

Progress and Challenges in Commercialization of Organic Electronics

Yueh-Lin Loo and Iain McCulloch, Guest Editors

Abstract

The field of organic electronics is entering its commercial phase. The recent market introduction of the first prototypes based on organic transistors fabricated from solution is set to augment the existing market presence of organic light-emitting diode applications. Organic photovoltaic products are not far behind. In this article, we provide a brief overview of these devices, with our main focus being organic transistor applications. In particular, we examine some of the key performance requirements for working devices. We also review some of the important advances in semiconductor design and device fabrication techniques and discuss some of the technical challenges that remain in the optimization of next-generation products.

Introduction

The basis of organic electronics is predicated on the ability of a class of functional organic molecules known as organic semiconductors to actively transport charge, emit light, or absorb light under appropriate conditions. Devices comprising these organic semiconducting materials include transistors, light-emitting diodes, and photovoltaic cells, all of which are reviewed in detail in this issue. From the fabrication perspective, materials can be broadly classified as processable either by evaporation or by solution. Whereas polymeric semiconductors are clearly in the solution-processable category, discrete small-molecule organic semiconductors can be functionalized to fall into either group. Historically, evaporative processing has led the development of most devices and is therefore more advanced. However, the potential to print at high throughput and high resolution from formulated inks offers the greatest commercial opportunity, driving solution-processable material development. Interest

is especially intense in the transistor and solar cell fields, where low cost is a strong market driver.

A prerequisite for the molecular composition of both categories of semiconductor is that they contain a conjugated π -electron system, where the delocalized molecular orbitals are energetically accessible and typically less than 3.5 eV apart. Organic transistors require that the organic semiconductor have a highly organized microstructure, with the molecular orbital systems closely packed together. Currently, most organic transistor's exhibit *p*-characteristics, that is, they transport holes rather than electrons. Work remains to develop robust trap free interfaces in organic transistors so the transport of electrons is also possible.

The active layer in a solar cell comprises a light-absorbing semiconductor, which typically is also the hole-transport material. This component is typically blended with organic semiconductors that exhibit *n*-characteristics. Challenges remain

in optimizing transport within the layer, absorbing more photons, and separating charge at the semiconductor interfaces.

Organic light-emitting diode (OLED) devices, particularly small-molecule evaporated devices, are becoming increasingly complex, requiring a range of injection, transport, blocking, and emissive materials. Both fluorescent and phosphorescent electroluminescent semiconductors can be used. Although phosphorescent dopants exhibit excellent efficiencies in both red and green, due in part to their ability to harvest both singlet and triplet excitons, deep blue emission remains a problem. Current displays typically still use fluorescent blue emitters as a result. New doped systems are reducing interfacial energy barriers, leading to lower voltage operation, and there are continual enhancements in device lifetime and efficiency of polymer emitters, as well as improvements in solution printing methods.

Commercial Status of Organic Electronics

Organic light-emitting diode technology is perhaps the most advanced organic device platform. Sony currently markets an 11-in. television based on OLED technology that boasts a 3-mm-thick panel and 178° viewing angle. In the display arena, OLED technology promises to compete with liquid-crystal and plasma technologies and offers unique attributes, such as ultrabright colors and low power consumption in addition to the features mentioned previously. Individual OLED devices, in their simplest form, consist of organic active layers, an emissive layer and transport layers, sandwiched between two electrodes, a cathode and an anode. When a voltage is applied across the electrodes, the cathode injects electrons into the emissive layer, whereas the anode withdraws electrons, generating holes in the whole transport layer. These electrons and holes drift to the interface between the emissive and transport layers under the applied cell potential; it is the recombination of electron-hole pairs that generates radiative emission. In organic semiconductors, holes are more mobile than electrons. Recombination thus frequently happens within the emissive layer.

