Celal Bayar University Journal of Science

Production and Characterization of Ag-Doped Multilayer Polyaniline Thin Films by Sol- Gel Method

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Received: June 20, 2025
Accepted: November 24, 2025
DOI: 10.18466/cbayarfbe.1721052

Abstract

Recently, studies on thin films have attracted increasing attention from scientists. Polyaniline thin films (PANI), which are among the thin films, are preferred for various applications due to their electrical conductivity, environmental stability, thermal stability and doping properties. PANI are used in many areas including supercapacitors, sensors, electronic devices, drug delivery systems. In this study, monolayer, five-layer, Ag-doped, and HCl-doped PANI thin films were synthesized by sol-gel method and coated on glass substrate via spin coating technique. The chemical, electrical, and morphological properties of glass substrates coated with polyaniline thin film were investigated. The effects of layer number and Ag addition on the characteristics of the PANI thin films were evaluated. SEM analysis revealed that PANI thin films possess a porous structure, and Ag doping improves surface homogeneity. SEM analysis proved that PANI thin films have a porous structure and Ag doping improves the surface morphology. Current–voltage (I–V) measurements were performed to determine the electrical properties of the films. The results showed that the conductivity of the five-layer PANI thin film was 25.75 times higher than that of the monolayer film. This finding suggests that Ag doping alters the charge transport mechanisms in PANI thin films and warrants further investigation.

Keywords: Thin film, polyaniline, sol-gel, Ag-doped, multilayer

1. Introduction

Polyaniline has been known for centuries and was first reported in the literature as "aniline black" in 1835. In its conductive form, it appears as a dark green powder and can be doped to achieve higher electrical conductivity [1]. Polyaniline (PANI), a member of the family of electrically conductive polymers, is one of the most remarkable conductive polymers due to its ease of synthesis, low cost, high stability, and wide tunable conductivity range upon doping [2]. In addition, PANI is used in many studies due to its doping / undopig properties. PANI exhibits electrical conductivity, pH sensitivity, low cost, simple synthesis, and excellent environmental stability [3]. Polyaniline exhibits thermal stability up to 250 °C and can be conveniently synthesized either chemically or electrochemically through oxidative polymerization in various organic solvents and/or aqueous solutions [4].

PANI can be synthesized in several oxidation states, including leucoemeraldine (fully reduced), emeraldine (semi-oxidized), and pernigranilin (fully oxidized). The conductive form of emeraldine is known as emeraldine salt (ES). The degree of conductivity depends on the oxidation state and the level of dopant incorporation [5]. In the literature, many studies have investigated the characterization of PANI thin films obtained synthesized using different methods. In a study conducted by Rajesh et al., polyaniline thin films were synthesized using a cost-effective solution polymerization techniques at room temperature. The physicochemical and optoelectronic properties of these thin films were examined to assess their potential for sensor applications [6].

Recent studies have demonstrated that conductive polymer thin films possess significant potential in applications such as supercapacitors, sensors, electronic devices, and drug delivery systems owing to their excellent electrical conductivity, environmental and thermal stability, and doping capabilities. While the effects of multilayer fabrication and metallic doping on PANI thin films have been independently investigated in the literature, there is still a lack of research addressing their combined effects. Specifically, the effect of Ag-doped multilayer PANI thin films synthesized at room temperature on their morphology and electrical performance has not been thoroughly studied. This study aims to fill this gap in the literature by synthesizing multilayer Ag-doped PANI thin films using aniline as the starting material, HCl as the solvent, and ammonium persulfate (APS) as the oxidizing agent, using the sol-gel method combined with spin-coating technique at room temperature. By analyzing the effects of both the number of layers and Ag doping on the structural and electrical characteristics, this work demonstrates enhancements in surface morphology alongside an unexpected decrease in electrical conductivity induced Ag doping. These findings provide valuable insight into the charge transport mechanisms within multilayer conductive polymers and present an energy-efficient approach for fabricating high-performance films suitable for electronic applications [7,8,9].

The properties of conductive PANI are mainly determined by two key factors: the type and concentration of additives. Additives play a crucial role in defining the overall characteristics of conductive polymers. The additive ratio, the type of acid used, the choice of acids, and the reaction temperature significantly influencethe surface morphology of the PANI film [10]. The additives utilized for conductive PANI include a wide range of acids such as hydrochloric, sulfuric, phosphoric, formic, oleic and sulfonic acids, among others. These acids may be either inorganic or organic in nature [11].

