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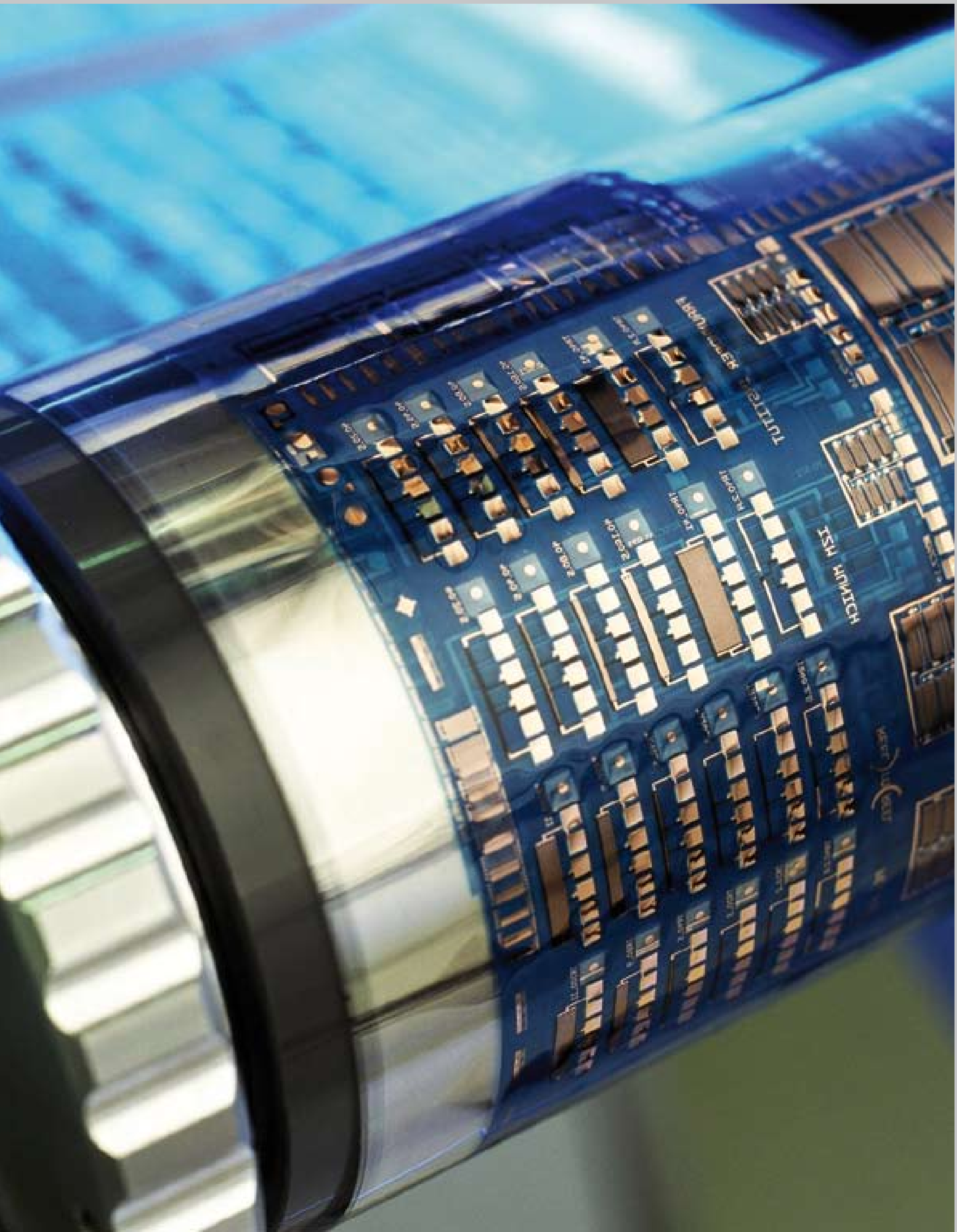

1st Edition

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VDMA

Organic Electronics Technology

By Bruce E. Kahn, Printed Electronics Consulting

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The purpose of this article is to give a broad overview of the materials used in organic electronics, to discuss some of the different types of printing processes that are typically used and how they work, and to show examples of some devices and applications that can be produced.

Organic electronics offers many exciting new opportunities, and may also reduce some limitations of conventional microelectronic fabrication. In conventional silicon microelectronics, patterning is most often done using photolithography (not to be confused with offset lithography), which is a subtractive process. The active material is deposited initially over the entire area, and selected areas of it are removed. Although very high-resolution and well established, the photolithographic process is very complex, expensive, uses extremely expensive equipment, requires many steps, is time consuming, subtractive, and only suitable for patterning small areas. Photolithography is not generally compatible with organic electronic materials or flexible substrates. The harsh conditions required for dissolving resists, etching the underlying layers, and removing the photoresist destroys the activity of most organic electronic materials. Furthermore, the temperatures and harsh reaction conditions required for photolithography are incompatible with most flexible substrates.

For these reasons, some of the major attractions of organic electronics are the possibilities to do things that are not possible with conventional microelectronic fabrication processes. Organic materials can be made soluble and/or solution processable. This enables a variety of deposition techniques that are not possible for conventional inorganic semiconductor materials. Solution processability enables printing or printing like processes. If one considers (conventional graphic) printing a manufacturing processes, it is easy to realize that it must be one of the highest volume and lowest cost manufacturing processes known. Printing presses commonly run at speeds of hundreds of m/min. with webs several meters wide, and are used to deposit (and cure) many different materials simultaneously. Printing produces large areas very quickly and inexpensively. If one could use these processes (or ones like them) to deposit functional materials, one could produce functional devices in high volume very economically. Such is the appeal of organic electronics. Making this happen, however, will require much effort and development, not only of new materials, but also of processes for using these materials. Like most other processes, for optimal performance, the materials will need to be developed with the process and conditions in mind. The disadvantages of photolithography offer great new opportunities for patterning materials, as well as corresponding challenges.

Materials

Organic electronics relies upon a wide variety of different types of electrically active materials. Among these materials, some of the most commonly used are conductors, semiconductors, dielectrics, as well as various luminescent, electrochromic or electrophoretic materials. Some type of supporting material is generally also used. Many other types materials can also be employed, such as surface active agents, encapsulation materials, dopants, etc.

