CdSe Reinforced Polyaniline Nanocomposites as Superior Material for Future Applications as Gas Sensor and Diodes

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Abstract
In the present research CdSe quantum dots were reinforced into as-polymerized polyaniline (PANI) to yield polymer nanocomposites. The lattice constants of CdSe and CdSe in the nanocomposites were calculated to be 6.24 Å and 5.44 Å, respectively for cubic phase. The surface morphology of pure PANI showed agglomeration of spherical particles. The EDAX spectrum confirmed the presence of compositional elements of PANI and CdSe in the nanocomposite. Ohmic behavior of composite evidenced the possibility of its use in P-N junction diodes. The morphological observations revealed that DC conductivity of PANI/CdSe nanocomposites was higher than that of the PANI. The value of short circuit current also increased from 0.3 [A (cm)^{-2}] to 150 [A (cm)^{-2}]. The observed findings revealed that the present material has potential to fabricate protective devices, P-N junction diodes, electronic devices, and gas sensor devices.

1. Introduction

The research field of materials science has shown tremendous growth in the area of gas sensors owing to the development of new and newer smart gas sensing materials making intensive use of conducting polymer based nanocomposites [1, 2]. Conducting polymers are organic polymers that conduct electricity [3–7]. In recent years, the development of inorganic/polymer hybrid nanomaterials has received significant attention due to their wide spread applications. Polymeric nanocomposites consisting of organic polymer and inorganic nanoparticles represent a novel class of materials which exhibit new and improved properties which exhibit remarkable difference from their individual counter parts [8–11].

Among various electrically conducting polymers, polyaniline (PANI) has drawn great attention due to its low-cost synthesis, good electronic properties, charge storage capability and high stability etc [12–14]. The nanocomposites made up of PANI can be used as a gas sensing material in gas sensors and portable devices like junction diodes. Porous structure of PANI allows the gaseous molecules from the environment to penetrate and get trapped within this polymer. Surface area, size, and volume also affect their sensing behavior [15, 16]. Sen et al reviewed PANI nanocomposites based gas sensors and also discussed various gas sensors for sensing LPG, humidity, biomolecules, H_2S, and NH_3 using PANI based nanocomposites [17]. Kausik et al investigated polymer nanocomposites based gas sensors for environmental monitoring. They also reported detection of various gases such as hydrochloric acid (HCl), ammonia (NH_3), hydrogen disulfide (H_2S), carbon dioxide (CO_2), carbon monoxide (CO) and oxides of nitrogen (such as N_2O and NO_2) using different organic-inorganic hybrid nanocomposites [1]. Besides gas sensing, PANI based nanocomposites also find applications in electronics, rechargeable batteries, photovoltaic cells, LEDs, molecular sensors, electromagnetic shielding, gas-separation membranes, nonlinear optical materials, conducting polymer-based sensors, LED etc [15, 18].

In recent years photovoltaic devices, solar cells and junction diodes are made using p-type conducting polymers with the combination of n-type inorganic semiconductor nanoparticles [19]. Due to high electron mobility of inorganic semiconductors and charge transfer mechanism in conducting polymers, conducting polymer/inorganic nanocomposites heterojunction have been used for various purposes such as photovoltaic...
cells, actuators in electronic industry, solar cells, batteries, sensors, and super-capacitors [20–22]. CdSe is an inorganic semiconductor which has a direct band gap of 1.74 eV falling in the near infrared range [9]. These quantum dots (QDs) are frequently used as inorganic nano-sized materials due to their excellent physical, electronic, optical and structural properties. II-IV semiconductors, like CdSe QDs, are inorganic particles having size less than 10 nm. The particles of CdSe exhibit quantum confinement because of their smaller size than the Bohr radius. These nanoparticles result in an increased electrical conductance [22–24].

