Anti-Fogging Nanofibrous SiO$_2$ and Nanostructured SiO$_2$–TiO$_2$ Films Made by Rapid Flame Deposition and In Situ Annealing

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Transparent, pure SiO$_2$, TiO$_2$, and mixed silica–titania films were (stochastically) deposited directly onto glass substrates by flame spray pyrolysis of organometallic solutions (hexamethyldisiloxane or tetraethyloorthosilicate and/or titanium tetra isopropoxide in xylene) and stabilized by in situ flame annealing. Silicon dioxide films consisted of a network of interwoven nanofibers or nanowires several hundred nm long and 10–15 nm thick, as determined by microscopy. These nanowire or nanofibrous films were formed by chemical vapor deposition (surface growth) on bare glass substrates during scalable combustion of precursor solutions at ambient conditions, for the first time to our knowledge, as determined by thermophoretic sampling of the flame aerosol and microscopy. In contrast, titanium dioxide films consisted of nanoparticles 3–5 nm in diameter that were formed in the flame and deposited on the glass substrate, resulting in highly porous, lace-like nanostructures. Mixed SiO$_2$–TiO$_2$ films (40 mol % SiO$_2$) had similar morphology to pure TiO$_2$ films. Under normal solar radiation, all such films having a minimal thickness of about 300 nm completely prevented fogging of the glass substrates. These anti-fogging properties were attributed to inhibition of water droplet formation by such super-hydrophilic coatings as determined by wetting angle measurements. Deactivated (without UV radiation) pure TiO$_2$ coatings lost their super-hydrophilicity and anti-fogging properties even though their wetting angle was reduced by their nanowicking. In contrast, SiO$_2$–TiO$_2$ coatings exhibited the best anti-fogging performance at all conditions taking advantage of the high surface coverage by TiO$_2$ nanoparticles and the super-hydrophilic properties of SiO$_2$ on their surface.

1. Introduction

Anti-fogging,¹ bacteria-resistant, and self-cleaning,² surfaces are created by depositing either super-hydrophilic or -hydrophobic (e.g., Lotus effect) films that impact diverse applications such as sport and sanitary equipment, lenses for optical devices, automobile windshields, windows, and mirrors, to name a few. In particular, anti-fogging coatings are feasible by preventing formation of small water droplets on the substrate surface (super-hydrophilicity).³ Furthermore, such coatings should be transparent, mechanically stable, and inexpensive to facilitate their commercialization. Nanoparticles can enhance drastically the super-hydrophilicity/phobicity of a surface by increasing its roughness and thereby the liquid/solid interface. In fact, super-hydrophobic coatings have been obtained by wet deposition of super-hydrophobic particles on glass surfaces.⁵

Super-hydrophobic coatings are made of metal oxides,⁴ polymers,² or their mixtures.¹ Metal oxide coatings are thermally stable over the long term to be used in rough environments. The super-hydrophilicity is created either by micro-⁶/nano-scale⁷ texture (nanowicking) or by functional (e.g., hydroxyl) groups on the material surface.⁸ For example, the super-hydrophilicity of TiO$_2$ is attributed to its photochemical activity and amphiphilic surface.⁹ In fact, without UV radiation TiO$_2$ surfaces lose their super-hydrophilicity quite rapidly.⁸ Silica is also super-hydrophilic at high surface concentration of hydroxyl groups especially for flame-made SiO$_2$.⁹

The coating method and material properties greatly influence film performance in terms of transparency, stability, and anti-fogging. Wet methods have the advantage of relatively high coating mechanical stability by the use of binders and calcination/annealing. Their major shortcomings are the long process time (hours to days), many steps, and sometimes limited scalability¹⁰ and even reproducibility of coating morphology.¹¹ In contrast, dry methods can deposit highly porous nanostructured coatings in short times with good control, strong adhesion, and reproducibility.¹² In fact, dry deposition of nanostructured films can be achieved by sputtering,¹³ spray pyrolysis,¹⁴ cluster beam deposition,¹⁵ classified aerosol deposition,¹⁶ combustion chemical

vapor deposition (CVD)\(^\text{17}\) or flame spray pyrolysis (FSP)\(^\text{18}\) but only few of these methods can be scaled up to coat large surfaces at low cost.