Conductors

Almost all printed devices require some type of electrode. The electrodes may need to satisfy a number of requirements including low resistance, smooth surface, chemical stability, and appropriate work function (the energy required for an electron to escape a solid surface) for

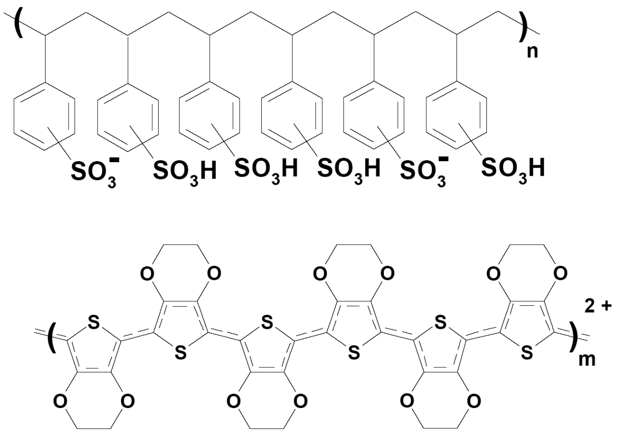

Figure 1. Chemical structure of PEDOT:PSS

charge injection into the semiconductor material. The materials used for conductors fall mainly into three categories – those based on metals, organic compounds, and metal oxides.

Metallic features can be printed a number of different ways. The most common technique is to use inks that contain metal particles. These particles may span a wide range of sizes and morphologies. Nanoparticles can also be used, and subsequently sintered at plastic compatible temperatures (< 150 °C) to give electrically continuous features. Metal precursors can also be used, sometimes in combination with other materials, and similarly thermally cured. Another technique that has been used in the printing of conductors is to print a seed layer, followed by plating another metal on top. In this way, printing can be used to define the pattern, and the plating process can be used to deposit a wide variety of metals, often much thicker than what could be printed. The plating process can run at high volume.

Even though certain polymers can conduct electricity, they are still > 1000 times less conductive than metals. The compounds that are most used for conductive polymers in printed are heteroaromatic polymers, based upon aniline, thiophene, and pyrole and their derivatives. Of all of the conducting polymers, the one that has been used the most as a conductor is probably PEDOT:PSS (also known as PEDT:PSS, Figure 1), which is commercially available. Dispersions of PEDOT:PSS have good film forming properties, high conductivity (< 400 S/cm), high visible light transmission, and excellent stability. Films of PEDOT:PSS can be heated in air at > 100 °C for > 1000 hours with only minimal change in conductivity.

Another class of conductive materials that is often used for electrodes are metal oxides, particularly Indium Tin Oxide (ITO). These materials are used primarily because of their transparency. They are used where transparent electrodes are needed, particularly for light emitting or optoelectronic devices. “They are widely used high- and low-tech applications such as antistatic coatings, touch display panels, solar cells, flat panel displays, heaters, defrosters, and optical coatings”. Flexible substrates (polyethylene terephthalate, PET) coated with ITO are commercially available.

Semiconductors

Many organic electronic devices use semiconductors in one or more layers. Frequently, the semiconductor is one of the most critical components, because it is where the mobile charge carrying species are formed and transported. The semiconductor is usually the most difficult material to deposit, and the one whose characteristics must be most critically controlled.

Semiconductor materials must satisfy a number of requirements simultaneously. The frontier orbital energies of the individual molecules (perturbed by their placement in a crystalline solid) must be at levels where electrons can be added or removed at accessible applied voltages, and across interfaces with conductors of reasonable work function. It is desirable to have electrical contacts between the semiconductor and the electrodes that are ohmic and have a small contact resistance. Similarly, it is desirable that the material be extremely pure, to eliminate inadvertent sources of traps for the mobile charges.

Organic semiconductors can be soluble and solution processable, hence they lend themselves to printing. The charge transport in organic semiconductors is highly dependent upon the deposition conditions, and can be influenced by many factors, including solvent, concentration, deposition technique, deposition temperature, surface treatment, surface roughness, etc. Environmental conditions can also be a major factor, however, some organic semiconductors are air stable and don't require encapsulation or an inert environment to maintain their performance.

For optimal charge transport, the molecular planes should be parallel to each other and as close together as possible. In this situation, the charge will be transported optimally in a single direction (the direction of the intermolecular overlap). This molecular orientation is shown schematically in Figure 2. In order to make use of this in a practical device, this direction may also need to be oriented with an appropriate direction in the device, for example, from the source to the drain electrode in a transistor. So not only do the molecules need to be aligned appropriately with each other, they also need to be aligned appropriately with respect to the electrodes. The direction of optimum charge transport is from left to right in Figure 2.

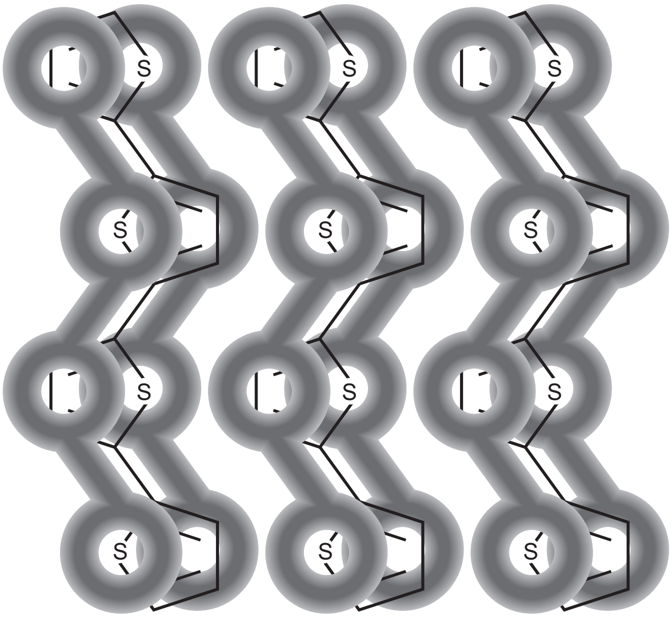

Figure 2. Diagram showing orientation of conjugated systems for maximum π orbital overlap

Many different families of organic semiconductors can be used, including small molecules (pentacene and its derivatives), oligomers (primarily oligothiophenes), and polymers (primarily polythiophenes). In the laboratory, organic semiconductors have been shown to have carrier mobilities of ~ 1 cm^2/Vs, which is very close to that of amorphous Si – which is commonly used for large area display backplanes. A large number of luminescent organic semiconductors (both small molecule and polymer) have also been developed for Organic Light Emitting Diode (OLED) applications.
One of the great advantages of organic semiconductors, is that it is possible to chemically tailor the structure of the molecule to achieve the desired properties. An important example of this is the use of alkyl side chains to both improve the solubility, as well as to induce molecular ordering, and thereby improve the molecular overlap and charge mobility.

