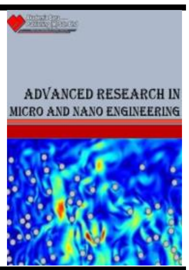
Journal of Advanced Research in Micro and Nano Engineering, 21, Issue 1 (2024) 1-15

Penerbit Akademia Baru

Journal of Advanced Research in Micro and Nano Engineering

Journal homepage: https://www.akademiabaru.com/submit/index.php/armne/index

ISSN: 2756-8210



Synthesis and Characterization of Cobalt-doped Titanium Dioxide Thin Films as Solar Cell Components using UV-SEM Analysis

Aris Doyan[1,*], Susilawati[1], Agus Abhi Purwoko[1], Muhammad Taufik[2], Dedi Riyan Rizaldi[3], Ziadatul Fatimah[4]

[1] Master of Science Education Program, University of Mataram, Lombok, West Nusa Tenggara, Indonesia
[2] Physics Education Program, FKIP, University of Mataram, Lombok , West Nusa Tenggara, Indonesia
[3] Madrasah Aliyah Plus Nurul Islam Sekarbela, Mataram, Lombok, West Nusa Tenggara, Indonesia
[4] Senior High School Nahdathul Wathan Mataram, Mataram, Lombok, West Nusa Tenggara, Indonesia

ARTICLE INFO

Article history:
Received 20 April 2024
Received in revised form 18 May 2024
Accepted 29 June 2024
Available online 30 July 2024

Keywords:
Thins films; titanium dioxide; cobalt doping; optical properties; morphology; solar cell technology

ABSTRACT

Research has been carried out in the form of the synthesis and characterization of thin films of titanium dioxide with the addition of cobalt doping. The purpose of this research was to synthesize and characterize thin films related to optical properties, morphological shapes, and components of thin film compounds that are good for use as basic materials for the development of nanoparticle technology in the form of solar cells. The research was carried out in two stages, namely synthesis such as preparation of glass substrates, preparation of sol-gel solutions, deposition of solutions onto glass substrates, and heating of TiO_2:Co thin film samples. The next stage is the thin film characterization test, where the optical properties of the thin film, such as absorbance, transmittance, gap energy, and activation energy, are measured using a UV-vis spectrophotometer, while morphological data and components of the thin layer compounds are measured using a Scanning Electron Microscope-Energy Dispersive X-rays (SEM-EDX). Based on data analysis and discussion, it was found that the optical properties, such as the transmittance value of the thin film, experienced the lowest point at a wavelength of 250–280 nm with a maximum percentage value of 62.14 to 78.85%. The greater the doping concentration, the lower the transmittance value. This condition is inversely proportional to the absorbance value of the maximum TiO_2:Co thin film, which is in the region with a wavelength of 280–300 nm and a value of 5.70–6.31. The greater the doping concentration, the greater the absorbance value. The energy bandgap values of TiO_2:Co thin films for doping concentrations (0, 5, 10, 15, 20)% were 3.44; 3.39; 3.38; 3.32; 3.22 eV for the direct energy bandgap and 3.86; 3.85; 3.84; 3.85; 3.82 eV for the indirect energy gap. The activation energy of the TiO_2:Co thin film decreased from 2.86 to 2.26 eV. As for the morphological data of the TiO_2:Co thin film, it was found that the greater the concentration of doping, the layer was deposited evenly, finely, and homogeneously. Regarding the data on the components of the thin layer compounds, it was found that the percentage of TiO_2 content was in the range of 64.48–95.94%, while for Co, it was in the range of 0.00–19.21%.

* *Corresponding author.*
E-mail address: aris_doyan@unram.ac.id

https://doi.org/10.37934/armne.21.1.115

1. Introduction

Solar cells are a nanoparticle-based technology that continues to experience a process of development and improvement both in terms of basic materials and the resulting performance in supporting various human activities [1]. This is, of course, because solar cell technology utilizes unlimited energy sources, namely sunlight, and is environmentally friendly, so it is a good alternative to replacing limited energy sources such as coal, gasoline, and others [2,3]. To be able to develop solar cells, materials that are semiconductors and have good absorption levels are needed in order to maximize solar radiation as the main energy source [4,5]. One of the compounds that can be used as a base material or precursor in the development of thin film-based solar cells is titanium dioxide, also known as TiO_2 [6,7].

TiO_2 compounds are often used in the development of solar cells due to several advantages, such as having high stability against photo corrosion, a high level of photocatalyst, a relatively cheap price compared to other compounds with the same use, and not causing side effects that are harmful to health. However, based on the various advantages previously possessed, there is one drawback of the TiO_2 material, namely that it still has a relatively large energy gap that has an impact on the level of absorption of light, which is still limited [8,9]. The absorption limitation is only in the ultraviolet light spectrum with low wavelengths. In general, the good properties of photocatalysts in solar cell technology are that the process of absorbing energy from sunlight can also occur in the visible light wavelength range [10]. A photocatalyst is a combined process between chemical synthesis processes involving light as a triggering factor and a catalyst as a factor that accelerates the reaction process [11,12].

Efforts that can be used to increase photocatalyst activity on TiO_2 materials are doped with either metal or non-metal elements. The purpose of the doping process is to optimize the electrical and optical properties of the thin films to be developed [13,14]. One of the dopings that can be used to change the characteristics of thin films is cobalt (Co) because the atoms of this metal can enhance the process of photocatalytic reduction and degradation. This is supported by several previous studies using cobalt doping, which was found to be able to reduce the band gap so that it can work in visible light (up to 550 nm) [15]. This condition is certainly expected to form on a thin layer of TiO_2 with Co doping using the sol-gel spin coating method as a material for developing solar cells.

2. Methodology

This research is pure experimental research. The variables of this research consist of the independent variable, namely variations in cobalt doping, while the dependent variable is the synthesis and characterization of TiO_2 thin layers as materials for developing solar cell components. This research was carried out through two stages of the process, namely synthesis and characterization. The synthesis process aims to produce TiO_2:Co thin film samples with concentration criteria of 0, 5, 10, 15, and 20%, consisting of four layers, and heated at 200 °C. Stages of synthesis start with: a) preparation of a glass substrate with a size of 15 x 15 x 3 mm; b) preparation of sol-gel solutions utilizing titanium dioxide precursor materials, cobalt doping materials, ethanol, and hydrochloric acid solvents with the help of a magnetic stirrer; c) deposition of sol-gel solutions on a glass substrate using a spin-coating method with the aid of a modified centrifuge; and d) heating the sample using an oven. In the next stage, after the sample has been successfully synthesized, the characterization process is carried out with the aim of determining the optical properties of the thin layer using a UV-Vis Spectrofotometer and the morphology and constituent components of the thin layer using a Scanning Electron Microscope-Energy Dispersive X-ray (SEM-EDX).

Analysis technique for measuring transmittance and absorption of UV light in the ultraviolet wavelength range (starting from 150 nm) to cover all wavelengths of visible light (up to 800 nm) using a UV-Vis Spectrophotometer. From the characterization process, data was obtained on the comparative value of the quality of pure TiO_2 thin films with TiO_2:Co thin films in terms of transmittance and absorbance levels. Then the absorbance values that have been obtained are analyzed using Microsoft Excel to find the energy band gap and activation energy values.

