



Photo-electrochemical Water Splitting Behaviour of Rare Earth Metal Oxide Based Phthalocyanines Nanocomposites

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ABSTRACT

Here, we describe the photo-electrochemical water splitting behaviour of Gd₂O₃ pc (GdPc) and La₂O₃ pc (LaPc), two phthalocyanines (Pc) based on rare earth oxides. The hydrothermal technique was utilised to synthesise the GdPc and LaPc. Using X-ray diffraction (XRD) analysis, the phase purity and crystallinity of LaPc and GdPc were investigated. The findings show that GdPc likewise has a high crystallinity with a cubic structure, while LaPc has a high crystallinity with a hexagonal structure. Field emission scanning electron microscopy (FESEM) was used to evaluate surface morphological findings. It is observed that organic phthalocyanine aggregates with rare earth oxide nanoparticles. Using UV-Vis spectroscopy, the light absorption characteristics of LaPc and GdPc were examined. The LaPc exhibited widespread absorption between 500 and 800 nm. GdPc similarly showed large absorption peaks between 500 and 800 nm and absorption peaks at 430 nm. In both dark and light circumstances, photo-electrochemical water splitting in 1M Na₂S electrolyte was carried out using the LaPc and GdPc as photo electrocatalysts. The LaPc photoelectrode demonstrated a current density of approximately 3.5 mA/cm² at 0.8 V (vs. Ag/AgCl) in light illumination and approximately 3.0 mA/cm² in the dark, according to Linear Sweep Voltammetry (LSV) tests. In a similar vein, under light illumination the GdPc photoelectrode had a current density of approximately 9.0 mA/cm² at 0.8 V (vs. Ag/AgCl) as opposed to ~7.5 mA/cm² in the dark. The LaPc photoelectrode demonstrated a greater current density of approximately 7.5 mA/cm² at 0.8 V (vs. Ag/AgCl) under light illumination as opposed to approximately 7.0 mA/cm² in the dark, according to the Chronoamperometric (CA) research observations. In a similar vein, the GdPc photoelectrode showed a current density of about 11.5 mA/cm² in the dark and ~11.5 mA/cm² at 0.8 V (vs. Ag/AgCl) in the light. According to the PEC data, GdPc showed greater water splitting activity than LaPc.

Keywords: Photoelectrochemical water splitting; Phthalocyanines; Hydrothermal synthesis.

1. INTRODUCTION

A crucial field of materials science research is the creation of stable catalysts for semiconductor-based photocatalysis, which has enormous potential to solve urgent energy and environmental issues. Using semiconductors to absorb light and produce electron-hole pairs that can then take part in redox reactions is known as semiconductor photocatalysis. When water is split, these processes take place when water is reduced to create hydrogen gas and when water is oxidised to create oxygen. Photoelectrochemical water splitting (PEC) represents one of the most advanced and promising technologies for generating hydrogen in an easy, inexpensive and durable way (Ouardi *et al.* 2024). The development and fabrication of metal oxides-based photocathodes and photoanodes have attracted a great interest for photoelectrochemical water splitting owing

to their numerous benefits including enhanced light absorption capacity, outstanding photo-electrochemical stability, greater charge separation efficiencies, low cost. Water splitting to produce hydrogen is an environmentally sustainable process that provides a carbon-free fuel and represents an attractive way to chemically store renewable energy (Guozhen *et al.* 2020; Alruwaili *et al.* 2024). The difficulty is in locating reliable and efficient catalysts that can facilitate these reactions, particularly on the semiconductor surface (Walter *et al.* 2010; Li *et al.* 2015).

It is true that the 1972 work of Akira Fujishima and Kenichi Honda was a seminal discovery that paved the way for a great deal of study in the area of photocatalysis for water splitting. "Electrochemical Photolysis of Water at a Semiconductor Electrode," their ground-breaking work, was released in the journal

Nature. Using a titanium dioxide (TiO₂) semiconductor electrode, Fujishima and Honda demonstrated the photoelectrochemical splitting of water into hydrogen and oxygen in their groundbreaking study. They found that the TiO₂ electrode produced a photopotential when exposed to light, which was adequate to propel the electrolysis of water. According to (Fujishima *et al.* 1972), the photoelectrochemical process produced oxygen gas at the anode and hydrogen gas at the cathode. Extensive research efforts have been focused on refining photocatalysts, comprehending the underlying mechanics, and enhancing the process's overall efficiency since this historic discovery. Researchers have looked into new catalysts, surface modifications, and semiconductor materials to improve the efficiency of photocatalytic systems for water splitting. TiO₂, WO₃, ZnO, and SnO₂, among other semiconductor-based metal oxides, have been thoroughly studied for their potential as photocatalysts in solar water electrolysis. It is true, though, that these materials have significant drawbacks, which scientists are working to improve in order to make them more effective and useful. Several typical restrictions consist of: broad band gaps, quick charge carrier recombination, low quantum efficiency, restricted redox activity, and problems with corrosion and stability (Su *et al.* 2011; Saito *et al.* 2012; Osterloh *et al.* 2013; Hernández *et al.* 2015).

