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TiO$_2$ nanotree films for the production of green H$_2$ by solar water splitting: From microstructural and optical characteristics to the photocatalytic properties

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**A B S T R A C T**

Green H$_2$ production by solar water splitting relies entirely on the intrinsic properties of the photocatalyst. In this study the impact of these intrinsic properties on the photocatalytic activity of anatase TiO$_2$, the quintessential component of state of the art photocatalytic systems was explored at the nanoscale. The exploration involved a holistic microstructural and optical characterization of fully crystallized anatase thin films synthesized by metalorganic chemical vapor deposition. A combination of electron microscopy, spectroscopic ellipsometry, and infrared spectroscopy revealed that when the deposition temperature increased, the morphology evolved from dense to porous and columnar nanostructures. Interestingly, the columns with a complex, tree-like nanostructure catalytic performance outweighs the detrimental aspects inherent to this evolution, namely the drop of the charge carrier transport and the increase of residual stress.

1. Introduction

Research on renewable energy is vital in the current context of global warming and societies that rely on high energy consumption. Hydrogen is a promising source of renewable energy and catalyzed solar water splitting (SWS) is a carbon-free method to produce it. Numerous materials have been tested to catalyze this reaction $[1,2]$. Among them, TiO$_2$ – because it is non-toxic, chemically stable, abundant and affordable has been widely investigated as a photocatalytic material since Fujishima and Honda’s seminal work $[3–8]$. Despite its high energy band-gap (3.2 eV), crystalline anatase TiO$_2$ shows attractive opto-electronic properties. It is an indirect semiconductor with a long exciton lifetime $[9,10]$; it has a conduction band minimum energy level below the redox potential of H+/$\text{H}_2$ (0 V vs. NHE) and a valence band maximum energy level above the redox potential of O$_2$/H$_2$O (+1.23 V vs. NHE) $[11,12]$. In contrast with powders,
anatase TiO$_2$ films can be used in photocatalysis as well as in electro-photocatalysis. They are produced by various methods: sol-gel [13], anodization [14], reactive magnetron sputtering [15], atomic layer deposition (ALD) [16] or metalorganic chemical vapor deposition (MOCVD) [4,7,18]. This last process interestingly enables the production of various hierarchical morphologies that have an impact on the photocatalytic properties [5,19].

One way to efficiently control the morphology is the deposition temperature ($T_d$), which allows obtaining nano- or microstructures that range from dense to columnar [20–22]. Such $T_d$ induced nanostructuration results in the increase of the specific surface area and therefore enhances the photocatalytic activity [23]. However, an increase in $T_d$ can concomitantly affect other properties, such as the texture, the electrical transport, the residual stress, and the nature of the external crystallographic facets in contact with the aqueous solution. These factors can either enhance or be detrimental to the photocatalytic activity [23–27]. Other aspects such as the stoichiometry can also influence the photocatalytic performance through the subsequent modification of the electronic properties.

A significant number of results has been reported on the determination of the morphology [16,19,28,29], the crystallographic phases [22], the mechanical residual stress [26,30], the purity [2], the electrical transport [9], and the optical band-gap [31]. However, there is no systematic, holistic study of TiO$_2$ films in the context of a strong morphology evolution that connects all of these characteristics to the evolution of their photocatalytic properties. The present work thus, focuses on an extended characterization of MOCVD anatase TiO$_2$ films in order to investigate their photocatalytic behavior and thereby improve the photocatalytic performance by monitoring deposition parameters. The outcomes of this work can be extended to nanostructured TiO$_2$ films synthesized by other techniques.

We deposit TiO$_2$ films by thermally activated MOCVD from titanium tetraisopropoxide (TTIP) at six temperatures between 325 and 500 °C. We quantify the surface morphology of the deposited films through image processing and analysis of field emission scanning electron microscopy (FESEM) micrographs. We apply, for the first time, electron backscatter diffraction (EBSD) to determine the growth direction of the anatase films. We determine the intrinsic mechanical residual stress of the films and their evolution with $T_d$ by grazing incidence XRD (GIXRD), and we probe the mechanical properties at the nanoscale by peak force quantitative nanomechanical (PF-QNM). The electrical properties are investigated at the nanoscale by conductive atomic force microscopy (C-AFM) and at the macroscale by Hall effect measurements. We fit spectroscopic ellipsometry (SE) measurements using the Cody-Lorentz model [32], a powerful tool to determine the thickness, the band-gap, and the refractive index that is affected by the porosity. We correlate the outcome of this comprehensive microstructural, electrical, electronic, and optical study with the photocatalytic activity measured by two techniques. First, we measure the photodegradation of stearic acid catalyzed by the TiO$_2$ films by Fourier transform infra-red (FTIR) spectroscopy, which is a variant of the Pilkington test [33–35]. Second, we measure the H$_2$ photogeneration under Xe lamp irradiation in a controlled atmosphere by gas chromatography [36].

2. Material and methods

TiO$_2$ films are deposited in a vertical, cylindrical, stagnant flow cold wall stainless steel MOCVD reactor, which has been described in detail elsewhere [37]. In each experiment, P light-doped (1–20 Ω·cm) and As high-doped (0.001–0.005 Ω·cm) n-type Si (100) wafers, and fused silica windows (Neyco) are placed on the heated sample holder. Titanium tetraisopropoxide (TTIP, 99.999%, Sigma-Aldrich) is conditioned in a double-walled glass bubbler and is thermally regulated at 20.5 °C. Pure nitrogen (99.9999% Messer) is used as both the carrier and dilution gas, and their flow rate is fixed to 4.7 and 52.4 sccm, respectively. All gas lines are thermally regulated at ca. 65 °C. Depositions are performed at 1 Torr fixed pressure, at different $T_d$ ranging from 325 to 500 °C, with various durations that are adapted to produce films of similar thickness (~350 nm).

