

SPECIALTY SUBSTRATES

Growing Applications for 21st Century Industrial Printers

This article describes the differences between specialty and conventional materials and discusses the roles these materials play in printed electronics.

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Global projections from a cross section of major industrial segments (automotive, consumer, aerospace, government pharmaceutical, textile, etc.) indicate that the 21st century will present widespread opportunities for industrial printing with innovations in printable electronics—also known as organic electronics. This glowing future includes applications in solar energy, medical sensors, smart labels, new generations of miniaturized computers, media players, smart phones, and even virtual battlefield weaponry. The list seems endless.

In addition to futuristic applications, these technologies are already in use in medical, military, outdoor displays, flatscreen televisions, and solar applications, among others—each with enormous potential for sustained growth. The majority of these futuristic applications will be manufactured by printing on plastic films, dramatically changing the manufacturing landscape for capital intensive and cumbersome silicon-chip foundries, and electronics contract manufacturing as we know it (three or four orders of magnitude less expensive).

This promise of the future will use enhancements of today's printing technologies, with different inks, printing-process controls, and printable substrates—enhancements that increase reproducibility and print-quality reliability, while lowering cost and ultimate size of the final products. Specifically, this widening use will require highly specialized substrates. There are

dozens of such substrates commercially available today, with tongue-twisting chemical names, such as polybenzimidazole, polyimide, polyetherimide, polyetheretherketone, polyethylene naphthate, and so on. Not surprisingly, each of these materials has acquired acronyms, such as PBI, PI, PEI, PEEK, and PEN, respectively. So what are the differences between these exotic materials, and which characteristics create differences in performance, cost, and other factors?

WHAT ARE SPECIALTY SUBSTRATES?

In my opinion, a specialty substrate is one that a printer is unfamiliar with, based on its performance characteristics and associated costs in the field and on press. Moreover, many label producers try to avoid so-called specialty substrates, because they have stereotyped them as too expensive.

When customers require specific performance characteristics that are not available with conventional, less expensive materials, the customer will pay for that value-based product because of performance, not a product at commoditized prices. The business model is as different as are the performance characteristics.

SPECIALTY SUBSTRATES ARE NOT ALL THAT DIFFERENT

Printing on specialty substrates for any industrial, or harsh environment is no different from printing on conventional, familiar substrates, such as PET and PVC,

among others. The print quality and image durability must meet either specific, customer-defined criteria, or other, well characterized criteria (UL 969, MIL-PRF-61002, and others). Typically, both of these must address the usual destructors of printed products: abrasion, extreme temperatures (both hot and cold, as well as maxima and minima) and duration of exposure to these conditions and exposure (and its duration) to chemicals, solvents, acids, caustic, oxidants, and any other process used in handling, manufacturing, or distributing the products and its printed surface(s). Given the nature of automated or conveyORIZED manufacturing operations, sequential exposures and other operations must be taken into account.

Higher performance requirements for a substrate generally result in higher substrate cost, compared to substrates with lower performance. However, unused features, including excessive margins of safety, offer only higher prices—that is, the application is over-engineered. Perhaps the most critical step in material selection is to define the performance characteristics that cannot be compromised under any circumstance. Can some specification requirements be loosened or minimized to lower cost without affecting performance appreciably? Simultaneously, when higher performance is inherently available in the specialty substrate, and it delivers the value required to satisfy the performance requirements, the customer will pay more

for it. In my opinion, the burden is on the printer to educate himself, his company, and the customer about the tradeoffs and issues of the specialty material to show the value of that substrate for the application at hand.

SOME PARADIGM SHIFTS ARE REQUIRED

We all know that excellent print quality requires proper matching of the ink(s) with the printing process used and the substrate surface. We use specific physical criteria, such as viscosity, solids content, pigment-particle size, distribution and uniformity of dispersion, and pot life, for each ink to ensure its general suitability for the printing process we plan to use. Moreover, we know that print quality and image durability rely on the chemical compatibility between the ink and the surface of the substrate—the proper matching of the surface tension of the ink and polymer systems with the surface energy of the substrate, as well as compatibility of the binders with these same surfaces in the dried/cured printed image.

We all agree that poor print quality means poor aesthetics and appeal. However, in the projected brave new world of printable electronics, the ultimate criteria for success will change from how good it looks aesthetically to how well it performs electronically. In the future, poor print quality will mean inconsistent product performance or short product lifetime or failure due to poor signal quality, rather than a cheap appearance due to poor aesthetics. The critical difference is that the printed images, circuits and components, are functional—that is, they perform work rather than project aesthetic appeal. Compromising that function for any reason unequivocally means marginal or intermittent circuit performance.

