Optical Coating Materials

Executive Summary

A variety of materials are used in thin film optics applications. Customers of thin film optics may be interested in becoming familiar with these materials and the important differences which make one material set more appropriate for your application. We propose that the most important intrinsic material considerations are material index, material bandgap and absorption edge. These material properties are discussed as they affect thin film optics performance in different scenarios.

Thin film optical systems such as the National Ignition Facility (NIF)[1] and the Laser Interferometer Gravitational Wave Observatory (LIGO)[2] have raised the bar on the demands placed on thin film optical systems. There are also many more common applications such as high power industrial laser systems where an understanding of the thin film properties of materials are important. Here, we'll try to generate a high level understanding for the reader on the important properties of thin film materials which lead to the material choices made for these applications.

The contrasting indices and subsequent optical transmission and reflection properties created between thin layers of two or more materials is the basis for the field of optical coating. Manufacture of thin film optics therefore typically requires a minimum of two materials with some difference in index of refraction present for the thin film effect to be generated. These thin film materials will be subjected to varying environmental conditions along with various laser operating parameters throughout their lifetime. Correct choice of thin film materials along with many process validation steps during manufacture will optimize odds that a laser optic will have a long lifetime once installed in an optical system. Here we will consider the material choices available for thin film optics and the trade offs involved to help thin film consumers to make good material choices.

The materials used in manufacture of thin film laser optics are dielectrics. The dielectric effect by definition is limited to materials with a non-zero band gap. For optical applications, bandgap refers to the energy gap that a photon must cross to ionize the thin film material's valence electrons. Ionization of a materials outer shell electrons is the first step toward the onset of absorption and failure of the film. To make the onset of laser damage as unlikely as possible, a higher bandgap is preferable to a smaller one for applications where significant laser fluence exists.

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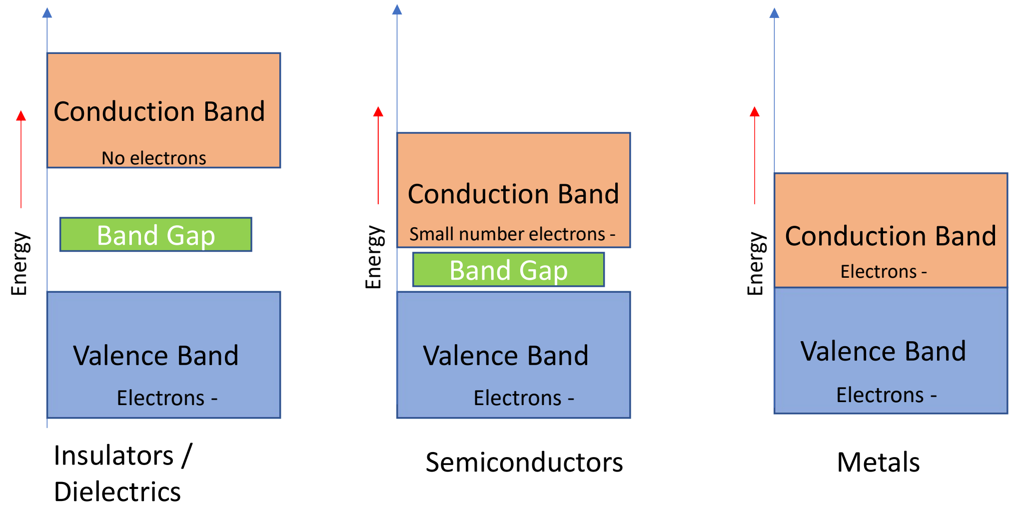

Figure 1. Energy Band Diagram

For applications where high laser fluence is present, dielectrics are the thin film materials of choice. Below is bandgap data of some common dielectric materials used for the optical manufacturing.

