During the communications boom of the early 1990s, new sputter coating techniques allowed telecoms developers to produce filters able to reflect all wavelengths outside a very narrow transmission band. These so-called dense wavelength division multiplexing (DWDM) filters now allow many signals to be transmitted down a single fibre optic cable before being easily de-multiplexed, each at a slightly different wavelength. These sputter coating techniques have found more and more applications in coating high-precision optical components, where the technique allows optical performance that would otherwise be impossible. The durability of sputter coatings means that they can be used with lasers at high power densities, or in the most hostile of ambient environments.

In order to understand what sputter coating can offer customers looking for high-end optical components, it is necessary to consider the alternatives. Prior to the development of sputtering, optical coatings were produced through evaporative physical vapour deposition processes.

Although evaporative coatings still account for most optical coatings produced, they have many shortcomings, as Mark Damery, VP of sales at REO, a spokesman for coatings specialist REO (Research Electro Optics, Boulder, Colorado), describes: 'The majority of thin films fabricated for optical applications are produced through traditional evaporative means; this means that you take [the coating] material and heat it up, either by passing an electric current through it or by hitting it with an electron beam [or “e-beam”], until it gets hot enough to boil and vapourise. This is all done in a vacuum chamber, so that the resulting vapour fills the chamber before re-condensing on every surface,' he says, noting that the parts to be coated are placed within that chamber.

‘You may have several different coating materials in the chamber that can be rotated into the path of the electron beam one after the other, so that you can produce a coating consisting of several different layered materials.’

The evaporative process, Damery explains, is not very energetic; as the coating material re-condenses on the surface of the optic, it does not encounter the substrate with a high energy, and the resulting coating is relatively porous. This porosity, he explains, is responsible for many of the limitations of optics coated by e-beam or other evaporative processes, because the voids in the coatings absorb moisture from the ambient environment. Moisture subsequently changes both the shape and refractive index of the coating, preventing it from functioning properly. In the case of laser optics, moisture in a porous coating can also lower the optic’s damage threshold. In harsh environments such as salt spray or steam, traditional evaporative coatings are even more limited in usefulness. ‘The bottom line on traditional evaporative coatings is that they have issues in terms of stability under changes of temperature or humidity,’ says Damery.
Evaporative coatings are, however, easy and quick to produce, and relatively inexpensive compared to other coating types. Evaporative techniques can be used with a wide range of coating materials to produce filters for use in the UV, visible, or IR regions of the spectrum. 'For many applications, evaporated coatings are still appropriate and still meet performance requirements, but there are a significant number of demanding and high-power applications in which e-beam coatings fall short,' notes Damery.

**Aiming denser**
Where e-beam coatings fall short, many customers opt for the intermediate technique of ion-assisted deposition (IAD). 'In IAD we take the same target and e-beam set up, but then we shoot high-energy ions into the chamber,' explains Damery. 'These act as little peening hammers to pound the coating material onto the substrate with more energy – pounding it into a state of higher density so as to reduce porosity,' notes Damery. IAD coatings are less porous than those produced by e-beam only, but they are not fully densified. 'In a fully densified coating, there is utterly no porosity – there is no space whatsoever for any moisture, cleaning solvents, or dirt to get into the coating.'

**Defining sputtering**
So what is sputtering? Ian Edmond, senior thin film engineer at REO, explains: 'Sputtering means taking a target material and using energetic ions to knock materials off. Instead of bulk heating the material to boil bits off (as in e-beam), we use the accelerated ions as little bullets to knock bits off at the atomic or molecular level. If you set it up right, and bombard the target with these very high energy ions, the fragments that come off also do so with high energy – five or 10 times the energy that they would have in an evaporative process.'

Environmental durability aside, coatings produced by ion beam sputtering also boast significant optical benefits, explains Edmond: 'They have the lowest scatter and absorption properties of any coating technology. It’s possible to produce low-loss mirrors with less than 1 ppm scatter and absorption. We can make a mirror that’s 99.9997 per cent reflecting, which is an enabling technology in itself for devices such as cavity ring-down spectrometers or ring-laser gyroscopes.'

Such low loss and scatter stems from the fact that an IBS coating can be deposited with approximately twice the precision of an equivalent evaporated coating, and when designing coatings to fractions of a wavelength, precision means performance. 'The reason for the greater precision is that rather than melting and boiling the material and then having faith that it’s going to condense with the right refractive index to the right thickness, when we’re ripping atom by atom from a target it is much more accurate and deliberate. The repeatability and controlability of the process is far superior, leading to about twice the precision in terms of both the accuracy of refractive indices, the consistency of those indices, and the accuracy of the physical thickness.'

**Coating technology has historically been a few steps ahead of metrology technology, so they’re only just starting to catch up with each other**

One further advantage of sputter-coating is that it allows optics manufacturers to control the stoichiometry of the coatings they produce, particularly when alloy-based coatings are used. 'If the target is an alloy, we don’t get dissociation of the two metals with sputter coating. In evaporative processes, on the other hand, the two metals have different melting points and so they would evaporate at different temperatures, and so we would not get a thin film of the alloy,' says REO’s Edmund.

**Stress reduction**
'Coatings always have an internal stress,' notes REO’s Damery, 'so that they are literally pulling on the substrate material below them, and in some cases they can pull it out of shape. When you’re talking about an optic with a flatness of λ/20, it doesn’t take much stress to pull that optic away from its proper shape. For this reason, the flatness of most optics is specified by its manufacturers prior to the coating process.'