The optical energy band gap value of a material is obtained by the following equation

$$\alpha hv = C\left(hv - E_{\mathrm{g}}\right)^{n} \quad (1)$$

Information:
α = absorbance coefficient
hv = photon energy (eV)
E_{g} = energy band gap (eV)
C = constant

The step to obtain the thin layer absorbance coefficient value is obtained by using the absorbance spectrum value in the equation.

$$\alpha(v) = \frac{2.303A}{d} \quad (2)$$

Information:
A=absorbance (obtained directly through the reading process with a UV-Vis Spectrophotometer)
d=thin layer sample thickness (mm)

Then the final step to determine the energy band gap value of the pure TiO_2 and TiO_2:Co thin films is obtained from the slope of the graph *(αhv)ⁿ* against the photon energy *hv*, with the electron transition constant n= ½ for direct allowed and n=2 for indirect allowed. Meanwhile, to calculate the activation energy using the Urbach-edge method, it is mathematically expressed through the equation

$$\alpha(\omega) = \alpha_0 exp^{\left(\frac{\hbar\omega}{\Delta E}\right)} \quad (3)$$

$$\ln \alpha(\omega) - \alpha_0 = \frac{\hbar\omega}{\Delta E} \quad (4)$$

$$\ln \alpha(\omega) = \frac{\hbar\omega}{\Delta E} + \alpha_0 \quad (5)$$

Because $\hbar = \frac{h}{2\pi}$ and $\omega = 2\pi v$, so

$$\ln \alpha(\omega) = \frac{h}{2\pi}\frac{2\pi\nu}{\Delta E} + \alpha_0 \quad (6)$$

$$\ln \alpha(\omega) = \frac{h\nu}{\Delta E} + \alpha_0 \quad (7)$$

Because $E_f = h\nu$, so

$$\ln \alpha(\omega) = \frac{1}{\Delta E} E_f + \alpha_0 \quad (8)$$

Eq. (8) is a linear equation that is proportional to the equation $y = mx + C$, with $m = \frac{1}{\Delta E}$, so the activation energy $(E_a) = \Delta E$. So that

$$E_a = \frac{1}{m} \quad (9)$$

Information:
$\alpha(\omega)$ = absorbance coefficient
α_0 = constant
ω = 2πv
E_a = Activation energy (eV)

The research flow procedure can be seen in the following Figure 1.

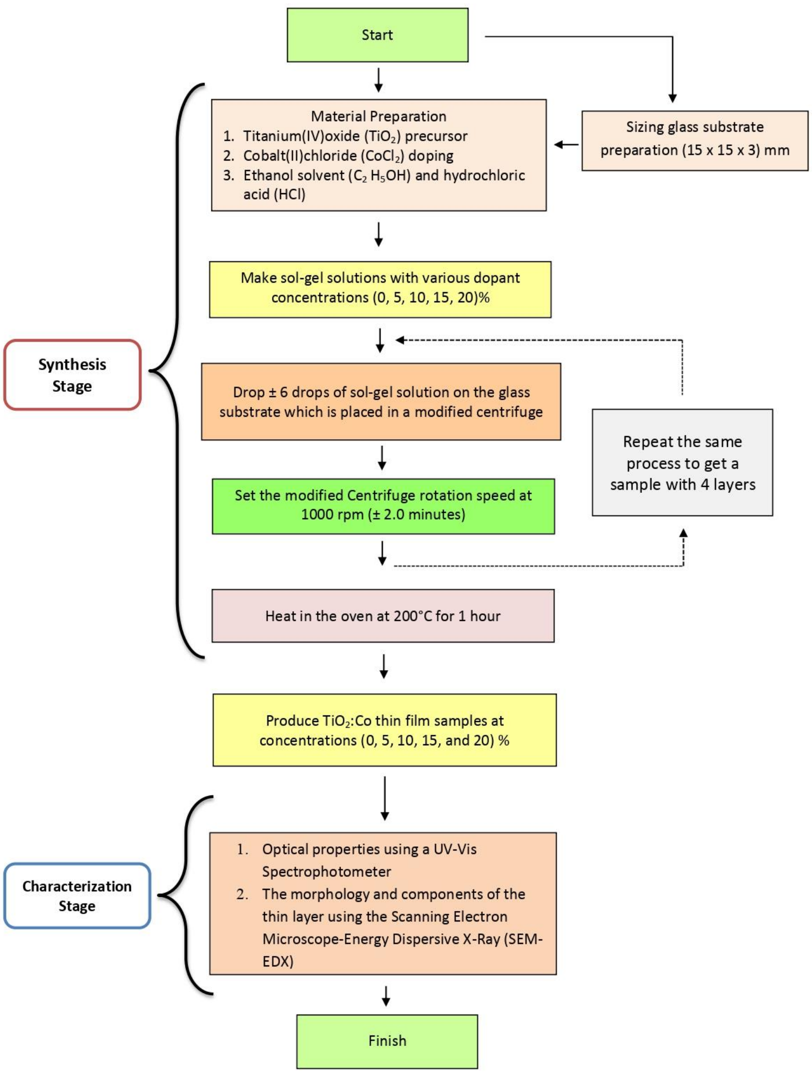


Fig. 1. Thin film research flow procedure TiO_2:Co

3. Results

3.1 Synthesis of Thin Film TiO_2:Co

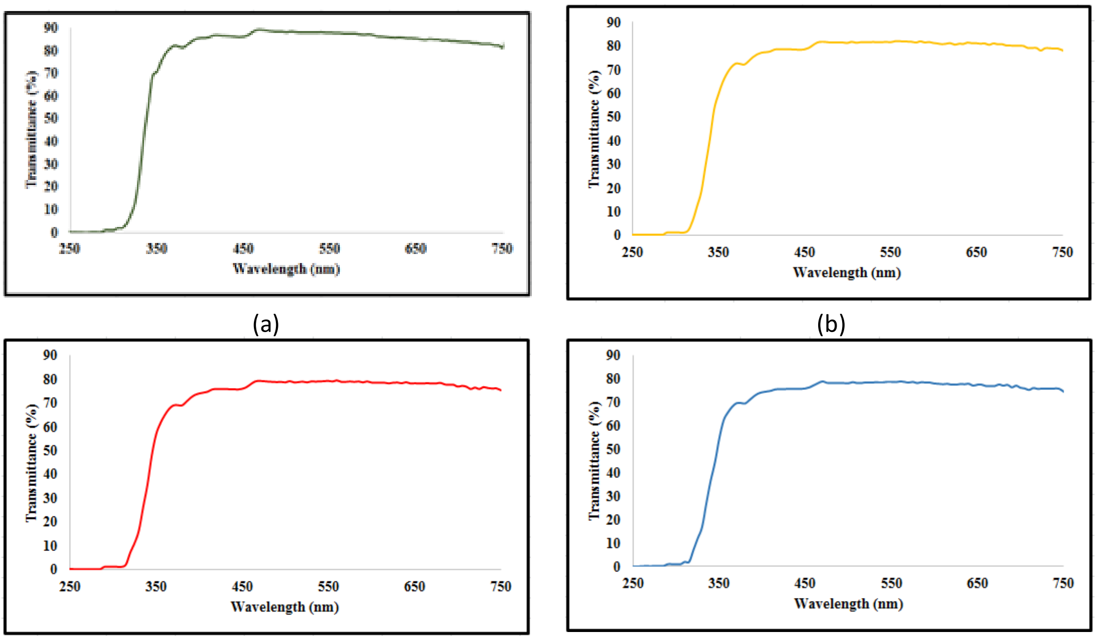
Based on the thin film synthesis process that has been carried out at the Basic Chemistry Laboratory, Faculty of Mathematics and Natural Sciences, University of Mataram, it can be seen that the sample of TiO_2 thin layer with cobalt doping has a white surface appearance, with the condition that the greater the concentration of doping given, the more average the deposition results of the solution on the surface of the substrate glass, as shown in Figure 2 below.

