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Determination and Improvement of Deposition Parameters of TiO_2 Thin Films via ALD

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Abstract: In recent years, with the development of technology, interest in microelectronics and thin film devices has increased considerably. Future improvements in microelectronics and thin film devices are dependent on the progress of novel materials and new deposition processes. In particular, the continuing drive to some devices such as silicon devices will soon require SiO_2 gate and oxide layers with a thickness on the order of a few nanometers as 1 or 2 nm. Titanium dioxide is a candidate material in microelectronic and thin film devices, a wide band gap semiconductor that exhibits various crystal structures. Similarly, thin film techniques like ALD (atomic layer deposition) attract attention for the preparation of these candidate materials with higher film uniformity and conformity. Present study demonstrates how TiO_2 thin films were growth by ALD technique on silicon substrates at 100 °C, 150 °C and 200 °C temperatures. Different deposition conditions were examined to determine to increase film quality and efficient production of set up. XPS (X-ray photoelectron spectroscopy) technique was used to obtain the surface composition of the TiO_2 films. Film thicknesses and crystal structures of the films were investigated by ellipsometry and XRD (X-ray diffraction) methods. Electrical properties of the films were measured by using four probe techniques, as well. Obtained results were evaluated in terms of repeatability of recipes and application potential.

Key words: TiO_2 films, ALD, film grown, optical properties.

1. Introduction

Titanium dioxide (TiO_2) is a wide band gap semiconductor that exhibits various crystal structures such as the tetragonal anatase and rutile. Though TiO_2 is possibly best known for its photocatalytic properties, it is also an interesting material for dielectric and transparent-conductor applications. Owing to its higher dielectric constant, rutile is the structure-of-choice for dielectric applications, while the higher electron mobility of anatase makes it more attractive to transparent-conductor applications [1]. Amorphous TiO_2 thin films are studied increasingly for subwavelength optical structures due to their high index of refraction and transparency within a broad wavelength region [2]. TiO_2 tends to have n-type conducting character due to intrinsic defects that easily form in its crystal lattice [1]. There are many studies on TiO_2 in the fields of diluted magnetic semiconductors, photocatalyst materials, and electrode materials for electrochromic devices [3].

In the past two decades, it has been considered almost certainly to be the most studied transition metal oxide due to its many unusual physical, chemical, electronic, electrochemical and photoactive properties unexceptionally. TiO_2 has also attracted vast interest in chemical engineering related research such as solar energy conversion via dyesensitized and quantum-dot-sensitized solid-state solar cells, water splitting and general photocatalysis, lithium ion

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batteries and supercapacitors, chemical/gas sensing, controlled release, environmental remediation including indoor air purification, wastewater treatment, antifogging, self-cleaning, deodorization and deactivation of bacteria [4-6]. As the firstly reported semiconductor material for photoelectrochemical water splitting, TiO_2 has been intensively studied by a large number of groups in the past decades [7-9]. Although poor ability to light absorption limits its application to a large extent, TiO_2 is still an excellent assistant for other materials arising from its stability over a range of pH [9-12]. TiO_2 protecting layer in the form of ultrathin film usually contains pinholes and cracks, which will activate an oxidative dissolution of the underlying substrate [13].

PVD (physical vapor deposition), CVD (chemical vapor deposition) and spin coating can be given as some of the fabrication ways of TiO_2 films [14]. Aside from these growth techniques, ALD (atomic layer deposition) shows the advantage of conformal growth and precise film thickness control, which are very important to the fabrication of future microelectronic [15] and the other devices. ALD, which is one of the thin film growth techniques, has become advanced fabrication method for a rich variety of applications including complementary metal oxide semiconductor transistors, DRAM memory, energy conversion, photovoltaic, and display devices [16-18]. ALD is a cyclic vapor phase deposition technique, which takes the privilege of temporarily separated and self-limiting reactions of two or more precursors and reactants [19] that thereafter grow an ideally desired film with one specific atomic layer thickness at a time [20]. This technique facilitates the growth of various kinds of coatings including ultra-thin pure and composite layers with precise control of composition by appropriate design of ALD recipe and process details [21, 22]. In ALD technique, the precursors are pulsed to the reactor chamber one after another with intermediate purging, which results in self-limited surface reactions. A sequence consisting of one pulse of each precursor and intermediate purging is called an ALD cycle shown Fig. 1. Ideally one ALD cycle deposits a monolayer of the target compound, and thus the film thickness is accurately controlled by the total number of cycles. Doping is realized by replacing single ALD cycles of a mother compound by an ALD cycle of a dopant compound [20]. Similarly, ALD is a convenient technique for the production of good quality thin TiO_2 films [23]. Obtained TiO_2 thin films by using ALD techniques have been widely used in energy and environmental science due to its high chemical stability, nontoxicity and favorable energy band structure [24]. As it is known, the properties of nanomaterials depend on their shapes, sizes, crystal structures, defects, impurities, and surface areas, the potential application areas of the films will be intensely affected by these features [25, 26].

