Why Organics

Organic materials in general and polymers in particular have been extensively researched for at least four decades by now. The reasoning behind this research varies with the years and the researcher involved. A sample of such motivations is 1. The resemblance to biological materials (DNA is a polymer) may assist us in understanding biological systems and even may allow us to mimic them, 2. These materials can be generally referred to as molecular-materials and hence, may serve as the building blocks of molecular size (sub micron scale) devices, 3. Organic materials promise technological advantages over their in-organic counterparts.

The bulk of the research during the past two decades is mainly driven by the last point. The discovery that the electrical conductivity in doped polyacetylene [1] can be tuned from that of an insulator to that of a metallic conductor suggested that these materials could be used in REAL applications. Not too long after that, the report of electroluminescence in sublimed molecular films [2] and conjugated polymers [3] suggested that these materials would soon be used in many optoelectronic-applications. These, and many other, results have started the snowball running and today organic materials are being considered in an ever-growing context.

Polymers are very attractive since they can be easily spin-cast from solution and do not require ultra-clean environment during any processing procedure. Moreover, these materials can be, easily, chemically tuned so that their emission colour would cover the entire visible spectrum. Paradoxically, the ease at which the properties of these materials can be changed makes them sensitive to unintentional chemical defects and varying microscopic structure (as alignment), introduced either in the synthesis or the processing stages. For many years the advance in this field was withheld due to non-reproducible polymer properties. To date, high quality polymers are being synthesised around the world with high degree of reproducibility. The lifetime of light emitting polymer diodes has largely increased and reaches thousands of hours [4-6]. Sustainable peak current densities are in the $kAcm^{-2}$ regime and the peak brightness is ~5 mw [7]. These high quality polymers were recently also found suitable for demanding applications such as lasers [8, 9]. Although we are mainly concerned here with light emitting polymers, the advance in polymer field effect transistors (FETs) was profound as well. The processability [10] mobility and on-off ratio [11] have been improving constantly and has recently led to "plastic" electronic

circuits [10] and to FET-LED optoelectronic integrated device [12, 13]. The availability of high quality and pure polymers makes it reasonable to look deeply into physical mechanisms governing the operation of such devices and at the same time explore new avenues where the advantages of polymers prove beneficial.

The Device variety

In the above we have mentioned that one of the key advantages is the ease by which polymer based devices can be made. The main procedure used in building such devices is casting (spin-coating) of a polymer solution on a given substrate. The electrical contacts are often applied using a vacuum evaporation source although it is also possible to use highly conductive polymers as contact layers (in the long-run this method will probably take over). For the industry this means that it is possible to compete and win over more traditional technologies (price wise). For the scientist, the majority of which are students, it means that one can go through all the procedures of making a device within a day or two. Namely, one spends most of his time in measuring/understanding the devices while still having an intimate contact with the processing procedure. In other words, it is relatively easy to see the BIG picture. Moreover, it is relatively easy to move between different device structure (LEDs, Transistors, Lasers, …) and we will outline some of them below (a more comprehensive discussion will appear later).
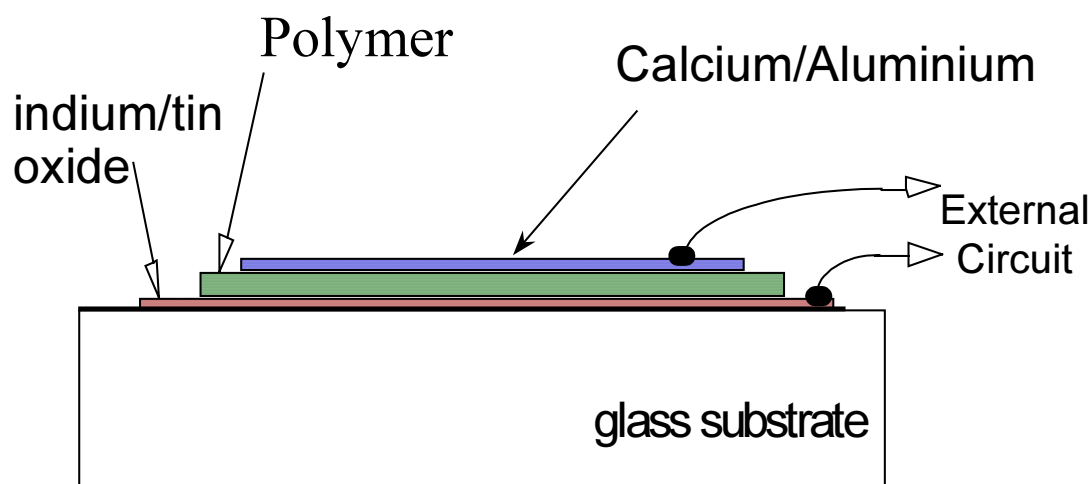

Figure 1. Typical structure of a vertical-emitting polymer based light emitting diode.