In the present study, native PANI and PANI/CdSe nanocomposites have been prepared by chemical oxidative polymerization method which is economically viable and gives large yield in less time. P-type PANI and n-type inorganic CdSe nanoparticles heterojunction shows high electron mobility and high charge transport property [21]. A judicious combination of polymer and inorganic materials may give rise to numerous nanocomposites which finds their industrial, biological and technological applications.

2. Experimental techniques

2.1. Materials

Cadmium acetate dihydrate ((CH₃COO)₂Cd.2H₂O) (98%), selenium (Se) metal powder (99%), thiourea (99%), aniline (ANI) (93.13%), ammonium persulphate ((NH₄)S₂O₈) (98%), hydrochloric acid (HCl) (35.37%), triethanolamine (TEA) (97%) and nitric acid (HNO₃) (71%) were procured from Thermo Fisher Scientific India Pvt. Ltd & Central Drug House, New Delhi, INDIA. The di-ionized water was used as solvent.

2.2. Polymerization of aniline

ANI monomer was polymerized by the chemical oxidative polymerization method. In this method, 2 mL of HCl was added to 20 mL of distilled water and 1 mL of aniline (ANI) was dissolved in this diluted HCl. The obtained monomer solution was stirred for 15 min and ultra-sonicated for 10 min to produce a clear solution. Thereafter, 0.5 M aqueous solution of ammonium persulphate (APS) was added drop wise to ANI solution with continuous stirring for polymerizing ANI. The resultant solution was further irradiated at 20 KHz frequency for ultrasonication. After completion of the reaction, the solution was kept at 4 °C for 6 h to complete polymerization. Finally, a viscous solution was obtained, which was filtered and washed several times with distilled water and acetone to remove impurities and un-reacted chemicals. The material so obtained was dark brown in color. After drying it at room temperature for 2 days, black color PANI was obtained. The % yield of the product was 90%–95% which reveals that this method is capable of producing larger yields of PANI. This was crushed to powder and stored in airtight glass tubes. The whole scheme of polymerization of ANI has been depicted in figure 1 as shown below:

2.2.1. Mechanism of polymerization of ANI

The mechanism of polymerization of ANI may be given as below,

\[ \text{S}^2\text{O}_8^{2-} \rightarrow 2\text{SO}_4^{-} \quad (R) \]

\[ \text{R} + \text{ANI} \rightarrow \text{R} - \text{ANI} \quad (2) \]

\[ \text{R} - \text{ANI} + n\text{ANI} \rightarrow R(\text{ANI})_{n+1} \quad (3) \]

\[ R(\text{ANI})_{m+1} + R(\text{ANI})_{m+1} \rightarrow R(\text{ANI})_{n+1} - R(\text{ANI})_{m+1} \quad (4) \]

In Equation (1) the persulphate ion dissociates to give two sulphate ion radicals (R') which react with the aniline molecule to give monomer radical (equation (2)). The as-produced monomer radical reacts with n
number of ANI molecules and produces ANI macroradicals (equation (3)). Such two macro radicals of ANI combine mutually and forms a macromolecule of ANI (equation (4)). Thus, these reactions result in the formation of PANI.