These constraints are being actively addressed by researchers using a variety of strategies, including as material design, surface modification, nanostructuring, and the creation of composite materials (Zhenbiao *et al.* 2024). Furthermore, research into alternative semiconductor materials beyond metal oxides is still under progress in an effort to identify materials that provide enhanced functionality and more effectively tackle the difficulties involved in solar water electrolysis (Giribabu *et al.* 2007; Jiasheng *et al.* 2024). Indeed, phthalocyanines are a class of chemicals that have drawn interest due to their photocatalytic qualities. They have found use in a number of applications, such as solar energy conversion, pollutant degradation, and water splitting. Phthalocyanines are planar-structured macrocyclic compounds that have a central metal atom that is usually coordinated to the macrocycle's nitrogen atoms. Although phthalocyanines have promising photocatalytic characteristics, researchers are still focused on issues including cost, scalability, and stability under prolonged irradiation. The advancement of practical applications in sustainable energy and environmental remediation is facilitated by the development of new phthalocyanine-based materials and the optimisation of their properties (Wang *et al.* 2015; Jadhav *et al.* 2022). In the fields of materials science and photocatalysis, the conjugated molecule Copper (II) phthalocyanine covalent organic framework (CuPc-COF) is an interesting and potential contender. A family of crystalline porous polymers with well-defined periodicities and topologies, covalent organic

frameworks (COFs) are appealing for a variety of applications. The metal phthalocyanine known as copper (II) phthalocyanine (CuPc) is made up of a coordinated phthalocyanine at its centre and a copper ion. CuPc's multimorphic nature, encompassing orthorhombic, triclinic, tetragonal, and monoclinic structures, contributes to its characteristics' complexity and tunability. The material's electrical and structural characteristics may be impacted by this polymorphic behaviour (You *et al.* 2016; Mapukata *et al.* 2020; Chindeka *et al.* 2020). Although there has been a lot of research on CuPc, there hasn't been much information on the combinational method about La₂O₃ or Gd₂O₃ phthalocyanine (Mostafa *et al.* 2022) which would undoubtedly be helpful in photoelectrochemical water splitting activity. Therefore, the main goal of this work is to investigate the photoelectrochemical water splitting behaviour of phthalocyanines, such as La₂O₃ and Gd₂O₃ nanocomposites.

2. EXPERIMENTAL PROCEDURE

2.1 Synthesis of La₂O₃

The La₂O₃ nanoparticles were synthesized through hydrothermal route, 1 M solution of Lanthanum(III) nitrate hexahydrate (La(NO₃)₃ 6H₂O) was dissolved in 30 ml of deionized water and stirred for 1 h. To this solution, 5 M solution of sodium hydroxide (NaOH) was added dropwise until the formation of precipitate. Further, the solution with precipitation was then transferred into Teflon-lined sealed stainless-steel autoclave. The sealed autoclave containing the solution mixture were placed in a oven and maintained at a temperature of 180 °C and the reaction continued for a duration of 8 h. The autoclave was removed from the oven after the reaction time was completed. The resultant solution was washed several times with water ethanol mixture solution and filtered then dried in hot air oven at 100 °C.

2.2 Synthesis of Gd₂O₃

The Gd₂O₃ nanoparticles were synthesized through hydrothermal route, 1 M solution of Lanthanum(III) nitrate hexahydrate (Gd(NO₃)₃ 6H₂O) was dissolved in 30 ml of deionized water and stirred for 1 h. To this solution, 5 M solution of sodium hydroxide (NaOH) was added dropwise until the formation of precipitate. Further, the solution with precipitation was then transferred into Teflon-lined sealed stainless-steel autoclave. The sealed autoclave containing the solution mixture were placed in a oven and maintained at a temperature of 180 °C and the reaction continued for a duration of 8 h. The autoclave was removed from the oven after the reaction time was completed. The resultant solution was washed several times with water ethanol mixture solution and filtered then dried in hot air oven at 100 °C.

2.3 Preparation of $\text{La}_2\text{O}_3\text{Pc}$ (LaPc) and $\text{Gd}_2\text{O}_3\text{Pc}$ (GdPc)

The preparation of LaPc and GdPc by complexing oxide nanoparticles with phthalocyanine is described below: The phthalocyanine was dissolved in acetonitrile and ethanol solution in a 1:1 ratio. The calcined La_2O_3 and Gd_2O_3 nanoparticles were mixed separately in the individual PC solutions and kept overnight in sealed containers in the dark. After the overnight immersion, the nanoparticles are retrieved from their respective PC solutions. The retrieved functionalized nanoparticles, which appear blue, are washed with ethanol and dried in vacuum is a common technique to remove any remaining solvent and ensure that the functionalized nanofibers are dry and ready for further use.