With the addition of Ag into thin films, new nucleation centers form, leading to a reduction in film thickness. In addition, it was observed that the morphological properties of thin films were improved with Ag additive [12].

Thin films can be produced using various techniques, including the sol-gel method, pulsed laser deposition method (PLD), physical vapor deposition method (PVD), thermal evaporation method, ion plating method, arc vapor deposition method, chemical vapor deposition (CVD) and RF magnetron sputtering method. These methods allow precise control over electrical conductivity, environmental stability, and thermal stability, thereby enabling the tailoring of PANI's physical and chemical properties. A wide range of industries profit from the use of sol–gel processes due to their flexibility in producing materials with tailored properties. After the sol-gel solution is obtained, thin films can be coated using techniques such as dip coating, spin coating, or drop coating [13]. In this study, undoped, HCl-doped, monolayer, and five-layer thin films were deposited onto glass substrates using the sol–gel method combined with the spin-coating technique.

2. Materials and Methods

2.1 Materials and chemical reagents

Aniline ($C_6H_5NH_2$), hydrochloric acid (HCl), ammonium persulfate $(NH_4)_2S_2O_8$, silver nitrate ($AgNO_3$), ammonium hydroxide (NH_4OH), methanol (CH_3OH) were purchased from Merck.

2.2 Chemical polymerization of aniline

PANI was synthesized using the chemical oxidative polymerization method. For this purpose, an acidic solution of aniline was prepared by mixing 0.02 mol (1.82 mL) of aniline in 50 mL of 0.2 M HCl at 850 rpm for 1 hour at room temperature. Separately, a 0.025 mol (5.71 g) ammonium persulfate solution was prepared in 50 mL of distilled water and stirred for 1 hour.[14]. The ammonium persulfate solution was then added dropwise to the aniline solution, and the mixture was stirred at 250 rpm for 24 hours at room temperature. After 24 hours, the precipitated polymer was filtered with filter paper and washed with distilled water and methanol to remove unreacted reagents. The resulting precipitate was mixed with 20 mL of 0.5 M NH_4OH for 4 hours. The mixture was left at room temperature for 24 hours. Finally, the polymer was washed with distilled water, filtered, and dried at 80 °C for 5 hours to obtain the PANI powder.

2.3 Additive PANI Production

For Ag addition, an aqueous solution of $AgNO_3$ (10 mL) was prepared in a 1:3 molar ratio, and 1 g of PANI was added to the solution and stirred overnight.

2.4 PANI Thin Film Production

Before spin coating, each glass substrate was thoroughly cleaned with ethanol followed by distilled water to remove any surface contaminants. The cleaned substrates were then sequentially placed in the spin coater. The speed of the spin coater was chosen as 850 rpm. A sufficient amount of polyaniline solution was dropped onto each glass substrate using a syringe to completely cover the surface, and coating was carried out for 1 minute. When the spin coating was finished, the glass substrate was removed from the device and placed in an oven to eliminate residual water and moisture in the thin film. Each glass substrate was dried at 80 °C for 5 min. This process was repeated for the monolayer HCl-doped Figure 1(a), five-layer HCl-doped Figure 1(b), monolayer Ag-doped Figure 1(c) and five-layer Ag-doped Figure 1(d) thin films, respectively.

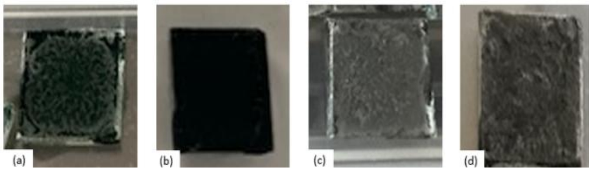

Figure 1. PANI thin films with spin coating

3. Results and Discussion

3.1 Analysis

X-Ray Diffraction (XRD) analysis was performed using a Thermo Scientific ARL K-Alpha instrument to determine the phase structure of PANI thin films. X-ray photoelectron spectroscopy (XPS) measurements were carried out using a Thermo Scientific K-Alpha instrument to analyze the chemical composition of the films. The surface morphology of polyaniline thin films was characterized by a Thermo Scientific Apreo S scanning electron microscope (SEM) at various magnifications at low vacuum. Film thickness measurements were also performed with the Thermo Scientific Apreo S instrument at low vacuum. The electrical conductivity of the PANI thin films was measured using a Keithley 2636B source meter for I–V characterization.