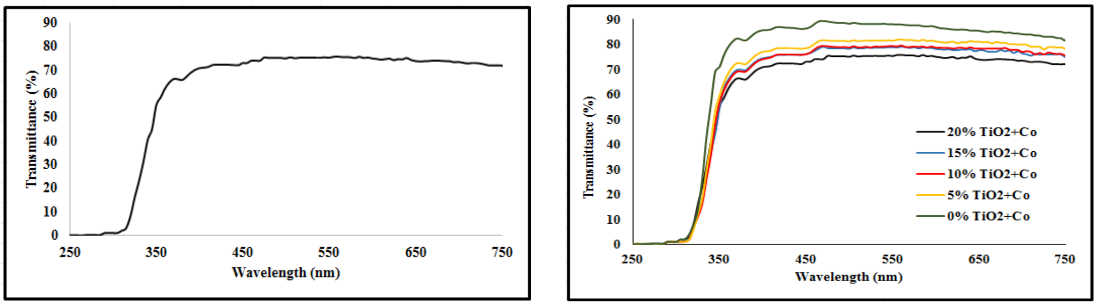
(a) (b) (c) (d) (e)

Fig. 2. Thin film samples TiO_2:Co at various concentrations (a) 0%, (b) 5%, (c) 10%, (d) 15%, (e) 20%

3.2 Characterization of Thin Film Optical Properties TiO_2:Co

The process of testing the characterization of the optical properties of TiO_2:Co thin films using UV-Vis spectrophotometers was carried out at the Integrated Science Laboratory, Mataram State Islamic University. The optical properties of the thin films tested and observed include the transmittance and absorbance properties of the thin film samples. Graphs of the transmittance and absorbance values of the TiO_2:Co thin film can be seen in Figures 3 and 4.





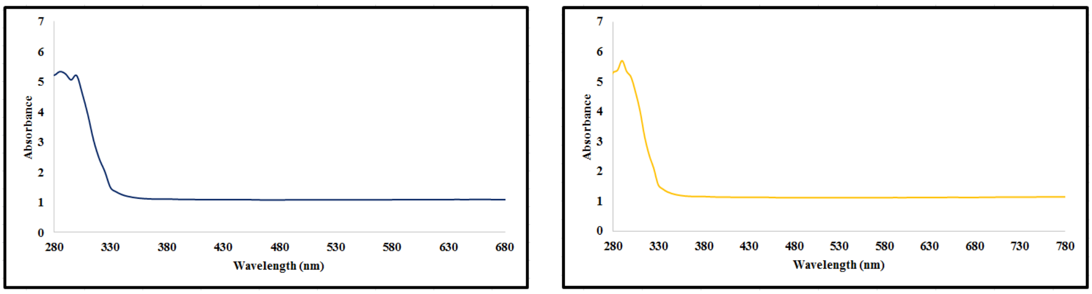
(e) (f)

Fig. 3. Graph of TiO_2:Co thin film transmittance at various concentrations (a) 0%, (b) 5%, (c) 10%, (d) 15%, (e) 20%, and (f) all concentrations

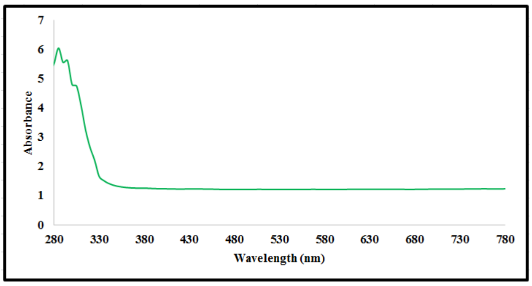
The transmittance value describes the ability of a thin layer to transmit or receive light emitted from a light source, in this case, a UV-Vis spectrophotometer [16]. Based on Figure 3, it can be seen that the lowest transmittance spectrum is in the wavelength range 250–280 nm (ultraviolet light region), while the highest intensity is in the wavelength range 350–750 nm (visible light region), with the highest value found in the TiO_2:Co thin layer sample at a concentration of 0% and a value of 89%. The low percentage of transmittance of the TiO_2:Co thin films is thought to be due to the addition of cobalt doping, which results in a thicker surface on the thin layer samples when compared to the thin layer samples without additional doping treatment. This is in line with the data that the higher the doping concentration is given, the percentage of transmittance of the thin film will decrease [17], [18]. Meanwhile, the increase in the transmittance spectrum shown in the graph shows that the TiO_2:Co thin layer samples are composed of materials with relatively homogeneous chemical stoichiometry on the surface of the glass substrate [19].

Referring to these conditions, the low transmittance factor in the ultraviolet region indicates that the TiO_2:Co thin layer sample developed in this study has a relatively high level of light absorption. This is in line with the relationship between transmittance properties, which is inversely proportional to the absorbance properties of a layer, namely that the higher the percentage transmittance of a surface, the lower the absorbance value [20-22]. This condition can be compared with the graph shown in Figure 4, where the highest absorbance of the TiO_2:Co thin film is in the wavelength range of 280–300 nm, with the highest value in the TiO_2:Co thin layer sample with a concentration of 20% and a value of 6.31, while the lowest is in the wavelength range of 330–680 nm. TiO_2 has the highest absorption rate in the ultraviolet wavelength range, which is characterized by its maximum absorbance value [23,24].

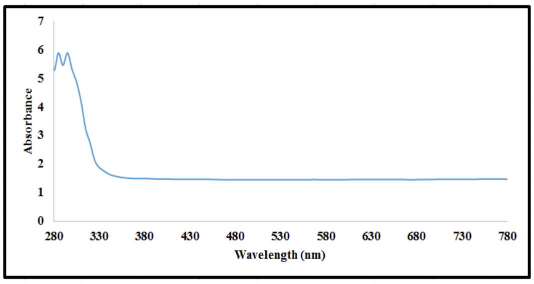
In addition to increasing the intensity of the absorbance value in the ultraviolet light wavelength range, the addition of cobalt doping is also able to increase the absorbance value of the thin film along the visible light wavelength range. Of course, this provides an opportunity to increase the chances of the absorption of light energy in various wavelength ranges.



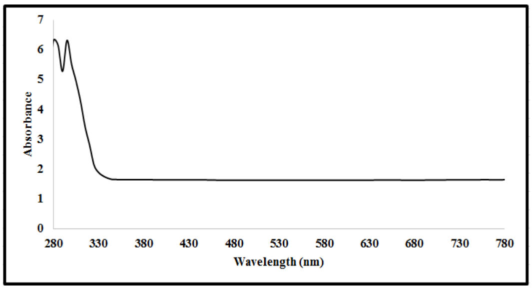
(a) (b)



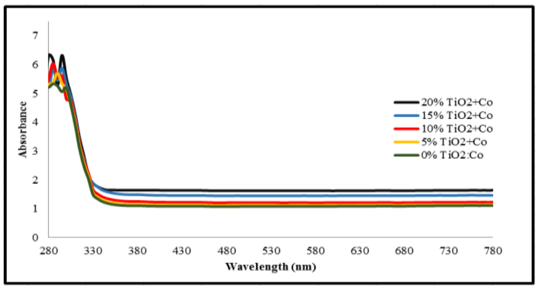
(c)



(d)



