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Advantages of Ion Beam Sputtering for Laser Optics in Material Processing

Particularly in the field of laser material processing, optics manufacturers are confronted with requirements that place heavy demands on their systems and production teams. The IBS process offers important parameters that make it possible to achieve values that cannot otherwise be achieved with classic coating methods.

Lasers are conquering more and more areas of life, and the technical requirements are continuing to increase. Just a few years ago, experts would have declared laser energies in the megajoule range and industrial material processing in the femtosecond region to be science fiction. Today, optics manufacturers must be prepared to deliver reliable quality for such applications in large quantities. Furthermore, the technical requirements often differ greatly depending on the area of application. For example, scientific petawatt systems and ultrashort industrial pulse lasers demand particularly high laser damage thresholds – sometimes on substrates with diameters of 20 centimeters or more. For cw lasers, such as those used for cutting and welding, the challenge is to achieve the lowest possible absorption to prevent the system from heating up and the quality from suffering.

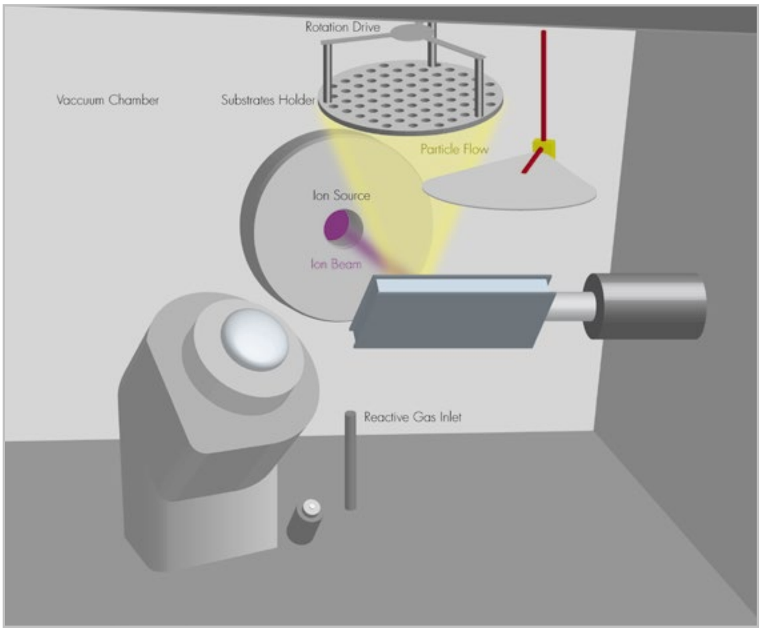

Figure 1:
Ion beam sputtering (IBS) -Lowest scattering losses and very high reflection rates: R > 99.95%

Even the wavelength ranges at which the laser sources emit are becoming more and more diverse. They now cover almost the entire spectrum. In microchip production, for example, particularly short-wave UV light is used, which places completely different demands on optics than wavelengths in the visible and infrared range. Another complicating factor for optics manufacturers is that customer demands are increasing at the same rate. Whereas there used to be a certain margin for tolerance, systems are now so maxed out that their manufacturers attach great importance to exact compliance with all specifications.

The industry is therefore almost inevitably always moving at the forefront of that which is technically feasible. The existing coating processes are constantly being further optimized in order to fully exploit their advantages. What is possible at the moment will be dealt with here using the example of ion beam sputtering (IBS) technology.

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What Makes IBS Different?

The procedure for ion beam sputtering is fundamentally different from other common processes. In e-beam or ion-assisted deposition (IAD), the coating materials are vaporized, condense on the substrate, and form a layer. In an IBS system, the coating material is prepared on a metal plate – the so-called target. A reactive gas such as oxygen or nitrogen is first admitted above the target to obtain the oxidic compounds for the transparent dielectric layers. To release the coating material, a high-energy ion beam is applied to the target in the reactive gas atmosphere. The ions strike the target surface with an energy of 1 keV, transfer their momentum to the molecules present there, and trigger a shock cascade (see Fig. 1). The number of sputtered particles can be calculated according to the following formula:

$$N(t) = N_{max}\left(1 - \exp\left(-\frac{YI_P}{eN_{max}}\,t\right)\right)$$

where e is the elementary charge, N_{max} is the number of particles on the surface (approx. 10^{15} cm^{-2}), Y is the sputtering yield (number of sputtered particles per impacting ion), and IP is the primary current.[1]

Sputtering imparts significantly higher kinetic energy to the molecules of the coating material than evaporation processes. This leads to better adhesion on the substrate, and particularly dense and homogeneous layers are formed.

In production, another important advantage of the IBS process comes into play: All essential process parameters such as scattering geometry (scattering angle), ion energy, angle of incidence, and the ratio of ions to mass can be controlled independently. This means that the stoichiometry and thickness of the dielectric layers can be precisely adapted to the needs of each individual application.[2] The detailed effects of this will be discussed below using a few examples:

Preventing Reflection Peaks with "Special Layers"

In laser material processing, the requirements for optics have changed. Today, powerful fiber lasers are primarily used in welding, cutting, and drilling; no other optics are not needed for beam guidance. However, these optics are found in the systems used to monitor the operating processes. Cameras in the visible or near IR spectrum are used to quickly detect defects such as welding sparks or hairline cracks. Dichroic optics prevent the intense light from the laser from over-illuminating the processes being monitored. The layer systems must be constructed in such a way that the laser wavelength is reflected while the filter allows the monitoring wavelengths to pass through to the detector.