FSP is a flexible and scalable\(^\text{19}\) process for synthesis and deposition of thick nanostructured coatings on large surfaces in very short time (seconds/minutes)\(^\text{17,18}\). The mechanical stability of FSP-deposited coatings can be increased by in situ film annealing (30–60 s) with an impinging flame.\(^\text{12}\) This rapid, two-step deposition method has been utilized recently to deposit sensor films of pure\(^\text{2}\) and SiO\(_2\)-doped\(^\text{20}\) SnO\(_2\) nanoparticles on CMOS-compatible microelectronic substrates.\(^\text{21}\)

Here, titania, silica, and mixed silica–titania nanostructured coatings (or films) are deposited by FSP of precursor solutions onto glass substrates and in situ stabilized by flame annealing. The coating mechanism for these materials is investigated by analysis of the aerosol and film properties. The film transparency, stability, and wetting are characterized as a function of deposition time (thickness and surface coverage) for each material and correlated to their anti-fogging performance. Furthermore, analysis of the wetting properties with and without UV radiation is used to determine the mechanism leading to TiO\(_2\) and SiO\(_2\)–TiO\(_2\) super-hydrophilicity.

2. Experimental Section

A FSP reactor was used in combination with a substrate holder as described in detail elsewhere\(^\text{18}\) for synthesis and direct deposition of TiO\(_2\), SiO\(_2\)–TiO\(_2\), and SiO\(_2\) nanostructured coatings onto glass substrates of 7.5 cm × 2.5 cm (VWR, EGN 631-1550). The film adhesion to the substrate was accomplished by in situ film annealing with a xylene-fed, particle-free spray flame.\(^\text{12}\) The TiO\(_2\) and SiO\(_2\) precursor solutions fed to FSP were prepared as follows: titanium(IV) isopropoxide (TTIP, Aldrich, purity > 97%) and hexamethyldisiloxane (HMDSO, Aldrich, purity > 99%) or tetraethyl orthosilicate (TEOS, Aldrich, purity > 99%) were mixed, as dictated by the final SiO\(_2\) molar content (0–40–100%), and diluted in xylene (Fluka, purity > 98.5%) with a total metal (Ti and Si) concentration of 0.05 mol/L. This solution was supplied at a rate of 5 mL/min through the FSP nozzle and dispersed to a fine spray with 5 L/min oxygen (pressure drop 1.5 bar). This spray was ignited by a supporting ring-shaped premixed methane/oxygen flame (CH\(_4\) = 1.5 L/min, O\(_2\) = 3.2 L/min). Additional 5 L/min sheath oxygen was supplied from an annulus surrounding that flame to ensure excess oxidant flow. At different heights above the burner (7, 11, 15, and 20 cm), particles were collected by thermophoretic sampling\(^\text{22}\) onto circular grids (Pelco) of 3 mm in diameter.

The average film thickness was either measured directly (e.g., SiO\(_2\) films) by atomic force microscopy (AFM) or calculated (e.g., TiO\(_2\) and SiO\(_2\)–TiO\(_2\) films) from the bulk thickness obtained by UV–vis transmittance spectra (Beer–Lambert’s law) utilizing a TiO\(_2\) absorption coefficient of 6 × 10\(^4\) cm\(^{-1}\) at 290 nm.\(^\text{23}\) For the latter, the porosity of the deposited films was assumed to be 98%\(^\text{18}\) as the in situ annealing was performed at too low temperature to alter the coating morphology as observed by SEM, in contrast to such stabilization of SnO\(_2\) sensor films with higher xylene feed rate (12 mL/min) to the impinging flame.\(^\text{12}\) These thicknesses were confirmed by scanning electron microscopy (SEM) analysis of the TiO\(_2\) films. The initial (10 s deposition) specific yields (%/cm\(^2\)) for SiO\(_2\)-fiber growth and TiO\(_2\)-particle deposition were calculated utilizing the concentration of the sprayed precursor and the corresponding deposited volume with density of 2.3 or 3.84 g/cm\(^3\) and molar weight of 60.1 or 80 g/mol for SiO\(_2\) or TiO\(_2\), respectively. The deposited SiO\(_2\) bulk volume was computed from the average SEM fiber length and diameter assuming a cylindrical shape and calculating their surface concentration no./cm\(^2\).

The TiO$_2$-film bulk volume was computed directly from the bulk thickness measured by light absorption as discussed above.

