

High Performance Optical Coatings Deposited Using Closed Field Magnetron Sputtering

D.R. Gibson, I.T. Brinkley, and J.L. Martin

Applied Multilayers LLC, 1801 SE Commerce Avenue, Battle Ground, WA 98604

ABSTRACT

Magnetron sputtering has many advantages over conventional evaporation processes for the deposition of oxides, transparent conductive oxides, photovoltaic layers, carbides and nitrides for various optical applications. The sputtering process is “cold”, making it suitable for use on the widest range of substrates including temperature sensitive substrates and polymers. Moreover, the drum format provide more efficient loading for high throughput production. In contrast to previous reactive DC sputtering strategies the Closed Field process does not require a separate ion or plasma source for activation. Neither does it require the vacuum chamber to be separated by vacuum pumps or baffles into deposition and reaction zones. Reaction occurs on the target and all the way round the substrate carrier resulting in low absorption. The use of the Closed Field and unbalanced magnetrons creates a magnetic confinement that extends the electron mean free path leading to high ion current densities. The combination of high current densities with ion energies in the range ~30 eV creates optimum thin film growth conditions. As a result the films are dense, spectrally stable, super smooth and low stress. This paper describes results for a wide variety of deposited films and use of an optical monitor for real time deposition control.

INTRODUCTION

Low loss optical coatings are used in a variety of applications including telecommunication DWDM filters, high laser damage coatings, narrow band/ edge filters for fluorescent microscopy and ring laser gyroscope mirrors.

Such coatings are usually deposited using plasma or ion assisted electron-beam evaporation although ion beam sputtering provides enhanced performance in relation to surface roughness and absorption.

However, ion beam sputtering has limited area coverage, high intrinsic film stress and low deposition rate. It has been reported previously [1, 2] that “closed field” reactive magnetron sputtering produces dense, low stress, spectrally stable metal-oxide optical coating material with refractive indices typically close to that of the bulk material. In this paper

we report new results that show CFM sputtering produces low stress, low loss thin films that are super-smooth with exceptional optical properties.

REACTIVE CLOSED FIELD MAGNETRON (CFM) SPUTTERING

The reactive closed field magnetron sputtering process was developed in 1991 by Teer [3] and has been used successfully for some time in the field of engineering coatings. Recently, the process control has been developed to enable sub-nanometer thickness precision [4, 5] for application to multilayer optical coatings.

The closed field process is illustrated schematically in Figure 1. The closed field configuration was developed to increase the ion current density in the plasma by arranging that neighboring magnetrons are of opposite magnetic polarity. Using this arrangement, the deposition volume in which the substrates are located is surrounded by linking magnetic field lines. This traps the plasma region, prevents losses of ionizing electrons, and results in significant plasma enhancement. The closed field system produces enhanced reactivity due to the high ion current density ($>1 \text{ mA.cm}^{-2}$). The ion energy is determined by the induced voltage on the substrate carrier which is typically in the range (20-30) eV. This combination of high ion current density and low ion energy produce ideal conditions for growth of optical quality thin films.

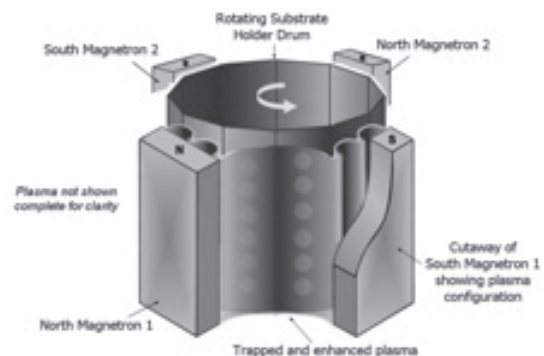


Figure 1: The “closed field” magnetron sputtering process does not need a separate ion source. Adjacent magnetrons are made opposite polarity to trap the plasma all the way round the drum. This ensures that all the metal deposited by the magnetrons is converted into metal-oxide.

During reactive oxidation in the closed field process, the oxygen is admitted into the unbalanced magnetron plasma. Target oxidation occurs but is controlled using target voltage control with feedback to the mass flow of oxygen. Surface charging is overcome by using pulsed DC power.

The key advantage of the process is that no separate ion source, plasma source or microwave ion source is required. Nor is it necessary to partition the working vacuum chamber into deposition and reaction zones. This simplifies the system, reduces cost, and improves reliability. It also makes it economical to scale the technology to virtually any batch size.

THE CLOSED FIELD MAGNETRON (CFM) SPUTTERING SYSTEM FORMAT

The thin film materials presented in this paper were deposited using a CFM450 system from Applied Multilayers LLC, and the system shown in Figure 2. It uses a 250 mm diameter vertical drum substrate carrier and up to four 405 mm linear magnetrons. The drum is divided into a number of segments on which the substrates are mounted. Access is made through a large hinged external door.



