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Dual-functional broadband antireflective and hydrophobic films for solar and optical applications

S. Pendse[a], K. Chandra Sekhar Reddy[a], C. Narendra[a], K. Murugan[a], S. Sakthivel[a,*]

[a] Centre for Solar Energy Materials, International Advanced Research Centre for Powder Metallurgy and New Materials, Balapur PO, Hyderabad 500 005, India

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ABSTRACT

We report hydrophobic modification of a high-performance broadband antireflective (AR) film comprising mesoporous MgF_2 nanoparticles. The MgF_2 film demonstrates high transmission, > 99% (400–800 nm) and > 97% (300–1500 nm) and is hydrophilic with a water contact angle of 27°. Hydrophobic modification with a fluorosilane containing silica sol by a simple dip coating process increases the water contact angle to 130° without affecting transmittance. Hence, this hybrid layer exhibits excellent anti-reflection in a broad wavelength range (98.8% (400–800 nm) and 97.03% (300–1500 nm)), along with good water-repellence. Moreover, the layer is also environmentally and mechanically stable indicating its suitability for solar and optical applications.

1. Introduction

Broadband antireflective coatings have received great research interest in the past decades. This is due to their wide potential applications in high power lasers, solar cell glass covers, automobile windshields, optical instruments, solar collectors, architectural glasses, windscreens, display panels, sensors and so on (Barshilia et al., 2012; Huang et al., 2007; Karthik et al., 2017; Liu et al., 2012; Moghal et al., 2012; Shimomura et al., 2010; Xi et al., 2007; Yoldas and Partlow, 1985). Self-cleaning broadband antireflective coatings are even more advantageous as they prevent dust accumulation which can lead to a loss in transparency of optical lenses and windshields and efficiency of solar cells (Adak et al., 2017; Arabatzis et al., 2018; Guldin et al., 2013; Huang et al., 2018; Li et al., 2013; Prado et al., 2010; Salvaggio et al., 2016; Xu et al., 2014b).

Considering the requirement of a low refractive index (RI), nanoporous films having an effective RI of the order of 1.22 are commonly used as AR coatings (Walheim, 1999; Xi et al., 2007). However, such coatings suffer from poor environmental durability. The porous films tend to absorb water and other contaminants from the environment, especially if any residual −OH groups are left on the film after processing (Cai et al., 2015; Dou et al., 2016; Meng et al., 2014; San Vicente et al., 2011; Xin et al., 2013; Yan et al., 2011; Zhang et al., 2013). This leads to an increase in their RI and consequent degradation of optical properties. Such films also lack mechanical stability (Mehmood et al., 2016). Since only weak physical van der Waal's forces exist between the nanoparticles of the films, they can be easily scratched off the substrate surface (Deng et al., 2011; Mehmood et al., 2016; Meng et al., 2014). Additionally, the coatings do not provide protection against dust and other contaminants that settle over solar glass covers in outdoor environments and severely impact the conversion efficiencies of solar cells (Adinoyi and Said, 2013; Deng et al., 2011; Jiang et al., 2011; Mehmood et al., 2016).

One way to overcome these drawbacks of porous antireflective films would be to modify their surfaces to repel water i.e. to render them hydrophobic (Yuan et al., 2015, 2016; Zhang et al., 2013). Such dual functional coatings would not only possess better environmental and mechanical stability but would also help in dust removal with the help of water droplets rolling off the surface. Several groups have successfully demonstrated hydrophobic coatings on glass substrates. However, these coatings do not improve transmission of light through the substrate (Bravo et al., 2007; Dhere et al., 2010; Latthe et al., 2010; Levkin et al., 2009; Ling et al., 2009; Nakajima et al., 1999; Xu et al., 2010).

Many groups have also attempted fabrication of hydrophobic coatings with enhanced optical transmission (antireflection) (Artus et al., 2006; Cai et al., 2015; Deng et al., 2011; Gao and He, 2013; Karunakaran et al., 2011; Kim et al., 2007; Li et al., 2010; Li and Shen, 2011; Mehmood et al., 2016; Meng et al., 2014; Xu et al., 2014a, 2012; Yuan et al., 2015; Zhang et al., 2013). However, to the best of our knowledge, a combination of both high transmittance (≥97%) in a broad wavelength range and high water contact angle (≥120°) has not been achieved so far. For instance, (Cai et al., 2015) prepared coatings from base catalyzed tetraethylorthosilicate (TEOS) sol mixed with acid catalyzed methyltriethoxysilane sol in a 3:7 ratio. The maximum transmittance of the coating was 99.89% at 550 nm (single wavelength) and the water contact angle was limited to 120°. (Meng et al., 2014)

* Corresponding author.
E-mail address: ssakthivel@arci.res.in (S. Sakthivel).

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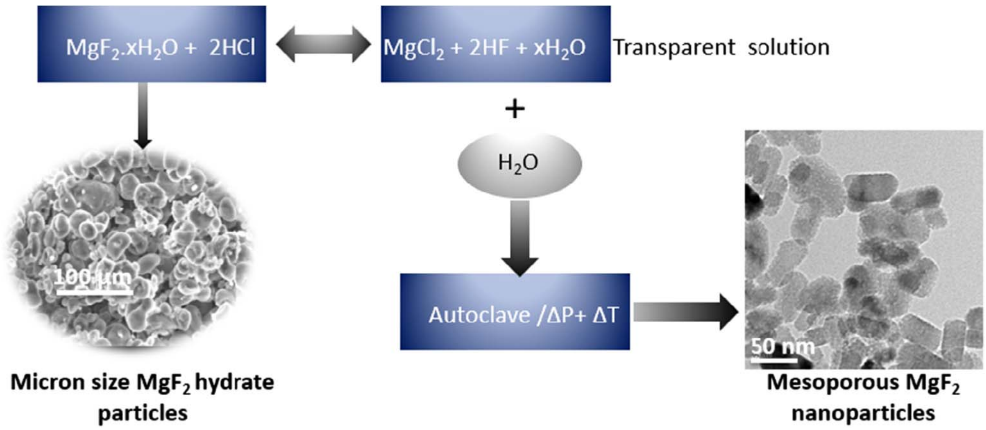

Fig. 1. Procedure for synthesis of mesoporous MgF_2.

