Plastics Topics – Plastics electronics

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1. Introduction

In other Plastics Topics we have discussed the electrical properties of plastics in terms of their excellent performance as insulators and indeed this was one of the first and most vital uses of plastics. Probably the first discovery that organic materials could carry a current was in 1862 when Henry Letheby discovered that certain compounds of aniline could act as semi-conductors. This and similar discoveries effectively lay dormant for over 100 years until 1977 when Heeger, MacDiarmid and Shirakawa published their landmark paper 'Synthesis of Electrically Conducting Organic Polymers: Halogen Derivatives of Polyacetylene, CHx' in the Journal of the Chemical Society[1]. This landmark paper was the birth of a new field of chemistry and laid the foundations for the field of plastic electronics. The paper was so important that Heeger, MacDiarmid and Shirakawa were awarded the Nobel Prize for Chemistry in 2000 for their work in conductive polymers.

Plastic electronics offers substantial benefits to the conventional silicon electronics in terms of flexibility and weight. The field was, until recently, an area of interesting concepts but the last 10 years have seen dramatic changes form developments in thin film technology, organic chemistry and printing technology. Many devices now routinely use plastic electronics and many more are in the research and development stage.

Plastics electronics is not limited to replacing conventional silicon electronics for semi-conductors, similar technologies can be used for organic dielectrics, conductors and light emitters. This is a potentially vast field. The market is forecast to increase to $330 billion by 2027 – this is larger than the silicon electronics industry of today and these forecasts do not include some of the new markets that will inevitably develop in the sector.

Plastics electronics is truly a 'disruptive technology' and yet it is still in its infancy and developing fast. The field of plastic electronics is now one of the most exciting development areas in plastics and electronics and will literally change the way we live, work and play.

2. The basics of conductive polymers

As with almost everything concerned with plastics, the structure of the plastic defines how the material reacts and plastics electronics has been developed through an understanding how structure affects the properties. Despite this, much of the basic science of plastics electronics is still poorly understood and there is still much work to be done to understand the relationship between the chemical and physical properties of materials and the function of devices.

For any material to conduct electricity there must be a movement of electrons. Conventional inorganic conductors, such as metals, can be imagined as having a 'cloud' of conduction electrons that are not tightly bound to the individual atoms. These free electrons can then move and as a result the materials conduct electric exceptionally well.

In the case of conventional polymers and other organic materials, the atoms are covalently bonded. This gives a tight bond that locks up the electrons so that they are not free to move and the materials are insulators. However, some groups of organic materials do not have this type of tightly bound electrons. One specific case is the familiar benzene ring show in Figure 1:

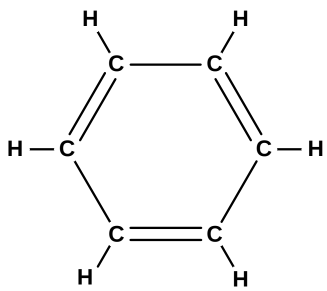

Figure 1: The ring structure of benzene

[1] H. Shirakawa, E. J. Louis, A. G. MacDiarmid, C. K. Chiang and A. J. Heeger, *J. Chem. Soc.*, *Chem. Commun.*1977, 578.

The structure shown is the strict chemical structure and shows the covalent bonds such that every atom is fully bonded. Whilst this is the strict structure chemists also illustrate the benzene ring with the symbol shown in Figure 2:

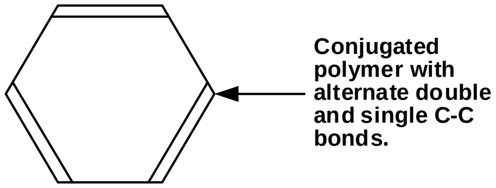

Figure 2: Representation for benzene showing double and single bonds

Figure 1 and Figure 2 show that every carbon atom has two types of bond to the other carbon atoms; a single bond on one side and a double bond on the other. When a polymer has carbon atoms with alternate single and double bonds it is termed 'conjugated'. The C – C single bonds have a 'localized' or tightly bound electron (a 'σ' electron) and the C – C double bonds have both a 'localized' electron and a 'delocalized' or weakly bound electron (a 'π' electron). In reality, the structure of the benzene ring would be more accurately represented by that shown in Figure 3:

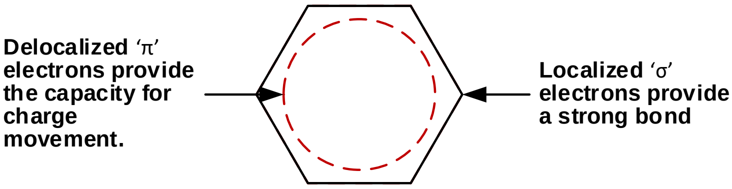

Figure 3: Representation for benzene showing 'delocalized' electrons

The delocalized electrons are not as tightly bound as the localized electrons and are effectively free to move around the ring structure of benzene, i.e., they form an electron cloud rather than being tied to specific carbon atoms. It is then possible to consider using these delocalized electrons to carry a current.

Traditional polymers such as PE (polyethylene) have single bonds and can be represented by the repeat unit as shown in Figure 4:

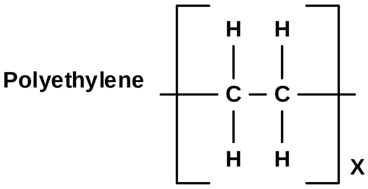

Figure 4: Conventional polymer with single C – C bonds

These plastics do not have a conjugated structure and are therefore the classic electrically insulating plastics.

There is, however, a group of polymers that also have conjugated bonds and the simplest of these is polyacetylene, the polymer that Heeger, MacDiarmid and Shirakawa worked with to first explore electrically conductive plastics. The structure of polyacetylene is shown in Figure 5 and the alternating single and double C – C is clearly seen:

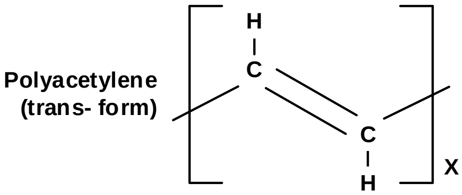

Figure 5: Polyacetylene – one of the simplest conjugated polymers

Conjugation is a prerequisite for conduction in polymers but Heeger, MacDiarmid and Shirakawa's 'big discovery' was that polyacetylene could be 'doped' with halogens (chlorine, bromine or iodine) to increase the conductivity by a factor of 10^9. This is similar to the way that silicon is doped to produce semi-conductors. 'Doping' injects charge carriers, either additional electrons or 'holes' (which can be considered to be the equivalent to a $^+$ve charge) into the polymer. The additional electrons or holes from the 'dopant' allow electrical charges and currents to be carried over long distances and the science of plastics electronics was born.

Naturally it is not all as simple as this description (you don't get a Nobel Prize for nothing) and the conduction mechanism also involves resonance stabilization, mobility gaps, tunnelling and phonon-assisted hopping.

3. The plastics

The plastics used for plastics electronics are not the conventional commodity, engineering or performance polymers that the industry is familiar with, i.e., the polymer chains must have conjugated bonds and also be subjected to the correct amount of doping to become electrically conductive.

This reduces the number of suitable plastics and repeating units of the main plastics used in plastics electronics are shown in Figure 6:

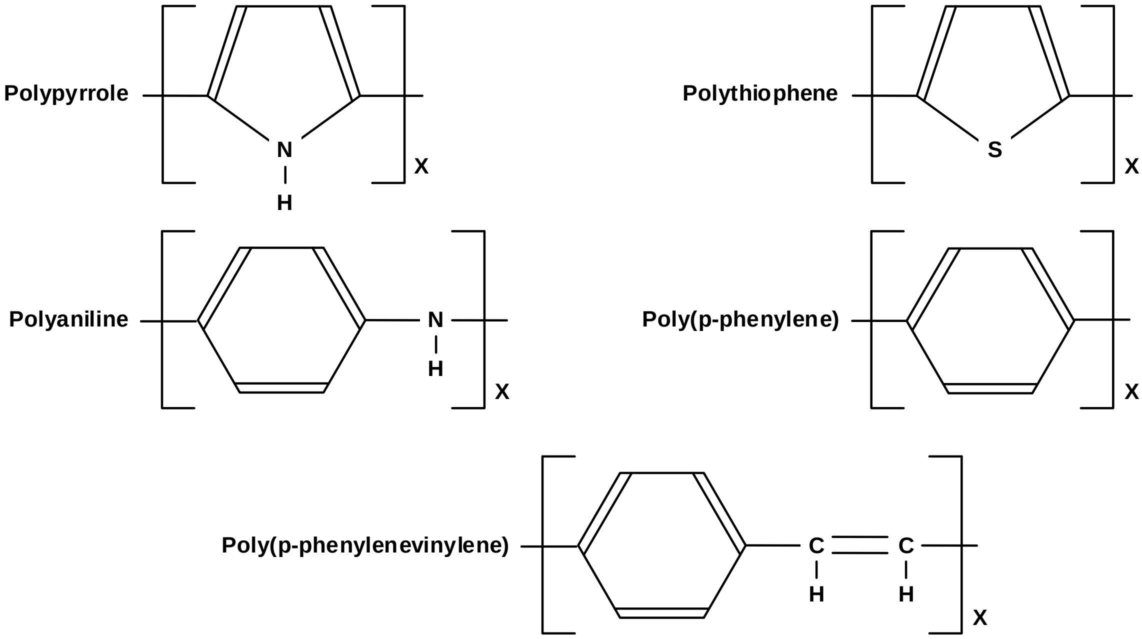

Figure 6: Some of the polymers used in plastic electronics

These are not familiar materials but represent the foundations of a new technology.

Despite the fact that the original discoveries were made with polyacetylene, this was not the first commercially available conductive plastic. Polyacetylene is one of the most crystalline of the conductive polymers but it is easily oxidized in air, is sensitive to humidity and not suitable for production purposes. Other conjugated and doped plastics are very stable in air, can be synthesized directly in the doped form and were the first commercially available materials, e.g., polypyrene[2] and polythiophene.

Each of the plastics shown in Figure 6 is either currently used in major applications or is being developed for an application that will change the way we live.

[2] It is interesting to note that the first reported observation of the possibility of doping polypyrrole to create a polymer with properties similar to an n- or p-type semi-conductor was made in 1963 (Bolto, McNeill and Weiss, Australian. J. Chem., 1963, 16, 1090.) but the importance of the discovery was not realized at the time and the discovery languished into obscurity until Heeger, MacDiarmid and Shirakawa. Wrong time, wrong place and no Nobel Prize.

4. Conductivity – measuring the benefits

Depending on the plastics chosen, amount of dopant and the specific dopant used, it is now possible to produce plastics with a wide range of conductivities. Conductivity (σ) depends only on the material and is independent of the sample size. Conductivity is a measure of how well a material conducts electricity; it is high for good conductors such as metals and low for insulators such as conventional plastics. The possible range of conductivities achievable with conducting plastics is shown in Figure 7:

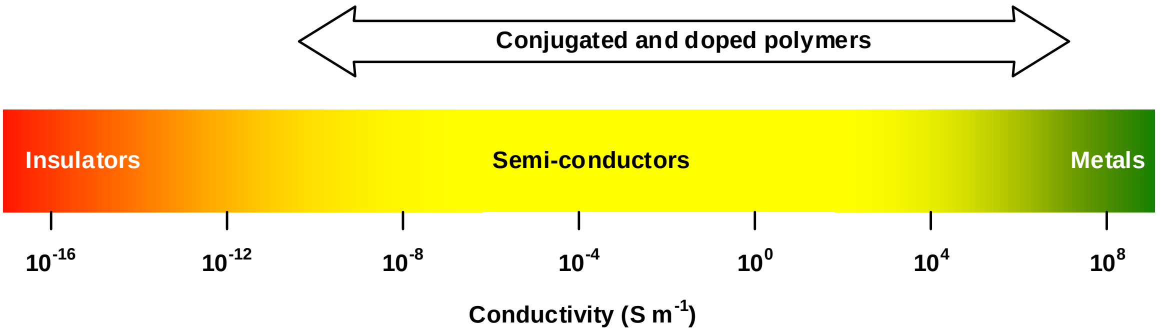

Figure 7: The range of conductivities possible with conjugated and doped polymers

This shows that plastics can now be produced with properties ranging from the traditional insulators through properties of traditional semi-conductors (such as silicon) and finally to properties which are broadly similar to those of conventional conductors (such as copper or aluminium). These are truly materials for all seasons.