2.4 Photo-electrochemical Water splitting Studies

The PEC studies were carried out using three electrode system. Platinum foil serves as the counter electrode, Ag/AgCl is used as the reference electrode and while LaPc and GdPc coated glassy carbon as working electrode(s). A 1M Na_2SO_4 solution with the pH of 13 was used as sacrificial electrolyte. Further, a 300 W Xenon lamp is used for illumination to produce the light intensity of 100 mW/cm^2 . Linear sweep voltammograms (LSV) are recorded by varying the potential between -0.8 V and 0.8 V vs. Ag/AgCl reference electrode with a scan rate of 10 mV/s. The chronoamperometry technique was employed to study the stability of the photo-electrocatalysts.

2.5 Characterizations

X-ray diffraction pattern was recorded on an (XRD Bruker D8-Advanced, Germany) angle between 10° - 80° angle with 6° per min. The absorption spectrum of the samples in UV-Vis region (200-1200 nm) were recorded on a (Varian Cary 5000) UV-Vis NIR spectrophotometer. FT-IR (Fourier Transform Infrared spectroscopy) was obtained transmittance data on FT-IR spectrometer (Bruker Tensor 27). Electrochemical workstation PARSTAT 2273 with power suite.

3. RESULTS AND DISCUSSIONS

3.1 X-ray Diffraction Analysis

The crystallinity of LaPc and GdPc were examined using XRD analysis and the respective patterns are presented in the Figure 1, respectively. Figure1 exhibits the peaks for hexagonal phase La_2O_3 along with the additional peaks which corresponds to phthalocyanines. The noticed planes of (002), (011), (012), (110), (013), (021), (014), (121) and (022) are well matched with standard JCPDF no: 98-004-6823.

