Chapter-3

PREPARATION OF ZnO-PEDOT:PSS NANOCOMPOSITE AND ITS APPLICATION IN ORGANIC LIGHT EMITTING DIODES

The application of organic light emitting diodes (OLEDs) in general purpose lighting and display devices requires good efficiency as well as stability. Efficiency of OLEDs can be improved by working on its internal efficiency ($\eta_{\text{int}}$) and light extraction efficiency ($\eta_{\text{out}}$). Internal efficiency depends upon several factors such as charge carrier injection, charge transport, charge balance factor, exciton formation efficiency and luminance efficiency. In OLEDs difference in work function of anode and hole transport layer (HTL) give rise to potential barrier for hole injection and hence results in high operating voltage and low internal efficiency. Therefore, to achieve high efficiency good hole injection is necessary. To increase hole injection in OLEDs various efforts have been made by many researchers, for example, use of hole injection layer (HIL), introduction of buffer layer between anode and HTL and doping of different materials in HTL etc. [118, 119].

Various types of hole injection materials based on organic and inorganic compounds and organic materials doped with inorganic structures have been reported. Brown et al used poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) as HIL in 1999 and
reported reduction of 0.5 V anode-EML interface potential barrier [120]. In year 2001 Zhou and group have co-evaporated tetrafluoro-tetracyanoquinodimethane (F4 – TCNQ) with 4, 4’,4’’-tris-N,N-diphenyl-amino)triphenylamine (TDATA) to use as HIL which resulted in drop of operating voltage of OLED [121]. Chen et al in 2004 have investigated influence of density and morphology of HIL on device performance by using four different materials, 4,4’,4’,4’’-tris{N,(3-methylphenyl)-N-phenylamino}-triphenylamine 4”-tris{N,(3-methylphenyl)-N-phenylamino}-triphenylamine) (m-MTDATA), 4,4’,4’, 4”-tris{N,-(2-naphthyl)-N-phenylamino}-triphenylamine4”-tris{N,-(2-naphthyl)-N-phenylamino}-triphenylamine, copper phthalocyanine (CuPC), and oxotitaniumphthalocyanine (OtiPC) as HIL [122]. However, due to lower glass transition temperature (Tg) of organic materials they show poor resistance to thermal changes which facilitates the causes of degradation of the device. Moreover, poor crystallinity results in higher turn on voltage due to accumulation of charge on anode-HTL interface. Some researchers have used HIL based on completely inorganic materials such as metal oxides (e.g. MoO3, RuO2 and V2O5 etc.) to improve the operating voltage and efficiency of the OLEDs [123-126]. Metal oxides are known to have poor thin film forming properties due to poor solubility in most of the solvents and high melting point. All these problems started the new era of hybrid material based HILs. These organic-inorganic based hybrid materials are becoming popular among the material scientists due to their combined properties of both components. In many reports hybrid HIL have been used by the researchers to improve stability, turn on voltage and efficiency of the OLEDs. Li et al have reported enhanced power efficiency by using hybrid HIL based on MoO3 doped CuPc [127]. Another group also studied the effect of doping of MoO3 in PEDOT:PSS on charge injection properties [128]. In 2005, better
luminescence efficiency and stability have been reported by Zhang et. al. using nanocomposite of zinc oxide (ZnO) nanorods and PEDOT:PSS polymer [129].

Hybrid nanocomposites comprising organic conducting polymers and semiconductor nanostructures inherit properties of both of its constituents. These polymer nanocomposites acquire their extraordinary electrical and mechanical properties due to interfacial third phase between nanostructure and polymer matrix [130]. PEDOT:PSS shows higher T$_g$ as compared to other known organic hole injecting materials. The polymers have good film forming properties with remarkable transparency up to 85% and conductivity approx ~10 Scm$^{-1}$ [131]. Hole injecting properties of PEDOT:PSS can further be improved by introducing inorganic semiconducting nanostructures in it. N. Semaltianos et al showed the better charge carrier transport/injection of PEDOT:PSS by incorporation of ZnO nanoparticles [132]. Among the inorganic semiconductors ZnO is known to have some interesting electrical and optical properties like band gap (3.37eV), large exciton binding energy (60 meV) and good chemical stability [133, 134]. A variety of techniques like spray pyrolysis, thermal decomposition, molecular beam epitaxy, chemical vapor deposition, laser ablation, electrodeposition and hydrothermal technique etc. have been widely used in the synthesis of nano materials and nanostructures [135-138]. Among all these techniques electrodeposition and hydrothermal methods are two important techniques used to fabricate thin films of ZnO nanorods [139-140].