Although OLED technology has clearly shifted from the research and development phase to the scale-up phase, where primary concerns now deal with processing yields, fundamental science concerning the stability of the active layer when exposed to high current densities over extended periods still remains to be resolved. OLED devices can be fabricated from either polymer or small-molecule materials. Recent scientific

interest has focused on polymer-based devices that can be used in large-area applications. In these applications, the use of small molecules is limited because they are not amenable to form smooth, conformal coatings because of their low solution viscosities.

More recently, solid-state lighting has been gaining interest. In this case, the pattern resolution requirements are relaxed. Both the architectural and display sectors represent potentially huge opportunities for new product designs. Device lifetimes, color shifts, and deep blue electroluminescence remain challenges to be resolved before these devices become common in the market. The article in this issue by So et al. describes the use of OLED technology for solid-state lighting and highlights recent developments in the synthesis of active materials and the design of new device architectures and light extraction schemes.

Another organic device platform is organic photovoltaics. These devices, also called solar cells, are also now emerging as a major area of interest, prompted both by favorable government policy in alternative energy and by the increasing commercial opportunities as cell performance improves. Organic solar cells operate on the reverse principle to OLEDs. The scheme in Figure 1 illustrates how an

organic solar cell functions. These devices are diode structures, typically comprising both an electron donor light-absorbing semiconductor and an electron acceptor semiconductor, with a blend microstructure or bilayer, creating an interfacial heterojunction. The cell operates by first absorbing incoming photons through promotion of an electron from the highest occupied molecular orbital (HOMO) energy level to the lowest unoccupied molecular orbital (LUMO) energy level. In conjugated systems, where the π electronic orbitals are delocalized, this is typically a π - π^* transition. The resulting bound electron and hole pair is referred to as an exciton, which can then diffuse from the electron donor domain, where it was formed, to the interface with the organic electron acceptor semiconductor. Because of the lower lying LUMO energy level of the electron acceptor semiconductor, it is energetically favorable for the electron to transfer to the electron acceptor semiconductor. In an optimal system, dissociated charges are then swept toward the electrodes by the built-in cell potential. Obviously, the more photons absorbed, the greater the charge generation, and the larger the power output.

Extensive research is being targeted at extending the absorption spectra of electron donor semiconductors to longer wavelengths, as a significant fraction of photons in this energy range are currently not being absorbed. Bulk heterojunction photovoltaic devices contain light-absorbing, hole-transporting semiconductor polymers that phase separate at the nanometer length scale from electron-transporting semiconductors during the fabrication process. These devices are particularly promising, and Brabec et al. review progress in this area in this issue.

The devices achieve a compromise between power conversion efficiency and compatibility with the type of manufacturing processes that enable low-cost production. Improvements in device efficiency are being achieved by focusing on new materials that have well-designed electronic energy levels capable of generating larger cell voltages, absorbing more light, improving charge separation, avoiding losses from the recombination of generated charges, and having optimal transport properties.

Low-bandgap electron donor polymers with lower-lying HOMO energy levels are being developed to be used in combination with soluble fullerene derivatives. These polymers enable longer wavelength absorption toward the infrared part of the solar spectrum, and their low HOMO energy levels can generate a larger open-

circuit voltage. Phase separation of *p* and *n* semiconducting components into discrete nanoscale domains, induced during thin-film processing can be enhanced through the incorporation of processing additives,¹ leading to more efficient devices.

The role of molecular orbital energy levels and geminate recombination processes in limiting the efficiency of the interfacial separation of photogenerated charges is also becoming an increasingly important area of research. Recent evidence³ shows that larger energies than expected are required for effective charge dissociation in thiophene-containing polymers with delocalized energy levels, which are commonly used in organic photovoltaics. Electrode materials are also an important subject of investigation, with the replacement of indium tin oxide (ITO) by lower cost printable inks² being a particular focus.

In addition to organic solar cells and organic light-emitting diodes, thin-film organic transistor devices are generating a high level of interest and are poised to enter the commercial phase. Several startup companies are leading the way with small monochrome electrophoretic display products that are driven by organic-transistor active-matrix backplanes. These displays create an image through electrophoresis, whereby the movement of charged pigment particles in a contrasting colored liquid medium is driven by the application of an electric field across the pixel cell.

