ORGANIC & PRINTED ELECTRONICS

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EXECUTIVE SUMMARY

In this roadmap, the members of the iNEMI TWG attempt to provide an overview of the most critical technologies necessary for commercial launch and market diffusion of organic & printed electronics based products. To the best of our knowledge, this roadmap is the first of its kind and as such should be viewed as a snapshot of the present industry. As with a traditional roadmap, the value of this roadmap will increase over time as it is updated and enhanced by capturing paradigm shifts and trend development in the industry.

BUSINESS ISSUES

Current Situation

- The National Institute of Standards and Technology Advanced Technologies Program (NIST ATP) starting in the late 1990's has invested in consortia established to develop platform organic & printed electronics technologies and product prototypes.[1,2,3]
- The Defense Advanced Research Projects Agency (DARPA) established a Macroelectronics initiative which funded several consortia focused on the development of the enabling large-area electronics technologies.[4,5]
- The Organic Electronics Association (OE-A) was established in 2005 in an attempt to identify critical elements necessary for the successful commercialization of organic & printed electronics.[6]
- Graphic arts printing and microelectronics are beginning to converge.
- Novel nanoscale electronics-grade materials are being developed by well-funded start-ups.
- The European Union (EU) 6th Framework is funding several consortia to develop enabling organic & printed electronics technology platforms.[7]
- Eight international conferences planned for 2006.
- Adoption of IEEE 1620-2004™ and IEEE 1620.1-2006™ international standards.[8, 9]
- New markets such as active packaging are beginning to emerge in addition to previously identified markets e.g. RFID, sensors, and displays.

Drivers of Change

- EU makes well-publicized commitment to organic & printed electronics by funding multi-million euro efforts for pre-competitive technology development.
- Availability of printable semiconductor materials such as solution processable pentacene, nanoscale silicon, and other novel inorganic and organic dispersions.

- Availability of printing equipment compatible conductive and dielectric materials.
- Development of low-cost manufacturing processes leveraging printing infrastructure.
- Growing demand for low-cost sensors, low-frequency wireless devices, and displays.

Enablers: Functional Inks, Processes, and In-Line/Off-Line Characterization Tools

- Adoption of the best manufacturing practices of the microelectronics industry by the organic & printed electronics industry.
- Improvements in organic & printed electronics will enable development of low-cost sensors, displays, and low-frequency wireless devices.
- Advances in organic and inorganic solution processable semiconductor technologies.
- Advances in the design and layout of organic & printed electronics.

Paradigm Shifts

- Integration of electronics in product packaging and printed media.
- Manufacturing platforms that enable large-area flexible electronics.
- Low-cost electronics for single-use applications.

Gaps and Showstoppers

- Rate of improvement in organic and printed semiconductor technology is not occurring rapidly enough to meet the cost/performance demands.
- Rate of development and integration of in-line/off-line characterization tools should increase to enable near-term commercialization.
- Rate of development of printed electronic systems should accelerate, otherwise a window of opportunity may be created for a disruptor to commercialize a competitive product.
- Lack of design and simulation tools could slow the diffusion of organic & printed electronics into the market.
- Lack of a well-developed supply chain and deep infrastructure could lead to products that are not cost competitive.
- Lack of workflow that combines functional electronic content with graphics content could slow organic & printed electronics enabled product commercialization.

INTRODUCTION

SCOPE

The organic & printed electronics chapter addresses technologies specific to functional inks, substrates, packaging, printing platforms, characterization tools, design and modeling, and reliability.

CHANGES SINCE THE 2004 INEMI COMPONENTS ROADMAP

In response to the growth of the organic and printed electronics field, the publishing of a roadmap is very timely. This is the first roadmap of its kind.

ORGANIC & PRINTED ELECTRONICS SYSTEMS

The applications and components listed in Table 1 are composed of organic inks and/or fabricated via printing processes. Several industry reports have projected that by 2010 the market could grow to $75B with products such as flexible displays, lighting, RFID, and smart packaging.

Table 1 Total available market (TAM) for several printed electronics opportunities in 2020

Printed Electronics System	TAM Opportunity	Technology
Displays/Signage	$30B	Emissive, reflective
Sensors	$6B	Chemical, biological, moisture, temperature
Low RF	$20B	Personal area network, RFID
Energy	$15B	Photovoltaic arrays, primary batteries
Lighting	$15B	OLED, electroluminescence
Logic & Memory	$30B	Crossbar
Authentication and Anti-tampering	$10B	Logic architecture

Data compiled from references 10 and 11.

PRODUCT EMULATORS FOR INEMI 2007 ROADMAP

Several opportunities exist to integrate an organic or printed electronics component/subsystem in the iNEMI product emulators. Due to the youth of this nascent field, early opportunities must be selected based on the performance and reliability requirements as specified by the product emulator. As with silicon-based component/subsystem technologies, it is envisioned that organic and printed electronics technologies will mature over time, offering improved performance and reliability attributes. Therefore, as organic and printed electronics become more robust it is possible that memory products may be developed for the *Aerospace and Defense* industry as an example. Table 2 identifies potential opportunities for integration of organic and printed electronics throughout its maturity cycle over the next 10 years.

Table 2 iNEMI Product Emulators and potential organic/printed electronics opportunities

Industry	Authentication and Anti-tampering	Displays	Memory	Power	RF Devices	Sensors
Aerospace and Defense	X	X		X	X	X
Automotive	X	X				
Medical	X					X
Networking	X				X	
Portable and Consumer Electronics	X	X	X	X	X	X

Broadly speaking, applications that can be designed using organic and printed electronics devices, circuits, & components may be classified by whether or not they incorporate a display (Tables 3 and 4).

Table 3 Potential display-based applications

• Retail	• Electronic Books
• Point-of-Purchase or Point-of-Sale Displays	• PDAs
• Shelf Edge Labels	• GPS/Electronic Maps
• Information	• Electronic Gaming Units
• Electronic Signs	• Automotive Displays & Instrumentation
• Electronic Posters	• Wearable Displays
• Electronic Billboards	• Smart Cards
• Portable Consumer Electronics	

Although these applications may serve radically different functions and appear to be very different to the end user, the devices for display applications are internally very similar. They all contain 1) a display, 2) a user interface (switches, touchpads, touchscreen), 3) driver electronics (display drivers, microprocessor, memory, audio, etc.), 4) a communications link (wireless or wired), and 5) a power source (battery, solar array, or other power supply).

In the near term, there is a likely role for organic and/or printed electronics in the fabrication of the display and the user interface. The display itself can be subdivided into a control element (backplane) and a visual element (frontplane). Of these two, the backplane is most likely to be printed, although it may also be possible to print the visual element for light emitting diode (emissive type) and color electrophoretic (reflective type) displays. Organic light emitting diode (OLED) and polymer light emitting diode (PLED) displays in particular would appear to be natural candidates for fabrication by printing, as printing-like technologies are already used by some manufacturers. OLED fabrication, however, remains a complex and delicate process with many steps that are incompatible with graphic arts printing. Significant progress will be required in the development of more robust processes for OLED fabrication before they can be positioned on a printed electronics roadmap.

Table 4 Non-display applications

- RFID
- Solar Cells
- Smart Cards
- Sensors

Of the non-display applications, radio frequency identification (RFID) tags and smart cards are the most complex, as they must contain a variety of components, some examples of which are listed in Table 5.

Table 5 RFID product components

- Antenna
- Rectifier
- An RF modulator
- Memory
- Timing circuitry

In the case of solar cells, the conductors for current collection provide a near-term opportunity for printed electronics. In the longer term, the active material could be an organic or hybrid composite material that is roll-coated in a process that integrates well with a subsequent printing step for the collectors. Smart cards appear as both display and non-display applications because, while they may include a display, they are also likely to have a contactless interface that will share many characteristics with an RFID device. While these cards contain many components (display drivers, a microprocessor, and flash memory) which could potentially be printed, the technologies for printing the antenna and display are much closer to realization. Sensors represent another family of active devices that provide functionality e.g. monitoring environments and processes. The sensor architecture could be simple e.g. a device that changes electrical and/or optical characteristics when subjected to an environmental change i.e., temperature, humidity, etc. This information can be sent wirelessly (or via wired line) to control units for further action.

Given these considerations, it can be expected that any technology required for the application of printed electronics to smart cards and solar cells will be similar to that required by more complex devices. Therefore, a discussion limited to the components listed in Table 6 will be sufficient to cover the majority of organic and/or printed electronics. Further, an analysis of the individual devices required for each of these components is quite revealing.

Device interconnects, and conductive elements within individual circuits will be wires printed from a suitably conducting ink. Similarly, resistors are most likely to be designed as a wire with a poor conductivity and/or a long length. From a device design perspective, all of the printable elements for user interfaces also involve variations on the theme of wires: the printing part requires only the patterning of a conductor, dielectric, resistor, and semiconductor. To date, most of the demonstrations of printed rectifiers for RFID applications use transistors wired in a diode configuration rather than Schottky or other diode technology. Therefore, the list of key electronic devices required for the design and manufacture of first generation of printed electronic commercial products is quite short, Table 6. It consists only of transistors, capacitors, resistors, inductors, and wires.