3.1.1 X-Ray Diffraction (XRD) Analysis

Figure 2 illustrates the XRD patterns of the monolayer HCI-doped PANI thin film (S1) and five-layer HCI-doped PANI thin film (S2), respectively. The XRD pattern of PANI reveals three peaks at 2θ = 21.67°, 2θ = 23.33°, and 2θ = 33.33°, corresponding to the (020), (112), and (104) planes, respectively [15,16,18]. Additionally, the XRD pattern of PANI shows a specific peak at 2θ = 21.67°, corresponding to the (020) PANI plane [16]. Figure 3 displays the XRD pattern of the monolayer Ag-doped PANI (S3), which exhibits a peak at 2θ = 38.33°, corresponding to the (111) PANI plane [15]. Figure 3 (S4) presents the XRD pattern of the five-layer Ag-doped PANI thin films. PANI's XRD pattern exhibits three peaks at 2θ = 31.67°, 2θ = 36.67°, and 2θ = 46.67°, corresponding to the (022), (111), and (200) planes of PANI, respectively [16,17,19].

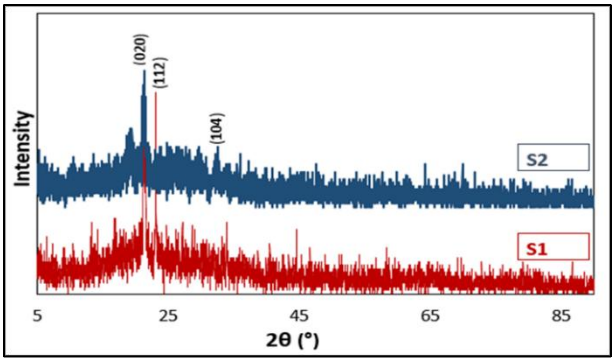

Figure 2. XRD pattern of monolayer HCI-doped PANI (S1), XRD pattern of five-layer HCI-doped PANI (S2)

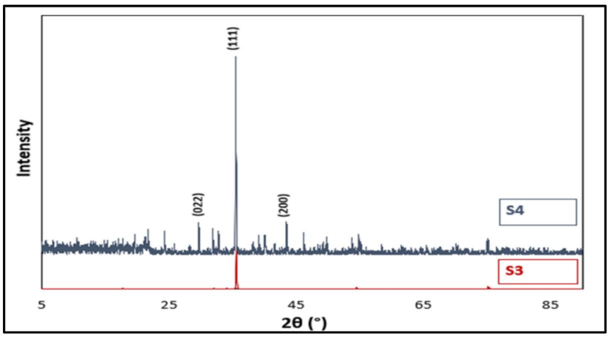

Figure 3. XRD pattern of monolayer Ag doped PANI (S3), XRD pattern of five-layer Ag doped PANI (S4)

3.1.2 Scanning electron microscopy (SEM) Analysis

SEM analysis indicates that Ag doping enhances the surface morphology of PANI thin films. As shown in Figure 5, the SEM images of the five-layer HCl-doped PANI thin films reveal a homogeneous surface morphology. Figure 6 presents the SEM images of the monolayer Ag-doped PANI thin films, which exhibit a porous structure. According to the SEM images of the five-layer Ag-doped PANI thin films in Figure 7, it is seen that the Ag addition makes the surface morphology more homogeneous. Similarly, Jamil et al., in their study, produced a thin film on the glass substrate with the chemical bath storage method (CBD) and concluded that the Ag additive increased the homogeneity of the thin films according to the SEM images[17].