Improvements in image contrast, resolution, and speed, as well as reductions in drive voltage, have stimulated recent interest, and commercial products are already available with monochrome front-plane electrophoretic display (EPD) effects from companies such as E Ink and SiPix. Higher complexity displays require both improved transistor performance and enhanced operating lifetimes; thus, significant development activities in new materials and processing still must be addressed.

Following behind are radio-frequency identification tag and logic applications, where adoption of standards, integration, and high-frequency operation are currently impediments to commercialization. Organic transistors for sensing applications are also interesting. For example, the article in this issue by Someya et al. details the use of organic transistors as pressure-sensitive sensors for the development of electronic skins. In the following sections, we highlight some areas in the organic transistor arena where progress in device performance and manufacturability has been made and others where challenges remain.

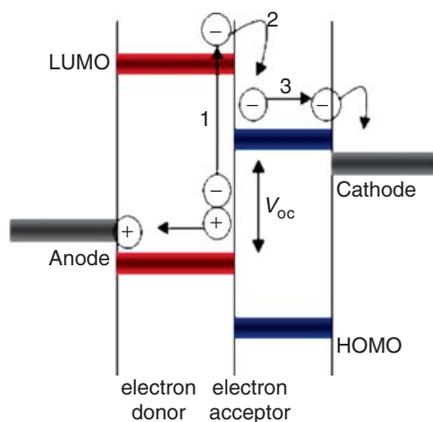


Figure 1. Heterojunction energy diagram of an organic photovoltaic cell, illustrating (1) light absorption and promotion of an electron into the LUMO of an electron donor semiconductor and formation of an exciton; (2) electron transfer from the LUMO of the electron donor semiconductor to the LUMO of an electron acceptor semiconductor, forming a charge-separated state; and (3) subsequent charge separation and transport to the electrodes. *Note:* HOMO is highest occupied molecular orbital, LUMO is lowest unoccupied molecular orbital, and V_{oc} is open-circuit voltage.

Organic Transistors in Displays

Currently, organic transistors are most promising in display applications, where the electrical performance of organic semiconductors is now acceptable for many display effects.⁴ Transistors are basic building blocks for integrated circuitry, and each transistor is a three-terminal device that effectively acts as a switch. (see Figure 2 for the architecture of an organic transistor.) When a bias is applied to the gate electrode, charges can accumulate capacitively at the organic semiconductor–dielectric interface. This, in turn, creates a channel in which holes or electrons (depending on the nature of the organic semiconductor and the bias applied) can transport between the source and drain electrodes. It is thus the gate bias that controls the switching of the device between its on and off states.

Most flat-panel displays can be described as comprising both a frontplane and backplane. The frontplane contains display optical effect which is used to control the outgoing light from an array of pixels, and collectively, these pixels generate the optical image. This image can arise from reflected (in the case of the electrophoretic display effect), emissive (OLED), or transmissive (LCD) light from the pixel area. In an active-matrix display, the backplane functions to individually address each pixel and houses the display electronics, as illustrated in Figures 3a and 3b.⁴ Both the electrophoretic and liquid-crystal display effects require the transistor to modulate an electric field across the pixel to switch the pixel on or off. In contrast, the OLED effect, which is current-driven, requires both a switching transistor and a driving transistor to supply the current across the OLED.

Currently, amorphous silicon is used as the semiconductor in many transistor backplanes where the performance requirements of the display effect are not

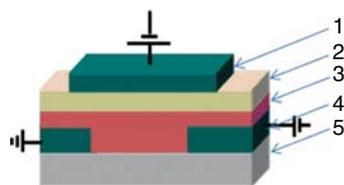


Figure 2. Top-gate, staggered-contact thin-film transistor (TFT) architecture, showing the (1) gate electrode, (2) dielectric (typical thickness = 100–500 nm), (3) organic semiconductor (typical thickness = 20–100 nm), (4) source and drain electrodes (channel length = 1–100 μm , channel width = 10–500 μm), and (5) substrate.

particularly high. For example, the electrophoretic display (EPD) effect is recognized as requiring the lowest semiconductor electrical performance from backplane transistors and is hence the most compatible with the performance limitations of organic transistors. As this is a reflective effect, each switching transistor can occupy almost the full area underneath the pixel. This means that the transistor width (W) can be maximized, thus delivering more current per pixel, compensating for the lower mobility of the organic semiconductor. As a result, mobility specifications are in the range of 0.01 $\text{cm}^2/(\text{V s})$ for a device operating at low refresh rates, low resolution, and small display size.

