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Impedance spectroscopic studies on polyindole by the dispersion of CdS nanoparticles for solid state electronics applications

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Abstract

In this research report, we have synthesized polyindole-cadmium sulfide nanocomposites by means of chemical oxidative polymerization technique. The analysis highlights the dispersion of cadmium sulfide (CdS) nanoparticles in polyindole (PIn) to enhance the dielectric characteristics of the synthesized nanocomposites. The structural evaluation of as-synthesized nanocomposites was carried out by Fourier transform infrared (FTIR) spectroscopy, X-ray diffraction (XRD) and Field emission scanning electron microscopy (FE-SEM) techniques. The impedance spectroscopy technique in the frequency and temperature ranges 20 Hz – 1 MHz and 308 – 393 K respectively was employed to investigate the transport properties of as-synthesized composites under study. The frequency variation of AC electrical conductivity for the obtained samples obeys Jonscher power law. The complex electric modulus spectra indicated the non-Debye nature of the prepared materials.

Key words: Polyindole-cadmium sulfide nanocomposite; Electrical conductivity; Impedance spectroscopy; Hopping distance.

1. Introduction

The polymeric nanocomposites are receiving considerable attention for fundamental studies from academic and industrial perspectives due to their high stability, ability to control the

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growth of nanocrystals, and electrical properties [1-4]. In this regards, the blends consist of organic polymer matrix and inorganic contents (semiconductors) has a good effect on these properties. These nanocomposites are extensively studied class of materials engineering, such materials found numerous potential applications in many areas of electronics [5, 6]. Moreover, there are several important electrical parameters associated with the polymer nanocomposites, which leads such materials to exhibits several electrical applications [7]. Beside to this, these nanocomposites are more popular due to their excellent electrical optical, thermal, chemical, dielectric and mechanical properties [8, 9]. Due to these desirable engineering properties, such nanocomposites behaves as an excellent engineering materials and are frequently used for new appearance [10]. The significant research efforts are currently being devoted to physico-chemical investigations on composite materials [11]. The conjugated polymers such as polyaniline, polypyrrole, polythiophene, polyindole are among the most widely used polymers in the synthesis of nanocomposites because of their availability and low cost [12-15]. Among the nanoparticles found in group II-VI compound semiconductors, ZnS and CdS are recognized as the most promising materials [16]. CdS (cadmium sulfide) is a II-VI semiconducting material characterized by a direct band gap of 2.42 eV at room temperature [17]. Extensive studies have been undertaken on this material due to its potential applications in large area electronic devices, especially as an active layer in thin film transistors (TFTs) [18], photovoltaics [19], photoconductors [20], and light emitting diodes [21]. As an n-type semiconductor, CdS acts as a window layer in solar cells. Improved crystallinity and a homogeneous grain size distribution lead to enhanced carrier mobility, resulting in superior device performance [22].

The influence of frequency on conductivity and dielectric properties serves as a sensitive approach to examine polymer structures, primarily due to the polarization effects from both polar and ionic contributions. In this article, we report the synthesis of PIn/CdS nanocomposites with different concentration of CdS in PIn as free standing matrix. The

primary objective of this research is to explore the effects of CdS nanoparticle loadings on the properties of PIn/CdS nanocomposites. The as-synthesized nanocomposites were characterized for their structural and morphological features to understand the effect of CdS content in PIn matrix. The electrical characteristics of PIn/CdS nanocomposites were thoroughly examined through various parameters to gain insights into the synergistic effects resulting from the incorporation of CdS into the PIn matrix. This analysis aimed to elucidate how varying levels of CdS loading influence the overall electrical behavior of the nanocomposites. By systematically investigating these properties, a deeper understanding of the interactions between the components was achieved, highlighting the significance of CdS in enhancing the performance of the PIn matrix.

The prepared samples of conducting copolymers have been characterized through FTIR, XRD and FE-SEM techniques, and AC impedance measurements.

Scheme 1. Schematic Representation of the Formation Mechanism of a) PIn b) PIn/CdS nanocomposite.

2. Experimental details

2.1 Materials Synthesis

All reagents were used as received without further purification. Indole monomer, ferric chloride (FeCl_3), hydrogen peroxide (H_2O_2), cadmium chloride monohydrate ($\text{CdCl}_2 \cdot \text{H}_2\text{O}$), zinc chloride (ZnCl_2), benzamide, lead acetate ($\text{Pb}(\text{CH}_3\text{COO})_2$), sodium nitrate (NaNO_3), and polyvinyl alcohol (PVA) (AR grade, 99% purity) were procured from SD Fine Chemicals. Throughout the synthesis double distilled (DD) water was used to prepare the solution.

2.1.1. Synthesis of CdS nanoparticles:

The synthesis of CdS nanoparticles was accomplished using the one-pot synthesis method, with polyvinyl alcohol serving as a capping agent. Aqueous solutions of cadmium chloride

and sodium sulphide, both at equimolar concentrations (1M), were combined at room temperature, and the pH of the resulting solution was maintained at 9.0. Following thorough mixing, a 1M aqueous polyvinyl alcohol solution was added, and the mixture was kept at 70°C for five hours. The precipitate of CdS nanoparticles was indicated by the colorless solution turning light yellow and then dark orange.

To remove unbound polyvinyl alcohol molecules, the CdS nanoparticles were subjected to centrifugation at 10,000 rpm for 20 minutes at room temperature. The purification process involved several cycles of centrifugation followed by redispersion in double distilled water. Finally, the nanoparticles were allowed to dry at room temperature for 24 hours.