In the present study, TiO_2 thin films were prepared by ALD technique on silicon substrates at 100 °C, 150 °C and 200 °C temperatures in order to determine appropriate recipe. Deposition conditions were tried to determine for increasing film quality and efficient production of set up. XPS (X-ray photoelectron spectroscopy) technique was used to obtain the surface composition of the films. Ellipsometric measurements and XRD (X-ray diffraction) analysis were carried out to determine of thicknesses and crystal structures of the films. Electrical properties of the films were measured, as well. Obtained results were evaluated in terms of repeatability of recipes and application potential.

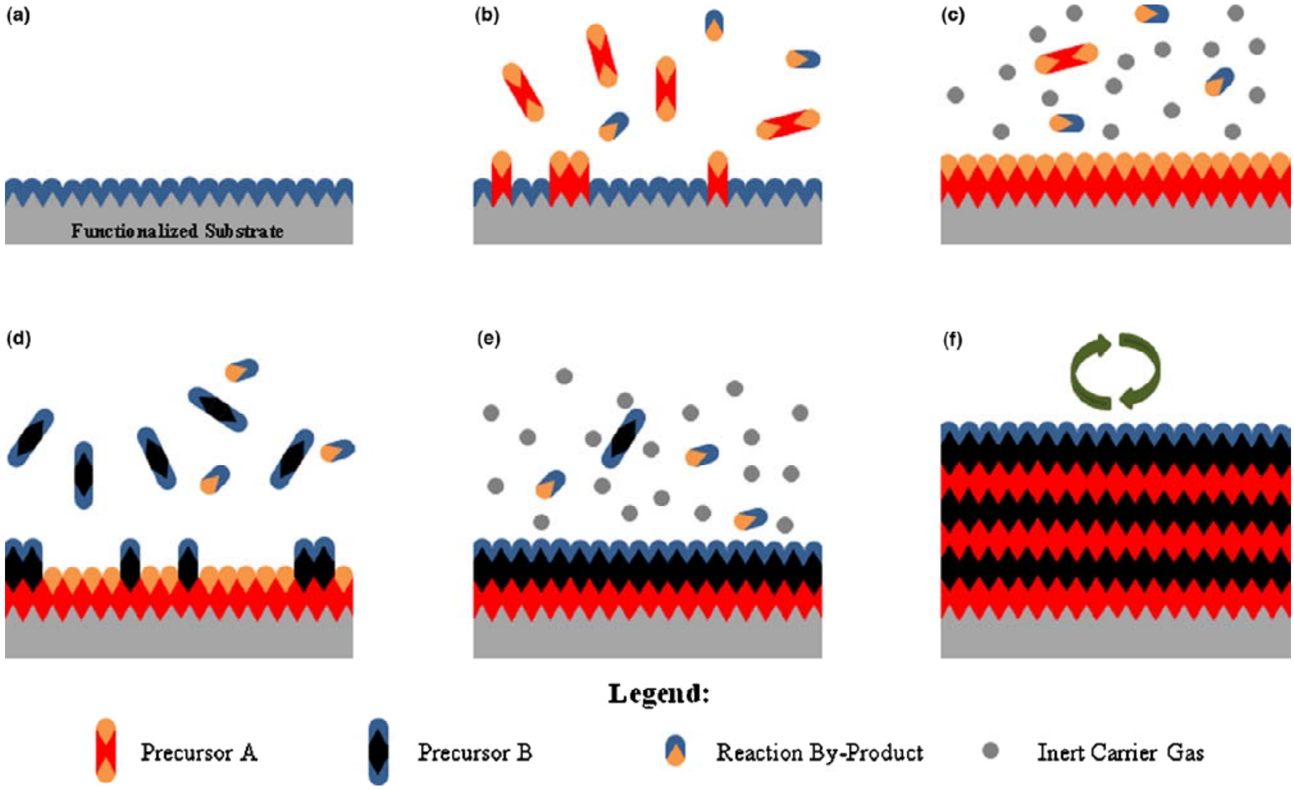

Fig. 1 Schematic representation of ALD process. (a) Substrate surface is treated to functionalize the surface. (b) Precursor A is sent and reaction starts with surface. (c) Excessive precursor and reaction by-products are purged with inert carrier gas. (d) Precursor B is sent and reacts with surface. (e) Excessive precursor and reaction by-products are purged with inert carrier gas. (f) Steps b to e are repeated until the desired film thickness is succeeded [18].

2. Materials and Method

Depositions of the thin films included in this work were carried out in OKYAY Tech. R&D (Fig. 2) ALD reactor at various temperatures. Prior to the deposition, Si (100) which is used as substrate for production of TiO_2 thin film was cleaned via using standard Radio Corporation of America (RCA) cleaning methods. The pulse and purge period of ALD cycles were optimized for TiO_2 for three different recipes until the self-limiting and uniform growth was observed on Si (100) substrates. For the proper recipe, the precursor dose and purge times were adjusted as 0.15 and 10.0 s, respectively. For some samples grown at 200 °C, optimized recipe was used, where the dose and purge sequence for precursors was (0.015-30-0.015-30) s. The temperature range for film growth was from 100 to 200 °C. The number of growth cycles was varied from 400 to 1,200 and corresponding film thicknesses of approximately 50 to 150 nm. Various heat treatments have been implemented for characterizing of anatase and rutile phases of TiO_2.