The first structure is that of the LED which is described in Figure 1. The substrate is ITO-coated glass, which is mainly manufactured for the LCD technology, with the ITO being a semitransparent hole injector which enables light emission in a vertical configuration. Next a polymer layer (layers) is deposited with a typical thickness of around 100nm (10^{-4}mm). Finally electron injection is via a metallic contact and a good contact usually requires a low work function metal as Calcium.
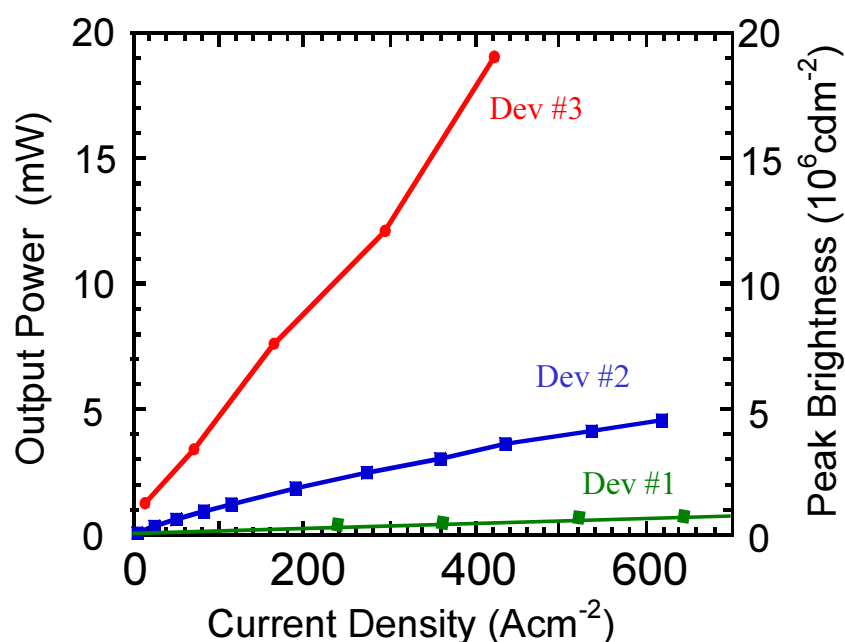

Figure 2. Output power as a function of current density for a mm^2 vertical-emitting polymer LEDs. Dev#1 is based on the PPV polymer. Dev#2 is based on an improved PPV (a PPV co-polymer), and Dev#3 makes use of a double polymer layer (heterostructure).