Table 6 Devices necessary to build display backplane, user interface, and RFID hardware.

Component	Devices
Display Backplane	Transistors Capacitors (includes wire crossings) Conductors (wires)
User Interface	Membrane Switches Touch Pad Sensors Touch Screen Sensors
RFID Antenna	Conductors
RFID Rectifiers	Diodes Capacitors
RF Modulator	Fast transistors
RFID Memory (*e.g.*, ROM)	Transistors Conductors Diodes
RFID Timing Circuitry	Transistors Conductors Resistors Capacitors Inductors

SITUATION ANALYSIS

BUSINESS ISSUES

Engraving and marking is ubiquitous throughout the world and parallels the making of tools in all cultures. The development of photographic processes as well as digital imaging and printing also play prominent roles. Books, magazines, catalogs, newspapers, and all printed material became critical and pivotal for the processing and distribution of information and content. During the Twentieth Century the application of lithography to semiconductor manufacturing became the driving force that led to the establishment of the trillion-dollar ($US) computing and communications industries. The manufacturing of printed wiring boards (PWB) and graphic arts printing share much of the same heritage, both based on imaging, etching and engraving processes. The printing/microelectronics industries are at the cusp of a new industry created by the merging of the graphic arts printing and microelectronics technologies – ORGANIC &

PRINTED ELECTRONICS – applying established print manufacturing systems and novel nanotechnology enabled functional inks to create electronic circuitry.

Printing equipment when used as an electronics manufacturing platform will provide a means for scaling with costs that increase at a rate several of orders of magnitude below the rates historically observed for silicon IC manufacturing.

- The costs associated with fabricating silicon ICs and assembling products designed with several IC chip sets are at least an order of magnitude higher than those that can be realized when using organic and printed electronics.
- Manufacturing economies of scale- printing of solution processable materials versus vacuum deposition and photolithography for silicon IC fabrication.
- Printing can deliver circuitry that provides similar performance attributes to silicon during the 1970's while silicon is driving for higher performance by developing equipment to fabricate nanoscale features (sub-65 nm channels).
- Printing of electronics in large-area form factors versus being limited to circular wafer dimensions (e.g., 300 mm wafers).

FUNCTIONAL INKS

Background

Due to the recent advent of various organic and printed electronics materials systems it is important to differentiate these materials based on processing: 1) solution processable materials and 2) thermal-vacuum processed materials. Furthermore, in this document the terms 'functional ink' or 'ink' will be used when referring to any solution processable material. Recently the term 'functional' was added to differentiate graphic arts inks that provide visual attributes from inks that provide intrinsic bulk electrical, thermal, chemical, or optical properties. Several families of functional inks, listed in Table 7, have been recently commercialized or are under development with plans for commercialization in the next few years. Over the past three years, significant R&D resources have gone into developing functional electronic inks (organic and inorganic) that can be printed on standard high-volume equipment commonly used in the printing industry. Functional inks can be grouped based on device application: 1) inks for passive devices and 2) inks for active devices.

Inks for Passive Devices: Several materials exist for general purpose insulating layers, although satisfactory high permittivity inks have yet to be developed. In the area of conductive materials, screen printable conductive pastes have been available for many years and have successfully penetrated applications such as membrane switches and touch screens. These formulations have high viscosities, which are not conducive to most high speed printing methods. Many low viscosity conductive inks have recently been commercialized or are near commercialization. These inks were designed for high throughput printing methods, i.e. flexography and gravure printing technologies.

Inks for Active Devices: To date, materials for active devices such as transistors and light emitting diodes (LEDs) have been primarily organic, or organic materials have been printed on prefabricated inorganic backplanes. At present, the state-of-the-art, all-printed devices are generally operated at 10 to 60 volts and have unloaded ring oscillator delays of a few seconds per stage, roughly nine orders of magnitude larger than the state-of-the-art silicon complementary metal oxide semiconductor (CMOS). However, new all-printed devices are showing markedly improved performance which will enable all-printed circuitry to operate at several kilohertz, a rate of improvement far exceeding the historical trend for silicon ICs (*i.e.*, Moore's Law). The driving force for developing organic and printed electronics is the fact that they are flexible, lightweight, and have the prospect of low cost manufacturing. Organic circuits with a performance suitable for certain applications have been demonstrated during the past few years. These applications include flat-panel displays, low-end smart cards, electronic identification tags as well as sensing devices.[12,13,14,15,16] Due to the fact that polymers cannot withstand high processing temperatures, one has to use low processing temperature techniques, which are in general compatible with low-cost processing.[17]

Table 7 Classes of functional inks and critical attributes

Functional Inks	Attributes
Conductor	• Metal, organic based • Sub-micron particulates • Bulk conductivity >10^4 S/m • Low processing temperature (<200 °C)
Dielectric	• Polymeric or Nano particulate based • Electrical resistivity >10^{14} Ω-cm • Film thickness <5 μm • Permittivity (2-20), low loss • Semiconductor compatible band gap • Low processing temperature (<200 °C)
Semiconductor	• Organic or inorganic • Electron mobility 10^{-2}-10^1 cm^2/V s • Low processing temperature (<200 °C)
Resistive	• Organic or inorganic • Resistance (10-100K Ω/□) • ±10% Nominal resistance tolerance

Status

Inks for Passive Devices: Conductive inks have received the most development attention to date, with several suppliers offering silver-based and carbon-based products. More suppliers and more material sets (*e.g.*, copper) are anticipated, particularly for the printable electronics market. Organic conductive inks such as polyaniline (PANI) and polyethylenedioxythiophene (PEDOT) are also available, although organics are typically 1000 times more resistive than metallic inks. Doping can be done to reduce the resistivity, but even doped layers are far more resistive than metal-based conductive inks. Dielectric inks have been formulated for several printed electronics applications. Commercially available dielectric materials have permittivity values in the range of 2-20. A few researchers have recently reported materials demonstrating permittivity values of greater than 20. Several carbon based, resistive ink formulations are commercially available with their sheet resistance values ranging from vendor-to-vendor.

Inks for Active Devices: Semiconducting inks are needed for the production of active devices from in-solution or from vapor phase deposition that can switch on and off or perform more complex functions. Several types of semiconducting materials are available including polymer, small molecule organic/inorganic hybrid or inorganic semiconductors. The current highest mobility values, on par with amorphous silicon (a:Si), have been obtained for pentacene-based devices.[18]

Polymers: Soluble semiconducting polymers for electronic applications were first developed in 1988 with the advent of substituted polythiophene and their introduction into thin film transistors (TFTs).[19] The discovery of the importance of regioregularity of the side chains, which increases the degree of ordering and preferential crystalline orientation,[20] led to a dramatic increase of the charge carrier mobility into the range of technological significance.[21] Recently, even higher performance polymer semiconductors have been developed that are competitive with amorphous silicon, however cost and stability remain an issue for many applications.[22]

Small Molecules: Most small molecule semiconductors are insoluble and can only be deposited in the vapor phase by thermal evaporation[23] or organic vapor phase deposition. Soluble precursors have been developed that can be thermally or photo converted into the semiconductor after deposition.[24] Several soluble versions of small molecule semiconductors have been synthesized by adding functional groups.[25,26,27] The performance of the solution processable small molecules is lower than that of the evaporated versions, but is typically equal to or better than semiconducting polymer films.

Inorganic and Hybrid Materials: Historically inorganic semiconductor films were typically deposited by atomic/chemical vapor deposition, evaporation, or sputtering and have significantly larger mobilities than organics. These deposition methods are generally not compatible with low cost processing, where the same high mobilities do not occur. In-solution deposited inorganic films can be made by casting a sol-gel based solution[28] or a suspension of nanoparticles or nanowires.[29,30]

Major Past Developments

The advent of a variety of functional inks is due to the development of various organic and nanoparticle synthesis technologies that provide new types of functional inks suitable for high speed print processes. Table 8 lists examples of common organic semiconductor materials along with their reported electron mobility. Although not as common as organic systems, the development of nanoparticle systems have the ability to reduce annealing/sintering temperatures yet achieve near-bulk materials properties, allowing for the use of less thermally stable and less expensive substrates.

Table 8 Families of solution processable organic semiconducting inks

Development Period	Chemical Family	Reported Mobility Range (cm^2/Vs)
2003-present	Pentacene	1.0 – 2.0
1990-present	Thiophene oligomers	0.01 – 0.1
1988-present	Polythiophene	0.01 - 0.7

Data compiled from references 31 and 32.

SUBSTRATES

In general four classes of substrates, show in Table 9, have been used for demonstrating the benefits of organic & printed electronics: 1) ceramic, 2) metal, 3) organic, and 4) composite.