XPS measurements were performed with a Thermoat a vacuum of 3×10^{-9} Torr (K-Alpha-Monochromated high-performance XPS spectrometer) instrument. Deposited thin films thicknesses were characterized via spectroscopic ellipsometry measurements. Structural properties of the films were acquired by using X-ray diffraction (Bruker D8 Advance & DIFFRAC Measurement Center Software) method. The electrical characteristics, mainly the resistivity, of the materials were obtained with a four-probe resistivity measurement method by using Keithley 2400 source meter. Surface morphology was examined by using SEM (scanning electron microscopy) (an FEI Nova Nano SEM 430 microscope operated at 10 kV).

Fig. 2 Thermal ALD device.

3. Results

The TiO_2 films were characterized by XPS technique to obtain the surface composition. The data analysis given in Fig. 3 involved spectra normalization, Shirley background subtraction, and curve-fitting Gaussian–Lorentzian line shapes [27]. Best fits were evaluated using a root-mean-square measure where line shape, peak width (FWHM) and binding energy were adjustable parameters. Shirley backgrounds were used in all fits to narrow scan spectra [28].

All XPS spectral peaks given in Fig. 3 were fitted with Thermo Scientific Avantage software. All spectra showed O 1s and C 1s spectral lines consist of a single peak (a singlet) whereas the Ti 2p spectrum consist of two peaks, a spin-orbit doublet. The C 1s spectral line was seen at 285.0 eV and the O 1s and Ti 2p spectra were adjusted to this energy. The O 1s spectrum of TiO_2 film has been twinned, one is peaked at 530.2 eV, and the other is peaked at 531.84 eV. The O1s spectrum of the obtained TiO_2 film can be determined into three peaks, one is peaked at 530.2 eV, and the other two are peaked at 531.84 eV and 532.4 eV, after annealing at 550 ^{o}C respectively. According to the literature, the main peak at the 530.2 is due to the oxygen lattice and Ti-O bond while the peaks at 531.2 eV correspond to water (O-H) and hydroxide absorbed on the surface and the peak at the 532.9 eV is probably due to the water and hydroxide Ti or basic OH on the surface [29-35].

Related to ellipsometric measurements, thicknesses of titanium dioxide films annealed at various temperatures showed the proper values ±5 nm with growth cycles. According to these results, the thin films thickness increases parallel to increasing cycles.