2.1.2 Synthesis of PIn/CdS nanocomposite

The synthesis of PIn/CdS nanoparticles was achieved via the in-situ polymerization method, employing polyvinyl alcohol as a surfactant. Specifically, indole monomer was polymerized in presence of CdS nanoparticles, with FeCl₃ acting as the oxidizing agent. Initially, the CdS nanoparticles were dispersed in a 1M PVA solution, formulated from a 4:1 ratio of chloroform to deionized water, and treated with ultrasonication for 20 minutes. This dispersion was then added dropwise to a chloroform solution containing indole. The mixture was stirred vigorously for 5 h to facilitate the adsorption of the indole monomer onto the CdS nanoparticles. Following polymerization, the product was separated, washed with deionized water, chloroform, and ethyl alcohol, and subsequently dried under vacuum at 70°C for 48 h. By varying the percentage of CdS a series of PIn/CdS nanocomposites was obtained named as PIn/CdS (5 wt%), PIn/CdS (10 wt%), PIn/CdS (15 wt%), PIn/CdS (20 wt%) and PIn/CdS (25 wt%).

2.2 Materials characterization

By using Bruker D8 advance with Cu-K α radiation the phase purity and structure of synthesized product were confirmed in which the pattern recorded in the range 10°– 70°. The FTIR spectrum was recorded to identify the functional and skelton peaks on Shimadzu

(Model-8201) spectrophotometer, in the KBr medium, at room temperature in the region $4000 - 400 \text{ cm}^{-1}$ at scan rate $16 \text{ cm} \cdot \text{sec}^{-1}$. The morphology and grain size of the samples were reported from FE-SEM (JEOL JSM-6360). For electrical conductivity measurements, samples were polished and conducting silver paste was deposited on either sides. The sample area was considered to be the area released to the electrode surface. The two silver electrodes were used to sandwich the sample in the four probe cell technique. The AC impedance measurements were performed through LCR meter, Agilent Technology, Singapore, interfaced to a computer for data acquisition over frequency range $20 \text{ Hz} - 1 \text{ MHz}$ and the temperature range $308 - 393 \text{ K}$. The DC electrical conductivity measurement as a function of temperature for all the samples were made by two-probe technique in the temperature range of $303 - 393 \text{ K}$.

3. Results and discussion

3.1 XRD analysis

X-ray diffraction patterns of as-synthesized PIn/CdS (5 wt%, 10 wt%, 15 wt%, 20 wt% and 25 wt%) nanocomposites are shown in figure 1 (a-e) respectively. For the PIn/CdS nanocomposites, the sharp peaks disappear, indicating a reduction in crystallinity due to the incorporation of CdS nanoparticles within the polyindole matrix. The XRD data mainly show amorphous phase. The broad peak at $15-320$ originates from PIn and CdS. The XRD patterns of the nanocomposite have higher background intensity, lower diffraction peak intensities, decreased interplaner spacing and reduced sharpness of the peak profiles than pure CdS, which confirmed the chemical interaction between PIn and CdS [23]. PIn/CdS nanocomposites showed a loading impact. The broadness of the amorphous hump of PIn/CdS nanocomposites was affected by CdS loading contents. Upon raising the CdS concentrations in polyindole matrix, the characteristic peaks at 26.58 , representing Bragg's reflections from (002), plane of the hexagonal phase [24]. These extra peaks in XRD study of nanocomposites confirm that CdS is present in the polyindole matrix. Average particle size (D) in these cases

is given by the Scherrer formula [25]. Particle sizes obtained using this formula lies in between 7 and 10 nm.

Fig. 1. X-ray diffraction pattern for PIn/CdS (a) 5 wt%, (b) 10 wt%, (c) 15 wt%, (d) 20 wt% and (e) 25 wt% nanocomposites.

3.2 FTIR analysis

Formation of nanocomposites of PIn/CdS (5 wt%, 10 wt%, 15 wt%, 20 wt% and 25 wt%) reveals its characteristic transmittance as shown in Figure 2(a-e) respectively. The typical transmission spectra for the nanocomposites of PIn/CdS are detectable; the incorporation of CdS leads to the shift of some FTIR bands of PIn toward the higher wave numbers. The FTIR spectra of CdS nanoparticles reveal a significant band at $3,100\text{ cm}^{-1}$, which corresponds to the O-H stretching vibrations of water molecules. Additionally, a band at $1,550\text{ cm}^{-1}$ is attributed to C-C stretching, while the bands at $1,290$ and $1,100\text{ cm}^{-1}$ are associated with the asymmetric and symmetric stretching of CdS, respectively [26, 27]. In the FTIR spectra of PIn, the band at $1,546\text{ cm}^{-1}$ is linked to C=C stretching vibrations. The in-plane deformation mode of C-H is identified at $1,317\text{ cm}^{-1}$ [28]. The distinctive bands of PIn, located at $1,315\text{ cm}^{-1}$, correspond to the stretching vibration of C-N. Additionally, the band at 751 cm^{-1} is assigned to out-of-plane deformation [29]. In the FTIR spectrum of PIn/CdS composites, a notable attenuation of N-H vibrations has been detected, implying that there is an interaction between PIn and the CdS nanoparticles.

Fig. 2. FTIR spectra of PIn/CdS (a) 5 wt%, (b) 10 wt%, (c) 15 wt%, (d) 20 wt% and (e) 25 wt% nanocomposites.

3.3 Surface morphology

The FE-SEM technique was applied to study the surface morphological characteristics of the as-synthesized PIn/CdS (5 wt%, 10 wt%, 15 wt%, 20 wt% and 25 wt%) nanocomposites and corresponding FE-SEM pictures have been shown in Fig. 3(a–e). The FE-SEM image for PIn/CdS nanocomposites indicated the presence of CdS nanoparticles embedded in the PIn matrix, displaying a mixed morphology with irregular agglomerations [23]. The micrographs clearly indicates that CdS nanoparticles were firmly integrated within the PIn matrix. In the case of the PIn/CdS nanohybrid, the CdS nanoparticles were entirely dispersed within the PIn matrix [30].

Fig. 3. FE-SEM micrographs of PIn/CdS (a) 5 wt%, (b) 10 wt%, (c) 15 wt%, (d) 20 wt% and (e) 25 wt% nanocomposites.

