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Introduction: Organic Electronics and Optoelectronics

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Organic electronics has been the focus of a growing body of investigation in the fields of physics and chemistry for more than 50 years. Up to only a short time ago, organic electronic and optical phenomena have been the domain of "pure research", somewhat removed from practical application.[1] The attraction of this field has been the ability to modify chemical structure in ways that could directly impact the properties of the materials when deposited in thin film form. While there was always a hope that organic materials would ultimately have uses in applications occupied by "conventional" semiconductors, for a long time their stability and performance fell well short of those of devices based on materials such as silicon or gallium arsenide. That situation changed dramatically in the mid-1980s, with the demonstration of a low voltage and efficient thin film light emitting diode by Ching Tang and Steven van Slyke at Kodak.[2] Although that particular first demonstration was not of sufficiently high performance to replace existing technologies, it nevertheless opened the door to the possibility of using organic thin films as a foundation for a new generation of optoelectronic devices.

Since that first demonstration, organic thin films have proven useful in a number of applications, some of them now reaching the consumer market. The most successful is the organic light emitting device, or OLED, which is currently used in long-lived and highly efficient color displays. Not far behind OLEDs are organic thin film transistors and low cost and efficient organic solar cells. Eventually, we may see more exotic devices such as organic lasers and memories.

This Thematic Issue provides an update on some of the best work and advances in organic electronic materials and devices. Authors worldwide who lead the field have written comprehensive reviews that provide an unprecedented depth of insight into the status and challenges yet facing the application of new organic electronic semiconductor materials and devices.

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As noted above, a key to the design of high performance optical and electronic organic devices is the understanding of the electronic structure of both molecular and polymeric materials. Subtle changes in structure or composition of an organic material can markedly alter its bulk properties. In their contribution, Coropceanu, Cornil, da Silva Filho, Olivier, Silbey, and Brédas use theoretical methods to explore a number of different and important organic material systems. Using their models and correlations with experimental data, they build a series of clear structure−property relationships. Their relationships can be used to understand the properties of existing devices and predict the ideal materials sets for use in the next generation of electronic and optoelectronic devices.

The charge carrier transport properties of molecular organic materials have been investigated extensively up until the present. Since the introduction of triarylamines as hole transporting materials into xerographic systems, a wide range of different molecular materials systems have been investigated as hole and electron transporting materials. Shirota and Kageyama discuss the theory of carrier conduction in both amorphous and crystalline organic materials, and extensively review the materials systems used as hole and electron transporters in organic LEDs, solar cells, and transistors.

Since many organic devices rely on amorphous organic materials, thermal stability is critical in many device applications, since low melting or glass transition temperatures can lead to device failure at ambient temperatures. Saragi, Spehr, Siebert, Fuhrmann-Lieker, and Salbeck have attacked the problem of forming thermal stability by incorporating many of the important semiconductor materials systems into a spirobifluorene framework. They discuss the synthesis of these materials as well as their utility in controlling their optical and electronic properties application in organic devices.

For use in high performance thin film transistors, with application to display and focal plane array backplanes, as well as very low cost logic circuits, the semiconducting material must have high carrier mobility, form crystalline films whose conductive axes are aligned between the source and drain electrodes, and be processable. Changes at the molecular level significantly affect all of these parameters, giving the chemist an unprecdented degree of flexibility in materials design. A number of different materials systems have been introduced into thin film transistor structures, as discussed by Murphy and Fréchet. In their contribution, they consider the fabrication of thin film transistors and the characterization methods used for both devices and thin films, and then they comprehensively review a wide range of molecular and oligomeric organic compounds in transistor structures, highlighting the advances that have been made in achieving high mobility materials.

The organic materials used in electronic and optoelectronic devices are generally split into two groups: i.e., small molecules and polymers. The former are typically deposited by vapor methods in low or high vacuum environments and have a well-defined molecular weight. Polymers, on the other hand, must be processed from solution and have a molecular weight distribution that is described by the polydispersity of the materials, giving polymers good glass-forming and mechanical properties. Dendrimers are a class of materials that in some ways fall between molecular and polymeric materials. Dendrimers are highly branched molecules, with the branches originating at the molecular core. They typically have very high but nevertheless well-defined molecular weights. Thus, while dendrimers are molecular in nature, their high molecular weight and irregular shape give them bulk properties resembling those of a polymer. In their contribution, Lo and Burn discuss the construction of dendrimers, including the use of the core−branch structure of dendrimers to control the properties of the materials on the nanometer scale, as well as their use in organic LEDs and solar cells.

While many of the electronic properties of organic materials and their associated devices are similar, the methods used for fabricating organic and inorganic based devices are considerably different. The use of organic compounds as active materials in electronic and optoelectronic devices opens the door to a large number of efficient and potentially low-cost methods for fabricating useful, and, in some cases, complicated structures that are inaccessible by conventional methods using conventional semiconductors. For example, the techniques available for processing and patterning organic materials move far beyond the lithographic methods that govern inorganic devices. Menard, Meitl, Sun, Park, Shir, Nam, Jeon, and Rogers review a number of such methods for the growth and patterning of organic materials. After reviewing the methods used for optically based patterning of organic materials, they discuss the use of a range of processes that are unique to organic materials, including embossing, imprint lithography, and capillary molding and printing, using a range of different stamping approaches.