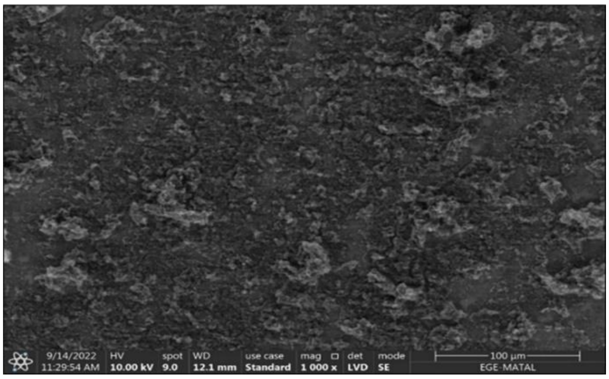

Figure 4. SEM image of monolayer HCI-doped PANI thin film

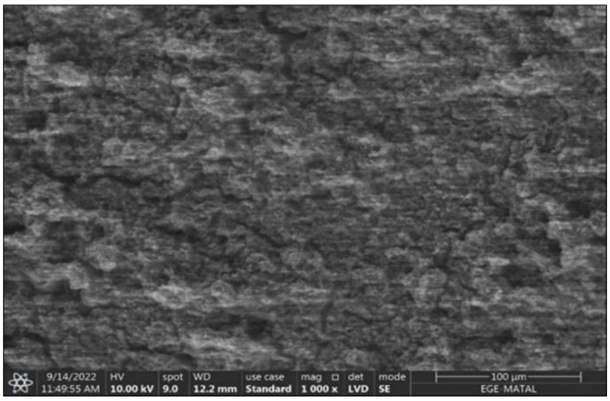

Figure 5. SEM image of five-layer HCI-doped PANI thin film

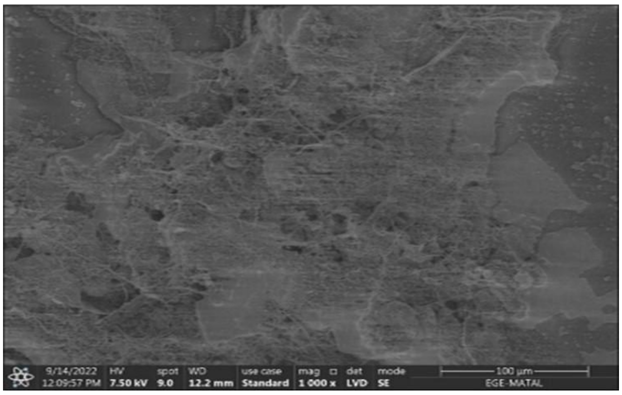

Figure 6. SEM image of monolayer Ag-doped PANI thin film

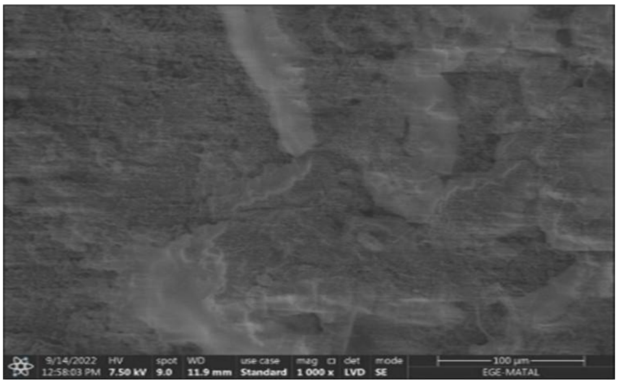

Figure 7. SEM image of five-layer Ag-doped PANI thin film

3.1.3 X-ray photoelectron spectroscopy (XPS) Analysis

Figure 8 (S1) shows the XPS analysis of HCI-doped monolayer PANI. XPS analysis of HCI-doped monolayer PANI samples shows the presence of oxygen (O(1s) ~ 532.53 eV, nitrogen (N(1s) ~ 400.22 eV), carbon (C(1s) ~ 285.29 eV). Figure 8 (S2) shows the XPS spectrum of the HCI-doped five-layer PANI thin film, which exhibits signals corresponding to oxygen (O(1s) ~ 532.07 eV, nitrogen (N(1s) ~ 400.49 eV), carbon (C(1s) ~ 285.23 eV). Figure 9 (S3) shows the XPS spectrum of the Ag-doped monolayer PANI thin film, where Ag $3d_{5/2}$ peaks are observed in the binding energy (BE) range of 367.66–368.17 eV. Figure 9 (S4) presents the XPS spectrum of the Ag-doped five-layer PANI thin film, which displays three distinct carbon peaks at 284.82, 286.22, and 289.16 eV, corresponding to C–C, C–O, and C=O bonds, respectively. The XPS analysis spectra in Figure 9 (S4) show Ag$3d_{5/2}$ peaks in the BE = 368.38 and 369.62 eV range. XPS analysis reveals that the Ag $3d_{5/2}$ peaks of the Ag-doped monolayer PANI (367.66–368.17 eV) correspond primarily to slightly oxidized metallic Ag^0, while those observed in the five-layer film (368.38–369.62 eV) indicate a dominance of Ag^+ species such as Ag_2O or AgO. This progression to higher binding energies confirms an increased degree of Ag oxidation and stronger Ag–O/N coordination within the polymer matrix, consistent with previous reports on Ag–PANI nanocomposites [7,18].