Figure 2: CFM450 coating system from Applied Multilayers LLC.

The distance between the magnetron and the segmented drum surface is 100 mm. Curved substrates are loaded behind apertures in the segment to ensure a reasonably constant average target to substrate distance.

The system used in these trials was pumped using a 2,000 liters/sec BOC Edwards Diffstak. A Meissner trap is used for rapid removal of water vapor and reduced pump-down times.

The system is also fitted with a rotating shutter to expose the substrate to the appropriate target. The shutter is also used to enable targets to be conditioned without exposure to the substrates. A schematic of the drum/shutter configuration is shown in Figure 3.



Figure 3: Drum/shutter configuration.

Optical monitoring can also be incorporated as shown in Figures 4a and b.

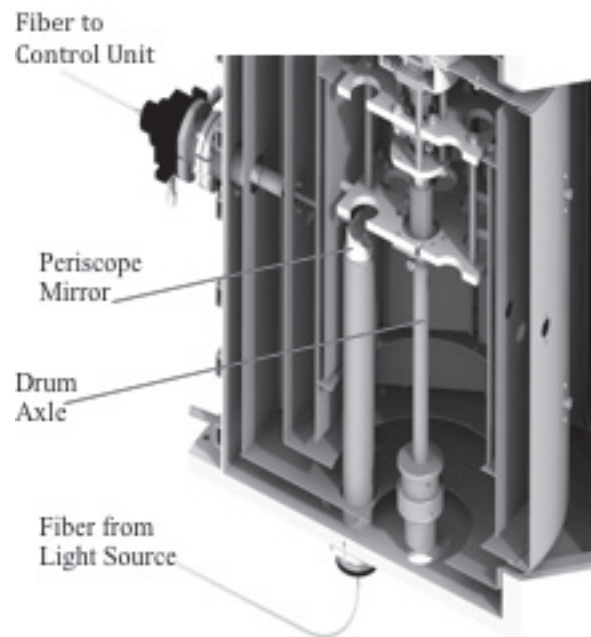


Figure 4a: Optical monitor light launch arrangement.

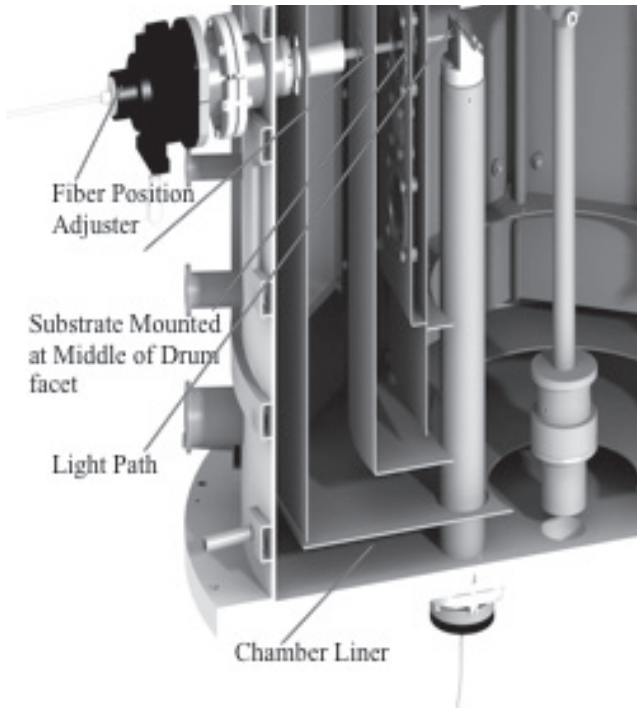


Figure 4b: Optical monitor light path through substrate.

OPTICAL

The trade-off between absorption coefficient (k) and deposition rate as a function of position on the hysteresis curve is shown in Figure 5 for niobia.

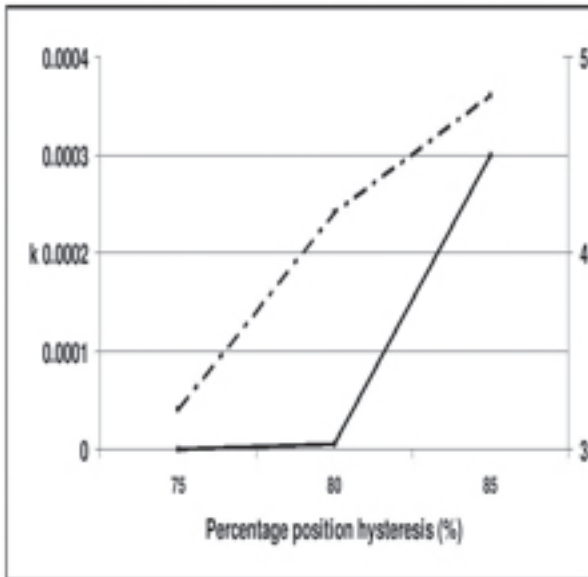


Figure 5: Niobia absorption coefficient and deposition rate as a function of percentage position on hysteresis curve.