Table 9 Types of substrates and attributes

Substrates	Attributes (CTE, modulus)
Ceramic(99.5% Alumina, thin film substrate)	• Weight (397 gm/m^2) • Visually opaque • High processable temperatures (3300 °C) • High elastic modulus • No permeability (O_2 & H_2) • Low electrical conductivity
Metal (Stainless Steel)	• Weight (800 gm/m^2) • Visually opaque • High processable temperatures (1000 °C) • High elastic modulus • No permeability (O_2 & H_2) • High electrical conductivity
Organic (Polyethylene Terephthalate PET)	• Weight (100 gm/m^2) • Visually transparent • Low-medium processable temperatures (100-300 °C) • Low elastic modulus • High permeability (O_2 & H_2) • No electrical conductivity
Composites (Epoxy/Glass Composite)	• Weight (220 gm/m^2) • Visually transparent • Medium processable temperatures (140-200 °C) • Medium elastic modulus • Low-medium permeability (O_2 & H_2) • No electrical conductivity
Paper	• Weight (various) • Visually opaque • Low processable temperatures (<150 °C) • Low elastic modulus • Low permeability (O_2 & H_2) • No electrical conductivity

Data compiled from references 33 and 34.

This section was included to highlight the importance of substrate selection for organic & printed electronics. Further discussion for substrates will be found in the "Flexible Electronics" section.

PACKAGING/BARRIERS

Background

Printed electronics, particularly organic semiconducting circuits, show strong sensitivity to ambient conditions such as moisture, oxygen and light. The performance of those devices and integrated circuitry diminishes quickly after exposure to the aforementioned conditions. In many cases the defects are irreversible. It has been concluded that in order to ensure high reliability, printed devices and circuits ultimately require shielded operation.

The role of barrier packaging is to protect printed electronics during device/circuit life cycle (manufacturing, storage, transportation, operation, etc.). In addition, barrier packaging protects printed electronics products from chemical attack, shear stresses and impact damage. Packaging/barrier protection is generally presented in 3 forms: 1) barrier films, 2) solution processable barrier coatings, and 3) vacuum deposited barrier coatings. Example packaging materials are presented in Table 10.

Table 10 Barrier properties of flexible packaging material

Category	Material	Water Vapor Transition Rate WVTR $\left(\frac{g}{100in^2 * day}\right)$	Oxygen Transition Rate O_2TR $\left(\frac{cc}{100in^2 * day * atm}\right)$
Films	Aluminum foil	< 0.00	< 0.000
	oPET	1.5	4.5
	Oriented Nylon	26.5	3.
	Cast Nylon	19.	3.5
	OPP	0.33	150.
	LDPE	0.9	NA
	HDPE	0.37	NA
	PVC	2.3	11.
Barrier Films	Polyacrylonitrile	4.5	0.7
	EVOH	1.4-8.0	0.006-0.12
	COC	0.21	NA
	LCP	0.015	0.04
	PCTFE	0.0094-0.026	7.0-15
Barrier Coatings	PVdC-coated PET	0.5	0.5
	PVdC-coated OPP	0.3	1.3
	PVdC-coated Nylon	0.65	0.7
	PVOH-coated PET	4.	0.2
	PVOH-acrylic-coated PET	0.37	0.002
	SiO_X-coated PET	0.02-0.04	0.003-0.04
	Al_2O_3-coated PET	0.002-0.3	0.005-0.045

Data compiled from reference 35.

Status and Major Past Developments

The use of a barrier film is an alternative, cost effective method to protect printed electronics from various environmental stimuli e.g. moisture, oxygen, light, etc. It is a mature technology used for products in the electronics, medical, pharmaceutical, food and industrial markets. In general, printed electronics based components require superior barrier attributes.

Barrier films can be either laminated to printed electronics substrates with pressure sensitive adhesion (PSA). Lamination can be optimized, depending on the type of substrates used and adhesion strength required. The type of adhesion will also dictate the preferable fabrication method and number of processing steps. In many instances a strong peelable seal will be a more cost effective solution than a weld seal, due to reduction of processing steps. The presence of surface modifiers on the printed substrate will reduce lamination strength and make the lamination process more challenging. Many custom formulated sealants must be developed to tailor the strength of adhesion.

Solution processable barrier materials commonly referred to as a conformal coating, have been used in traditional electronics for many decades. They can also be applied in thin and conformal layers onto printed electronics substrates to provide environmental and mechanical protection to significantly extend the life of printed electronics. Conformal coatings can also be used to reduce the oxidation rate and electrochemical reactivity rate in metal conductors. Solution processable conformal coating can be processed using many available, well established coating techniques such as: atomized spraying, dip coating, curtain coating or brush coating to name a few.

Vacuum deposition processes guarantee precise control of coating and uniformity. These deposition methods have better penetration rate than conformal coatings and can create thin, pinhole free layers. Parylene is the most popular coating material used for vacuum deposition. It has good chemical resistance, exhibits impressive mechanical strength, thermal stability, high dielectric constant and superior barrier properties. This is a promising technology since it can be integrated onto a roll-to-roll (R2R or RTR) platform. Vacuum-deposited parylene coatings provide the greatest barrier properties offered by conformal coatings and provide an alternative barrier application method to lamination; vacuum deposition may be required if interfacial compatibility is an issue when using lamination.

PRINTING PLATFORMS

Background
Traditionally printing technologies are classified into two categories: 1) contact printing and 2) non-contact printing. Table 11 lists the reported dry film dimensions of various printing technologies; the values provided are for general guidance and do not represent the limitations of the depicted printing technologies. Examples of contact printing platforms include letterpress, gravure, flexography, offset, and screen while examples of non-contact printing include micro-dispensing, jetting and "off contact" screen printing. Each technology has its advantages and disadvantages which determine their specific market place in the printing industry. For example, screen printing is commonly used for thick film deposition (*i.e.* the thickness of printed material is greater than 25 um) of conductors, resistors, and capacitors. As an example, screen printing is a preferred technology for membrane switch printing where reliability and conductivity of the traces is achieved by printing a thick line of conductive material to withstand repeated impact strains (pressing of the keypad to activate a function) and power intensity during operation activation by the switch. However, the printing resolution achieved by screen printing is generally coarser when compared to other printing technologies; the resolution is a direct result of the wire gauge and spacing that forms the screen mesh. Recent applications of screen printing in printed electronics have targeted RFID antenna fabrication, which requires electrically conductive and mechanically robust, thick films.

Table 11 List of roll-to-roll printing platforms and typical dimensions

Printing Technology	Minimum Lateral Resolution μm	Average Dry Film Thickness μm
Gravure	15	0.8-8
Flexo	20	0.8-2.5
Offset	15	0.5-2
Screen	50	3-35
Inkjet	50	0.3-10
Micro-dispensing	50	5-100
Laser Assessed Forward Transfer	10	0.01-1
Electro Static	30	1-10

Data compiled from references 31, 36, 37, 38, 39, and 40.

A second common printing technology is called flexography, which is a form of relief printing where the mirror of the image to be transferred is raised above the surface of a photopolymer or elastomeric printing plate. Flexography is believed to have been invented during the 1860's and was known as aniline printing, up until 1952, because the inks were derived from aniline oils. This type of printing especially lends itself to printing on non-porous materials such as metal foils or plastic films. Since flexography is a finer resolution printing technology, it is quickly gaining interest by RFID antenna printing suppliers that are assessing manufacturing options that offer higher throughput than screen printing. However, the rheology of the ink used in flexography has a lower viscosity than that of screen printable inks and typically yields printed dry films of less than 2.5 microns. Therefore, the materials used in flexographic printing of RFID antennas usually require higher bulk conductivity than those used in screen printing to compensate for the decrease in film thickness. An alternative method to increase printed film thickness is to conduct multiple pass printing; however, this can result in lower printed feature tolerance due to layer-to-layer mis-registration.

Similar to flexography, gravure printing is another technology that is quickly establishing itself as a viable manufacturing platform for printed electronics due to its high print resolution and throughput capabilities. Gravure printing is a type of intaglio printing where the reverse of the image to be transferred is engraved or etched onto an image carrier, such as, a cylinder. Commonly reserved for long print runs due to the cost of engraving the cylinder, gravure printing has increasingly been selected for short runs due to recent cylinder imaging technology advances. The ability of gravure to print variable film thicknesses in one print unit, a feature which is limited in both lithography and flexography, at high resolution and throughput has heightened its potential as a printed electronics technology enabler. To date, superior resolution is achieved by the ultra-high image definition of the chromium coated gravure cylinder which has a hard surface that undergoes minimal distortion during the printing process. Also, the thin chromium cylinder allows for the fabrication of thin film thickness (<3 um) due to the self eliminated dot gain phenomenon.

Compared to the previously mentioned printing technologies, offset lithography printing which is commonly referred to as simply offset printing can also provide high resolution printed features.

The high resolution is achieved by precision control and balance of the plate surface energy for ink (imaging) and water/oil (masking) wetting. During high volume printing, the printed dry film thickness approaches 1 micron with very tight tolerance.

