Conductive Polymers Synthesis Properties and Practical Applications

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Introduction

Most organic polymers are considered to be insulators in their nature. However, conducting polymers, which are formed from organic polymers, can conduct electricity. The ICPs (Intrinsic conducting polymers) exist and contain alternating double and single bonds found along the backbone of the polymer (conjugate bonds), or they are composed of aromatic rings like phenylene, anthracene, thiophene, pyrrole, and also naphthalene that are connected to each other by a single bond of carbon to carbon. The conductive polymers allow excellent control of the electrical stimuli (Richard, Nigel, and Sarah 2341). They have very good optical and electrical characteristics and higher conductivity ratios, and they can form biodegradable, biocompatible, and also porous products. In addition, the greater advantages of the conductive polymer are the physical, electrical, and chemical characteristics, which can be transformed into vast applications.

The idea of conductive polymers started several years ago, and at present, there are more than twenty-five conductive organic polymers. There was the merging of the positive characteristics of the metals and the conventional polymers, i.e., the ability for charge conduction, electrical conductivity, and optical characteristics, as well as the ease in the synthesis and processing. The first work on conductive polymers was prompted by the discovery of polyacetylene and the observation that was done on it. This polymer is only known for being a semiconductor, and it increases to ten million folds when there is an oxidation of the polyacetylene with iodine vapour. The underlying phenomenon of oxidation was named doping and, therefore, essential in the conduction of the polymers since it’s the only process through which they can gain their ability to conduct electricity. Since polyacetylene became very difficult to synthesise and was also unstable while in the air, it led to the intense research and study of a new and better conductive organic polymer. Therefore, in this paper, we are going to discuss conductive polymer materials, their use and application in various fields, and how they are made.

How the conductive organic polymers are made

The conductive polymers are made using both doping and non-doping methods. The electrical conduction of the conjugate and nondoped polymers like polyacetylene is due to the existence of a

conducting band that is similar to metal. For the conjugated polymers, “the three of four electrons of the valence from strong σ bonds through sp2 hybridization where electrons are strongly localized” (polymerdatabase.com). The other remaining electrons that are not paired with every carbon atom are retained in the “Pz orbital.” They overlap with the neighbouring “Pz orbital” so that they can form the “π bond.” The electrons of π in the “conjugate Pz orbital” continue to overlap so that they can form the extended “Pz orbital system,” which allows the movement of the electrons freely (Ghasemi). This implies that the π electrons are delocalized. However, the non-doped polymers are considered to have low conductivity.

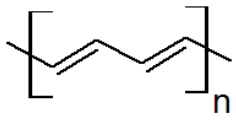
It is only when an electron is detached from the valence band through oxidation, which is p doping, or an electron is added to a conducting band through reduction, which is n doping, that the polymer turns out to be highly conductive. There are four different methods of doping. The first one is Redox p-doping. In this method, some π bonds are oxidized by giving treatment to the polymer by use of oxidizing agents like chlorine, iodine, arsenic pentafluoride, and many more. The second method of doping is by redox n-doping, where some π bonds are reduced through the treatment of the polymer by the use of a reducing agent like sodium naphthalene and lithium. The third method of doping is electrochemical n- and p-doping. In this method, the doping process is achieved through anodic reduction (N) or even cathode reduction (P). The last method of doping is photo-induced doping, in which the polymer should be exposed to higher radiation of the energy, which allows electrons to move to the electrical conducting band. In this case, both the negative charge and the positive charge are localized to the few bonds.

Doping of the polymers raises the electrical conductivity by many different orders of magnitude. It has been reported that the values of conduction are very high, from 102 S/m to 104 S/m. The other method that is essential in increasing the conductivity is through mechanical alignment of the polymer chains. For instance, the conductivity of polyacetylene is very high at the rate of 105 S/m and is several magnitudes below the conductivity of copper and silver, which have 108 S/m, but it has sufficient electronic applications like the “polymer-based transistors, lasers and the light emitting diodes.”