In addition to organic semiconductors, nanoparticulate inorganic semiconductors or hybrid organic-inorganic semiconductor materials have also been used. These materials promise both the superior carrier mobility of inorganic semiconductors and the processability of organic materials.

Dielectrics

In general, a practical dielectric material should have a high capacitance, high dielectric strength, high on/off ratio, high uniformity, high dielectric breakdown, low hysteresis, and be defect free and easily processable. High capacitance is important, because it allows a higher charge density to be induced at lower voltages. This enables the reduction of the threshold and operating voltages, while achieving this at a lower gate field. The capacitance can be increased by using a thinner dielectric or by using a high permittivity insulator material. Unfortunately, when the dielectric layer gets too small, breakdown and reliability issues (defects and yield) can occur. Since the mobility of organic semiconductors is usually fairly low, and the charge transport in organic semiconductors occurs within a few nanometers of the interface between the dielectric and the semiconductor; the properties of the dielectric, and particularly its surface, are critically important.

A variety of materials can be used as dielectrics. While much work has been done using inorganic (silica, alumina, and high dielectric constant oxides) dielectrics, these are not generally printable. A variety of organic polymers including polypropylene, polyvinyl alcohol, polyvinyl phenol, poly methyl methacrylate, and polyethylene terephthalate can also be used as dielectrics. Most of these are polymers that are widely used for non electronic purposes, and available in bulk quantities quite inexpensively.

Substrates

For organic electronics, flexible polymeric substrates are generally used. Flexible substrates pose a number of challenges, however. Flexible substrates are usually not completely dimensionally stable, and this can greatly affect the resolution and registration of features printed on them. The surfaces of flexible substrates are usually too rough for device fabrication. Flexible substrates can melt or deform when exposed to high temperatures, which limits the kinds of processing that can be applied to them. Many types of flexible substrates are also incompatible with some solvents used for organic electronic components. When exposed to such solvents, the substrates may either dissolve or swell.

The flexible polymeric substrates that have been used the most in organic electronics are the polyesters polyethylene terephthalate (PET) and polyethylene naphthalate (PEN). Polyimide, and polycarbonate have also been used. Paper is of great interest for printing electronics. It has been widely used for printing antennas, and as a support for sensors and various types of displays. Compared with polymeric films, the surface of paper is very rough, which limits some of its use in organic electronics. Its temperature capability is limited, and it is not generally compatible with solution processing. These problems can be alleviated to some extent however, by using coated paper substrates.

Printing Processes

In organic electronics, there are three major types of considerations for determining the printing process used. Techniques are chosen based upon their suitability for printing the desired materials (viscoelastic properties), as well as by their capability to print the desired feature sizes (lateral resolution, ink thickness, surface uniformity) required by the device. Economic considerations such as process throughput are also important. Some of the most important specifications for the major printing processes used in electronics are shown in Table 1. As can be seen in Figure 3, lateral resolution (essentially, the size of the smallest

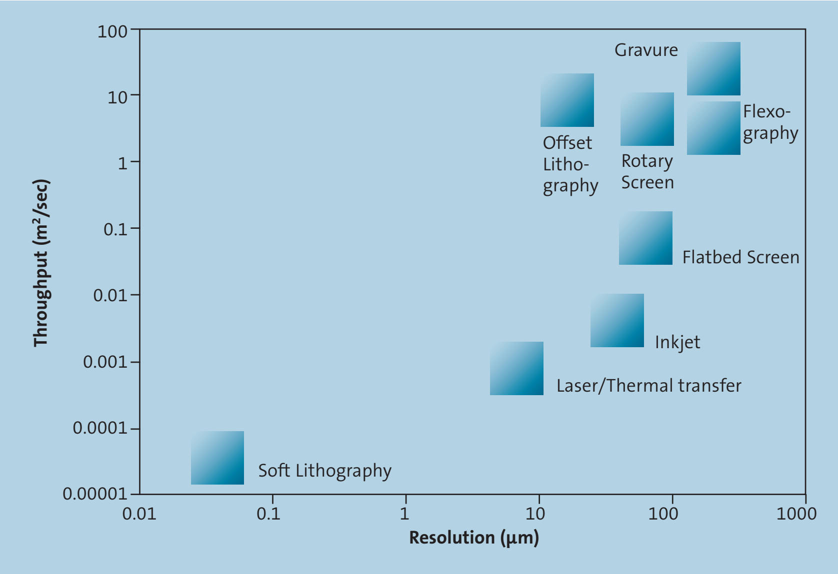

Figure 3. Throughput vs. Resolution of different kinds of printing processes. Source: Printed Electronics Consulting

feature that can be printed), is related to the throughput. The printing processes with the highest resolution capability are also generally those with the lowest throughput (and vice versa). The techniques having a throughput > 1 m^2/sec, are known as “high volume” printing processes. These high volume printing processes are highly desirable to enable the lowest cost production.

Flexography

The principles of flexographic printing are shown diagrammatically in Figure 4. In the normal implementation (also known as “two roll”), ink is transferred from the ink pan via a fountain roll to the anilox roll. The anilox roll controls the amount of ink that is transferred to the printing plate. The anilox roll consists of a number of small cells that are engraved into the surface of the roll. Different anilox rolls are available that contain different size cells and cell volumes. The raised areas on the printing plate pick up the ink from the anilox roll as shown in Figure 4, and transfer it to the substrate.

Another way of getting ink to the anilox roll is by using a chambered doctor blade, as shown in Figure 4. This method is greatly preferred for printing functional electronic materials, as the ink is contained, and evaporation can be greatly reduced. This method is also environmentally preferred (if not required) for organic solvent based materials, because the organic solvent vapors can be controlled.

Although the conventional wisdom is that the resolution limit of flexographic printing is on the order of 100 µm, it may be possible to reduce this considerably. In conventional flexographic printing of graphics, halftone dots exist that are ~ 20 µm.