Figure 6 shows a typical spectral transmission curves for silica in relation to position on the respective hysteresis characteristic.

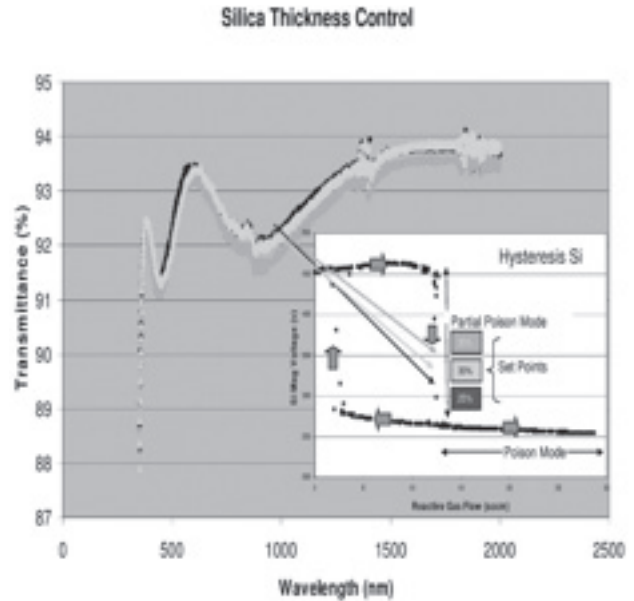


Figure 6: Spectral transmission control in relation to hysteresis.

Figure 6 illustrates automatic deposition rate correction to ensure accuracy of layer thickness control irrespective of target oxidation state. A transmission spectrum shows decreasing transmission (increasing absorption) as target is run in a less poisoned state.

However automatic deposition rate correction to achieve same deposited thickness is demonstrated through same minima and maxima positions on spectral transmission profile.

A table of the optical properties of the most important metal-oxides utilized for optical coatings applied to displays is shown in Table 1. The refractive index of these oxides is close to that of the bulk material, due to the high energy of the process. The films are spectrally stable due to the absence of porosity. The absorption is also exceptionally low due to the efficiency of oxidation.

Table 1: The refractive index and extinction coefficients for a range of metal oxides.

Material	Refractive Index	Absorption
SiO ₂	1.47	1x10 ⁻⁶
Nb ₂ O ₅	2.37	5x10 ⁻⁵
ZrO ₂	2.06	5x10 ⁻⁵
TiO ₂	2.45	3x10 ⁻⁴
Ta ₂ O ₅	2.17	1x10 ⁻⁴
HfO ₂	2.08	1x10 ⁻⁴

MULTILAYER OPTICAL COATINGS

Figure 7 shows measured performance for three consecutive coating runs of a 19-layer TiO₂/SiO₂ edge filter utilized for color contrast control together with theoretical design. Close agreement between theory and measured results were obtained, with run-to-run reproducibility $\pm 0.2\%$ achieved with optical monitoring.

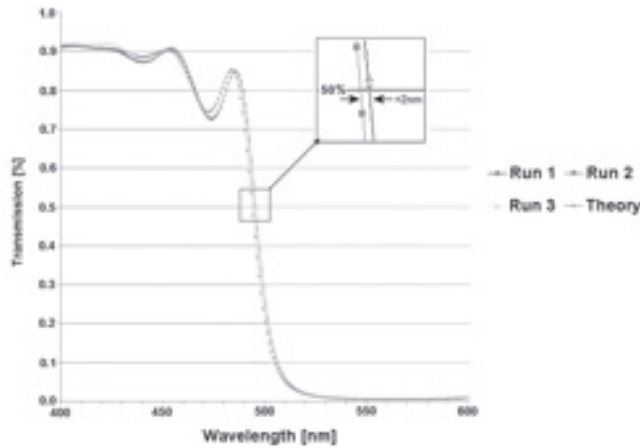


Figure 7: Measured performance for three consecutive coating runs of a 19-layer Nb₂O₅/SiO₂ edge filter and comparison with theoretical design.

Actual and film simulation of optical monitor signal shown in Figure 8.