The temperature behind the substrate was measured by an n-type thermocouple. During deposition, the burner–substrate (BS) distance was 20 cm, and the substrate reached a maximum temperature of 550 ± 20 °C. The coatings were annealed in situ by lowering the substrate holder to BS = 14 cm and by impinging a particle-free (no metal precursor) xylene-fed (6 mL/min) spray flame onto the film for 15 s. During in situ annealing, the substrate reached a maximum temperature of 820 ± 20 °C at its front and 220 °C at its back. The supporting flame and sheath oxygen flows were those used during FSP deposition.

Transmission electron microscopy (TEM) was conducted in a Hitachi H600 microscope, operated at 100 kV. The morphology, patterning characteristics, and thickness of the deposited layers were investigated by SEM with a LEO 1530 Gemini (Zeiss/LEO, Oberkochen) and a Tecnai F30 microscope (FEI (Eindhoven); field emission cathode, operated at 300 kV). The coating morphology was investigated by AFM (Asylum Research MFP-3D) in tapping mode at standard room conditions with scan sizes ranging from 600 nm to 5 μm and elaborated with WSxM software. 24 Throughout the analysis, n-doped silicon tips with a resistivity of 0.01–0.025 Ω cm were used (Nanosensors, Neuchatel, Switzerland, type PPP-NCHR-W). The transmittance of the coatings was measured using a Varian Cary 500, UV–vis spectrophotometer.

Figure 2. Image of a 730 nm thick SiO$_2$–TiO$_2$ coating (40 mol % SiO$_2$). This film consists of lace-like structures made of airborne particles similar to pure TiO$_2$ films. In contrast to the smooth TiO$_2$ particle surfaces, here, spike-like endings are visible.

3. Results and Discussion

3.1. Nanostructured TiO$_2$-Based Films. Figure 1 shows top views of 190 (a) and 260 (d) nm thick, FSP-deposited, and surface annealed TiO$_2$ films on glass substrates placed at 20 cm height above the burner (HAB). These coatings have high porosity and surface roughness. After deposition of a 190 nm thick TiO$_2$ film (Figure 1a), polydisperse nanostructures are randomly distributed on the substrate surface. The size of these nanostructures is on the order of ten to a few hundred nanometers. Their morphology is similar to TiO$_2$ airborne agglomerates of nanoparticles thermophoretically collected from this FSP–aerosol at 20 cm HAB (Figure 1b). These agglomerates have a count mean diameter (CMD) of 57 nm and a geometric standard deviation (GSD) of 1.56 and consist (Figure 1b) of many primary particles less than 5 nm in diameter that have been assembled by Brownian coagulation and sintering. 26 Indeed, titania nucleates early in the flame and already at 7 cm HAB non-agglomerated particles of 3–5 nm in diameter are collected by thermophoretic sampling (Figure 1c). At higher magnification, a set of lattice fringes are visible throughout the particle with an interfringe distance of 3.57 Å consistent with the anatase (101) crystallographic plane. 27 Although some of these primary particles have been sintered forming aggregates, most are held together by weak physical bonds (agglomerates) and are dispersed easily. 26 This low cohesion and adhesion of agglomerates undermines the mechanical stability of the resulting coatings (Figure 1a,d) similar to FSP-made SnO$_2$ sensor films. 12

Prolonging the TiO$_2$ deposition time from 10 to 15 s increases the film thickness (from 190 to 260 nm: Figure 1a,d) that resulted in a constant specific yield of 0.041%/cm$^2$ indicating constant deposition rate. This specific yield could be increased (e.g., doubled) by decreasing the substrate HAB (e.g., from 20 to 12 cm HAB) as observed for thermophoretic deposition of SnO$_2$ particles in the same FSP burner. Furthermore, the deposition rate is nearly proportional to the precursor concentration. These deposited nanostructures form a network of primary

particles (Figure 1d,e) with lace-like morphology (Figure 1a,d) and poor mechanical stability. In fact, mapping their morphology by AFM was not possible as the nanostructures were displaced even by the AFM tip. Further stabilization of these nanostructures by in situ annealing was only partially possible in comparison to previous in situ annealed SnO$_2$ films on Si wafers as, here, the glass substrates cracked upon impingement of the annealing flame so its xylene feed rate and duration had to be reduced, as stated in the experimental part.