Film composition is investigated by X-ray photoelectron spectroscopy (XPS). The photoelectron emission spectra are recorded using a monochromatized Al K$_\alpha$ ($h\nu = 1486.6$ eV) source on a ThermoScientific K-Alpha system with a 400 μm X-ray spot size. Depth profiling is performed by means of Ar$^+$ ion etching under 2 keV.

The crystal structure is investigated by XRD in a Bruker-D8 diffractometer equipped with a Cu Kα ($\lambda_{CuKα} = 0.154$ nm) anode in theta-theta mode with a ~3° offset. In addition, GIXRD is used to determine residual stress using a 4-circles goniometer (Panalytical X’Pert) equipped with a Cu anode ($\lambda_{CuKα} = 0.154$ nm) at 40 kV and 40 mA, with Soller slits to get a nearly parallel beam, and a fast recording detector (Xcelerator, Panalytical). The sin$^2$ψ method (11 $ψ$ angles ranging from −60° to 60°), in one direction ($ϕ = 0°$), was applied to the samples deposited on fused silica substrates. The (020) family plane (2θ = 48.08°) is analyzed from 45.7° to 51.2° with a 0.066° step, with the step time varying between 2000 and 2700 s depending on the sample. The XRD penetration depth is estimated at 100 nm for dense TiO$_2$. The modus operandi to determine the strain from XRD measurements is explained in the Supplementary Information (SI section 1).

EBSD measurements are performed in a FESEM Jeol JSM 7100F TTLS LV on the sample surface to explore crystalline orientation. 8633, 4604, and 7888 points are measured on the 500 °C, 400 °C, and 325 °C samples, respectively, on 38 μm² surfaces. Because each grain is probed only once to avoid overrepresentation of one grain orientation, the distribution remains statistical. Mid-IR (MIR) FTIR and far-IR (FIR) FTIR spectra are recorded by Perkin Elmer Frontier, and Nicolet iS50 ThermoFischer Scientific spectrometers, respectively. Films deposited on fused silica are investigated by transmission, total and diffuse reflectance spectroscopy in the 200–1650 nm spectral range, using an Agilent-Cary 5000 spectrophotometer equipped with an integrating sphere. Samples deposited on Si coupons are analyzed by spectroscopic ellipsometry (SE) in the same spectral range with an incidence angle of 75° using a Semilab SE-2000 apparatus. Spectroscopic ellipsometric porosimetry (SEP) is performed with a Semilab GESSE spectroscopic ellipsometer (250–1000 nm) coupled with a lab-made cell in which ethanol pressure is increased step by step to progressively acquire ellipsometric data adsorption isotherms in almost steady state. Before any data acquisition, the cell is pumped down to 50 mTorr, whereas the sample is heated up to 200 °C in the vacuumed cell for several minutes for a complete desorption from the TiO$_2$ film. The ellipsometry data are analyzed on the energy range 1.24–4.25 eV by the Semilab SEA software using a two-layer architecture. A Cody-Lorentz oscillator model is used to describe the optical properties of the film, and a Bruggeman effective medium approach is chosen to simulate the surface roughness.

With this full optical model, the regression goodness of fit in this range is over 0.98. The Cody-Lorentz model enables us to probe band-to-band transitions at the optical band edge and above the band edge, as well as band tails in the transparent spectral domain.

Top view and cross sectional scanning electron microscopy (SEM) micrographs of the Pt-metalized samples are obtained with a field emission FESEM Jeol JSM 6700F instrument. Before analyzing top view SEM images with the nanoTOPO-SEM™ software provided by Nanometrics, they are processed to normalize the contrast of their illumination. Transmission electron microscopy (TEM) and high resolution TEM (HRTEM) data are obtained with a JEOL JEM 2100F microscope. TEM specimens are prepared using a FEI Helios Nanolab600i dual beam SEM FIB (focused ion beam). The ion column is operated at 30 kV for all steps except final cleaning of the specimen, where a voltage of 5 kV and 2 kV is used. Beam currents vary between 47 nA and 15 pA. The electron beam is used to deposit a layer of C 200 nm thick over an area of 20 μm × 2 μm. The ion beam was then used to deposit a layer of Pt 3 μm thick over the same area. The sample was lifted out in situ and then attached to a copper support grid. Thinning of the specimen
could proceed using a gradual cross-section cleaning milling pattern, with a final milling beam current of 80 pA. Finally, a 5 kV and 2 kV cleaning steps were carried out on each side.

Surface topography is probed by a Bruker Multimode 8 AFM apparatus in PF-QNM mode with Si-tip (Tesor-V2, Bruker). The mechanical deformation is mapped using maximum contact force of ca. 65 nN. The tip sensitivity and its spring constant k are determined by force distance curve on Si reference wafer and by thermal tune, respectively. The vertical nanoscale charge transport is locally probed on thin films deposited on highly doped Si wafers by the AFM in conductive mode using a SCM-PtSi (Bruker) tip. A contact force of 27 nN and a sensor sensitivity of 100 nA/V are used. Hall measurements are conducted in a DC magnetic field with AC current from a Keithley 6221 current source and with an amplifier MFLI from Zurich Instruments. The contacts are Cu/Be and the injected current is of the order of $10^{-7}$ A.