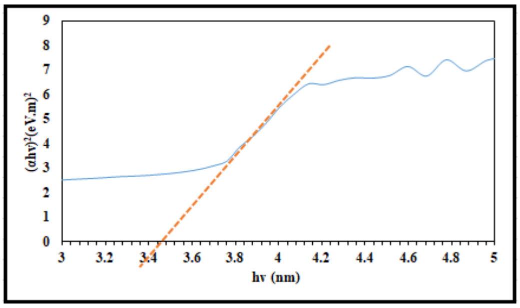
(e)



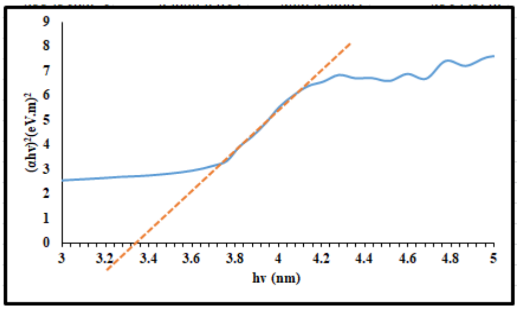
(f)

Fig. 4. Graph of absorbance of TiO_2:Co thin films at various concentrations (a) 0%, (b) 5%, (c) 10%, (d) 15%, (e) 20%, and (f) all concentrations

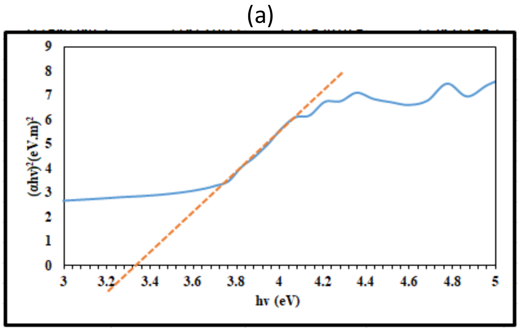
The absorbance value of the measurement results from the UV-Vis spectrophotometer was analyzed using Microsoft Excel to obtain the energy band gap value of the TiO_2:Co thin film sample. Analysis of the value of the energy band gap with reference to the Tauc Plot graphical method, which describes the relationship between *hv* and $(ahv)^n$ [25-27]. The value of the energy band gap is seen from the slope gradient formed at the intersection of $(ahv)^n$ with the *hv* axis. The energy band gap values obtained consist of direct and indirect energy band gaps, which can be seen in Figures 5 and 6.



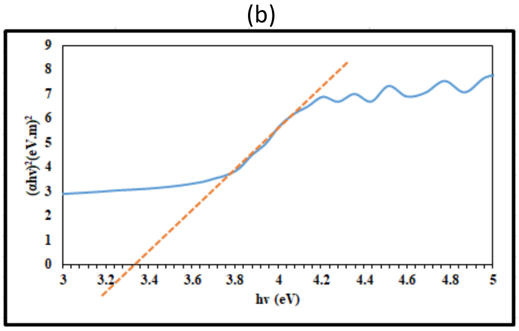
(a)



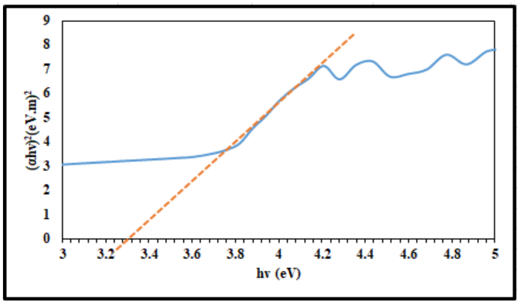
(b)



(c)

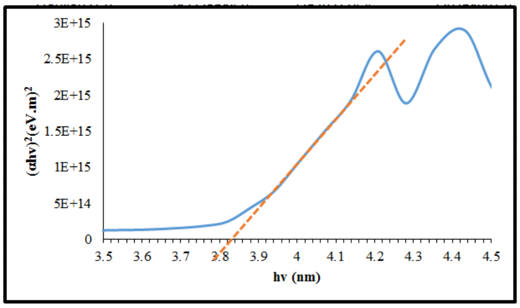


(d)

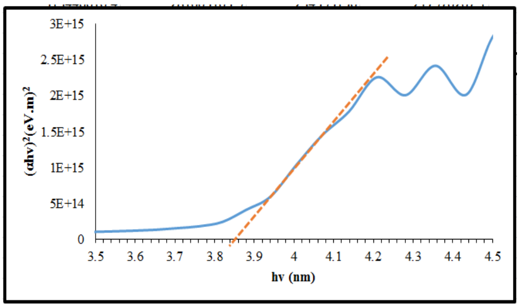


(e)

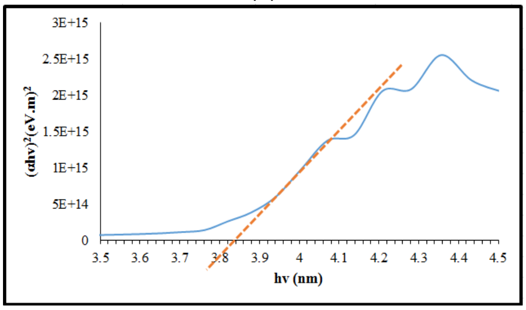
Fig. 5. Graph of the direct energy band gap of TiO_2:Co thin films at concentrations of (a) 0%, (b) 5%, (c) 10%, (d) 15%, and (e) 20%



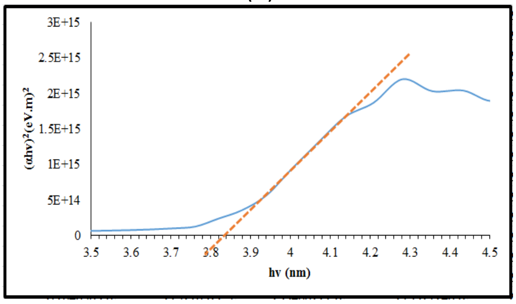
(a)



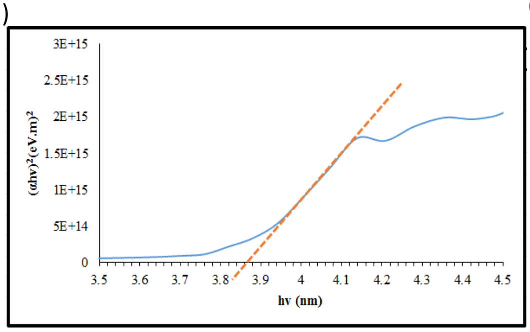
(b)



(c)



(d)



(e)

Fig. 6. Indirect energy band gap graph of TiO_2:Co thin films at concentrations of (a) 0%, (b) 5%, (c) 10%, (d) 15%, and (e) 20%

In general, TiO_2 shows the highest absorbance value in the wavelength range of 280–300 nm, followed by a constant intensity at a wavelength of 300–600 nm with a value of 1.08. However, after the process of adding cobalt doping, there was an increase in absorbance at a wavelength of 300–600 nm, with values ranging at concentrations of 5, 10, 15, and 20%, respectively: 1.12, 1.21, 1.45, and 1.62.

