American Journal of Polymer Science & Engineering
http://www.ivyunion.org/index.php/ajpse/

Review Article

Review on Structure, Properties and Appliance of Essential Conjugated Polymers

Ayesha Kausar[a,*]

[a] *Nanoscience and Technology Department, National Centre For Physics, Islamabad, Pakistan*

Abstract

One of the important classes of polymers is conductive polymers. These polymers mainly comprise of aromatic and aliphatic backbone. Polyaniline is one of most important type of conjugated polymers due to its excellent conductivity and other essential physical properties. Consequently, main focus of this review is structure, properties and application of technically important conjugated polymer. The conducting polymers such as polyaniline, polythiophene, polypyrrole, polyacetylene and pol(*p*-phenylene) have been discussed. Conductive polymer offers significant conductivity values similar to that of metal and semiconductors. Finally, the uses of polymers in different technical fields such as sensors, rechargeable batteries, photovoltaics, and fuel cells have been conversed.

Keywords: Conducting polymer; Polyaniline; Conductivity; Sensor

Received: September 14, 2016; **Accepted**: October 8, 2016; **Published**: October 16, 2016
Competing Interests: The authors have declared that no competing interests exist.

***Correspondence to:** Ayesha Kausar, Nanoscience and Technology Department, National Centre For Physics, Quaid-i-Azam University Campus, Islamabad, Pakistan
E-mail: asheesgreat@yahoo.com

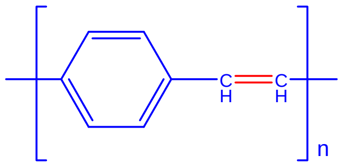
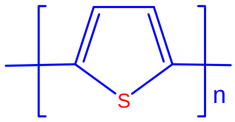
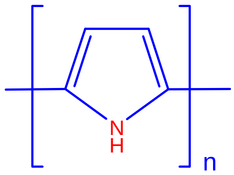
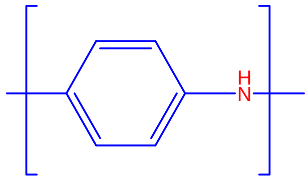
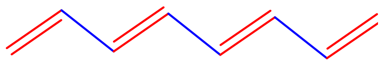
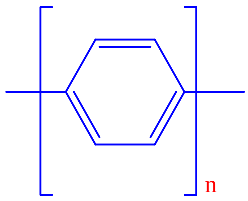
1. Introduction

During the past decade, nanotechnology has become an active field of research because of tremendous potential for a variety of applications [1]. There are mainly four types of nanostructures i.e. zero-, one-, two- and three-dimensional structures. Among them, one-dimensional (1D-) nanostructures have been the focus owing to their unique physical, chemical, and electronic properties in nanoscale systems. The second characteristic of 1D-nanostructure is its device function, which can be exploited as device elements in many kinds of nano-devices [2, 3]. Conducting polymer discovery is remarkable in its completion as possible substitute for semiconductors and metallic conductors. The struggle for having tailor-made polymer with reference to it's mechanical, electrical, thermal, and optical features have been followed by numerous research groups [4]. Consequently, recent understanding and state of art of conducting polymer (based on aromatic system) would be highly necessary and thus inspired dedicated researchers in this field [5]. The progress in conducting polymers with conductivity equal to that of metals and semiconductors are shown in Table 1. Conductive polymers related to polyaromatics or polyenes mainly polythiophene, polythiophene, polypyrrole, poly(p-phenylene), poly (phenylene vinylene) class have been widely studied [6]. Polyaniline is of main interest among family of conjugated polymers due to its outstanding conduction mechanism and good environmental stability in the presence of water and oxygen. Polyaniline is also one of most conductive polymer. The decade of 70s witnessed evolution of various conductive polymers. However, these polymers show poor solubility in most of common solvent. They also have low thermos-plasticity, which reduced processing of conductive polymers research for preparation of soluble forms of conductive polymer [7].

2. Conjugated Polymer

Conducting polymer discovery and doping capability over full range of insulator to metals resulted in generation of new category of material with combined electrical, optical, and electronic properties, and mechanical features [8]. Furthermore, the capability to control electronegativity and electronic features by molecular design has made conducting polymer considerable. Conductive polymers are plastics that have ability to conduct electricity just as semiconductors and metals [9]. The prolonged π-orbital of conjugated polymer result in quasi-one dimensional electronic structure with related new non-linear excitations (polarons, solitons, bipolarons). The excellent combination of electrical, electronic, mechanical and electrochemical features of these semiconductors and synthetic metals have made them excellent candidates. The capability to control their features with rational chemical synthesis have made conjugated polymers a potential field of interdisciplinary research [10]. A new class of materials which demonstrate highly reversible redox behavior and strange deal of properties of metal and plastics are conductive polymers. Conducting polymers was first synthesized in 1960s as they are the most current invention in polymers. Conducting polymers have both optical and electrical properties related to those of metals and inorganic semiconductors. The potential benefit of conductive polymers with effective relevance in number of growing technologies (telecommunication, biomolecular electronics, display devices, and electrochemical storage systems) have been considered [11]. Polymers with freely held electrons in their backbones are frequently recognized as conducting polymers. Each atom beside the backbone has π bond, which is much weaker than σ bonds holding atoms in polymer chain together. First formed several decades ago, there are more than 25 conductive polymers known today [12].