The normalized Pilkington tests follow the photodegradation of stearic acid under UV–visible light (above 355 nm), as described elsewhere [28]. The relative quantity of stearic acid on the TiO$_2$ films is analyzed every 20 min by following the most intense stearic acid FTIR peak intensity evolution. For each sample, the test is repeated once after water cleaning. After the first run, the 500 °C film is delaminated, in contrast with the others which present perfect integrity. Finally, TiO$_2$ induced water photodissociation tests are performed in a quartz reactor filled with a water-ethanol solution (1:1 vol) under Xe-lamp (300 W) illumination. The produced H$_2$ quantity is measured every 6 h with a gas chromatography apparatus connected to the photodissociation reactor (PlotQ column (30 m) and PE-moliseive column (30 m); thermal conductivity detector; carrier gas: Ar).

A substantial effort has been made to ensure that only the final analysis for each sample is destructive or potentially destructive. To this end, both H$_2$ photogeneration and stearic acid photodgradation are realized on different samples for each $T_d$, which have not been exposed to other destructive analyses.

3. Results

3.1. Crystallographic phase and texture

The composition of the TiO$_2$ films, which was determined on a preliminary basis by XPS, showed no other contamination than the classical surface carbon due to adsorption of organic molecules, as revealed by the depth profiles.

Fig. 1a shows XRD patterns obtained in a theta-theta mode, of ca. 350 nm TiO$_2$ films deposited on SiO$_2$ substrates at the different $T_d$. In this figure, and in the rest of the text, the following color coding is used: dark blue, light blue, green, yellow, orange, and red for $T_d$ of 325, 350, 375, 400, 450, and 500 °C, respectively.

Peaks measured at 25.4, 38.5, 48.1, 55.1, 62.7, 70.3, 75, and 76° correspond to the (101), (112), (020), (121), (024), (220), (125), and (031) crystallographic planes of anatase, respectively, according to the 99-100-9704 JCPDS powder card depicted for comparison. No peak from rutile or brookite is detected. All diffractograms present different intensity ratios than the powder reference pattern (shown in black), revealing textured films. Diffractograms of films deposited between 325 °C and 400 °C are rather similar, with two major peaks (101) and (020) that increase slightly with increasing $T_d$. By contrast, diffractograms, of films deposited at 450 °C and 500 °C show a general and significant intensity decrease, along with a change in peak ratio. The (101) and (020) peaks vanish while the (112) and the (220) (Fig. 1b) peaks increase.

Khalifa also reports a general decrease of XRD peak intensity with increasing $T_d$ especially above 400 °C, for TiO$_2$ films deposited by MOCVD in similar conditions [22]. In this temperature range, a change also occurs in the relative intensities between the (101) and (112) peaks, with the latter becoming predominant. The author attributes this behavior to the decrease of the migration length of the precursor.

![XRD patterns of TiO2 films deposited on SiO2 substrates at different Td. The inset (b) presents an enlargement of the (220) peak.](image-url)
molecules with increasing $T_d$, which subsequently allows less time for entities to arrange themselves in dense structures and leads to the increase of the nucleation rate. A high $T_d$ would favor the formation at the surface of the (112) plan, less dense than (101), and would explain the change of the texture [22]. Alternatively, the observed changes in the XRD pattern are attributed to the decrease of the c/a ratio arising from the near transition from anatase to rutile [38]. This possible initiation of change of phase and texture could explain the general decrease in intensity of the XRD pattern with increasing $T_d$. To further investigate the change of texture, EBSD analysis was performed on three samples deposited at 325 °C, 400 °C, and 500 °C, respectively. The EBSD pole figures are presented in Fig. 1c with the substrate surface in the XY plane. Color mapping (same color level for all maps) represents the multiples of uniform distribution (MUD), in which a high value indicates a special orientation of the corresponding crystallographic plane. The low $T_d$ densely structured films present a (100) growth direction, revealed by the MUD value of 5 in the center of the corresponding pole figure. However, if the growth was following only the (100) direction, it would result in an additional signal pointing at ca. 90° in the same pole figure, the two signals corresponding to the < 100 > and < 010 > directions, equivalent in the tetragonal system. The absence of this feature means that at least one additional texture component exists, with another growth direction whose Miller indexes are different from 0 and 1. Nevertheless, the inference that < 100 > is one of the main growth direction at low $T_d$ is in accordance with the evolution of the XRD patterns vs $T_d$ in Fig. 1a, which show that the (020) peak (corresponding to the < 100 > direction in the tetragonal system) is the most intense at low $T_d$. The intermediate $T_d$ sample (400 °C) does not present any MUD value higher than 3, indicating a transient regime with weak texture. This could be explained by a transition state between low- and high-$T_d$ films. In contrast, the highest $T_d$ sample (500 °C) shows a (110) growth direction. The corresponding most intense MUD value of 8 reveals the strongest texture among all samples. This evolution is consistent with XRD results in Fig. 1b, which show that the intensity of the (220) peak increases with increasing $T_d$ and reaches a maximum at 500 °C. There is strong evidence of at least one more texture component in this sample. Indeed, the (110) pole figure shows not only the central disk and a circle at ca. 90°, both belonging to the texture component already mentioned, but also a supplementary ring at ca. 25°. Furthermore, the (001) pole figure shows a ring at ca. 50°, in addition to the ring at ca. 90° that belongs to the first texture component.

