Effect of Humidity on electrical properties of p-Polyaniline/n–PbS Heterojunction

Dr. Sandip V Patil,
Assistant Professor,
Department of Physics,
Shri Pancham Khemraj Mahavidyalaya (Autonomous) Sawantwadi
spkphysics.svp@gmail.com,

***Abstract*— This study focuses on the fabrication and performance analysis of a novel p-polyaniline/n-PbS heterojunction. The heterojunction was constructed using a layer-by-layer deposition technique, where PbS and polyaniline were deposited onto a stainless steel substrate via chemical and electrodeposition methods, respectively. Structural and morphological characterizations of the films were carried out to assess their quality. The effect of humidity on the forward-biased electrical characteristics of the heterojunction was investigated for optimized thicknesses of both PbS and polyaniline layers. Measurements were conducted under varying relative humidity levels ranging from 40% to 90%. The maximum current density, 12.53 mA/cm², was recorded at 90% relative humidity, demonstrating the device's potential as a humidity sensor.**

Key Words : Heterojunction, polyanilne, PbS

I. INTRODUCTION

Humidity sensing has become increasingly important in environmental monitoring, healthcare, industrial processing, and smart electronics. Traditional humidity sensors, while effective, often struggle with slow response, low sensitivity, and signal instability under varying environmental conditions. To overcome these limitations, heterojunction-based sensors—formed by interfacing two semiconductors of differing conductivity types—have emerged as promising alternatives due to their enhanced interfacial charge transfer, increased active surface area, and tunable electrical properties in response to water vapor adsorption[1-2]. Among the various materials explored, conducting polymers such as polyaniline (PANI) are widely favored for their high environmental stability, reversible doping behavior, and moisture-sensitive conductivity [3-4]. However, the performance of pure PANI films is often limited by slower response and low sensitivity under dynamic humidity ranges. Combining PANI with inorganic nanomaterials, especially metal oxides (e.g., ZnO, TiO_2) or 2D semiconductors (e.g., MoS_2, graphene), significantly enhances performance due to synergistic effects at the heterojunction interface[5-6]. For instance, PANI/ZnO nanofiber composites have demonstrated fast response and recovery times with high reproducibility [2], while rGO/$BiVO_4$-based heterojunctions exhibit superior linearity and stability across wide humidity ranges[7]. Additionally, TiO_2/$NaNbO_3$[8] and MoS_2/CuO[9] junctions further confirm the benefit of dual-phase systems where water adsorption modulates the depletion region and electron mobility. Emerging 2D hybrid sensors such as black phosphorus (BP)/graphene and WS_2-based composites have also achieved sub-10 second response times, ultra-thin form factors, and low hysteresis [10-11]. Despite these advancements, the full potential of narrow-bandgap semiconductors such as PbS, when paired with p-type PANI, remains largely untapped. Given PbS's high charge mobility and strong interaction with adsorbed species, a p–PANI/n–PbS heterojunction could offer enhanced humidity sensing through improved interfacial modulation and carrier dynamics. The present work demonstrate the use of PbS-Polyaniline as a humidity sensor.

II. EXPERIMENTAL

i. Deposition of PbS thin films

Polycrystalline PbS thin films were deposited onto stainless steel substrates using a chemical bath deposition method [12]. An aqueous solution containing 0.02 M lead acetate and 0.2 M thiourea was prepared and maintained at room temperature (300 K). The pH of the solution was adjusted to 9 by the dropwise addition of ammonia solution. Deposition of PbS occurred when the ionic product of Pb^{2+} and S^{2-} ions exceeded the solubility product of PbS. After 12 hours of deposition, uniform and well-adherent PbS films with a thickness of approximately 0.65 µm were obtained. The films were removed from the bath, thoroughly rinsed with doubly distilled water, dried, and stored. The resulting films exhibited a grayish coloration.

ii. Deposition of Polyaniline thin films

Polyaniline thin films were electrodeposited using electrolyte solution consists of 0.45 M H_2SO_4 containing 0.5 M of aniline. The solution was boiled for 30 min. by taking proper care to avoid air oxidation, filtered, cooled and used to deposit polyaniline thin films. For electrodeposition of polyaniline thin films, a scanning potentiostat (EG &G Princeton Applied Research Model 263A) was used. Stainless steel substrates were used to deposit polyaniline thin films. Polyaniline film was deposited galvanostatically onto predeposited, 0.65m thick PbS film by applying 12 mA/cm^2 current density for 400 s. The optimized thicknesses of PbS and polyaniline films were 0.65 and 0.55 µm, respectively.