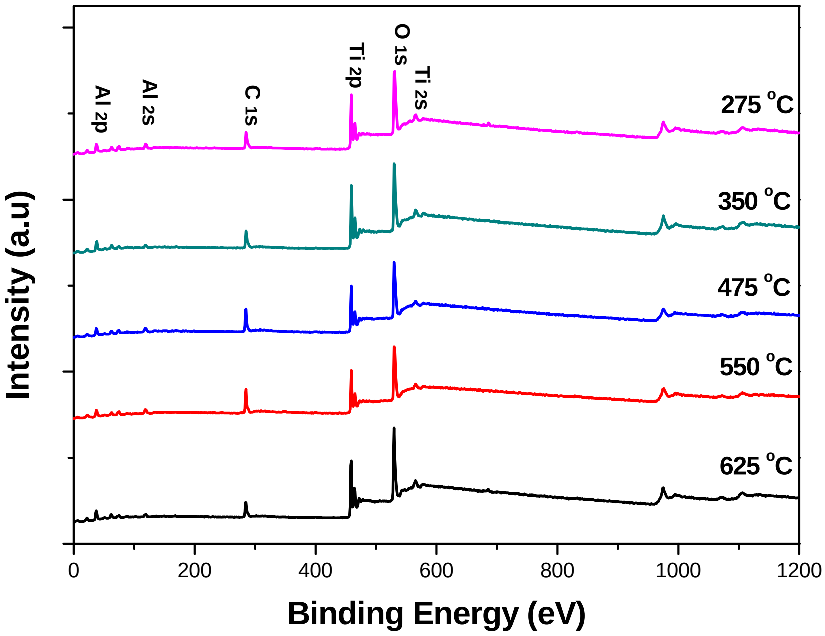

Fig. 3 XPS spectra of ALD-grown titanium dioxide films annealed at various temperatures.

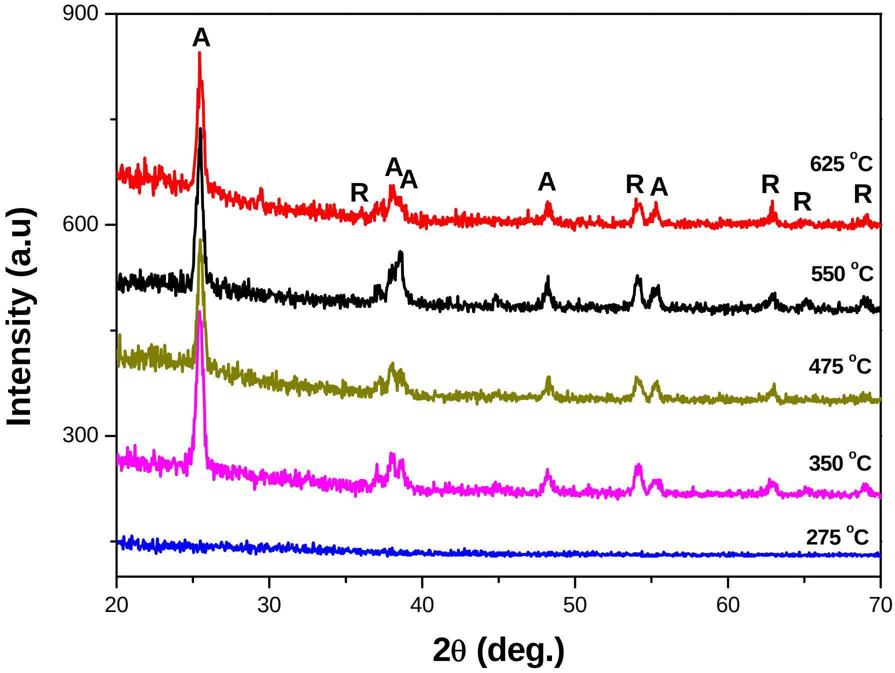

Fig. 4 XRD spectra of ALD-grown titanium dioxide films annealed at various temperatures.

To clarify the crystal structure of ALD grown TiO_2 films, the XRD spectra was investigated which gives anatase and rutile phases after the heat treatment of 275 °C in Fig. 4. According to XRD data, the films grown at 275 °C were amorphous. All the films annealed at higher temperatures contained crystalline phases of TiO_2. X-ray diffraction studies revealed formation of anatase phases at 2θ = 25.48; 37.92; 38.12; 48.20; 55.28 and rutile phases at 2θ = 36.04; 54.00; 62.92; 64.76; 69.12, respectively. Also, the contents of the anatase and rutile structures and electrical properties of ALD-grown TiO_2 films annealed at various temperatures have been given in Table 1.