Ink jet printing is a non-contact printing technology which has been actively pursed for printed electronics over the past decade; it is categorized as 1) continuous or 2) drop-on-demand. Continuous ink jet technology is based on a stream of ink interrupted into regularly spaced droplets and is most often used for industrial applications to print batch numbers and expiration dates on manufactured items. To ensure a level of control and reproducibility of the continuous ink jets, a predetermined perturbation is typically applied at the jet orifice that causes a breakup of the jet into a series of regularly spaced droplets. The second ink jet technology, drop-on-demand, is the most common technology and is used in desktop and wide-format printers. During operation of a drop-on-demand printer, droplets are generated when needed via a thermal (bubble jet) or an acoustic (piezoelectric jet) process. The most attractive benefits for using ink jet printing for printed electronics development include: 1) digitally driven fabrication, 2) on-the-fly product variability, 3) additive processing, and 4) non-contact printing.

Status and Major Past Developments

Several advances have been reported in the past few years as the number of companies involved in the printed electronics industry continues to increase. The majority of the efforts have focused on a variety of graphic arts printing technologies, mainly gravure, flexography, offset and inkjet.

Gravure: Inroads in organic & printed electronics are being made in gravure print equipment. Recent advancements in mechanical engraving have demonstrated imaging capabilities of 10 µm. However, current developments in laser technology for imaging gravure cylinders are quickly evolving and are just starting to be more widely used in the graphic arts printing industry. This development will provide higher resolution organic & printed electronics manufacturing. Examples of such systems are:

- A pulsed laser system has been developed which can directly image onto zinc surfaces. This system is more widely used in Europe than in the United States.[41]
- Another type of laser imaging system uses an ablation process to remove a polymer coating from a copper plated cylinder. The cylinder is chemically etched to remove a prescribed amount material from the exposed copper surfaces. The remaining polymer coating is removed and the entire cylinder is chrome plated.[42]
- Another laser imaging system uses a reverse plating process to remove copper from the cylinder instead of chemical etching after a polymer coating has been ablated.[43]
- An imaging system has been developed for imaging directly onto copper for gravure and flexo applications.[44]

Flexography: Flexography has come a long way in recent years. Quality and resolution have greatly improved and now compare well to offset lithography. The greatest improvements in resolution and print quality are primarily the result of advanced plate materials for higher resolution imaging in addition to digital laser imaging of both the plates and the anilox roller.

Laser imaging provides finer control in making cells on the anilox roller. This in-turn allows for more accurate control over ink film thickness applied to the substrate. Digital laser imaging of harder and finer plate material now supports much more detail for smaller lines and halftone screens enabling resolutions from 2,000 dpi to 4,000 dpi (12 to 6 μm). Modern digital flexography plates for security elements (packaging, labels, tickets for example) are able to print with an imaging resolution of up to 8,000 dpi. Screening technologies such as stochastic and mixed transitional screens of amplitude modulated (AM) and frequency modulated (FM) screening have helped considerably.[45]

Flexography can use a wide range of inks and can be used to print on a variety of different substrates. The inks are more like gravure and have low viscosity. Ink and press configuration can be deployed to enable fast drying including additions like UV drying between each print unit if needed.

The combination of the laser imaged anilox roll, ink flexibility, doctor blade removal of excess ink and finer features of laser imaged plates put flexography in a good position to control ink film thickness, feature size and registration. Today's flexography can be applied to printed electronics R&D and focused product types that can be designed within the current process resolutions. Examples of flexography improvements include:

- Flexographic press manufacturers are developing systems that are able to image and run 500 lpi screened images using existing flexo technology. To relate this to printed feature size; a 20% screen dot at 500 lpi would be representative of a spot size of ~10 μm.[46]
- Computer-to-plate laser devices are enabling fine imaging of flexography plates with imaging resolution of 2032 dpi to 3556 dpi which translate to spot size of 13 μm to 7 μm, respectively. Such systems have demonstrated micrometer repeatability plate-to-plate using resolution enhancing software that improves the imaging of fine screening for flexography.[47]
- Modern multi-function imagers equipped with lasers for flexo, gravure, and specialty printing, are demonstrating resolution capabilities of up to 5080 dpi with 5 μm addressability.[48]

Offset: Testing of registration and minimal printable micron size is ongoing. See Road Map and Technology Needs and Potential Solutions Sections for statistics. Inroads in registration control have increased over the last decade. However, more precise registration is still needed. Tested features have shown capability of printing 20 μm on paper with registration limits of 30 μm.

- New offset inking systems combine efficient ink temperature control units along with the traditional flexo anilox roll to precisely meter the amount of ink applied to the substrate materials. The resolution and registration control of offset combined with this new inking system might afford additional options for printed electronics.[49]

Inkjet: Over the years inkjet printing has been actively pursed as a low-cost alternative to fabricating flexible electronics. One of the driving features for implementing jetting into and electronics manufacturing technology its data driven printing capability. Some non-traditional applications of inkjet have included: electrical[50] & optical interconnects,[51] flexible organic displays,[52] sensors,[53] medical diagnostics,[54] drug delivery,[55] MEMS packaging,[56] photovoltaic,[57] 3D rapid prototyping,[58] nanostructure,[59] and photoresist[60] materials deposition. More recent developments in commercial ink jet platforms continue to further progress jet printing as an in-line metallization process for the manufacture of printed RFID antennas, display front planes and backplanes and circuit electrodes. Some examples include:

- Ink jet silver organometallic materials for solar cell front contact electrodes are currently being pursued as an alternate means of fabrication.[61]
- An inkjet laboratory system for printed electronics products, such as, organic light emitting diodes and displays, liquid crystal displays, sensors, solar cells, packaging, printed circuit boards and other organic and inorganic printable applications have been developed.[62, 63]
- A full color inkjet printing platform for use in light emitting polymer and organic light emitting display (OLED) manufacturing has been under development.[64]
- An in-line, ink jet metallization platform is approaching commercialization. The system uses piezoelectric ink jet technology and UV curable conductive ink to direct write metals, such as solid copper, onto non-porous flexible substrates, including polyester (PET), polyethylene naphthalate (PEN), polyamide and other electronics-grade materials.[65]
- A prototype of a full color 40 inch OLED display is manufactured using ink jet printing technology.[66]

IN-LINE CHARACTERIZATION TOOLS

Background/Status

Printed electronics is currently in the midst of a period of transitional research and development. University and corporate R&D are just beginning to move into manufacturing systems development. Commercial print manufacturing today has become a sophisticated platform of closed-loop controls, distributed systems and automated set-up and defect detection.

Laser imaging has raised the bar in prepress image writing. Some applications are currently running in the range of 5 μm imaging resolution which is well suited for printed circuitry development. The average finest feature imaged for commercial graphic arts print product is typically in the 20 to 30 μm range. However, press registration and guidance controls are generally more geared / programmed to resolve print quality for human vision, 40 to 80 μm.[67]

Major Past Developments

Over the last 20 years print and prepress technology has undergone an intense period of evolution driven by electric systems, computerization and digitization. Programmable Logic Controllers (PLC's) and systems have replaced the hands-on manual controls of early printing. The printing press has evolved from high craft-based machinery to a manufacturing system with fully automated tracking of all events impacting quality, from splices and blanket washes to out-of-register and color-control adjustments. A printing press is now a complex manufacturing line with hybrid process control involving discrete, batch and closed loop systems. Ink metering, web guidance, registration, speed are monitored and control computer systems displays. A major development today is automated camera based defect detection and purging. The camera systems used today can resolve features and ink density to manage color, registration and defect detection. Some of the in-line characterization parameters of interest are listed in Table 12.

Table 12 In-line characterization

Technique	Description
Electrical	• Resistance • Capacitance • Electrical conductivity • Magnetic permeability • RFID validation/programming
Optical	• Surface inspection • Porosity detection • Dimension measurement • Infrared inspection • Character recognition • Coated film thickness • Barcode validation • Color tracking

OFF-LINE CHARACTERIZATION TOOLS

Background/Status

Different from in-line characterization tools, off-line characterization tools collect detailed information for organic & printed electronic circuits without the time and speed constraints imposed by the rapid manufacturing speeds anticipated (hundreds of feet-per-minute or thousands of sheets-per-hour). In the research and development stage, detailed information of the electrical performance of the functional materials and the resulting printed circuit performance is crucial in developing an optimized fabrication process. This information is also instrumental in establishing quality control methods required for manufacturing. Therefore, the data obtained by off-line characterization tools should provide: 1) information concerning the materials structure and device performance, 2) very accurate measurements, and 3) information describing the measurement conditions and parameters.

Off-line characterization tools are required because of the large number of potential functional inks available for the fabrication of organic & printed electronic circuits. These characterization tools help identify the contributions to performance variations by specific materials (intrinsic and extrinsic properties) and processing methods because the deviations in device performance are critically dependent upon the local molecular orientation, morphology, and interfacial structure of the functional inks. A complete set of characterization tools must provide information spanning multiple disciplines: device physics, material electronic structure, chemistry, and materials science.