III. Fabrication of Heterojunction and Optimization of Thickness

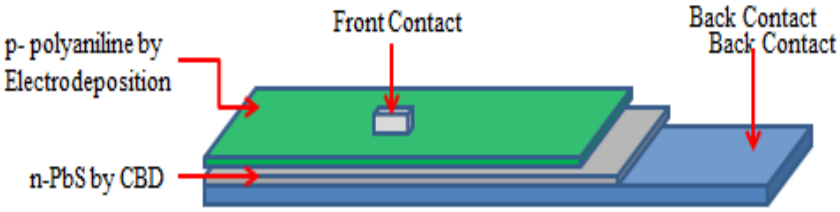

Figure 1

Figure 1 illustrates the schematic diagram of the p-polyaniline/n-PbS heterojunction. The structure is built on a stainless steel substrate, onto which PbS and polyaniline films are sequentially deposited using chemical bath deposition and electrodeposition methods, respectively. Electrical contacts are established by applying silver paste: the top contact is made to the p-polyaniline layer, and the back contact to the n-type PbS layer. The contact points have a diameter of approximately 0.1 cm, and conducting wires are connected to these contacts for electrical measurements.

IV. Result and Discussion

i. Structural Analysis

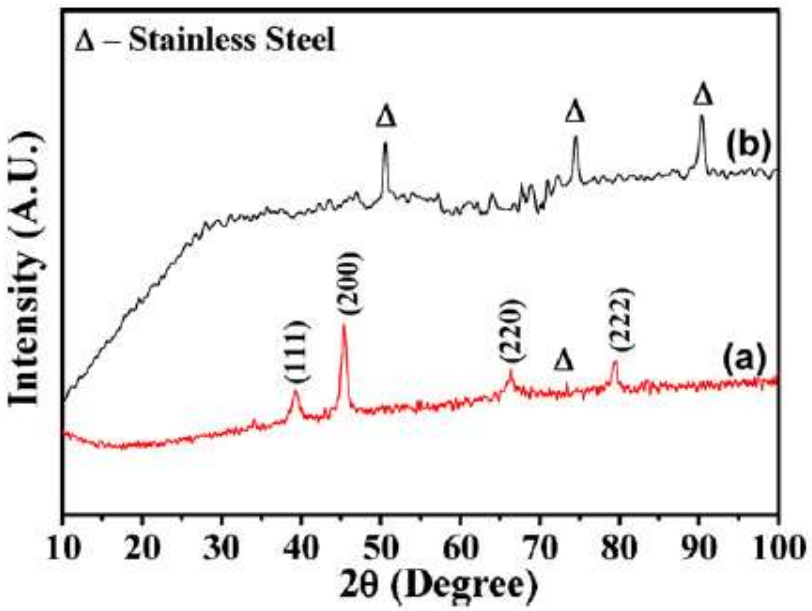

Figure 2 The XRD patterns of (a) PbS and (b) Polyaniline thin films on to stainless steel substrates

The appearance of several diffraction peaks in Fig. 2(a) confirms that the lead sulfide (PbS) thin film exhibits a polycrystalline nature. Among these, the (200) diffraction peak stands out with high intensity, while weaker peaks at (111), (200), and (222) are also present. These patterns align well with the face-centered cubic (FCC) crystal structure outlined in the JCPDS database (card no. 05-0592). When compared with the standard reference data, the preferential crystal orientation is evident along the (200) plane. Fig. 2(b) shows no distinct diffraction peaks, confirming that the polyaniline layer is amorphous—lacking long-range structural order.

ii. Morphological analysis

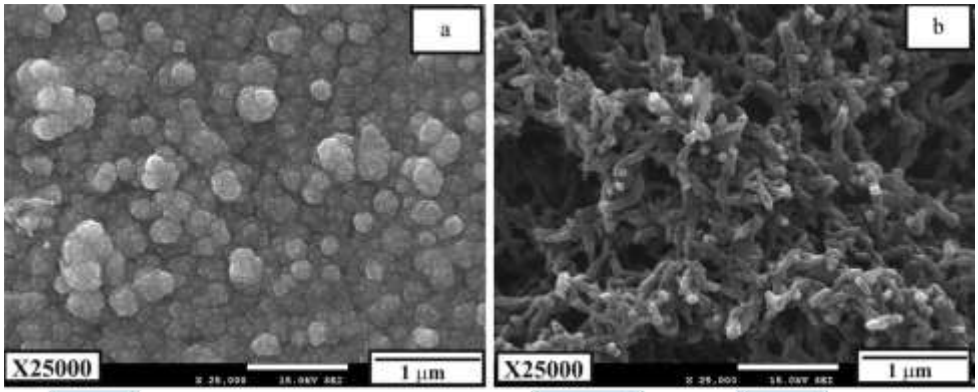

Figure 3(a) presents the scanning electron micrograph of the PbS and Polyaniline thin films

Figure 3(a) presents the scanning electron micrograph of the PbS thin film at a magnification of ×25,000. The surface is compact and uniformly covered with smooth, irregularly shaped nanograins of varying sizes. These nanograins are interconnected, forming dense clusters across the film. The average size of the grains is estimated to be in the range of 60–90 nm. In contrast, Figure 3(b) shows the SEM image of the polyaniline thin film, which exhibits a highly porous, interconnected nanofibrous network. The nanofibers have an average diameter of 65–75 nm and typical lengths ranging from 350 to 420 nm, providing a large surface area beneficial for surface-dependent applications.