Fig. 2a shows the FIR-FTIR spectra of the TiO$_2$ films normalized by their thicknesses as a function of $T_d$. The FIR transmission spectra were obtained with normal incidence. The spectra present peaks at 260 and 440 cm$^{-1}$, which correspond to the anatase transverse optical phonons TO$_1$ and TO$_2$, respectively, as reported by González et al. [38]. Two broad shoulders centered at ca. 340 and 400 cm$^{-1}$ are noticeable. The first shoulder corresponds to the TO$_2$ contribution. With increasing $T_d$, the TO$_1$ and TO$_2$ bands experience a general broadening, corresponding to the greater contribution of the previously mentioned shoulders, and an intensity decrease resulting from the increase in the porosity. Therefore, the TO$_1$/TO$_2$ intensity ratio increases.

Moreover, a third shoulder emerges at ca. 520 cm$^{-1}$ at 375 °C and above. The increase of the intensity of this broad shoulder with increasing $T_d$ is explained by the progressive increase of voids among the crystallites [29].

Fig. 2b shows MIR-FTIR spectra with an incidence angle of 70°. This configuration enables probing the longitudinal optical (LO) modes, which have a wave vector perpendicular to the film surface, in addition to the TO modes. This phenomenon, known as Berreman effect, has been highlighted by Trasferetti et al. [40] to identify the LO and TO bands of anatase, rutile, and amorphous TiO$_2$. In the present case, the FTIR analysis shows that the films are composed of anatase only, with two major peaks around 440 cm$^{-1}$ (TO$_1$) and 855 cm$^{-1}$ (LO$_2$), in agreement with XRD and Raman analysis (not shown here) that did not reveal any other crystal phase. The evolution of the TO$_2$ peak intensity with increasing $T_d$ remains the same as previously described for normal incidence FIR measurements. In addition, LO$_2$ peak intensity decreases as well, but to a lesser extent, resulting in the increase of the LO$_1$/TO$_2$ peak intensity ratio. In addition, a shoulder is observed at ca. 750 cm$^{-1}$, which can be related to the contribution of the LO$_2$. The evolution of the LO bands may be connected to the change in texture observed by EBSD and could suggest that high $T_d$ samples have an orientation of the crystallites that favors the LO probe [41]. Moreover, with increasing $T_d$ the LO$_1$ peak shifts progressively from 860 cm$^{-1}$ to 842 cm$^{-1}$, as highlighted by the arrow, with a concomitant increase of the LO$_2$/TO$_2$ intensity ratio. This is not discussed in the literature for TiO$_2$; however, Primeau et al. observed a drop of the LO$_1$/TO$_2$ intensity ratio and an inherent blue-shift of the LO$_2$ band with an increase in the annealing temperatures of SiO$_2$ samples [42]. This behavior could be related to the densification of the structure and the decrease of disorder. Therefore, the observed LO$_2$ red-shift and the increase of the LO$_2$/TO$_2$ intensity ratio with increasing $T_d$ can be explained by the increase in porosity and by the subsequent impact on density and disorder. Another indirect indication of the increase in the porosity is a broad and weak band in Fig. 2c, centered at ca. 3300 cm$^{-1}$, which corresponds to the stretching vibration of un-dissociated water [43,44]. The broad band intensity is globally higher for the high $T_d$ samples, because of their highest porosity (as previously shown by the emergence of the
520 cm$^{-1}$ contribution), which results in a higher amount of water adsorbed on the surface.

The crystallinity of the highest $T_d$ sample was investigated by TEM as follows: the diffraction pattern of a selected area was divided in six sections and the six resulting dark field images were superimposed (Fig. S1, SI). Since bright parts are crystalline (and well oriented) in dark field images, if a dark part is crystalline on the superimposition image, then every brighter section is crystalline as well. For this reason, the area in the small black square on the figure, which is one of the darkest parts of the probed sample zone, was investigated by high resolution TEM (HRTEM). Its fast Fourier transform, also presented in Fig. S1b (SI), reveals diffraction spots corresponding to the crystallographic planes of anatase. It is thus concluded that the entire area and, consequently, the film as a whole (considering the good homogeneity of the sample), is crystalline. Fig. S2b–c (SI) shows the diffraction pattern of two encircled areas of the dense lowest $T_d$ sample (325°C) and Fig. S2b–c (SI) shows the summit of a grain and its crystallographic planes: both reveal that this film is entirely crystalline.

3.2. Morphology

The morphological evolution of the TiO$_2$ films with $T_d$ is studied by FESEM. Fig. 3 presents top-down (left) and 25° tilted cross-sectional (right) FESEM micrographs of the TiO$_2$ films. With increasing $T_d$, both surface and cross-sectional micrographs show a decrease in the size of the various structures, with morphologies evolving from dense and angular structures to isolated and nanostructured tree-like columns. It is noticeable that the films deposited at 325 and 350°C show similar morphologies, and the same holds for those deposited at 450 and 500°C. The transition from compact to columnar morphology is initiated at 375°C, as shown by the subdivision of grains on the top-down micrograph (left). The morphology evolves further at 400°C, at which point a rather disordered columnar structure emerges. The evolution of the morphology with the increase of $T_d$ is accompanied by a significant increase in the porosity: at 375°C, it is manifested only between grains, whereas at 400°C and above, it is also manifested in the small features that can be observed within the columns. Therefore, the specific surface area of the films increases considerably with increasing $T_d$.

Images were analyzed with the nanoTOPO SEM™ software (Fig. 4) to achieve a quantitative description of the film morphology. Fig. 4a shows the evolution of the correlation length (CL) and the spatial periodicity, which are related to the grain size and density, with $T_d$. Fig. 4b shows the evolution of skewness and kurtosis, which are related to the porosity.