Table 1 Conductivity of some conjugated polymer.

Conducting polymer	Conductivity (S/cm)	Structural formula
Poly(phenylene vinylene)	1	
Polythiophene	200	
Polypyrrole	600	
Polyaniline	10	
Polyacetylene	5	
Poly(*p*-henylene)	500	

3. Structure and Properties of Conjugated Polymer

The superior values of the electrical conductivity achieved in such organic polymers have led to the name ‘synthetic metals’. Various applications of conducting polymers comprising biosensing devices and analytical chemistry have been developed [13]. Conducting polymers exhibit π-electron backbone which have strange electronic features such as low energy optical transitions, electrical conductivity, low ionization potential, and high electron affinity. This comprehensive π-conjugated system of the conducting polymers has irregular single and double bonds all along the polymer chain and their conductivities and structures [14]. In 1977, the discovery that polyacetylene could be easily oxidized (by electron acceptors) or reduced (by donors) was a breakthrough in the area of conductive polymers. Nowadays, conductive polymers are promising basis of number of new technologies comprising plastic electronics. These polymers are important in determining device performance [15]. The surface modification of conventional electrodes provide new and fascinating features. They are useful in membrane separations, electro catalysis and chromatography. They also generate new technological potentials in design of biochemical and chemical sensors [16]. Polyaniline (PANI) is an essential member in the family of inherently conductive polymers (ICPs). PANI has been considered due to ease of synthesis, good environmental stability, and comparatively good processability. Due to its electronic, chemical and optical features, it has gained enormous interest. Thus it signify well-organized class of conductive polymers in materials science [17]. The electrochemical oxidation of aromatic benzenoid, heterocyclic, or non-benzenoid molecules habitually lead to the development of electrically conducting organic polymer film at the electrode surface. These films usually have excellent electrical contact and adhesion to electrode surface. Thin films, when supported by an electrode surface, can be electrochemically cycled between the conducting state, oxidized, neutral, and insulating state. Thicker films can be produced in the conducting state oxidized, and can be peeled off from the surface of electrode to give free-standing, electrically conducting films [18]. Because these films are in the oxidized state, they signify polymeric cations, whereas their whole charge balance is obtained by integration of oppose anions from electroplating solution [19]. According to this approach, conducting films have now been formed from broad range of organic molecules. These comprise heterocyclic compounds such as thiophene, pyrrole, indole, furan, carbazole, and thianaphthene. Conducting polymeric films have also been generated from polycyclic nonbenzenoid and benzenoid hydrocarbons such as fluorene, azulene, fluoranthene, pyrene, and tri-phenylene [20].

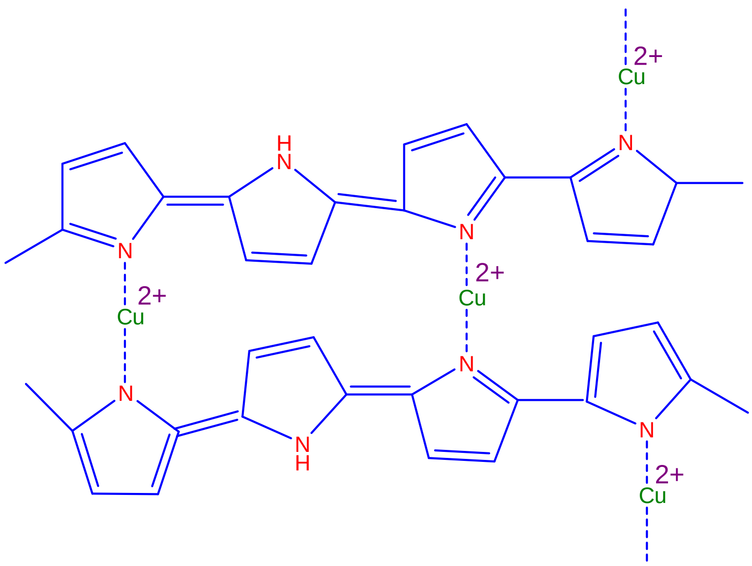


Fig. 1 Ion exchange mechanism by coordination chemistry.