The presence of Ag^+ instead of metallic Ag^0 explains the observed decrease in electrical conductivity: oxidized silver acts as an electron acceptor, stabilizing charge carriers (polarons/bipolarons) in PANI and creating trap states that reduce carrier mobility [7]. In addition, Ag_2O-like regions formed at grain boundaries can create potential barriers to charge transport, as reported for metal oxide-PANI hybrid films [18]. Consequently, although metallic Ag can increase conductivity, ionic Ag^+ suppresses carrier migration and increases resistivity, in agreement with previous findings for Ag-PANI and related conducting polymer systems [7,18].

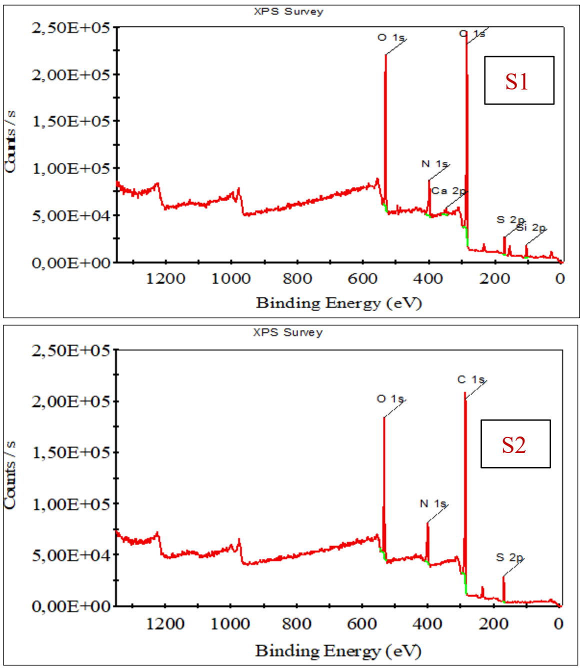

Figure 8. (S1) XPS image of monolayer HCI-doped PANI, (S2) XPS image of five-layer HCI-doped PANI

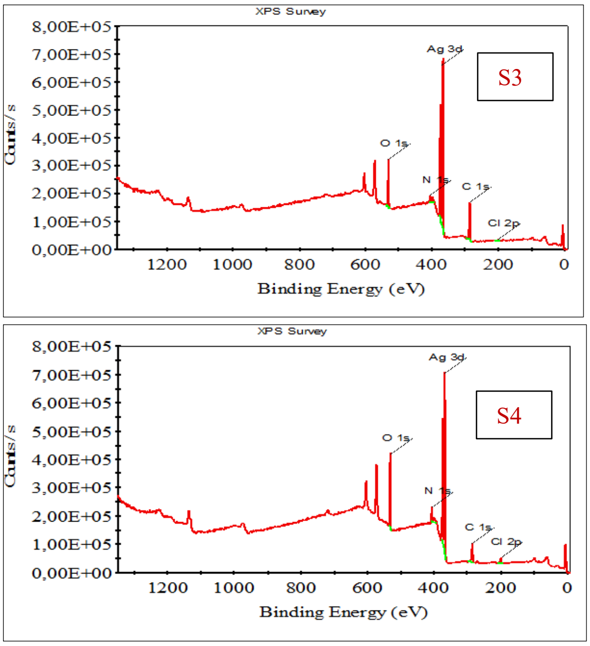

Figure 9. (S3) XPS image of monolayer Ag-doped PANI, (S4) XPS image of five-layer Ag-doped PANI

3.1.4 Thin Film Thickness Analysis

Belgherbi et al. observed that the thickness of monolayer polymer thin films ranges from 0.1 µm to 7 µm [21]. Table 1 shows the thickness values of the PANI thin films. The monolayer HCI-doped PANI thin film has a thickness of 1.39 µm, while the five-layer HCI-doped PANI thin film exhibits a thickness of 25.52 µm. Similarly, the Ag-doped monolayer PANI thin film has a thickness of 1.21 µm, whereas the Ag-doped five-layer PANI thin film exhibits a thickness of 30.99 µm.