The high quality and robustness of these polymers and devices is illustrated in Figure 2. Note that it is possible to pass current densities of kAcm^{-2} and that the output power can be tens of mW. The right hand axis is a parameter used in display technology and it takes into account the sensitivity of the eye in the visible spectrum. As a reference point, a normal screen has a brightness of about 100cdm^{-2}.
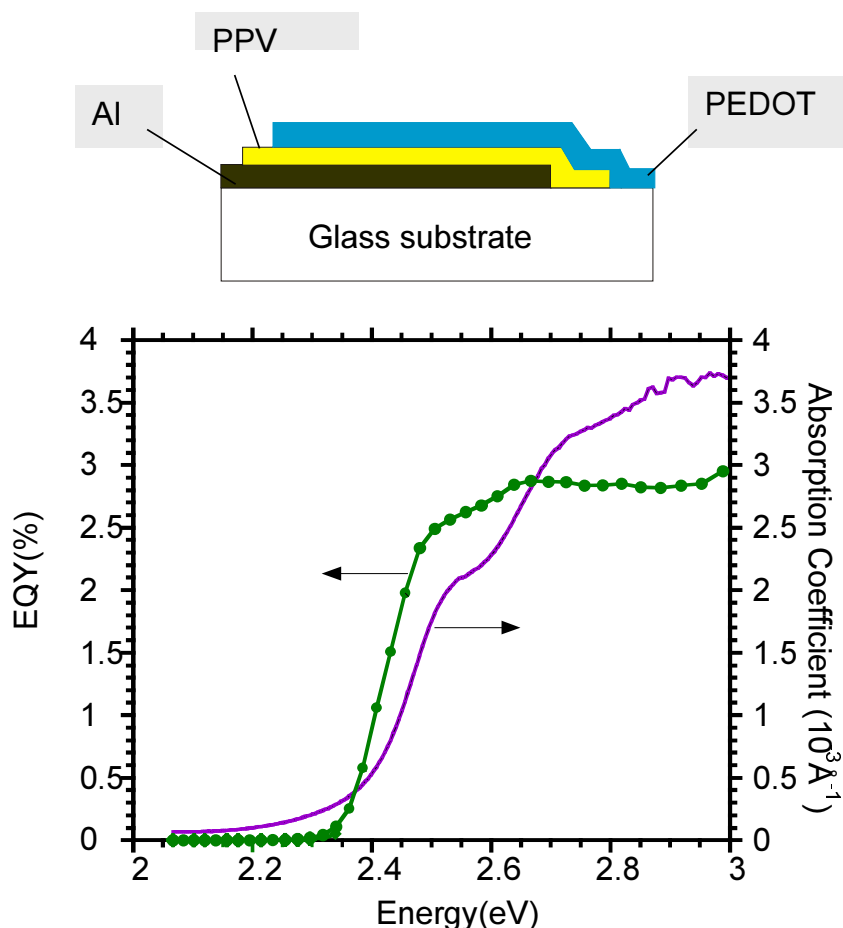
Figure 3. Spectral response of a photovoltaic cell. Note that the top electrode is a conducting polymer (courtesy of A.C. Arias).

The same device preparation procedure can be used to produce a photovoltaic cell, a device that converts light into voltage (or current). The device structure is shown at the top of Figure 3 and we note that in this case the top electrode was also applied using the spin coating technique and it consists of a conducting polymer. The purpose of this device is very different to that of an LED and hence the optimum device design is not the same. However, the same skills and equipment are used thus making it possible to study some phenomena through the "eyes" of more than one device. This point becomes more evident below when we describe the polymer based field effect transistor.
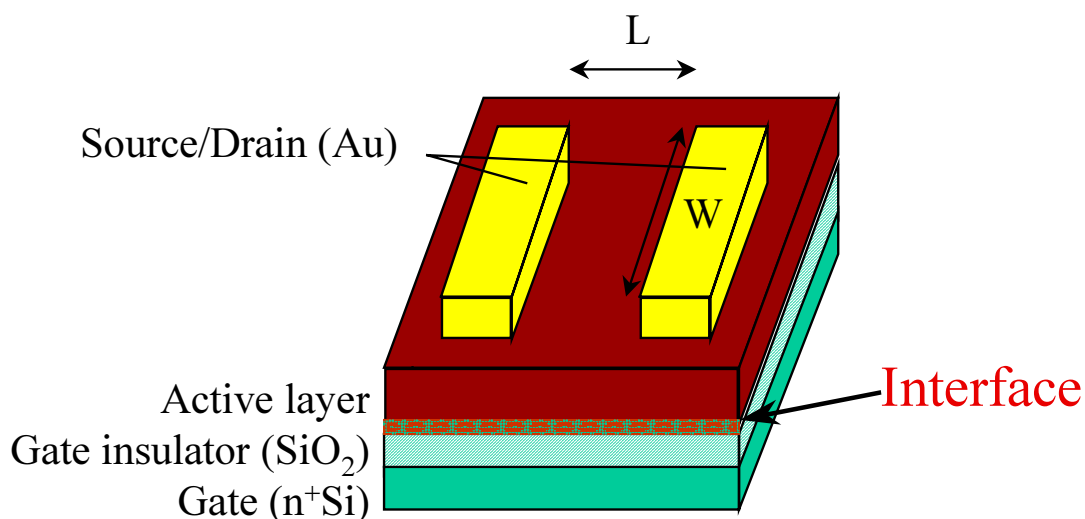
Figure 4. Schematic representation of a polymer based field effect transistor (FET).