3.1. Polyaniline

Polyaniline (PANI) is one of most extensively studied conducting polymers due to its strong bimolecular interaction, superficial synthesis, existing electrochemical, electrical and optical features. Due to outstanding tuneable conductivity either by charge transfer doping and protonation, it holds great potential in comparison to other conducting polymers [21]. Due to its low synthetic cost, and outstanding thermal and environmental stability, it is most extensively studied conducting polymer.

There are three main forms of PANI, namely the fully oxidized (pernigraniline) state, fully reduce (leucoemeraldine) and the more conducting emeraldine base (half oxidized). Thus by doping to form emeraldine salt, emeraldine is most conductive form. Polyaniline can be easily synthesized either electrochemically or chemically from acidic aqueous solutions. The chemical route has great importance because it is sensible route for PANI mass production. Thus, the most common synthesis route is the oxidative polymerization with ammonium peroxodisulfate as oxidant [22]. Polyaniline is ranked among the most studied conducting polymers. Besides its electrical features, catalytic, optical, electrochemical, and surface features have been considered. However, in the typical approaches, PANI is synthesized from aniline, oxidant, and small molecule. It has very poor solubility in common solvents such as ethanol, methanol, and acetone. PANI nanostructures with large interfacial areas between PANI and their surroundings can have an enhanced dispersibility in the hosting matrixes [23]. Ion exchange mechanism in polyaniline is shown in Fig. 1.

3.2. Polythiophene

Polythiophene (PTh) is of growing interest among conducting polyheterocycles prepared from five-membered heterocycles because of excellent stability to moisture and oxygen [24]. Polythiphene has been synthesized by both chemical and electrical polymerizations. By electrochemical polymerization route, highly conductive PTh with conductivity ranges between 10-100 S/cm, have been achieved. Although, the chemical polymerization route generates less conductive black powder. It has significances mainly simple procedure, short reaction time, and easy processing. The most extensively used chemical oxidative polymerization is Grignard coupling of 2,2' -diiodothiophene, 2,2' -dibromothiophene or three methyl thiophene in presence of initiator and consequent doping of obtained polymer with suitable oxidant [25]. The polymer conductivities thus achieved ranges between 0.1-1 S/cm. A one step chemical polymerization and thiophene doping have been achieved by employing AsF_5 as oxidants. The conductivity of the polymer was 2×10^{-2} S/cm which is three order of magnitude smaller than those of electrochemically prepared PTh. The reaction of 2,2' -bithiophene (BT) with copper percholate or iron percholate give both doping and oxidative polymerization [26]. The obtained PTh have outstanding conductivity in the range of 3-17 S/cm.

3.3. Polypyrrole

One of the most widely used polymer is conductive polymeric view of bioanalytical sensors. Due to easy synthesis and processing of polypyrrole (PPy), good conductivity and better cyto-compatibility are seen. For biomedical applications, doped PPy have been explored for biomedical applications mainly biosensors, and tissue engineering applications. PPy can be synthesized by electrochemical or chemical method by varying advantages. The electrical conductivity of PPy can be improved from 10^{-12} to ~10^{2} S/cm depending on extent and type of doping [27]. The electrons in monomers are attracted to nuclei in neighboring monomers to generate mobility between the chain and along chain, generating conductivity in PPy. Its conductivity can be enhanced with doping ratio and percentage vary with preparation route and dopant [28, 29].

3.4. Polyacetylene

The simplest conjugated polymer is polyacetylene. It comprises weakly coupled chain of CH monomers forming pseudo-one-dimensional lattice. Three out of four valence electrons are in sp^2

hybridized orbitals. Two a-type bond forms 1-d lattice while with hydrogen side group forms three a-bond. The bond angle of 120 ° between the three electrons can be fulfilled through two possible arrangements of carbons trans –$(CH)_x$ and cis –$(CH)_x$ with two and four CH monomers per unit cell (Fig. 2). The remaining valence electrons in either isomer have symmetry of 2 pz orbital with charge density of lobes perpendicular to planes defined by other three. In terms of energy band description, the a-bonds form low lying completely filled bands, while π bond led to partially filled energy band structure responsible for significant electronic features. The bond length of all are equal.

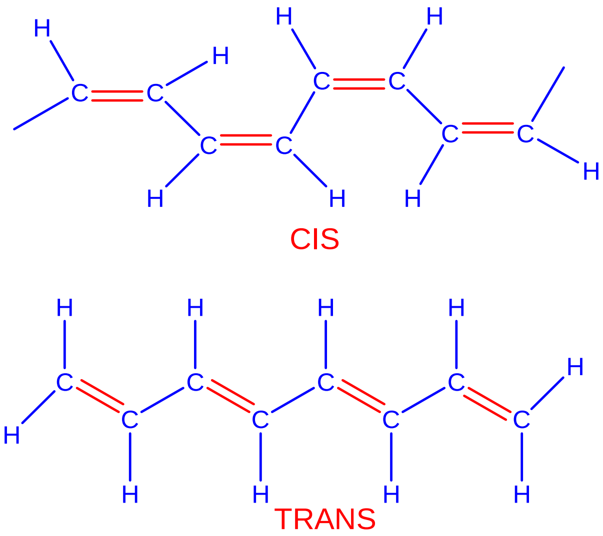


Fig. 2 Polymer chain structure of cis and trans -(CH)x.