Deposition of mixed SiO$_2$–TiO$_2$ (40% mol SiO$_2$) films resulted in morphology similar to that of pure TiO$_2$ films (Figure 2). A slight difference is the shape of these structures. In contrast to the smooth TiO$_2$ primary particle surfaces (Figure 1e), the SiO$_2$–TiO$_2$ ones tend to be covered with SiO$_2$, as it will be shown later, having spike-like endings (Figure 2). Perhaps limited HMDSO condensation and oxidation followed by SiO$_2$ surface growth takes place on the surface of freshly formed TiO$_2$ particles competing effectively with CVD on the substrate. Unfortunately, it was not possible to identify TiO$_2$ or SiO$_2$ segregated regions by SEM and energy-dispersive X-ray spectroscopy as within the instrument resolution the phases were too well dispersed.

3.2. Films of SiO$_2$ Nanofibers. Coating with SiO$_2$ led to a drastically different, fibrous-like film morphology consisting of 10–15 nm thick and several hundred nm long SiO$_2$ fibers (Figure 3a). At 7 cm HAB (Figure 3b), it was not possible to detect any particles on the grids (b, c) employed for thermophoretic sampling of the combustion aerosol at various heights above the burner (HAB).

![Figure 4.](image_url) Surface mapping (a), top view (b), and line topography of a 230 nm thick SiO$_2$ coating by AFM. The coarse, chain-like structures detected by AFM (a, b) consist of several overlapping fiber bundles. A minimal fiber bundle thickness of 41 nm is detected here (c) which corresponds to 2–3 times the fiber diameter seen by SEM (Figure 2e).

![Figure 5.](image_url) Transmittance spectra of SiO$_2$ (solid line), SiO$_2$–TiO$_2$ (dashed-dotted line), and TiO$_2$ (dashed line) coatings having 310, 240, and 340 nm thickness, respectively. All coatings are completely transparent to visible light while a small increase in transmittance is detected for the TiO$_2$ coating above 370 nm indicating anti-reflection.
material was coating the TEM grid and only few particle-like spots were detected. This is in agreement with the slower formation and growth of SiO$_2$ particles by HMDSO oxidation than that of TiO$_2$ ones by TTIP oxidation in vapor-fed flames. The striking difference between SiO$_2$ and TiO$_2$ thermophoretic sampling indicates two different film synthesis routes: while TiO$_2$ coats the substrate by deposition of airborne particles, fibrous SiO$_2$ coatings are formed probably by CVD of SiO$_2$ on the substrate surface from HMDSO vapor that condenses onto the cold TEM grid before full oxidation. No fibers were observed downstream of the substrate or onto the exhaust filter. Using higher HMDSO concentrations (e.g., 0.5 mol/L) in the FSP precursor solution did not lead to fiber formation but to particle deposition as with TiO$_2$ which is equivalent to “snow formation” in CVD processes. Using TEOS instead of HMDSO at equivalent concentrations led also to formation of shorter fibers on the glass substrate. The formation of these fibers was reproducible (more than 10 samples have been analyzed by SEM), and their growth is initiated most probably by impurities that are usually present in glass substrates. In contrast, mesoporous silica films without any fibers (not shown) were formed on stainless steel substrates regardless of Si precursor. This indicates that SiO$_2$ fiber growth is achieved probably by preferential CVD of HMDSO or TEOS on the glass substrate during FSP of their precursor solutions.

Silica nanofibers or nanowires have been grown routinely from silicon metal at low pressure in the presence of noble metal or metal oxide catalyst nanoparticles or in solution with good control of nanofiber morphology. Here it is the first time to our knowledge that such SiO$_2$ nanofibers have been grown by combustion of Si-containing precursor solutions on glass substrates.

The (substrate) surface coverage obtained by these SiO$_2$ nanofibers (Figure 3a) is lower than that with TiO$_2$ nanoparticles. This has implications on their anti-fogging properties as will be shown later on. After moderate in situ annealing, the thin fibrous structures are preserved (not shown) and adhere even better on the substrate as indicated by AFM. In contrast to TiO$_2$ (or SnO$_2$) agglomerates (Figure 1), these SiO$_2$ fibers are bonded to the substrate. In fact, their high adhesion and cohesion allowed for their mapping by AFM (Figure 4) even without in situ surface annealing. Analysis of such 230 nm thick SiO$_2$ films by AFM (Figure 4a) shows a highly rough surface with a maximal height of

Figure 6. Evolution of water droplet (0.5 μL) contact angle (θ) on substrates flame-coated with TiO$_2$ (a), SiO$_2$ (b), and SiO$_2$–TiO$_2$ (c) films of various thicknesses (120–340 nm) under normal solar radiation as a function of contact time. All films have super-hydrophilic properties with the contact angles reaching 3°–8° in 0.5 s for all thicknesses.