The CL describes distances with pixels of same gray levels on the FESEM images. Therefore, in the present case, it depends on the grain size and illustrates its evolution. With increasing $T_d$, CL decreases drastically from 67 nm at 325°C to 13 nm at 375°C, and then reaches a plateau. This behavior is attributed to the co-existence of two grain sizes in the surface morphology of films deposited between 350 and 450°C. Since CL is calculated from the short-distance behavior of the autocorrelation function of image pixels, it is more sensitive to the smaller size: consequently, in the present case, it captures the very first appearance of the columnar structure in surface morphologies at 375°C.

The spatial periodicity is calculated from the inverse of the spatial frequency, which corresponds to the more prominent peak of the Fourier transform of the FESEM image. For samples deposited at 325 and 350°C, which are characterized by closely packed structures, the spatial periodicity value is ca. 500 nm. This evaluation of the size of the repeat unit corresponds to the width of a pack with different local elevations. Increasing $T_d$ results in an overall decrease in the spatial periodicity. Stabilization occurs for the samples deposited at 450 and 500°C: ca. 88 nm. In this case of discrete surface features, this value describes the mean distance between one side of a column and the equivalent position on the next column, including the inter-columnar porosity. In contrast with CL, which already reaches a plateau at 375°C, the spatial periodicity saturates only at the end of the morphological transition when the compact structures have been completely eliminated and the vertical columns cover the whole surface. This is due to the method of evaluating the spatial periodicity, which is sensitive to the presence of large features when mixed morphologies, composed of compact and columnar structures, co-exist. Complementary to CL, which marks the beginning of the surface morphological transition at 375°C, the spatial periodicity is an indicator of the end of the transition.
that occurs at 450 °C.

Skewness and kurtosis (Fig. 4b) are two parameters describing the shape of the grey level histogram of images. Kurtosis describes the flatness of the histogram, thereby discriminating the case in which there is a strong contribution of the dark and light pixels (kurtosis < 3) from the images in which the vast majority of pixels is around the mean grey level (kurtosis > 3). Kurtosis values are higher than 3 for the three samples deposited between 325 and 375 °C, corresponding to a significant contribution for these samples from mean grey pixels, and consequently to relatively flat surfaces with small local slopes. For the three samples deposited at the highest $T_d$, kurtosis values are lower than 3 because of the greater contribution of brighter pixels (corresponding to the extremities of columns) and darker pixels (corresponding to the porosity among columns). Skewness characterizes the symmetry of the histogram; i.e. whether the darker (skewness < 0) or the lighter (skewness > 0) pixels are the more prominent. It becomes negative above 375 °C, revealing the gradual darkening of the micrographs that marks the emergence of the inter-columnar porosity.

Fig. 4c illustrates the evolution of the arithmetical mean deviation ($R_a$) and the root mean squared ($R_q$) roughness of the assessed profile with increasing $T_d$. The $R_a$ and $R_q$ of films deposited at 325 °C equal 33 and 42 nm, respectively. These values show consistent evolution, i.e. they monotonically decrease with increasing $T_d$ and are stabilized at 5 nm at 450 °C and above. A complementary approach to the estimation of the roughness is provided by SE analysis, where roughness is simulated by a surface layer composed of a volume fraction of void and of TiO$_2$ following the Bruggeman effective medium approximation. Fig. 4c also shows the evolution of the thickness of this roughness layer vs $T_d$. The thickness is 40 nm at 325 °C, which then decreases to 28 nm at 375 °C and finally increases to reach the maximum value of 42 nm at 500 °C. Whereas the three lowest $T_d$ samples give consistent roughness results regardless of the probing technique (photons or mechanical probe), the values for the columnar samples depend strongly on the probing method, namely on its depth sensitivity. SE analysis seems to take into account the beginning of the inter-columnar void below the summits, in contrast with the AFM tip, which cannot probe the porosity among adjacent columns at a fine scale.

To obtain a deeper insight into the morphology of the columnar 500 °C film, we compare TEM and FESEM micrographs in Fig. 5. The sample is 15° tilted in the plane of the images on all TEM images. The FESEM cross-section image, Fig. 5a, shows bottom-up oriented, cypress-like columns, illustrated by the inset scheme. The surface micrograph of Fig. 5b shows compact triangular superstructures, which are

![Fig. 4. FESEM images analysis parameters vs $T_d$. (a) Correlation length (CL) and spatial periodicity. (b) Kurtosis and skewness. (c) AFM $R_a$ and $R_q$ roughness values, and ellipsometric roughness vs $T_d$.](image)

![Fig. 5. Electron microscopy images of the 500 °C anatase film. (a) Cross-section FESEM image. (b) Top-view FESEM image. (c–d) Cypress-like TEM image. (e–f) Fir-like TEM image. (g) HRTEM of the cypress-like summit. (h) HRTEM of the apparent conical-shaped summit.](image)
comparable with the top view scheme of cypress-like columns. Bottom-up oriented cypress-like columns are also visible in the TEM cross-section in Fig. 5c–d. However, in some rare cases, the layers of the structure are oriented toward the substrate, resembling a fir-like morphology as shown in Fig. 5e–f. We conclude that the layered structures present a wide range of orientations, with an apparent predominance toward the top. Fig. 5 (panels g and h) shows HRTEM micrographs of two columns, a cypress-like summit and an apparently conical one, which may represent the same structure from two different perspectives. All micrographs highlight the high specific surface of the 500 °C samples formed by such columnar morphology.

TEM analysis indicates that the column summits are monocrystalline. In contrast with the low Td morphology composed of monolithic grains, this 500 °C film morphology composed of a forest of tree-like nanostructures is far more complex. It exhibits small-scale details and large variability in the orientation of the films. Therefore, taking into account the different sides of each column and column layer, this implies that the columnar structure exhibits a higher diversity in the crystallographic facets at the surface than the dense films.

