diameters of up to 400 mm and heights of up to 100 mm fit into each electrode. Typical materials are silicon, titanium tantalum. Sputtering is done with the target surfaces completely oxidized (the fully poisoned mode) in order to work in a stable part of the hysteresis curve. The process gases are introduced above the cathodes, which operate at similar sputtering pressures and powers as planar magnetron sputtering.

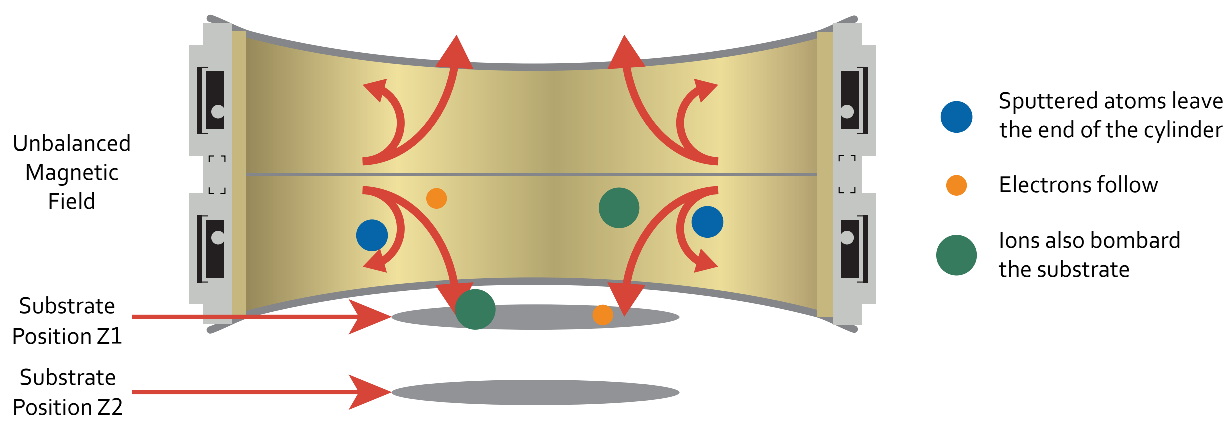


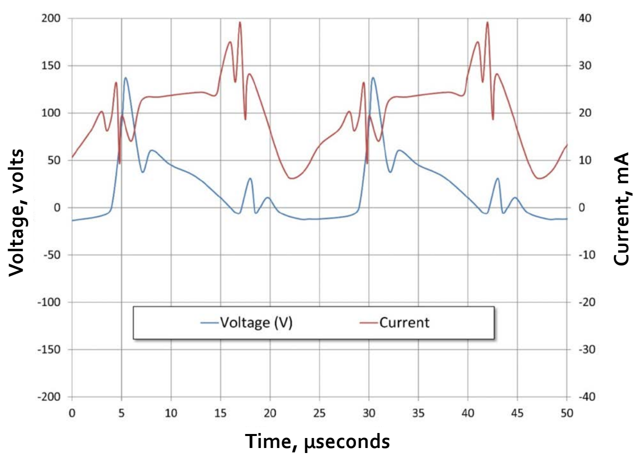
Figure 1. Cutaway view of a cathode showing the unbalanced magnetic field and off-axis substrate configurations.

Figure 1 shows two alternative substrate locations, referred to as the z position. Thickness uniformity on substrates with different curvatures is controlled by simply adjusting the z position of the substrate holder.

Ion Assisted Deposition without an Ion Source

The ICM cathodes incorporate unbalanced magnetic fields, as illustrated by the arrows in **Figure 1** [1,2]. A very important consequence of this magnetic field configuration in combination with mid-frequency power is that significant ion production occurs when secondary electrons cross the field lines as they flow to the instantaneous anode [3]. In addition, secondary electrons can move easily along the unbalanced field lines, represented by the large arrows extending out the ends of the cathode, and they produce a significant negative self-bias on the substrate. The self-bias and high ion density result in a low energy ion flux of approximately 2 mA/cm^2 that bombards the growing film [2]. This is similar to the ion fluxes found in other ion enhanced deposition systems, but without the need for a separate ion source.

Floating Potential Ion Current



- Floating potential V peaks when adjacent target becomes anode
- Ion flux = 1.2 X 10^{16} /cm²s
- Ion flux comparable to other ion enhanced processes

Glocker et. al., "Inverted cylindrical magnetron sputtering of optical coatings," 57th Annual SVC Technical Conference Proceedings, 2014, 233-238.

There are several additional advantages to the cathode design and off-axis configuration. Because the substrates do not face the targets directly, they are not bombarded by high energy reflected neutral atoms and negative oxygen ions formed at the target surface, which are known to produce high levels of stress in sputtered coatings. For the 400mm diameter configuration, the total target area in each cathode is 2,500 cm² so that cylindrical targets that are only 2 mm thick provide the same material inventory as a 25 cm diameter by 1 cm thick conventional circular magnetron. The much shallower erosion grooves that result with thin targets have a minimal effect on the sputtered material distribution over the target lifetime. Finally, the large target area permits operation at power densities of 3 W/cm² or less, which virtually eliminates arcs and microarcs that are sources of particulates that can get entrained in the coatings.