Development of nanocomposite based on ZnO nanostructures and conjugated polymer PEDOT:PSS have become popular due to their remarkable properties among the researchers. A lot of work has been done to develop ZnO-PEDOT:PSS nanocomposites by
different methods such as electrodeposition, laser ablation etc. Still cluster formation of nanostructure is one of the major problems restricting their success in devices. Traditional method used to avoid aggregation is the use of ultrasonic vibration to break these clusters. Surfactants are widely used to make nanostructures well dispersed in polymer matrix. These methods results in degradation of polymer matrix or compromise with purity of the nanocomposite.

In the present chapter, preparation of different nanostructures of ZnO using two different methods has been explained. Also, structural and optical properties of ZnO nanostructures obtained by two different methods have been compared. Furthermore, a new approach to elude agglomeration of ZnO nanorods in PEDOT:PSS matrix has been discussed. In-situ synthesis of ZnO nanorods directly in polymer matrix can be selected which results in stable thin film of ZnO-PEDOT:PSS nanocomposite without any degradation of polymer. Devices based on hybrid HIL comprising uniformly distributed ZnO nanorods in polymer matrix were fabricated and characterized.

3.1 Methodology

3.1.1 Synthesis of Different Zinc Oxide Nanostructures

Different nanostructures of zinc oxide were obtained via simple chemical route and by electrodeposition using zinc nitrate hexahydrate ($\text{Zn(NO}_3\text{)}_2\cdot 6\text{H}_2\text{O}$) and hexamethylenetetramine (HMT) as starting materials.
(A) Deposition of Thin Film Of ZnO Nanorods by Electrodeposition

ZnO nanorods were prepared by electrodeposition using 0.1 M Zn(NO$_3$)$_2$.6H$_2$O and 0.1 M HMT as Zn$^{2+}$ and OH$^-$ ion sources, respectively. Equal amount of two solutions were mixed together and potential of 0.8 V was applied using ITO coated glass plate and Platinum as electrode. Temperature was maintained at 60$^\circ$C for deposition of zinc oxide Nanorods on ITO plates. Obtained milky layer was then cured at 100$^\circ$C (ZnO-1). The solution left after electrodeposition was drop casted on a cleaned glass plate and cured at same temperature of 100$^\circ$C (ZnO-2)

(B) Deposition of Thin Film of ZnO Nanorods by Two-Step Hydrothermal Method

This process involves two steps, deposition of seed layer followed by the growth of ZnO nanorods. For seed layer, 0.03M solution of potassium hydroxide (KOH) in methanol was added drop wise to 0.1M an alcoholic solution of zinc acetate (Zn(O$_2$CCH$_3$)$_2$) with continuous stirring until the solution became milky. This mixture of two solutions was kept at constant temperature of 50$^\circ$C for 2 hrs and spin coated 4-5 times on clean glass plates. These seeded plates were then baked in oven at 350$^\circ$C.

Obtained seeded layers were then used for the fabrication of thin film of ZnO by dipping them in aqueous solution of zinc nitrate (0.15M) and HMT (0.1M) for 5 hrs at a constant temperature of 60$^\circ$C. After deposition of ZnO, the samples were rinsed with distilled water to remove extra salt and cured at 100$^\circ$C (ZnO-3). Few drops of solution left after the reaction was then drop casted on glass substrates and then dried at 100$^\circ$C (ZnO-4).
Structural and optical properties of all the samples (ZnO-1 to ZnO-4) were compared using SEM, PL spectroscopy and UV-Vis spectroscopy. Sample ZnO-1 and ZnO-3 were boiled in propanol to check the stability. Table 3.1 gives the details of different samples deposited using various methods.

Table 3.1: ZnO samples and techniques used for their fabrication.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Fabrication technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnO-1</td>
<td>Electrodeposition</td>
</tr>
<tr>
<td>ZnO-2</td>
<td>Drop-casted from the reaction mixture of electrodeposition</td>
</tr>
<tr>
<td>ZnO-3</td>
<td>Two-step hydrothermal method</td>
</tr>
<tr>
<td>ZnO-4</td>
<td>Drop-casted from the reaction mixture of two-step</td>
</tr>
<tr>
<td></td>
<td>hydrothermal method</td>
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3.1.2 Fabrication of Thin Film of ZnO Nanorods-PEDOT:PSS Nanocomposite by Modified Two-Step Hydrothermal Method