In addition to characterization tools providing structural information, off-line electrical characterization systems, including hardware and software, are needed. These systems should be developed for, and be compatible with, organic & printed circuits in terms of large size and flexibility of the substrates. Electrical equipment is needed that is capable of: 1) high impedance measurements, 2) low current measurements, 3) low noise, and 4) high supply voltages. The system should also include environmental control such as temperature control stages, visual light and ultra violent shielding, and humidity and oxygen control - due to the sensitivity of the functional inks to various environmental conditions. Software should provide the ability to perform manual and automatic characterization by following the measuring techniques described in organic & printed electronics standards (e.g. IEEE 1620-2004™ and IEEE 1620.1-2006™). After capturing this electronic information, it should / can be analyzed with respect to the materials and interface data to yield the needed correlations between interfacial structure and circuit performance.

Major Past Developments

Currently, sophisticated measurements are being developed to provide the needed interfacial materials structure information, including electron microscopy, atomic force microscopy, x-ray diffraction, and optical spectroscopy. Non-destructive, depth-profiling techniques that are new to the area of organic & printed electronics have been developed that provide information with nanoscale spatial resolution and the ability to distinguish chemically similar molecular defects. Some available techniques include: 1) soft x-ray synchrotron spectroscopy, 2) neutron and x-ray reflectometry, and 3) non-linear optical and dielectric spectroscopy. These methods have provided important information concerning the materials structure needed to improve the understanding and prediction of the properties and structure needed to obtain the optimal printed circuit performance. These characterization methods are inherently slow and may not be readily accessible. Their use is limited to investigating fundamental problems rather than to providing fabrication line quality control and quality assurance issues.

For off-line electrical characterization, several standards have been created by the organic & printed electronic industry to define procedures and ensure consistency in data reporting (see Roadmap Standards Section). Also, companies have developed product lines that are compatible with high impedance measurement with multiple channels specialized for semiconductor circuit characterization. Examples of off-line characterization tooling are listed in Table 13. These systems are currently available either with integrated computer software for user defined operation/protocols, or with individual libraries that allow design engineers to establish enhanced customizable procedures and to integrate intelligent algorithms. Recent studies have been discussed where electrical characterization tools were evaluated with respect to materials characterization tools to inform on processing and materials effects on circuit performance; such studies are valuable as off-line characterization tools are developed for deployment in manufacturing environments.

Table 13 Off-line characterization tools

Measurement Need	Description
Electrical	Device: I-V, leakage, capacitance, parametric model extraction. Passive: Resistance, C-V, high frequency impedance. Circuit: Output voltage and current, impedance, speed, logic, performance with temperature.
Material and Interfacial Structure	Structure of functional inks at critical interfaces: molecular order, grain size, crystalline morphology.
Pattern Quality	Registration, printing quality, dimensions.
Mechanical	Layer thickness, surface roughness, surface defects, material wetting, substrate dimensional stability.

Data compiled from references 68 and 69.

DEVICES AND CIRCUITS

Background

The first organic active electronic device was reported in 1974, where an electric field was used to produce ON/OFF states in semiconducting melanins.[70] Active devices generally refer to switching devices such as transistors; however light-emitting diodes, diodes, and photovoltaic devices are often placed in this category. Organic active devices are still less advanced than the corresponding passive devices made of organic resistive, conducting and dielectric materials.

The success of organic semiconductors in xerography during the 80s advanced the field of organic electronics from academic research to commercialization. Organic photoreceptors formulated as solid mixtures of molecular semiconductors in an inert polymer phase could efficiently transport electric charge carriers and generate high resolution images on photocopiers and laser printer drums. The vast majority of copiers and laser printers now use those materials.

Organic & printed semiconductors have captured the interest of the electronics industry due to a wide range of attractive properties such as solubility in organic solvents for thin film coatings, and for the color of light emission which can be tuned through materials chemistry and formulation. This tuneability can facilitate the device engineering to fit specific requirements, for example as sensors or radio-frequency identification tags. Thin film coatings can be applied over large areas and to a variety of substrates, including mechanically flexible substrates. Arrays of organic LEDs and TFTs have been developed, and their feasibility for large-scale manufacturing has been demonstrated for applications in large-area displays along with the corresponding interconnects and embedded passive devices. Today, low charge carrier mobility, relatively large operational voltage and low dynamic range compared to silicon, limit the number of applications envisioned for active devices. On the other hand, the infrastructure for printing passive devices, which includes interconnects for signal and bias distribution, resistors and capacitors, is much more mature.

Status

Organic light emitting devices have already appeared in consumer goods, and plastic circuitry and digital memory are not far behind. Significant effort is now being expended globally to bring organics to wide-scale commercial reality. Major efforts are in place in Japan (National Institute of Materials Science), the UK (Cambridge, Oxford, Imperial College London and University College London) and at several major US centers (Arizona State, Georgia Tech, Penn State, and University of California at Santa Barbara for instance). This field is highly multidisciplinary, and a concerted effort requires synthesis, fabrication, characterisation, device engineering and fundamental understanding through quantum chemistry and theoretical condensed matter physics. Organic lasers, fuel cells, batteries and photodetectors have been demonstrated using typical manufacturing processes for printing organic inks at high speeds on similar, or the same, equipment.

According to reference 11, the global market for organic electronics will grow from $0.65B in 2005 to $30B by 2015 with logic, displays and lighting products contributing the greatest. The report further projects that organic electronics can potentially grow to be $250B by 2025, with products as diverse as logic/memory, OLED displays for electronic products, OLED billboards, signage etc, non-emissive organic displays, OLED lighting, batteries and photovoltaics, and sensors. These products can be all-printed or constructed using printed flexible, laminated structures. Other potential products such as laminar organic fuel cells and organic electrostatic and RF protection are also in the forecasts. A new organic & printed electronics market will be created that does not cannibalize existing electronics markets. Organic & printed electronics are on their way from lab-scale R&D to pilot production. Several start-up companies are launching organic electronic products in the form of smart packaging, electronic billboards, posters, signage, and electronic books. As an example, Figure 1 shows a flexible display prototype developed by Fujitsu.

Figure 1 New bendable electronic paper from Fujitsu.

Due to the market potential for printed flexible displays, enabled by organic & printed electronics, several large and start-up companies in Europe and Asia are actively developing deep organic & printed electronics intellectual property portfolios.

Major Past Developments

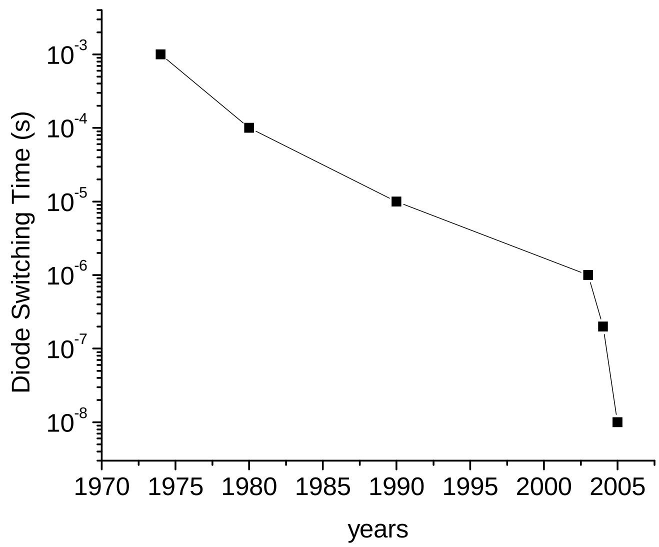
Large differences in performance requirements between electronic systems (and even between some technologies for a particular system) make the development of general/global performance requirements across systems inappropriate. Rather, appropriate metrics and standards must be defined or developed for a particular system and associated technology. For emissive displays, the thin film transistor performance requirements (operation and reliability) differ greatly depending on whether the transistor is providing current to charge the capacitance of a liquid crystal light valve or providing current to drive a light emitting device (OLED or PLED). Large differences in thin film transistor performance requirements also exist for reflective displays, depending on the reflective cell material (for example, electrophoretic ink or polymer dispersed liquid crystal material). Factors such as the display size, resolution, and refresh rate (i.e., e-book or video applications) place additional constraints on the thin film transistor performance.

Basic TFT configurations include: (1) double-gate Structure for a large current capability, (2) staggered TFT for thick and thin (inverted) semiconducting films, and (3) vertical TFT. Field-effect mobility is often used as a figure of merit for transistors since it relates directly to the current delivering capability of the device. Thus, thin film transistors with mobility ranging from 10^{-2} to near 50 cm^2/Vs could find use in specific display technologies.