Another favorable aspect of the EPD effect is that, once the pixel is charged, no further power is required to retain the image; in other words, it is bistable. The duty cycle load on each transistor is therefore minimized, and consequently, the devices last longer, as their operating times are reduced. Increasing the display complexity, leading to higher numbers of rows and columns, faster pixel charging speeds, and consequently higher on currents, translates into higher semiconductor mobility requirements, as described in Figure 4.

EPD displays with higher complexity are further from commercialization, not only because of the need to further develop the backplane circuitry, but also because the frontplane technology enabling full color and video speed is not yet fully developed.

Comparing EPD and LCD panels with identical resolutions and sizes, it is often the case that the EPD cell leaks current as a result of ionic impurities and thus

requires higher mobilities than would be predicted to switch the cell. A comparison should bear in mind, however, that the transistor size of the EPD pixel can be larger, and thus, the corresponding mobility requirements of the transistor should be lower. The LCD effect is transmissive, in contrast to the EPD effect, and to maximize the light output through the pixel, the opaque transistor should be as small as possible (i.e., the pixel should have a high aperture ratio). Thus, to compensate for a small transistor size per pixel, the current output per device width should be correspondingly larger, requiring higher semiconductor mobilities.

The technology to manufacture high-performance liquid-crystal displays (LCDs) already exists and moves forward inexorably. Most larger displays currently employ amorphous silicon transistors (although high-resolution displays often require polysilicon). The opportunity to replace this entrenched technology might be possible only where lower cost manufacturing can be achieved through potentially fewer mask steps in fabrication and where new product features such as flexibility and ruggedness are desired.

Using an organic transistor to drive an organic light-emitting diode display is an extremely attractive proposition in the quest to drive down production costs and enable new functionality. In such a production scenario, the display can potentially be fabricated by high-throughput techniques, such as inkjet printing, or even contact printing methods, such as gravure, thus eliminating the need for the currently expensive mask-based lithographic steps. Although a top-emitting OLED could potentially allow larger

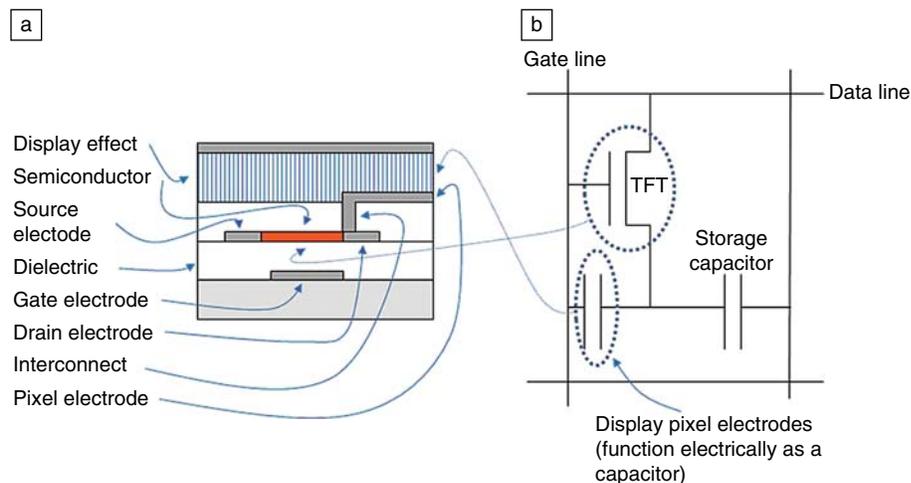


Figure 3. (a) Cross section of a simple display pixel, illustrating the interconnect between the thin-film transistor (TFT) and pixel electrode and (b) circuit diagram of the backplane layout.⁴