Seeding layer was prepared by the same method as mentioned above. Fig 3.1 shows the schematic diagram for nanocomposite film fabrication. For the fabrication of nanocomposite thin films, precursors of (Zn(NO$_3$)$_2$.6H$_2$O) and HMT were taken in a molar ratio of 3:2 and mixed with 20 ml PEDOT:PSS. This solution was stirred to ensure proper mixing of precursors in PEDOT:PSS. Seeded plates were then dipped vertically and kept undisturbed at a temperature of 50°C for 5 hrs. Finally obtained layer was heated at 80°C for 2 hrs.
3.1.3 Device Fabrication

To study the charge injection properties of ZnO-PEDOT:PSS nanocomposite, it was used as HIL in OLEDs. For this, nanocomposite films were directly grown on pre-cleaned and etched ITO coated glass plates by the same method as explained above. For HTL and EML, α-NPD and Alq$_3$ thin films were fabricated by thermal evaporation, respectively. Finally the buffer layer of LiF and thin film of aluminum were thermally deposited as anode. A reference device was also fabricated using PEDOT:PSS thin film as HIL. Figure 3.2 (a) and (b) shows the device structure of reference and hybrid device, respectively. The configurations of reference and hybrid devices are as follows:
Reference device: Glass/ITO/PEDOT:PSS (HIL)/300 Å α-NPD (HTL)/350 Å Alq₃(EML)/5 Å LiF/1000 Å Al (anode)

Hybrid device: Glass/ITO/ZnO NR-PEDOT:PSS (HIL)/300 Å α-NPD (HTL)/350 Å Alq₃(EML)/5 Å LiF/1000 Å Al (anode)

Figure 3.2: Device structure of (a) reference and (b) hybrid device.
3.2 Results and Discussion

3.2.1 Synthesis of Nanostructures by Electrodeposition and Hydrothermal Method

ZnO Nanostructures were fabricated by two different methods as explained above. For both the methods same precursors were used. In the process of electrodeposition, ZnO formation takes place at the negative electrode. Whereas in hydrothermal synthesis, temperature act as a driving force for the formation of ZnO nanostructures and seeding layer act as nucleation site for ZnO nanorods. Zinc nitrate dissolves in water to give ions and thermal decomposition of HMT provides ions according to the chemical reaction given below:

\[
\text{Zn(NO}_3\text{)}_2(\text{aq}) \rightarrow \text{Zn}^{2+}(\text{aq}) + 2\text{NO}_3^-(\text{aq}) \quad (3.1)
\]

Thermal decomposition of HMT:

\[
\begin{align*}
\text{C}_6\text{H}_{12}\text{N}_4 + 6\text{H}_2\text{O} & \xrightarrow{\Delta} 6\text{HCHO} + 4\text{NH}_3 \\
\text{NH}_3 + \text{H}_2\text{O} & \rightarrow \text{NH}_4^+ + \text{OH}^- 
\end{align*}
\]  

(3.2)

These Zn\(^{2+}\) and OH\(^-\) ions then reacts to give zinc hydroxide (Zn(OH)\(_2\)) and finally dehydration of Zn(OH)\(_2\) results in ZnO nanostructures.

\[
\text{Zn}^{2+} + 2\text{OH}^- \rightarrow \text{Zn(OH)}_2 \quad (3.3)
\]

\[
\text{Zn(OH)}_2 \xrightarrow{\Delta} \text{ZnO} + \text{H}_2\text{O} \quad (3.4)
\]

(A) Morphological Studies

Morphological analyses of obtained nanostructures were done using scanning electron microscope. Figures 3.3 (a) and (b) show the SEM images of film of nanorods obtained at cathode by electrodeposition (ZnO-1) and the film prepared by drop-casting the left over
solution after the completion of reaction (ZnO)-2). Figures 3.3 (c) and (d) show SEM images of thin film fabricated by two-step hydrothermal method (ZnO-3) and the drop-casted ZnO film from the reaction mixture.