2.3. Synthesis of CdSe nanoparticles
CdSe nanoparticles were prepared by chemical co-precipitation method. CdSe nanoparticles were synthesized using Se metal as source. In this method, few drops of HNO$_3$ were poured over 4 g of Se metal with continuous mixing. The material so obtained was dissolved in 20 mL double distilled water. This solution was then refluxed at 90 °C for 13 h under constant stirring. The resulting solution was filtered and allowed to cool in dark. This was marked as solution ‘A’. Solution ‘B’ was prepared by mixing 2 M thiourea in 10 mL of distilled water by stirring the solution for 30 min. Solution ‘C’ was prepared by mixing 1.5 M cadmium acetate and 20 mL distilled water and stirred for 1 h. Thereafter, solution ‘B’ was added dropwise into the solution ‘C’ to get cadmium sulphide (CdS). Afterwards, the solution ‘A’, was slowly added into the CdS solution. On addition of Se solution into the CdS solution, the color of the resulting solution turns milky within 10 s. Soon after few seconds it turns yellow, after few minutes to orange, then red, and finally it turns dark red in color. 3 mL TEA was added to the final solution to control the nucleation reaction. The pH of the above solution was maintained at about 12 by adding the few drops of aqueous ammonia solution. The precipitate so obtained was separated out and centrifuged at 9000 rpm for 10 min. The process of centrifugation was repeated 4–5 times. The final precipitate so obtained contains CdSe nanoparticles which were isolated and washed several times with distilled water and finally with acetone. The nanoparticles were then dried in hot air oven at 200 °C for 6 h. The % yield of CdSe nanoparticles was 60%–70%. Finally it was crushed properly to get powdered CdSe(S) nanoparticles which were stored in airtight glass tubes. The synthesis of CdSe nanoparticles can been represented as depicted below (figure 2):

2.3.1. Mechanism of the formation of the CdSe Nanoparticles

\[
\text{Se(Metal)} + 2\text{HNO}_3 \rightarrow \text{H}_2\text{SeO}_3 + \text{NO}_2 + \text{NO} \tag{5}
\]

\[
\text{H}_2\text{SeO}_3 \rightarrow (\text{SeO}_3)^{2-} + 2\text{H}^+ \tag{6}
\]

\[
(\text{SeO}_3)^{2-} + 6\text{H}^+ + 6\text{e}^- \rightarrow \text{Se}^{2-} + 3\text{H}_2\text{O} \text{(due to moderate oxidizing nature)} \tag{7}
\]

\[
\text{Cd(\text{CH}_3\text{COO})}_2 \rightarrow \text{Cd}^{2+} + 2\text{CH}_3\text{COO}^- \tag{8}
\]

\[
\text{Cd}^{2+} + \text{Se}^{2-} \rightarrow \text{CdSe} \tag{9}
\]

Thus, these reactions ultimately lead to the formation of CdSe nanoparticles.

2.4. Synthesis of PANI/CdSe nanocomposites
PANI/CdSe polymer nanocomposites were successfully synthesized by chemical oxidative polymerization method. At first, ANI solution was prepared by injecting a definite volume of ANI into 20 mL HCl (10%). The obtained solution was continuously stirred for 30 min. Thereafter, it was ultra-sonicated at 20 KHz frequency and the ANI solution was added slowly into CdSe nanoparticles. The suspension of ANI and CdSe was stirred and ultra-sonicated to mix them together at 20 KHz frequency. 2 M of APS was dissolved in 40 mL of distilled
water and sonicated to prepare a solution of oxidizing agent. This solution was then added into ANI/CdSe suspension to polymerize it. The mixture was stirred vigorously for 24 h to form homogeneous matrix of CdSe nanoparticles and polyaniline. The polymerization was allowed to proceed for 12 h at 4 °C, afterwards dried at 60 °C for 48 h in an oven to get green color powder of PANI/CdSe nanocomposites. The % yield of the product was 90%–95%. This method produced larger yields of PANI/CdSe nanocomposites. The synthesis of PANI/CdSe nanocomposite is shown in figure 3 as depicted below:

The prepared conducting polymer (PANI) and PANI/CdSe nanocomposites were then characterized by different analytical techniques. The results so obtained show drastic changes in their structural, optical, morphological, electrical properties.

2.5. Characterization techniques
In order to characterize the as-prepared samples Fourier transform infrared spectroscopy (FTIR) spectra were recorded using Jasco 660 plus Japan in the wavenumber range 4000–450 cm⁻¹. X-ray diffraction (XRD) measurements were performed on Bruker D8-Discover system. Bruker D8-Discover system consisting of θ–θ goniometer along with 3 circle eulerian cradle was used for XRD measurements. Field emission scanning electron microscopy (FESEM) and energy dispersive x-ray analysis (EDAX) were performed using Carl Zeiss SIGMA 2–12 FESEM with EDAX λ-METER. DC conductivity measurements were performed using an electrical probe station (Make: Ecopia, Model: EPS500) and a source measure unit (Make: Keithley, Model: 2450).