	Physical Master (Analog)						No Physical Master (Digital, NIP)	
	Relief				No Relief			
	Raised		Lowered					
	Flexography	**Soft Lithography**	**Gravure**	**Pad**	**Offset Lithography**	**Screen**	**Ink-Jet**	**Thermal/ Ablation**
Lateral Resolution (µm)	75	0.03	75	20	10–50	30	20–50	5
Ink Thickness (µm)	3–8	Monolayer	2–5	4–6	< 2.5	100	~ 0.1	< 1
Ink viscosity (mPas)	50–500		50–200	> 50	20,000–100,000	500–50,000	< 20	N/A
Throughput (m^2/sec)	10	1.E-05	60	0.1	20	< 10	0.01	0.002

Table 1. Printing process parameter comparison. This table is a compilation of best individual values for graphics applications, which were obtained from various manufacturers specifications and other published reports. These specifications should be considered as only approximate upper limits. Actual values that can be achieved for a particular system will depend upon many other factors. Source: Printed Electronics Consulting

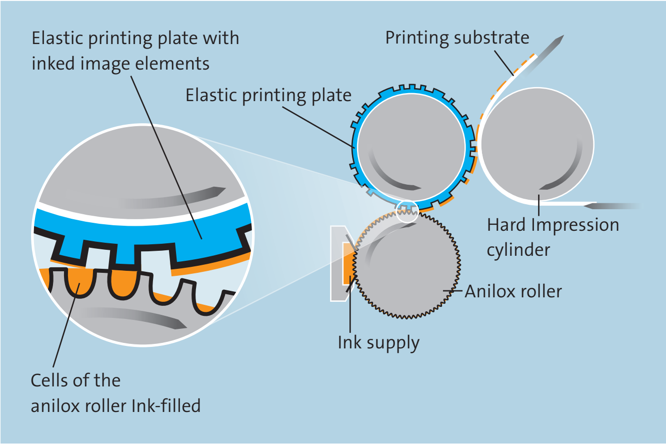

Figure 4. Flexographic printing process.
Source: VDMA

One potential disadvantage of flexographic printing for functional materials, is that a halo tends to form around the edges of printed features. This is caused by the squeezing of the ink out from under the edges of the printing plate.

Flexographic printing offers a number of attractive features for printing functional materials. It is a high throughput (volume) process. Printing plates are easily made and relatively inexpensive. A variety of plate materials exist, from a number of different manufacturers. Plate materials are available that tolerate some organic solvents. The inks used are relatively low viscosity, can be formulated from functional organic materials or particulate suspensions. The printing process is conformal, and is tolerant of substrate abnormalities. The ink layer printed is relatively thick (Table 1).

Flexographic printing has a number of disadvantages as well for printing functional materials. The resolution is somewhat limited, and also dependent upon the size of the cells in the anilox roll. Edges tend to form a halo around them. There needs to be enough flow of the ink so that the deposits from individual cells of the anilox roll can join. There can be a compatibility issue between the printing plates and organic solvents. Some combinations of plate material and solvents may cause the printing plate material to swell, or change its viscoelastic properties.

Flexographic printing is just starting to see use in organic electronics. It has been used for printing conductive materials – both silver particle containing inks, conductive organic polymers, devices containing both, and to pattern the source and drain electrodes of an organic transistor.

Soft Lithography

Soft lithography is the name for a family of related printing processes, first described by Whitesides in 1993. What these processes have in common is that a master is made using conventional microelectronic fabrication techniques. Typically, the master is made from either silicon or photoresist. Once the master is created, stamps can be made from it by applying a liquid prepolymer (usually polydimethylsiloxane PDMS, Sylgard 184), then subsequently curing it. These techniques have been extensively reviewed, and will not be discussed in detail here.

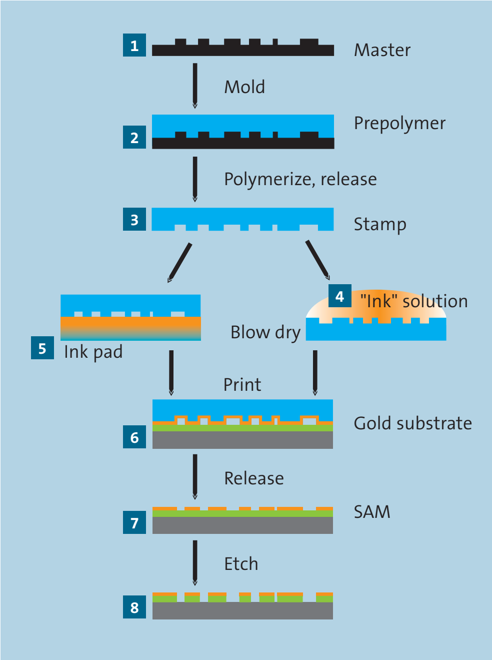

Figure 5. Diagram of the microcontact printing process.
Source: VDMA

The most common soft lithography process is called Micro Contact Printing (µCP). Figure 5 illustrates how the µCP process is performed. First, a master is created using microfabrication processes. Second, the liquid prepolymer is applied to the surface of the master. Third, the prepolymer is cured (by heating), and removed from the master. Now, ink needs to be applied to the surface of the stamp. This can be done by either applying the ink direction to the stamp (4) or by using an ink pad (5). Most often, the inks used are molecules which form self assembled monolayers (typically thiols) on the surface (typically gold). Sixth, the stamp is brought into contact with the surface to be patterned. Seventh, upon removal of the stamp, a self assembled monolayer (SAM) of ink is formed on the substrate surface. Finally, this SAM is used as an etch resist to selectively etch the underlying substrate surface.

Reminescent of flexographic printing, microcontact printing can also be employed using cylindrical stamps. Cylindrical stamps have been demonstrated for patterning gold and silver. The flexible nature of the stamp, allows microcontact printing to be used for substrates which are not planar.

Gravure

The gravure printing process is shown schematically in Figure 6. It is one of the highest volume printing processes, and often used commercially to produce high quality graphic materials, for example magazines. It is one of the few printing processes that can be used to deposit different amounts of material in different locations. Due to the nature of the engraved pits, the edges of printed features may not be smooth and straight.

A derivative of gravure printing is gravure offset printing, more commonly known as pad printing. This process is also known as offset gravure printing or tampography. In pad printing, there is an intermediate step between inking the plate and transferring the ink to the substrate (hence offset). The ink is transferred from the plate to an intermediate surface (pad).