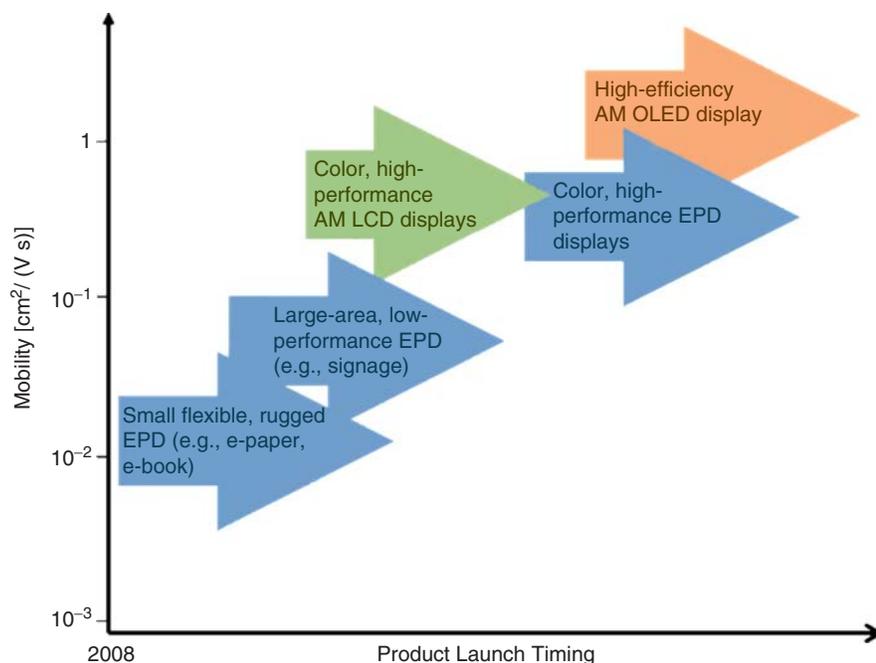


Figure 4. Thin-film transistor semiconductor carrier mobility requirements to enable active-matrix display frontplanes. Note: AM is active-matrix, EPD is electrophoretic display, LCD is liquid-crystal display, and OLED is organic light-emitting diode.

transistors per pixel than LCD backplanes with the same pixel size, the prerequisite for multiple transistors per OLED pixel means that the transistors need to be smaller than for the equivalent EPD device where there needs to be only one transistor per pixel. Whereas both EPD and LCD devices are electrical field-driven, OLED devices are current-driven, demanding higher performance from the transistor, not only in terms of mobility, but also in terms of transistor to transistor uniformity, as the current output from the transistor dictates the brightness of the pixel. Compensation is often required to prevent nonuniform brightness and color shifts across the display, arising from both transistor instabilities and pixel differential aging effects.

Organic Transistor Semiconductors

Small-molecule semiconductors, designed so they assemble in highly ordered crystalline microstructures when thermally evaporated, are currently the front-runners in high-mobility organic semiconductors for thin-film transistor applications. Both single crystals⁵ and thin-film devices⁶ can be fabricated by low-pressure evaporation techniques, which have already been developed for OLED display fabrication. These devices have demonstrated the highest electrical performances to-date, giving an advan-

tage over solution-processed polymer semiconductors. Translation of these device architectures and fabrication conditions to a robust production technology has been a major challenge, however, and solution-based approaches remain an attractive alternative.⁷

Many groups originally assumed that fabrication of transistor devices by a solution printing process would require polymeric semiconductors that satisfy the rheological requirements of the printing ink, as well as the physical and coating requirements of the thin film. Although polymers do offer these advantages, it was shown by pioneering work of the Mueller/Philips groups⁸ and John Anthony,⁹ among others, that it is possible to prepare highly ordered, high-performing thin-film semiconductor devices with small-molecule semiconductors deposited from solution.