Film Properties

A number of optical materials have been characterized in the ICM cathode. Rates, refractive indices, and power densities are shown below for some typical materials.

Material	Power Density	Deposition Rate	Index (632 nm)
Ta_2O_5	2.4 W/cm²	1.8 Å/s	2.14
SiO_2	1.2 W/cm²	2.5 Å/s	1.47
TiO_2	1.8 W/cm²	0.5 Å/s	2.54
Si_3N_4	0.8 W/cm²	2.3 Å/s	2.05

Thickness uniformity is dominated by the Z height under the cathode. Uniformity can be further enhanced by adding substrate rotation. This can be centered single axis rotation, offset single axis rotation, or dual axis rotation. Dual axis rotation has been demonstrated for substrates up to 51mm diameter.

As previously mentioned, for curved optics, excellent uniformity is obtainable by adjustment of Z height. Single film uniformity for both flat and curved optics is shown below.

Single Layer Uniformity Summary

Substrate Shape	Diameter (mm)	RoC (mm)	Motion	Thickness Uniformity
Flat	51	-----	Dual Axis	± 0.1%
	100	-----	Single Axis	± 0.3%
	200	-----	Stationary	± 0.5%
	250	-----	Stationary	± 1.5%
Convex	51	50	Dual Axis	± 0.3%
	51	100	Dual Axis	± 0.15%
	51	200	Dual Axis	± 0.15%
Concave	51	50	Dual Axis	± 0.5%

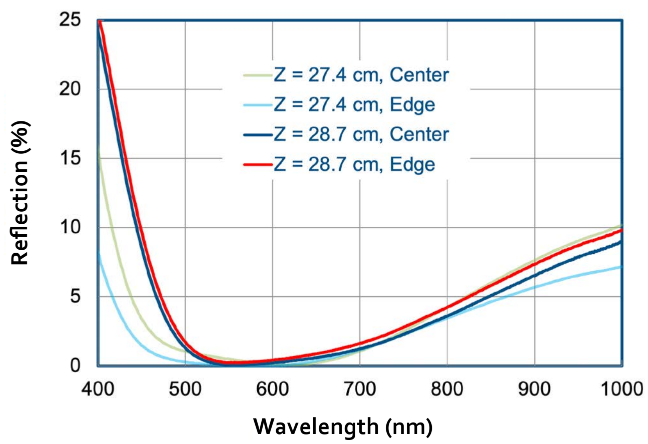
Recent results have also been demonstrated on a 100mm hemisphere similar to the image below. Comparing apex to edge, the thickness uniformity is below +/- 2%. This was achieved using single axis rotation only. There is simply no other practical way to achieve such results using PVD methods.

Similar results have been demonstrated for multilayer coatings. The chart below shows the effect of Z height on a 4-layer anti-reflection coating deposited on a 50mm radius of curvature plano-convex lens. The similarity in reflectance at Z=28.7cm between the center and edge measurements shows remarkable consistency.

Effect of Z Position on AR Coating Uniformity

51 mm Diameter by 50 mm RoC Plano-Convex Lenses

Coated at Z = 27.4 cm and Z = 28.7 cm



Design

BK7	
Ta_2O_5	24.2 nm
SiO_2	35.7 nm
TiO_2	70 nm
Si_3N_4	106 nm

Measurements using Filmetrics F10 - AR

Conclusion

These results clearly show that an inverted cylindrical cathode configuration can provide excellent uniformity when depositing thin film coatings onto both flat and curved surfaces, without the need for masks or other process enhancements, such as an ion assist source.

To achieve best results for your application, you need to invest in a thin film deposition system that can be directly integrated with an inverted cylindrical cathode. Denton Vacuum’s magnetron sputtering system design is completely optimized for use with an inverted cylindrical cathode, giving you a proven, flexible solution for your application.

ICM cathodes are in production on a wide variety of applications. With Denton as your thin film deposition system partner, you will be able to coat complex or curved surfaces for optics, medical components, roll-to-roll precious metals, and many other applications. Our team of engineers can help configure an application-specific design that meets your exact specifications for real-world performance. Leverage our experience to address unique application challenges, like hard-to-coat substrates, high system flexibility requirements, and temperature limitations, with a streamlined solution.

We will help you optimize your process from end to end so you are not just meeting thin film requirements; you are ensuring specific application requirements are met while prioritizing efficiency and lowering your total cost of ownership.

References

1. D. A. Glocker and M. M. Romach, Unbalanced plasma generating apparatus having cylindrical symmetry, U. S. Patent No. 6,497,803, issued December 24, 2002

2. M. M. Romach, G. Scherer, J. Eichenberger, J. Lanzafame, D. Glocker, M. Jaszcar and B. Rayner, Inverted cylindrical magnetron sputtering of optical coatings, Proceedings of the 57th Annual Technical Conference of the Society of Vacuum Coaters, 233-238 (2014)

3. D. A. Glocker, M. M. Romach and V. W. Lindberg, Recent developments in inverted cylindrical magnetron sputtering, Surface and Coatings Technology, Vol. 146-147, 457-462 (2001)

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