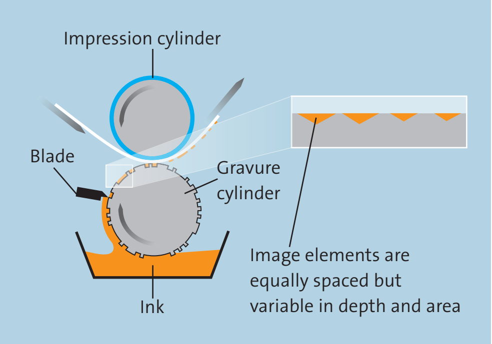

Figure 6. Gravure printing process: Source: VDMA

Offset Lithography

Offset lithography is one of the most common printing processes. As described above, it works based on the principle of a difference in surface energy (wetting) of the printing plate (Figure 7). Normally two solutions are applied to the plate simultaneously – an ink solution, and an aqueous (water based) fountain solution. The ink sticks to the image areas of the plate, and the fountain solution wets the non image areas. Another version of offset lithography uses special silicone printing plates which do not require the fountain solution. This is known as waterless lithography. The term offset comes from the fact that the ink is transferred from the plate to an intermediate and then to the substrate. The intermediate cylinder is known as the offset cylinder.

Offset lithography offers high resolution capabilities, good edge definition, high throughput, and thin ink layers. In organic electronics, it has been used primarily for printing conductive features. Some work has also been done using offset lithography for printing organic polymers, but it has not been used very extensively in organic electronics. One of the reasons for this may be the viscoelastic requirements necessary to formulate offset lithographic inks.

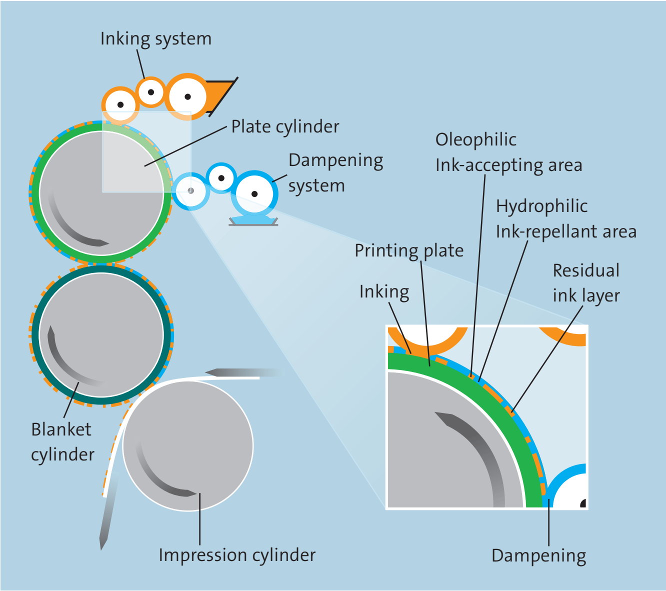

Figure 7. Offset lithographic printing. Source: VDMA

The inks need to start out very thick (no shear), and thin out considerably when sheared. In order to achieve these viscoelastic properties, additives are generally required which can reduce or inhibit the electrical functionality. Also, the thin ink layers make it more difficult to achieve electrical conductivity. Multiple impressions may be required to achieve sufficient conductivity. Offset lithography has been used to print doped conductive polymers like PEDOT:PSS, which can be used as either conventional inks (with some modification), or contained in the aqueous fountain solution.

Screen

The screen printing process is shown in Figure 8. Historically, screen printing was called silk-screen printing. Today, silk is not used any more, and the process should be known as screen printing, not silk-screen printing. Screen printing is basically a slightly more elaborate version of stencil or mask printing. In screen printing, the mask (emulsion) is supported by a screen (usually made of polyester or stainless steel). The screen support allows the use of areas which are not connected, which would fall through a regular stencil or mask. In screen printing, a wide variety of different screen parameters are available. When practiced appropriately, screen printing is a non contact printing process. The screen itself should not touch the substrate. The ink is spread out over the screen and forced through it with a squeegee. Although screen printing is not normally considered a high volume printing process, the volume can be increased considerably by using rotary screen printing. The rotary screen printing process is shown in Figure 9. In rotary screen printing, the screen is wrapped around a cylinder, and the ink is contained inside the cylinder. The cylinder rotates continuously, and the ink is fed through it. In this way, rotary screen printing can operate continuously, and increase the throughput considerably over flat bed screen printing.

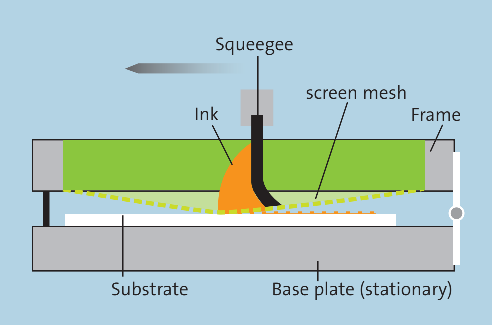

Figure 8. Screen printing process. Source: VDMA

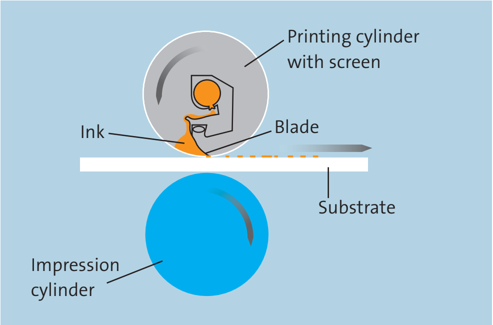

Figure 9. Rotary screen printing process. Source: VDMA

Ink-jet

In recent years, Ink-jet printing has been receiving growing interest as a method to deposit functional materials, as opposed to the more conventional graphics applications. Ink-jet printing is particularly good for the deposition of small amounts of materials that have specific electrical, optical, chemical, biological, or structural functionalities onto well defined locations on a substrate. The materials deposited can be soluble liquids, dispersions of small (or nano) particles, melts or blends. Some types of functional molecules, such as polymers or large biomolecules can not be deposited by the conventional vacuum deposition techniques, and need to be deposited using a solution based technique. One of the most unique and useful capabilities of ink-jet printing is its capability of variable printing, that is, the ability to change what is printed at will – without making a new printing plate, etc. This variable data capability has been widely exploited in ink-jet printing for printing "sell by" dates, product identification codes, instant awards, etc. Using a camera and image analysis software, the printed image can be adjusted "on the fly" to compensate somewhat for many of the registration errors that plague other types of printing process.

There are two primary mechanisms for ejecting drops from an ink-jet nozzle. In thermal ink-jet, a small portion of the ink solvent is evaporated, forcing ink out of the nozzle In piezoelectric ink-jet, a voltage is applied to a piezoelectric material which causes it to change its shape (expand), thereby forcing ink out of the nozzle (Figure 10). A number of manufacturers now produce print heads that are designed specifically for printing functional materials.