3.4 DC electrical conductivity

The dimensions of the obtained samples are used to determined the DC electrical conductivity. The variation of temperature dependent conductivity in range 303 – 393 K for all samples of PIn/CdS nanocomposites is shown in figure 4(a). As seen in figure, DC conductivity plots are governed by the relation $\sigma_{dc} = \sigma_0 \exp(-E_\sigma/k_B T)$ [31]. The slope of linear graphs is utilized to ascertain the values of activation energy (E_σ). As the temperature of the sample increases, it become soft, which imports in the mobility of main chain segment as well as the rotation of side groups. The conductivity increases with increase in temperature, which ranging from $10^{-5} - 10^{-3} \text{ Scm}^{-1}$ within measured temperature range. The increased in the conductivity is attributed to an increase in charge-carrier concentration. From the plot, it clearly observed that the conductivity of obtained samples does not show any abrupt jump with temperature [32]. This shows that the synthesized materials have completely amorphous structure. The sample PIn/CdS (15 wt%) shows optimum DC conductivity (σ_{DC}), which is estimated to be $1.87 \times 10^{-3} \text{ Scm}^{-1}$ at 393 K. Also, the activation energy (E_{DC}) required to

overcome the potential barrier is found to be 0.091 eV which is the lowest value among all the obtained samples.

The polarization current verses time plots of PIn/CdS nanocomposites are obtained which exhibit typical behavior of ionic charge transport. The total ionic and electronic transference number has been calculated from the plot using the equations 2 and 3 [33]. Figure 4(b) illustrates the graph of polarization current in relation to time for the PIn/CdS nanocomposite samples. The total current eventually reaches a nearly constant non-zero value over time. The ultimate residual current is mainly attributed to the presence of electrons and holes. The transference numbers calculated for the samples are ranging from 0.74 to 0.86. This indicates that charge transport in all samples is mainly facilitated by ions.

The values of DC conductivity and activation energy of the samples of PIn/CdS nanocomposites are listed in table 1.

Fig. 4(a) Temperature dependence of DC conductivity and (b) Plot of polarization current versus time for PIn/CdS (a) 5 wt%, (b) 10 wt%, (c) 15 wt%, (d) 20 wt% and (e) 25 wt% nanocomposites.

Table 1. DC conductivity and activation energy values of PIn/CdS nanocomposites.

3.4 AC conductivity and Impedance analysis

Figure 5(a) shows frequency-dependent AC conductivity plot for the optimized sample PIn/CdS (15 wt%) nanocomposite at different temperature. The figure 5 (a) shows two phase of conductivity. In low frequency region, conductivity values are almost constant, This indicate that conductivity is almost frequency-independent, indicating that ionic diffusion is

predominantly random and is less influenced by the activated hopping process. In higher frequency region, conductivity values show a marked increase with rising frequency, suggesting that there is a direct relationship between the applied frequency and conductivity, which intensifies sharply as frequency increases. The dielectric transition with accessible flexible polar bonds takes place due to rotation of bond at higher frequency. This will lead the formation of complex charge transfer which attribute to enhances the AC and DC electrical conductivity due to chemical change occurs in the polymer chain [34-36]. In other words, it is evident that AC conductivity depends upon both frequency and temperature and increases with increasing frequency and temperature. However, in the low frequency region, the influence of temperature is more prominent on AC conductivity, while at the high frequency side edge the values of AC conductivity display proximity. At lower frequencies, the applied electric field forces the charge carriers to drift over longer distances with increase in temperature, a tendency to retain almost constant values is recorded. When frequency is upturned, the mean displacement of the charge carriers is lowered down and the real part of conductivity, after reaching a certain critical frequency follows the hopping conduction mechanism [37]. The values of σ_{AC} for the samples of PIn/CdS nanocomposites at different frequency and temperature are as listed in table 2.

Fig. 5. (a) AC conductivity plot of $\text{Log}(\sigma)$ versus $\text{Log}(\omega)$, (b) Impedance plots (cole-cole) for PIn/CdS (15 wt%) nanocomposite at different temperature.

Table 2. AC electrical conductivity values for the samples of PIn/CdS (a) 5 wt%, (b) 10 wt%, (c) 15 wt%, (d) 20 wt% and (e) 25 wt% nanocomposites.

The complex impedance measurements are carried out to study the AC electrical conductivity and also the dielectric behavior of the obtained nanocomposites over a range of temperature and frequency. Figure 5(b) shows the impedance plot (Z' versus Z'') obtained for the optimized sample PIn/CdS (15 wt%) nanocomposite at different temperature. The observed impedance trend for the synthesized sample resembles a semicircle, reflecting a single conduction mechanism [38]. The center-point of the impedance curve is noted to be located beneath the real axis. This occurs due to the fact that, the relaxation of charges, whether polaron or free ions, in the obtained sample curve is characterized as non-Debye in nature [39]. The semicircle observed diminishes progressively as the temperature increases, indicating that the sample exhibits greater conductivity at elevated temperatures. The extrapolation of this plot revealed a depressed semicircle. This depressed semicircle in the high-frequency range is attributed to bulk relaxation phenomena [40].

The variation of Z' and Z'' with frequency for the optimized sample PIn/CdS (15 wt%) nanocomposite at different temperature is shown in figure 6. As illustrated in figure 6 (a), the values of Z' at lower frequencies remain same across all the values of the temperature. With an increase in frequency, the values of Z' decreases as temperature rises. This decrease in Z' implies that the AC conductivity of as-synthesized sample enhances with higher frequency and temperature. As the temperature increases, the release of space charge and the reduction in potential barrier of the obtained sample align the Z' values at higher frequency ranges for all values of temperature [41, 42]. Figure 6 (b) shows the plots of Z'' as a function of frequency for the optimized sample PIn/CdS (15 wt%) nanocomposite at different temperature. The nature of the plot distinctly illustrates the non-Debye-type peaks, which are linked to the existence of distributed relaxation times. In this graph, the frequencies associated with the peak maxima (f_z) are observed to shift towards the higher frequency region as the temperature rises. Based on the aforementioned discussion, it can be inferred that the relaxation peak is temperature-dependent according to the Arrhenius model. The

activation energy values obtained from both conductivity data and modulus analysis suggest that the ion transport follows a hopping mechanism [43].