Jessica Black, sales engineer at Deposition Sciences Inc. (DSI, also in Boulder, Colorado), confirms that minimising the stresses in coatings is an important consideration: 'Increasing the energy of the coating process makes the great, non-shifting substrates we’re looking for, but the energy also leads to more stress in the coating. As the material condenses on the substrate, there can also be a difference.'
In the coefficient of thermal expansion between the two, it is bit of a problem, and DSI and other coating companies tend to stress-compensate coatings. The most common way to do this is to flip the optic over and put an anti-reflective coating or some kind of sacrificial coating on the reverse side, so if we’ve curled it in one direction we then flip it over and curl it back again,” she explains. Annealing and other techniques are also employed to varying degrees in order to obtain a flat optic. ‘The nice thing about sputtered-coated optics,’ says Black, ‘is that the flatness doesn’t change; whatever it is when the coating is completed, it will stay that way. The flatness of an optic with an evaporated coating, on the other hand, will actually change as the coating relaxes and absorbs humidity.’

Plastic options

‘The other exciting advantage of sputter coating,’ says Black, ‘is that it can be done at 100°C, give or take a few degrees, and so we can sputter onto plastic substrates, or those that are temperature sensitive. Although we could evaporate a coating onto a substrate at a lower temperature, it would usually lead to poor adhesion, and so most people [using an evaporative process] would heat the substrate within the chamber so as to increase the energy and reduce the porosity of the coating.’

REO’s Edmond adds that even where the substrate isn’t deliberately heated to increase bonding, evaporative processes themselves tend to heat the optic substantially. ‘Because IBS is a momentum-transfer process, rather than a boiling process, there is very little substrate heating, and so the technique is suitable for plastic substrates.’ Plastic optics are important in weight-sensitive applications.

IBS is not the only kind of sputter coating available, however. DSI predominantly coats optics and films using magnetron sputtering. Compared to IBS, the energy of magnetron sputtering is lower, and so the films are not as dense, and cannot be produced to the same high precision. They are, however, produced quickly – meaning that this technique is used for coating windows and films.

The limitations

The high energies used in IBS do mean that some coating materials cannot be sputtered, as Black explains: ‘Pretty much the only limitation for sputtering is that the target material has to be a metal, an oxide, or a nitride, and customers working in the far-IR or deep-UV parts of the spectrum are usually looking for fluoride coatings.’ When sputtering a metal fluoride material, the fluoride ion will dissociate from the metal ion, leading to an ineffectual coating and a build-up of dangerous fluoroine gas. Edmond elaborates: ‘Metals and metal oxides are fine, but there’s so much energy in the IBS process that sulphides, selenides, and fluorides will dissociate. Fluoride materials are typically used in coatings because they’re transparent right down into the deep UV, whereas oxides absorb sharply below 266nm.’ As such, sputter-coated optics are not suitable for applications such as excimer laser microlithography at 193nm.

The importance of control

Gregory Fales, product line manager at US-based Edmund Optics, says that the company’s development work is going into improving the blocking density of the filters produced. Much of the performance of the final optic depends, he says, on the accuracy of the measurements the company is able to make during the deposition of the coating. ‘Newer metrology will allow us to produce coatings with blocking densities of up to 8x easily. Right now we could design a coating with a theoretical blocking density of 10 to 14x, but achieving this relies on measuring the thickness of coatings during deposition, and that has always been the technical challenge. Coating technology has historically been a few steps ahead of the metrology technology, so they’re only just starting to catch up with each other,’ he says.

I would not have started using IBS if I hadn’t have had the right experts with many years of experience in this field
The high performance of sputtered coating is achieved only when used with high-precision metrology. Wolfgang Ebert is CEO and owner of Laseroptik (Hanover, Germany), a company that offers IBS, magnetron, and evaporated coatings. “Sputtering is more complex than other PVD processes,” he says. “You can buy a sputtering system off-the-shelf and be happy enough with [the results], even with a low level of in-house knowledge, particularly if you produce high volumes of just a few standard products. This, however, wouldn’t work with our business at Laseroptik, because we produce a mix of both high- and low-volume components on our sputtering machines. In our situation we need good experience of our own, and ambitious in-house experts with plenty of expensive metrology equipment. IBS is capable of producing coatings with outstanding characteristics, such as low particle [impurity] numbers and the best stoichiometry, but this performance doesn’t just come naturally,” he says, adding that the ion guns used in sputtering machines require particularly special attention. “IBS is the cutting-edge technique, with the results in terms of total losses sometimes only limited by the quality of the substrates, but I would not have started using IBS if I hadn’t have had the right experts with many years of experience in this field.”

When it comes to monitoring the deposition process, techniques that were suitable for an evaporative process may not be suitable for IBS, as Rob Beeson, VP of Engineering at Idex (Rochester, New York, USA), explains: “We use optical techniques to monitor our IBS coatings; although this can be used for soft-coated [evaporated] filters, it’s used that often.” When producing evaporated filters, he adds, it’s more common to use crystal monitoring, in which a vibrating crystal is placed in the chamber alongside the substrate. This crystal vibrates at a frequency that depends on how much mass has accumulated on it. “It’s a more noisy process, and it doesn’t give a direct optical measurement,” he says. “The crystal gives a measurement of the thickness of the coating, but thickness is not the whole picture; we want to know the index and the optical path, and optical monitoring gives us both of those parameters.”

The optical measurement equipment shines light through the coating itself as it is being deposited, explains Beeson, and the resulting signals allow the deposition machine to determine when to stop depositing layers, even incorporating a degree of auto-correcting.

For companies producing optical coatings, a unique selling point often stems from the degree of control they can guarantee, rather than the kind of machine they’re using. “The entire optical monitoring system is developed in-house,” says Beeson, “and most high-end coating companies will have their own optical monitoring systems, or at least their own algorithms. Most companies don’t develop their own coaters or coating processes (although a few do), and mostly it’s about what you do with the coater, how you run it, and how you control it that makes a difference.”

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