Self-Amplifying Sensory Materials: Energy Migration in Polymer Semiconductors

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Summary: Signal amplification for ultra-sensitive detection has been achieved by energy migration in conjugated semiconducting polymeric assemblies. Critical to optimizing this effect is the synthesis of non-aggregate polymers, the multi-dimensional directional transport of excited states (excitons), and extending the intrinsic excited state lifetime of conjugated polymers. We developed new water-soluble non-ionic conjugated polymers for use in biosensory applications, which can be used to provide highly sensitive/specific ultra-trace detection that is immune to specificity problems that plauge ionic conjugated polymers.

Keywords: conjugated polymers, energy migration, non-aggregate polymers, semiconducting polymeric assemblies, signal amplification

Introduction

Fluorescent semiconductive polymers are powerful tools to create ultra-sensitive sensory materials and their unique electronic properties provide a new transduction capablity in sensory detection schemes.[1,2] We have focused on conjugated polymers with rigid rod-like structures consisting of aromatic groups connected directly or with double or triple bonds, where π-electrons are delocalized along the polymer chain. The origin of the amplification that enables these materials to produce ultra-sensitive sensors is the extended electronic structures that create energy bands (a conduction band and a valence band). Excited states (excitons) can move through these energy bands and in this way the conjugated polymer behaves as a molecular wire for the transport of excitons. The excitons travel along these molecular wires by a combination of Förster (long range dipolar interaction through space) and Dexter (strong electronic coupling by short range interaction) transport mechanisms, and the sensory detection event is realized when the excitons encounter a energy trap at a receptor site that is activated by a bound analyte molecules.[3] In most schemes, the excitons are quenched at an occupied receptor sites, and thus the fluorescence is diminished. In our schemes, the key factor leading to the high sensitivity of conjugated polymeric sensors is the migration of excitons through the material. Therefore, our efforts have focused on increasing

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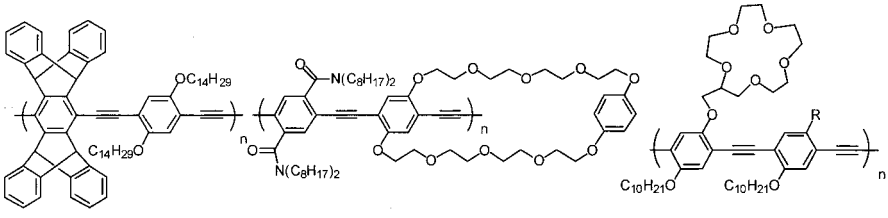
the efficiency of excition transport, which in turn increases the overall exciton diffusion length and thus the probability of the exciton encountering a receptor site occupied by an analyte molecule. According to this principle, we have designed new sensory systems based upon conjugated polymers, particularly poly(arylene ethynylene) derivatives (PAEs). In our quest for greater sensitivity, we have gained new insight into different electronic properties of semiconducting polymers important to exciton transport.

Non-aggregated Polymers

In our fundamental studies of the optical properties of PAE-aggregates using Langmuir Blodgett film techniques, we have shown that aromatic planer structures of PAE's backbone stack and aggregate strongly and, unless prevented by steric factors, display strong intermolecular electronic coupling to give non-emissive self-quenched materials.[4, 5, 6] In order to prevent this unfavorable event for exciton transport and thereby keep high quantum yields, we have designed pentiptycene[7] and rotaxane[3, 8] containing PAEs (Polymer **1** and **2**) that prevent strong interactions between polymer chains that leads to a non-emissive solid state. Pentiptycene-based PAE (Polymer **1**) showed a high fluorescence quantum yield in the film and a strong response to trinitro-toluene (TNT) molecules by fluorescence quenching[7]. In addition to non-aggregation of the polymers, this structure provides cavities that accommodate small aromatic molecules and enhance TNT binding in the films. Recently, this pentiptycene monomer was incorporated in cationic PAE particles for the purpose of DNA detection in water by fluorescence quenching.[9]



Polymer **1** Polymer **2** Polymer **3**

In contrast to the non-aggregation approach, chemosensors that make use of fluorescence self-quenching of PAEs have also been developed.[10] In this case PAEs were designed with pendant crown ether groups (Polymer **3**). The 15-crown-5 ethers do not display selectivity for specific alkali metal ions. However polymer **3** is endowed with specificilty due to the fact that 15-crown-5 ethers engages in multivalent (2:1) binding of potassium ions, however with sodium and lithium they display only 1:1 complexes. The resultant intermolecular multivalent

process produces a highly discriminating sensor for potassium ions, wherein the K^+ ions pull the polymer chains together and induce the formation of non-emissive aggregates.