Fig. 6. Plot of Z' and Z'' as a function of frequency for PIn/CdS (15 wt%) nanocomposite at different temperature.

3.6 Complex dielectric analysis

The variation of real (E') and imaginary (E'') part of the permittivity with applied frequency for PIn/CdS (15 wt%) nanocomposite are illustrated in Fig. 7(a) and 7(b), respectively. The values of E' and E'' were found to be strongly frequency dependent. The permittivity values are notably high at low frequencies, attributed to intense polarization effects, and they tend to reach a constant level as the frequency increases.

The substantial dispersion noted at lower frequencies is largely attributed to Maxwell-Wagner-Sillars polarizations, which result from the interactions at electrode interfaces, interfacial polarizations, and the alignment of dipoles. With the increase in applied frequency, the values of E' and E'' decreases for the studied composite, attributed to the disappearance of different polarization mechanisms at higher frequencies [44, 45].

Fig. 7. Variation of ϵ' and ϵ'' for PIn/CdS (15 wt%) nanocomposite at different temperature.

The dielectric loss factor $\tan(\delta) = \epsilon''/\epsilon'$ reflects the phase difference due to the loss of energy within the sample at a particular frequency [46]. The frequency dependence of $\tan(\delta)$ at different temperature for the optimized sample PIn/CdS (15 wt%) nanocomposite is shown in figure 8 (a). This plot demonstrates that in the lower frequency domain, the dielectric loss factor intensifies with increasing frequency and temperature. This factor attains a maximum

value at certain frequencies for different temperature levels. The frequency maxima shifted towards higher frequencies with an increase in temperature. The rise in $\tan(\delta)$ may be attributed to the active component rather than the reactive component. Within the raised frequency spectrum, an increase in frequency results in a reduction of the dielectric loss factor, attributed to the proportional rise of the reactive component [47]. The measured dielectric loss can be attributed to two primary factors. The foremost factor pertains to the thermally activated relaxation of Debye-type freely rotating dipoles, where thermal energy functions as the only excitation mechanism. The second factor involves electrical conditions that lead to electron-phonon interactions occurring at elevated temperatures [48].

The hopping frequencies ω_p were calculated by using specific formula [49].

$$A\omega_p^s = \sigma_{dc}(0)$$

The results show that the hopping frequency increases with increasing temperature and wt. % of CdS. The scaling of conductivity $\sigma(\omega)/\sigma_{dc}(0)$ at different temperatures was calculated according Almond-West conductivity formalism formula [50].

$$\sigma(\omega) = \sigma_{dc}(0) [1 + (\omega/\omega_p)^s]$$

The conductivity curves of the PIn/CdS nanocomposite were confirmed to be superimposed on a single master curve defined by an equation with values of the frequency exponent s , which are in the range of 0.32 to 0.68, as shown in Figure 8 (b).

Fig. 8. (a) Variation of $\tan(\delta)$ versus frequency, (b) Conductivity scaling data of PIn/CdS (15 wt%) nanocomposite at different temperature.

3.7 Modulus analysis

The electric modulus is an alternative approach to investigate the complex electrical response of materials, which compensate the electrode polarization effect. The figure 9 shows plot of M' and M'' versus $\log(\omega)$ for the optimized sample PIn/CdS (15 wt%) nanocomposite at different temperature. As illustrated in figure 9(a), the real component of the dielectric modulus (M') attains a stable maximum value at higher frequencies, while at lower frequencies it tends towards zero, suggesting that electrode polarization has a minimal impact [51]. The differences noted among these frequencies are ascribed to conductivity relaxation. As illustrated in figure 9(b), the curves exhibit a non-Lorentzian shape, with the peak frequency shifting towards higher frequencies as the temperature increases. This phenomenon may be attributed to the distribution of attempt frequencies that facilitate penetration through the potential barrier [52].

Fig. 9. Plot of M' and M'' versus $\log(\omega)$ for PIn/CdS (15 wt%) nanocomposite.

The relationship between imaginary part (M'') and real part (M') of dielectric modulus called as Argand diagram for the prepared samples. Figure 10 represents the plot of M' and M'' for the optimized sample PIn/CdS (15 wt%) nanocomposite at different temperature. The graph illustrates an almost semi-circular shape centered along the M' axes. This observation may result from the distribution of a specific physical characteristic within the sample obtained. This phenomenon is studied with the aid of an electronic circuit that comprises a constant phase element. The impedance associated with this element is described by equation (3) [53]. As a result, the presence of non-Debye type relaxations has been confirmed via the complex dielectric modulus formalism. The frequency-dependent conductivity $\sigma(\omega)$ adheres to the universal power law equation [54].

$$\sigma(\omega) = A\omega^s$$

The values of s at different temperatures were determined from the linear slope of $\log\sigma(\omega)$ versus $\log\omega$, as illustrated in Figure 10 (a). The value of s decreases with the increase of temperature as illustrated in Figure 10 (a) for different samples of PIn/CdS nanocomposites.

The maximum barrier height (R) was calculated by using equation [55]

$$R = \frac{6kT}{1 - S}$$

The maximum barrier height increases with increase in temperature and decreases with increase in wt. % of CdS whereas the optimized sample PIn/CdS (15 wt%) nanocomposite shows lowest values of maximum barrier height (R) as depicted in figure 10 (b).

Fig. 10. (a) Variation of frequency exponent (s) with temperature, (b) Variation of maximum barrier height (R) with temperature for PIn/CdS (a) 5 wt%, (b) 10 wt%, (c) 15 wt%, (d) 20 wt% and (e) 25 wt% nanocomposites..