The energy band gap describes the intrinsic properties of semiconductor materials, which can be estimated through optical absorbance measurements [28,29]. Based on Figure 5, it can be seen that the addition of cobalt doping reduces the energy band gap in the TiO_2 compound, which is the basic material (precursor) in the development of thin films based on solar cells. Decreasing the energy band gap is an important advance in this research because decreasing it reduces the minimum energy required for electrons to undergo an excitation process or move from the valence band to the conduction band. This is because a decrease in the energy band gap in a thin film causes more energy ranges that can be used as a source of electron and hole pairs [30-32]. The decrease in the energy band gap causes the absorption spectrum or the absorbance ability of the thin film to shift to the right towards a wider wavelength so that more visible radiation intensity can be absorbed by the TiO_2:Co thin layer [33,34]. The importance of a shift in absorption in the visible light region is due to the presence of these rays on Earth more than ultraviolet rays. This is in line with research conducted by Doyan and Munadar which proves that the addition of doping can reduce the gap energy in a thin layer precursor with direct gap energy starting from 3.58 eV to 3.54 eV, while indirect gap energy starts from 3.90 eV towards 3.87 eV [17]. In addition, by reducing the band gap energy of thin layers, the performance of photocatalysts in these layers as semiconductor materials can be improved [15].

A comparison of the band gap values of direct and indirect TiO_2:Co thin films can be seen in the following table 1.

Table 1
Comparison of the direct, indirect, and activation energy band gaps of TiO_2:Co

Doping concentration TiO_2:Co	Energy band gap (eV)		Activation energy (eV)
	Direct	Indirect	
0%	3.44	3.86	2.86
5%	3.39	3.85	2.69
10%	3.38	3.84	2.42
15%	3.32	3.85	2.28
20%	3.22	3.82	2.26

In addition to obtaining the energy band gap value, the next indicator obtained from the data analysis process of the absorbance value of the thin film is the activation energy value of the TiO2:Co thin film. Activation energy is the energy required for a chemical reaction to occur in a thin film sample [35,36]. The smaller the activation energy, the easier it will be for a compound to react with other compounds. It can be seen in Table 1 that there is an effect of the concentration of the addition of cobalt doping, where the higher the percentage of doping used, the lower the activation energy of the thin layer sample.

3.3 Morphological Characterization and Thin Film Composition Components TiO_2:Co

The appearance of the morphology of TiO_2:Co thin films can be done by a surface scanning process using a Scanning Electron Microscope (SEM). SEM analysis provides a two-dimensional picture of the material by utilizing high resolution. The morphology of the TiO_2:Co thin film from the measurements can be seen in Figures 7 and 8 as follows.

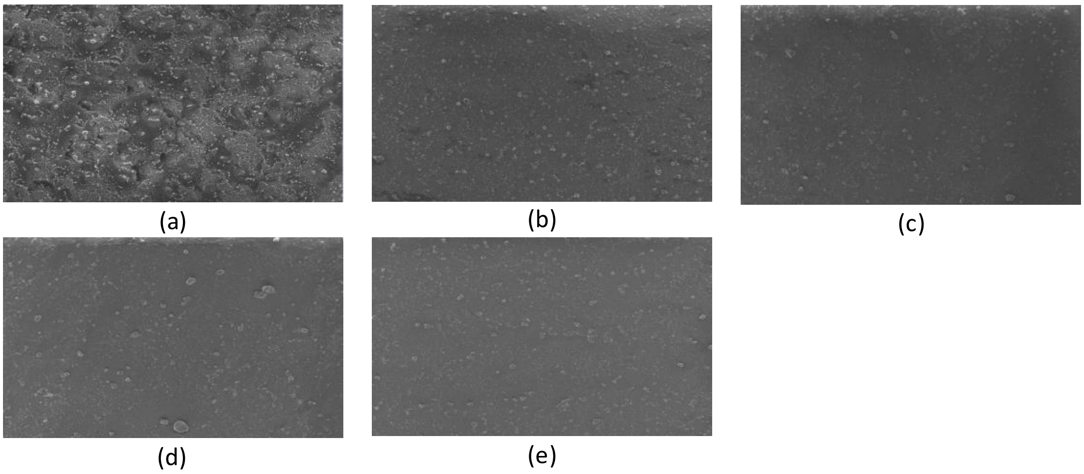


Fig. 7. Surface morphology of TiO_2:Co thin film with 100x magnification at concentrations of (a) 0%, (b) 5%, (c) 10%, (d) 15%, and (e) 20%

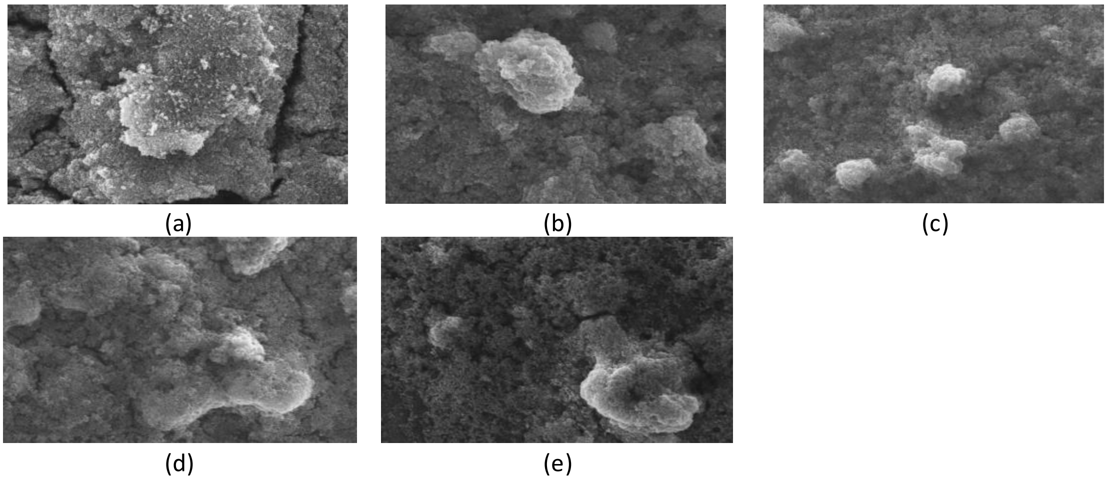
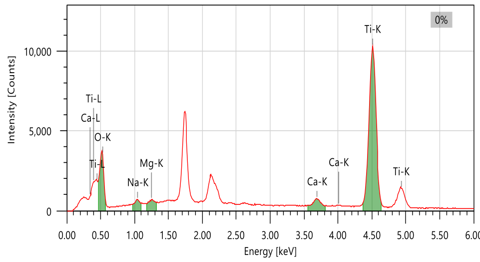
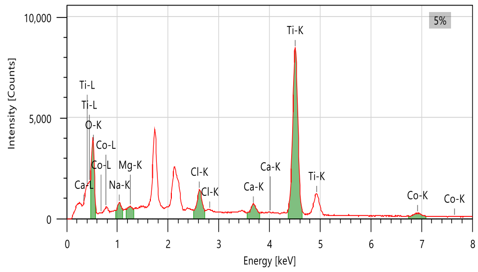
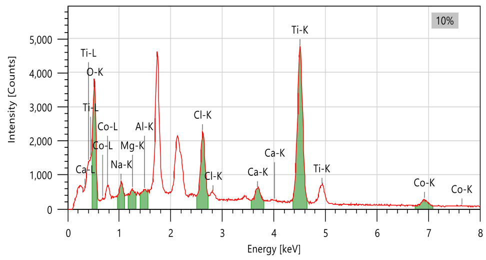
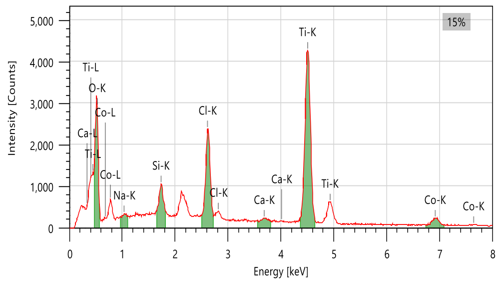
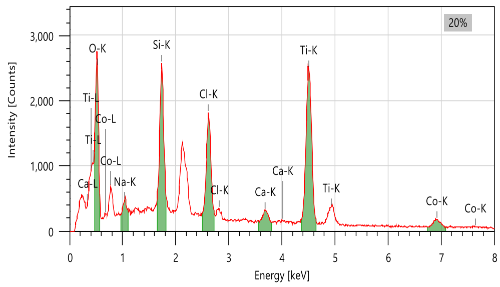