Design of these solution-processable molecular semiconductors has focused on two approaches: a precursor approach, in which thermally labile, solubilizing groups that facilitate thin-film formation from solution are introduced and can be subsequently removed so the semiconductor forms a crystalline film, or a solubilizing approach in which functional groups are incorporated on the semiconductor molecules. In particular, design criteria have been developed for synthesizing functionalized oligoacene semiconductors, such as alkynyl-substituted pentacene and

anthradithiophene. In these materials, the functional group attachment on the fused acene can be used to tune the molecular stacking of these planar structures and their subsequent crystal motif, which, in turn, influences the charge-carrier transport properties. Intermolecular overlap between electronic orbitals on neighboring molecules, optimal for transport, can be guided by the subtle balance of electrostatic and van der Waals forces and the steric size effects of carefully chosen side groups, leading to mobilities of greater than $1 \text{ cm}^2/(\text{V s})$.¹⁰

Polymer semiconductors have also shown recent improvements,¹¹ where the elucidation of the impact of electronic delocalization, backbone conformation, and arrangement of side chains influence the thermal properties and thin-film microstructure has led to more optimized processing regimes and higher electrical performance.

It is clear that, even allowing for the inevitable performance drop on transitioning from laboratory to production, both small molecules and polymers offer sufficient mobilities to enable first-generation displays.

The focus is now shifting to optimizing secondary properties, such as the ability to withstand device processing temperatures reaching up to 200°C without degradation, interlayer diffusion, or even a change in morphology. Lateral anisotropy in semiconductor mobility can occur in a polycrystalline film, where there is a strongly preferred crystalline direction for transport and domain sizes that are at least the length scale of the transistor channel length. This is particularly prevalent in small-molecule films. Applications where tolerances to device-to-device nonuniformity are particularly low, such as OLED and complex gray-scale displays or large integrated circuitry, will require a substantial reduction in this anisotropy.

The article in this issue by Siringhaus and Ando provides a comprehensive overview of organic transistors fabricated with solution-processable organic and polymeric semiconductors. It examines in further detail the materials and processing requirements for the practical incorporation of such organic transistors as drivers in backplanes for displays, as well as for use in radio-frequency identification tags.

Processing–Structure–Property Relationships of Organic Semiconductors

Given the library of organic semiconductors—be it small-molecule or polymeric in nature—available as active materials in organic transistors, design rules that pro-

vide guidance for the synthesis of next-generation materials are beginning to emerge. Regardless of the inherent electronic properties of the active material, the processing that is required to incorporate organic semiconductors as active layers in organic transistors influences the device performance dramatically.

In a solution-processable substituted anthradithiophene derivative, for example, the degree of crystallization can dramatically influence device performance. In a recent study, spin coating the anthradithiophene derivative from a good solvent resulted in an amorphous active layer. Subsequent exposure of the same active layer to organic solvent vapors induced controlled crystallization of the film (see Figure 5); the device performance, as characterized by the saturation mobility, of the organic transistors improved accordingly by more than two orders of magnitude.¹² Other handles to control the crystallization of the active layer, including the manipulation of surface interactions, the use of binary phases, and spinodal decomposition, have also been demonstrated. The details of processing can also dramatically alter the structure and morphology of polymer semiconductors, which, in turn, affect the device characteristics.

The structure–property relationships of polymer semiconductors in organic transistors are detailed in the articles in this issue by Chabinyk et al. and Anthony et al. These studies, along with many others that have emerged, point to the importance of processing details when fabricating organic transistors. To realize the applications mentioned above, understanding of the processing–structure–property relationships is key to making robust organic

transistors in a reliable and reproducible fashion.