3. Results and discussion
3.1. FTIR-based compositional analysis
FTIR spectra were recorded using Jasco 660 plus Japan using KBr pellet technique over the range of 4000–450 cm⁻¹. FTIR spectra of PANI, CdSe(S) and PANI/CdSe(S) nanocomposites are shown in figure 4. FTIR spectra of CdSe nanoparticles show the presence of spectral peaks corresponding to C–C, C–O, –C–H, O–H groups and strong peak of CdSe. The absorption peak at 3429 cm⁻¹ shows the presence of water molecules (OH bond), and the peak at 1627 cm⁻¹ corresponds to stretching vibrations of C=O=C. The absorption peaks at 1185 cm⁻¹ and 1110 cm⁻¹ suggest for the presence of C–O bond and 1400 cm⁻¹ show the bending vibrations of –C–H bond. The absorption peak at 1004 cm⁻¹ corresponds to the deformation of O–H bond due to the addition of CdSe. The strong absorption peak at 618 cm⁻¹ may be assigned to CdSe nanoparticles [6, 9]. The spectra of PANI show the presence of C–N stretching of benzoid and quinoid rings, –N–H stretching vibrations, para di-substituted aromatic rings, thus confirming the formation of polymer.

The FTIR spectra of PANI/CdSe show the spectral shifts in the peaks when PANI forms nanocomposites with CdSe. The absorption band at 3426 cm⁻¹ is shifted to 3474 cm⁻¹ which corresponds to N–H stretching vibrations. The absorption peak at 2923 cm⁻¹ is shifted to 2852 cm⁻¹ and may be assigned to N–H stretching vibrations. The absorption peak at 1578 cm⁻¹ also gets shifted to 1564 cm⁻¹ which corresponds to C–N stretching of quinoid rings. The absorption peaks at 1490 cm⁻¹ is shifted to a higher wave number of 1494 cm⁻¹. This peak represents the C–N stretching of benzoid rings. The absorption peaks at 1307 cm⁻¹ gets shifted to 1309 cm⁻¹ which corresponds to aromatic C–N stretching indicating secondary aromatic amine group. The absorption peak at 1112 cm⁻¹ is shifted
The main absorption peak of native PANI at 803 cm\(^{-1}\) shows the formation of para di-substituted aromatic rings indicating polymer formation. The main absorption peak of CdSe nanoparticles at 618 cm\(^{-1}\) is shifted to 743 cm\(^{-1}\) in CdSe PANI/CdSe nanocomposites. The shifting of these spectral peaks confirms the presence of CdSe nanoparticles in PANI matrix.

### 3.2. XRD based structural analysis

Most of the polymers are amorphous or non-crystalline in nature. But, it is in correct to say that polymers are 100% noncrystalline. The crystallinity of polymers varies in between the amorphous and semiconductor. This structural nature of polymers can be studied through XRD analysis. Both the crystalline and amorphous regions can be observed from XRD. The diffraction patterns of x-ray provide information about phase, average particle or crystallite size, lattice constant, etc.

XRD patterns of native PANI, native CdSe and PANI/CdSe nanocomposites are depicted in figure 5. The XRD spectra of native PANI show one broad peak at 26.11°, 2\(\theta\) thus suggesting for the amorphous nature of the material. XRD spectra of pure CdSe show four characteristic peaks at 2\(\theta\) values of 25\(^{\circ}\), 42\(^{\circ}\), 45\(^{\circ}\) and 49\(^{\circ}\), which are indexed as (111, 220, 103) and (311), respectively. Peaks (111, 220, and 311) are characteristic peaks of cubic phase, whereas the peak (103) refers to hexagonal phase. The prominent peaks are observed at 25\(^{\circ}\), 2\(\theta\). The spectra of CdSe show the presence of both cubic and hexagonal phases, but the prominent peak corresponds to cubic phase of CdSe nanoparticles.