Thus quasi-1-d metal is obtained from pure trans –$(CH)_x$ with half-filled band. Such system is unstable with reference to dimerization alteration (Peirls instability) [30, 31]. The movement of neighboring CH group occur towards each other forming alternatively long (for single) and short bond (for double). Thus, energy of system is lowering. Generally, one could interchange single and double bond by symmetry disagreement without effecting in energy. Thus there are two lowest energy states, L and R having two perspective bonding structures. This two-fold degeneracy lead to presence of nonlinear topological excitation bond-alternation domain walls or solitons, which appear to be responsible for several remarkable properties of (CH)x [32].

3.5. Poly(*p*-phenylene vinylene)

The first conjugated polymer displayed to exhibit electrolumiscence is poly(*p*-phenylene vinylene) (PPV). It has excellent temperature stability and is intractable. PPV is thermally stable above 400 ℃ (up to its decomposition temperature) in absence of chemical species mainly oxygen [33, 34]. The presence of (poly-electrolyte) precursor route permits solution processing at high solution viscosity at low solid content. Techniques mainly blade or spin coating of precursor polymer utilized to achieve thin films which results in thick and pin hole free films of PPV [35]. Light emitting polymer (LEP) are formed by precursor coating on substrate such as indium-tin-oxide (ITO) coated glass monitored by thermal conversion to PPV and final cathodic deposition. The layers of polymer thickness ranges in order of 100 nm in such LEP devices. Thus, PPV polyelectrolyte precursor was developed that comprises of random copolymer with side groups containing acetate and tetrahydrothiophenium groups with bromide counter ions and mixture of methanol/water as solvent [36, 37].

4. Application of Conjugated Polymer

In last couple of years, polymer-based electronics has become one of fascinating field with applications comprising of polymer light-emitting diodes (PLEDs), photodiodes, and transistors (Table 2). Although, polymer is employed as active layer in most cases or as thin buffer layers on inorganic conductor mainly indium tin oxide (ITO) and metal electrodes [38]. The aim is to develop large area, low cost, and flexible electronic devices based on polymer processing and deposition route. A basic example of application for such technology would be found in energy conversion of photovoltaic based on solar energy. Here, the chief attraction of polymer photovoltaic cell has been found in low cost and easy processing [39, 40].

Table 2 Applications of conducting polymer in device.

Conductive Polymers	Device Applications
Polythiophene and substituted polythiophene	*(i)* Electrochemical capacitors *(ii)* Microlithography *(iii)* Electroluminescence *(iv)* Corrosion inhibitors *(v)* Cathode material for battery
Polyaniline and substituted polyaniline	*(i)* Rechargeable battery *(ii)* Sensors *(iii)* Photolithography *(iv)* Corrosion inhibitors *(v)* Electrochemical capacitors *(vi)* Electrochromic display
Poly(p-phenylene) (PPP) *p*-phenylenevinylene (PPV)	*(i)* Photoconductors *(ii)* Laser material *(iii)* Electroluminescence *(iv)* Solar energy cells
Polypyrrole and substituted polypyrrole	*(i)* Photolithography *(ii)* Electroluminescence *(iii)* Electrochromic display *(iv)* Rechargeable battery *(v)* Sensors *(vi)* Corrosion inhibitors

Solar cell composed of polymer film containing sensitizer is shown in Fig. 3. Polyaniline is one of capable conducting polymer for sensors. It is highly sensitive to vapors because of its conductivity. A common platform of device for construction of such sensors is chemiresistor. In characteristic polyaniline chemiresistor, thin film of polyaniline is usually coated by drop casting or spin coating on electrodes as sensitive layer for chemical vapors. On introduction to chemical vapors, a change in film resistance can be readily recorded by computer controlled circuit. The potential of such chemiresistor is determined by interaction between polymer and chemical vapors [41]. Polypyrrol with band gap of about 2.0 eV in its neutral state appeared to be good photoconducting candidate, since comprises strong intrinsic absorption in visible range. Generally, no severe influence has been made in observing/attempting of photoconductivity of polythiophene. Although, it has been reported that such films are quite insensitive to moisture and air, which is the most serious problem influencing the performance of photoconductor. Electrochemically produced polypyrrole films with band gap of 3.2 eV, after sensitization with one of above mentioned route, can be expected to exhibit excellent photoconductivity. The doping influence of on photoconductive device made up of poly p-vinylene (PPV) has been studied [42]. In electrographic applications, electrochemical polymerization route can be found to have significant in the sense that photoconducting polymer can be mold on metallic object of any shape. The grouping of liquid toner and photoconductor comprising charged particle suspended in an organic medium together with counter electrode gives a display device and electrophoretic image storage.