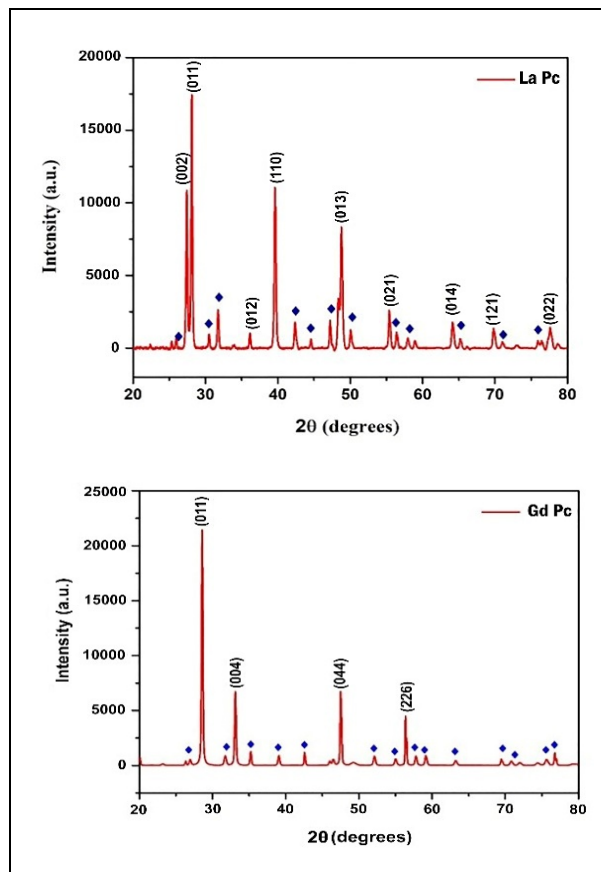


Fig. 1: X-Ray diffraction pattern for LaPc and GdPc

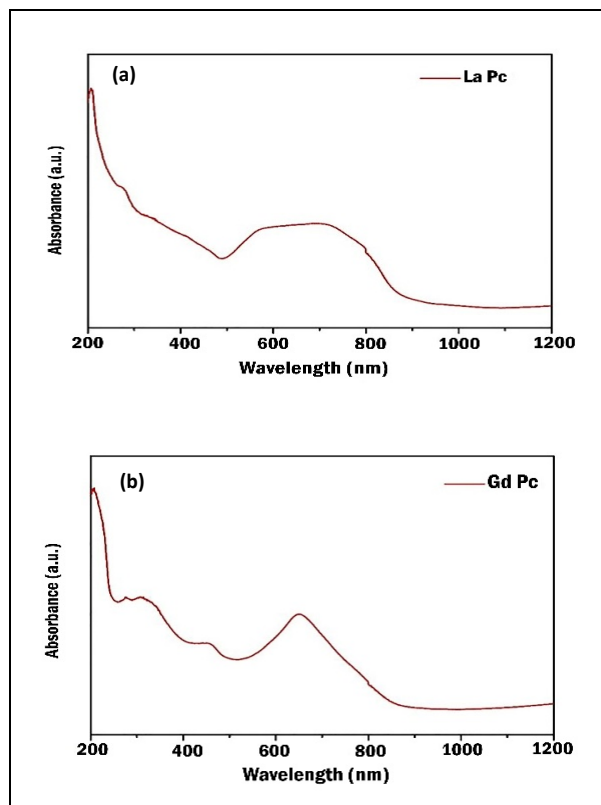


Fig. 2: UV-vis absorbance spectrum of (a) LaPc and (b) GdPc

The presence of both La_2O_3 and phthalocyanines indicate the complexation and formation of LaPc the crystalline size is 80 nm. Similarly, the Figure 1 exhibits the peaks for cubic phase Gd_2O_3 along with the additional peaks which corresponds to phthalocyanines. The noticed planes of (011), (004), (044) and (226) are well matched with standard JCPDF no: 98-006-6924. The presence of both Gd_2O_3 and phthalocyanines indicate the complexation and formation of GdPc the crystalline size is 100 nm.

3.2 UV-Vis Spectra

The UV-visible spectra of LaPc and GdPc phthalocyanines are shown in Figure 2 respectively.

The LaPc showed absorption peaks at 300 nm (which may correspond to La_2O_3) and a broad peak between 500 and 800 nm, corresponds to phthalocyanine. The band gap of LavPc is calculated as 1.55 eV. Similarly, GdvPc exhibited absorption peaks at 430 nm (which may correspond to Gd_2O_3) and a broad peak between 500 and 800 nm, corresponds to phthalocyanine. The band gap of GdPc is calculated as 1.50 eV (Fig. 3).

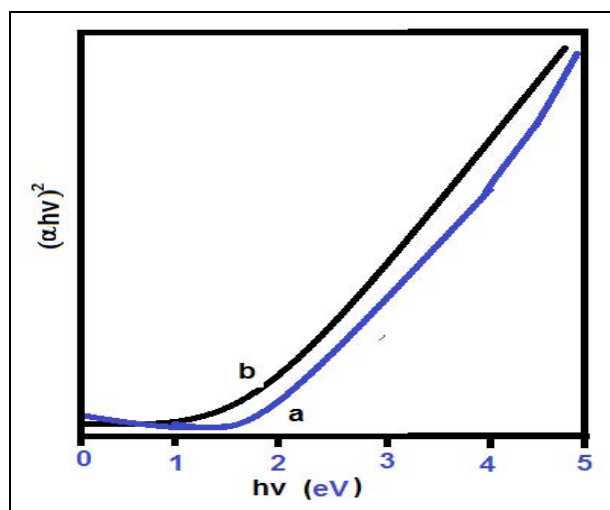


Fig. 3. Tauc plot of (a) LaPc and (b) GdPc

3.3 FT-IR Spectroscopy

FT-IR spectroscopy was used to understand the functional groups, which are present in LaPc and GdPc and the respective spectrums are shown in Figure 4, respectively. The spectrum shows peak at $\sim 700\text{ cm}^{-1}$ corresponding the vibration of hexagonal La_2O_3 . The spectrum shows peaks at 1330 cm^{-1} (C–N stretch), 1735 cm^{-1} (C=O stretch) and 3300 cm^{-1} (O–H stretch) attributed to the presence of the Pc. Similarly, Figure 4, spectrum shows peak at 510 cm^{-1} and 800 cm^{-1} which are attributed to the Gd–O bonding in cubic crystal. The peak at 3100 cm^{-1} attributed the adsorbed hydroxyl groups.