The XRD spectra of PANI/CdSe show that all the peaks are shifted towards higher 2\(\theta\) values. The characteristic peaks at 2\(\theta\) values of 42\(^{\circ}\), 45\(^{\circ}\) and 49\(^{\circ}\) are shifted to 43\(^{\circ}\), 46\(^{\circ}\) and 52\(^{\circ}\), respectively. The prominent peak [111] of CdSe, which corresponds to cubic phase and prominent peak [110] of PANI (JCPDS card no. 53–1891) gets overlapped. Both cubic (111 and 311) and hexagonal (110 and 102) (JCPDS card no 65–2891, 77–2307) phases are present in PANI/CdSe(S) nanocomposites which might be due to the presence of

| CdSe(S) peaks (cm\(^{-1}\)) | PANI Peaks (cm\(^{-1}\)) | PANI/CdSe(S) peaks (cm\(^{-1}\)) | Bonding |
|-----------------------------|-------------------------|---------------------------------|---------|
| 618.80                      | 474.94                  | 743.15                          | Formation of Cd-S |
| 803.12                      | 882.06                  | Para di-substituted aromatic rings indicating polymer formation |
| 1112.16                     | 1185.74                 | C-H bonding                     |
| 1307                        | 1309.32                 | Aromatic C-N Stretching; secondary aromatic amine group |
| 1490.11                     | 1494.28                 | C-N stretching of benzenoid rings |
| 1578.70                     | 1564.76                 | C-N stretching of quinoid rings |
| 3426.19                     | 3474.31                 | N-H bonding; stretching vibrations |

Figure 4. FTIR spectra of pure PANI, pure CdSe and PANI/CdSe nanocomposites.

Table 1. Comparison of the absorption peaks of PANI, CdSe and PANI/CdSe nanocomposites.

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CdSe nanoparticles. The lattice constants of pure CdSe and CdSe in PANI/CdSe nanocomposites were calculated from XRD spectra was found to be 6.24 Å and 5.44 Å, for cubic phase. The lattice constant of CdSe in PANI/CdSe nanocomposite was found to be $a = 3$ Å and $c = 5.7$ Å for hexagonal phase. The calculated numerical values of lattice constants were found to be very close to the standard values (5.818 Å, JCPDS card no. 19–019 and 10–0454) [28–30].

The crystallite size of native PANI was found to be 1.09 nm while that of CdSe, calculated from XRD spectra, was found to be 4.5 nm. An increase of 1.35 nm in the crystallite size of PANI was observed when CdSe (S) is reinforced into the PANI matrix. The crystallite size of pure CdSe and PANI/CdSe nanocomposites were calculated by using Debye Scherer’s formula [31],

$$D = \frac{K\lambda}{\beta \cos \theta}$$

Where, $D$ is the crystallite size; $K$ is the Scherer’s constant (0.9); $\lambda$ is the wavelength (1.5406 Å) of x-ray used; $\theta$ is the Bragg’s angle and $\beta$ is the full width at half maximum (FWHM) measured in radian. The XRD analysis indicates that the amorphous content of native PANI decreases and semi crystalline nature occurs when CdSe is added into the PANI matrix.

### 3.3. Morphological study (FESEM)

Surface morphology of conducting polymer (PANI) and its nanocomposites can be analyzed with FESEM technique at high resolution. The magnification and resolution range make it easier to examine the surface of nanoparticles on conducting polymer matrix. Figures 6 and 7 show the surface morphologies of PANI and PANI/CdSe nanocomposite, respectively. The surface morphology of pure PANI is shown in figure 6. The agglomeration of PANI particles is also visible. The diameter of these particles is 1.5 μm. The volume and surface area of these particles are 1.76 μm$^3$ and 7.065 μm$^2$, respectively. It is also clear that irregular shaped pores are also present. Thus, such porous material offers lower conductivity in comparison to conducting materials and metals.