This new era of printable electronics requires additive processes because electronic components such as resistors, capacitors, power sources, and the like will be printed directly on the substrates, along with the conductive elements for the connections between components. This direct printing eliminates multiple process steps used in etching of circuits, a subtractive process, followed by sequential component placement, soldering, etc., thereby reducing overall product costs. Smaller form factors result, which in turn create new market opportunities for electronic products.

Success requires that specific choices be made from a broad array of specialty inks, coatings, and substrates that are compatible with the printed patterns (circuits and components) to deliver the wide range of electrical responses required for electronic performance. This also requires understanding and control of the substrate's surface uniformity and smoothness. For example, in printed-electronics applications, a highly planarized PET is a specialty substrate for printed electronic products, because of the performance requirements of the circuits in the final device, compared to PET—a commodity for most applications.

The driving force for print quality is the fidelity (purity or clarity) of the electronics signal(s) in the circuitry. Because the circuits and components are now printed with functional inks, the results of each printed area depend on the specific properties and the amount of the material used. For example, a surface coating can be changed from a conductive one (surface resistivity between $1 \times 10^2 - 1 \times 10^5 \Omega^3$), to static dissipative (surface resistivity between $1 \times 10^5 - 1 \times 10^{11} \Omega^3$), to a dielectric/insulative one (surface resistivity $> 1 \times 10^{11} \Omega^3$) in one of three ways:

- Composition and concentration of the functional materials used
- Coating thickness, ranging from Å (angstroms) to nm (nanometers), to μ (microns)
- Surface uniformity, or planarity—surface roughness causing variations in coating thickness.

Different materials in an ink or coating determine the resistivity of the printed image. Indium-tin oxide (ITO), carbon black, PEDOT, carbon nanotubes, nanoparticle silver, and many others are typical of conductive materials from which we can choose. Each has strengths and weaknesses, depending upon the requirements under consideration. Not surprisingly, each is used at different concentrations in a given ink formulation to support the required functional performance within the technical limitations for each material.

Likewise, each specific printing process lays down a different amount of ink, which results in a different amount of conductive material being deposited from one process to another. Less conductive material available for circuit continuity generally means higher circuit resistance and/or lower signal fidelity. Variations in coating thickness