The third structure we wish to illustrate is that of the field effect transistor (FET) as shown in Figure 4. The device fabrication is essentially similar to that of the LED and it consists of spin coating a polymer onto a given substrates followed by metal deposition. In this case the substrate constitutes the gate electrode and the device is in an up side down configuration with respect to conventional inorganic FETs.
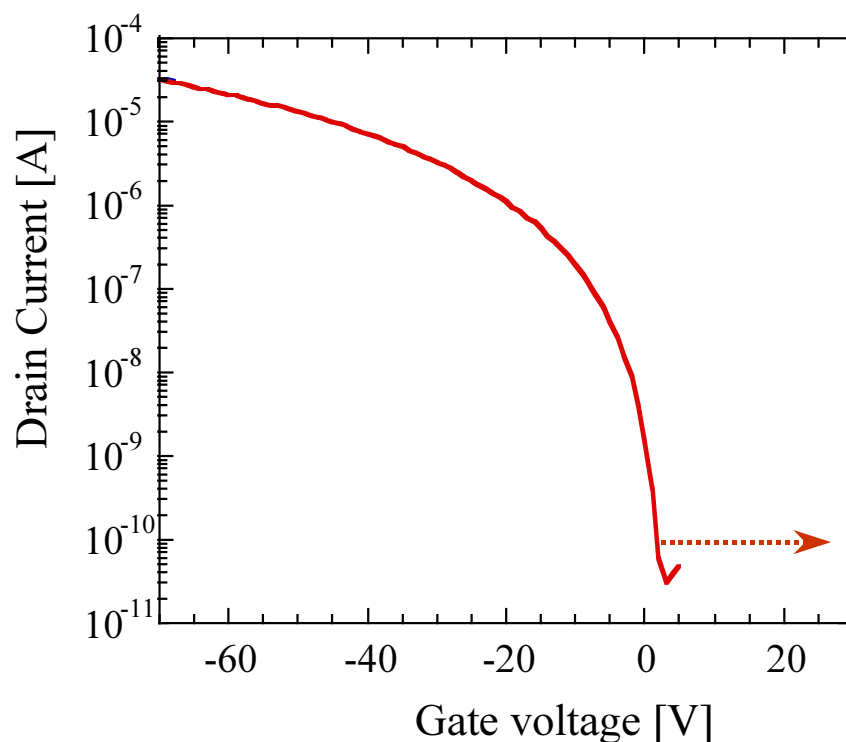

Figure 5. Device characteristics of a polymer FET (courtesy of H. Sirringhaus).

Figure 5 describes the characteristics of a polymer FET which can have on-off ratio of 10^7 and mobility values approaching 0.1 cm^{2}v^{-1}sec^{-1}.

Mirror 1   **Mirror 2**
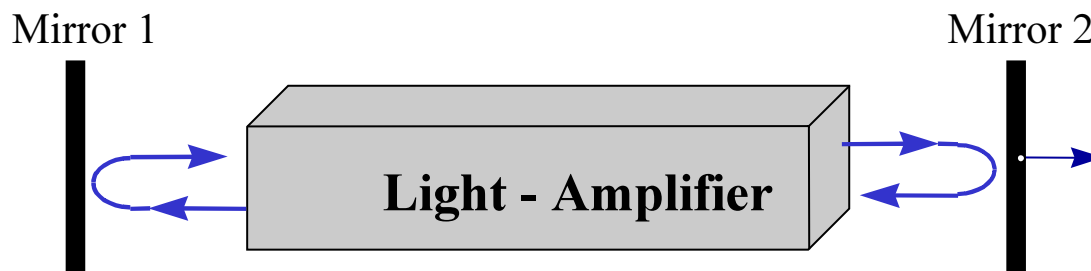
Light - Amplifier

Figure 6. Schematic description of a laser oscillator.

The last device to be described here is the organic laser [8]. By organic laser we mean that the amplifying medium (see Figure 6) is made of organic materials. Since the issue of lattice matching is irrelevant and it is possible to deposit polymers on almost any substrates the choice of mirrors or the feedback structure is limited by ones imagination only.