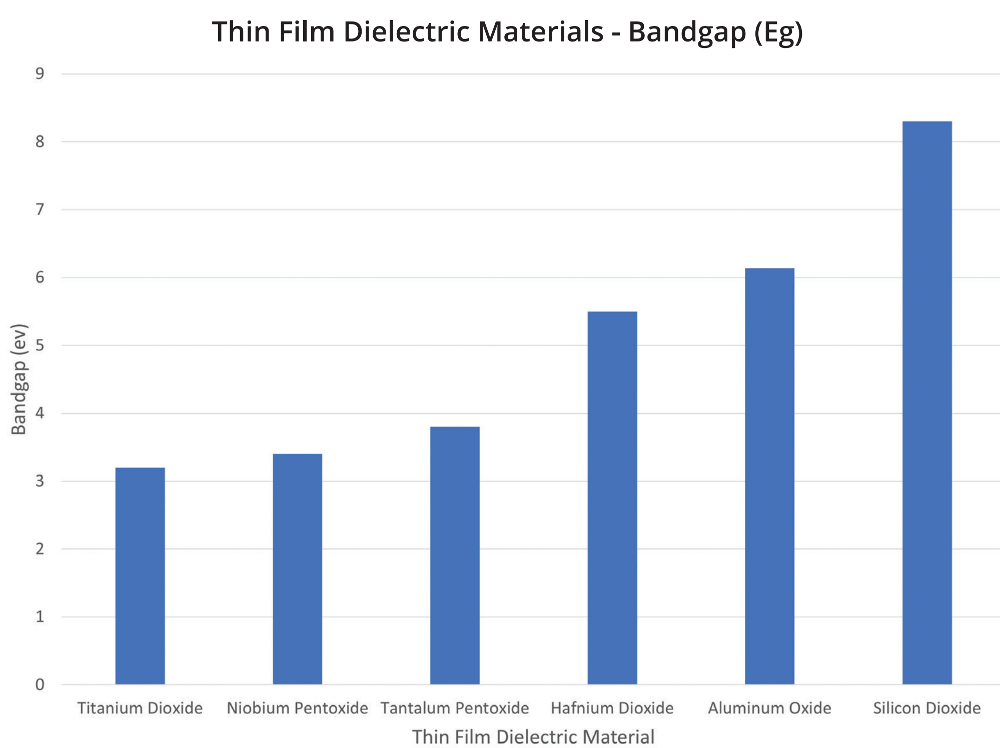

Figure 2. Various Dielectric Materials Bandgaps[3]

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Increasing bandgap is well correlated with increasing laser damage resistance. This relationship is well established but only holds true when other factors such as surface quality of substrate, film cleanliness and presence of microstructural crystallization are held constant. These other extrinsic thin film properties are critical and will be considered in future discussions. Intrinsic material properties are being considered here with the understanding that both extrinsic and intrinsic material properties are important.

This energy barrier defined by the bandgap is what allows materials to resist the ionizing force of incident laser fluence. Dielectric materials as shown in figure 2 have bandgaps from around 3eV to >8eV. Metals, by contrast, have overlapping valence and conduction bands. These overlapping bands have the effect of dramatically increasing material absorption or k-value while decreasing the refractive index. A non-zero bandgap reduces or eliminates absorption which allows a material to withstand the ionizing force of high laser fluence. This resistance to high levels or laser fluence makes the dielectric materials shown above excellent candidates for laser optic materials.

There is also a relationship between dielectric materials bandgap and refractive index. Remember that increasing bandgap is well correlated with increasing laser damage threshold.