Multi-Dimensional Directional Energy Migration

When the conjugated polymer sensor is used in dilute solution, movement of excitons is limited within a single polymer chain and the migration can be regarded as a one-dimensional random walk along the polymer chain. This results in the excitons visiting the same spot on the chain multiple times during the lifetime and spending majority of its lifetime close to where it was created. This inefficiency of energy migration in one-dimension reduces the chance for excitons to sample more receptors, which is needed to increase the probability of encountering analyte molecules to give a sensory response. Energy migration is enhanced when in a thin film where the exciton can move from one polymer to another by Förster and/or Dexter transport mechanisms and may diffuse beyond the length of individual polymer chains. As the exciton's ability to sample different receptor sites is very fast relative to the off-rate of the bound analytes, increasing dimensionality and the number of receptor sites an exciton can visit during its lifetime increases the amplification. For example a two-dimensional film behaves as a sheet transporting excitons rather than just a wire.

The enhancement in thin films is best highlighted by the extraordinary sensory properties of pentiptycene-based PAE (Polymer **1**). This material is the basis of an ultrasensitive detector for TNT that displays orders of magnitude (10^4-10^5) more sensitivity than any other explosive-detection systems.[7] However the excitons still have finite diffusion lengths, and to increase diffusion lengths 3-dimentional multi-layer polymer films have been designed, wherein the excitons are directed though polymer layers to transduction sites. As mentioned earlier, fluorescence of PAE solid films (and indeed most conjugated materials) tend to decrease due to formation of non-emissive aggregates. Therefore the rigid three-dimensional structures that prevent strong interaction with neighboring polymer chains (Polymer **1** and **2**) are necessary. By inducing a directional (vectorial) migration of excitons in polymer films with an energy gradient, energy migration is made more efficient.[8]

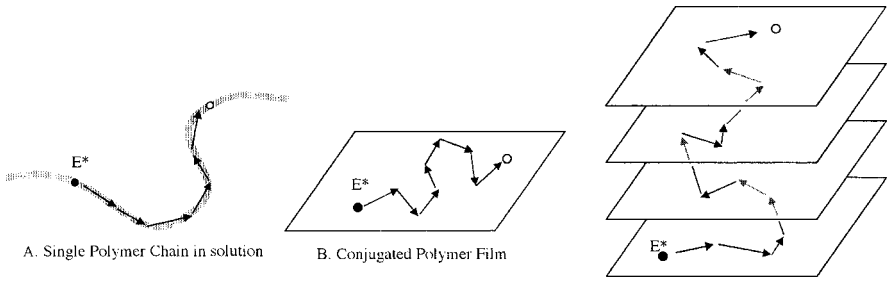
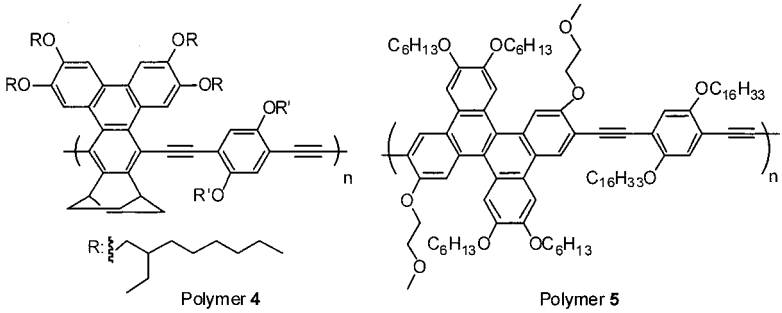


Fig. 1. Schematic presentation of multi-dimensional random walk of exciton (E*): (A) along a isolated polymer chain in solution (one-dimension), (B) on a conjugated polymer thin film (two-dimention), (C) within a conjugated polymer multi-layer film (three-dimension). In all cases the forward and backward random walks are present. In the single polymer chain the exciton spends much more of the time retracing its path. This is less likely in thin films and can be further minimized by creating an energy gradient in multi-layer films.

