

Synthesis of Titanium-Dioxide using Pulsed Laser Deposition at Various Pulsed Laser Energies

Rami S. Mohammed¹, Makram A. Fakhri^{1,*}, Forat H. Alsultany², and U. Hashim³

¹Laser and Optoelectronics Engineering Department, University of Technology-Iraq ²Al-Mustaqbal University College, Department of Medical Physics, Iraq ³Institute of Nano Electronic Engineering, University Malaysia Perlis, 01000 Kangar, Perlis, Malaysia

ABSTRACT

Titanium dioxide (TiO₂) is a widely available transparent conducting oxide (TCO). In recent years it attracted the attention of researchers due to its compatibility with several applications. To achieve the best TiO₂ thin film properties possible, the deposition parameters must be optimized. In this research, TiO₂ was deposited on silicon and quarts by pulsed laser deposition (PLD) technique aiming to study the effect of changing the energy of the PLD Nd-YAG laser between 500, 600, and 700mJ. The optical properties have been investigated using a UV-Vis spectrophotometer, morphological properties using Atomic Force Microscopy, and structural properties using an X-ray diffractometer and Raman spectrometer. 700mJ was proven to provide the best thin film properties, the tests and measurements have shown a crystalline structure, and the distribution of the grains was regularly in the film. Raman spectroscopy showed two diffraction peaks corresponding to anatase Eg and rutile Eg. This observation is typically used in dye-sensitized solar cells, separation sensor devices, and more.

Keywords: Titanium dioxide, transparent conducting oxides, pulsed laser deposition

1. INTRODUCTION

Titanium dioxide (TiO_2) is a transparent conducting oxide (TCO) that has a wide optical band gap which attracted a wealth of attention from researchers in several applications like dye-sensitized solar cells, paints, light-emitting diodes (LEDs), separation sensor devices, photocatalysis, and more[1-6] due to its good chemical and physical properties, and high stability[7-9]. Titanium Oxide could exist in three phases, anatase, rutile, and brookite, with band gaps of 3.2ev, 2.96ev, and 3.02ev, respectively, which differ in particle size and distribution [10-14]. TiO₂ rutile phase has a tetragonal structure with six atoms per unit cell. TiO₂ anatase phase same as rutile, has a tetragonal structure; however, in anatase, the distortion of the TiO₆ octahedron is slightly larger[15-18]. In a rutile structure, each octahedron is coordinated with ten neighbors, while in anatase, it is in contact with eight. Anatase is less stable than rutile at most pressures and temperatures; however, it is more suited to TCO applications [19-22]. TiO₂ appears amorphous as it is prepared and could be transformed to anatase by annealing at 300-500° C. At further temperatures of 600-700° C, it could be transformed into rutile[23-26]. Synthesis of TiO₂ is done by using amorphous titania and hydrothermally treating it with NaOH, sodium titanate is formed, which is then transformed to pure rutile TiO₂, or it is prepared from titanium IV isopropoxide with acetic acid to form phase pure anatase $TiO_2[27-30]$. Pulse laser deposition (PLD) is an effective and fast method for growing different oxides, polymers, metallics, etcetera [31-33]. PLD can be controlled with different parameters (pulse energy, pulse frequency, gas pressure, temperature of substrate, number of pulses, and laser wavelength) [34-37].

^{*} Makram.A.Fakhri@uotechnology.edu.iq

Each parameter change will influence the thin film's optical properties and surface morphology. Any specific application for particular material appoints the characteristics of the thin film, which an optimum value of each parameter can achieve [38-42].

In this paper, a study was made on a nanostructure TiO_2 thin film preparation using the PLD system to ablate the nanomaterial and deposit it on heated quartz and silicon substrates in a full vacuum, discussing the effect of laser pulse energy changing on optical and structural properties of the thin films.