Metal
Emitter

DBR

Metal/dielectric
microcavity

Laminated
microcavity

WGM laser

Ring
Laser

2D Bandgap

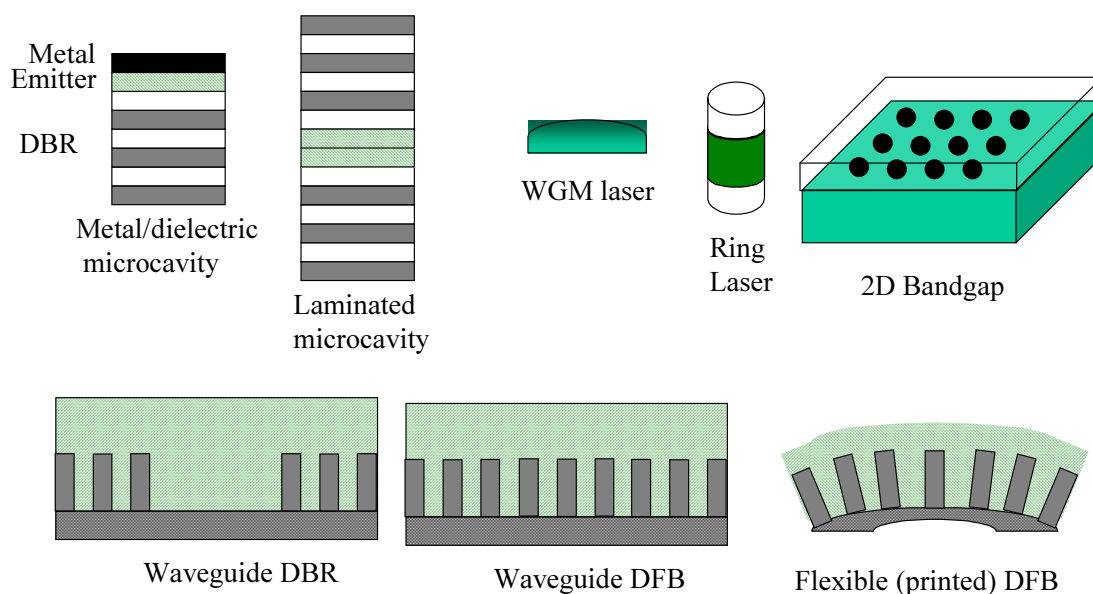Waveguide DBR   Waveguide DFB   Flexible (printed) DFB

Figure 7. Schematic description of the various laser structures that have been demonstrated using semiconducting organic materials. The acronyms stand for: DBR - distributed Bragg reflector, DFB - distributed feedback, and WGM - whispering gallery mode.

The various laser structures [14] that have been demonstrated are illustrated in Figure 7. Figure 7 clearly demonstrates the versatility of organic materials and some of the advantages of the solution processable ones. It will be hard to find another material system where lasers can be printed [15, 16], laminated [17], bent on flexible substrates [18], cover a wide spectral range [19-21], and all in a relatively non-expensive environment. This figure also show how useful these materials can be in

testing non-standard optical cavities as the 2D bandgap laser [22] or the ring laser on metal wire [23].

The parameter tuning

In the above discussion we were not concerned with the exact material (polymer) used or its structure. The materials are now of high quality and reproducibility so that one can detach the process of making the materials from the devices/experiments based of these materials. This resembles the situation found in inorganic devices where the device-physicist is rarely concerned with the exact dimensions/structure of the unit cell, which constitutes the bulk material. Unlike other fields the need to know material details is largely driven by the interdisciplinary nature of this field and the potential long-term benefits in cross-communicating between physics, engineering, chemistry, material science, and others.

To illustrate the relative ease of tuning material properties we draw in Figure 8 the structures of various materials which posses different properties. However, the similarity and the repeating building blocks are clearly observed.
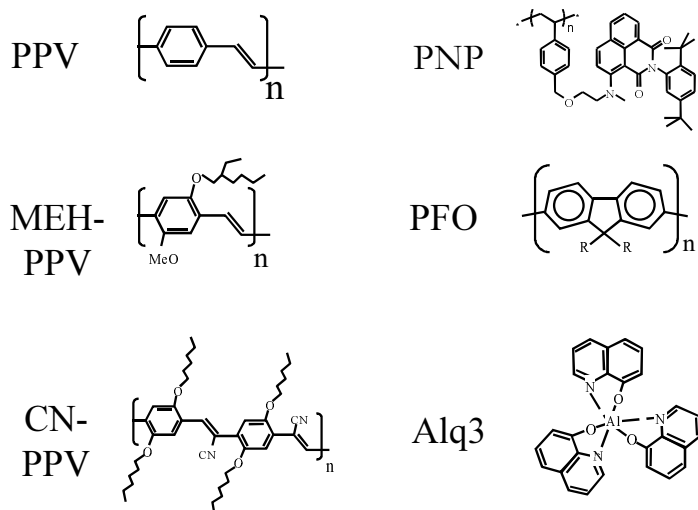
Figure 8. The structure of a sample of luminescent organic materials.