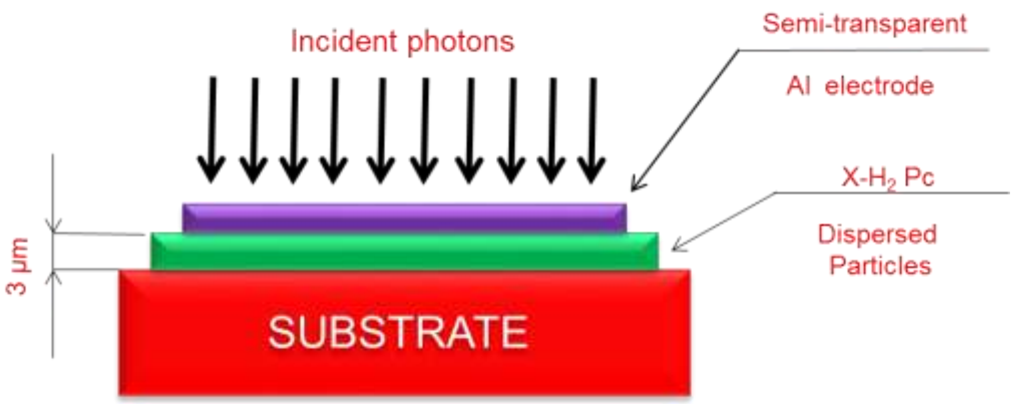


Fig. 3 Solar cell composed of polymer film conducting sensitizer.

It was found that the arrangement in very similar to electronic setup defined with only difference in suspended charge particle. Such applications for electrochemically polymerized semiconducting films appears to be relatively feasible. Since, one of the most heterocyclic polymers have an intrinsic band gap in visible range [43]. On background of present day energy problems, solar cells have gained much of interest as alternative energy source because of its abundance and non-depleting/non-polluting nature. Photovoltaic conversion has gained extensive interest among several methods of solar energy conversion because of its potential capability to provide cheap electricity in non-transporting units. The recent development in electroactive polymers, as new class of semiconducting materials, has generated remarkable interest in fabrication of polymer-based solar cells. Photovoltaic devices based on conjugated polymer/C_{60} heterojunctions have been investigated by utilizing polymers such as poly 3-alkyl thiophene (P_3AT), MEH-PPV [44]. Conducting polymers because of their electronic abilities are excellent candidate as cathode in rechargeable batteries. They have various significance such as processability, ease of manufacture, low cost and light weight. In 1981, research finding on polyacetylene lithium battery was reported [45]. Solid-state batteries are also possible to make employing $(CH)_x$. Some of these type of batteries has been fabricated. Conductive polymers have long life, rechargeability, current density up to 50 mA/cm^2, and energy density of 10 Watt-h/kg. Lithium ion batteries are especially important among all the batteries since they have high discharging voltage [46-51]. General setup for electrochemical polymerization is shown in Fig. 4. Moreover, polymer composite electrolyte having fine electrical and mechanical characteristics has been utilized in rechargeable polymer lithium ion batteries because of stability towards environmental factors [52-58].