2. EXPERIMENTAL WORK

 TiO_2 nanopowder of more than 99.8 percent purity and 30 ± 5 nm particle size (Changsha Santech company) was provided, a hydraulic press pressed 3.5g of the TiO_2 nanopowder with a 10-ton weight into a cylindrical shape of 5mm height and 20mm diameter forming the target. The target was then placed in the rotating base of the PLD system that consists of a vacuum pump and a 1064nm Q-switched Nd-YAG laser with a 12cm focal length lens. A 250mm height – 150mm diameter and 10mm thick glass vacuum chamber inside it is the rotator attached to the base of the target, which is placed at an angle of 45 degrees, a 600w AC halogen lamp working as the heater of the system, a thermocouple to measure the temperature, and a stand where the substrate can be placed separated by 2cm to the target base, Figure 1 shows the PLD system as a schematic diagram. Two types of substrates were used; the first one is a one-side polished (P111) type silicon of a 525±25 micron thickness cut to make a 1cm square shape substrate, and the second substrate was a 1mm thick quartz cut to make a 2x1cm rectangular shape. The two substrates were cleaned and sanitized, then attached to a piece of glass with thermal tape and placed in the PLD system, the vacuum chamber was sealed, the vacuum pump, as well as the halogen lamp, was turned on, and after the full vacuum was reached and a temperature of 300°C, the rotator of the target was turned on, after that the Nd-YAG laser was operated using 200 pulses striking the target at 3Hz pulse repetition rate with three deferent energies (500, 600, 700) mJ. Each of the three energies worked to deposit TiO₂ thin film on the substrates. The 2x1cm quartz substrates were used in the investigation of the transmittance of the films using a UV-Vis spectrophotometer (Metenech SP8001) in a (200-1000) nm spectral range and in Field Emission Scanning Electron Microscopy (FESEM) (MIRA3 TESCAN). The 1cm silicon substrates were used to investigate the crystal structure, morphology, and optical properties with an X-ray diffractometer (XRD) (1.5406Ang), Atomic force microscopy (AFM), and Raman spectrometer (Sunshine). Figure 2 shows a schematic diagram of the work steps.



Figure 1. Schematic diagram of the PLD system.



Figure 2. Schematic diagram of the experimental work.

3. RESULTS AND DISCUSSION

The XRD pattern is shown in Figure 3 informs the formation of phase pure tetragonal rutile and anatase, where "A" and "R" indicate anatase-phase crystals and rutile-phase crystals, respectively[15], as seen in the figure, for the energies 500, 600, and 700mJ keeping this order the peaks for plane A(101) were located at 2θ = 24.8, 24.4, and not shown for the 700mJ, for plane R(110) at 2θ = 27.44, not shown, 27.48, for plane A(103) at 2θ =not shown, 38.12, 36.12, for plane A(004) at 2θ = 38.12, 38.6, not shown for 700mJ, for plane R(211) at 2θ = not shown, 54.2, 54.32, for plane R(310) at 2θ = 63.16 only with 600mJ, and plane R(002) at 2θ = 61.76, 61.76, 61.76 as we notice most of the peaks are in phase between the deferent energies with some peaks having small shifts referring to crystallization differences.

The crystallite size (D) of all anatase and rutile peaks was calculated by using the Scherrer equation [43-48].

$$D = \frac{K\lambda}{\beta\cos\theta} \tag{1}$$

Where (K) is Scherrer's constant equal to 0.94 (depends on the crystal shape, equals 1 for spherical shape), (λ) is the wavelength of the X-ray and equals 0.15406 nm, (β) is the (FWHM) full width at half maximum of the peak (in Radians), and θ_B represents the position of the peak. The dislocation density (δ) was calculated using [49-53].

$$\delta = \frac{1}{D^2} \tag{2}$$

And the strain (ϵ) was calculated by [54-57]

$$\varepsilon = \frac{\beta}{4\tan\theta} \tag{3}$$

All the calculations were tabled in (Table 1)[16]. As seen in the XRD patterns (002), rutile is the highest intense peak at 2θ =61.760, so one could assume that it will be the most exposed facet of the material in catalytic reactions.