Organic Transistor Dielectrics

The interface between the dielectric and the semiconductor is crucial for device performance. For both electron and hole transporting devices, polar dielectric surfaces (with a high dielectric constant, κ) have been shown to both trap charge and increase energetic disorder, leading to a reduction in field-effect mobility. Therefore, although dielectrics with higher κ are preferable for low-voltage operation, low- κ dielectrics are currently favored¹³ and present a range of processing challenges. In a top-gate device, the dielectric is deposited on top of the semiconductor. Soluble small-molecule semiconductors typically have wider solubility parameter profiles than polymers, and to ensure a discrete interface, the solvent used to deposit the dielectric layer must be orthogonal to the semiconductor (i.e., not dissolve it), forcing solvent selection at the extreme ends of solvent polarity. Because of the prerequisite for low dielectric polarity, coupled with the fact that semiconductor solubilities often extend to low-polarity solvents, top-gate organic dielectrics are therefore often fluoropolymers, dissolved in fluorosolvents.

Bottom-gate dielectrics have a different set of requirements. To withstand exposure to the range of semiconductor formulation solvents that are deposited on the dielectric surface, as well as to any etchant or developer solvents employed during electrode patterning, it is preferable that the dielectric be cross-linked after deposition to ensure solvent orthogonality. The cross-linking chemistry should not require or produce

polar functionality, and ideally, it should not require the addition of an initiator. If an initiator needs to be used, it should be consumed during the reaction or removed in a subsequent washing step or be inert to the semiconductor during transistor operation. Optimal dielectric surface energy is required for wetting and confinement of the deposited semiconductor, as well as promotion of the semiconductor morphology. Poor adhesion between these low-surface-energy layers is an undesired consequence of material optimization and is an area of current focus.

Printing Transistor Devices

As the momentum shifts from the laboratory to production, fabrication options are required that enable the transitions from area to patterned printing by additive rather than subtractive methods, from low to higher throughput on flexible rather than rigid substrates, and from high to low materials utilization using hybrid processing rather than a single printing technique. For example, in the fabrication of a top-gate device, it is conceivable that a higher resolution printing technique such as surface-patterned inkjet or microcontact printing could be used to pattern the source and drain electrodes, whereas the semiconductor can be deposited by higher throughput but lower resolution gravure or even continuous inkjet printing. The substrate surface, on which potentially both the electrodes are patterned and the semiconductor is deposited, needs to enable adhesion at both interfaces but also promote the semiconductor microstructure during the drying process. The dielectric layer, which is required to be both uniformly flat and relatively thick, could

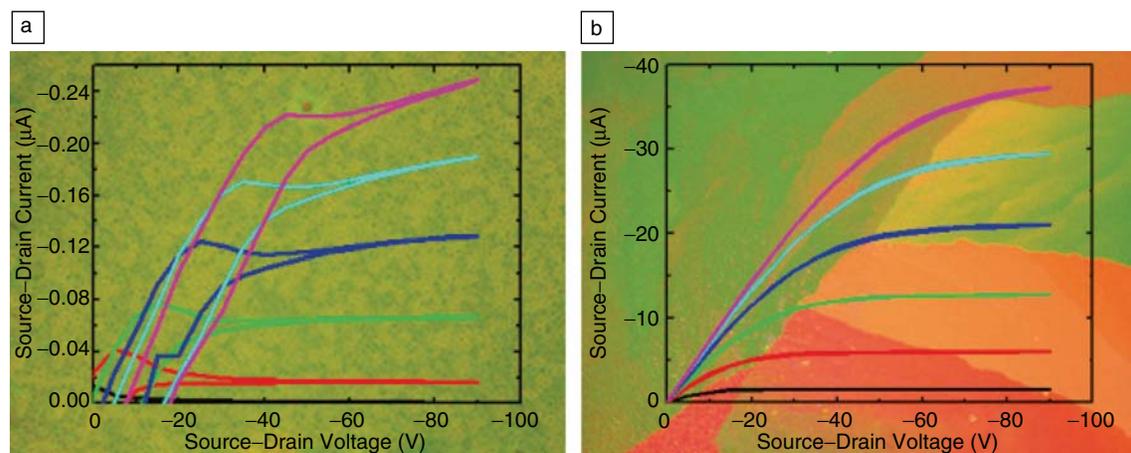


Figure 5. Optical micrographs of the channel region of an organic transistor with solution-processed triethylsilylethynyl anthradithiophene as the active layer and the accompanying current–voltage characteristics of the transistor (a) before and (b) after organic solvent vapor annealing. The colors in the (b) micrograph show different grains in the organic semiconductor thin film. The colored lines represent sweeps at different gate voltages.