Figure 7. In the absence of UV light, evolution of water droplet (0.5 μL) contact angle (θ) on glass substrates flame-coated with pure (filled symbols) and 40 mol % SiO$_2$-containing TiO$_2$ (open symbols) 180–260 nm thick films. The TiO$_2$ films lose their super-hydrophilicity as they do not reduce their droplet contact angle below 5° within 1 s while the super-hydrophilic SiO$_2$–TiO$_2$ films preserve it. Prior to these experiments all samples were kept in the dark (without UV light also) for 50 h.


562 nm with steep (20–40 nm) indentations (Figure 4b,c). Bumpy structures extend over the film substrate surface (Figure 4a) resembling cross overlapping fibers as observed by SEM (Figure 3a). Such bumps (Figure 4a) are too wide (≈200 nm) to be single fibers. In fact, surface topography along one of these bumpy structures (Figure 4b) reveals a discontinuous profile (Figure 4c) indicating several overlapping fibers. As a result, AFM cannot resolve single fibers (Figure 4c), so the minimal peak width of approximately 40 nm corresponds to 2–3 times the single fiber SEM diameter. The film thickness was increased from 150 to 310 nm by increasing the deposition time from 10 to 20 s. This results in an initial (10 s deposition) specific yield of 0.02%/cm² which is nearly half of that measured by TiO₂-particle deposition. Nevertheless, SEM analysis at higher deposition time (e.g., 20 s) suggests an increase in specific yield in agreement with the additional surface available for SiO₂ nucleation. Decreasing the precursor concentration to 0.01 mol/L reduced the fiber growth (or deposition) rate as observed by SEM. At any deposition time, the roughness of these SiO₂ films is similar and comparable to that obtained by bilayer impregnation.

### 3.3. Film Transparency, Wetting, and Anti-Fogging

Up to 340 nm thickness (Figure 5), all coatings were transparent (100% transmission at λ = 380–750 nm). The TiO₂ coatings started absorbing around 365 nm (broken line) in agreement with their bandgap of 3–3.1 eV. Above this wavelength (365 nm), the TiO₂ coating demonstrated slight anti-reflection increasing the transmittance from 100 to 102%. The SiO₂ coatings (Figure 5, solid line) were completely transparent down to 323 nm, in agreement with their wide bandgap of 8.9 eV. The SiO₂–TiO₂ coatings (dot-broken line) had an intermediate transmittance spectrum between that of TiO₂ and that of SiO₂ as one might expect. The complete transparency of these coatings is attributed to the ability of depositing extremely small amounts of homogeneously dispersed nanostructures and their high band gap energy. In fact, deposition of SiO₂ nanoparticles on glass surfaces by wet-chemistry methods reduced slightly the substrate transparency most probably by formation of larger agglomerated structures that scatter light quite effectively.

All coatings increased the hydrophilicity of the glass substrates as the steady state contact angle (θ) was decreased from 23° to 0°. Nevertheless, time-resolved θ measurements revealed differences. For anti-fogging surfaces, θ should drop below 10°–5° in about 0.5 s. Under normal solar radiation, all coatings (TiO₂, SiO₂, and SiO₂–TiO₂) of 120–340 nm thickness had similar performance (Figure 6) with θ reaching 10°–5° in 0.5 s. This result is remarkable as the contact angle with the bare/unmodified glass substrates was 23° even after 60 s.

The θ decreased rapidly reaching 6°–5° after 0.5 s for all film thicknesses or deposition times (Figure 6a,b). The super-hydrophilic properties of SiO₂ coatings (Figure 6b) are attributed to their high surface concentration of hydroxyl groups while TiO₂ performance is augmented by its photochemical activity. The mixed oxide coating (Figure 6c), however, appear slightly better than pure oxides. In fact, a 240 nm thick mixed oxide film

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(Figure 6c, circles) has wetting performance superior to all others. Apparently, the better surface coverage of stochastically deposited TiO₂ nanoparticles increases the substrate coverage while their coating with super-hydrophilic SiO₂ provides the best combination for minimal wetting angle. The coating stability was investigated by flushing these films with water, drying, and measuring the contact angle again. The stability of the in situ annealed coatings was high enough to withstand water flushing regardless of deposition time as observed previously for FSP directly deposited and in situ annealed SiO₂ layers.¹²