Table 1. Thickness values of PANI thin films

Sample Name	Number Of Layers	Film Thickness Value (µm)
S1	1	1.39
S2	5	25.52
S3	1	1.21
S4	5	30.99

3.1.5 Conductivity Analysis

Table 2 represents the conductivity values of PANI thin films. According to the literature, the conductivity of polyaniline thin films is reported as $2.77x10^{-5}$ $(\Omega.cm)^{-1}$ [15]. In our study monolayer HCI-doped PANI thin films exhibit a conductivity of $2.31x10^{-5}$ $(\Omega.cm)^{-1}$, while the five-layer HCI-doped PANI thin film showed a significantly higher conductivity of $59.5x10^{-5}$ $(\Omega.cm)^{-1}$. On the other hand, the monolayer Ag-doped PANI thin film displayed a conductivity of $1.51x10^{-5}$ $(\Omega.cm)^{-1}$, while the five-layer Ag-doped PANI thin film exhibited a lower conductivity of $3.25x10^{-7}$ $(\Omega.cm)^{-1}$. It was observed that the conductivity of HCI-doped PANI thin films increased with the number of layers, while the conductivity of Ag-doped PANI thin films decreased as the number of layers increased. I-V measurements revealed that the addition of Ag reduced the conductivity in the monolayer thin films.

Table 2. Conductivity values of PANI thin films

Sample Name	Number Of Layers	Film Conductivity Value $(\Omega.cm)^{-1}$
S1	1	$2.31x10^{-5}$
S2	5	$59.5\ x10^{-5}$
S3	1	$1.51\ x10^{-5}$
S4	5	$3.25\ 10^{-7}$

Although Ag doping increased the surface homogeneity of multilayer polyaniline (PANI) films produced by the sol-gel method, it caused an unexpected decrease in electrical conductivity. This result indicated that the addition of Ag altered the charge transport pathways within the polymer matrix. The electrical performance of PANI thin films depends not only on the structural arrangement but also on the doping level, morphology, and connectivity of conductive domains; therefore, structural improvement alone does not guarantee higher conductivity [22,23]. Several mechanisms may be responsible for this conductivity decrease. First, in multilayer architectures, Ag accumulation at interlayer boundaries can create grain boundaries scattering regions that hinder long-range charge transport through the film thickness [24]. Second, if Ag is non-uniformly dispersed, Ag particles may disrupt existing PANI conduction channels instead of forming low-resistance bridges; poor dispersion has been shown to increase contact resistance and hinder the construction of continuous conductive paths [22,25]. Third, chemical interactions during Ag doping can disrupt the protonation and oxidation states of PANI. Therefore, it can reduce the number of charge carriers available for conduction [26].

4. Conclusion

In this study, conductive polyaniline (PANI) thin films were synthesized at room temperature using the sol–gel method combined with the spin-coating technique. For this purpose, aniline was used as the starting monomer, hydrochloric acid (HCl) as the solvent, and ammonium persulfate (APS) as the oxidizing agent. PANI thin films were synthesized as monolayer, five-layer, Ag-doped and HCI-doped samples and where characterized by SEM, XRD, thin-film thickness analysis, I-V analysis and XPS analysis. This work successfully demonstrated the synthesis of PANI thin films, a polymer with diverse application potential. The results revealed that the conductivity of HCl-doped PANI thin films increased with the number of layers, whereas the incorporation of Ag improved surface homogeneity but led to a decrease in electrical conductivity.

From a thin-film application perspective, the results of this study are of great importance. For supercapacitors, where both high conductivity and a large accessible surface area are critical, Ag doping should be optimized to achieve a balance between morphology and charge transport efficiency. The concept of achieving an optimal balance through controlled doping is consistent with strategies in PANI systems [27]. In sensing applications, improved morphology can increase sensitivity but may degrade signal strength or response time in conducting polymers [28]. Future research can be conducted by varying the Ag concentration to determine conductivity-morphology trade-offs and an optimal doping regime. Investigating alternative dopants other than Ag (e.g., gold (Au) or copper (Cu)) and comparing their effects on PANI thin film morphology and electrical behavior under the same processing conditions would also be beneficial for future studies. Furthermore, investigating the effects of different deposition techniques (CVD, PVD, ALD, etc.) on PANI thin film morphology and electrical performance will aid in the tailoring of conductive polymer films for energy storage, sensors, and supercapacitors [29]. According to the literature, the electrical conductivity of undoped polyaniline (PANI) thin films depends on the synthesis method, thickness, and additive. HCl-doped PANI values generally range from $\sim10^{-8}$ to $\sim10^{-3}$ S/cm (i.e., $(\Omega\cdot cm)^{-1}$) for thin films produced by spin coating or other fabrication methods. Conductivity can be increased when secondary doping and interface defects are controlled [30].