The control of the interfacial properties within organic electronic and optoelectronic devices is critical in achieving high efficiencies. Both organic−organic and organic−inorganic interfaces are important in this regard. In their contribution, Zahn, Gavrila, and Salvan discuss the use of vibrational spectroscopic methods to probe the structure of the interfacial properties of organic systems, such as geometric structure, band bending, and interfacial chemistry. While these methods can be equally well applied to both polymeric and molecular materials, this review focuses on archetype molecular organic materials with application to devices. Using these approaches, it is possible to “fine-tune” the properties of the interface, controlling organic structure as well as the electronic properties of the structures containing these heterogeneous material junctions.

As noted above, the most highly advanced organic devices are organic light emitting diodes (OLEDs). These devices have been demonstrated with near unity quantum efficiencies, and they have been developed to the point that that they are commercially available in small, hand-held, full color displays. While the demonstrated efficiencies for OLEDs are very high, their operating voltages can be high, limiting their power efficiencies (optical power/electrical power). Walzer, Maennig, Pfeiffer, and Leo discuss the methods that have been developed to lower the operating voltages to circumvent this deficiency that ultimately will govern the usefulness of OLEDs in mobile displays and interior illumination applications. Incorporating p- and n-type dopants in the transporting layers of the devices lowers their operating voltages to levels close to the theoretical limits, i.e., where the operating voltage approaches that of the emitted photon energy. Their contribution discusses the physics behind conductivity doping of organic materials, the methods that are used to prepare these material, and their use in high power efficiency OLEDs.

Organic materials for use in laser emission have been a subject of investigation since the first report of a dye laser.

However, the lasers that have become ubiquitous in society for use in applications ranging from optical communications, to optical memories, and to biomedical testing are entirely based on inorganic semiconductor materials. Nevertheless, organic semiconductors combine novel optoelectronic properties with simple fabrication techniques and offer the scope for tuning the chemical structure to give desired features (such as emission wavelength), making them attractive for use in many laser applications. Samuel and Turnbull review the current state of the art in organic semiconductor lasers, covering both the theory behind their operation as well as the materials, structures, and performance of these devices. They also highlight the challenges that lie ahead in achieving electrically pumped lasing in organic materials.

Transistors based on inorganic semiconductors form the basis for a wide range of electronic devices that utilize their high speed and small size for integration on a massive scale. Organic transistors have the potential to have a great impact. However, they will not compete directly with silicon or gallium arsenide due to the lower charge mobilities and device lifetimes of organic based systems. Nevertheless, organic transistors and circuits are technologically interesting because they have potential to serve in inexpensive (perhaps disposable) and flexible electronic circuits. Major applications include radio frequency identification tags and flexible display backplanes. These circuits can be potentially fabricated by simple printing methods, not requiring the demanding environment needed for silicon based circuitry. In their contribution, Zaumseil and Sirringhaus review the principles of transistors and discuss the issues most important to organic transistors. After this introduction, they discuss the fabrication and properties of n-channel devices as well as ambipolar transistors, and they finish their technical discussion by considering the more exotic light emitting transistor.

One of the earliest applications of organic optoelectronic devices is in solar cells.[3] Inorganic semiconductor solar cells are well developed and are being deployed worldwide; however, the high cost of their manufacture ultimately limits their widespread acceptance as a source of renewable energy. The potential for low-cost manufacturing afforded by organic devices gives organic solar cells the potential to significantly impact the energy landscape, making them useful in a wide range of environments. In their contribution, Günes, Neugebauer, and Sariciftci discuss the advances made in developing organic solar cells. The authors discuss the device structural approaches that have been used to prepare these devices, as well as the design of materials for simultaneously achieving high solar absorptivity and optimal device structure for harvesting this electrical energy. Their review emphasizes polymeric and composite polymeric/molecular materials, although rapid advances have also been achieved using small molecular weight compounds.

Chemical sensing is also emerging as an important application for organic materials. Uses in military, biomedical, and industrial environments are ubiquitous, and having the ability to sensitively detect specific chemicals, both accurately and inexpensively, could vastly expand their applications. Research on advanced organic materials has led to marked improvements in the sensitivity and versatility of chemical sensors. In their article, Thomas, Joly, and Swager describe the design and performance of chemical sensors based on fluorescent conjugated polymers. They focus on the parameters that control sensitivity and response time in sensing, and they discuss the methods that are used to design the optimal materials and sensor structures for detecting and quantifying analytes ranging from explosives to complicated biomolecules.

Overall, most of the major topics now being investigated in this large and ever growing field are covered by the articles in this Thematic Issue on organic electronic materials and devices.

References

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