In 2005 Philips and PolyIC presented vacuum-deposited organic semiconducting components that would enable the world's first polymer-based RFID. The components were stable under ambient conditions and showed good rectification performance up to frequencies well above 13 MHz. This is an important step towards the realization of 13.56 MHZ radio frequency identification (RFID) tags.[71]

The time line for organic device & circuit maturity is shown in Figure 2, where the Diode Switching Time (DST) is used as the figure of merit. It is seen that from the time of demonstration of the first organic diode in 1974 the switching speed increased by several orders of magnitude, from 10^{-3} s to approximately 10^{-8} s. Most of the development took place recently, for example, a 50 MHz organic rectifier was demonstrated in 2005.[72] It is noted that parameters other than DST, such as Ring Oscillator Frequency and Transistor Switching Time, would be more appropriate indicators of performance; however, published data is not readily available for such devices. The organic & printed electronics community is actively developing standards within The Institute of Electrical and Electronics Engineers (IEEE) that will publish consensus based metrics providing greater discipline for the dissemination of organic & printed electronics performance data (IEEE 1620-2004™, IEEE 1620.1-2006™).

Figure 2 Timeline for organic device & circuit maturity



FLEXIBLE ELECTRONICS

Background, Status, and Major Past Developments

Flexible electronics will grow into a multibillion-dollar industry over the next decade and will revolutionize our view of electronics and how we, as a society, interact with intelligent and responsive systems. The unique properties of flexible electronics, such as its compliant structures, ultra-thin profiles, low weight and potential low cost and high reliability could have enormous impact on consumer electronics, aviation and space electronics, life sciences, military applications and telecommunications. Flexible electronics will enable a broad range of devices and applications not possible today. For example, through flexible electronics, simple devices like medical bandages, objects we take for granted and have used largely unchanged since their invention thousands of years ago, can be given the ability to sense both wound healing and the presence of infection, alert medical staff to changes in a patient's condition and deliver needed medication, all at low cost. Lightweight, foldable, rugged solar panels and electronics will change many space and aviation applications. Smart clothing with integrated electronics and displays will have many consumer and military applications.

One of the critical enabling technologies for flexible electronics is R2R (roll to roll) processing. Today R2R is practiced in many mature industries (paper, film, printing, etc.). Due to its attributes R2R high-volume manufacturing has been proposed for electronics as a means to lower the cost of non-Si wafer based flexible electronics such as displays.[73] Display technology will drive the need for materials and processes that can make 2-5 μm features, at high yields, on a 24-inch web at a rate of at least two feet per minute. While a more complete list of hurdles for R2R success is discussed below, a significant factor in the success of R2R for flexible electronics lies in the selection of the flexible substrate material.

In order to choose a substrate, there are a number of important material properties that must be considered, namely, thermal and mechanical stability, level of permeability to moisture and chemicals, flatness, and optical transparency for light emitting devices. While pricing is not a material property, it is a major issue that must be considered once all the other properties have been examined.

There have been many material choices proposed. Although glass has several properties that make it attractive, glass cannot be used because it is still cost prohibitive to make it flexible (when less than 200 microns thick). Metal substrates also demonstrate many of the needed requirements of flexible substrates; they have a high modulus of elasticity and do not lose their physical form during roll to roll processing.[74] For example stainless steel is typically considered completely impermeable; its metal surface can be planarized to meet the surface requirements of flexible substrates and can be produced in large rolls - facilitating roll to roll manufacturing. However, metal substrates are opaque, and thus are unsuitable for transmissive types of displays.

Polymeric materials provide the attributes required for flexible electronics substrates when compared to other alternatives. Today commercially available heat-stabilized polyethylene terephthalate (PET), polyethylene naphthalate (PEN), polyarylate (PAR), and polycarbonate based materials are seen as promising materials for flexible displays. The materials when used as substrates have several distinct advantages, such as ruggedness, robustness, compact, light weight, flexibility and conformability, and impact resistance over glass substrates, which are primarily used in flat panel displays (FPDs) today.[74,75] In addition, polymer substrates will enable R2R manufacturing due to their low cost.[76] However, these materials have low thermal and mechanical stability, are permeable to moisture and other chemicals, and have melting temperatures below those used in traditional electronics manufacturing processes. Advances in technology have been able to address these problems by increasing the melting temperature or reducing processing temperatures. Either of the above solutions is difficult to practice and will impact cost and yield. The permeability to moisture and gas is high in nearly all forms of polymers. Permeability can be reduced by applying barrier layers to polymer films, such as a thin layer of aluminum (Al).[77] The barrier layers do not provide adequate protection necessary for OLEDs and are not transparent. Deposition of a thin oxide layer(s) has been tested and found to significantly decrease permeation rates and maintain transparency.[78] The permeability was also reduced by multiple orders of magnitude but it is still insufficient for OLEDs and multiple layers must be stacked in order to achieve the low levels. Reasonable levels of permeation have been accomplished by stacking alternate layers of organic and inorganic materials. With this method, OLEDs with polymer substrates have been shown to have lifetimes on the order of 10^3 hrs.[79] Continued development of polymeric material with high transparency, optimal surface roughness, and low gas permeability is required to realize many of the forecasted future commercial display applications.

ELECTRICAL DESIGN, LAYOUT, AND SIMULATION TOOLS

Background

The design tools in the semiconductor / microelectronics industry usually combine electrical simulation, circuit design, and layout software as a suite. These tools also can accept input from external simulation software packages. Typically the design tools include several functions that are deemed critical by the electrical designer: 1) a design rule checker, 2) a layout extractor, and 3) support for IEEE design and verification language standards. They provide specific design functionality for electrical engineers and IC/PWB designers in addition to offering quick time to market product design and integration cycles. Several of the most common circuit design and simulation tools are listed in Table 14.

The most common graphic arts software packages are capable of importing encrypted postscript formatted data and other mainstream graphic arts data file formats.[80] These packages support vector formatted data and are often used to receive circuit layout files. Another common software tool used for image file modification providing additional flexibility is available for use on different computer operating systems.[81] Both of these software packages create an extrapolated graphic arts image based on the converted electronic design files which can be subsequently converted to a variety of different file formats (*i.e.* *.ai, *.bitmap, *.tiff).

Printers typically use software tools to layout pages and to print high resolution images.[82,83] These software tools interpolate the designs received from publishing and design professionals, and convert them to machine language.

Table 14 Common software for microelectroinics, graphic arts, and printing.

Process and Device Modeling	Semiconductor/Microelectronics Layout Software	Graphic Arts Software	Printer Software
CADENCE™ PSPICE™ SUPREM™ FLOOPS™	OrCAD™ L Edit™ GerbTool™ Mentor Graphics™ AutoCAD™	Illustrator™ Photoshop™	Quark™ In Design™

Status

Currently the conversion of the electronic design to a printer readable design requires manual operations and a final visual inspection. Based on the electrical design software used, there are a few conversion software pathway options, *i.e.* from *.gds to *.eps, or from *.gdt to *.eps. As an example, the most common graphic arts software can import *.eps formatted files and convert them to *.ai format which can be imported to one of the printer preferred software tools. After this final import operation, the electronics designer must visually inspect the design to remove unwanted/missing features that occurred during the file conversion operations.

RELIABILITY

Background
Reliability is defined as the observed statistical performance of components and products subjected to well-controlled environmental conditions. The environmental conditions are product specific and therefore the reliability testing parameters and testing standards vary.

Reliability testing is typically discussed in the context of: 1) component level and 2) system level. Component level testing is typically performed to detect incompatibility of material systems (such as adhesive failure) and thermo-mechanical structural failure modes in individual components. System level testing is conducted to attempt to predict product field life and potential structural thermo-mechanical induced mismatch stresses created during component integration (or assembly). The reliability testing results provide the engineer with valuable data to optimize the material systems and processes before the commercial launch of the product.

Different testing conditions and reliability requirements are applied to different consumer products, medical (implant and system) products, automotive products, military products, etc. Table 15 lists a few examples of common reliability tests and test parameters that are used for wireless communication product qualifications.

Table 15 Common reliability tests and parameters

Type of Reliability Tests	Test Failure Mode Determination	Example Test Parameters
Temperature Cycling (JESD22 A-104, IPC-9701)	Component and solder joint mechanical stress test	–55°C to +150°C temperature range, number of cycles from 200 to 6000 depending on requirement
High Humidity High Temperature Reverse Bias (JESD22 A-101)	High temperature and humidity conditions to accelerate the diffusion of moisture to investigate interface adhesion and material moisture absorption rate	1000 hrs at 85°C, 85%RH with device reverse biased at 80% of rated breakdown voltage up to a max of 100V
Thermal Shock (JESD22-A106)	Determine the thermo-mechanical induces stress level of a component when subjected to an instantaneous and large change in temperature	The samples go from a low temperature to a high temperature rapidly, *e.g.*, –40°C to +125°C, 5 min. transfer time

Additional information for the various adopted reliability tests and standards can be found in references 84, 85, 86, 87, and 88.

Status
In general, and whenever possible, organic & printed electronics based products will be subjected to industry accepted reliability tests and testing parameters (Table 16). Depending on the product requirements, as governed by the use environment, new tests may need to be defined

by combining existing tests and / or modified test conditions will need to be outlined. In situations where an industry test has not been developed, (*e.g.*, crumple test) engineers will be required to develop new tests accordingly.

