New magnetron sputtering systems for high throughput AR coating

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Magnetron sputtering is a key thin film deposition technology widely acknowledged to produce the highest quality optical coatings. In this article, the authors describe the high throughput CFM reactive sputtering process for anti-reflection coating that is scaleable and allows any sized laboratory to participate. Compared to previous strategies, the CFM process does not need an auxiliary ion or plasma source, making it much more simple and less expensive. It also produces AR coatings with outstanding optical properties and durability.

Anti-reflection coating is popular with spectacle wearers because it reduces reflection and glare. Lenses are also cosmetically more appealing with an AR coating. Over recent years, most international markets have seen growth in the proportion of spectacles treated with an AR coating. As a result, coatings are becoming an increasingly important activity in optical laboratories.

Magnetron sputtering is a key deposition technology and the technique of choice in most areas of surface coating. It is used routinely in semiconductor processing and is also used to coat flat glass for architectural and automotive applications. The technique is more energetic than conventional electron beam evaporation and as a result it produces denser and more durable coatings. Sputtering systems have already been introduced to the industry for small batch, fast turnaround AR coating for retail opticians and small laboratories. Also, lens manufacturers are using huge, industrial scale sputtering systems for AR coating stock lenses in volume. This article de-scribes a new approach by US-based Applied Multilayers LLC that is scaleable and that now allows the advantages of sputtering to be accessed by laboratories of all sizes.

Magnetron sputtering

Sputtering is not a new process, it was discovered in London in 1852 by Sir William Grove, an English physicist. It is a simple process in which material is removed from a surface by incident energetic particles, rather like sandblasting on the atomic scale. In sputter deposition, the incident particle is usually an argon ion and the target is the material of which the thin film is to be made. The argon ions are usually extracted from an argon 'plasma' formed around the magnetron.

Figure 1 shows the plasma generated around a linear magnetron. Permanent magnets located behind the magnetron target generate magnetic fields to form a trap that confines electrons to move in a closed loop path over the sputtering target surface. This 'race-track' increases the number of ionising collisions per electron in the plasma.

Figure 1: *The plasma generated around the 'race track' mimics the magnetic field intensity generated by permanent magnets behind the target material.*

The target is biased using a negative voltage. The bias voltage accelerates positive argon ions to the target surface where they sputter atoms into the vacuum and onto the adjacent lenses. Sputter erosion is maximised in the 'race-track' where the magnetic field is strongest. The deposition rate in a sputtering system is directly proportional to time and film thickness is obtained simply using time and computer control. There is no need for expensive quartz crystal monitoring.

Magnetron sputtering has a number of key advantages over conventional physical vapor deposition techniques such as electron beam and thermal evaporation. For example, the kinetic energy of the sputtered atoms is typically 10 times higher than that of evaporated species, resulting in much harder and much more adherent coatings. The energy of the process also removes the need for lens heating during deposition. This means that deposition is carried out at room temperature, allowing different materials such as glass and plastic to be coated in the same batch. Compact magnetron sources are also capable of high deposition rates which result in fast process cycle times.

Closed field magnetron (CFM) sputtering

The metal oxide materials used in multilayer optical coatings are good electrical insulators and while it is possible to sputter insulators using radiofrequency power, the deposition rates are too low to be economical. To overcome this problem, techniques have been developed in which a few monolayers of metal are deposited using d.c. sputtering in one zone of a vacuum chamber and the metal is then oxidised in another zone using an ion or plasma source as the substrates rotate. The deposition rate is limited by the efficiency of oxidation and residual absorption is a problem if the rates are too high. Also, the ion or plasma source adds a significant cost.

Machine	Drum Diameter	Magnetron Length	72mm lenses
CFM 450	250mm	330mm	30
CFM 650	400mm	450mm	60
CFM 850	500mm	750mm	140