5. The advantages

Manufacturing costs

A major advantage with plastics electronics is the ability to process the electronics from solution. Conventional silicon-based electronics needs chip fabrication factories that cost over $1bn to build and fabrication can not only take up to 8 weeks but is also energy and resource intensive and modifications to designs can be difficult to implement. Plastics electronics can use solution processing to dramatically reduce costs, lead times and resource intensity. Imagine being able to replace a $1bn factory with a bank of relatively cheap ink-jet printers and still being able to produce a better product. This is disruptive technology at its best.

Portability

The light weight, low cost and low power demands of plastics electronics means that they can be easily integrated into packaging, fabrics, buildings and structures. This increases portability and allows electronics to become not only portable but also pervasive. Plastics electronics open up the future of electronics to portable devices and connectivity that could not previously be dreamt of.

Flexibility

Silicon based products are rigid stiff and brittle. Plastics electronics products can be made to be flexible and this opens up applications where silicon-based products could not function or would suffer damage during use.

Scale

Silicon based products are limited in size due to the complex fabrication process. Plastics electronics can be fabricated by simple printing and the size is limited only by the size of the printer. In most case this is a width limitation only and printing can be onto rolls with almost unlimited length. For applications such as solar panels (see below) this opens up the possibility of much larger scale panels.

6. Application areas

OLEDs and pLEDs

Organic light-emitting diodes (OLEDs) or plastic light-emitting diodes (pLEDs) are thin-film devices using an organic layer to emit light when a current is passed through it. These have much lower weight, are thinner and use less power than conventional LCDs. They are readable from every direction, have a wide operating temperature and have a very high switching speed. When compared to conventional light sources, OLEDS offer longer life, lower environmental impacts and greatly reduced energy consumption. By varying the plastic and the treatment it is also possible to vary the colour of the light emitted – a major breakthrough in the production of full colour OLED/pLED displays. The colour pLEDs using three different polymers for three base colours can be processed directly from solution and full colour displays can be produced using ink-jet printing.

OLEDs can be used for mobile phone displays, MP3 players and televisions. There is also the potential for very flexible lighting elements!

The use of OLEDs is one of the most mature markets for plastics electronics and products are already in use for screens for mobile phones, MP3 players and cameras. The mobile phone market is the largest end-user market but this is only the start and Japanese companies are already working on a project to develop 40 inch and larger OLD television displays.

Displays

Not all displays are light emitting and plastics electronics allows the reflection and transmission properties of a material to be locally changed by the application of an electric field. This means that displays can be produced on flexible plastic, metal or even paper substrates to produce displays that can be rolled out of mobile phones, e-readers and e-books. It will even be possible to produce low resolution large area displays for active billboards (e-posters and e-billboards?) – enhancing the drive to work as well! It may even be possible to produce e-wallpaper which can be changed to reflect your mood or needs – no more repainting of the house, simply set the e-wallpaper to a different colour or picture!

This type of display is flexible, light-weight and can be printed on roll-to-roll processing for rapid production and easy product modification. The rise of the e-book and light-weight readers will drive developments in this area.

Batteries

Batteries are currently manufactured of two dissimilar metals separated by an electrolyte and clad in a metal case. These are generally heavy and must be of a specific shape to minimize stresses and strains on the battery. The rise of plastics electronics means that batteries can now be manufactured with an anode made from one plastic, a cathode made from a different plastic, a conducting plastic electrolyte and all clad in a plastic case. These are very light weight, have a similar energy capacity to conventional batteries, more damage resistant and can be manufactured in virtually any shape or size that the application needs.

Plastics batteries at present are primarily for low capacity and discontinuous use but proposed developments will enable higher capacities for continuous use and eventually direct integration into packages and systems.

Electronic components

Plastics electronics began with the production of n- or p-type semi-conductors and these can be a direct replacement for conventional solid-state electronics that is currently based on silicon. The use of conventional plastics as insulators it is then possible to build any type of electronic component, e.g., transistors, resistors and capacitors, and to then integrate these into larger scale components. The potential for producing integrated circuits (a large collection of transistors and other components) by printing is one of the most exciting areas of plastic electronics and is one of the building blocks for many of the other actual and potential advances in plastics electronics. Simple multi-layer printing techniques can not only create the integrated circuits but also the circuit boards that carry the chips. Flexible ICs on flexible circuit boards open up a huge range of computing and other applications for plastics electronics.