Laser Energy	Peak label	Peak position (degree)	FWHM (degree)	Crystallite size (D) (nm)	Average size (nm)	Dislocation density (δ) (10 ¹⁴) (1/m ²)	Strain (ε) (10 [.] ³)
500mJ	A101	24.8	0.04	212.49	166.799	0.22	0.79
	R110	27.44	0.105	81.38		1.51	1.87
	A004	38.12	0.038	231.109		0.19	0.48
	R002	61.76	0.068	142.22		0.50	0.49
600mJ	A101	24.44	0.06	141.56	154.906	0.50	1.21
	A103	38.12	0.065	135.11		0.55	0.82
	A004	38.6	0.05	175.9		0.32	0.62
	R211	54.2	0.05	186.48		0.29	0.43
	R002	61.76	0.13	74.39		1.81	0.95
	R310	63.16	0.045	216		0.21	0.32
700mJ	R110	27.48	0.13	65.74	99.705	2.31	2.32
	A103	36.12	0.09	97.01		1.06	1.20
	R211	54.32	0.06	155.48		0.41	0.51
	R002	61.76	0.12	80.59		1.53	0.87

Table 1 Calculation of XRD results



Figure 3. XRD test of the three samples of TiO₂ thin film.

Raman spectroscopy recorded in the range of 0-1000 cm⁻¹, shown in Figure 4, reveals information about the film's structure. Two characteristic Raman active modes, one for anatase with E_g symmetry observed at (200 to 150 cm⁻¹) which is shifted as the laser energy increases from 96

500mJ to 700mJ, and one for rutile also with E_g symmetry observed at 450cm⁻¹ with a slight shift between deferent laser energies[58-61], all of the anatase and rutile peaks were broad. The Raman and XRD analysis confirmed the presence of phase pure rutile and anatase TiO₂ in the thin film.



Figure 4. Raman spectra of TiO_2 thin film.



Figure 5. Transmission and absorption spectra of the thin film.

The transmission spectra of TiO_2 thin films created by laser energies of 500, 600, and 700mJ are shown in fig. 5. As noticed, the transmission is overall decreasing with increasing laser energy because the higher the energy more ablation of the nano TiO_2 occurs from the target then the

deposition rate increased, so the thickness of the thin film goes from 76-89-97nm that which was measured using Fizeau fringes interferometer method[62-64]. The colors of the thin films were white to gray, and as seen, it has high absorption in the region of 200-350nm (UV), referring to the small particle sizes of the nanomaterial. The bandgap was wide and direct, making the TiO_2 a good material for optoelectronic applications such as solar cells. Figure 6 is a plot of (hv) versus $(ahv)^2$. With this graph, it is possible to find the energy bandgap (E_g)[65-68], the values of E_g were found to be 3.95, 3.96, and 3.85 eV, respectively, to energies from 500-700mJ that indicate a red shift in the absorption spectrum and is agreeing with [69-71].



Figure 6. Energy band gap of TiO₂ film prepared at three laser energies of PLD.

The TiO₂ surface topography was studied with the help of the AFM test. The AFM shows some uniformity in the distribution of the grains, with some individual grains stretched vertically, making some high peaks. As the laser energy increased from 500 to 700mJ in the step of 100mJ, the roughness (Ra) and the root mean square (RMS) values were also increased starting from (Ra=1.03nm, Rms=1.48nm) at laser energy of 500mJ, reaching their maximum values of (Ra=1.1nm, Rms=1.51nm) at 700mJ laser energy as shown in table 2, this is due to the crystallization of TiO₂ was at its best at 700mJ laser energy when compared to the other energies [72-74], for this reason, this value of energy is considered to be better than the two other energies. The FESEM photomicrograph shows a homogeneous and smooth structure with a good distribution of grains at 700mJ laser energy. Figure 7 shows the AFM and FESEM images of the 700mJ samples.

|--|

Laser energy (mJ)	Root mean square (RMS) (nm)	Roughness (Ra) (nm)	
500	1.48	1.03	
600	1.5	1.04	
700	1.51	1.1	



Figure 7. (a) AFM image of TiO₂ film prepared at 700mJ PLD laser energy. (b) FESEM images of TiO₂ at 700mJ PLD laser energy with three different magnifications.