![SEM images of thin film of ZnO structures](image)

*Figure 3.3: SEM images of thin film of ZnO structures (a) ZnO-1, (b) ZnO-2, (c) ZnO-3 and (d) ZnO-4.*

Nanorods with average length = 3.5 μm and width = 500 nm can be seen from the SEM image of ZnO thin film fabricated by electrodeposition. Whereas in case of two-step hydrothermal route nanorods were found to be smaller with average length of 200 nm and diameter of 50 nm. It was observed that these nanorods were stuck into each other which resulted in covering all the area of the substrate. Also the surface of the films was comparatively uniform in case of hydrothermal route. SEM images of samples prepared
from the residue solution in both the cases of electrodeposition and hydrothermal method show micro clusters and nanoparticles, respectively. Morphology of the ZnO nanostructure is highly dependent on the reaction conditions therefore different methods result in different ZnO nanostructures [141-143]. Furthermore, stabilities of the ZnO films (ZnO-1 and ZnO-3) were tested by boiling them in propanol. Film obtained by hydrothermal method was found to be stable and adherent to the substrate due to the presence of seeding layer which strengthen the bond between substrate and ZnO nanorods layer.

(B) Optical Properties of ZnO Nanostructures

Transmittance measurements were done by UV-Vis spectrometer. As shown in fig 3.4, sample ZnO-3 shows approximately 80% transmittance in visible region (400-700 nm) as compared to the sample ZnO-1 for which transmittance was only up to 15%.

![Transmittance spectra of ZnO thin film deposited by electrodeposition (ZnO-1) and hydrothermal route (ZnO-3).](image)

Figure 3.4: Transmittance spectra of ZnO thin film deposited by electrodeposition (ZnO-1) and hydrothermal route (ZnO-3).
PL spectra of both the films were recorded by irradiating it by a wavelength of 320 nm using spectrofluorimeter. As shown in Fig 3.5, both the samples show the emission in ultraviolet region which is well-known for ZnO and reported in literature by researchers [144, 145]. PL spectrum for ZnO-3 was observed to be slightly red shifted of about 4 nm. This red shift may be attributed to the defects generated during the synthesis of ZnO.

![Graph showing PL spectra of ZnO thin film deposited by electrodeposition (ZnO-1) and hydrothermal route (ZnO-3).](image)

*Figure 3.5: PL spectra of ZnO thin film deposited by electrodeposition (ZnO-1) and hydrothermal route (ZnO-3).*

On comparing these two methods, it was observed that the film fabricated by the two-step hydrothermal route was more stable and transparent and this method is more suitable for fabrication of ZnO thin film for the device applications.
3.2.2 Fabrication of Thin Film of ZnO Nanorods-PEDOT:PSS Nanocomposite by Modified Two-Step Hydrothermal Method

In case of ZnO-PEDOT:PSS nanocomposite, in-situ synthesis of ZnO nanorods took place directly into the polymer matrix by using PEDOT:PSS bath mixed with precursors as reaction site. Same chemical reactions were followed as explained earlier for the formation of ZnO. Polymer thin film deposition and synthesis of ZnO nanostructure occurred at the same time. Mechanism of fabrication of nanocomposite thin film can be explained as follows.

As shown in Fig. 3.6, Zn$^{2+}$ and OH$^{-}$ ions present in solution get attracted towards the polar surface of seeding layer which act as nucleation site for the growth of ZnO nanorods [146]. Both the ions reacted at the surface of seeding layer to give ZnO nanorods according to the reaction discussed previously (equation 3.4).

![Figure 3.6: Schematic of the interaction between different components in the reaction mixture.](image_url)
Thiophene rings of PEDOT:PSS polymer chains present in reaction mixture also interact with ZnO seed layer and the generated ZnO nanorods which results in deposition of thin film of polymer and ZnO NR simultaneously.

(A) Structural Studies of Nanocomposite Thin Films

Before using nanocomposite thin film for the device application it was characterized by using X-ray diffraction and Scanning Electron Microscope (SEM). Fig. 3.7 shows the XRD pattern of nanocomposite film prepared by the method described above. The presence of a broad peak at around $2\theta = 18.6^\circ$ approves the presence of amorphous polymeric PEDOT:PSS [147, 148].

![X-ray pattern of ZnO-PEDOT:PSS nanocomposite thin film](image)

*Figure 3.7: X-ray pattern of ZnO-PEDOT:PSS nanocomposite thin film*

Diffraction pattern of nanocomposite film shows number of characteristic peaks which confirm the presence of wurtzite crystal structure of ZnO in nanocomposite thin film. Peaks
at $2\theta = 31.7^\circ, 34.4^\circ, 36.4^\circ, 47.74, 56.8^\circ, 63.1^\circ, 66.4^\circ, 68.1^\circ$ and $69.3^\circ$ are ascribed to (100), (002), (101), (102), (110), (103), (200), (112) and (201) plane of ZnO. All these peaks coincide with the standard JCPDS data no. 36-1451 and the XRD pattern of nanocomposite published in literature [149].