4. Conclusions

To summarize, a series of PIn/CdS nanocomposites were synthesized in a simplistic way by implementing in situ oxidative polymerization technique. We have successfully integration CdS nanoparticles into a pure PIn matrix, as confirmed by XRD and FTIR analysis. The uniform distribution of CdS nanoparticles over polymeric matrix was confirmed by FESEM analysis. The dc conductivity follows a simple hopping type of charge conduction mechanism for all as-synthesized samples. The frequency dependent electrical properties such as AC conductivity, dielectric and impedance measurements were carried out in these composites. The variation of CdS content in PIn matrix has significantly contributed towards enhanced

electrical properties. The PIn/CdS composites used in the present investigation exhibit percolation dependent electrical properties. Among various as-synthesized samples, PIn/CdS (15 wt%) nanocomposite exhibits a low value of dielectric permittivity, dielectric loss, impedance and a high value of AC conductivity compared with other samples.

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Figure captions

Fig. 1. X-ray diffraction pattern for PIn/CdS (a) 5 wt%, (b) 10 wt%, (c) 15 wt%, (d) 20 wt% and (e) 25 wt% nanocomposites.

Fig. 2. FTIR spectra of PIn/CdS (a) 5 wt%, (b) 10 wt%, (c) 15 wt%, (d) 20 wt% and (e) 25 wt% nanocomposites.

Fig. 3. FE-SEM micrographs of PIn/CdS (a) 5 wt%, (b) 10 wt%, (c) 15 wt%, (d) 20 wt% and (e) 25 wt% nanocomposites.

Fig. 4. Temperature dependence of DC conductivity and Plot of polarization current versus time for PIn/CdS (a) 5 wt%, (b) 10 wt%, (c) 15 wt%, (d) 20 wt% and (e) 25 wt% nanocomposites.

Fig. 5. (a) AC conductivity plot of $\text{Log}(\sigma)$ versus $\text{Log}(\omega)$, (b) Impedance plots (cole–cole) for PIn/CdS (15 wt%) nanocomposite at different temperature.

Fig. 6. Plot of Z' and Z'' as a function of frequency for PIn/CdS (15 wt%) nanocomposite at different temperature.

Fig. 7. Variation of ε' and ε'' for PIn/CdS (15 wt%) nanocomposite at different temperature.

Fig. 8. (a) Variation of $\tan(\delta)$ versus frequency, (b) Conductivity scaling data of PIn/CdS (15 wt%) nanocomposite at different temperature.

Fig. 9. Plot of M' and M'' versus $\log(\omega)$ for PIn/CdS (15 wt%) nanocomposite.

Fig. 10. (a) Variation of frequency exponent (s) with temperature, (b) Variation of maximum barrier height (R) with temperature for PIn/CdS (a) 5 wt%, (b) 10 wt%, (c) 15 wt%, (d) 20 wt% and (e) 25 wt% nanocomposites.