The structures in Figure 8 follow the convention that, unless otherwise shown, at the end of each line there is a carbon atom. Although the structures are projected onto the plane of the paper one should remember that the real structure is 3D like and not necessarily planar. For the polymers, which are a long chain, only the basic unit

(monomer) is sketched and the "()$_n$" means that this structure repeats itself many times to form the polymer chain.

The exact structure of each compound is not important at this stage and they are sketched here only to show that there is an obvious similarity between compounds. Together with Figure 9 it becomes apparent that it is relatively easy to tune properties of organic compounds. Here we choose to illustrate the emission colour and that organic materials can cover the entire visible spectrum and in the above example PFO is blue, PNP is green, and CN-PPV has an emission extending to the infra-red (see Figure 9).
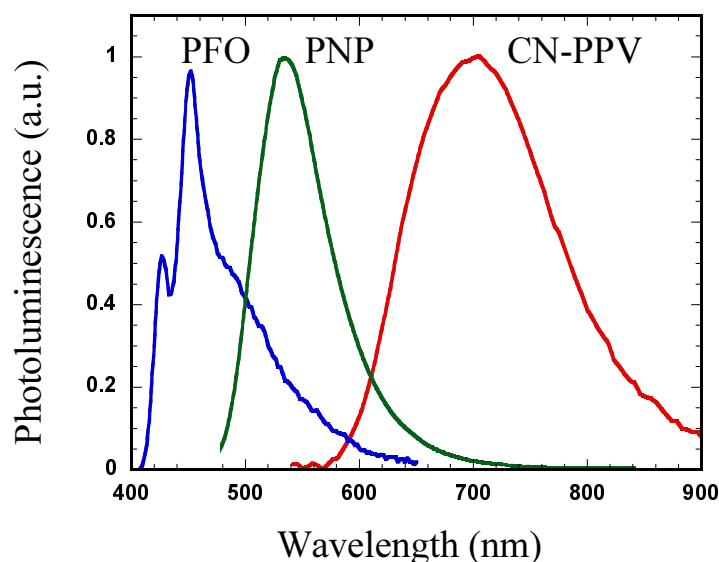

Figure 9. **Photoluminescence spectrum of a sample of polymers covering the visible spectrum.**

Not only the optical properties can be altered through structural modifications and a similar approach can be used to alter the electrical properties of organic materials. As an example, we show in Figure 10 the position of the conduction and valence bands (levels) of a few polymers. Note both the band-gap and the offset are varying between the polymers. This kind of approach has been successfully used to produce efficient heterostructure devices (see also Figure 2).
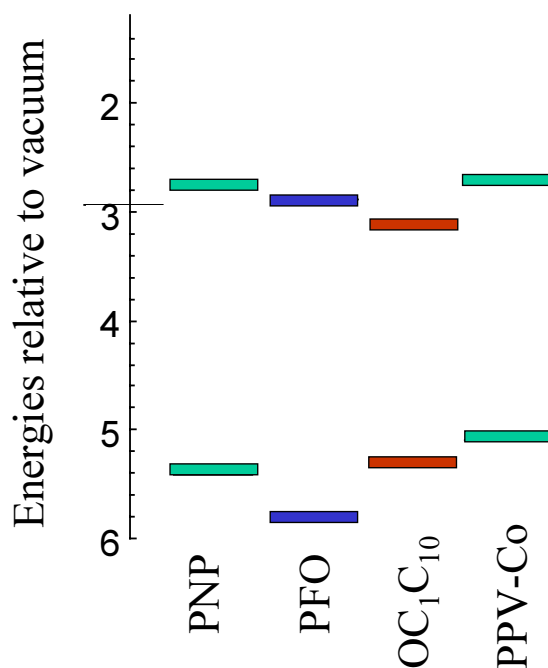
Figure 10. Energy levels (conduction/valence) of a few light emitting polymers.

So finally we can answer the question we started this document with – why organics. **Simply because it is fun!!** There are so many things one can do with this material system and there are still many important and <u>still open</u> questions so that it becomes almost trivial to learn new things and be productive at the same time. If you add to this the commercial impact and the fact that this subject is "hot", the answer becomes obvious. It is not only fun, it is important and there is a future in it for many different people.

Nir Tessler

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