4. CONCLUSION

TiO₂ thin films were prepared using the PLD technique. The XRD test confirmed the formation of phase pure anatase and rutile TiO₂; the highest was at 2θ =61.76°, making it the most exposed material facet. As the laser energy reached 700mJ, the crystallization became more specified to show two obvious rutile and two anatase peaks. Raman spectroscopy also confirmed the formation of anatase and rutile TiO₂, both with the E_g structure plane. The optical properties were investigated with a UV-Vis spectrophotometer. The transmission decreased as the thickness increased from 76nm to 97nm, resulting in increased laser energy. Determined from the transmission value, the absorption was at its highest in a wavelength range of 200-350nm, and the measured energy gap of the three samples was (3.95, 3.96, and 3.85)eV. The morphology, which was tested by AFM, showed the highest roughness and root mean square values at 700mJ laser energy, conforming to the best crystallization at this energy, so it could be considered the best value of the tested energies.

REFERENCES

- [1] Djibrilla, M., Sanda, A., Badu, M., Awudza, J.A.M., Boadi, N., 2021. Chemistry International. 7 (Issue 1), 9-20.
- [2] Salim E.T., Ismail, R.A., Halbos, H.T., 2019. Materials Research Express. 6, 116429.
- [3] Abood, M.A., Salim, E.T., Saimon, J.A., 2019. Journal of Ovonic Research. 15, 109 115.