Figures

Figure 1

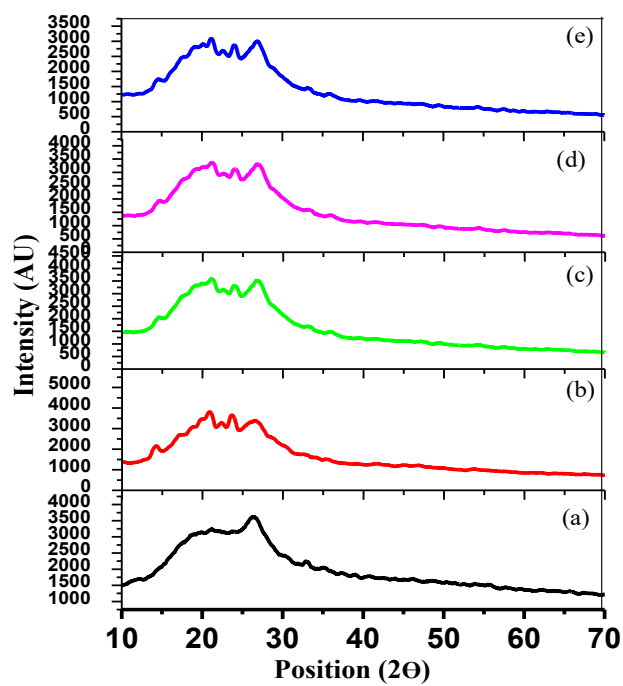


Figure 2

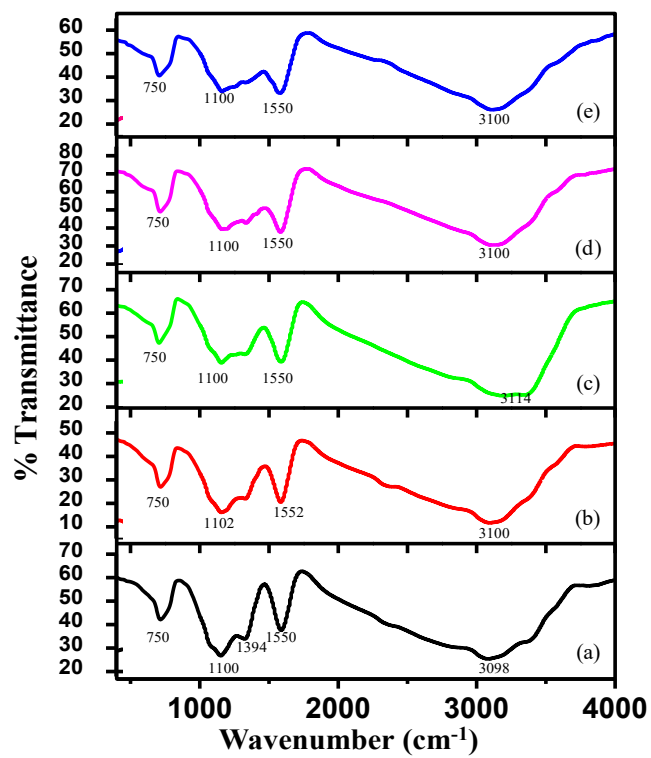


Figure 3

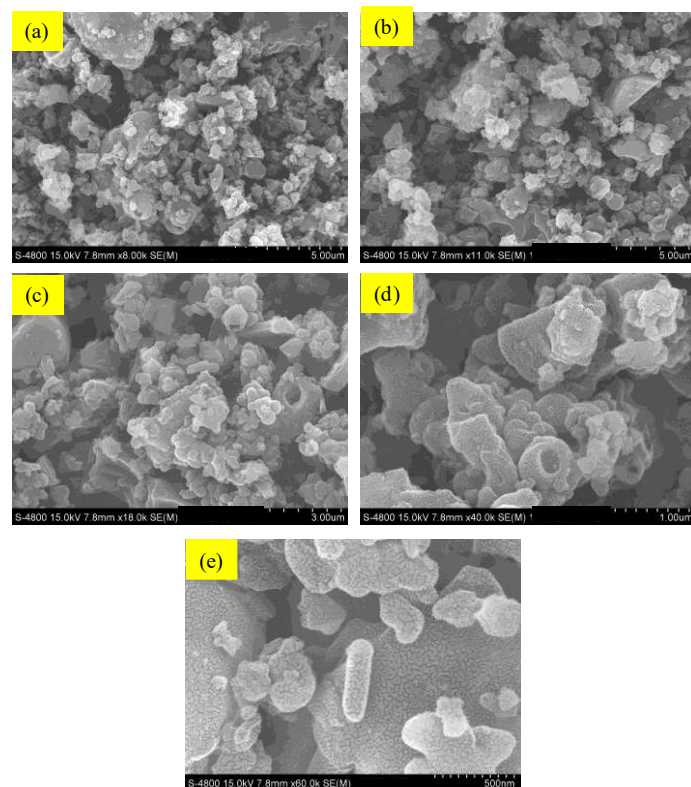


Figure 4

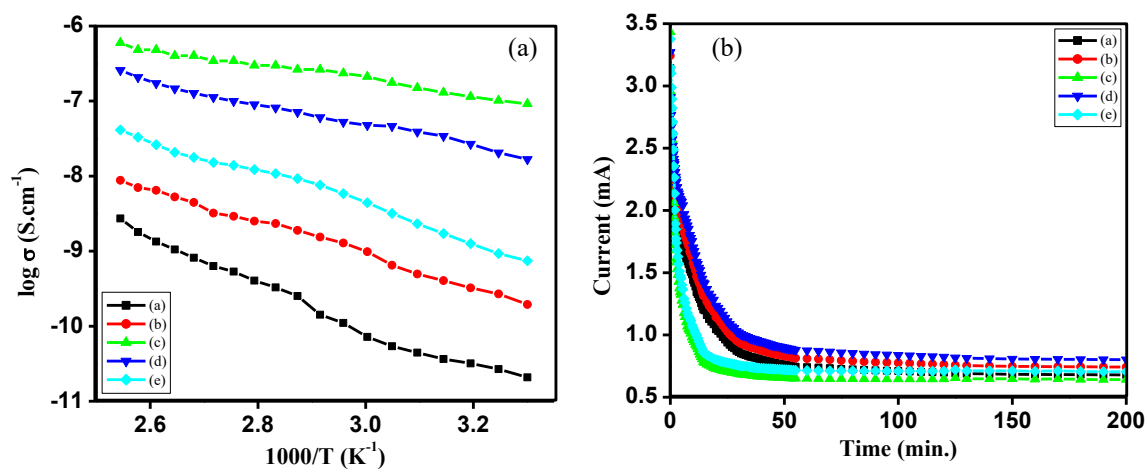