iii. Current density vs Voltage characteristics of PbS-Polyaniline Heterojunction for different humidity's

The influence of ambient conditions on the electrical behavior of the p-polyaniline/n–PbS heterojunction was investigated through a humidity study. This study was conducted using optimized layer thicknesses of 0.65 µm for polyaniline and 0.55 µm for PbS. Figure 4 illustrates the variation in current density (J) at different relative humidity levels: (a) 40%, (b) 60%, (c) 80%, and (d) 90%. The results show a clear increase in forward current with rising humidity. This enhancement in current is likely due to an increase in electron concentration caused by adsorbed water molecules, which donate electrons to the heterojunction. The highest current density, 12.53 mA/cm², was recorded at 90% relative humidity, indicating strong humidity sensitivity of the device.

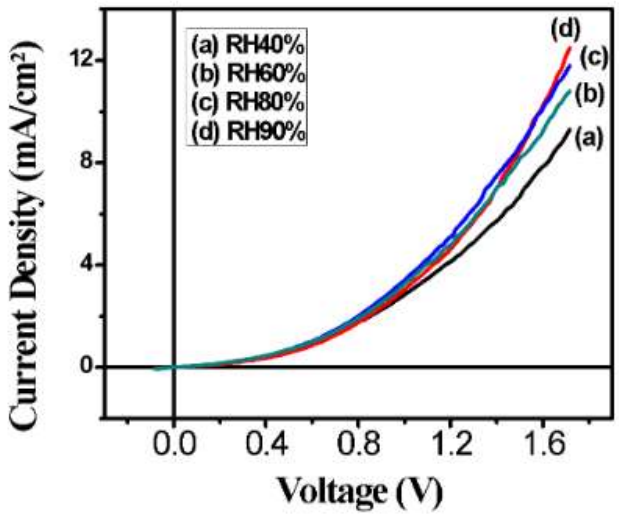

Fig 4 shows the variation in the current density (J) of p-polyaniline/n-PbS heterojunction at relative humidity's (a) 40 (b) 60 (c) 80 and (d) 90%.

V. CONCLUSION

This study successfully demonstrates the fabrication and performance evaluation of a novel p-polyaniline/n-PbS heterojunction using layer-by-layer deposition techniques on a stainless steel substrate. Structural analysis confirmed that the PbS film is polycrystalline with a preferential orientation along the (200) plane, while the polyaniline film is amorphous. Electrical measurements under varying humidity conditions revealed that the forward current density increases with rising relative humidity, indicating a strong sensitivity of the heterojunction to moisture. The observed maximum current density of 12.53 mA/cm² at 90% relative humidity highlights the potential application of this heterojunction as an effective and responsive humidity sensor.

VI. REFERENCES

[1] Y. Zhang et al., "Polyaniline-Based Composite Materials for High-Performance Humidity Sensors," Polymers, vol. 13, no. 16, p. 2722, 2021.

[2] H. Parangusan et al., "Electrospun PANI–ZnO composite nanofibers for humidity sensing," RSC Adv., vol. 11, no. 41, pp. 25210–25218, 2021.

[3] Q. Lin et al., "A fast-response humidity sensor based on electrospun polyaniline nanofibers," Sens. Actuators B, vol. 161, no. 1, pp. 967–972, 2012.
[4] J. Wen et al., "Recent progress in polyaniline-based materials for humidity sensors," J. Mater. Chem. A, vol. 12, no. 5, pp. 7643–7663, 2024.
[5] M. Ali et al., "Enhanced Humidity Sensing Properties of a rGO–$BiVO_4$ Nanocomposite," ACS Appl. Mater. Interfaces, vol. 13, no. 19, pp. 22211–22220, 2021.
[6] S. Chen et al., "Humidity sensors based on TiO_2/$NaNbO_3$ heterostructures," Sensors, vol. 21, no. 15, p. 5184, 2021.
[7] B. Singh et al., "TiO_2/SnS_2 nanoheterostructures for high-performance humidity sensors," Crystals, vol. 13, no. 3, p. 482, 2023.
[8] A. Ahmed et al., "Humidity sensing using MoS_2/CuO heterojunctions," J. Alloys Compd., vol. 847, p. 156298, 2020.
[9] S. Al Shami et al., "Recent developments in hybrid humidity sensors: A review," Sensors, vol. 23, no. 3, p. 1234, 2023.
[10] R. Kiani et al., "High-performance 2D BP/Graphene humidity sensors," Sci. Rep., vol. 7, p. 10936, 2017.
[11] J. Liu et al., "Flexible humidity sensors based on WS_2 nanosheets," Adv. Mater. Interfaces, vol. 7, no. 4, p. 1901572, 2020.
[12] Sengupta, S.; Perez, M.; Rabkin, A.; Golan, Y. In situ monitoring the role of citrate in chemical bath deposition of PbS thin films. CrystEngComm, 18 (Issue 1), 149–156, 2016