Scanning electron microscope (SEM) was used to analyse the surface morphology of the thin film of PEDOT:PSS-ZnO nanocomposite. Fig. 3.8 (a) shows the SEM image of thin film of pristine PEDOT:PSS polymer lacking any ZnO nanorods. Film for pure polymer was found to be uniform. Nanocomposite film was also compared with the thin film of ZnO nanorods fabricated by the two-step hydrothermal method (Fig 3.3 (c)). In comparison of these two, SEM image of nanocomposite (Fig. 3.8(b)) shows ZnO nanorods embedded in the PEDOT:PSS polymer matrix. The average size of the nanorods in nanocomposite thin film was around 400 nm. Roughness of the film was also found to be increased in comparison to uniform PEDOT:PSS film without ZnO NRs which was expected to improve the charge injection properties by increasing the interfacial surface area [150].

Figure 3.8: SEM images of thin films of (a) PEDOT:PSS (b) ZnO-PEDOT:PSS nanocomposite
(B) Stability Studies

Prior to the use of ZnO-PEDOT:PSS nanocomposite as HIL in device, the films were also analysed for their stability with humidity. As reported by various researchers, electrical properties of pristine PEDOT:PSS films can highly be affected in the presence of moisture. Humidity plays an important role in degradation of various films of OLED which result in deteriorated device performance. Fig. 6 illustrates the change in resistance of both the films as a function of humidity. It was found that the prepared nanocomposite film of ZnO-PEDOT:PSS is more stable in comparison of pristine PEDOT:PSS polymer film. Resistance of the polymer film was humidity dependent whereas the nanocomposite film was comparatively stable.

![Resistance versus humidity of PEDOT:PSS and ZnO-PEDOT:PSS nanocomposite film](image)

Fig 3.9: Resistance versus humidity of PEDOT:PSS and ZnO-PEDOT:PSS nanocomposite film
(C) Device Characterization

Fabricated ZnO-PEDOT:PSS nanocomposite thin films were tested in OLED as HIL. Current density versus voltage (J-V), luminance versus voltage (L-V) and electroluminescence (EL) measurements were done to characterize the device. J-V curves were plotted as shown in Fig. 3.10 to analyze the effect of ZnO NRs on charge injection properties of PEDOT:PSS. It can be seen that hybrid nanocomposite based HIL is useful in better charge injection in comparison to pure PEDOT:PSS. Operating voltage observed @100 cd/m² for device with ZnO-PEDOT:PSS nanocomposite was 5.9 V in comparison to reference device for which it was 6.3 V.

![Graph showing J-V curves for reference and hybrid devices.](image)

*Figure 3.10: Current density versus voltage characteristic of reference and hybrid device.*

Furthermore, Electroluminescence (EL) measurements were done for both reference and hybrid device with varying voltages as given in Fig. 3.11 (a) and (b), respectively. Emission
spectra for both devices show one emission peak at wavelength of 520 nm. It can be seen that EL at all the voltages were enhanced for nanocomposite based device. Maximum EL for hybrid device observed was 6801 whereas for controlled device only 2016 maximum EL was recorded. There was approximately 3.7 times enhancement in maximum EL at 9V. Similarly at 8V, approximately 4.6 times improvement in EL of hybrid device can be seen.

\[\text{Figure 3.11: Electroluminescence spectra of (a) reference and (b) hybrid device with varying voltages.}\]
Luminance versus voltage curve for reference and the hybrid devices are plotted in Fig. 3.12. It is clear that there is significant enhancement in luminance by incorporating ZnO in PEDOT:PSS at all the voltages. Luminance for hybrid device was 3610 cd/m² which is approximately 4.6 times of luminance (780 cd/m²) for controlled device at same voltage.

![Luminance versus voltage characteristic of reference and hybrid device.](image)

*Figure 3.12: Luminance versus voltage characteristic of reference and hybrid device.*

To evaluate the overall device performance current and power efficiencies were calculated according to the mathematical expressions given below. Current efficiency ($\gamma$) of a device depends upon luminance ($L$) and current density ($J$) [151].

$$\gamma = \frac{L}{J} \quad (3.5)$$

Where, $L = \text{luminance or brightness (cd/m}^2\text{)}$
\[ J = \text{current density (A/m}^2\text{)} \]

And power efficiency (\(\eta\)) can be calculated as [151],

\[ \eta = \frac{\pi}{V} \]  

(3.6)