Table 16 Example relaibility tests for organic & printed electronics

Reliability Test	Testing Parameters
High temperature storage	125°C for 24 hrs
Temperature/humidity	85%RH, 85°C for 100 hrs
Liquid-liquid thermal shock	0°C to 60°C for 100 cycles
Air-to-Air temperature cycling	0°C to 60°C for 100 cycles
Off-axis bending, flexure	10 degrees, 100 cycles
Tensile/compression	±10%, 100 cycles
Solvent resistance	Acid/base dip or wash

STANDARDS

Background

The need for standards for printed, organic, and molecular electronic devices was identified in part due to the increasing number of academic groups, startup companies, and large corporations involved in the development of new materials, processing techniques, and device structures. Often data is reported that others cannot duplicate. It was found that evaluation of the quality of such measurements and the ability for independent confirmation varied considerably from organization to organization. Since sharing of accurate and standardized information between entities is necessary for building a supply chain for manufacturing, the effort of creating a formalized suite of standards for printed electronic devices, circuits, and applications was initiated in 2002.

As printed electronics is to date not yet widely commercialized, standardization efforts have focused on pre-competitive needs, particularly standard measurement and reporting techniques. These are intended to educate the best known techniques to all participants, who may have varying levels of in-house characterization expertise. Standard measurement and reporting practices also help to streamline evaluation, adoption, and/or rejection of new materials and processing techniques.

Status

Standardization for organic & printed electronics has been most active under the umbrella of the IEEE Standards Association (IEEE-SA), starting in 2002 with the founding of Working Group IEEE 1620. A summary of these efforts is given in Table 17. The first standard, IEEE 1620-2004™ was approved in 2004, and subsequently was adopted by the European Union PolyApply consortium as the standard technique for characterizing and reporting device performance data between member organizations. The second organic & printed electronics standard IEEE 1620.1-2006™ was approved in 2006 and adoption of IEEE 1620.1-2006™ by PolyApply is currently under consideration.

Table 17 Potential areas for organic and printed electronics standards

Topic	Status
Devices (FET)	IEEE 1620-2004™ completed
Circuits (ring oscillator, diode bridge)	IEEE 1620.1-2006™ completed IEEE P1620.2 currently under development
Components (RF engine, display backplanes)	Future activities
Products (sensors, displays)	Future activities
Manufacturing (incoming BOM inspection, process control, quality assurance)	Future activities
Reliability	Future activities

ROADMAP OF QUANTIFIED KEY ATTRIBUTE NEEDS, GAPS, AND SHOWSTOPPERS

INTRODUCTION

The key elements to launch an organic & printed electronics based product (power, circuitry, and user interface such as display) are at different stages of maturity. The following sections provide insight to the deficiencies of the various organic & printed electronics technologies.

FUNCTIONAL INKS: TECHNOLOGY REQUIREMENTS

The needs and gaps identified for functional inks are presented in Table 18.

Table 18 Several critical technology requirements for functional inks

Technology/Functional Ink Property	Market Status and Drivers
Increased charge carrier mobility in semiconductors	The performance is currently sufficient for some applications but the impact of the technology would be greatly improved with a higher mobility
High- and low-k dielectrics	Thus far high performance has only been achieved at high gate voltage. High dielectric constant materials (or thinner gate insulators) may allow the necessary charge to accumulate at much lower voltages. High permittivity inorganic materials such as barium titanate (BTO) and barium strontium titanate (BST) are being studied. Low permittivity dielectrics may be needed for reducing parasitic capacitance and to reduce the trapping density at the dielectric/semiconductor interface.
Contacts	A technique for making stable, low resistance contacts is lacking. This will greatly impact performance as mobility is improved. The structure could involve heavy doping or some type of band matching, but current technology contacts are one to two orders of magnitude too resistive for high performance

	devices.
Doping	To be able to better control device characteristics, one would like to develop cost-effective ways of tailoring the doping profile of printed semiconductor layers. Dopant concentrations should be well controlled and able to allow semiconductor carrier concentration to be varied as much as 10^{10} to 10^{21} cm^{-3}.
Interface with insulator	Devices require a low trap density insulator and insulator/semiconductor interface to avoid 1) high operating voltages, 2) excessive leakage in the off state, and 3) poor mobility.
Improved materials stability	The type of stability depends on the application. For solid state lighting and displays, for example, the material must be stable for long-term high-intensity luminescence. Other applications require stability under a large electric field; and still others, stability at high temperature. In general, however, stability of inks, particularly when used as active layers, is a major issue. The use of encapsulation and environmental barriers increase manufacturing costs, so improved stability provides a cost savings. Inorganic films hold substantial promise for superior performance and stability compared to organics, but at present cannot be processed in a sufficiently low-cost manner.
Environmentally friendly solvents	Current processes use solvents and require the removal of residual products of precursor conversion reactions. Most high performance semiconducting polymers are only soluble in chlorinated organic solvents like dichlorobenzene and chloroform which may be banned from production quantity usage in the near future in many parts of the world.
Functional ink purity	As an example, small molecule based inks typically contain impurities resulting from the precursor conversion reaction. These impurities can act as charge traps or could reduce the stability of the material. Maximum impurity levels must be quantified and maintained when supplying functional inks.
Low temperature processing	Most in-solution deposited inorganic semiconductor inks composed of a suspension of inorganic nanoscale particles in a carrier form films with a large number of grain boundaries (e.g. particle to particle contact points). Annealing increases performance, but is incompatible with most plastic substrates, increases the processing cost and introduces registration problems. Depositing suspensions of nanoparticles or nanowires avoid the problems associated with defective in-solution deposited inorganic films, but create their own problems with regards to alignment, packing density, and percolation.
Reduced cost materials	Due to the relative immaturity and unavailability of functional inks, suppliers are demanding relatively high prices to

	compensate for past R&D investments. Prices will reduce as demand increases due to the commercialization of organic & printed electronics based products.

Information compiled from references 89, 90, 91, 92 and 93.

Gaps and Showstoppers

No major showstoppers are foreseen at the present time. It is a question of how many markets and to what extent, the technology will penetrate. Presently, manufactured backplanes provide sufficient performance (if not reliability) for simple displays, but are far too slow for even simple computation. If the needs listed above can be met, however, organic & printed electronics are expected to support a very large market. If not, it will remain more of a niche area.

PACKAGING/BARRIERS: TECHNOLOGY REQUIREMENTS

Needs

Recent developments in organic & printed electronics technology demand improved barrier requirements. The industry is currently developing barrier-packaging materials that will satisfy the specification of a water vapor transition rate (WVTR) of 10^{-6} g/m^{2}day and oxygen transition rate (O_2TR) of 10^{-4} cc/m^{2}day·atm. Devices using less sensitive organic & printed material systems require WVTR in the range of 10^{-2} to 10^{-3} g/m^{2}day. Barrier films that satisfy these criteria are available; however, they are offered at a premium price. Low cost barrier products are required for low cost printed electronics applications.

In addition to barrier film bulk permeability to oxygen and moisture, the adhesive at the interface between the barrier film and the printed functional devices must be compatible to the underlying functional materials and must provide adequate barrier properties. Since the coating material is applied directly on the functional circuitry, it must possess a high dielectric constant and create minimal stress during the curing process. Any mechanical/thermal incompatibility of the barrier film will degrade printed device performance. In general, barrier film thickness has a direct impact on the barrier properties as well as flexibility of the final structure. To ensure the fabrication of a pin-hole free barrier, a thicker layer or multiple layers can be applied; however, these solutions typically negatively impact the flexibility of the packaged devices. Therefore, there is a need for a conformal coating with a lower permeability rate that will form a thin pin-hole free layer.

Gaps and Showstoppers

Recent development efforts have focused on the improvement of barrier properties, WVTR and O_2TR, Unfortunately, there is still not enough emphasis placed on chemical compatibility between barrier film/coating and active components of a printed circuit. Improvement of the interfacial compatibility and the development of alternative barrier application processes for higher performance should continue.

PRINTING PLATFORMS: TECHNOLOGY REQUIREMENTS

In order to properly analyze the needs, it is crucial to identify the applications which are being considered. Several potential applications for printable electronics are given below:

- Display TFT backplanes. Backplanes are comprised of TFT arrays for various reflective and emissive display types, including LCDs, OLEDs, and electrophoretic
- RFID tags
- Logic and simple electronic components for smart packaging and e-labels
- Display front-planes. This category includes LCD color filters, OLED/PLED material deposition, and electroluminescence (EL) displays.