The basic principle involved in the sensing property of a sensor is that the gas to be sensed needs be adsorbed on the surface or it diffuses into the pores of the sensor material. If the pore size of the material (PANI) matches
with the atomic radii of the gas to be sensed, it can be used as a sensor for those gases. Yesappa and Raut also observed the similar morphology of PANI particles. Yesappa et al. observed grain like porous structure of PANI [15] whereas Raut et al. reported a fibrous structure of PANI [8].

The surface morphology of PANI/CdSe nanocomposites is also shown in figure 7. Surface particles of pure PANI are spherical and agglomerated in PANI/CdSe nanocomposites. Agglomerated and scattered CdSe QDs are clearly seen spread over the entire PANI matrix. In the nanocomposite, the number of pores is reduced in comparison to their number in pure PANI. The porous morphology in PANI/CdSe indicates that the electrical conductivity of composites material is higher that of the pure PANI which might be due to reduced number of pores. It is on expected lines as decreased number of pores in composite phase causes reduced scattering of charge carriers, thus causes lower resistance. This refers to increased conductivity in composite phase then the bulk. PANI/graphite oxide composite has also been reported as humidity sensing material [16]. Joshi and co-workers used PANI/CdSe nanocomposites as sensing material to sense liquefied petroleum gas [32].

3.4. Elemental composition study (EDAX)
EDAX spectra of PANI and PANI/CdSe nanocomposites provide information about elemental composition of conducting polymer (PANI) and semiconductor nanoparticles shown in figures 8(a) and (b), respectively. Secondary x-ray corresponding to each energy level of elements plotted in the form of EDAX spectra shows the presence of materials taken during the synthesis. EDAX spectra of pure PANI shown in figure 8(a), confirm the presence of elements C, N and Cl. The spectral peaks of carbon and nitrogen are due to PANI, whereas Cl is due to HCl which was used as a solvent for ANI monomer needed for the polymerization of ANI. The peak height clearly shows the formation of PANI. The nitrogen peaks obtained might be due to the ammonium persulfate ((NH₄)S₂O₈) which was used as a polymerization initiator.
The EDAX analysis of PANI/CdSe nanocomposites was also conducted and the results are shown in figure 8(b). EDAX spectra of PANI/CdSe nanocomposites confirm the presence of C, N, Se, S, Cl and Cd. In this spectrum peak height of carbon and nitrogen show the maximum percentage of PANI in nanocomposites. Moreover, since the PANI is the host material in the nanocomposite, the peaks of cadmium and selenium confirm the formation of CdSe in the PANI matrix, whereas the peak of sulfur is due to the thiourea which was used as a stabilizing agent during the synthesis of CdSe nanoparticles. The EDAX spectra of nanocomposites reveal that semiconductor nanoparticles are incorporated in the host PANI matrix.

3.5. Electrical measurements

3.5.1. Voltage-current characteristics of conducting polymer nanocomposites (PANI/CdSe)

When the voltage is applied across the given material, the current passing through it changes. For designing any electrical devices, V-I plot is an important electrical study. In the present study, the voltage refers to the voltage across a pallet of pure PANI and PANI/CdSe nanocomposites and the current is the flow of charge carriers through the pallet of PANI and PANI/CdSe nanocomposites.