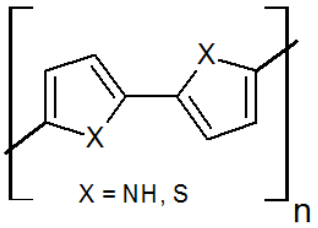
Conductive polymeric materials and their uses

At present, intense research has been conducted on intrinsic conducting polymers. These materials are considered to be polymeric or oligomeric materials that are composed of phenylene rings and related units like those of anthracene, naphthalene, and also heteroaromatic rings like the pyrrole and thiophene (Wallace and Smyth). These are connected with one another by a single bond of carbon to carbon or by the vinylene group, which is denoted by –C=C-. This kind of polymeric material has unique thermophysical and electrical characteristics. Because they have low halogen content and aromatic structure, they illustrate excellent thermal, chemical, and oxidation stability. They are practically not soluble in the common solvents. The materials have the potential to conduct electricity, especially when they are doped.

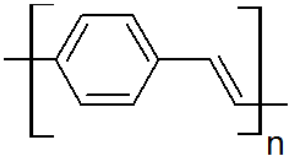
They have a very high restriction on the mobility of repeat units, which results in a very high softening point and melting point due to their aromatic ring structure and the absence of the free-rotating groups of electrons. This causes the processing and synthesis of these kinds of resins to be expensive and difficult (Guiseppi 2712). Thus, the viscosities of the melting point are often very high, which means the injection moulding and processing methods are not practical or even feasible. Therefore, some of the conductive polymer materials are illustrated below.



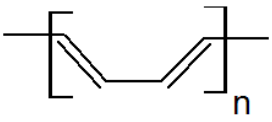
trans-Polyacetylene



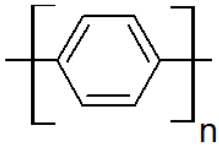
Polypyrrole (NH), Polythiophene (S)



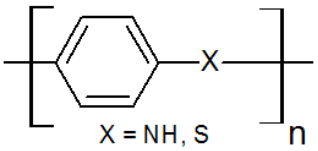
Polyphenylene Vinylene



cis-Polyacetylene



Poly(para-phenylene)



Polyaniline (NH), Polyphenylene sulfide (S)

The first one is polyphenylenes. They are one of the important classes of conductive polymers. The phenylene unit from these types of polymers is connected with the other by the single bond of carbon-carbon atoms. This results in linear polymers that have a backbone that comprises only the aromatic ring. More so, the greatest attention has been focused on PPP (“Poly Para Phenylene”). This type of polymer has been considered to be so stable up to the temperature range of 500 to 600 degrees Celsius with minimal slow oxidation. It is not soluble in many solvents and has a high melting point (Zhou, Cui, and Hines). This polymer possesses unusual optical and electronic properties, and it can be processed into a skinny crystalline film; for instance, through vacuum deposition, it is electrically conducting when it is doped. PPP can be photoconductive and has the potential to make electroluminescence applications like those of light-emitting diodes.

The second conducting polymer material is polyphenylene vinylenes. The “Poly (para-phenylene vinylenes)” denoted by PPVs and the derivatives are the other class of electrically conducting polymers that are being studied thoroughly due to a lot of interest and the possibility of useful photoelectrical and optical properties. The unit of the phenylene that is found in the polyphenylene vinylenes is connected to the other phenylene by the double bond of carbon to carbon, leading to the outcome of the rigid and rods-like linear polymer that comprises only aromatic ring and the double

bond (Logan 112). This polymer can be processed to form a highly ordered thin crystalline film that can conduct electricity when it is doped. Similar to PPP, PPVs are capable of being used in electroluminescence applications and can also be used in the form of an emissive layer to the light-emitting diodes of the organic-based polymers like the electroluminescent displays. Also, PPVs were the first conductive polymer materials to be used to serve this purpose. Polyphenylene vinylenes and other copolymers are also being used as efficient acceptors in the PSCs (polymeric solar cells).

The other essential electrical conductive organic polymer is the doped polyaniline. PAN denotes it. This type of polymer is not considered part of the family of polyphenylene since it possesses amine groups as one of the components of its backbone. Polyaniline is considered to be an attractive conductive organic polymer since it is somehow not expensive, its synthesis is easy, and it is chemically easy to modify. It is no surprise that it is the most conductive polymer that has been studied, and it finds many applications as a conductor and an electromagnetic shield for electronic circuits. Also, polyaniline is being used as a corrosion inhibitor and in the manufacture of conducting nanofiber.