- [4] Guo, Q., Zhou, C., Ma, Z., Yang, X., 2019. Advanced Materials. 31 (Issue 50), 1901997.
- [5] Salim, E.T., Halboos, H.T, 2019. Materials Research Express. 6, 066401.
- [6] Fakhri, M.A., Salim, E.T., Wahid, M.H.A., Abdulwahhab, A.W., Salim, Z.T., Hashim, U., 2019. Journal of Physics and Chemistry of Solids. 131, 180-188.
- [7] Zhao, X., Murayama, M., Guan, S., Yida, K., Shirashi, K., Ishii, T., Komuro, S., 2018. Optics and Photonics. 8 (Issue), 146-164.
- [8] Salim, E.T., Hassan, A.I., Naaes, S.A., 2019. Materials Research Express. 6, 086416.
- [9] Fakhri, M.A. Salim, E.T. Wahid, M.H.A. Abdulwahhab, A.W. Hashim, M.U. Salim, Z.T., 2019. Optik. 180, 768-774.
- [10] Salim E.T., Fakhri, M.A., Ismail, R.A., Abdulwahhab A.W., Salim, Z.T., Hashim, U., 2019. Superlattices and Microstructures. 128, 67-75.
- [11] Islam, Md. T., Dominguez, A., Turley, R.S., Kim, H., Siltana, K.S., Shuvo, M., Alvarado-Tenorio, B., Montes, M.O., Lin, Y., Gardea-Torresdey, J., Noveron, J.C., 2020. Science of The Total Environment. 704, 135406.
- [12] Halboos, H.T., Salim, E.T., 2018. IOP Conference Series Materials Science and Engineering. 454, 012174.
- [13] Al Wazny, M.S. Salim, E.T. Bader B.A. and Fakhry, M.A., 2018. IOP Conference Series Materials Science and Engineering. 454, 012160.
- [14] Salim, E.T., Saimon, J.A., Abood M.K, Fakhri, M.A., 2019. Materials Research Express. 6, 046420.
- [15] Xu, J., Xu, N., Zhang, X., Xu, P., Gao, B., Peng, X., Mooni, S., Li, Y., Fu, J., Huo, K., 2017. Sensors and Actuators B: Chemical. 244, 38-46.
- [16] Salim E.T., Ismail, R.A. Fakhri, M.A. Rasheed, B.G. Salim, Z.T., 2019. Iranian Journal of Science and Technology, Transactions A: Science. 43, 1337–1343.
- [17] Fakhri, M.A. Numan, N.H. Kheder, M.H. Badr, B.A. Khalid, F.G. Hashim, U. Salim, E.T. and Salim, T., 2018. AIP Conference Proceedings. 2045, 020019.
- [18] Doubi, Y., Hartiti, B., Siadat, M., Labrim, H., Fadili, S., Stitou, M., Tahri, M., Belfhaili, A., Thevenin, P., Losson, E., 2022. Journal of Electronic Materials. 51, 1-13.
- [19] Fakhri, M.A. Numan, Alshakhli, N.H.Z.S. Dawood, M.A Abdulwahhab, A.W. Khalid, F.G. Hashim, U. and Salim, E.T., 2018. AIP Conference Proceedings. 2045, 020015.
- [20] Abood, M.K., Wahid, M.H.A., Saimon, J.A., Salim, E.T., 2018. International Journal of Nanoelectronics and Materials. 11, 237-244.
- [21] Fakhri, M.A., Bader, B.A., Khalid, F.G., Numan, N.H., Abdulwahhab, A.W., Hashim, U., Salim, E.T., Munshid, M.A., Salim, Z.T., 2018. AIP Conference Proceedings. 2045, 020017.
- [22] Wunderlich, W., Oekermann, T., Miao, L., Thi, N.H., Tanemura, S., Tanemura, M., 2004. Journal of Ceramic Processing & Research. 5 (Issue 4), 343-354.
- [23] Fakhri, M.A., Rashid, B.G., Numan, N.H., Bader, B.A., Khalid, F.G., Zaker, T.A., and Salim, E.T., 2018. AIP Conference Proceedings. 2045, 020016.
- [24] Abood, M.K., Saimon, J.A., Salim, E.T., 2018. International Journal of Nanoelectronics and Materials. 11, 55-64.
- [25] Badr, B.A., Numan, N.H., Khalid, F.G., Fakhri, M.A., Abdulwahhab A.W., 2019. Journal of Ovonic Research. 15, 127-133.
- [26] Linsebigler, A.L., Lu, G., Yates Jr., H.T., 1995. Ceramical reviews. 95 (Issue 3), 735-758.
- [27] Fakhri, M.A., Abdulwahhab A.W., Dawood, M.A., Raheema, A.Q., Numan, N.H., Khalid, F.G.M., Wahid, H.A., Hashim U., Salim, E.T., 2018. International Journal of Nanoelectronics and Materials. 11, 103-108.
- [28] Mohsin, M.H., Ismail, R.A., Mhadi, R.O., 2021. Appl. Phys. A. 127, 214.
- [29] Fakhri, M.A., Numan, N.H., Mohammed, Q.Q., Abdulla, M.S., Hassan, O.S., Abduljabar, S.A., Ahmed, A.A., International Journal of Nanoelectronics and Materials. 11, 109-114.
- [30] Saimon, J.A., Mahdi, R.O., Khashan, K.S., Abdulameer, F.A., 2020. AIP Conference Proceedings. 2213, 020312.
- [31] Ruan, X., Cui, X., Cui, Y., Fan, X., Li, Z., Xie, T., Ba, K., Jia, G., Zhang, H., Zhang, L., Zhang, W., Zhao, X., Leng, J., Jin, S., Singh, D. J., Zhemg, W., 2022. Advanced Energy Materials. 12 (Issue 16), 2200298.