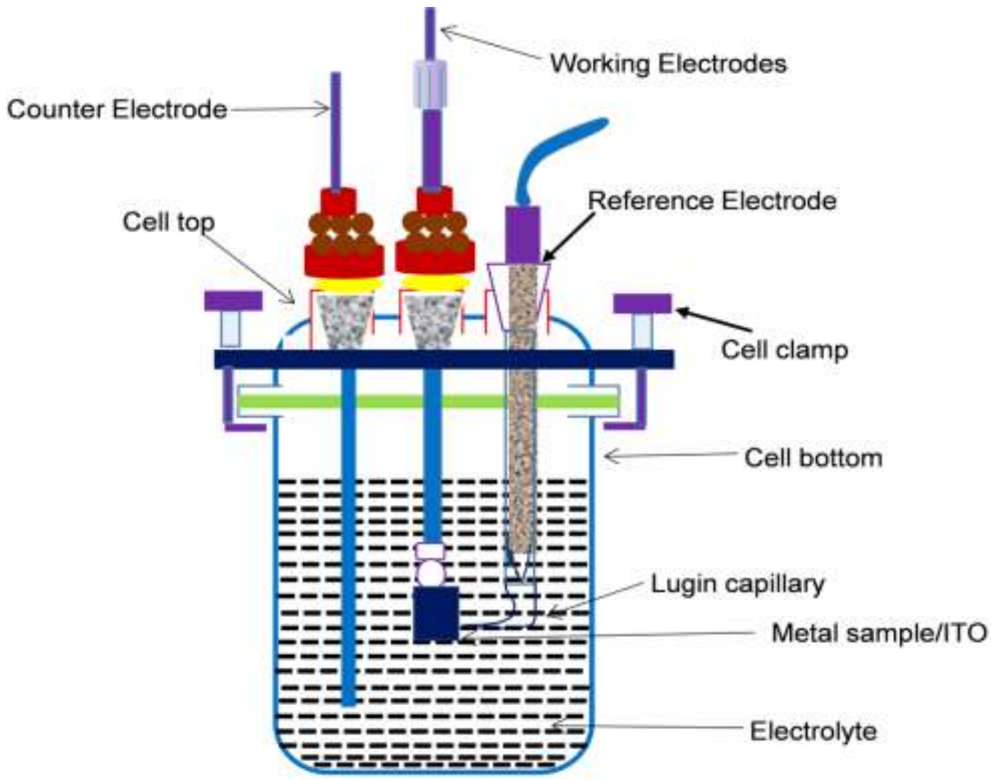


Fig. 4 General setup for electrochemical polymerization.

5. Conclusion

In this review, different types of conducting polymers have been discussed. Polyaniline is one of most studied and employed conducting polymer. The type of conducting polymers discussed are polypyrrole, polyaniline, polythiophene, poly (*p*-phenylene), and polyacetylene. Consequently, they have structure similar to that of metals and semiconductors. Due to superior electrical conductivity, organic polymers are also named as synthetic metals. The conducting polymers have extensive applications in numerous technical fields such as fuel cells, rechargeable batteries, sensors, and photo-electrodes.

Reference

1. Hussain ST, Abbas F, Kausar A, Khan MR. New polyaniline/polypyrrole/polythiophene and functionalized multiwalled carbon nanotube-based nanocomposites Layer-by-layer in situ polymerization. ***High Perform Polym.*** 2013, 25:70-78
2. Kausar A, Ashraf R, Siddiq M. Polymer/nanodiamond composites in Li-ion batteries: A review. ***Polym-Plast Technol Engineer.*** 2014, 53:550-563
3. Kausar A, Hussain ST. Synthesis and properties of poly(thiourea-azo-naphthyl)/multi-walled carbon nanotube composites. ***J Plast Film Sheet.*** 2013, 30:6-27
4. Ashraf R., Kausar A, Siddiq M. High-performance polymer/nanodiamond composites: synthesis and properties. ***Iranian Polymer Journal.*** 2014, 23:531-545
5. Shah R, Kausar A, Muhammad B, Shah S. Progression from graphene and graphene oxide to high performance polymer-based nanocomposite: A review. ***Polym Plast Technol Engineer.*** 2015, 54:173-183
6. Kumar D, Sharma RC. Advances in conductive polymers. ***Europ Polym J.*** 1998, 34:1053-1060
7. Greenham NC, Moratti SC, Bradley DDC, Friend RH, Holmes AB. Efficient light-emitting diodes based on polymers with high electron affinities. ***Nature.*** 1993, 365:628-630
8. Kausar A, Hussain ST. Effect of multi-walled carbon nanotube reinforcement on the physical properties of poly (thiourea-azo-ether)-based nanocomposites. ***J Plast Film Sheet.*** 2013, 29:365-383
9. Sattar R, Kausar A, Siddiq M. Thermal, mechanical and electrical studies of novel shape memory polyurethane/polyaniline blends. ***Chines J Polym Sci.*** 2015, 33:1313-1324
10. Nasir A., Kausar A, Younus A. Polymer/graphite nanocomposites: Physical features, fabrication and current relevance. ***Polym Plast Technol Engineer.*** 2015, 54:750-770
11. Sattar R, Kausar A, Siddiq, M., Influence of conducting polymer on mechanical, thermal and shape memory properties of polyurethane/polythiophene blends and nanocomposites. ***Adv Mater Lett.*** 2016, 7:282-288
12. Meer S, Kausar A, Iqbal T. Trends in Conducting Polymer and Hybrids of Conducting Polymer/Carbon Nanotube: A Review. ***Polym Plast Technol Engineer.*** 2016, 55:1416-1440
13. Sun ZW, Frank AJ. Characterization of the intrachain charge-generation mechanism of electronically conductive poly (3-methylthiophene). ***J Chem Phys.*** 1991, 94:4600-4608
14. Malhotra BD, Kumar N, Chandra S. Recent studies of heterocyclic and aromatic conducting polymers. ***Prog Polym Sci.*** 1986, 12:179-218
15. Loutfy RO,Sharp, JH. Photovoltaic properties of metal ‐ free phthalocyanines. I. Al/H2Pc Schottky barrier solar cells. ***J Chem Phys.*** 1979, 71:1211-1217
16. Gurunathan K, Murugan AV, Marimuthu R, Mulik UP, Amalnerkar DP. Electrochemically synthesised conducting polymeric materials for applications towards technology in electronics, optoelectronics and energy storage devices. ***Mater Chem Phys.*** 1999, 61:173-191
17. Gurunathan K, Murugan AV, Marimuthu R, Mulik UP, Amalnerkar DP. Electrochemically synthesised conducting polymeric materials for applications towards technology in electronics, optoelectronics and energy storage devices. ***Mater Chem Phys.*** 1999, 61:173-191
18. Jelle BP, Hagen G, Nødland S. Transmission spectra of an electrochromic window consisting of polyaniline, prussian blue and tungsten oxide. ***Electrochimica Acta.*** 1993, 38:1497-1500
19. Bergveld P. Future applications of ISFETs. ***Sens Actuat B: Chem.*** 1991, 4:125-133
20. Gurunathan K, Murugan AV, Marimuthu R, Mulik UP, Amalnerkar DP. Electrochemically