Figure 5

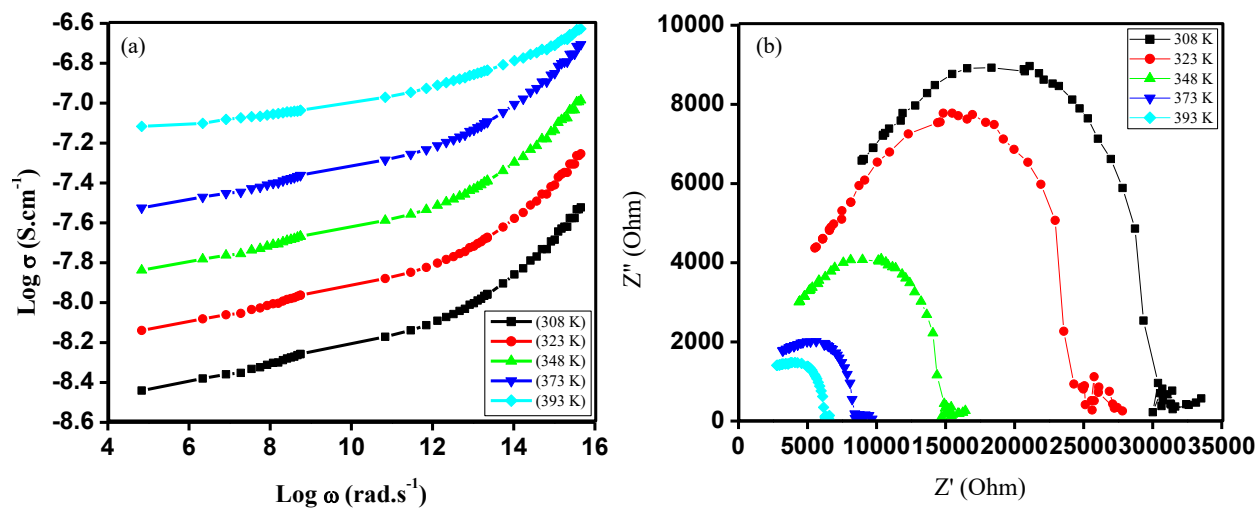


Figure 6

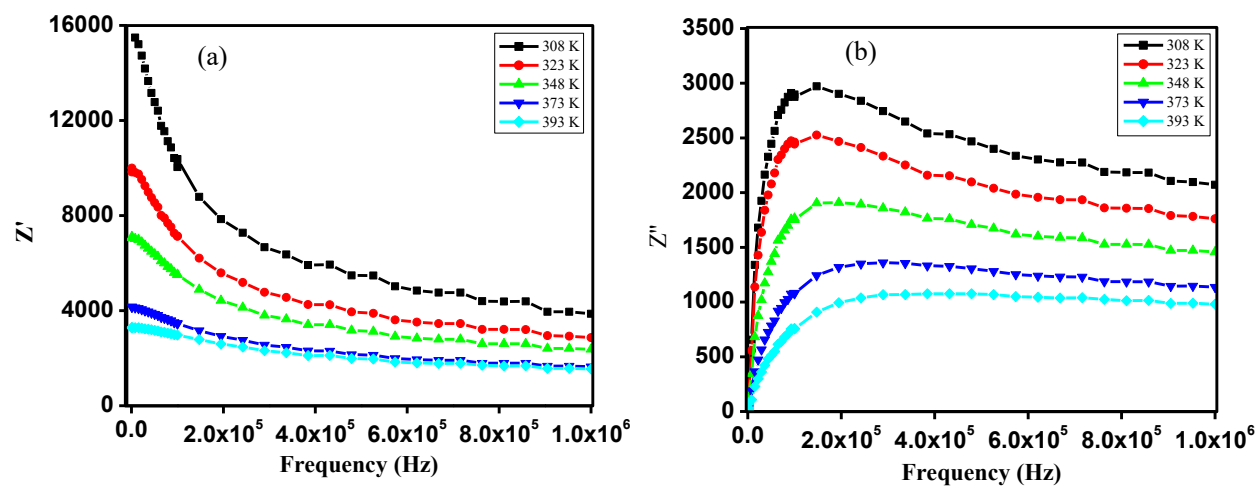


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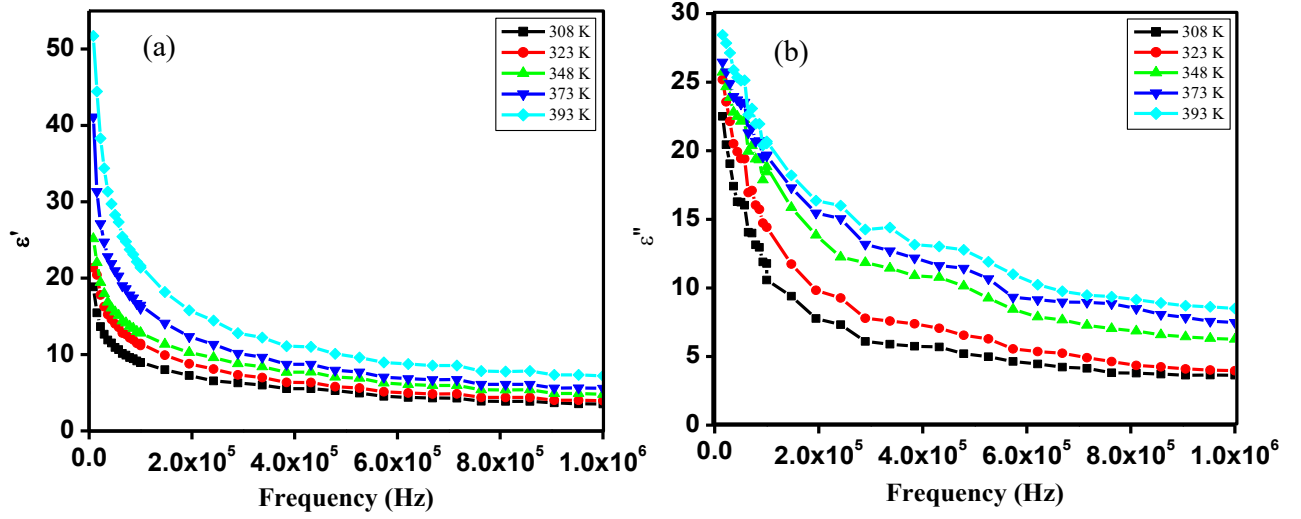