Fig. 8. Surface morphology of TiO_2:Co thin film with 5000x magnification at concentrations of (a) 0%, (b) 5%, (c) 10%, (d) 15%, (e) 20%

Based on Figure 7, it can be seen that the morphology of the TiO_2:Co thin film at 100x magnification changes towards a denser and more homogeneous direction as the concentration of cobalt doping is increased. It can be seen in Figure 7(a) that the morphology of the TiO_2 thin layer sample without doping was obtained and that the sol-gel solution was not evenly distributed on the surface of the glass substrate. In contrast to the morphological appearance of the TiO_2 thin layer after being given cobalt doping, the sol-gel solution was deposited evenly on almost all surfaces of the glass substrate. This can happen because cobalt as a dopant material functions to dissolve TiO_2 compound precursors so that they are homogeneous during the deposition process by utilizing centrifugal force in a modified centrifuge device.

Meanwhile, based on Figure 8(a) for 5000x magnification, the TiO_2 thin layer without cobalt doping has an irregular shape, a broken texture, an inhomogeneous size, and a brighter color. In contrast to Figure 8(e), the thin layer of cobalt-doped TiO_2 with the highest concentration shows that the arrangement is almost uniform, there is no significant difference in size, and it looks darker. This indicates that the TiO_2:Co thin layer sample has a high absorption rate, which is supported by the high absorbance value in the previous discussion.

Table 2
EDX analysis results of TiO_2:Co

Concentration TiO_2:Co	Mass (%) TiO_2	CoO	SiO_2	Cl	Compiler composition chart
0%	95.94±0.86	-	2.15±0.56	1.70±0.12	
5%	88.33±0.87	4.12±0.28	5.07±0.21	2.70±0.08	
10%	76.89±1.03	7.48±0.47	5.42±0.19	7.60±0.17	
15%	73.14±1.07	8.11±0.51	4.36±0.21	9.16±0.20	
20%	64.48±1.11	19.21±0.56	6.85±0.48	9.18±0.23	

EDX characterization was carried out to determine the various elemental contents contained in the TiO_2:Co thin film sample. Based on the test results, there were at least four elements or compounds that were found to have the highest percentage level in the TiO_2:Co thin layer samples, including TiO_2 (precursor base material), CoO (doping agent), SiO_2 (glass substrate content), and Cl (solvent), as shown in Table 2.

The two elements or compounds that appeared, namely TiO_2 and CoO, indicated that the thin film samples already contained precursor and doping, as expected by the researchers, which were obtained through a deposition process using a modified centrifuge. Meanwhile, two other elements or compounds with a high percentage that appeared, namely SiO_2, indicated that there was still a surface of the glass substrate that had not been deposited perfectly or evenly, while the Cl element was the residual result of the heating process, which was sourced from the solvent used, namely ethanol (C_2H_5OH) and hydrochloric acid (HCl). The appearance of the percentage of SiO_2 and Cl in the thin film synthesis process is a natural thing because it is closely related to the substrate used and the dissolution process between the precursor and doping materials [37-40]. So it is very likely that these two elements/compounds were found through the SEM-EDX test process.

If seen in Table 2, it can be seen that the greater the percentage of doping concentration used, the higher the percentage of CoO elements, which causes a decrease in the percentage of TiO_2. This is in line with the treatment carried out by researchers, where the greater the amount of dopants used, the smaller the amount of precursor material. In addition, the high percentage of TiO_2 and CoO indicates that the deposition process on the substrate using the spin-coating method provides [41-44] a great opportunity for the sol-gel solution to adhere to the surface of the glass substrate. The bonding process between the solution and the substrate is influenced by the adhesion force, which is strengthened by utilizing the centrifugal force, which will spread the sol-gel solution along the surface of the glass substrate [45].

4. Conclusions

The process of synthesis and characterization of TiO_2 thin films with cobalt doping has been carried out. The results of the UV-Vis spectrophotometer test showed that the energy bandgap values of the TiO_2:Co thin films for doping concentrations (0, 5, 10, 15, 20)% were 3.44; 3.39; 3.38; 3.32; 3.22 eV for the direct energy bandgap and 3.86; 3.85; 3.84; 3.85; 3.82 eV for the indirect energy gap. The activation energy of the TiO_2:Co thin film decreased from 2.86 to 2.26 eV. As for the morphological data of the TiO_2:Co thin film, the results of the SEM-EDX test showed that the greater the doping concentration, the layer was deposited evenly, finely, and homogeneously. Regarding the data on the components of the thin layer compounds, it was found that the percentage of TiO_2 content was in the range of 64.48–95.94%, while for Co, it was in the range of 0.00–19.21%.

Acknowledgement
Thank you to the University of Mataram for providing funding for PNBP research, the Basic Chemistry Laboratory of the Faculty of Mathematics and Natural Sciences, University of Mataram, in the process of making thin layer samples, and the Integrated Science Laboratory of Mataram State Islamic University in the process of testing and analysing thin layer sample data.

References
[1] Moharam, Marwa Mostafa, Ayat Nasr El Shazly, Kabali Vijai Anand, Diaa EL-Rahman Ahmed Rayan, Mustafa KA Mohammed, Mohamed Mohamed Rashad, and Ahmed Esmail Shalan. "Semiconductors as effective electrodes for dye sensitized solar cell applications." *Topics in Current Chemistry* 379, no. 3 (2021): 20. https://doi.org/10.1007/s41061-021-00334-w

[2] Triyanto, Aripin, Gaguk Firasanto, Marfin Marfin, Edwar Mualim, Donie Agus Ardianto, and Luki Utomo. "Implementasi dan sosialisasi prototipe panel surya 30 wp sebagai pembelajaran di lab smk khazanah kebajikan pondok cabe pamulang, tangerang selatan." *Jurnal Abdi Masyarakat Indonesia* 2, no. 6 (2022): 1849-1856. https://doi.org/10.54082/jamsi.554