synthesised conducting polymeric materials for applications towards technology in electronics, optoelectronics and energy storage devices. ***Mater Chem Phys.*** 1999, 61:173-191

21. Le TH, Trinh NT, Nguyen LH, Nguyen HB, Nguyen VA, Nguyen TD. Electrosynthesis of polyaniline–mutilwalled carbon nanotube nanocomposite films in the presence of sodium dodecyl sulfate for glucose biosensing. ***Adv Natur Sci: Nanosci Nanotechnol.*** 2013, 4:025014
22. Kryszewski M. Heterogeneous conducting polymeric systems: dispersions, blends, crystalline conducting networks-an introductory presentation. ***Synth Met.*** 1991, 45:289-296
23. Anilkumar KR, Parveen A, Badiger GR, Prasad MA. Effect of molybdenum trioxide (MoO 3) on the electrical conductivity of polyaniline. ***Physica B: Conde. Matter.*** 2009, 404:1664-1667
24. Österholm JE, Passiniemi P, Isotalo H, Stubb H. Synthesis and properties of $FeCl_4$-doped polythiophene. ***Synthetic Met.*** 1987, 18:213-218
25. Kobayashi M, Chen J, Chung TC, Moraes F, Heeger AJ, Wudl F. Synthesis and properties of chemically coupled poly (thiophene). ***Synth met.*** 1984, 9:77-86
26. Ruckenstein E, Park JS. Polythiophene and polythiophene-based conducting composites. ***Synth Met.*** 1991, 44:293-306
27. Rivers TJ, Hudson TW, Schmidt CE. Synthesis of a novel biodegradable electrically conducting polymer for biomedical applications. ***Adv Function Mater.*** 2002, 12:33-37
28. Tourillon G. Polythiophene and its derivatives. In: Skotheim TA, ed. Handbook of Conducting Polymers, vol I. New York: Marcel Dekker 1986, 293-350 (这个没看懂)
29. Heeger AJ. Semiconducting and metallic polymers: the fourth generation of polymeric materials. ***J Phys Chemis B.*** 2001, 105:8475-8491
30. Bein T. Conjugated and conducting nanostructures in zeolites. ***Stud Surf Sci Catalys.*** 1996, 102:295-322
31. Etemad S, Heeger AJ. Polyacetylene, (CH)x: The prototype conducting polymer. ***Ann Rev Phys Chem.*** 1982, 33:443-469
32. Su W, Schrieffer JR, Heeger AJ. Solitons in polyacetylene. ***Phys Rev Lett.*** 1979, 42:1698
33. Samuel IDW, Crystall B, Rumbles G, Burn PL, Holmes, AB, Friend RH. Time-resolved luminescence measurements in poly (p-phenylenevinylene). ***Synth Met.*** 1993, 54:281-288
34. Hoeg DF, Lusk DI, Goldberg EP. Poly‐p‐xylylidene. ***J Polym Sci Part B: Polym Lett.*** 1964, 2:697-701
35. Bradley DDC. Precursor-route poly (p-phenylenevinylene): polymer characterisation and control of electronic properties. *Journal of physics D:* ***Appl Phys.*** 1987, 20:1389
36. Tang CW, VanSlyke SA. Organic electroluminescent diodes. ***Appl phys Lett*** 1987, 51: 913-915.
37. Sheats JR, Antoniadis H, Hueschen M, Leonard W. Organic electroluminescent devices. ***Science.*** 1996, 273:884
38. Granström M, Berggren M, Pede D, Inganäs O, Andersson MR, Hjertberg T, Wennerström O. Self-organizing polymer films‐a route to novel electronic devices based on conjugated polymers ***Supramolecul Sci.*** 1997, 4:27-34
39. Kim JS, Granström M, Friend RH, Johansson N, Salaneck WR, Daik R, Cacialli F. Indium–tin oxide treatments for single-and double-layer polymeric light-emitting diodes: The relation between the anode physical, chemical, and morphological properties and the device performance. ***J Appl Phys.*** 1998, 84:6859-6870
40. Campbell AJ, Bradley DD, Antoniadis H. Dispersive electron transport in an electroluminescent polyfluorene copolymer measured by the current integration time-of-flight method. ***Appl Phys Lett.*** 2001, 79:2133-2135