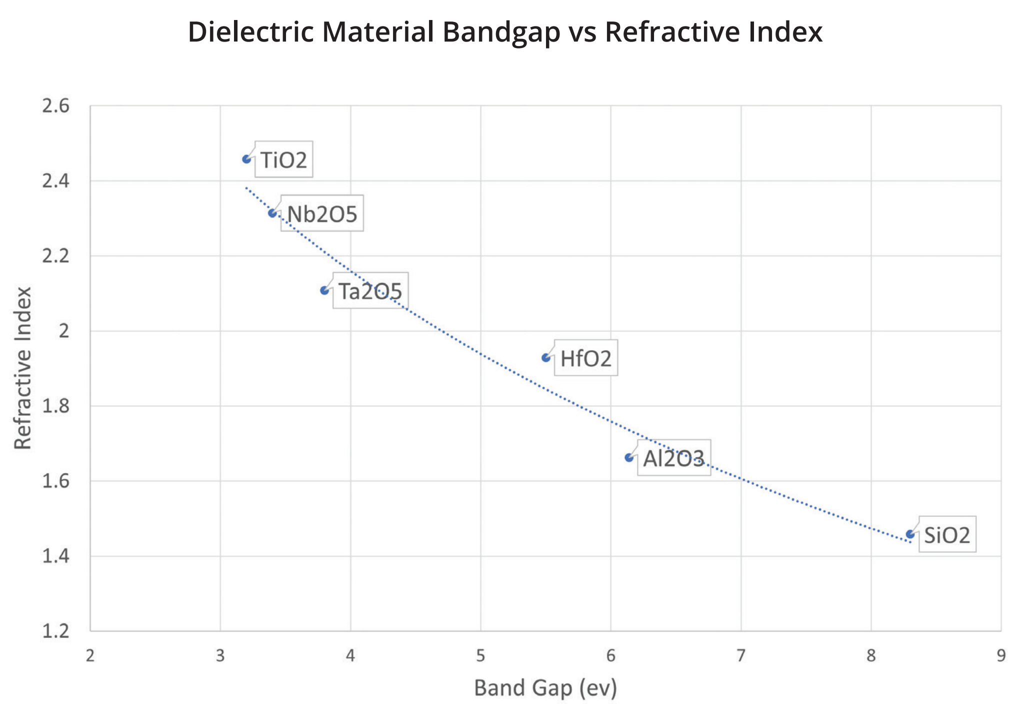

Figure 3. Bandgap Vs Refractive Index Diagram

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One might guess that Al2O3 and SiO2 would be one possible material combination that would provide excellent laser damage resistance based on the graphical data. Indeed, this material set is occasionally utilized. However, the more common dielectric laser material choice however is hafnium dioxide combined with silicon dioxide. The reason is related to the lower index contrast between silicon dioxide and of aluminum oxide. This low contrast leads to a very narrow anti-reflection coating region and also a very limited range for reflective coatings. In addition to these issues, a much larger number of layers is required to make acceptable reflectors with a small difference in indices between high and low materials.

As an example, the plot below is an illustration of two coatings with equivalent 99% reflection at 355nm. One reflector is made with HfO2-SiO2 and the other with Al2O3-SiO2. Note the much more limited reflection range of the Al2O3 based reflector. As mentioned, the number of layers required for the two different coatings is also very different at only twenty layers for the HfO2 coating vs forty-eight for the Al2O3 coating. The extra equipment time required for the additional twenty-eight layers is costly in production volume which leads to hafnia being the more common choice.

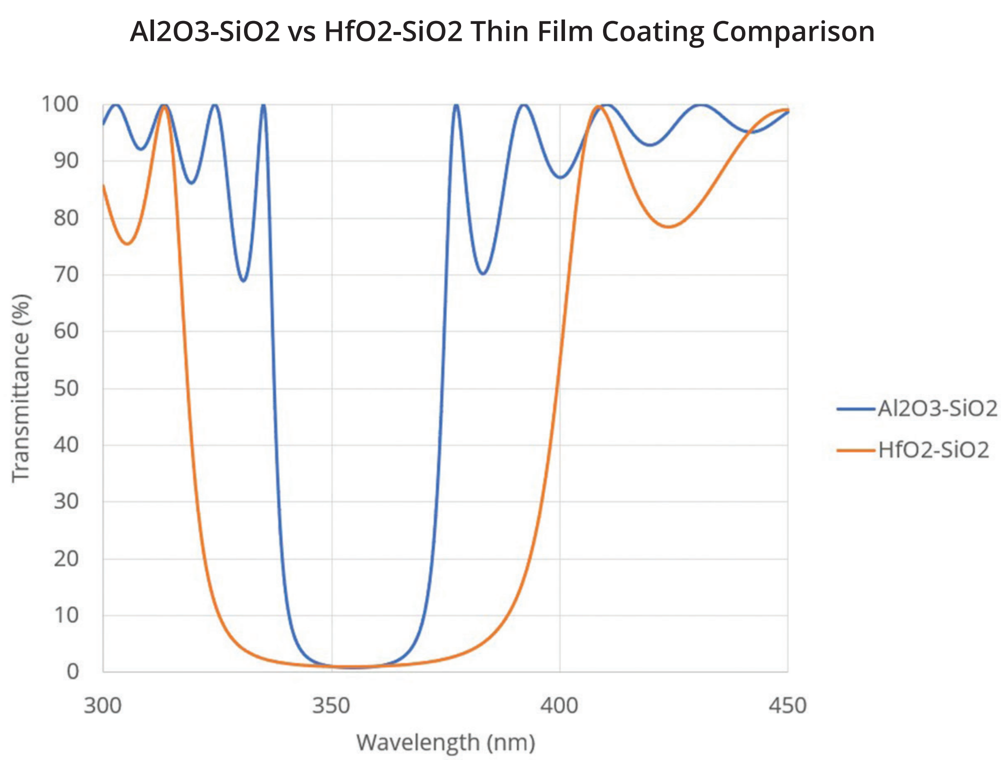

Figure 4. Alumina – Silica Coating Compared with Hafnia – Silica Coating

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One final intrinsic material property worth mentioning is material absorption edge. This is the minimum wavelength which a material can be used without measurable absorption in the thin film. The transition is also relatively sharply defined as material behavior changes from dielectric to semiconductor at the onset of absorption. A rough idea of the relationship between material index and absorption edge is shown here.