3.3. Mechanical characteristics

Fig. 6a–c presents the AFM surface micrographs of the 325, 375 and 450 °C samples. The observed morphology is in agreement with the FESEM images. Deformation maps of the same probed sample area for a maximum applied force of 65 nN are shown in Fig. 6d–f. Fig. 6g is the deformation occurrence diagram of the six samples. The dense 325 °C film exhibits a mechanical response to stress that differs from one grain facet to another, resulting in the observation of six different deformation areas (see the blue arrows). For intermediate Td, three different deformation areas remain, whereas at higher Td (450 °C and 500 °C) the deformation is homogenous over the surface. At low Td, the diversity in mechanical responses is probably linked to small variations in the Young’s modulus as a function of crystallographic orientation [45]. At high Td we link the decrease in the diversity of deformation areas to the general decrease in the grain size, which means that what is probed at higher Td is the mechanical response of a group of nanostructured tree-like columns with different crystallographic planes. It is also noticeable that the mean deformation under a fixed applied force increases globally with Td, i.e. with the change in morphology from dense to columnar. This is compatible with the increase in the porosity within and between the grain, which enables easier deformation.

The residual stress of the films was investigated by GIXRD. For all samples, the residual stresses are compressive and increase from −150 ± 20 MPa at 325 °C to −300 ± 100 MPa at 450 °C, as shown in the inset of Fig. 6g. These values are low compared to the Young's modulus of bulk (195 GPa [45]) and the stress of anatase films reported in the literature for different deposition techniques (sol-gel: −2185 MPa [46], sputtering: −890 MPa [26], ALD: −700 MPa [45]). As mentioned in Section 2 of the SI, these anatase films are supposed to be quasi-isotropic and two stress origins can be considered: σth, the film growth stress induced during the deposition and σres, the thermal stress induced by the difference in the thermal expansion coefficients of the SiO2 substrate and the TiO2 film during cooling after deposition. The residual stress can be a mixture of thermal and growth stress. For the films deposited, the estimates of thermal stress σth in the film range between 798 and 1256 MPa, as shown in Section 2 in SI. Therefore, excluding the thermal stress, the growth stress for all the samples is strongly compressive, ranging between −948 and −1425 MPa. This compressive growth stress is very likely to ensue from the evolution of

![Fig. 6. (a–c) Evolution of topography and (d–f) deformation for three different Td, 325 °C (a, d), 375 °C (b, e) and 450 °C (c, f). (g) Mechanical aspects: influence of Td on deformation occurrence, the insert shows the residual stress σ against Td probed by GIXRD. (h–j) Topographic maps corresponding to the current maps: (h) 325 °C, (i) 375 °C and (j) 450 °C.](image-url)
the morphology and texture.

3.4. Electrical characteristics

Fig. 6b-j shows the current maps of the TiO$_2$ samples deposited at 325, 375, and 450 °C, probed under negative voltage. The maps show a decrease in the maximum current (see the current scale on the right) with the increase of $T_d$. However, these maximum values are related to very small areas of the maps. Therefore, the mean values are more representative of the evolution of the electrical properties of the films. Under the same applied voltage of -3 V, they are $-108$, $-6$, and 0 nA for samples deposited at 325, 375, and 450 °C, respectively. They take into account the conductive area ratios, which are 50, 14, and 10%, respectively. The general decrease in charge transport with the increase in $T_d$ follows the appearance of the columnar structures and of the increase in the porosity.

Hall effect measurements on samples deposited at 325 and 400 °C evidence the n-type character of the TiO$_2$ films. It is reasonable to assume that the samples deposited at intermediate $T_d$, i.e. 350 and 375 °C, are n-type semiconductors as well. Furthermore, charge carrier density for the 325 °C sample is $1 \pm 0.3 \times 10^{18}$ cm$^{-3}$ and that for the sample deposited at 400 °C is $2.9 \pm 0.2 \times 10^{18}$ cm$^{-3}$. This increase implies a decrease in the charge mobility, which can be attributed to the increased complexity of the morphology with the emergence of voids between and inside the nanostructures.

3.5. Optical characterization

In order to determine the optical band-gap $E_g$ of the films, we plot in Fig. 7a the Tauc plot of the absorption coefficient $a$ for indirect semiconductors. Despite the fact that all films present similar thicknesses determined by SE and by FESEM (295–435 nm), it is clear that interference fringes below the optical absorption edge disappear for low $T_d$ films (< 400 °C). This is because of light scattering caused by larger nanostructures above 300 nm that clearly emerge below 400 °C, as shown by FESEM and AFM (Fig. 3 and Fig. 6a-c). This is confirmed by the diffuse reflectance spectra showing a significant increase in intensity while $T_d$ decreases to below 400 °C (Fig. S3a, SI). In addition, we also analyze the optical properties below the band-gap by SE using the exponential Urbach formalism of the Cody-Lorentz model [47].

The evolution of the absorption coefficient $a$ with decreasing $T_d$ is shown in Fig. 7a. The inset shows the fit results for the Urbach tail transition (i.e. the slope $E_u$) and the demarcation energy $E_d$, as determined by SE. $E_u$ is an estimate of the Urbach tail width, and $E_d$ is an estimate of the Urbach tail transition energy. The results of $E_u$ with $T_d$ (Fig. S4, SI) are similar to previous SE spectra reported in Fig. S6 (SI) using the Cody-Lorentz model is similar to previous SE spectra used to analyze amorphous and crystalline anatase [32,49,50]. We observed an increase in $E_u$ with decreasing $T_d$ (Fig. S6, SI). This increase in porosity is caused by the rise in the density. Thus, the rise of the optical reflectance (Fig. S3b SI), which is mainly due to scattering, is explained by the concomitant increase of the size of the nanostructures and the refractive index.