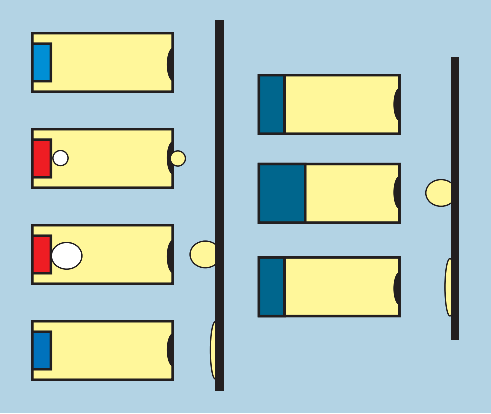

Figure 10. Ink-jet deposition mechanisms.
Thermal (left), piezo (right).
Source: VDMA

There are also a number of problems using ink-jet printing for functional materials. Functional materials may require the use of organic solvents which can dissolve plastic print head components. Ink-jet inks can be subject to high mechanical shears in piezoelectric print heads, or high temperatures in thermal ink-jet heads. Upon ejection from the print head, droplets of functional materials should not clog the print heads, or cause other problems. Fluctuations in droplet volume or trajectory can adversely affect the device performance. Uniformity of the deposited film can be difficult to achieve. A frequent problem observed with ink-jet printing is the so called "coffee-stain" effect, whereby jetted materials tend to migrate to the edges of the printed dot. One technique that has been used to reduce ink spreading (and thereby increase resolution) is to patterning the surface energy of the substrate, thereby constraining the spreading of the jetted droplet.

Recently, a variation on ink-jet printing called "Self Aligned Printing" was used to pattern features as small as 60 nm. By modifying the surface energy of a printed droplet (after printing), subsequent droplets rolled off the first one, leaving an extremely small channel (estimated to be ~ 60 nm!) between the two droplets. Using this technique, organic transistors were prepared having channel lengths nearly the same as those used in modern Pentium™ computers! These ink-jet printed organic transistors were reported to be over two orders of magnitude faster than previous printed organic transistor circuits.

Liquid dispensing

The development of a printing technique that is capable of high resolution printing in three dimensions with minimal material requirements is extremely important for organic electronic materials research. To this end, we have been investigating the use of a MicroPen to pattern organic electronic devices. The MicroPen direct writing system is a unique fabrication tool that deposits materials under pressure through a fine conical capillary tip. The capillary tip rides on the bead of material being dispensed but has substantial vertical travel and is highly tolerant of substrate topology. The MicroPen allows writing features in 3 dimensions, and can be used for the fabrication of more complicated (three dimensional) structures than what can be fabricated using conventional patterning methods. Almost any liquid can be patterned using this device. This technique offers minimal constraints on the fluid properties, and is ideal for use with functional polymeric materials.

Liquid dispensing can be used to pattern organic features having extremely smooth surfaces (approximately as smooth or even smoother (according to AFM) than the substrate), and very high aspect ratios. A 3D profile and some cross sections of lines printed on glass using this technique are shown in Figure 11. Of particular interest are the nearly vertical edges, and flat tops of these features. This technique has been used to make features as small as 15 µm.

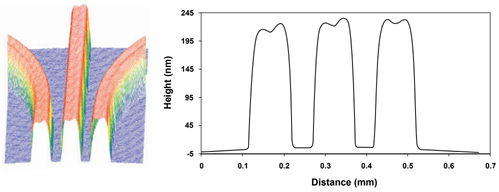

Figure 11. 3D profile and cross sections of lines patterned using MicroPen

Thermal/ablation

There are several printing techniques based upon the principle of thermal transfer. In the graphics world, these techniques are sometimes known as dye transfer, dye sublimation, thermal dye transfer, or thermal imaging. As depicted in Figure 12, these techniques work by using a laser to induce the transfer of material from a donor sheet to the substrate of interest. The laser energy melts or vaporizes the surrounding organics, transferring them from the donor layer to the receiver. Unfortunately, this laser energy is sufficient to decompose many organic materials. Although these are serial printing techniques, and therefore,

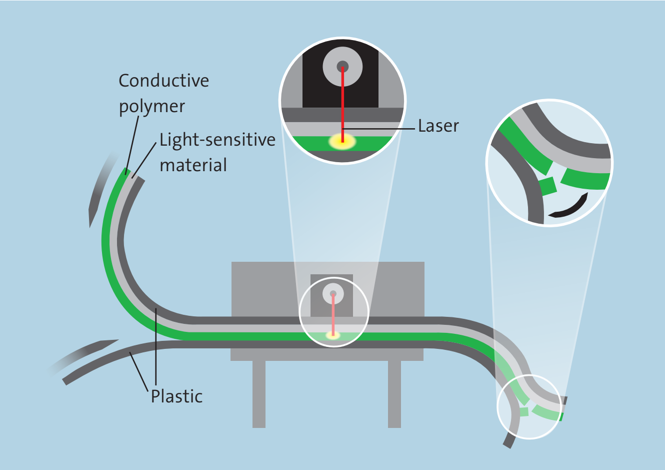

Figure 12. Illustration of the Printing Process. The two flexible films, a multilayer donor and a receiver are held together by vacuum. The laser beam is focused onto a thin absorbing layer that converts light into heat, an optional ejection layer placed directly underneath, and the functional material to be transferred coated on top. The heat generated at the metal interface decomposes the surrounding organics creating a gas bubble that transfers the conducting layer onto the receiver. After imaging is completed the donor and receiver films are separated. Source: VDMA

relatively low throughput (1 000 cm^2/min), they offer the advantage of a completely dry process, good resolution (~ 5 µm), and good registration (< 200 µm registration errors have been reported over areas > 3 m^2).

Devices and Applications

Organic electronics can be used to make a variety of types of devices, which can be broadly classified based upon whether they are passive or active devices. Active devices are those which are used to perform functions such as switching, rectification, memory, detection, or light emission. Examples of active devices that can be made with organic electronics are transistors, diodes, OLED's, sensors, memory, displays, batteries or photovoltaic cells. Some examples of passive devices or components that can be made with organic electronics are conductive traces, antennas, resistors, capacitors, or inductors.