41. Janata J, Josowicz M. Conducting polymers in electronic chemical sensors. ***Nat mater.*** 2003, 2:19-24
42. Zhang YF, Tang YH, Wang N, Yu DP, Lee CS, Bello I, Lee ST. Silicon nanowires prepared by laser ablation at high temperature. ***Appl phys lett.*** 1998, 72:1835-1837
43. Chiang CK, Gau SC, Fincher Jr CR, Park YW, MacDiarmid AG, Heeger AJ. Polyacetylene,(CH) x: n‐type and p-type doping and compensation. ***Appl Phys Lett.*** 1978, 33:18-20
44. Sariciftci NS, Heeger AJ, Nalwa HS. Handbook of Organic Conductive Molecules and Polymers. ***John Wiley and Sons Ltd.*** 1997, 1:414
45. Kumar D, Sharma RC. Advances in conductive polymers. ***Europ Polym J.*** 1998, 34:1053-1060
46. Jonas F, Heywang G. Technical applications for conductive polymers. ***Electrochimica Acta.*** 1994, 39:1345-1347
47. Kuhn HH, Child AD, Kimbrell WC. Toward real applications of conductive polymers. ***Synthet Met.*** 1995, 71:2139-2142
48. Ali W, Kausar A, Iqbal T. Reinforcement of high performance polystyrene/polyamide/polythiophene with multi-walled carbon nanotube obtained through various routes. ***Compos Interfac*** 2015, 22: 885-897.(这篇文章，正文中没找到引用的地方)
49. Ashraf R, Kausar A, Siddiq M. Preparation and properties of layered carbon nanotube/polyazopyridine/nanodiamond composites. ***J Plast Film Sheet.*** 2014, 30:412-434
50. Ashraf R, Kausar A and Siddiq M. Preparation and properties of multilayered polymer/nanodiamond composites via an in situ technique. ***J Polym Engineer.*** 2014, 34:415-429
51. Naz A, Kausar A, Siddiq M. Fabrication and properties of novel polyaniline/poly (styrene-co-maleic anhydride) cumene terminated/4,4′-oxydianiline/graphite-based nanocomposites via layered polymerization. ***Polym Plast Technol Engineer.*** 2016, 53:1542-1552.
52. Kausar A. Thermal and Rheological Properties of Waterborne Polyurethane/Nanodiamond Composite. ***Nanosci Nanotechnol,*** 2016, 6:6-10
53. Kausar A. Effect of Halloysite Nanoclay on Polymerization and Properties of Poly (3, 4-(2, 2-dimethylpropylenedioxy)-thiophene-co-aniline). ***Am J Polym Sci.*** 2015, 5:30-34
54. Kausar A. Synthesis And Characterization Of New Polyamides, Poly (Amide Imide) s, Polyimides And Polyurethanes Bearing Thiourea Moieties. ***Doctoral dissertation.*** 2011, Quaid-i-Azam University, Islamabad
55. Kausar, A. Novel Polyamide Nanocomposite with Montmorillonite Clay and Gold Nanoparticle Nanofillers. ***Nanosci Nanotechnol.*** 2016, 6: 43-47
56. Kausar, A. Development of Non-flammable Poly[(o-cresyl glycidyl ether)-co-formaldehyde] System with Poly (ethylene glycol) bis (amine) and Bis (4-trifluoromethylphenyl) phosphine. International ***J Compos Mater.*** 2016, 6: 129-132
57. Kausar, A., Thermal Conductivity Measurement of Polyvinylpyrrolidone/Polyethylene/Graphene Nanocomposite. ***Nanosci Nanotechnol.*** 2016, 6: 34-37
58. Kausar A and Siddiq M. Conducting Polymer/Graphene Filler-based Hybrids: Energy and Electronic Applications. Editor: A. Méndez-Vilas & A. Solano-Martín. ***Polymer Science: Research Advances, Practical Applications and Educational Aspects.*** ISBN (13): 978-84-942134-8-9, Publisher: Formatex Research Center, 2016, pp. 177-187