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WHITE PAPER: Anti-reflective optical components for glass covers, imaging and high power lasers

Anti-reflection coatings

Anti-reflection coatings[i] (ARCs) are commercial devices broadly employed in a plethora of applications such as imaging[ii] (e.g. in low-light conditions or to minimize the effect of ghost images), photovoltaic[iii] (e.g. to maximise the light-to-electricity conversion), extreme UV optics[iv] (e.g. for high resolution photolithography), medical treatments[v] (e.g. ophthalmology, dentistry, oncology, cosmetics), and high-power lasers[vi] (e.g. for welding, cutting, surface processing, peening). They can be used on curved optics (e.g. lenses) or on flat surfaces (glass covers), over very large extensions (e.g. m^2 for solar panels[iii]) or small surfaces (e.g. 100 μm^2 for optical fibres[vii]). Beyond optical performances (e.g. very large transmission >99%, broad-band and wide acceptance angle), depending on the application, ARCs must obey to a diverse set of hard requirements, such as having a high laser-induced damage threshold and low absorption, be water and/or oil repellent, scratch resistant, etc.

ARCs can be classified based on their working principle. The most popular ones use thin films to coat the substrate producing a destructive interference between the incident and reflected light beams: appropriate thickness and refractive index of the film[i] can produce extremely efficient devices whose reflection can be below 0.1% at specific wavelengths. However, this approach suffers from several limitations. For instance, single layers ARCs work well when their optical constant is $n_{coat} = \sqrt{n_{sub}}$ (for devices surrounded by air). It is not easy to match such a value when low-refractive index substrates are concerned (e.g. glass, fused silica, sapphire, zinc-selenide, polymers). Adding porosity in the ARC material is a viable solution to lower its refractive index. However, this entails the potential infiltration by humidity (e.g. typically found in the atmosphere) changing the optical constants and affecting the ARC performances. Moreover, ARCs based on single films are efficient in a limited interval of wavelengths and angles, thus restraining their exploitability to specific applications. These problems are addressed with ARCs composed by many layers. However, when high-performances are required, the fabrication processes can be long and expensive. Moreover, 2D interferential coatings are not well adapted to handle high-power lasers: owing to the differences in the thermal expansion coefficient of the substrate and of the thin film stack, the device performances are quickly degraded.

An emerging class of bio-inspired ARCs[viii] ("moth eye") leverages on a smooth change of refractive index from the surrounding medium to that of the underlying substrate (adiabatic index matching) using small 3D structures[ix]. It is becoming more popular thanks to the progress in the fabrication process of 3D nano-structures. In fact, it exploits tiny slanted pillars or cones featuring a large vertical aspect ratio (height over lateral size $h/d \gtrsim 1$), a height typically larger than the wavelength of the incident light ($h \gtrsim \lambda$), and a high spatial density ($\gtrsim 10/\lambda^2$). Their performances can overcome those of conventional interference coatings, with a high transmission (T > 99.5%) in a broad interval of wavelength (> 500 nm), a large acceptance angle (T > 99% up to 50 degrees of beam incidence) and withstand a large laser flux.

Nano-fabrication methods

Structuring the surface of a wafer can also render it hydrophobic, oil repellent, and anti-glare, that are important features for their use in open air. However, the presence of tiny structures poses serious concerns on the mechanical strength of these ARCs. For instance, soft materials such as polymer can be framed in small 3D structures over very large surfaces (e.g. by nano-imprint lithography, NIL), are typically not stable against rubbing and scratches, they have a scarce thermal stability and low resistance to high power lasers. As such, their use as ARCs is rather limited. Conversely, dielectric wafers can be directly engraved to form a moth eye ARC leveraging on their intrinsic mechanical strength.

"Subtractive", top-down nano-fabrication methods based on lithography (Figure 1, left panel) can deliver moth eye ARCs but must face all the issues of scaling the production of nano-architectures having typical size in the range of 100 nm for ARCs working at visible and near-infrared frequencies. Delivering large surfaces textured with high precision, repeatability and homogeneity is very challenging and expensive[x]. For instance, top-down lithographic approaches require several fabrication steps, involve toxic resists, powerful UV-lamps, precious materials, chemicals and fluorinated gases (e.g. SiF_4, CF_3, and C_4F_8). All these issues pose serious concerns on the sustainability of the process that is costly, polluting, and potentially dangerous for the people working in production. CO_2 production (a gas responsible for the greenhouse effect), and fluorinated gases (harmful to the ozone layer) are further problems that several countries (e.g. EU[xi]) are trying to address by replacing conventional nano-fabrication with more sustainable approaches.