Electrical measurements in native PANI and PANI/CdSe nanocomposites were done using two probe methods. Current-voltage characteristics of PANI bulk (pallet) at room temperature are shown in figure 9. In the forward bias, the voltage was varied from 0 to 5 V and in the reverse bias, it was varied from −5 to 0 V. The current was measured in both, forward and the reverse bias configurations. In forward bias, the current obtained with respect to applied voltage is almost symmetrical and show ohmic behavior. This ohmic behavior of current with applied voltage can be related to the conduction of free charge carriers ‘polarons and bipolarons’. This
conduction induces the formation of charge carriers with in the sample. Thus, this increase in charge carriers increases the current through the sample. In the reverse bias, it was observed that the value of the current also increases linearly when the voltage varies from 0 to −5 volt. Patidar et al [12] also reported the similar V-I plots of pure PANI.

The current–voltage characteristics of PANI/CdSe nanocomposite at room temperature are shown in figure 9. PANI is a p-type material and CdSe is an n-type material, the pallet of PANI/CdSe nanocomposites is expected to behave like P-N junction diode. In order to have forward bias, PANI is made positive with respect to CdSe. When voltage is applied in forward bias, the current rises due to the directional movement of polaron and electrons or holes. This causes the width of depletion layer to minimize at the interface. In the reverse bias, width of the depletion layer increases due to high barrier potential. Here the current is just because of minority charge carriers which produce small current across the junction [20, 33, 34]. The V-I curve of PANI/CdSe a nanocomposite resembles to that of P-N junction diode. Similar type of electrical conduction in CdS/polyaniline hetrojunction was reported by Patidar et al and Nempal et al [12, 35], respectively.

3.5.2 2DC Conductivity of PANI and PANI/CdSe Nanocomposites

The conductivity of conducting polymer originates from its own electronic structure. In π-conjugated polymer, charge carriers are delocalized making single and double bonds along the polymer chain. The conductivity increases due to the movement of delocalized polarons and bipolarons in π-conjugate system. DC conductivity of native PANI and its nanocomposites PANI/CdSe are shown in figure 10. The plot indicates that the DC conductivity increases rapidly with increasing potential (−5 to 0 volt) in reverse bias and in forward bias it also increases with the increasing voltage. In reverse bias, there is a decrease in conductivity as the potential is changed from −5 to 0 volt, in both PANI and PANI/CdSe nanocomposites. This might be due to the mutual interaction in between the charge carriers which enhances the resistivity. In forward bias, there is an increase in conductivity in both, PANI and its nanocomposites, which might be due to either charge transfer, inter and intra chains, hopping of charge carriers or movement of delocalized charge carriers. In composite, the value conductivity is more in comparison to native PANI. This is expected because of the presence of semiconductor CdSe. This distinctly reflects the diode like behavior of the pure PANI and its nanocomposites. In the case of pure PANI, the value of conductivity increases from $5 \times 10^{-6}$ to $3.2 \times 10^{-5}$ Scm$^{-1}$ in reverse bias. In forward bias its conductivity increases from $5 \times 10^{-6}$ to $2.2 \times 10^{-5}$ Scm$^{-1}$. In the reverse bias, composites show lower conductivity up to −2 V thereafter it increases as the voltage increased. In forward bias at all voltage the conductivity is higher in composite as compared to pure PANI.

In case of PANI/CdSe nanocomposites, the value of conductivity increases from $1 \times 10^{-3}$ to $1.18 \times 10^{-2}$ Scm$^{-1}$ in the reverse bias. In forward bias the conductivity increases from $1 \times 10^{-3}$ to $1.13 \times 10^{-2}$ Scm$^{-1}$. Bhaiawar et al have reported the variation in DC conductivity of PANI/CdS with temperature [27] and Kaneto et al have also reported electrical conductivity of polythiophene boro fluoride film [36].