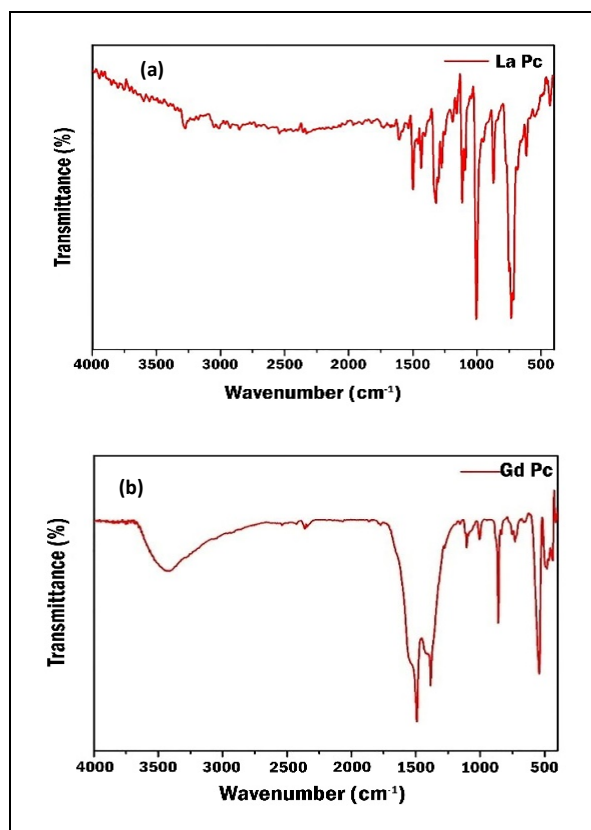


Fig. 4: FTIR spectrum of LaPc and GdPc

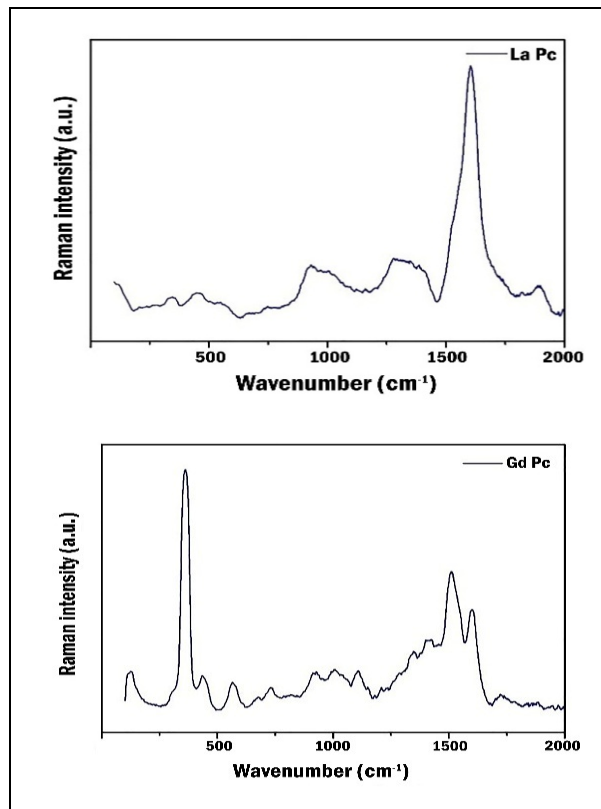


Fig. 5: Raman spectrum of LaPc and GdPc

3.4 Raman Spectroscopy

Raman spectroscopy of LaPc and GdPc are shown in Figure 5, respectively. The metal oxides has been reported dominant peaks at 945 cm^{-1} , 1365 cm^{-1} , 1623 cm^{-1} , 1834 cm^{-1} for LaPc and 520 cm^{-1} , 675 cm^{-1} , 932 cm^{-1} , 1023 cm^{-1} , 1230 cm^{-1} , 1543 cm^{-1} , 1646 cm^{-1} for GdPc. The D (at 1000 cm^{-1}) and G (1500 cm^{-1}) characteristic carbon material bands.

3.5 Surface Morphological Analysis

The surface morphologies of LaPc and GdPc are shown Figure 6 & 7 respectively. The FESEM images of LaPc shows the irregular bunch of cauliflower shaped nanoparticles and smaller size granular observation noticed for GdPc also the nanoparticles are agglomerated.



Fig. 6: FESEM images of LaPc

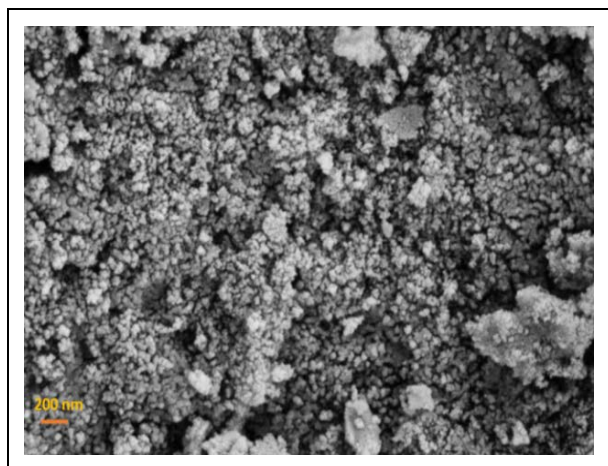


Fig. 7: FESEM images of GdPc

3.6 EDAX

The energy-dispersive X-ray (EDX) were applied to characterize and qualitative elements

components of La_2O_3 and Gd_2O_3 . Figure 8 shows the element were distributed in the composite and confirms the existence.