100

- [32] Badr, B.A., Numan, N.H., Khalid, F.G., Fakhri, M.A., Abdulwahhab, A.W., 2019. Journal of Ovonic Research. 15, 53-59.
- [33] Mhadi, R.O., Ismail, R.A., Mohsin, M.H., 2019. Mater. Res. Express. 6, 126202.
- [34] Saimon, J.A., Madhat, S.N., Khashan, K.S., Hassan, A.I., Mhadi, R.O., Nasif, R.A., 2018. AIP Conference Proceedings. 2045, 020003.
- [35] Mo, S., Ching, W.Y., 1995. Physical Review B. 51 (Issue 19), 13023.
- [36] Mahdi, R.O., Hadi, A.A., Taha, J.M., Khashan, K.S., 2020. AIP Conference Proceedings. 2213, 020309.
- [37] Alwazny, M.S., Ismail, R.A., Salim, E.T., 2022. International Journal of Nanoelectronics and Materials. 15 (Issue 3), 223–232.
- [38] Salim, E.T., 2013. Surface Review and Letters. 20 (Issue 5), 1350046.
- [39] Navrotsky, A., Jamieson, J.C., Kleppa, O.J., 1967. Science. 158 (Issue 3799), 388-389.
- [40] Kadhim, A., Salim, E.T., Fayadh, S.M., Al-Amiery, A.A., Kadhum, A.A.H., Mohamad, A.B., 2014. The Scientific World Journal. 2014, Article ID 490951, 6 pages.
- [41] Alshaikhli, Z.S., Alhasan, S.F.H., Salim, E.T., Parmin, N.A., 2022. Defect and Diffusion Forum. 418, 89-97.
- [42] Muhsien, M.A., Salem, E.T., Agool I.R., Hamdan, H.H., 2014. Appl. Nanoscience. 4, 719–732.
- [43] Hu, Y., Tsai, H., Huang, C., 2003. Materials Science and Engineering: A. 344 (Issue 1-2), 209-214.
- [44] Hassan, M.A.M., Al-Kadhemy, M.F.H., Salem, E.T., 2015. International Journal of Nanoelectronics and Materials. 8 (Issue 2), 69-82.
- [45] Salim, E.T. Mahmood, R.S., Khalid, F.G., Hashim, U., 2022. Defect and Diffusion Forum. 418, 79-88.
- [46] Fakhri, M.A., Ismail, R.A., Abass, A.K., Mohammed, L.Z., Alsultany, F.H., Hashim, U., Silicon. 2022. https://doi.org/10.1007/s12633-022-01902-5
- [47] Wang, W., Gu, B., Liang, L., Hamilton, W.A., Wesolowski, D.J., 2004. The Journal of Physical Chemistry B. 108 (Issue 39), 14789-14792.
- [48] Khashan, K.S., Saimon, J.A., Hadi, A.A., Mahdi, R O., 2021. J. Phys.: Conf. Ser. 1795, 012026.
- [49] Mohsin, M.H., Haider, M.J., Al-Shibaany, Z.Y.A., Haider, A. J., Mehadi, R. O., 2022. Silicon. 14, 1349–1355.
- [50] Salim, E.T., Saimon, J.A., Abood, M.K., and Fakhri, M.A., 2019. Mat. Res. Express. 6 (Issue 12), 126459.
- [51] Hattab, F., Fakhry, M., 2012. First National Conference for Engineering Sciences (FNCES 2012). 1-5
- [52] Fakhri, M.A., Al-dDouri, Y., Hashim, U., Salim, E.T., Prakash, D., Verma, K.D., 2015. Applied Physics B. 121 (Issue 1), 107-116.
- [53] Challagulla, S., Tarafder, K., Ganesan, R., Roy, S., 2017. Scientific Reports. 7 (Issue 8783), 1-11.
- [54] Tawfiq, Z.H., Fakhri, M.A., Adnan, S.A., 2018. IOP Conf. Series: Materials Science and Engineering. 454 (Issue 1), 012173.
- [55] Fakhri, M.A., Salim, E.T., Wahid, M.HA., Salim, Z.T., Hashim, U., 2020. AIP Conference Proceedings. 2213 (Issue 1), 020242.
- [56] Kajava, T.T., Lauranto, H.M., Feriberg, A.T., 1994. Journal of the Optical Society of America A. 11 (Issue 7), 2045-2054.
- [57] Fakhri, M.A., Salim, E.T., Wajid, M.H.A., Hashim, U., Salim, Z.T., Ismail, R.A., 2017. Journal of Materials Science: Materials in Electronics. 28 (Issue 16), 11813-11822.
- [58] Salim, E.T., Fakhri, M.A., Tareq, Z., and Hashim, U., 2020. AIP Conference Proceedings. 2213 (Issue 1). 020230.
- [59] López, R., Gómez, R., 2012. Journal of Sol-Gel Science and Technology. 61 (Issue 1), 1-7.
- [60] Leprince-Wang, Y., Yu-Zhang, K., 2001. Surface and Coatings Technology. 140 (Issue 2), 155-160.
- [61] Ma, H., Yu, L., Yuan, X., Li, Y., Li, C., Yin, M., Fan, X., 2019. Journal of Alloys and Compounds. 782, 1121-1126.