Current efficiency and power efficiency versus voltage curves for both the devices are given in Fig. 3.13. Maximum current efficiency for the controlled and hybrid device was 4.9 cd/A and 11.68 cd/A, respectively. Improvement in current efficiency was approximately 2.8 times in case of device with hybrid HIL. Similarly, there is affluent improvement in power efficiency for hybrid device in comparison to reference device. Power efficiency was improved approximately by 2.4 times in the presence of ZnO nanorods. At 8V power efficiency for hybrid device was found to be 4.34 lm/W in comparison to 1.81 lm/W for reference device.

\[ \text{Figure 3.13: Current efficiency and power efficiency for reference and hybrid device.} \]
This improved device performance can be the outcome of number of factors including improved charge injection by the nanocomposite films and better light out coupling due to the presence of nanostructures. Device performances of two devices are concluded in table 3.2 given below:

<table>
<thead>
<tr>
<th></th>
<th>Operating Voltage @ 100 cd/m² (V)</th>
<th>Current density @ 100 cd/m² (A/m²) @8V</th>
<th>Luminance (cd/m²) @8V</th>
<th>Current efficiency (cd/A) @8V</th>
<th>Power efficiency (lm/W) @8V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference device</td>
<td>5.9 V</td>
<td>80</td>
<td>781</td>
<td>4.62</td>
<td>1.81</td>
</tr>
<tr>
<td>Hybrid device</td>
<td>6.3 V</td>
<td>44</td>
<td>3609</td>
<td>11.03</td>
<td>4.34</td>
</tr>
</tbody>
</table>

Mechanism of this significant enhancement can be explained as follows. PEDOT:PSS chains are known to have two type of conformational structure called coiled and linear/expended-coils. Also, benzoid and quinoid two type of resonating structures are suggested for PEDOT:PSS as shown in fig 3.14. In benzoid resonating structure, bond between α-carbons two monomer units show σ characteristics whereas in quinoid structure, α-carbons two monomer units are attached to each other by π-bonds.

![Benzoid Structure](image1.png)  ![Quinoid Structure](image2.png)

Figure 3.14: Chemical structure of benzoid and quinoid structure of PEDOT.
Fig 3.15 shows the two type of conformation of PEDOT:PSS chains. In coiled conformation planes of two thiophene rings are much more deviated to each other therefore electron cloud of two neighboring rings are departed from each other. Consequently, σ-bond is preferred and benzoid structure dominates resulting in discontinuous path for charge carriers. In comparison to coiled conformation, linear PEDOT:PSS chains choose quinoid structure due to the positioning in same plane. Orientation in same plane results in delocalized electron density which leads to continuous path for charge carriers. In case of ZnO-PEDOT:PSS polymer nanocomposite, ZnO interacts with thiophene ring of PEDOT:PSS. This type of interaction is well known for this type of nanocomposites and also reported by numerous researchers [129, 152]. Due to this interaction between ZnO nanorods and thiophene rings PEDOT:PSS chains attained linear conformation which results in continuous path for charge carriers and improves the charge injection properties.

Figure 3.15: Illustration of coiled and linear confirmation of PEDOT:PSS.
Furthermore, due to the roughness of ZnO-PEDOT:PSS nanocomposite film interfacial contact area increases between HIL and hole transport layer (HTL) of α-NPD which results in enhanced charge injection density. Again one of the major factor that influence the better device performance is better light out coupling due to the presence of ZnO nanostructures in nanocomposite film. Light out coupling enhancement by nanostructures is very common phenomenon reported by many researchers [153-155]. All these aspects collectively results in improved performance of hybrid device based on HIL comprising of ZnO nanorods uniformly embedded in PEDOT:PSS matrix.

3.3 Conclusion

Thin films of ZnO-PEDOT:PSS nanocomposite with well dispersed ZnO nanorods and improved stability were successfully fabricated. ZnO nanorods were directly synthesized in PEDOT:PSS matrix by a simple technique including in-situ synthesis of ZnO nanorods. Nanocomposite films were also tested as hole injection layer in Alq3 based organic light emitting. Conformation change of PEDOT:PSS due to the interaction between ZnO and thiophene ring resulted in improved charge injection in OLED devices is enhanced. Device performance with hybrid HIL was improved in terms of turn on voltage, brightness and efficiency. Luminance was improved by 4.5 times for device with ZnO-PEDOT:PSS composite based HIL. There was an improvement of 2.4 times and 2.8 times in power and current efficiency, respectively, in case of hybrid HIL based OLED as compared to the reference device with only PEDOT:PSS as HIL layer.