Table 1 also shows the calculated carrier mobility, threshold voltage, subthreshold slopes, and I_{on}/I_{off} ratios of fabricated TiO_2 devices. Extrapolation method in the saturation region (ESR) is used to extract $\sqrt{I_D} - V_G$ characteristics of the devices [36-38]. Subthreshold slopes are extracted from $\log(I_D - V_G)$ characteristics with $dV_G/dLog(I_D)$ relation. Carrier mobility values were extracted from output $I_D - V_D$ characteristics. Oxide capacitance is calculated using $C_{ox} = \varepsilon_{ox}/t_{ox}$ and $C_{ox} = \varepsilon_0.\varepsilon_r/t_{ox}$ relations, where ε_r denotes dielectric permittivity of ALD deposited TiO_2.

It is known that electrical properties of TFT devices follow a similar trend with outcome of XPS measurements. O/Ti ratio in the film decreases with increasing deposition temperature. This results in higher effective doping due to defects [39-41]. At low deposition temperatures, O-H bonds passivate the defects and therefore reduce carrier concentration and increase I_{on}/I_{off} ratio. Typical I_D-V_{DS} characteristics of a device annealed at 475 °C shows maximum value. A maximum I_{on}/I_{off} ratio of 2.5×10^6 is recorded as 25× improved compared to the highest reported for this kind of devices up to now. After ALD growth, thin films annealed at 475 °C have the optimal Ti:O stoichiometry, therefore the lowest defect density. It can be said that this result is in good agreement with the tendency observed in threshold voltage vs. annealing temperature.

However, when the electrical properties compared with the XRD results, it is understood that the films annealed at 475 °C have the highest anatase content regarding to higher electron mobility.

SEM images of two different samples were given in Fig. 5. SEM images of the ALD grown TiO_2 films were taken at about 6 mm working distance, high vacuum mode, 10 kV accelerating voltage, X40000 for cross-sectional and X 80000 for surface image. SEM

Table 1 Anatase and rutile content and electrical properties of ALD-grown titanium dioxide films annealed at various temperatures.

$T_{Annealing}$	Anatase (%)	Rutile (%)	$V_{Threshold}$ (V)	I_{on}/I_{off} subthreshold	Slope (V/dec)	Mobility ($cm^2/V\cdot s$)
275	73	27	-1.8	10^2	6.55	0.330
350	84	16	0.2	10^2	5.21	0.400
475	99	1.0	6.5	2.5×10^6	0.35	0.670
550	88	12	4.3	4×10^5	1.36	0.17
625	96	4.0	7.1	10^6	0.35	0.27