Fig. 7c shows the volume fractions of void ($f_{void}$) vs $T_d$ estimated from n/$\delta$33 nm of the films, and of bulk anatase following the Lorentz-Lorenz equation. In this case, $f_{void}$ is an estimate of the total porosity, including the closed porosity, whereas the volume fraction of ethanol resulting from SEP corresponds only to the open mesoporosity with a maximum pore size of ca. 20 nm. We attribute the difference between the results to the fact that the large mesoporosity and macroporosity cannot be filled by ethanol by capillary condensation. The closed
porosity, inaccessible to ethanol, could be negligible in the porous structure. No model using effective medium approximations composed of void and crystalline and/or amorphous anatase could significantly fit the SE data, since it cannot accurately describe band-gap and scattering intensity variations. Therefore, the values reported in Fig. 7c inset vs $T_d$ are only indicative. However, the increase of both volume fractions with increasing $T_d$ reflects the increase in porosity within and between the nanostructures, which is apparent in the FESEM and HRTTEM images (Fig. 5).

3.6. Photocatalytic evaluation

To study the evolution of the SWS photocatalytic properties of the TiO$_2$ films vs $T_d$, two tests were carried out. First, water photodissociation rates are quantified by the cumulative H$_2$ production. Fig. 8a shows the amounts of H$_2$ as a function of time produced by photocatalysis by the films deposited between 450 and 325 °C, corresponding to the entire range of morphologies. All films display constant H$_2$ production throughout the 66 h of the analysis, as shown by the linearity of the curves, revealing their high stability. Furthermore, the repeatability of the experiments has been established by testing a 450 °C sample thrice and acquiring the same results. After 66 h, the well-organized, nanotree-shaped TiO$_2$ (450 °C) displays the highest cumulative H$_2$ production of 78.9 mmol.m$^{-2}$. After the same duration, the TiO$_2$ with disorganized columns (400 °C) shows a production of only 36.2 mmol.m$^{-2}$, i.e., less than half of the production of the film deposited at 450 °C. The intermediate, 375 °C sample displays a production of 12 mmol.m$^{-2}$ for 350 and 325 °C, respectively. The well-organized columnar film shows the best photocatalytic performance, which is far better than the others. Comparison of these results with the literature is difficult because of the diversity of the reported photocatalytic protocols used, in terms of solutions, protocol pressure, normalization, or intensity of the light source [51].

A second photocatalytic analysis was performed by the Pilkinson test, shown in Fig. 8b, following the photodegradation of stearic acid under UV-light illumination. The results of three samples (325, 375, and 450 °C) exhibiting the three characteristic morphologies are shown, revealing that the photocatalytic activity of the high $T_d$ sample is better than the 375 and the 325 °C ones. The highest photodegradation rate is close to the rate from PECVD-processed pure anatase TiO$_2$ film reported by Zhou et al [34].

The straight hierarchy between the photodegradation rates of the three samples shown on the Fig. 8b can be attenuated by the other samples results (Fig. S7, SI) that show, for instance, that the 400 °C sample is more efficient than the 450 °C sample. Additional results on Fig. S7 (SI) also show that initially, the sample deposited at 350 °C is more active than the one deposited at 325 °C.

Both analyses show the strong tendency of higher $T_d$ samples to show higher photocatalytic activity. For H$_2$ photogeneration, there is only one small exception to this trend – the samples deposited at 325 and 350 °C – since the former exhibits slightly better activity than the latter. However, as described earlier, several samples do not follow the trend for stearic acid photodegradation. These exceptions are not surprising when one considers the fact that competition among a number of properties and characteristics results in the final photocatalytic performance of the materials. This is especially the case given that the properties do not show a steady evolution with $T_d$. For instance, this is the case with the mean current probed by C-AFM, which shows a strong early decrease with the increase of $T_d$, or for the evolution of XRD patterns, in which significant change begins only at 450 °C. Moreover, the evolution of some properties is not quite monotonous: for example, the porosity as determined by ellipsometry between 325 and 350 °C.

Finally, the initial amount of stearic acid on surface samples could be different from one sample to another because of specific surface differences between them, which could explain the fact that stearic acid photodegradation results show more exceptions to the general trend. Therefore, the 400 °C sample, which is less porous than the 450 °C one, could have less acid stearic to photodegrade in the first place. For all these reasons, we focus in the following discussion on only the general trend, which is indisputable.