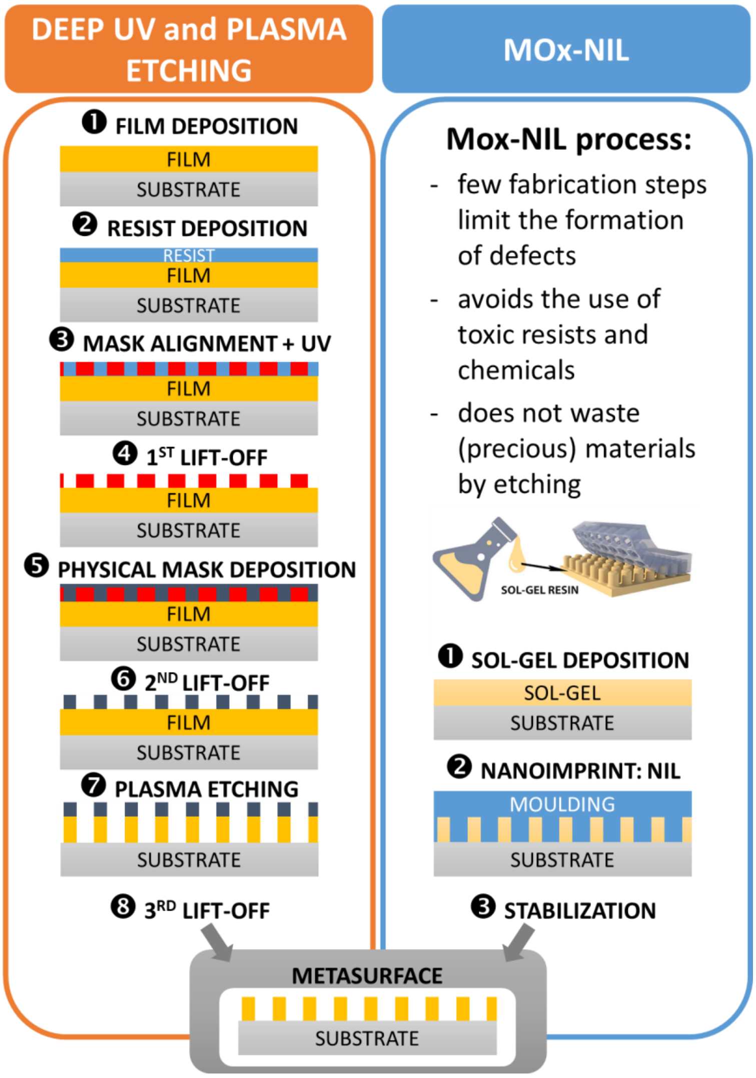

Figure 1. Left panel: description of the nano-fabrication of photonic metasurfaces by deep-UV and plasma etching. Right panel: nanofabrication by sol-gel coating and nano-imprint lithography (MOx-NIL) by SOLNIL.

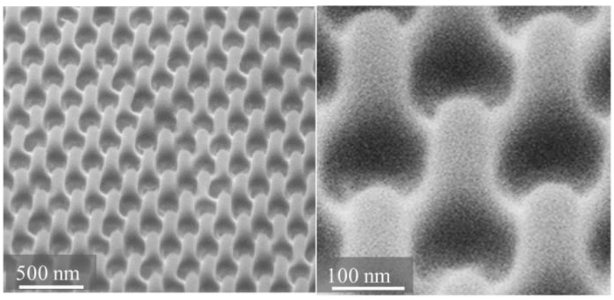

Figure 2. Scanning electron micrographs of an ARC printed on fused silica via MOx-NIL.

Sol-gel coating and nano-imprint lithography (MOx-NIL)

SOLNIL[xii] has developed metal-oxide materials (MOx) transparent from near-UV to MWIR adapted to high-quality optical coatings as well as a fabrication process to print them. These materials can be framed in 3D structures adapted to

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moth eye ARCs and beyond[xiii]. Sol-gel coating and nano-imprint lithography (MOx-NIL, Figure 1, right panel and Figure 2) is a sustainable nano-fabrication process, alternative to conventional, subtractive approaches. It delivers a device in a few fabrication steps: dip- or spin-coating, moulding and stabilization by annealing at high temperature. It is more sustainable and environmental friendly than photo-lithography, as it avoids the use of toxic resists, chemicals, and precious materials. It cuts the production of CO_2 by 90% with respect to deep-UV and plasma etching[xiv] and avoids the use of fluorinated gases. The final structures are composed of hard ceramic stable against rubbing, high-temperature, and aggressive chemical environments[xv].