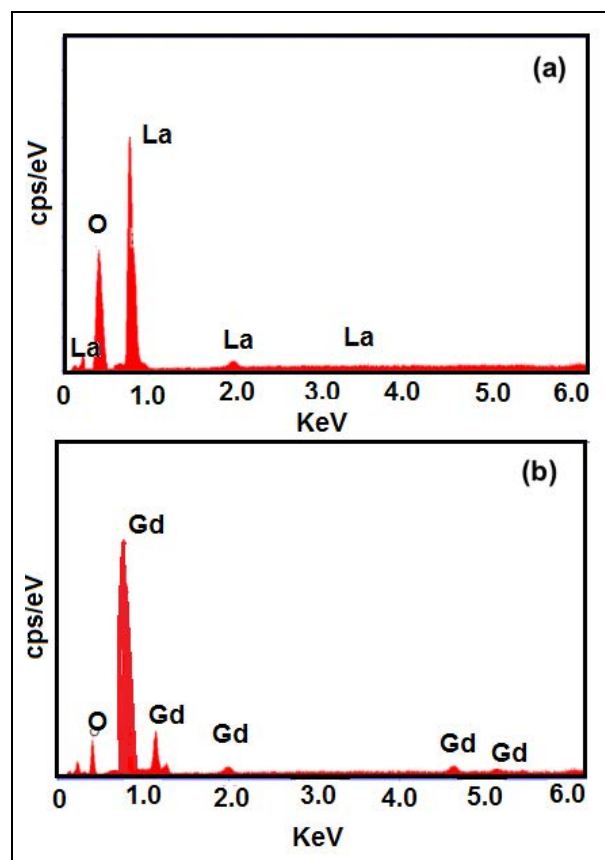


Fig. 8: EDAX of (a) LaPc and (b)GdPc

3.7 Photo-electrochemical Water Splitting

The LSV curves of LaPc indicating the photoelectrochemical water splitting its activity under light and dark conditions is shown in Figure 9&10.

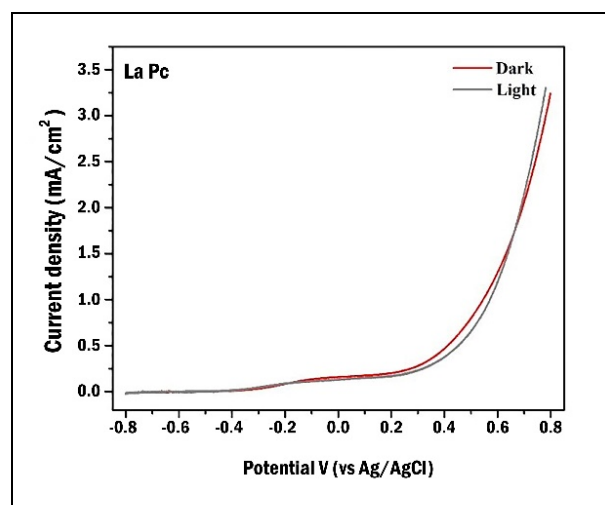


Fig. 9(a): LSV curves of LaPc

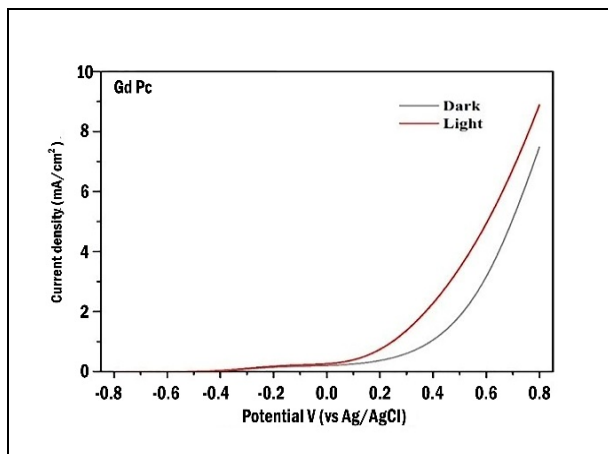


Fig. 9(b): LSV curves of GdPc

Linear Sweep Voltammetry (LSV) (Fig 9(a,b)) studies revealed that the LaPc photo electrode showed current density of $\sim 3.5 \text{ mA/cm}^2$ at 0.8 V (vs. Ag/AgCl) under light illumination and about $\sim 3.0 \text{ mA/cm}^2$ in the dark. The Chronoamperometric (CA) studies (Fig 10) observations indicated that the LaPc photoelectrode had a higher current density of $\sim 7.5 \text{ mA/cm}^2$ at 0.8 V (vs. Ag/AgCl) under light illumination compared to $\sim 7.0 \text{ mA/cm}^2$ in the dark.