The fourth conductive polymeric material is polypyrrole. This is one of the promising conductive polymeric materials and is denoted by PPy. PPy can be processed easily, and it possesses a lot of interesting characteristics of electrical conduction. The polymer is very stable in terms of both electrical and thermal conduction. In comparison to the other full aromatic organic polymers, PPy has been experimentally illustrated as an electrical insulator (Shirakawa, Louis, and MacDiarmid). When PPy is oxidized with an oxidizing agent, it turns and becomes an electrical conductor. The electrical conductivity of the polypyrrole highly depends on the techniques that are being used in its preparation, and the polymer additives that are being used are essential in increasing the conductivity by two orders of magnitude. The uses of this polymer include coating the anti-electrostatic material used to act as the gas sensors, as a solid electrolytic capacitor, and as one of the components in electronic devices.

The fifth conducting polymeric material is the polythiophenes. This type of polymer and its derivatives are very promising since when polythiophenes have not been doped, the conductivity of the electricity is considered to be very low. However, when the polythiophenes are doped with a low level or less than one per cent of the doping materials, the conductivity of electricity increases many times. The regioregular PATs (poly 3-alkyl thiophene) are of greater interest due to their respective structural orders that lead to greater charge-carrier mobility. These types of polymers are very soluble and also fusible, and therefore, they are used to demonstrate some novel properties like “thermochromism” and “solvatochromism.” The absorption or even emission can be adjusted from ultraviolet to IR by just changing the polythiophene substituents.

The last type of conductive polymeric material is polyacetylene, sometimes called polyethene. It is composed of the repeating units of C2H2, which are very rigid and rod-like. They contain a long chain of carbon that has alternating double and single bonds within the atoms of carbon. It is well known that the electrically conductive polymers began by doping the organic polymers. Polyacetylene was

the first polymer that had conductivity synthesis. The electrical conductivity of this polymer was discovered by Alan Heeger, Shirakawa Hideki, and also MacDiarmid Alan, who all received the Nobel Prize in the field of Chemistry in 2000 due to this discovery (Skotheim and Elsenbaumer). They first synthesized the polymer in 1974. In that year, they prepared polyacetylene from acetylene in the form of a thin silvery film, including the Ziegler-Natta catalyst. The result was a metallic appearance of the polymer, but the attempt didn't yield the conductive polymer. After three years of research, they discovered that oxidation with the halogen vapour would lead to the production of a very conductive film of polyacetylene. The conductivity of this polymer became significantly higher than that of the initial conductive polymer. Hence, this discovery initiated the development of many other electrically conductive organic polymers. Despite the fact that the discovery of polyacetylene began the development of conductive polymeric materials, this type of polymer does not have any commercial use or application.

Application of conductive polymeric materials

There are many applications of conductive polymeric materials in different fields. Some of them have been illustrated below. The first one is supercapacitors. The supercapacitor consists of electrodes whose materials are classified into three different categories, including the transition metal oxide, the conducting polymer, and the higher surface carbon. This supercapacitor, sometimes called the electrochemical capacitor, is essential in the development of the hybrid electric vehicle and is also used in electronic devices that are portable for their urgency and increased demand (Murata and Sarac 232). The Supercapacitor has been used in this appliance due to the increased power supply, simplicity, long life cycle, and a higher dynamic of the charge propagation.

The second one is the light-emitting diode (LED). The polymer light-emitting diode is based on the PPV and, at the moment, is coming out as a commercial product. In a comparison between the organic and inorganic materials used to develop LEDs, the benefit of the polymer electroluminescence is that the device has a fast response time in processing ability, a low voltage of operation, the possibility of covering a larger area and many more. The polymers found in the electronic company have established the passive role of being the insulators and are now being involved in active roles like designing microlithography applications.

The third application is in the solar cell. Polymeric materials are involved in the design of low-cost electronic devices like photovoltaic devices, and other organic electronics have been received with greater attention. In a comparison between organic technology and the silicon-based photovoltaic materials used in the solar panels, organic photovoltaic provides a low thermal budget, a very high speed of processing, and a low-cost processing solution. The fourth application is in field-effect transistors, where the conducting polymers are found in different applications, such as smart pixels and sensors. The last application is biosensors, which are devices used in biological sensing of the elements that are connected to the transducer with the aim of producing an electronic signal that is proportional to the set chemicals. The conducting polymers have been applied to the biosensors to

enhance speed, stability, and also sensitivity. Therefore, they have been recommended for medical diagnosis.

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