No longer will there be a need for 'ruggedized' computers, they will all be rugged simply from the way they are made.

Photovoltaic films for solar cells

Organic photovoltaic (OPV) cells can be manufactured to use solar energy to generate electricity. OPV cells can be manufactured by low-cost ink-jet printing or coating processes such as those used for photographic printing to produce a solar cell on a flexible substrate. These solar cells are flexible, much lighter and much cheaper to produce than conventional silicon and glass-based PV cells. OPV cells are not yet as efficient as silicon PV (which is still only in the region of 20% efficient) but the cost and advantages mean that much greater areas could be economically used to overcome the lower efficiency.

Printed OPV cells have the potential to create a truly distributed electricity generation capacity at exceptionally low cost, to integrate the PV cells directly into the building structure and even to connect back to the grid for grid-connected power generation.

RFID and smart tags

Radio frequency identification (RFID) tags use wireless technology to store and retrieve data remotely. Plastics electronics can be used to dramatically reduce the size and cost of RFID tags through printed tags. This opens up the possibility of pervasive electronics through RFID. Imagine your frozen pizza 'talking' to the fridge and giving it the use-by date, noting that you have eaten the pizza and automatically ordering a new one from the store.

Small, lightweight and flexible plastic electronics RFID tags can also be produced to create intelligent clothing, intelligent packaging and other items to create a world of 'pervasive' electronics.

How will our civil liberties be affected when our clothing and food tells everybody not only where we are but also what we eat?

Sensors

The lightweight RFID technology can also be used to produce small and robust sensors to monitor time and temperature of food and other sensitive articles during their lifecycle. This can be used to check if food has exceeded storage times or temperatures before delivery and, perhaps more importantly, can be used to ensure that medicines needing a 'cool chain' reach the user in perfect condition for use.

Small, flexible printed plastic electronics can be used to produce medical sensors to monitor or diagnose health conditions and even communicate with health professionals if any safe limits are exceeded.

Intelligent embedded sensors offer remarkable opportunities for monitoring of the condition of almost any system or component.

Storage media

Plastics are also being investigated for storage media using 'spintronics' and the first room-temperature plastics spintronics device has already been claimed by researchers at Ohio State University. Spintronics controls the spin of individual electrons to store information. This innovation could allow the use of plastics to replace conventional storage devices (flash memory and hard discs) as it will run faster, use less power and run cooler than conventional media. Plastics electronics may allow you to not only view your media but also store the files on the display. Imagine a flexible roll up screen that not only displayed all of your media but also stored it all and could still be rolled up and easily carried.

Smart textiles

The flexibility of plastic electronics opens up the possibility of 'smart textiles'. These could incorporate keypads, sensors, light effects, integrated displays, photovoltaic cells or even fuel cells integrated into the fibre. Possibilities include:

- Don't like the colour of your suit/shirt/tie/dress/blouse/shoes, change it with the plastics electronics – think of the saving in wardrobe space.

- Don't like the cut of your suit, change it to look more modern and up-to-date. One suit, multiple styles and multiple colours.
- Want to become 'invisible', set the sensors to detect the background and then set the clothing to match the background.
- Want to be really connected, use the integrated fuel cell to power your integrated mobile phone and remain in contact all the time. A truly terrifying thought!

Smart objects

Smart objects are an extension of smart textiles and could easily include:

- Smart tickets: Flexible tickets that automatically include your photo ID/passport, can track your progress and can be reused indefinitely by simple refilling as required.
- Smart windows: Coatings and sensors printed on the glass change the performance of the glass to match the outside/inside temperatures, detect that the sun isn't shining and automatically obscure the windows. Smart windows can reduce energy losses and make curtains obsolete.

The use of light-weight flexible smart objects will gradually become pervasive and affect every part of our everyday life.

7. Summary

Plastic electronics is a young technology and many people in the conventional plastics processing field have not had much professional contact with this dynamic new group of technologies. The potential for this field is as exciting and vibrant as the potential for conventional plastics has been in the past. The "just one word" that was whispered to young Benjamin in 'The Graduate' may in future be replaced with "just two words" – plastic electronics.