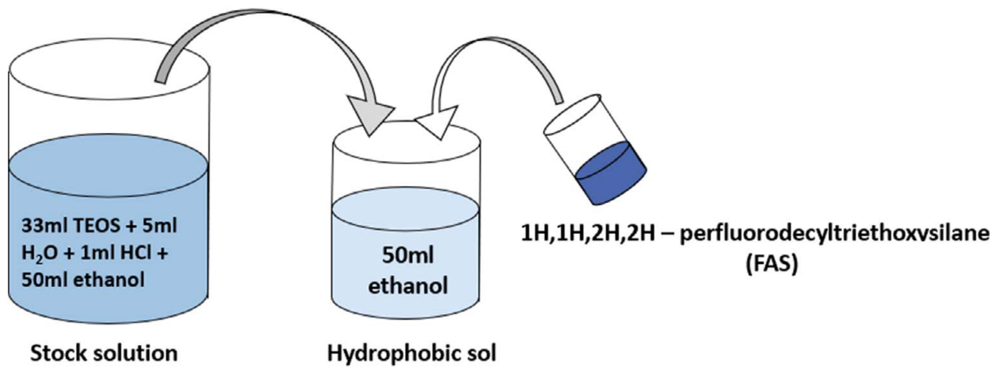

Fig. 2. Preparation of hydrophobic sol.

prepared porous bilayer antireflective coatings by acid catalyzed sol-gel process using TEOS as silica precursor and cetyltrimethyl ammonium bromide as template. This was followed by hydrophobic modification with trimethylchlorosilane. The average transmittance of their optimized coating was 96.6% (400–800 nm) and water contact angle was 130°. (Li et al., 2010) coated non-spherical silica nanoparticles onto glass substrates by layer by layer assembly followed by chemical vapor deposition of 1H,1H,2H,2H-perfluorooctyltriethoxysilane (POTS) for hydrophobic modification. While they achieved a water contact angle of ~152°, the maximum transmittance of the coated substrates was only 94%. (Xu et al., 2012) deposited hollow silica nanoparticles and poly(methylmethacrylate) on glass substrates and modified the layer with hydrophobic hexamethyldisilazane and POTS. Although the water contact angle was ~162°, the maximum transmittance did not exceed 93%.

Moreover, most reports related to water-repellent antireflective coatings have been based on silica nanoparticles (Bravo et al., 2007). Very few attempts have been made for hydrophobic modification of films based on other materials. MgF_2 is noted as an ideal material for high performance antireflective coatings due to its low refractive index (1.38) (Bernsmeier et al., 2014; Noack et al., 2012; Scheurell et al., 2015a,b). Hence, hydrophobic modification of MgF_2 films, if successfully demonstrated could be useful for various applications that require water repellence as well as good transmission. (Yan et al., 2014) fabricated hydrophobic, antireflective films based on MgF_2 from MgF_2 precursor sols modified with methyl silicone. As the content of methyl silicone in the sols was increased, water contact angle increased but the transmittance of coatings decreased. Films prepared from the sol containing 20% silicone, exhibited a maximum transmittance of 99.5% and a water contact angle of 105°. Moreover, the water contact angle did not exceed 110° even after addition of 80% silicone while the maximum transmittance dropped to 94.5%.

Dual functional antireflective, hydrophobic coatings present a technical challenge because hydrophobicity requires a rough, low-energy surface. However, rough surfaces can lead to extensive light scattering making hydrophobicity and transparency competing properties (Adinoyi and Said, 2013; Dhere et al., 2010; Levkin et al., 2009; Nakajima et al., 1999; Xu et al., 2010). In the present contribution, we describe a facile route to fabricate antireflective, hydrophobic coatings based on MgF_2 nanoparticles that results in a water contact angle of 130° and a high average transmittance of > 98% (400–800 nm). A simple dip-coating technique, which is easy to implement on an industrial scale, is suitable for the development of the coating on large surfaces. The antireflective property of MgF_2 remains largely unaffected by hydrophobic modification which is contrary to most of the previous observations. The resulting dual functional coatings are more environmentally and mechanically stable as compared to conventional antireflective coatings. Hence, such coatings can not only improve the efficiency of solar cells by ensuring that maximum solar radiation is transmitted but can also pave a way to solving problems of dust and surface contamination faced while operating large area solar power plants in an outdoor environment.

2. Experimental section

Development of the dual-functional antireflective and hydrophobic coatings involves three steps – synthesis of mesoporous MgF_2 nanoparticles, development of MgF_2 antireflective base layer and development of a hydrophobic layer over the antireflective base layer.

2.1. Synthesis of mesoporous MgF_2 nanoparticles

Highly crystalline mesoporous MgF_2 nanoparticles were synthesized by a lyothermal synthesis developed by our group and described

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