MOx-NIL-based anti-reflection coatings

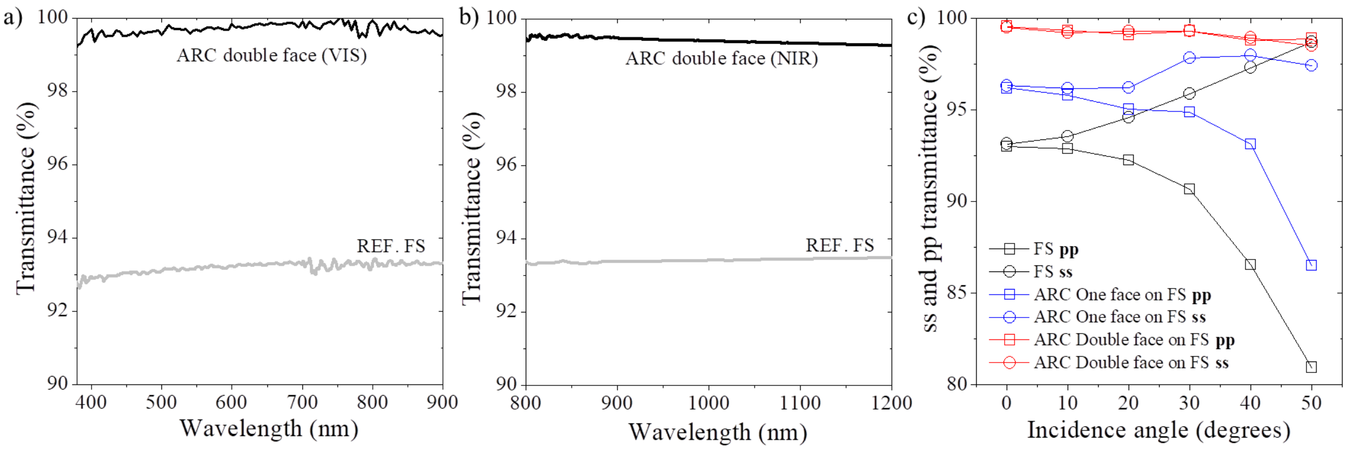

Figure 3. a) Total transmission for an uncoated fused silica substrate reference (REF. FS) and for a MOx-NIL-based ARC printed on both faces of the substrate working at visible frequency (VIS). B) Same as a) for an ARC working at NIR frequency. c) Total transmission at 600 nm for ss and pp polarization for uncoated fused silica, single and double face ARC.

SOLNIL has developed high-performance ARCs devices for applications at visible (VIS) and near-infrared (NIR) frequencies exploiting its original MOx-NIL process. They are adapted to many applications including glass covers for imaging, lightening, detection, telecommunication, photovoltaic and quantum optics.

Figure 3 displays the typical performances of SOLNIL's ARCs: they showcase high total transmission and achromaticity (99.5% < T < 99.8% from 390 to 900 nm and 99% < T < 99.5% from 800 to 1400 nm) and wide angular acceptance for both polarization channels (T > 99% up to 50 degrees for pp and ss polarization).

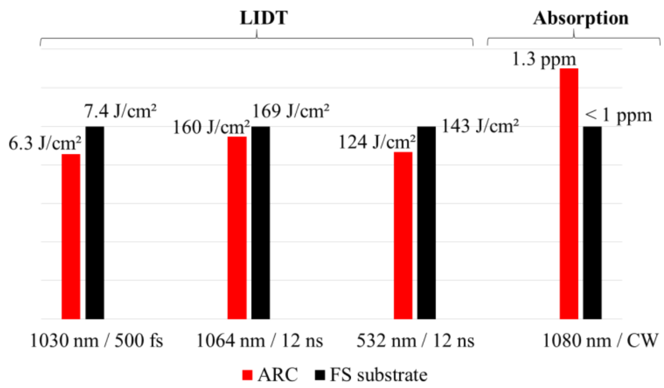

Figure 4. LIDT and absorption measurements reported for MOx-NIL-based ARCs and Fused Silica substrates (FS). The data are normalised to the FS substrate values.

Laser induced damage threshold and absorption.

Our ARCs were tested with high-power lasers. Typical values of the laser induced damage threshold (LIDT) in the sub-picosecond regime are LIDT > 5 J/cm 2 at 1030 nm, 500 fs, in the nanosecond regime LIDT > 150 J/cm 2 at 1064 nm, 12 ns and >100 J/cm 2 at 532 nm, 12 ns. In the CW regime they show very low absorption < 1.3

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ppm at 1080 nm, which corresponds to about 1 mW of power absorbed in the coating for a 1 kW of laser power. All these values are close to those of the fused silica substrate accounting for the high quality.

Conclusion

SOLNIL has undertaken a step beyond in the ARCs industry leveraging on the best combination of printable sol-gel resists and the MOx-NIL process. Our nano-fabrication process takes into account the main issues affecting conventional methods reducing pollution and improving safety in production. The direct moulding process of hard ceramics is compatible with plate-to-plate and roll-to-plate fabrication, improving productivity and cutting costs.

Here we showed ARC devices working at near-infrared and visible frequencies for their relevance to high-power lasers. Nonetheless, thanks to their wide angle performances they can be used also on glass covers for imaging, photovoltaic, telecommunications and much more. They can be used with laser operating at near infrared frequency, typical of Neodymium or Ytterbium lasers, that are the most common ones used in industrial applications (e.g. cutting and welding steel and semiconductors, engraving, etching, marking metals and plastics, metal peening), defense (direct energy weapons, inertial confinement fusion) or medical treatments (e.g. thermotherapy, ophthalmology, dentistry, oncology, cosmetics).

Thanks to the versatility of MOx-NIL, the working range of the ARCs can be adapted to other wavelengths by changing size and period of the 3D structures (e.g. typical size of the 3D structures can be tuned in a very broad range covering three orders of magnitude, from ~ 10 nm up to ~ 10 µm[xvi]). By changing the properties of the printable sol-gel inks, many different materials can be obtained[xvii], adapting their refractive index from 1.17 to 2.7.

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