Table 2: *The standard CFM machine formats and batch sizes for 72mm lenses*

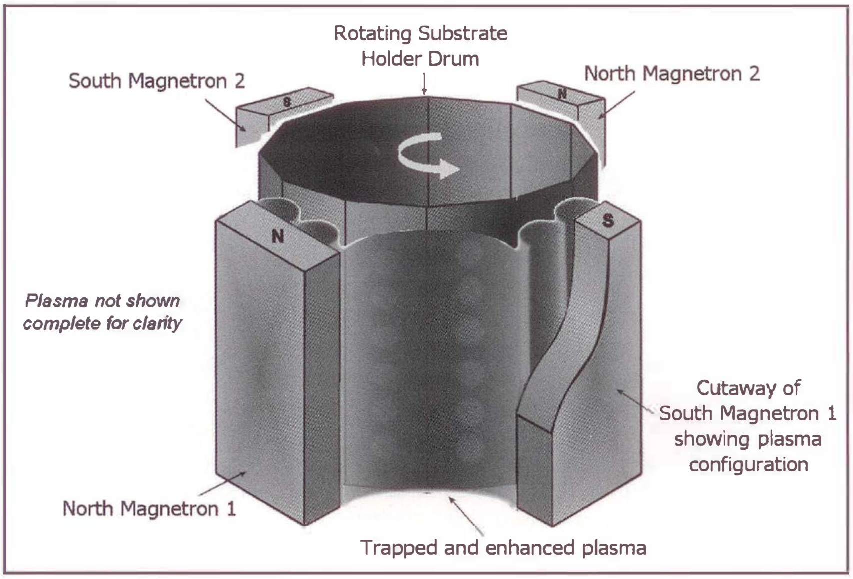

Figure 2: *The 'closed field' traps the reactive plasma all the way around the drum lens-holder, ensuring that all the metal sputtered from the targets is oxidised.*

The closed field process overcomes the limitations of using separate deposition and oxidation zones. The idea is simple and is shown in Figure 2. Essentially, adjacent magnetrons are made with magnets of opposite polarity. This configuration of the magnetrons produces a magnetic 'bottle' which supports an intense, chemically activating, plasma in which the oxidation, takes place. As a result, the process does not require a separate ion or plasma source for oxidation making the process simpler and less expensive. Oxidation at the target is controlled using a plasma emission monitor with feedback to the oxygen gas admission.

When the 'closed field' process is used with the latest pulsed dc power supplies it produces metal oxides such as silicon dioxide and niobium oxide with outstanding optical properties. Details of the optical properties of the most important metal oxides are 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.

Material	Refractive Index	Absorption
SiO_2	1.47	$1x10^{-6}$
Nb_2O_5	2.37	$5x10^{-5}$
ZrO_2	2.06	$5x10^{-5}$
TiO_2	2.45	$3x10^{-4}$
Ta_2O_5	2.17	$2x10^{-4}$

Table 1: *The refractive index (n) and absorption coefficient (k) at 550nm for a range of materials using the CFM process.*

Rotating drum and linear magnetrons

The CFM series of AR coating systems from Applied Multilayers uses the closed field process together with a drum lens carrier and linear magnetrons. The dimensions of the standard systems available are shown in Table 2 (above).

The distance between the magnetron and drum surface is typically only 100mm. In contrast, the distance between crucible and calotte in an electron beam evaporation system is usually 1 metre. For the same machine volume, a sputtering system is able to coat up to four times the number of lenses as an evaporation system and this is one of its fundamental advantages. The drum is segmented into a number of columns, each with apertures to accommodate lenses up to 80mm in diameter. Lenses are simply loaded into the segment and the segment is then latched onto the drum.

Figure 3: *The CFM 850 with a 500mm drum is capable of AR coating up to 140 lenses per hour.*

During coating, the drum rotates at 50 r.p.m. to provide coating uniformity. The process time for a typical anti-reflective coating is 15 minutes excluding vacuum pump down. Loading and unloading takes place through the large chamber door. A CFM 850 machine is shown in Figure 3. This machine is capable of AR coating 120 lenses per hour.

Coating materials

The CFM series of optical coaters can be fitted with up to four or six magnetrons. One is always fitted with a silicon target for the deposition of SiO2, which is always the low index layer. A second magnetron is available for the high index material from a choice of niobium, zirconium, tantalum or titanium, all of which work well with the CFM process. Niobium is becoming more popular because it has a high refractive index (n=2.37) and very low absorption. Two spare magnetron positions are available, providing the option of using other materials such as indium tin oxide (ITO) for its anti-static properties, chromium as an adhesion layer or alumina for its wear resistance.

Anti-reflection coatings

The structure of a modern anti-reflection coating is shown in Figure 4. The AR coating is a simple interference filter. The number of layers as well as the thickness and refractive index of each of the layers determine the color and intensity of the residual reflection. By simply altering times for each of the layers it is possible to change the reflection color to green, blue or gold or whatever is the current fashion. Likewise mirror coatings for sun wear applications are designed in the same way.