Figure 8

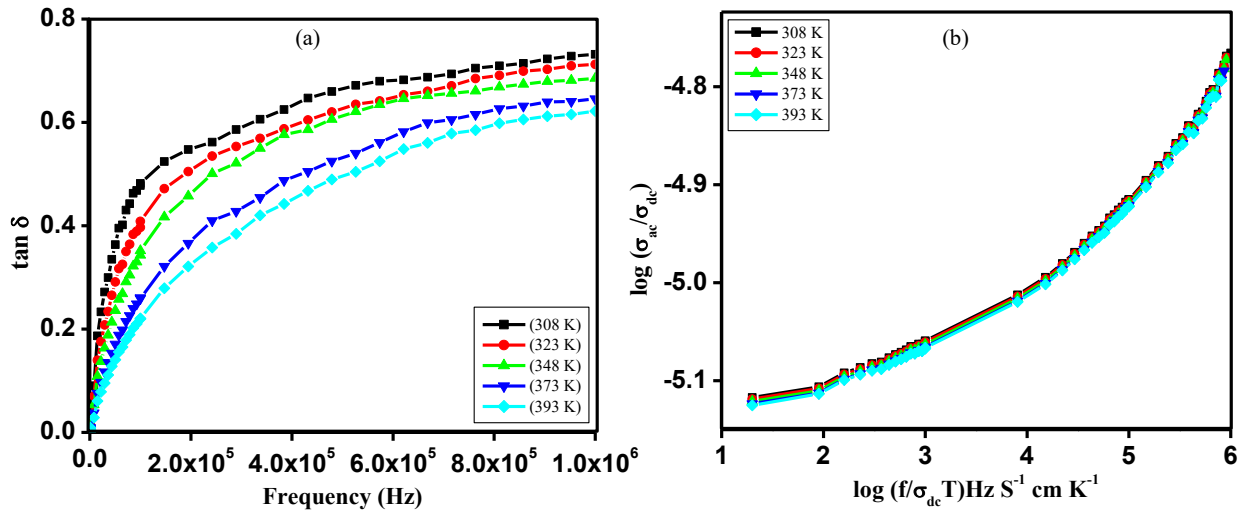


Figure 9

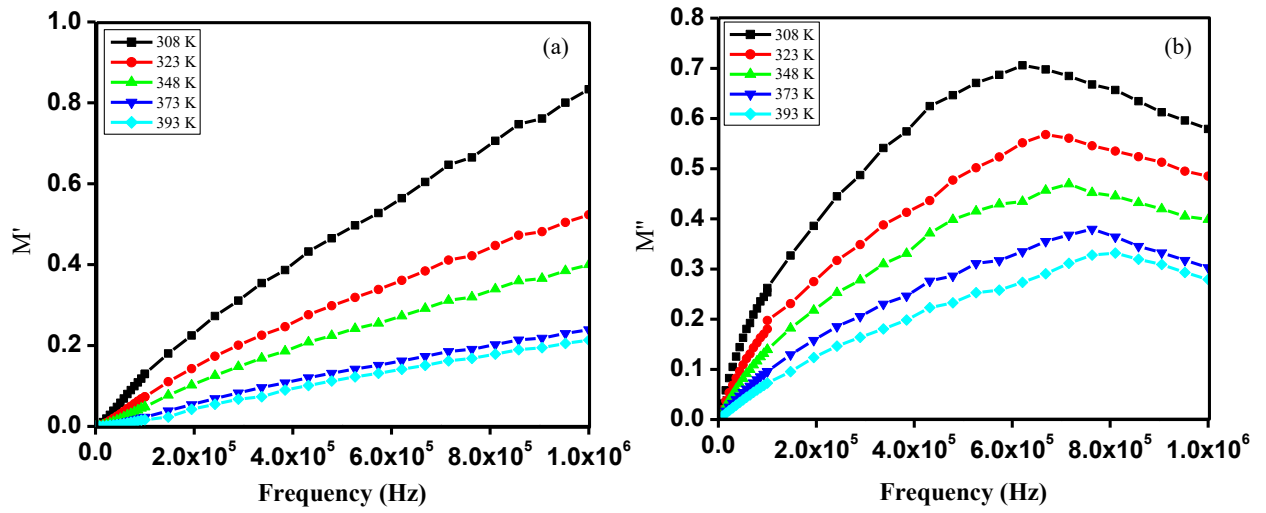


Figure 10

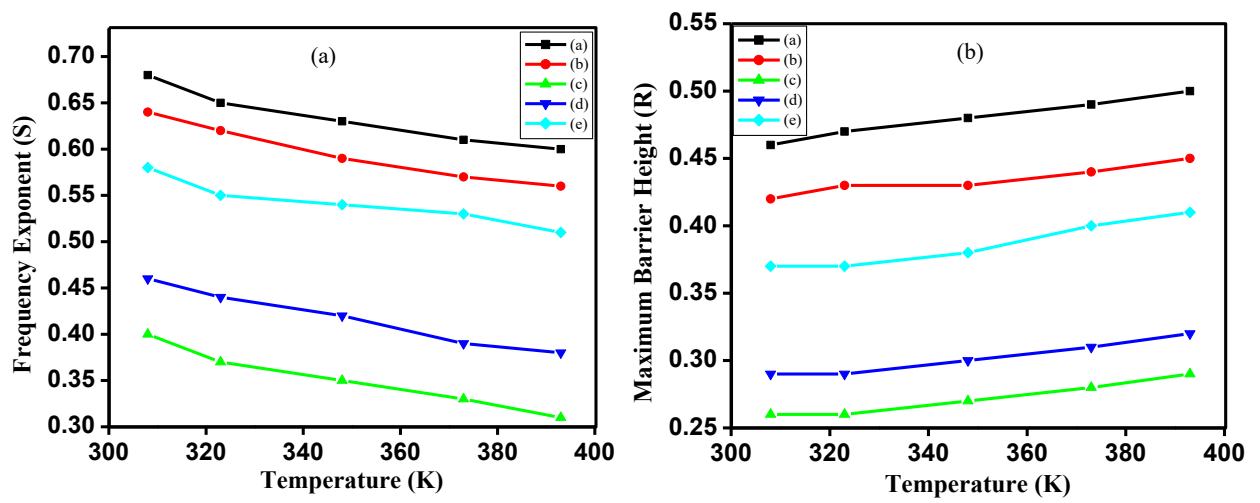


Table captions

Table 1. DC conductivity, activation energy for the samples of PIn/CdS nanocomposites.

Samples	$\sigma_{AC} \times 10^{-4} \text{ (Scm}^{-1}\text{) at 308 K}$	$\sigma_{AC} \times 10^{-3} \text{ (Scm}^{-1}\text{) at 373 K}$
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Table 2. AC electrical conductivity values for the samples of PIn/CdS nanocomposites at different frequency and temperature.

Table 1.

Samples wt%	Conductivity (S cm ⁻¹) at 303 K	Conductivity (S cm ⁻¹) at 393 K	Activation energy (eV)
PIn/CdS (5 wt%)	8.58×10^{-5}	3.46×10^{-4}	0.192
PIn/CdS (10 wt%)	1.02×10^{-4}	5.10×10^{-4}	0.115
PIn/CdS (15 wt%)	6.89×10^{-4}	1.87×10^{-3}	0.091
PIn/CdS (20 wt%)	3.51×10^{-4}	6.57×10^{-4}	0.136
PIn/CdS (25 wt%)	2.47×10^{-4}	5.25×10^{-4}	0.197

	1	100	500	1	1	100	500	1
	KHz	KHz	KHz	MHz	KHz	KHz	KHz	MHz
PIn/CdS (5 wt%)	0.622	0.155	0.236	0.273	0.598	0.779	1.45	1.77
PIn/CdS (10 wt%)	0.213	0.359	0.378	0.419	1.26	1.34	2.07	2.74
PIn/CdS (15 wt%)	0.719	0.883	0.911	0.979	3.241	3.37	3.48	3.69
PIn/CdS (20 wt%)	0.151	0.458	0.665	0.851	2.218	2.652	2.876	2.92
PIn/CdS (25 wt%)	0.11	0.202	0.381	0.462	1.28	1.3	1.65	2.18

Table 2.

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