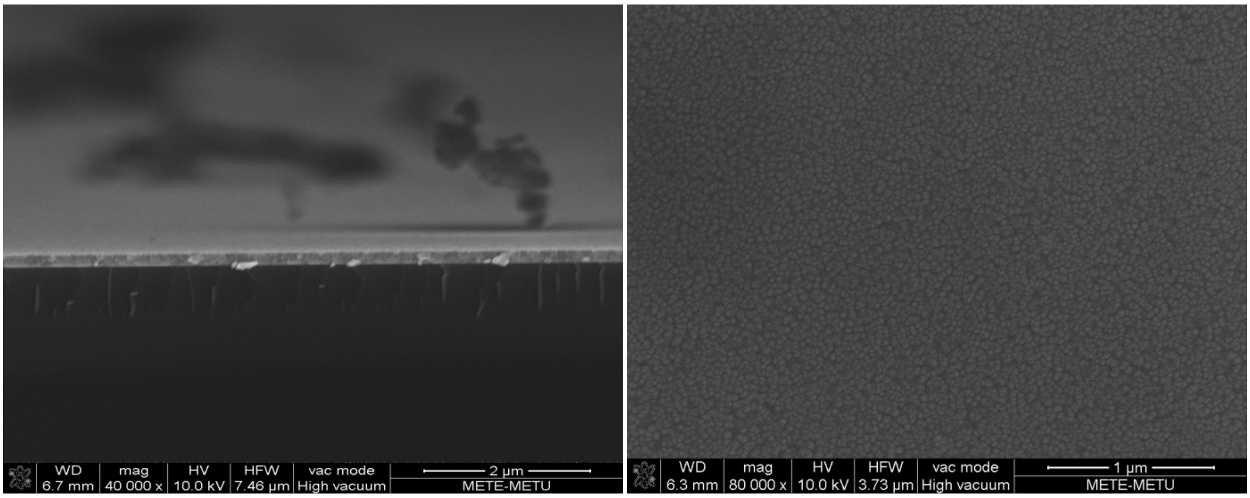

Fig. 5 SEM images of the titanium dioxide films by ALD, annealed at various temperatures: (a) cross-sectional image; (b) surface image.

images of the thin film demonstrated the homogeneous phase distribution of the TiO_2 (Fig. 5b). Some porosityis seen on the surface morphology of these thin films, which is influenced by the growth temperatures, annealing and process parameters. After ALD growth, thin films annealed at 475 °C have the optimal Ti:O stoichiometry, therefore the lowest defect density. It can be said that this result is in good agreement with the tendency observed in threshold voltage vs. annealing temperature.

When obtained results in all experimental studies are evaluated, it can be said that ALD thin films presented at this study are ideal candidates for microelectronic devices and optical applications.

4. Conclusion

In order to improve deposition parameters of TiO_2 thin films via ALD have been investigated and conclusion can be drawn as follows:

As a result, we made a comprehensive study on the deposition parameters for growth TiO_2 films by using ALD technique. For this purpose, various recipe and annealing temperatures have been used and ideal one determined the best one. By the way, it is tried to determine the impact of deposition condition on the structural, electrical properties of the ALD grown TiO_2 film. An ideal recipe showed that the growth temperature is 200 ^oC. Our results demonstrate that deposition parameters affect the structural, surface and electrical properties of the ALD TiO_2 films, as well.

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References

[1] Niemelä, J. P., Marin, G., and Karppinen, V. 2017. "Titanium Dioxide Thin Films by Atomic Layer Deposition." *Semiconductor Sciences and Technology* 32 (9).

[2] Saleem, M. R., Silfsten, P., Honkanen, S., and Turunen, J. 2012. "Thermal Properties of TiO_2 Films Grown by Atomic Layer Deposition." *Thin Solid Films* 520: 5442-6.

[3] Chen, X., and Mao, S. S. 2007. "Titanium Dioxide Nanomaterials: Synthesis, Properties, Modifications, and Application." *Chemical Reviews* 107: 2891-959.

[4] Bahnemann, D. W., Hilgendorff, M., and Memming, R. 1997. "Charge Carrier Dynamics at TiO_2 Particles: Reactivity of Free and Trapped Holes." *Journal of Physical Chemistry B* 101: 4265-75.

[5] Furube, A., Du, L. C., Hara, K., Katoh, R., and Tachiya, M. 2007. "Ultrafast Plasmon-Induced Electron Transfer from Gold Nanodots into TiO_2 Nanoparticles." *J. Am. Chem. Soc.* 129: 14852-3. https://pubs.acs.org/doi/pdf/10.1021/ja076134v.

[6] He, Y. B., Tilocca, A., Dulub, O., Selloni, A., and Diebold, U. 2009. "Local Ordering and Electronic Signatures of Submonolayer Water on Anatase TiO_2 (101)." *Nature Materials* 8: 589-95.

[7] Fujima, A., and Honda, K. 1972. "Electrochemical Photolysis of Water at a Semiconductor Electrode." *Nature* 238: 37-8.

[8] Chen, X., Liu, L., Yu, P. P., and Mao, S. S. 2011. "Increasing Solar Absorption for Photocatalysis with Black Hydrogenated Titanium Dioxide Nanocrystals." *Science* 331: 746-50.

[9] Luo, C., Ren, X., Dai, Z., Zhang, Y., Qi, X., and Pan, C. 2017. "Present Perspectives of Advanced Characterization Techniques in TiO_2-Based Photocatalysts." *ACS Applied Materials and Interfaces* 9 23265-86.

[10] Kafizas, A., Ma, Y., Pastor, E., Pendlebury R. S., Mesa, C., Francás, L., et al. 2017. "Water Oxidation Kinetics of Accumulated Holes on the Surface of a TiO_2photoanode: A Rate Law Analysis." *ACS Catalysis* 7: 4896-903.