If the coating substrate is a plastic such as CR39, polycarbonate, or some other high index material, it must first be hard coated. The quality of the hard coat determines to a large extent the long-term durability of the AR coating. The hard coating is preferably a thermally cured polysiloxane dipped so that both sides of the lens are treated in the same way. Applied Multilayers offer their own range of ultrasonic cleaning equipment and dip hard coating units.

The hydrophobic coating is extremely thin (~5nm) and provides the outer surface with a slippery feel, which is easier to clean. These coatings can be applied to the lens surface *in situ* or dipped and cured external to the vacuum system.

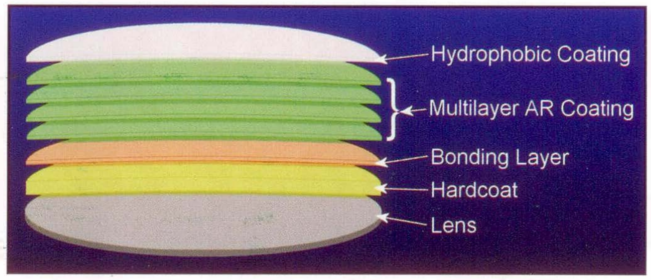

Figure 4. *The structure of an AR coating stack on a plastic lens. Note that the hard coating (3 to 5 microns) is much thicker than the total thickness of the four-layer AR coating (0.2 to 0.3 microns). The hydrophobic coating is only 5nm thick.*

The density of the sputtered AR coating makes it spectrally stable so that there is no change to the residual reflection color with time. The density also improves scratch resistance and the combination of a sputtered AR coating with a high quality thermally cured hard coat produces a combination with superior overall durability.

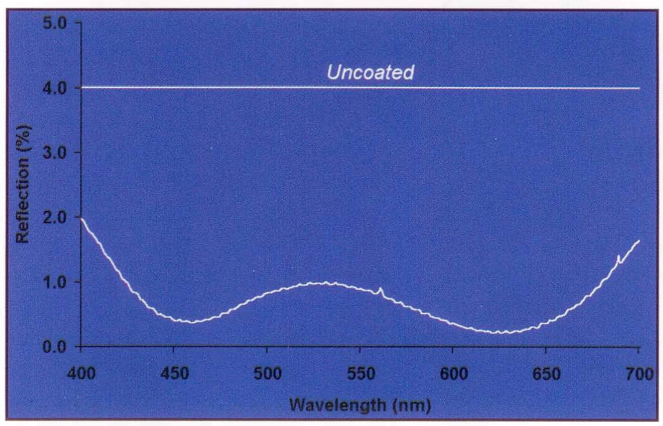

Figure 5: *The reflection curve obtained before and after the application of a four-layer AR coating.*

The AR coating itself is usually a four or six-layer design. Designs are entered into the system computer and accessed at the touch of a button. In general, the greater number of layers results in a lower residual reflection. However, use of a high index material such as niobium oxide can provide the same performance with only four-layers saving both material and process time. A reflection curve from a four-layer AR coating using Nb_2O_5 and SiO_2 is shown in Figure 5. The peak reflectance is green at 530nm with a peak reflectance of 1 per cent. The overall transmission is better than 99 per cent compared with a 92 per cent transmission for the uncoated lens surface. The wings of the reflectance curve at 400nm and 700nm are also very low, making this design very tolerant of process shifts with time.

Summary

Magnetron sputtering technology lends itself to compact machine design and full automation at a much lower cost than conventional vacuum coaters. Although sputtering based machines have been used since the early nineties for small batches of lenses, it is only with the introduction of the CFM series of optical coaters that systems are available for medium and large batch production.

Sputtering produces high quality, dense coatings with excellent adhesion, uniformity and scratch resistance. When applied to a suitable hard coat, sputtered AR coatings offer premium optical quality and durability, which leads to enhanced customer satisfaction and improved profitability for optical laboratories.

The CFM machines also offer great flexibility. For example, the smaller systems (CFM 450 and CFM 650) can be loaded with four deposition materials, while the CFM 850 can be fitted with six different materials. This allows the systems to be upgraded and allows simple installation of new process developments. These advantages, combined with easier machine maintenance, high reliability and lower cost, offer the laboratory an attractive alternative to conventional box coaters.