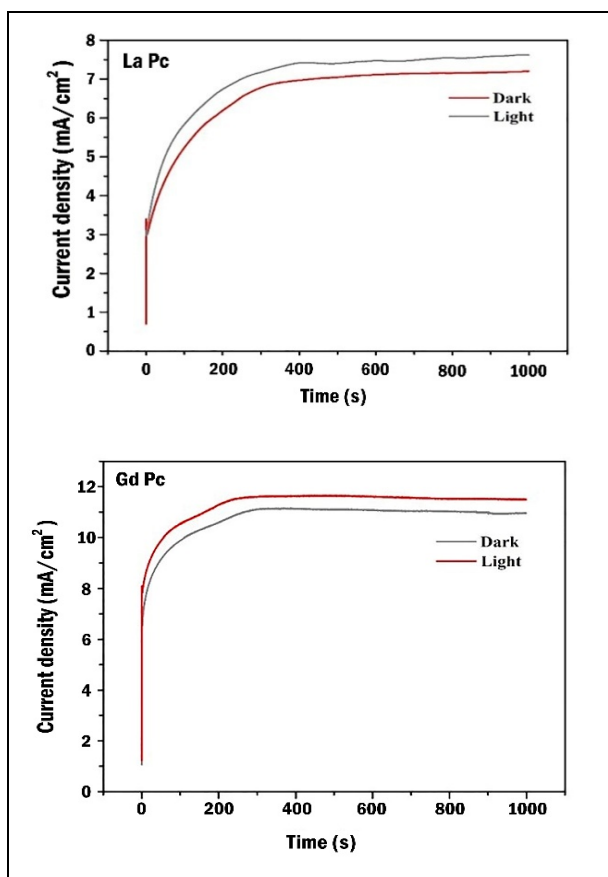


Fig. 10: Chronoamperometric analysis of LaPc and GdPc

Similarly, the GdPc photoelectrode showed current density of $\sim 9.0 \text{ mA/cm}^2$ at 0.8 V (vs. Ag/AgCl) under light illumination compared to $\sim 7.5 \text{ mA/cm}^2$ in the dark. Similarly, the GdPc photoelectrode demonstrated a current density of $\sim 11.5 \text{ mA/cm}^2$ at 0.8 V (vs. Ag/AgCl) under light illumination compared to $\sim 10.5 \text{ mA/cm}^2$ in the dark. The PEC results reveal that GdPc demonstrated higher water splitting activity than LaPc. This study reveals that the GdPc demonstrated a higher current density than LaPc in both LSV and CA measurements under light illumination.

4. CONCLUSION

Herein, we report the photo-electrochemical water splitting behaviour of rare earth oxide based phthalocyanines i.e. La_2O_3 (LaPc) and Gd_2O_3 (GdPc). The studies revealed that the LaPc photoelectrode showed current density of $\sim 3.5 \text{ mA/cm}^2$ at 0.8 V (vs. Ag/AgCl) under light illumination and about $\sim 3.0 \text{ mA/cm}^2$ in the dark. Similarly, the GdPc photoelectrode showed current density of $\sim 9.0 \text{ mA/cm}^2$ at 0.8 V (vs. Ag/AgCl) under light illumination compared to $\sim 7.5 \text{ mA/cm}^2$ in the dark. The Chronoamperometric (CA) studies observations indicated that the LaPc photoelectrode had a higher current density of $\sim 7.5 \text{ mA/cm}^2$ at 0.8 V (vs. Ag/AgCl) under light illumination compared to $\sim 7.0 \text{ mA/cm}^2$ in the dark. Similarly, the GdPc photoelectrode demonstrated a current density of $\sim 11.5 \text{ mA/cm}^2$ at 0.8 V (vs. Ag/AgCl) under light illumination compared to $\sim 10.5 \text{ mA/cm}^2$ in the dark. The PEC results reveal that GdPc demonstrated higher water splitting activity than that of LaPc.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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REFERENCES