Transistors

Among the active devices or components, transistors are probably one of the most important or fundamental. They can be used as the building blocks for many other types of devices, such as logic, displays, sensors, etc. Organic electronic transistors are three terminal, multilayer devices, and generally based upon thin film transistors configurations. They are generally known as organic TFT's (OTFT), or organic field-effect transistors (OFET). An example of the configuration of a typical OFET is shown in Figure 13. The transistor is basically a switch. Current flow between the source and drain electrode is switched, depending on the voltage present at the gate electrode. In order to optimize the transistor performance, the channel length should be as small as possible (for printed transistors, typically 10–50 µm), and the dielectric as thin as possible without defects (typically a few hundred nm). There should be minimal overlap of the gate electrode with the source and drain electrode. The dielectric/semiconductor surface should be smooth and defect free. It is desirable (but virtually impossible to achieve) to have low resistance ohmic electrical contacts between the semiconductor and the source and drain electrodes.

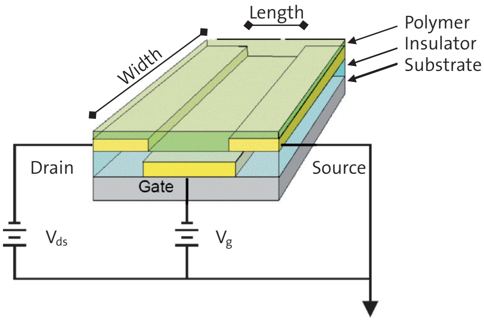

Figure 13: Typical OFET configuration and connections

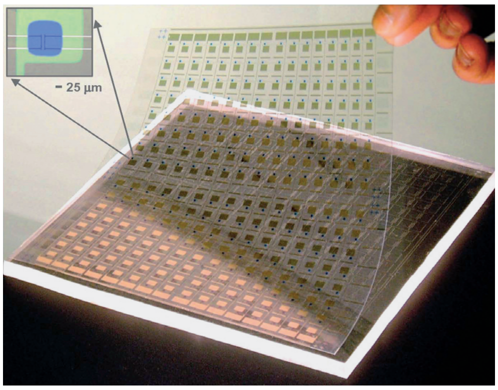

Figure 14[1]. Plastic active-matrix backplane circuit and the planar stamp that was used for printing. The inset shows a micrograph of one of the several hundred transistors in this circuit. The organic semiconductor is blue, the gate electrode is green, and the source/drain electrodes and related interconnects are gold.

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[1] From John A. Rogers, „Rubber Stamping for Plastic Electronics and Fiber Optics," MRS Bulletin Vol. 26, No. 7 (2001) p. 531, Figure 5. Reproduced by permission of the MRS Bulletin.

Displays

Some of the main advantages and economic driving forces for printed electronics are the ability to manufacture devices inexpensively, on flexible supports, and over large areas. One area where these forces converge is the opportunity for printing displays. Many of the major companies involved in organic electronics are directing their technology toward the production of displays.

Some of the earliest applications of printed organic transistors were for the fabrication of backplanes for flexible displays (Figure 14). Electrophoretic displays (Figure 15) are well-suited for organic transistors, because they are essentially field (voltage) driven devices, and do not require much current flow to drive them. Furthermore, they are bi-stable, which means that they can retain their state (image) without power. Power is only required when necessary to switch the state of the display.

One popular type of electrophoretic display material consists of small spheres which are filled with smaller (white) charged spheres and a colored (black) liquid (Figure 15). Upon application of an appropriate electric field, the charged (white) spheres move either toward the top or the bottom of the liquid. When the (white) spheres are toward the observer, the display looks (white). When the (white) spheres are at the other side (bottom) of the display, the color of the liquid (black) is seen. The spheres and liquid can be made to be any color. The contrast is independent of viewing angle, and significantly better than newsprint.

Other types of display materials that are capable of being driven by printed organic transistors are polymer dispersed liquid crystals (PDLC), and electrochromic materials.

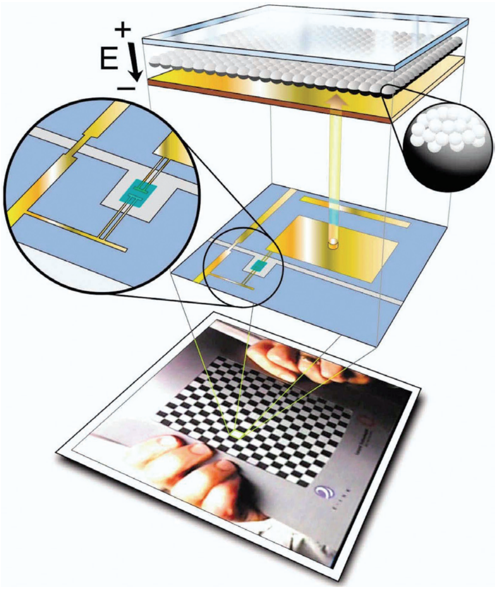

Figure 15[2]. Electronic-paper display (bottom) and exploded view of the components of a unit cell. Middle and left inset: rubber-stamped organic transistor. The semiconductor is blue, the gate electrode is gray, and the source/drain electrodes and related interconnects are gold. Top and right inset: microencapsulated electrophoretic "ink."

In addition to transistors and backplanes, organic electronic materials are also used to make emissive devices, such as Organic Light Emitting Diodes (OLED's). It is even possible to integrate organic transistors with OLED's, and fabricate a completely organic emissive display. In the future, completely printed organic emissive displays having integrated organic circuitry may be possible.

Logic and circuits

In addition to using organic transistors for relatively simple applications like driving display pixels, organic transistors can be combined together to make integrated circuits, which can be used to perform relatively complex logic functions. In order to be able to combine transistors together into circuits, they must display voltage amplification. Circuits as complex as a 32-stage shift register composed of 1888 transistors have been demonstrated.

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[2] From John A. Rogers, „Rubber Stamping for Plastic Electronics and Fiber Optics," MRS Bulletin Vol. 26, No. 7 (2001) p. 531, Figure 4. Reproduced by permission of the MRS Bulletin.

RFID

Since the mandates from Wal-Mart and the United States Department of Defense in 2003, there has been immense interest in using printing technologies for RFID. The "Holy Grail" has been described as the 5 cent tag. If RFID tags could be produced for 5 cents, item level tagging would become practical. The potential market for such tags would be in the billions or trillions of tags per year, and has captured the attention of many. It is commonly thought that the only way to reduce the price sufficiently, and produce billions or trillions of tags per year is by printing both the circuitry (using organic materials, see Figure 16), and the antenna, in an integrated process (see Figure 17).