[11] Son, H. J., Prasittichai, C., Mondoch, E. J., Luo, L., Wu, J., Kim, W. D., et al. 2013. "Day Stabilization and Enhanced Photoelectrode Wettabilitiy in Water-Based Dye-Sensitized Solar Cells through Post-Assembly Atomic Layer Deposition of TiO_2." *Journal of American Chemical Society* 31: 11529-32.

[12] Chen, W. Y., Prange, D. J., Dühnen, S., Park, Y., Gunji, M., Chidsey E. D. C., and Mclntyre, C. P. 2011. "Atomic Layer-Deposited Tunnel Oxide Stabilizes Silicon Photoanode for Water oxidation." *Nature Materials* 10: 539-44.

[13] Liu, M., Xue, F., Wang, X., Fu, W., Wang, Y., Lu, Y., and Li, N. 2017. "Conformal Deposition of Atomic TiO_2 Layer on Chalcogenide Nanorod with Excellent Activity and Durability towards Solar H_2 Generation." *Chemical Engineering Journal* 341: 335-43.

[14] Zhao, C., Hedhili, M. N., Li, J., Wang, Q., Yang, Y.,

Chen, L., and Li, L. 2013. "Growth and Characterization of Titanium Oxide by Plasma Enhanced Atomic Layer Deposition." *Thin Solid Films* 542: 38-44.

[15] Kim, H., Lee, R. B. H., and Maeng W.-J. 2009. "Applications of Atomic Layer Deposition to Nanofabrication and Emerging Nanodevives." *Thin Solid Films* 517: 2563-80.

[16] Kim, H. 2011. "Characteristic and Applications of Plasma Enhanced-Atomic Layer Deposition." *Thin Solid Films* 519: 6639-44.

[17] Sammelselg, V., Rammula, R., Aarik, J., Kkas, A., Kooser, K., and Käämbre, T. 2007. "XPS and AFM Investigation of Hafnium Dioxide Thin Films Prepared by Atomic Layer Deposition on Silicon." *Journal of Electron Spectroscopy and Related Phenomena* 156-158: 150-4.

[18] Johnson, W. R., Hultqvist, A., and Bent, F. S. 2014. "A Brief Review of Atomic Layer Deposition: From Fundamentals to Applications." *Materials Today* 17: 236-46.

[19] Zhuiykov, S., Kawaguchi, T., Hai, Z., Akbari, K. M., and Heynderickx, M. P. 2017. "Interfacial Engineering of Two-Dimensional Nano-structured Materials by Atomic Layer Deposition." *Applied Surface Science* 392: 231-43.

[20] Leskelä, M., and Ritala, M. 2002. "Atomic Layer Deposition (ALD): From Precursors to Thin Film Structures." *Thin Solid Films* 409: 138-46.

[21] Coy, T., Yate, L., Kabaciñska, Z., Tancelewicz, M., Jurga, S., and Latsunskyi, I. 2016. "Topographic Reconstruction and Mechanical Analysis of Atomic Layer Deposited Al_2O_3/TiO_2 Nanolaminates by Nanoindentation." *Materials and Design* 111: 584-91.

[22] Luka, G., Wachnicki, L., Witkowski S. B., Jakiela, R., and Virt, S. I. 2017. "Structure-Property Relationships in ZnO:Al-hdyroquinone Films Grown on Flexible Substrates by Atomic and Molecular Layer Deposition." *Materials and Design* 119: 297-302.

[23] Suisalu, A., Aarik, J., Mändar, H., and Sildos, I. 1998. "Spectroscopic Study of Nanocrystalline Thin Films Grown by Atomic Layer Deposition." *Thin Solid Films* 336: 295-8.

[24] Edy, R., Zhao, Y., Huang, S. G., Shi, J. J., Zhang, J., Solovev, A. A., and Mei, Y. 2016. "TiO_2 Nanosheets Synthesized by Atomic Layer Deposition for Photocatalysis." *Progress in Natural Science: Materials International* 26: 493-7.

[25] Chen, K., Jiang, Z., Qin, J., Jiang, Y., Li, R., Tang, H., and Yang, X. 2014. "Synthesis and Improved Photocataltic Activity of Ultrathin TiO_2Nanosheets with Nearly 100% Exposed (001) Facets." *Ceramics International* 40: 16817-23.