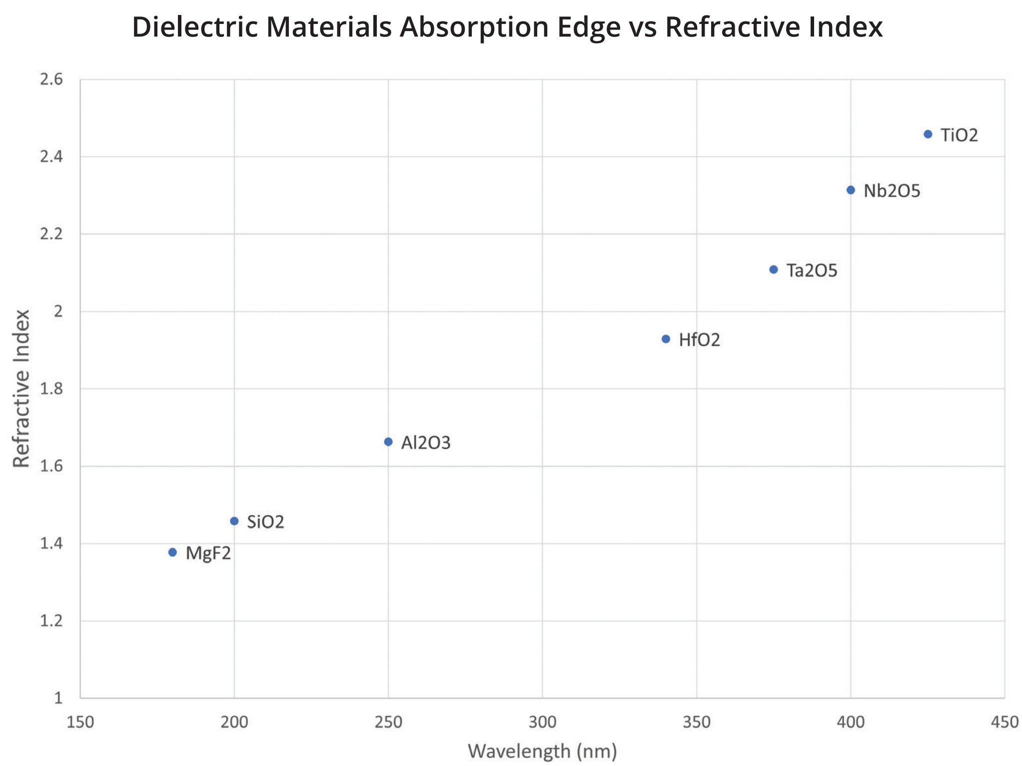

Figure 5. Alumina – Absorption Edge vs Refractive Index

Similar to material bandgap vs index, a nearly linear relationship also exists here. This can also be a limiting factor in choice of thin film optic material. Operating close to the absorption edge can be a recipe for trouble in your optical system. While operating near the absorption edge of a material, factors such as multi-phonon absorption may become important. Multi-phonon absorption deserves treatment independently as the theory behind it can be somewhat complex. It's an interesting topic for those so inclined and investigation of this phenomena is highly recommended.

Thin film material choice is critical to optimizing both the cost and lifetime of thin film optics. Correct choice will enhance performance and allow for the most durable optic for your application.

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   N-BK7 — Schott Corporation

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Plasma Optik manufactures bandpass filters, notch filters, edge filters, polarizing beam splitters, non-polarizing beam splitters, mirrors and anti-reflective coatings. Our optical monitoring capability combined with ion beam sputtering technology allows us to manufacture precision optical coatings from the ultra-violet to near infrared wavelength ranges. Plasma Optik is always happy to talk about thin film materials choices.

Contact Plasma Optik for further information and find out how we can help you to optimize performance for your application's thin film optics.