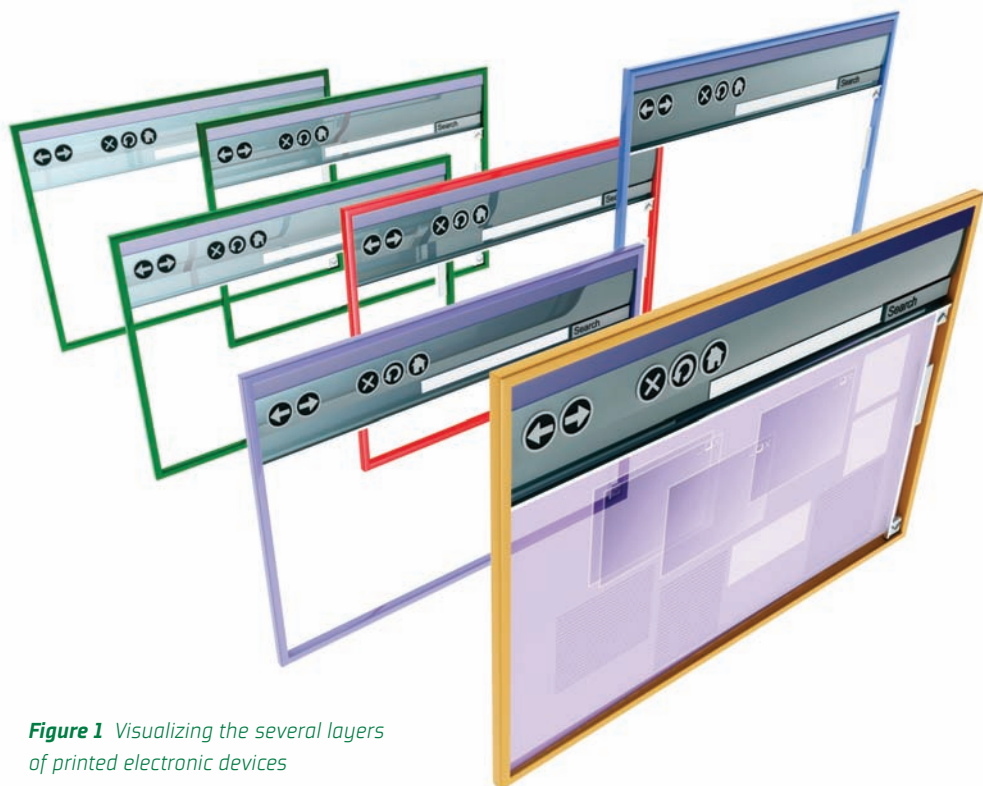


Figure 1 Visualizing the several layers of printed electronic devices

WVTR (g/m ² /day)	Application(s)	
<10 ⁻⁶	Organic bio-sensors	OLED displays
10 ⁻⁵ – 10 ⁻⁶	OLEDs	
10 ⁻⁴ – 10 ⁻⁵	Organic solid state lighting	Solar cells organic photovoltaics
<10 ⁻⁴		
<10 ⁻³	Thin-film batteries	Inorganic photovoltaics (2 nd generation)
<10 ⁻²	Sensors, electrophoretic	
<10 ⁻¹	Sensors & devices	RFID electrochromic displays
10 ⁻¹	Medical packaging	Food packaging

Table 1 Market segments defined by barrier performance

from point to point along a circuit, due to surface-area roughness, also contributes to decline of signal purity. The ink will be thicker in rough areas as it tries to flow into peaks and valleys, compared to a smoother area. Finally, it is clear to all of us that the compatibility of the ink with the substrate determines the surface-contact area between the two layers, as well as the adhesion strength between them. As noted above, surface smoothness also influences coating thickness and uniformity.

Specialty substrates play a critical role for the success of printable electronics. A typical electronic device is truly built in layers (**Figure 1**). The printer builds the components layer by layer on the board, which is now a plastic film. The subtleties of the printed circuitry and components each require specific ink and/or substrate characteristics, as layers of printed components are registered upon other layers of printed components and circuits. Alignment problems with membrane-switch assemblies promise to be child's play compared to the alignment of coating patterns as resistors, capacitors, and diodes are printed one layer over another in very tight registration, along with precise connection—again, by printing—with the conductive paths of the circuits.

Dimensional stability of the film provides the mechanical and thermal stability for the device. These characteristics influence not only print-to-print registration during printing processes, but they also determine processing and end-use temperatures for the products. Physical surface properties in terms of roughness and physical cleanliness influence the layer quality of the printed matter on the substrate

surface dramatically. Compatibility of the inks and coatings with the substrate—surface energy and solvent resistance—also influences layer quality. Chemical resistance is important because components are overprinted in discrete layers one upon the other. Finally, barrier properties of each substrate chosen determine the type of device that can be manufactured. Just as components today are encapsulated (resistors, chips, LEDs, diodes, etc.) to protect them, the new components and circuits must be protected as well.

In addition to heat, dust, and UV radiation, the worst enemies of the new electronics are water vapor and oxygen, which can interfere with or destroy the performance of the new-era electronics. In general, it is widely accepted that for printed electronic devices to be viable, the barriers for oxygen exposure (known as the OTR, or oxygen transmission rate) should be on the order of 10⁻³-10⁻⁵ cc/m²/day, and for water vapor (known as the WVTR or water vapor transmission rate), on the order of 10⁻³-10⁻⁶ g/m²/day. To put this in perspective, many films for pharmaceutical and food packages that printers already use, such as metalized mylar or high-tensity-oriented polypropylene, require OTRs in the range of 10⁰-10⁻² cc/m/day and WVTRs between 10⁻¹-10⁻³ g/m²/day. Different types of electronic devices require different levels of protection. For example, **Table 1** shows market-segment definition based on the protection against water vapor.

To summarize, there are a stack of engineering criteria that must be considered when selecting the optimum substrate for each printable-electronics requirement:

- Low coefficient of thermal expansion
- Low shrinkage at appropriate temperatures
- Upper temperature for processing
- Surface smoothness
- Barrier (OTR, WVTR)
- Solvent/chemical resistance
- Moisture resistance
- Clarity
- Transparency
- Rigidity
- Commercial availability

The entire stack must be considered in the context of processing and use environments when selecting substrates for printed-electronics applications. From this perspective, each new electronic product may require its own unique specialty substrate. As applications progress from simple circuitry to those with organic active matrix (AM) backplanes, to inorganic AM backplanes, to OLED lighting, the substrate structure necessarily becomes more complex, requiring a more demanding property set from the stacks listed above.

In closing, I will reiterate that even these specialty substrates are not all that different from the ones we are comfortable with today. Based on years of experience in working with plastic films, such as PET, we take for granted many of the properties highlighted above; or, they are not important for success in our traditional business. It is our technical and process-related understanding of the differences required for proper printed functionality—compared to printed appearance—that must change. We can accomplish this by educating ourselves, our colleagues, and our customers about these new materials and processes, using common sense, controlled process experimentation, and realistic expectations. 🎯



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