[26] Xie, Y., Wu, Q., Liu, M., and Piao, L. 2014. "Effect of Different Base Structures on the Performance of the Hierarchical TiO_2Photocatalysts." *Catalysis Today* 225: 74-9.

[27] Zakaznova-Herzog, V. P., Nesbitt, H. W., Bancroft, G. M., and Tse, J. S. 2006. "High Resolution Core and Valence Band XPS Spectra of Non-conductor Pyroxenes." *Surf. Sci*. 600: 3175-86.

[28] Shirley, D. A. 1972. "High-Resolution X-Ray Photoemission Spectrum of the Valence Bands of Gold." *Phys. Rev. B* 5: 4709.

[29] Chastain, J. 1992. *Handbook of X-Ray Photoelectron Spectroscopy*, Perkin-Elmer.

[30] Young, V., and Otagawa, T. 1982. "XPS Studies on Strontium Compounds." *Appl. Surf. Sci.* 20: 228-48.

[31] Briggs, D., and Seah, M. 1983. *Practical Surface Analysis by Auger and X-Ray Photoelectron Spectroscopy*, edited by D. Briggs, and M. P. Seah, John Wiley & Sons, Chichester, xiv+ 533.

[32] Wagner, C., Zatko, D., and Raymond, R. 1980. "Use of the Oxygen KLL Auger Lines in Identification of Surface Chemical States by Electron Spectroscopy for Chemical Analysis." *Anal. Chem*. 52 (9): 1445-51.

[33] Xiao, S. J., Textor, M., Spencer, N. D., and Sigrist, H. 1998. "Covalent Attachment of Cell-Adhesive, (Arg-Gly-Asp)-Containing Peptides to Titanium Surfaces." *Langmuir* 14 (19): 5507-16.

[34] Viornery, C., Chevolot, Y., Leonard, D., Aronsson, B. O., Pechy, P., Mathieu, H. J., Descouts, P., and Gratzel, M. 2002. "Surface Modification of Titanium with Phosphonic Acid to Improve Bone Nonding: Characterization by XPS and ToF-SIMS." *Langmuir* 18 (7): 2582-9.

[35] Smith, N. A., Antoun, G. G., Ellis, A. B., and Crone, W. C. 2004. "Improved Adhesion between a NiTiSMA Wire and a Polymer Matrix via Silane Coupling Agents." *Composites A—Appl. Sci. Manuf* 35 (11): 1307-12.

[36] Kim, Y., Koo, J., Han, J., Choi, S., Jeon H., and Park, C. 2002. "Low-Temperature Growth of SiO_2 Films by Plasma-Enhanced Atomic Layer Deposition." *J. Appl. Phys*. 92: 5443.

[37] El-Atab, N. F., Ozcan, A., Alkis, S., Okyay, A. K., and Nayfeh, A. 2014. "Low Power Zinc-Oxide Based Charge Trapping Memory with Embedded Silicon Nanoparticles via Poole-Frenkel Hole Emission." *Applied Physics Letters* 104 (1): 013112.

[38] Krajewski, T., Guziewicz, E., Godlewski, M., Wachnicki, L., Kowalik, I. A., Wojcik-Glodowska, A., Lukasiewicz, M., Kopalko, K., Osinniy, V., and Guziewicz, M. 2009. "The Influence of Growth Temperature and Precursors' Doses on Electrical Parameters of ZnO Thin Films Grown by Atomic Layer Deposition Technique." *Microelectronics Journal* 40 (2): 293-5.

[39] Pearton, S. J., Norton, D. P., Ip, K., Heo, Y. W., and Steiner, T. 2003. "Recent Progress in Processing and Properties of ZnO." *Superlattices and Microstructures* 34 (1–2): 3-32.

[40] Ozgur, U., Alivov, Y. I., Lui, C., Teke, A., Reshchikov, M. A., Doğan, S., et al. 2005. "A Comprehensive Review of ZnO Materials and Devices." *Journal of Applied Physics* 98 (4): 041301-3.

[41] Klingshirn, C. 2007. "ZnO: From Basics towards Applications." *Physica Status Solidi (B)* 244 (9): 3019.