Some of the major obstacles to be surmounted for RFID applications are high frequency operation and rectification using organic materials. Operational frequencies as high as 600 kHz have been shown. A polymer based half wave rectifier which can operate at frequencies up to 20 MHz has been demonstrated. At 13.56 MHz (one of the key RFID frequencies) 3V DC was obtained from 15V AC. This demonstrates that rectification at RFID frequencies is possible (although not very efficient) using polymer rectifiers. A working demonstration of an organic based 16 bit RFID tag with a read range of 7.5 cm has recently been shown.

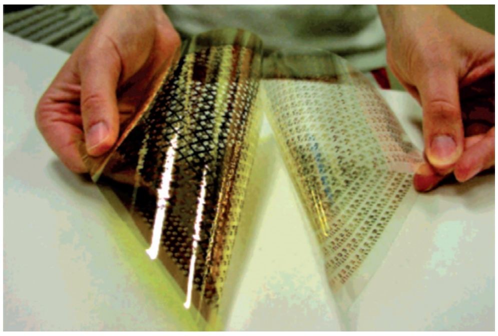

Figure 16[3]. Optical image of 6x6" RFID circuit array (right) fabricated with the polymeric shadow mask (left).

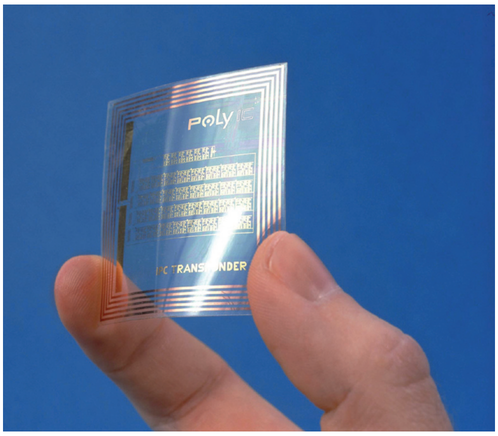

Figure 17. Model of a polymer flexible RFID tag (Source PolyIC)

Power sources

Organic electronics has also been applied to the generation of power, in both batteries and photovoltaics. Although batteries generally use inorganic materials for the anodes and cathodes, organic materials are important for both electrolyte and separator materials. There is a great deal of effort underway to produce polymer electrolytes that offer comparable ionic conductivity to liquid electrolytes. Organic separator materials are also frequently used for batteries, and it is also important for these to maintain high ionic conductivity. Printed batteries are now being used in products as diverse as power sources for RFID, and for cosmetic applications.

One of the most challenging and exciting applications of organic electronics is in solving the worlds energy problems. To this end, much work is being carried out on organic semiconductors in photovoltaic cells. The vision is to have cheap, light weight, flexible, and energy efficient power production from solar energy. Although the efficiencies of inorganic semiconductors are still greater than those of their organic counterparts, organic semiconductors may lend themselves better to high volume, large area, low cost manufacturing processes. Several companies are actively attempting to commercialize this technology.

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[3] Figure 16. Reproduced with permission from Kelley, et. al., Chemistry of Materials 2004, 16(23), 4413-4422. © 2004, American Chemical Society.

Sensors and actuators

Another important application of organic electronics is in the diverse area of sensors. Many different stimuli can be sensed using organic electronics, including temperature, pressure, light, and chemical identity.

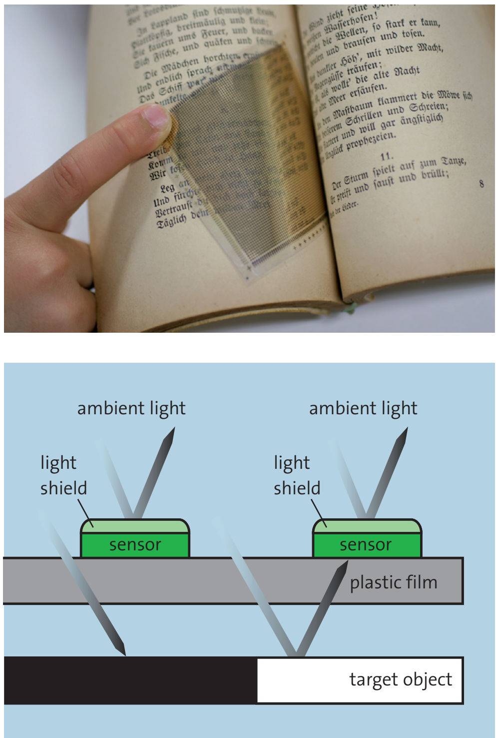

Figure 18. Flexible sheet scanner. Source: Prof. Takao Someya, University of Tokyo

These principles have been used to produce a variety of different types of devices, including tamper detecting packaging, data logging pill dispensers, chemical sensors, electronic noses and tongues, photodiodes (Figure 18), light scanners (Figure 18), photovoltaic (solar) cells, temperature and pressure sensors integrated into an artificial skin (Figure 19), etc. Actuators have also been made using organic electronics. An electronic Braille actuator was recently demonstrated (Figure 20), which provided sufficient stimulus to be read by a blind person.

Figure 19. "Artificial skin" flexible integrated pressure and temperature sensors. Made by Prof. Takao Someya, University of Tokyo.

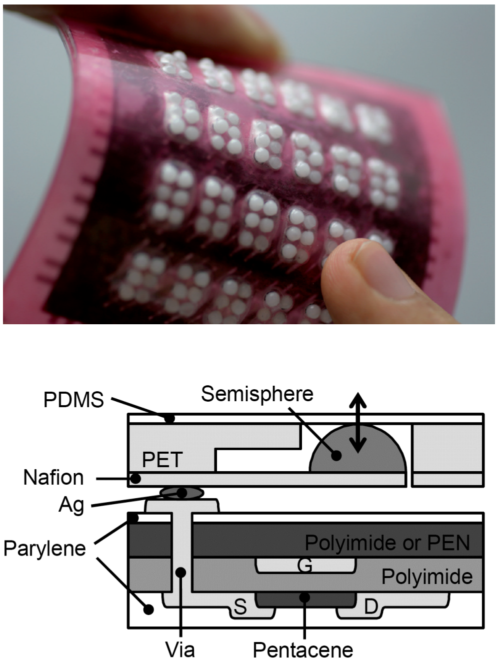

Figure 20. Braille actuator, and operational diagram. Courtesy Prof. Takao Someya, University of Tokyo.

Imprint

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