[3] Utari, Evrita Lusiana, Ikhwan Mustiadi, and Yudianingsih Yudianingsih. "Pemanfaatan energi surya sebagai energi alternatif pengganti listrik untuk memenuhi kebutuhan penerangan jalan di dusun nglinggo kelurahan pagerharjo kecamatan samigaluh kabupaten kulon progo." *Jurnal Pengabdian Dharma Bakti* 1, no. 2 (2018).
[4] Hastuti, Erna. "Analisa Difraksi Sinar X TiO2 dalam Penyiapan Bahan Sel Surya Tersensitisasi Pewarna." *Jurnal Neutrino: Jurnal Fisika dan Aplikasinya* (2011). https://doi.org/10.18860/neu.v0i0.2416
[5] Kamat, Prashant V., Kevin Tvrdy, David R. Baker, and Emmy J. Radich. "Beyond photovoltaics: semiconductor nanoarchitectures for liquid-junction solar cells." *Chemical reviews* 110, no. 11 (2010): 6664-6688. https://doi.org/10.1021/cr100243p
[6] Haran, Noura H., and Qahtan A. Yousif. "The efficiency of TiO2 nanotube photoanode with graphene nanoplatelets as counter electrode for a dye-sensitised solar cell." *International Journal of Ambient Energy* 43, no. 1 (2022): 336-343. https://doi.org/10.1080/01430750.2019.1636880
[7] Yarmohamadi-Vasel, Mazaher, Ali Reza Modarresi-Alam, Meissam Noroozifar, and Mohammad Saeed Hadavi. "An investigation into the photovoltaic activity of a new nanocomposite of (polyaniline nanofibers)/(titanium dioxide nanoparticles) with different architectures." *Synthetic Metals* 252 (2019): 50-61. https://doi.org/10.1016/j.synthmet.2019.04.007
[8] Azmi, Nurul, Ismail Ismail, and Mursal Mursal. "Pengaruh Penambahan Co-Doping Mg/La Terhadap Karakterisasi Tio2 Sebagai Fotoelektroda." *Jurnal Teori dan Aplikasi Fisika* (2021): 79-86. https://doi.org/10.23960/jtaf.v9i1.2633
[9] Fatmawati, Dewi, and Anthoni B. Aritonang. "SINTESIS DAN KARAKTERISASI TiO2-KAOLIN MENGGUNAKAN METODE SOL GEL." *Jurnal Kimia Khatulistiwa* 8, no. 2 (2019).
[10] Lang, Xianjun, Xiaodong Chen, and Jincai Zhao. "Heterogeneous visible light photocatalysis for selective organic transformations." *Chemical Society Reviews* 43, no. 1 (2014): 473-486. https://doi.org/10.1039/C3CS60188A
[11] Pataya, Stefanie Amni, Paulus Lobo Gareso, and Eko Juarlin. "Karakterisasi Lapisan Tipis Titanium Dioksida (TiO2) yang Ditumbuhkan dengan Metode Spin Coating di atas Substrat Kaca." *Jurnal Fisika, Universitas Hasanuddin* (2016).
[12] Ameta, Rakshit, Meenakshi S. Solanki, Surbhi Benjamin, and Suresh C. Ameta. "Photocatalysis." In *Advanced oxidation processes for waste water treatment*, pp. 135-175. Academic Press, 2018. https://doi.org/10.1016/B978-0-12-810499-6.00006-1
[13] Doyan, A., I. K. Mahardika, D. R. Rizaldi, and Z. Fatimah. "Structure and optical properties of Titanium Dioxide thin film with mixed Fluorine and Indium doping for solar cell components." In *Journal of Physics: Conference Series*, vol. 2165, no. 1, p. 012009. IOP Publishing, 2022. https://doi.org/10.1088/1742-6596/2165/1/012009
[14] Rizaldi, Dedi Riyan, Aris Doyan, and Susilawati Susilawati. "Sintesis Lapisan Tipis TiO2:(F+ In) pada Substrat Kaca Dengan Metode Spin-Coating Sebagai Bahan Sel Surya." *ORBITA: Jurnal Pendidikan dan Ilmu Fisika* 7, no. 1 (2022): 219-224. https://doi.org/10.31764/orbita.v7i1.4655
[15] A. Pradana, H. Sutanto, and E. Hidayanto, "Deposisi, karakterisasi sifat optik dan uji degradasi Db71 pada lapisan tipis Zno:Co konsentrasi tinggi," *Youngster Physics Journal*, vol. 6, no. 3, pp. 242–248, 2017.
[16] Doyan, Aris, and Humaini Humaini. "Sifat Optik Lapisan Tipis ZnO." *Jurnal Pendidikan Fisika dan Teknologi* 3, no. 1 (2017): 34-39. https://doi.org/10.29303/jpft.v3i1.321
[17] Doyan, Aris, and Haris Munandar. "Optical Characteristics of Tin Oxide Thin Films Doped with Indium and Aluminum Using the Sol-Gel Spin Coating Technique." In *7th International Conference on Research, Implementation, and Education of Mathematics and Sciences (ICRIEMS 2020)*, pp. 396-403. Atlantis Press, 2021. https://doi.org/10.2991/assehr.k.210305.057
[18] Sutjahjono, Hary, Robertoes Koekoeh KW, Ahmad Adib Rosyadi, and Muhammad Trifiananto. "Variasi Waktu Perendaman TiO2 didalam Dye Antosianin Kulit Terong Ungu Terhadap Efisiensi DSSC." *STATOR: Jurnal Ilmiah Teknik Mesin* 5, no. 1 (2022): 12-15.
[19] Siagian, Sinta Marito, Suci Khairani, Samaria Chrisna HS, and Ferdinan Rinaldo Tampubolon. "Sintesis dan Karakteristik Sifat Optik Semikonduktor ZnO dan ZnO Dopping Cu." *ORBITA: Jurnal Pendidikan dan Ilmu Fisika* 8, no. 1 (2022): 79-83. https://doi.org/10.31764/orbita.v8i1.8406
[20] Hassanien, Ahmed Saeed, and Alaa A. Akl. "Optical characterizations and refractive index dispersion parameters of annealed TiO2 thin films synthesized by RF-sputtering technique at different flow rates of the reactive oxygen gas." *Physica B: Condensed Matter* 576 (2020): 411718. https://doi.org/10.1016/j.physb.2019.411718
[21] Othman, M. S., Kh A. Mishjil, H. G. Rashid, S. S. Chiad, N. F. Habubi, and I. A. Al-Baidhany. "Comparison of the structure, electronic, and optical behaviors of tin-doped CdO alloys and thin films." *Journal of Materials Science: Materials in Electronics* 31 (2020): 9037-9043. https://doi.org/10.1007/s10854-020-03437-0
[22] Mohammed, Hassan Rasim, and D. Mohammed Hadi Shinen. "Study the optical properties of Titanium dioxide Nano films." *Materials Today: Proceedings* 81 (2023): 459-463. https://doi.org/10.1016/j.matpr.2021.03.613
[23] Mursal, Iin Lidia Putama. "Pengaruh Penambahan CTAB Terhadap Nilai Absorbansi dan Morfologi Lapisan Tipis TiO2." *Journal Online of Physics* 1, no. 2 (2016): 5-9.