potentially be deposited by flexo or even screen printing. However, if the formulation is based on a fluorosolvent, the use of inkjet printing is typically excluded due to nozzle plate wetting. Gate electrode deposition requires accurate registration to ensure placement over the channel between source and drain, with minimum electrode overlap. The challenge of printing the gate onto a low-energy dielectric surface is also nontrivial, often requiring an additional interlayer or pretreatment prior to deposition to increase surface energy, thus permitting wetting and adhesion. Finally, a passivation layer is typically deposited over the device to protect it from any further chemical exposure during the etching and development steps as the pixel is completed. In all of these steps, solvent orthogonality is required. Polymer semiconductors offer an advantage here, as their narrow solubility parameter profiles permit a wider range of orthogonal solvents for next-layer deposition.

Conclusions

There is justifiable optimism for the future of organic electronics. Recent invest-

ments in production facilities, growing industrial research and development efforts, and significant advances in performance are encouraging. The value chain from materials supply to end user is assembling, and weaknesses in viable printing technology are now being addressed. Although it is clear that organic light-emitting diode displays will compete directly with the existing liquid-crystal display technology and well-defined applications already exist and are in consumer demand, both organic transistors and organic photovoltaic still need a broader range of compelling applications to ensure sustainability. Progress in this area is expected.

Acknowledgments

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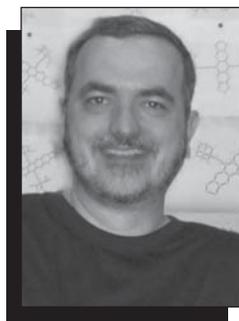
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James R. Durrant

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Brabec is the chief technology officer of Konarka Technologies Inc., founded in 2001, which is pioneering the field of organic photovoltaics. After earning his PhD degree, Brabec joined the group of Nobel Prize winner Alan Heeger at the University of Santa Barbara for a sabbatical, where he continued to work on the optoelectronic properties of organic semiconductors. Afterward, Brabec was an assistant professor at the University of Linz under Sariciftci. He directed the research and development efforts for QSEL, an academic spin-off company in the field of organic solar cells, as a Christian Doppler fellow from 1998 to 2001. Before joining Konarka in 2004, Brabec was a project



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Leslie H. Jimison

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Beng S. Ong

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Katz is a professor of materials science and engineering at The Johns Hopkins University and the department chair as of July 2008, with a joint appointment in the Department of Chemistry. He holds bachelor's degrees from the Massachusetts Institute of Technology in chemistry and music, and completed his PhD degree at the University of California Los Angeles in organic chemistry in 1982 under Donald Cram. Katz was a Distinguished Member of Technical Staff at Bell Laboratories from 1998 to 2004. His research interests include organic/hybrid materi-



Jonathan Rivnay

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Alberto Salleo

research activities focus on organic light-emitting diodes (OLEDs). He invented white OLEDs in 1993 and is working on development of high-performance OLEDs. Kido's work has been recognized through awards from the Society of Polymer Science, Japan, and the Society for Information Display, USA, in 2002.

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Henning Sirringhaus

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Henning Sirringhaus is the Hitachi Professor of Electron Device Physics at the Cavendish Laboratory at the University of Cambridge. He has undergraduate and PhD degrees in physics from ETH Zürich. From 1995 to 1996, Sirringhaus worked as a postdoctoral research fellow at Princeton University on a-Si thin-film transistors for active-matrix liquid crystal displays. He has been working in the field of organic transistor devices since 1997. Sirringhaus' research interests include the realization of functional nanostructures using solution

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ing printed organic transistor and flexible display technology for applications in electronic readers.

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