4. Discussion

The strong increase in the morphological complexity of anatase films obtained with increasing $T_d$ has a positive impact on the photocatalytic performance. This impact can be analyzed by the following photocatalytic mechanisms: carrier photogeneration, carrier concentration, carrier transport, and properties of the surfaces exposed to the aqueous catalytic solutions. Changes in the morphology of TiO$_2$ films with increasing $T_d$ have been reported extensively in the literature. Taylor et al. [21] observed the same morphological evolution of MOCVD TiO$_2$ films from TTIP. According to them, the increase of $T_d$ results in the decrease in the migration length of active species and in a concomitant decrease in the number of hops before reaction. Therefore, at low $T_d$, reactive species have time to diffuse, which results in large and compact structures, whereas high $T_d$ favors nucleation and leads to preferential growth on pre-existing structures. This, in turn, leads to the formation of the columnar complex nanotrees, which GIXRD reveals to be compressed, and more subject to deformation under fixed applied force. This growth mechanism leads to highly porous films at high $T_d$, estimated to be ca. 26 vol% of void by SE. Further evidence is provided by FTIR, which shows a significant decrease in the number of Ti–O
TO\textsubscript{2}– excitation vibrations with increasing \( T_d \) by the concomitant drop in the TO\textsubscript{2}/LO\textsubscript{2} intensity ratio, which is also an indication of increasing disorder, and by the LO\textsubscript{3} red-shift. The high porosity generated by the nanotree structuration is mainly in the form of space between columns, as revealed by the analysis of the plan-view FESEM images and shown by the inter-columnar gaps in the cross-sectional FESEM and HRTEM images. This nanostructuration leads to nanotree morphologies, the most common of which exhibits branches directed toward the top, resembling a cypress. The conical shaped summits seem to belong to the same morphology but observed from a different side. This results in a high specific surface which is also evidenced by the appearance of the 520 cm\(^{-2}\) FTIR contribution. The change in the morphology of the TiO\textsubscript{2} films with increasing \( T_d \) also results in a stronger crystallographic texture and in a change in the growth direction after a transitional step, as evidenced by BSED, and potentially by FTIR [41]. Besides, HRTEM suggests that the diversity and the number of the crystallographic facets exposed to the contact with the aqueous solutions for \( H_2 \) photo-generation or with stearic acid for the Pilkington test increase significantly with increasing \( T_d \). Murakami et al. suggested that a balanced ratio between (101) and (001) surfaces would improve the photocatalytic performance by improving charge separation and, therefore, the lifetime of the excitons, because of the presence of both oxidative and reductive surfaces [52]. Such surfaces were confirmed by the work of Yu et al. [53], and the oxidative character of particularly the (100) surface was confirmed by Roy et al. [54]. Nevertheless, these studies concern free nanocrystallites and not films composed of dense or porous structures, where charge carrier transport plays a more significant role in the photocatalytic properties. We observed that charge carrier transport decreases significantly with the strong nanostructuration of the morphology, and the decrease in grain size, as revealed by both C-AFM and Hall effect measurements. This is consistent with the work of Chen et al., who showed that the charge mobility of small anatase nanorods (0.57 cm\(^2\)V\(^{-1}\)s\(^{-1}\)) [55] is much lower than that of large crystallites (20 cm\(^2\)V\(^{-1}\)s\(^{-1}\)) [9]. Further, we suspect that a larger number of grain boundaries in the nanotree TiO\textsubscript{2}, which act as diffusion centers [56], and a higher disorder may cause charge carrier traps and ohmic behavior. Finally, the intensity of reflected light increases with increasing \( T_d \) mainly because of scattering.

We witness here the competition among different effects involved in the photocatalytic performance of the TiO\textsubscript{2} films with increasing \( T_d \). The beneficial effects include the drop in the optical reflection, the increase in charge density, the huge enhancement of the exchange surface, and the higher diversity of the crystallographic facets. These effects overcome the detrimental effects, which include, potentially, the compressive residual stress [20,30], and the decrease in charge carrier mobility. The latter effect may indicate that the redox reactions mainly involve excitons generated at the extreme TiO\textsubscript{2} surface. As for the effect of the potential narrowing of the optical band-gap, that could hinder the photocatalytic activity by decreasing the number of absorbed photons. However, the narrowing could also be beneficial: if this downshift is strong enough to position the conduction band below the H\textsuperscript{+}/H\textsubscript{2} redox potential, the reduction reaction would be compromised. By contrast, high \( T_d \) samples would benefit from the thermodynamic driving force arising from a suitable position of the conduction band [57], as shown in Fig. 8a.

5. Conclusion

We deposited anatase TiO\textsubscript{2} films by thermal MOVD. In this process, increasing \( T_d \) induces a strong increase in morphological complexity through the formation of nanotree-like columnar structures. The positive impact of this change on the water-splitting performance is investigated. We observe a 66 h cumulative \( H_2 \) production that increases from 4.4 to 78.9 mmol.m\(^{-2}\) as \( T_d \) increases from 325 to 450 °C. In the complex competition between the numerous properties affecting the photocatalytic mechanisms, we attribute the better activity of the high \( T_d \) samples to the strong increase in the specific surface area. This increase is induced by spaces between the nanotree-like columnar structures and possibly by the smaller space within each column, which were observed by both FESEM and HRTEM, in accordance with FTIR analyses. We also observe a significant increase in the porosity with increasing \( T_d \). The maximum volume fractions of void corresponding to the open mesoporosity (estimated by SEPF) and full porosity (estimated by SE) were 9% and 26%, respectively. Moreover, we observe a decrease in the optical reflection with increasing \( T_d \) which is mainly caused by scattering and which may favor the photocatalytic process. In addition, the inherent increase in the diversity of the exposed crystallographic facets with the increase in the morphological complexity may have a positive impact on the \( H_2 \) production performance as well. Notably, we show for the first time by EBSD a change of one of the main growth direction: \(< 100 \) at 325 °C and \(< 110 \) at 500 °C. However, we observe a decrease of the charge mobility, which is detrimental to the photocatalytic performance, as could be the case with the increase in the residual compressive stress. Therefore, we have performed an extended investigation of the nanoscale electronic and electrical properties with regard to the crystallographic properties of the nanotree-shaped TiO\textsubscript{2}. The results of this analysis will be published in a forthcoming paper.

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Appendix A. Supplementary data

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References