In our study, we found that monolayer HCl-doped PANI thin films exhibited a conductivity of 2.31×10^{-5} $(\Omega\cdot cm)^{-1}$, which is at the lower end of the literature range. Increasing the number of layers to five resulted in a significantly increased the conductivity (our results show 59.5×10^{-5} $(\Omega\cdot cm)^{-1}$). In contrast, Ag-doped PANI thin films displayed an opposite trend: the monolayer Ag-doped PANI exhibited a conductivity of 1.51×10^{-5} $(\Omega\cdot cm)^{-1}$, while the five-layer Ag-doped PANI showed a marked decrease to 3.25×10^{-7} $(\Omega\cdot cm)^{-1}$. This suggests that adding Ag to a multilayer thin film can create trap states, disrupt optimal conduction paths, cause scattering, or lead to inhomogeneous distribution. Literature on metal nanoparticle or metal ion doping in conducting polymers also indicates that beyond an optimal doping concentration, conductivity may decrease rather than increase [31]. These observations suggest that optimizing Ag doping parameters, such as concentration, particle size and distribution, film thickness, and number of layers, is critical to compensate for morphology improvements rather than maintaining or increasing electrical conductivity. These properties are particularly important for PANI thin-film applications in supercapacitors, sensors, and flexible electronics, where both morphology and electrical performance are critical.

Acknowledgement
We would like to express our sincere gratitude to the Ege University Scientific Research Projects (BAP) Coordination Unit for their support of our project (Project Code: FYL-2021-23295).

Author's Contributions

Dicle Öntaş: Material preparation, data collection, and analysis were carried out by Dicle Öntaş. The manuscript was written by Dicle Öntaş and Çiğdem İçhedef.

Çiğdem İçhedef: Çiğdem İçhedef supervised the research, verified the results, and critically reviewed the manuscript. All authors read and approved the final version of the article.

Ethics

There are no ethical issues after the publication of this manuscript.

References

[1] Cherrington, R., & Liang, J., 2016, Materials and deposition processes for multifunctionality. Materials and Deposition Processes for Multifunctionality, 19-51.

[2] Bhadra, J., Alkareem, A., & Al-Thani, N., 2020, A review of advances in the preparation and application of polyaniline-based thermoset blends and composites. Journal of Polymer Research, 27, 102–122.

[3] Beygisangchin, M., Rashid, S., Shafie, S., Sadrolhosseini, A., & Lim, H., 2021, Preparations, properties, and applications of polyaniline and polyaniline thin films—a review. Polymers, 13(2), 46.

[4] Jaymand, M., 2013, Recent progress in chemical modification of polyaniline. Progress in Polymer Science, 138, 1287–1306.

[5] Rahayu, I., Eddy, D., Novianty, A., Anggreni, A., Bahti, H., & Hidayat, S., 2019, The effect of hydrochloric acid-doped polyaniline to enhance the conductivity. Materials Science and Engineering, 13th Joint Conference on Chemistry.

[6] Rajesh, A. J., 2016, Preparation and characterization of polyaniline thin films for sensor applications. *Polymers*, 4, 51–55.

[7] Beygisangchin, M., Arjmand, M., Sundararaj, U., & Park, C. B., 2021, Preparations, properties, and applications of polyaniline. Materials, 14(14), 4003.
[8] Kaushik, P., Singh, D., & Dutta, V., 2024, Progress in synthesis and applications of polyaniline: A review. Polymer, 298, 126987.

[9] Saini, P., Choudhary, V., Gupta, R., 2013, High permittivity polyaniline–barium titanate nanocomposites with excellent electromagnetic interference shielding response. Nanoscale, 5(10), 4330–4339

[10] Kakde, K., 2017, Synthesis and characterization of polyaniline doped with HCl, H2SO4, and PVA as secondary dopant for toxic gas (ammonia) sensor. Indian Journal of Science and Technology, 10, 1–4.

[11] Geethalakshmi, D., Muthukumarasamy, N., & Balasundaraprabhuc, R., 2014, Effect of dopant concentration on the properties of HCl-doped PANI thin films prepared at different temperatures. Optik, 125, 1307–131.

[12] Diliegros-Godines, C., Santos Cruz, J., Mathews, N. R., & Pal, M., 2018, Effect of Ag doping on structural, optical, and electrical properties of antimony sulfide thin films. Journal of Materials Science, 53, 11562–11573.

[13] Bahuguna, G., Mishra, N., Chaudhary, P., Kumar, A., & Singh, R., 2016, Thin film coating through sol-gel technique. Research Journal of Chemical Sciences, 6, 65–72.

[14] Diantoro, M., Purwaningtyas, D., Muthoharoh, N., Hidayat, A., Taufiq, A., & Fuad, A., 2012, The influence of iron- and copper-doped PANI thin film on their structure and dielectric properties. *AIP*

Conference Proceedings, 1454, 268–271.