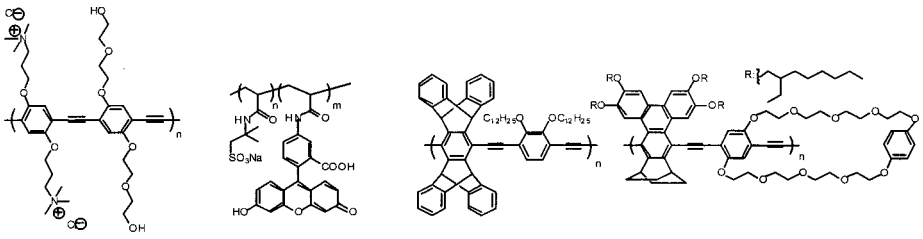
Lifetime Modulation

Another approach for increasing sensitivity is to extend the intrinsic lifetime of excited state of PAEs. Based upon what we have determined regarding the mechanisms of energy transfer in PAEs,[11] larger lifetimes of excited states leads to longer exciton diffusion lengths, which increase the chance that excitons will encounter receptor sites bound with analyte molecules. The lifetimes of PAEs have been extended by integrating larger two-dimensional polycyclic aromatic structures into the polymer backbone. Larger lifetimes have been realized in triphenylene[11] or dibenzo[g,p]chrysene[12] based-polymers (Polymer **4** and **5**) as compared with simple (phenylene-ethynylene) polymers, with similar fluorescence quantum yields.[11]



Light Harvesting

Fluorescence resonance energy transfer (FRET) is a widely used method to probe biological macromolecular conformations in proteins and DNA and also detect trace amounts of analyte molecules and biomolecular recognition events. In FRET schemes, specific emission can be observed depending on the pair of chromophores. A limitation of fluorescence quenching detection schemes is that a multitude of potential interfering species can cause quenching and the detection signal may not always be specific to the quencher. As we mentioned above, multilayers of conjugated polymers have been designed for the directional transportation of excited states. The ability to control the direction of energy migration in PAEs provides a number of opportunities to construct excellent chemosensors based on FRET schemes. The key feature is that excitons are directionally transported toward an acceptor to which the excited state energy is transferred. The acceptor can receive energy effectively from multiple polymer segments, which have been transported over large distances; so light-harvesting FRET produces an amplified emissive signal from the acceptor. We have demonstrated this principle to produce a turn-on chemosensor involving FRET between a chromophore and PAE.[13] Polymer thin films were constructed by layer-by-layer deposition of cationic PAE (Polymer **6**) and anionic polyacrylamide (Polymer **7**) modified with aminofluorescein, a chromophore widely used in biological and biosensory schemes, and the emission signal from the fluorescein is amplified. This study demonstrated that the PAE film harvests light and transfers it efficiently to a small dye molecule (fluorescein). Multi-layer polymer assemblies that consist of three different PAEs (Polymer **2**, **8**, **9**) having different energy gaps were also designed.[14] The bandgaps decrease from the bottom layer (Polymer **8**) to middle layer (Polymer **2**) and to surface layer (Polymer **9**) so that the film has a vectrical energy gradient. In this case, the polymers have fulfilled the FRET requirement of spectral overlap of a donor emission and an acceptor absorption. The excited state of the bottom layer, Polymer **8**, migrates directionally to the polymer layers with lower bandgaps toward surface via Förster mechanisms, and dominant emission is from the surface polymer (Polymer **9**) with the smallest band gap. This directional migration of excitons enforced by an energy gradient makes exciton transport length longer and thus energy migration more efficient because multiple visits of the same site are reduced. This result also revealed that we can extend the exciton diffusion in multilayer conjugated polymer assemblies, and this is beneficial to development of not only chemosensors, but also organic electronics and electrooptical devices.