- [62] Fadhil, R.B., Salim, E.T., Khalef, W.K., 2022. Journal of Materials Science: Materials in Electronics. 33, 21688–21701.
- [63] Parka, C., Honga, M., Chob, H.H., Park, H., 2018. Journal of the European Ceramic Society. 38, 125-130.
- [64] Fadhil, R.B., Salim, E.T., Khalef, W.K., 2022. Egyptian Journal of Chemistry. 10.21608/EJCHEM.2022.129669.5749.
- [65] Lee, H., Kim, B., Gao, C.Y., Choi, H.J., Ko, C., Seo H., Park, J., 2019. Molecular Crystals and Liquid Crystals. 679, 38–47.
- [66] Jabbar, H.D., Fakhri, M.A., AbdulRazzaq, M.J., 2022. Silicon. https://doi.org/10.1007/s12633-022-01999-8.
- [67] Jeona, J., Jeona, D., Sahooa, T., Kima, M., Baekb, J., Hoffmanc, J.L., Kimc, N.S., Leea, I., 2011. Journal of Alloys and Compounds. 509, 10062–10065.
- [68] Faisal, D., Kalef, W.K., Salim, E.T., Alsultany, F.H., 2022. Journal of Ovonic Research. 18 (Issue 2), 205–212.
- [69] Kennedy, J., Murmu, P., Leveneur, P.J., Markwitz, A., Futter, 2016. J., Appl. Surf. Sci. 367, 52.
- [70] Ali, S.B., Alhasan, S.F.H., Salim, E.T., Alsultany, F.H., Dahham, O.S., 2022. Journal of Renewable Materials. 10 (Issue 11), 2819-2834.
- [71] Berengue, O.M., Lanfredi, A.J., Pozzi, C. L. P., Rey, J. F. Q., Leite, E. R., Chiquito, A. J., 2009. Nanoscale Res. Lett. 4, 921.
- [72] Fakhri, M.A., Alghurabi, M.N.A., Alsultany, F.H., Wahid, M.H.A., 2022. Defect and Diffusion Forum. 418, 109-118.
- [73] Berengue, O.M., Rodrigues, A.D., Dalmaschio, C.J.A., Lanfredi, J.C., Leite, E.R., Chiquito, A.J., 2010. J. Phys. D: Appl. Phys. 43, 045401.
- [74] Alhasan, S.F.H., Abduljabbar, M.A., Alshaikhli, Z.S., Fakhri, M.A., Parmin, N., 2022. Defect and Diffusion Forum. 418, 99-107.