Figure 7 compares the effect of UV radiation on the performance of TiO₂ and SiO₂-TiO₂ coatings of two thicknesses. The TiO₂ coatings lost their super-hydrophilicity (Figure 7, filled symbols) after TiO₂ deactivation that took place by keeping the coated substrate in the dark for 50 h and performing the measurement with the aid of a UV filter. Once the TiO₂ was deactivated, the contact angle measured after 1 s increased from 4° under normal solar radiation (Figure 6a, triangles and squares) to 13° and 8° for the 190 and 260 nm thick films, respectively (Figure 7, filled symbols). This drastic θ increase without UV irradiation indicates that a significant portion of the super-hydrophilicity of these TiO₂ coatings did not come from their nanowicking (roughness and porosity, Figure 1). Indeed, the contact angle was decreased (8°-13°) in comparison to the bare substrate (23°) by their nanowicking as suggested previously.¹³,¹⁰ This was not sufficient, however, to achieve super-hydrophilicity. As a result, a significant portion of the present film super-hydrophilicity is attributed to the photocatalytic activity of TiO₂:water molecules are chemisorbed on Ti⁴⁺ sites generated by photoreduction of Ti³⁺, thereby inducing a super-hydrophilic behavior of the TiO₂ surface.³⁸

This was supported further by contact angle analysis of SiO₂-TiO₂ coatings. As discussed above, such coatings have similar substrate surface coverage (Figure 2) to pure TiO₂. In contrast to TiO₂, the SiO₂-TiO₂ coatings preserved their super-hydrophilicity also after TiO₂ deactivation consistent with sol-gel-made SiO₂-TiO₂ films.³⁷ In fact, the contact angles of the deactivated SiO₂-TiO₂ coatings after 0.5 s were 6° and 4.5° (Figure 7, open symbols) for the 180 and 240 nm films, respectively. This striking difference between TiO₂ (Figure 7, filled symbols) and SiO₂-TiO₂ (Figure 7, open symbols) films clearly shows that the super-hydrophilic properties of the nanoparticles determine the wetting properties of the coatings.

Uncoated glass substrates were fogged completely (Figure 8a) in a few seconds by condensation of small water droplets on their surface. Films having thicknesses of 150, 120, and 190 nm for SiO₂, SiO₂-TiO₂, and TiO₂, respectively, reduced differently the surface fogging (Figure 8b,d,f). Despite the added super-hydrophilicity by these coatings, some droplets are formed at these low film thicknesses (or coverage) especially on SiO₂-based films thereby partially fogging the glass (Figure 8b,d). This is attributed to the smaller substrate surface coverage of these coatings (Figure 3) than that made by dispersed pure TiO₂ particles (Figure 1). In fact, the SiO₂-TiO₂ coatings have an intermediate anti-fogging performance between that of SiO₂ and that of TiO₂ ones. Increasing the film thickness up to 310, 240, and 340 nm for SiO₂, SiO₂-TiO₂, and TiO₂, respectively, prevented fogging of all glass substrates (Figure 8c,e,g). This confirms that a minimal surface coverage is required to avoid formation of small droplets on the substrate; otherwise, its surface can be partially fogged from droplets forming on its uncoated area.

4. Conclusions

Rapid synthesis of water stable, transparent anti-fogging coatings of SiO₂, TiO₂, and SiO₂-TiO₂ by direct flame aerosol deposition and in situ annealing on transparent glass substrates was achieved. A minimal thickness of 200-300 nm of as deposited coatings or films was necessary to obtain full anti-fogging performance. The mechanical stability of the coatings was increased by rapid in situ annealing for 15 s. The in situ annealed coatings preserved their super-hydrophilicity and anti-fogging functionality after being flushed with water. The anti-fogging properties were attributed predominantly to the photocatalytic effect for TiO₂ and to the super-hydrophilic nature of flame-made SiO₂. Most notably, it was discovered that SiO₂ nanofibers or nanowires 10-15 nm in diameter and tens to hundreds of nanometers in length were made by FSP of solutions containing silicon precursors such as HMDSO and TEOS on glass substrates without any pretreatment. Such nanofibers were similar to those grown routinely on Si metal using noble metal or metal oxide nanoparticles as catalysts. Finally, the easy synthesis of complex composites by FSP can enhance further the functionalities of such coatings as observed for SiO₂-TiO₂ films which possess both the anti-fogging properties of SiO₂ coatings and the self-cleaning photocatalytic effect of TiO₂ ones.

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