[24] Agusu, La, and Rosliana Eso. "Pengaruh penambahan mangan alam terhadap daya absorbsi cahaya tampak pada keramik TiO2." *Einstein's: Research Journal of Applied Physics* 1, no. 1 (2023): 1-8. https://doi.org/10.33772/einsteins.v1i1.145
[25] Efelina, Vita. "Preparasi Dan Penentuan Energi Gap Film Tipis TiO2: Cu Yang Ditumbuhkan Menggunakan Spin Coating." *Jurnal Pendidikan Fisikadan Keilmuan* 3, no. 1 (2017): 19-27. https://doi.org/10.25273/jpfk.v3i1.941
[26] Johannes, Albert Zicko, Redi Kristian Pingak, and Minsyahril Bukit. "Tauc Plot Software: Calculating energy gap values of organic materials based on Ultraviolet-Visible absorbance spectrum." In *IOP conference series: materials science and engineering*, vol. 823, no. 1, p. 012030. IOP Publishing, 2020. https://doi.org/10.1088/1757-899X/823/1/012030
[27] Maalmarugan, J., V. Yokeswaran, R. Divya, H. Ganesan, R. P. Patel, G. Flora, K. SenthilKannan et al. "Synthesis, growth, XRD, NLO, CHNSO, structure by theoretical approach, dielectric, absorbance, photoconductivity and bio studies of 4-(4-Acetyl-5-Methyl-1H-1, 2, 3-Triazol-1-yl) Benzonitrile crystals for optical, opto-electronic, and photonics utilities." *Journal of Materials Science: Materials in Electronics* 32 (2021): 13850-13858. https://doi.org/10.1007/s10854-021-05960-0
[28] Doyan, Aris, Susilawati Susilawati, Muhammad Taufik, Syamsul Hakim, and Lalu Muliyadi. "The Optical Properties of Thin Films Tin Oxide with Triple Doping (Aluminum, Indium, and Fluorine) for Electronic Device." *Solid State Phenomena* 317 (2021): 477-482. https://doi.org/10.4028/www.scientific.net/SSP.317.477
[29] Susilawati, A. Doyan, L. Muliyadi, S. Hakim, M. Taufik, and Nazarudin. "Characteristics and Optical Properties of Fluorine Doped SnO2 Thin Film Prepared by a Sol–Gel Spin Coating." In *Journal of Physics: Conference Series*, vol. 1397, no. 1, p. 012003. IOP Publishing, 2019. https://doi.org/10.1088/1742-6596/1397/1/012003
[30] Hamed, N. K. A., M. K. Ahmad, N. H. H. Hairom, A. B. Faridah, M. H. Mamat, A. Mohamed, A. B. Suriani et al. "Dependence of photocatalysis on electron trapping in Ag-doped flowerlike rutile-phase TiO2 film by facile hydrothermal method." *Applied Surface Science* 534 (2020): 147571. https://doi.org/10.1016/j.apsusc.2020.147571
[31] Rahman, Dui Yanto, and Rita Sulistyowati. "Aplikasi Fotokatalis TiO2 Dan Alternatifnya Untuk Degradasi Pewarna Sintesis Dalam Limbah Cair." *Environmental Science Journal (Esjo): Jurnal Ilmu Lingkungan* (2023): 89-105. https://doi.org/10.31851/esjo.v1i2.12023
[32] Veziroglu, Salih, Muhammad Zubair Ghori, Anna-Lena Obermann, Katharina Röder, Oleksandr Polonskyi, Thomas Strunskus, Franz Faupel, and Oral Cenk Aktas. "Ag nanoparticles decorated TiO2 thin films with enhanced photocatalytic activity." *physica status solidi (a)* 216, no. 14 (2019): 1800898. https://doi.org/10.1002/pssa.201800898
[33] Akshay, V. R., B. Arun, Guruprasad Mandal, and M. Vasundhara. "Visible range optical absorption, Urbach energy estimation and paramagnetic response in Cr-doped TiO 2 nanocrystals derived by a sol–gel method." *Physical Chemistry Chemical Physics* 21, no. 24 (2019): 12991-13004. https://doi.org/10.1039/C9CP01351B
[34] Clarissa, Elyta, Adhitiyawarman Adhitiyawarman, and Anthoni B. Aritonang. "Synthesis Of Co (Ii)-Tio2/Kaolinite As A Antibacterial Escherichia Coli Photocsintesis Co (Ii)-Tio2/Kaolin Sebagai Fotokatalis Antibakteri Escherichia Coli Dengan Bantuan Sinar Tampak (Synthesis Of Co (Ii)-Tio2/Kaolinite As A Antibacterial Escherichia Coli Photocatalyst Under Visible Light)." *Indonesian Journal of Pure and Applied Chemistry* 4, no. 3 (2021): 124-131. https://doi.org/10.26418/ijopac.v4i3.47020
[35] Hermaw, Dadang, Andy Hardianto, Purbo Suwandon, and Febi Rahmadianto. "Pengaruh Temperatur Pirolisis Terhadap Energi Aktivasi Pada Tar Limbah Plastik." *Prosiding SENIATI* 5, no. 4 (2019): 351-357.
[36] Punith Gowda, Ramanahalli Jayadevamurthy, Rangaswamy Naveen Kumar, Anigere Marikempaiah Jyothi, Ballajja Chandrappa Prasannakumara, and Ioannis E. Sarris. "Impact of binary chemical reaction and activation energy on heat and mass transfer of marangoni driven boundary layer flow of a non-Newtonian nanofluid." *Processes* 9, no. 4 (2021): 702. https://doi.org/10.3390/pr9040702
[37] Fairus, Sirin, H. Haryono, Mas H. Sugita, and Agus Sudrajat. "Proses pembuatan waterglass dari pasir silika dengan pelebur natrium hidroksida." *Jurnal Teknik Kimia Indonesia* 8, no. 2 (2009): 56-62. https://doi.org/10.5614/jtki.2009.8.2.4
[38] MacDowell, J. F., and G. H. Beall. "Immiscibility and crystallization in A12O3-SiO2 glasses." *Journal of the American Ceramic Society* 52, no. 1 (1969): 17-25. https://doi.org/10.1111/j.1151-2916.1969.tb12653.x
[39] Parikin, Parikin, Bambang Sugeng, Mohammad Dani, and Sulistioso Giat Sukaryo. "Ketahanan Oksidasi Baja Super Austenitik 15% Cr-25% Ni pada Temperatur 850 C." *Jurnal Sains Materi Indonesia* 18, no. 4 (2017): 179-184. https://doi.org/10.17146/jsmi.2017.18.4.4128
[40] Wardani, Aprilya Hartinah, and Mochammad Zainuri. "Pengaruh Variasi Massa SiO2 Terhadap Sudut Kontak dan Transparansi Pada Lapisan Hydrophobic." *Jurnal Sains dan Seni ITS* 7, no. 2 (2019): 59-65. https://doi.org/10.12962/j23373520.v7i2.34769

[41] Doyan, Aris, Susilawati Susilawati, Ahmad Harjono, Syifa Azzahra, and Muhammad Taufik. "Characterization of Tin Oxide Doping Antimony Thin Layer With Sol-Gel Spin Coating Method for Electronic Device." In *Materials Science Forum*, vol. 966, pp. 30-34. Trans Tech Publications Ltd, 2019. https://doi.org/10.4028/www.scientific.net/MSF.966.30

[42] Lukong, Valantine Takwa, Kingsley Ukoba, and Tien-Chien Jen. "Review of self-cleaning TiO2 thin films deposited with spin coating." *The International Journal of Advanced Manufacturing Technology* 122, no. 9 (2022): 3525-3546. https://doi.org/10.1007/s00170-022-10043-3

[43] Mustafa, Haveen Ahmed Mustafa, and Dler Adil Jameel. "Modeling and the main stages of spin coating process: A review." *Journal of Applied Science and Technology Trends* 2, no. 02 (2021): 119-123. https://doi.org/10.38094/jastt203109https://doi.org/10.12962/j23373520.v11i5.108566

[44] Tyona, M. D. "A theoritical study on spin coating technique." *Advances in materials Research* 2, no. 4 (2013): 195. https://doi.org/10.12989/amr.2013.2.4.195

[45] Shabrina, Nabella, Gatut Yudoyono, and Sudarsono Sudarsono. "Karakterisasi Struktur, Morfologi, dan Sifat Optik Lapisan Tipis Titanium Dioksida yang Dideposisi Menggunakan Teknik Spray Pyrolysis." *Jurnal Sains dan Seni ITS* 11, no. 5 (2023): B1-B6. https://doi.org/10.12962/j23373520.v11i5.108566