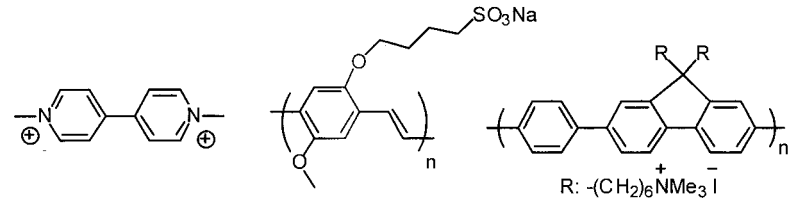


Polymer 6 Polymer 7 Polymer 8 Polymer 9

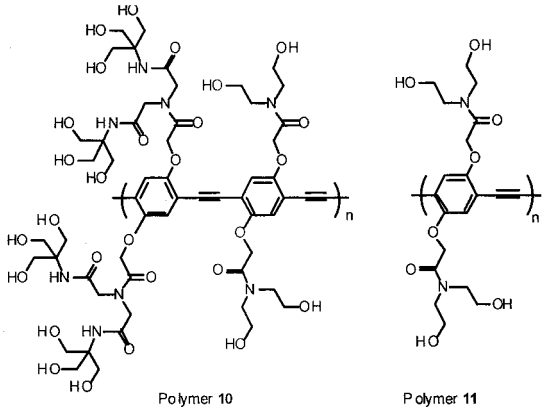
Conjugated Polymers for Biosensors

The sensory schemes discussed above also have great potential for producing highly sensitive biosensory materials. In particular, water-soluble conjugated polymers can find many applications for producing ultra-sensitive biosensors that function in aqueous environments for diagnostic use in medicine, biotechnology, and security applications, with the latter being greatly needed to counter the threat of bio-weapons. Indeed conjugated polymer-based biosensors in thin film form and/or in organic media have received considerable attention.[2] One of the major problems for conjugated polymeric materials in these applications is the intrinsically hydrophobic nature of the conjugated system that gives rise to poor water-solubility. This strong hydrophobic nature of polymer backbone generally results in aromatic π-π stacking which limits their solubility in water. This strong interaction between polymer chains enhances the formation of non-emissive aggregates that reduce sensitivity. To overcome this difficulty, ionic conjugated polymers have been utilized in biosensory schemes.[2,17,18,19] Ionic groups such as sulfonate,[15] carboxylate,[16] or ammonium groups[17] in the sidechains provide strong hydration and electrostatic repulsions between polymer chains that promote water solubility of the conjugated polymers. By making use of the fact that these ionic conjugated polymers (conjugated polyelectrolytes) can electrostatic complex with ionic molecules, new detection schemes have been proposed and examined. Chen et al.[18] have recently made use of our amplification principles and have demonstrated that fluorescence of water-soluble anionic PPV derivative with sulfonate group on the side chain (MPS-PPV) was quenched efficiently by methylviologen (MV^{2+}) as shown in our earlier studies. The strong fluorescence quenching of MPS-PPV results from formation of electrostatic complex of the anionic polymer and the cationic quencher. In this scheme the fluorescence of MPS-PPV is quenched by B-MV that binds electrostatically to the polymer and the fluorescence of the polymer was recovered removing the quencher through avidin binding. Also building upon our principles MPS-PPV has been shown to be quenched electron transfer protein, cytochrome *c* (cyt *c*), reported by Fan et al.[19] and DNA detection

using a cationic conjugated polymer (CCP) was reported by Gaylord et al.[17] The latter scheme makes use of our earlier FRET method and a fluorescein-labled neutral peptide nucleic acid (PNA-C*) that has complementary sequence with target DNA was paired with DNA/CCP hydrides by nucleic acid matching. In this process, target DNA served as a specific interaction to connect a fluorescent probe (PNA-C*) and CCP. This complexation brings the fluorecein in the vicinity of CCP and thus results in signal amplification from the fluoescein by FRET.



Methylviologen (MV^{2+}) MPS-PPV CCP



Polymer **10** Polymer **11**

In spite of these laboratory demonstrations ionic conjugated polymers have severe limitations for use in biosensor schemes because (1) the solution conditions (pH, ionic strength, temperature) have to be adjusted to prevent polymer aggregation and (2) electrostatic interaction between ionic polymers and biomolecules such as proteins and DNA are non-specific and therefore will reduce specificity for target molecules. To overcome these problems we have synthesized non-ionic water-soluble conjugated polymers, which promise to constitute a platform for producing biosensors with higher specificity. Polymer **10** was designed to be surrounded by dendritic side chains with a number of hydroxyl group and

amide bonds.[20] This structure was designed to shield the hydrophobic polymer backbone from water and promote the solubility in water. Polymer **10** is completely water-soluble, wehereas less hydrophilic Polymer **11** has a limited solubity in water.

In summary, we have developed fluorescent conjugated polymers and their assemblies as a versitle platform from which to produce ultra-sensitive sensory materials. The high sensitivity in detection was obtained by intricate designs of chemical structures directed at producing high quantum yield fluorescent polymers, extended lifetimes, and structured films for efficient exciton transport in the materials. These design principles are presently being extended by ourselves and others to biosensor and bioconjugates with semiconducting polymers.

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