Using coatings with conventional λ/4 stacks for such optics causes problems with reflection peaks. These appear at all fractions of the desired wavelength. For example, with an Nd:YAG laser (1064 nm), the wavelengths 532 nm (λ/2), 354.6 nm (λ/3), 266 nm (λ/4), etc. would be reflected (see Fig. 2). This can be avoided by including additional "interference layers" that prevent this effect in the layer design (see Fig. 3). Since these layers have to be very thin, they can best be created using the IBS process.

The opposite effect can also be achieved in the same way: Then it becomes important to achieve very good transmission values and keep the losses at the processing wavelength low.

[1] https://www.chemie.de/lexikon/Sputtern.html
[2] https://www.dentonvacuum.com/products-technologies/ion-beam/

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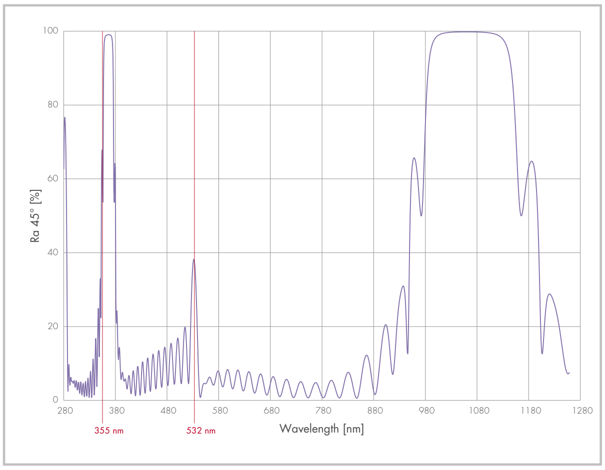

Figure 2:
Reflection peaks based on coatings with conventional λ/4 stacks, using a deflection mirror for 1064 nm as an example

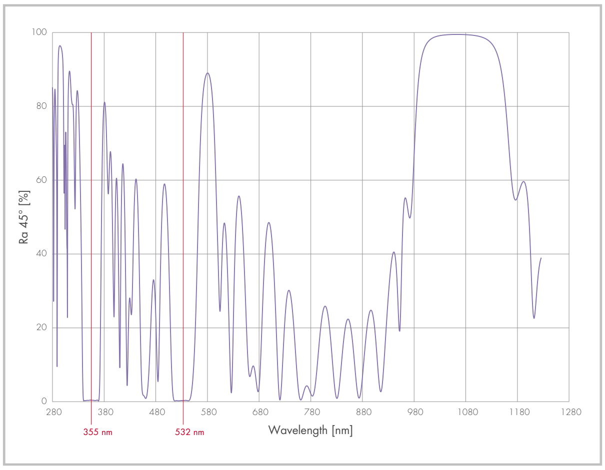

Figure 3:
Optimized design for a deflecting mirror at 1064 nm, with interference layers for suppression at 532 nm and 355 nm

Practical Advantages for Mirrors

Ion sputtering also offers tangible advantages when particularly thick layer stacks of several µm are required. This is the case, for example, when as many wavelengths as possible need to be reflected. This requires large quantities of the coating material. The crucibles in which the metals are evaporated in the e-beam and IAD processes have a very limited capacity. To achieve the desired coating thickness, one would have to interrupt the coating process to refill material. This is, of course, prone to errors. The target in IBS, on the other hand, can have any thickness.

High Reflection, Low Losses

In laser material processing, optics must withstand cw laser power output of several kW. Rough surfaces cause uncontrolled scattering that could heat up and damage surrounding mechanical elements. If absorption is too high, the optics themselves heat up and are destroyed. At the same time, reflections of more than 99.9% are required to protect the detectors of monitoring systems. The IBS process offers several advantages: The large coating thickness allows particularly smooth surfaces that prevent light from dispersing.

Above all, however, it pays off that this sputtering process has many "adjusting screws" with which the coating process can be precisely controlled. According to the formula described above, the ion beam can be adjusted so that the coating thicknesses correspond exactly to the desired value. This allows the gain of important percentage points in reflection. By dosing the reactive gases correctly, manufacturers can reduce the absorption value of the optics. It is important to precisely control the amount of gas to produce exactly the right amount of oxides and nitrides. A quantity of gas that is too high would slow down the sputtering process.

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In the End It Is the Experience that Counts

These examples clearly show that the IBS process offers additional solutions. Nevertheless, the conventional coating methods still have their place in the world. As always, it is important to weigh all the options in each individual case. There is no such thing as an optical system that offers optimum values for all requirements. For example, a reflectivity of more than 99.95% has to be paid for in losses in damage threshold. As mentioned above, high reflectivity values can only be achieved with many dense layers. However, with each additional layer, the small irregularities add up, which can lead to a lower LIDT. The forces acting in the densely packed IBS layers also cause the substrate to bend. Thus, the flatness of the optic also suffers. Compensation layers can prevent this but in turn also affect the optical properties (see Fig. 4). In addition, there are factors to consider outside the realm of physics: It all has to be affordable. With all these considerations, it is the experience of the manufacturer that ultimately determines which solution is offered to the customer. The production team works closely with the development team and sales department. The product engineers translate the customer's requirements into specifications for production. It is therefore always worthwhile to cover as many options as possible with an extensive production facility that offers coating experts the ability to select the right technology.

	E-Beam	IAD	IBS
R_{max}	+	++	+++
Complexity	–	++	+++
Thermal drift	–	+++	+++
Flatness	++	+	–
$LIDT_{max}$	+++	++	++
Absorption	++	++	+

Figure 4: Advantages and disadvantages of the various coating processes

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