The dc conductivity of pure PANI and its composites can also be calculated using the formula reported in the literature [37, 38]. It is observed that when CdSe is mixed with PANI matrix, the DC conductivity increases from $10^{-5}$ Scm$^{-1}$ to $10^{-4}$ Scm$^{-1}$. The conductivity and resistivity are related by the following relation,

$$\sigma = \frac{1}{\rho} \quad (11)$$

Where, $\rho$ is the resistivity of the pallet of PANI and PANI/CdSe nanocomposites. The resistivity $\rho$ is defined by using the formula [38] given below,
Where 'A' is the surface area and 'l' is the thickness of the pallet \([38]\). The enhanced DC conductivity of PANI/CdSe in comparison to that of the native PANI shows that the nanocomposites may be suitable for designing electronic devices, memory devices, light emitting diode, energy storage devices, different diodes etc Kamat and Chandraprabha have also reported the DC conductivity of polythiophene at different potentials \([33, 35, 39]\).

3.5.3 Current density analysis

In the present work the current density was analyzed for obtaining the short circuit current of pure PANI and PANI/CdSe nanocomposites. Short circuit current is an important parameter to be given emphasis before designing any protective electronic device. Sometimes, when the circuit breaks, fuses and fire in electronic power system cause major accidents. For designing protecting devices, measurement of short circuit current is required for safety concern. Short circuit current is the maximum current that any electronic device can sustain. The variation of current density for native PANI and PANI/CdSe nanocomposites in forward bias are shown in figure 11. In this plot the current density of the native PANI and its nanocomposites increases with voltage in both the forward and reverse bias. This increase in current density might be due to the interaction in between the polaron-polaron, polaron-bipolaron and polaron-free charge carriers, intra-inter chain charge transfer and intermolecular interaction, respectively.

In reverse bias also, the current density in the native PANI and PANI/CdSe nanocomposites increases which might be due to migration of polarons and free minority charge carriers of CdSe. The short circuit current \(I_{sc}\) increases from 0.3 [A(cm\(^{-2}\)] to 150 [A(cm\(^{-2}\)], when CdSe was reinforced into the PANI matrix. This may be due to the increased PANI/CdSe interface area and improved conduction path for charge extraction. Because of the enhancement in short circuit current \(I_{sc}\) in nanocomposites, they may be used for fabrication of energy storage devices and in various potential applications in electronic industries \([15, 19, 40–42]\). The electrical parameters such as current, DC conductivity, and short circuit current for pure PANI and PANI/CdSe nanocomposites have been evaluated and summarized in table 2 as shown below:

4. Conclusions

PANI and PANI/CdSe(S) nanocomposites are successfully synthesized by chemical oxidative polymerization method. The FTIR spectral analysis confirms the presence of CdSe in the polymer (PANI) matrix. The XRD spectra of native PANI indicate its amorphous nature. On the other hand, the nanocomposite is found to exhibit semi-crystalline nature. EDAX data show the elemental composition of CdSe and PANI in the nanocomposite. FESEM images show the surface morphology of PANI having surface area 7.06 \(\mu\text{m}^2\). The surface morphology of nanocomposites confirms that the conductivity of PANI/CdSe nanocomposites is higher than that of the native PANI. Surface morphology of pure PANI indicates the possibility of using this conducting polymer in making different electronic devices for gas sensors applications. These morphological results were confirmed by DC conductivity analysis. The DC conductivity of nanocomposites is \(10^{-2}\) S.cm\(^{-1}\) which is higher than that \(10^{-5}\) S.cm\(^{-1}\).
of pure PANI-I-V plot of PANI/CdSe nanocomposites shows ohmic behavior and it acts as a P-N junction diode. The value of short circuit current in the nanocomposites is 150 [A(cm⁻²)] which is higher than that of the native PANI (0.3 [A(cm⁻²)]). The observed results indicate that the nanocomposites, PANI/CdSe(S), behave like P-N junction diode and show its characteristics. The results obtained in the present work suggests for the possibility that the present material is more efficient to be used to fabricate protective devices, electronic devices, and in gas sensors applications. The most important application of the present research is the possibility of its use as P-N junction diode in the device applications.

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On the behalf of all authors, I have declared that there is no conflict of interest.

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