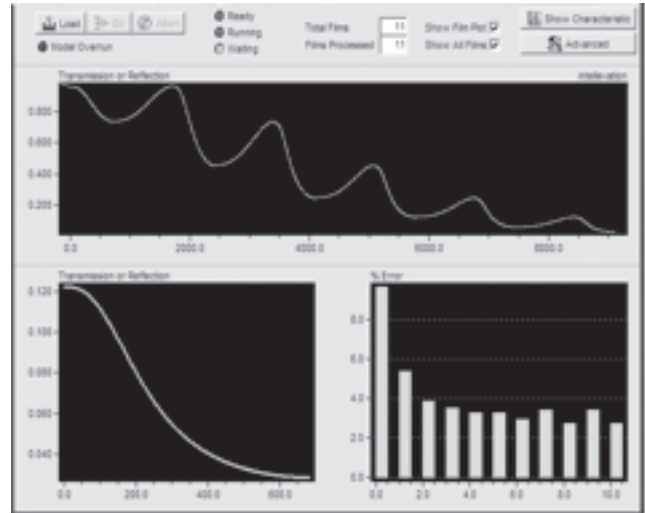


Figure 8: Optical monitor transmission signal swings.

Note expected overshoot of each film using QW cut in bar chart at bottom right of above screen print. This prediction along with the revised actual refractive index for the materials can be used to fine tune the quarter wave time and by comparison with actual quarter wave time from data the depositions rates can be reset to more accurate values.

Figure 9 also compares spectral transmission before and after exposure to supersaturated steam at fifteen psi for one hour, showing no measurable shift in spectral characteristic.

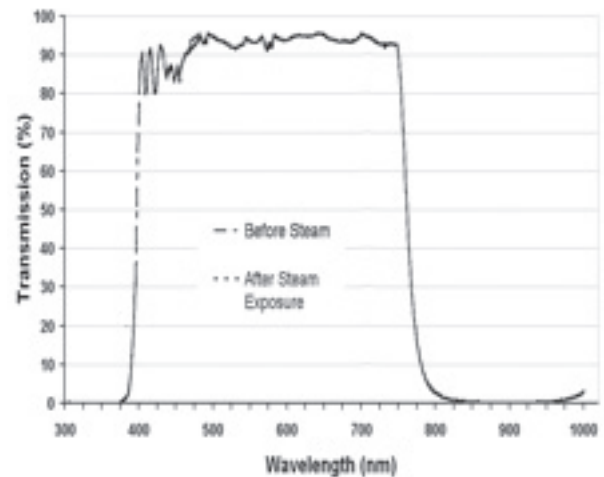


Figure 9: Transmission of filter before and after steam exposure.

STRESS

Film stress was evaluated from measured substrate curvature before and after film deposition. Stress was calculated from the Stoney formula [6]. Curvature was measured along two perpendicular axes across the wafer. Typical values are indicated in Table 2. Typical measurement error is $\pm 5\%$.

Table 2: Measured stress for a range of oxide films (negative value indicates compressive stress).

Material	Stress
SiO ₂	-150 MPa
Nb ₂ O ₅	-30 MPa
ZrO ₂	-80 Mpa
ITO	-70 Mpa

The values indicated in Table 2 are significantly lower than values reported recently [7] for oxide materials. The lower stress is attributed to lower ion energies and higher ion fluxes provided by the CFM sputter process.

DISCUSSION

Closed field reactive magnetron (CFM) sputtering has been used for many years to produce highest quality tribological coatings. The same basic process produces optical coatings with outstanding optical properties. Also the process is capable of producing low stress, dense, super-smooth coatings with low optical scatter. These properties are all derived from the fundamental advantage of the closed field strategy inherent in the combination of high ion current density combined with low ion energy.

The CFM process can be exploited in batch format or in-line format. The process does not require an auxiliary ion or plasma source and without this overhead, the batch systems are scaleable to meet the demands for a small development system through to high throughput production systems.

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REFERENCES

1. D.R. Gibson, I. Brinkley, D.G. Teer, P. Teer, J. Hampshire, and M. Walls, *46th Annual Technical Conference Proceedings of the Society of Vacuum Coaters*, p. 387, 2003.
2. D.R. Gibson, I. Brinkley, D.G. Teer, P. Teer, J. Hampshire, and M. Walls, *47th Annual Technical Conference Proceedings of the Society of Vacuum Coaters*, p. 377, 2004.
3. D.G. Teer, US Pat. #5,556,519, Sept. 17, 1996.
4. D.G. Teer, *Wear* **251** (2001) 1068.
5. D.R. Gibson and M. Walls, *Europhotonics* **9** (2004), 32.
6. M. Ohring, *Materials Science of Thin Films* (Academic, New York 1992).
7. J E Klemberg-Sapieha et al, *Appl Optics*, Vol 43, No.13, 1 May 2004.