- Alruwaili, M., Roy, A., Alhabradi, M., Yang, X., Chang, H. and Tahir, A. A., Heterostructured WO₃-TiVO₄ thin-film photocatalyst for efficient photoelectrochemical water splitting, *Heliyon*, 10(3), e25446(2024).
<https://doi.org/10.1016/j.heliyon.2024.e25446>
- Chindeka, F., Mashazi, P., Britton, J., Oluwale, D. O., Mapukata, S. and Nyokong, T., Fabrication of dye-sensitized solar cells based on push-pull asymmetrical substituted zinc and copper phthalocyanines and reduced graphene oxide nanosheets, *J. Photochem. Photobiol. A Chem.*, 399, 112612(2020).
<https://doi.org/10.1016/j.jphotochem.2020.112612>
- Ouardi, E. M., El, I. A., Ait, A. H., Baqais, A., Saadi, M. and Arab, M., Current advances on nanostructured oxide photoelectrocatalysts for water splitting: A comprehensive review, *Surf. Interfaces*, 45, 103850 (2024).
<https://doi.org/10.1016/j.surf.2024.103850>
- Fujishima, A. and Honda, K., Electrochemical Photolysis of Water at a Semiconductor Electrode, *Nature*, 238(5358), 37–38 (1972).
<https://doi.org/10.1038/238037a0>
- Giribabu, L., Vijay, K. C., Gopal, R. V., Yella, R. P., Srinivasa, R. C., Jang, S. R., Yum, J. H., Nazeeruddin, M. K. and Grätzel, M., Unsymmetrical alkoxy zinc phthalocyanine for sensitization of nanocrystalline TiO₂ films, *Sol. Energy Mater. Sol. Cells*, 91(17), 1611–1617 (2007).
<https://doi.org/10.1016/j.solmat.2007.05.004>
- Guozhen, F., Zhifeng, L., Changcun, H., Enhancing the PEC water splitting performance of BiVO₄ co-modifying with NiFeOOH and Co-Pi double layer cocatalysts, *Appl. Surf. Sci.*, 515, 146095 (2020).
<https://doi.org/10.1016/j.apsusc.2020.146095>
- Hernández, S., Hidalgo, D., Sacco, A., Chiodoni, A., Lamberti, A., Cauda, V., Tresso, E. and Saracco, G., Comparison of photocatalytic and transport properties of TiO₂ and ZnO nanostructures for solar-driven water splitting, *Phys. Chem. Chem. Phys.*, 17(12), 7775–7786 (2015).
<https://doi.org/10.1039/C4CP05857G>
- Jadhav, H. S., Bandal, H. A., Ramakrishna, S. and Kim, H., Critical Review, Recent Updates on Zeolitic Imidazolate Framework-67 (ZIF-67) and Its Derivatives for Electrochemical Water splitting, *Adv. Mater.*, 33, 2107072 (2021).
<https://doi.org/10.1002/adma.202107072>
- Jiasheng, C., Zhi, J., Jiawei, Y., Afsanehsadat, L., Zhiliang, W., Lianzhou, W. and Wenfeng, S., Recent advancements in bismuth vanadate photoanodes for photoelectrochemical water splitting, *Mater. Today Chem.*, 26, 101060 (2022).
<https://doi.org/10.1016/j.mtchem.2022.101060>
- Li, X., Yu, J., Low, J., Fang, Y., Xiao, J. and Chen, X., Engineering heterogeneous semiconductors for solar water splitting, *J. Mater. Chem. A*, 3(6), 2485–2534 (2015).
<https://doi.org/10.1039/C4TA04461D>
- Mapukata, S. and Nyokong, T., Development of phthalocyanine functionalised TiO₂ and ZnO nanofibers for photodegradation of methyl orange, *New J. Chem.*, 44(38), 16340–16350 (2020).
<https://doi.org/10.1039/D0NJ03326J>
- Mostafa, A. M. A., Elbashir, B. O., Shams, I. A. M., Uosif, M.A.M., Antoaneta Ene, Merfat Algethami, Omemh Bawazeer, El Agammy, E.F., Hesham M.H.Zakaly, Influence of combining Al₂O₃, La₂O₃, Gd₂O₃, and Dy₂O₃ with barium borosilicate glass-ceramics: a case study of gamma radiation interaction parameters, *J. Mater. Res. Technol.*, 19, 1972-1981 (2022).
<https://doi.org/10.1016/j.jmrt.2022.05.095>
- Osterloh, F. E., Inorganic nanostructures for photoelectrochemical and photocatalytic water splitting, *Chem. Soc. Rev.*, 42(6), 2294–2320 (2013).
<https://doi.org/10.1039/C2CS35266D>
- Saito, R., Miseki, Y. and Sayama, K., Highly efficient photoelectrochemical water splitting using a thin film photoanode of BiVO₄/SnO₂/WO₃ multi-composite in a carbonate electrolyte, *Chem. Commun.*, 48(32), 3833 (2012).
<https://doi.org/10.1039/c2cc30713h>
- Su, J., Guo, L., Bao, N. and Grimes, C. A., Nanostructured WO₃/BiVO₄ Heterojunction Films for Efficient Photoelectrochemical Water splitting, *Nano Lett.*, 11(5), 1928–1933 (2011).
<https://doi.org/10.1021/nl2000743>
- Walter, M. G., Warren, E. L., McKone, J. R., Boettcher, S. W., Mi, Q., Santori, E. A. and Lewis, N. S., Solar Water splitting Cells, *Chem. Rev.*, 110(11), 6446–6473 (2010).
<https://doi.org/10.1021/cr1002326>
- Wang, X., Gao, J., Xu, B., Hua, T. and Xia, H., ZnO nanorod/nickel phthalocyanine hierarchical hetero-nanostructures with superior visible light photocatalytic properties assisted by H₂O₂, *RSC Adv.*, 5(106), 87233–87240 (2015).
<https://doi.org/10.1039/C5RA15821D>
- You, H., Synthesis, Characterization and Visible Photocatalytic Performance of Iron (III) Tetracarboxyphthalocyanine-Sensitized TiO₂ Photocatalyst, *J. Phys. Chem. Biophys.*, 6(1), 1000199 (2016).
<https://doi.org/10.4172/2161-0398.1000199>
- Zhenbiao, D., Dongmei, Q., Junjie, M., Zhenyu, L. and Sheng, H., Bulk-phase and surface dual-defective engineering enabled Ti-based nanotubes photoanode for highly efficient photoelectrochemical water splitting, *Renewable Energy*, 231, 121004 (2024).
<https://doi.org/10.1016/j.renene.2024.121004>