[15] Jarad, A., Ibrahim, K., & Nasser, A., 2016, Synthesis and characterization thin films of conductive polymer (PANI) for optoelectronic device application. International Conference on Nano-electronic Technology Devices and Materials.

[16] Chougale, U., Sadigale, S., Mulla, H., Patil, S., Kamble, B., & Fulari, V., 2020, Electropolymerised fibrous conducting polyaniline thin films for supercapacitor application. Bulletin of Laser and Spectroscopy Society of India, 26, 64.

[17] Jamil, N. Y., Burjus, A. Y., & Khalil, H. M. T., 2018, The effect of Ag doping on the structural, optical, and electrical properties of CdSe thin films. Rafidain Journal of Science, 27, 146–152.

[18] Kumar, H., Yadav, A., & Pandey, R. K., 2022, Ag_2O@PANI nanocomposites for advanced functional applications. Journal of Alloys and Compounds, 899, 163250.

[19] Badr, H., Mahallawi, I., Elrefaie, F., & Allam, N., 2019, Low temperature thermoelectric performance of novel polyaniline/iron oxide composites with superior Seebeck coefficient. Applied Physics A.,125,24.

[20] Butoi, B., Groza, A., Dinca, P., Balan, A., & Barna, V., 2017, Morphological and structural analysis of polyaniline and poly(o-anisidine) layers generated in a DC glow discharge plasma by using an oblique angle electrode deposition configuration. Polymers, 9, 732.

[21] Belgherbi, O., Seid, L., Lakhdari, D., Chouder, D., Akhtar, M., & Saeed, M., 2021, Optical and morphological properties of electropolymerized semiconductor polyaniline thin films: Effect of thickness. Journal of Electronic Materials, 50, 3876–3884.

[22] Nan, X., Zhou, J., Zhao, L., Wang, Y., Li, M., Xie, J., et al., 2024, A review of the establishment of effective conductive pathways of conductive polymer composites and advances in electromagnetic shielding. Polymers, 16(13), 2539.

[23] Naghdi, S., Rhee, K. Y., Hui, D., & Park, S., 2018, A review of conductive metal nanomaterials as conductive, transparent, and flexible coatings, thin films, and conductive fillers: different deposition methods and applications. Coatings, 8(8), 278.

[24] Al-Mur, B. A., Aljohani, H. A., Aldalbahi, A., Alqarni, M., Ali, S., Khan, S., et al., 2023, Silver anchored polyaniline@molybdenum disulfide nanocomposite (Ag/PANI@MoS_2) for highly efficient ammonia and methanol sensing under ambient conditions: a mechanistic approach. Nanomaterials, 13(4), 828.

[25] Kayishaer, A., Rehman, S., Kadir, A., Rahman, S., & Gul, H., 2024, Influence of surfactant on conductivity, capacitance and morphology of polyaniline films. Frontiers in Materials, 11, 1330790.

[26] Bednarczyk, K., Ciszewski, A., & Łapkowski, M., 2021, Effect of polyaniline content and protonating dopants on structural, conductive and morphological properties of polyaniline-based composites. Polymers, 13(7), 1095.

[27] Gawli, Y., Banerjee, A., Dhakras, D., Deo, M., Bulani, D., Wadgaonkar, P., Shelke, M., & Ogale, S., 2016, 3D polyaniline architecture by concurrent inorganic and organic acid doping for superior and robust high-rate supercapacitor performance. Scientific Reports, 6, 21002.

[28] Rani, G., Bhawna, & Ahlawat, R., 2024, A critical examination of polyaniline and its composite materials: Augmenting supercapacitor performance and diversifying application potential. Journal of Energy Storage, 97, 112690.

[29] Okafor, O. B., Popoola, A. P. I., Popoola, O. M., & Adeosun, S. O., 2025, Review on the recent development on polyaniline and transition metal oxides composite electrode for supercapacitor application. Results in Engineering, 22, 101926.

[30] Kim, Y.-G., Nguyen, H.-L., & Kinlen, P., 2021, Secondary dopants of electrically conducting polyanilines. Polymers, 13(17), 2904.

[31] Yadav, A. K., Mohammad, N., Chamanehpour, E., Mishra, Y. K., & Khanna, P. K., 2024, Polyaniline (PANI) nanocomposites with Se, Te and their metal chalcogenides: a review. RSC Applied Polymers, 2(5), 775–794.