Several of these applications are commercially available today and are designed with silicon based IC's. Moreover, these applications are manufactured using clean-room compatible photolithography processing tools. These manufacturing tools enable resolution of submicron (nanoscale) features which has provided the semiconductor and display industries with market growth sustainability. The semiconductor market growth has been achieved by continual development of expensive processing tools to fabricate higher performance devices via finer features. In contrast, the organic & printed electronics industry will most likely not compete with silicon, nor will its sustainability be measured by continued improvement in device feature resolution. The intrinsic low cost of printing will be leveraged by maintaining device features of greater than 1 micron due to the exponential increase in equipment and processing costs related with submicron feature printing. Unlike silicon, the organic & printed electronics industry sustainability will be based on the continued design and commercialization of products that are conformal and have novel design form factors. Table 19 lists the device/circuit dimensional requirements based on the necessary electrical performance attributes of the product. These dimensions are determined based on the performance of the available organic and printed electronics materials. As the performance of the semiconductor materials continue to improve the dimensional requirements of the printed structures could be relaxed without sacrificing electrical functionality.

Table 19 Electronic device/circuit dimensional requirements for various applications.

Parameters/Applications	Display TFT Backplanes	Display Front-plane	Logic and Simple Electronic Components	RFID
Critical Dimension / Minimal Feature Size [μm]	5-10	20-50	5-10	2-3
Addressability [μm]	1	3-5	2	2
Layer to Layer Registration [μm]	1	3	2	2

Gaps and Showstoppers

Gaps can be identified by analyzing the organic & printed electronics needs and comparing them to the current printing technology.

Table 20 summarizes the current performance of the most advanced digital and mass-printing technologies.

Table 20 Several critical technology requirements for functional inks

Parameters/Printing Technologies	Laser Imaging	Inkjet	Flexo	Gravure	Offset
Critical Dimension / Minimal Feature Size [μm]	2-3	20-50	20	20	10-15
Addressability [μm]	2	5	5	5	5
Layer to Layer Registration [μm]	1	1	50	50	50

Reviewing the table, it becomes clear that commercially available printing platforms can not provide the full needs of printable electronics today and that further development is required.
The main challenges are:

Registration:

- This issue is further complicated if flexible substrates are used, since they might deform during the imaging process such that registration of subsequent layers may not be possible with predetermined parameters, and thus "active" registration and anisotropic distortion control may be required.
- With traditional printing methods, where the substrate travels inside the machine between subsequent deposition processes, the issue is further complicated
- The high throughput in printed electronics manufacturing platforms requires advanced development in vision and registration adjustment feed-back loops to coordinate with the manufacturing characteristics.

Minimal feature size / Critical dimension:

- Laser imaging and inkjet are still under active development and minimal feature sizes could be expected to further drop. Traditional mass printing techniques are mature and historically have not been challenged to reduce features; however, recently effort has been initiated to exercise the limits of several printing hardware consumable e.g. gravure cylinder engraving technology, flexography plates. This effort must continue to reduce the minimal achievable feature sizes for commercially available mass printing technologies.

IN-LINE CHARACTERIZATION TOOLS: TECHNOLOGY REQUIREMENTS

Needs

Successful transition from individual testing in an R&D environment, to system testing on a high volume manufacturing line, will depend on product goals, conductive ink availability and final printed feature resolution. There will likely be a need for hybrid presses combining gravure, flexography, offset and maybe even inkjet printing units; each unit will require testing to ensure high quality yield prior to transferring the printed structures to the subsequent printing cell.

It could also make sense to manufacture and convert both the viewable printed image in addition to the functional electronics in a single pass. The press system should be highly configurable to support evaluation of different ink types, drying/curing processes, substrates, etc.

The imaging of plates and cylinders for print today is capable of resolution in the range 5 to 10 microns. Typical finished print products can achieve color-to-color registration between 40 and 80 µm; the more uniform the substrate the better the result. By employing tight control on a single printed layer, some printing systems should be able to attain 10 µm printed structure feature resolution. Imaging equipment will need to be well matched to print image carrier. Direct "ink" application to substrates will be the optimal approach to control features. This means Flexography, Gravure (and Intaglio) and Inkjet should have an advantage. Offset print directly from plate to substrate could be similar.

Layer-to-layer registration must be managed to within current machine and system tolerances; the best achievable in-line registration is believed to be within the range of 15-25 µm. Well-controlled layer thickness can be achieved using flexography or gravure with reverse image application.

Gaps and Showstoppers

Two of the greatest gaps in the near term are likely to be: 1) the design and implementation of automated systems to monitor for in-line registration, coating thickness and defects at the needed resolution and 2) the possible need for the configuration of disparate press units for complex circuits and products. Today's presses are generally built for speed at the above stated resolutions. Slower speeds could improve in-line monitoring and possibly allow integration of traditional older generation fab inspection devices.

A complex integrated circuit needing 10, 20 or more passes though different print units will additionally highlight registration control, repeatability, and substrate stability issues. Printing of TFT based circuitry should be attainable after enhancing print-manufacturing platforms appropriately to achieve higher resolution printed features with high yield.

While there are no apparent showstoppers, the gaps do present challenges. Focusing capital budget and resources for print platform development and testing could be a huge problem from the commercial printer point of view. It will be very important to conduct market analysis to match the different high-resolution press configurations to the opportunity of organic & printed electronics based products. Likely, a traditional fab circuit manufacturer would more easily see ROI in employing print techniques and equipment.

OFF-LINE CHARACTERIZATION TOOLS: TECHNOLOGY REQUIREMENTS

Needs

Published studies have shown that it is difficult to develop meaningful correlations between printed device performance and the structure, properties, and chemistry of the critical interfaces because the performance of the printed devices is determined by the structure of the materials within 1 to 2 nm of the interfaces. Also, the wide range of potential materials that may be used further complicates the development of strong material-device performance correlations that can be used to develop device physics models. Identifying the contributions to performance variations (by specific materials intrinsic properties and processing methods) requires integrated metrology tools spanning multiple disciplines: device physics, material electronic structure, chemistry, and materials science. Although non-destructive methods for molecular scale characterization of the interfaces of both model and fabricated devices (multiple ~ 100 nm layers on an organic flexible substrate with complete encapsulation) have been developed, they are currently inadequate and must be refined with additional data.

The existing commercially available electrical characterization equipment and standards provide a strong foundation for organic & printed electronic off-line characterization tools. The industry must begin to integrate the tools onto platforms with the necessary environmental controls that are specialized for large area and flexible electronics. Also, more sophisticated software platforms are required for specific characterization tasks, as well as data extraction and analysis. Unless a robust tool is developed, as device and circuit performance improves, the lack of information and scientific understanding of the electronic structure of flexible electronic devices may impede the development of products.

It has been stated that the electronic structure of the constituent interfaces comprising printed electronic devices, notably the density and distribution in energy of stable and metastable electrically active traps, plays a critical role in determining device electrical characteristics. Challenges in determining the electronic structure of critical interfaces include: 1) unambiguously separating the contributions to the extrinsic device behavior of multiple device interfaces and 2) the lack of physical models accurately describing the device operation when stimulated electrically and optically.

Gaps and Showstoppers

The primary gaps in off-line characterization tools are: 1) establishing clear correlations between interfacial material structure and device performance and 2) economical access to the tools needed to make these correlations. Currently, access is generally limited to the measurement tools that are able to characterize the interfacial structure (x-ray spectroscopy, electron microscopy, nonlinear optical characterization) in sufficient detail to correlate with electronic circuit performance. Optical methods such as infrared spectroscopy and variable angle spectroscopic ellipsometry may be sufficient to provide the needed information on interfacial structure and molecular orientation, but the correlations to performance remain to be clarified and clearly articulated.

Another gap that remains is the development of an industrial scale environmental control platform for large area electronics testing. This platform would be comprised of commercially available electrical testing equipment that complies with the organic & printed electronics standards that have been adopted as well as those that are presently being written for measurement and reporting methods. The development of complementary characterization methods (such as combinations of optical spectroscopy and electrical measurements) may provide determination of the electronic structure of critical device interfaces and assist in the validation of predictive models. These gaps could then be closed when standard methods and models are developed to inform researchers and engineers about degradation in device performance from electrically active traps (for example, created during device processing and biasing) which would allow device performance to be improved.

DEVICES AND CIRCUITS: TECHNOLOGY REQUIREMENTS

Passive devices

Passive device usually refers to resistors, capacitors and inductors; but can also include thermistors, varistors, transformers, temperature sensors, and almost any non-switching analog device. The concept of "integrated", "integral", "embedded", "arrayed", or "networked" passives involves manufacturing them as a group in or on a common substrate instead of in their own individual packages.

Capacitors

Capacitors in printable electronics will most likely be of a planar thin-film design, and are best characterized by *Ci*, their capacitance per unit area. For charge storage applications, *Ci* should be as large as possible. What can be achieved in practice will be a function of the permittivity of available inks, and the minimum reliable thickness that can be printed. Several researchers have stated that a likely upper limit on the permittivity of a high-k nanoparticle-loaded ink (that is still printable) is 20, while a likely lower limit on the film thickness is 1 µm, leading to an upper limit on *Ci* of approximately 2×10^{-4} F/m^2.

For wire crossings and other passivation applications on the other hand, *Ci* should be as low as possible. Typical polymers have permittivity values in the range of 2 to 4, so that moderately thick films (~5 µm) will have *Ci* in the range of a few microfarads per m^2.

For both applications, the most critical capacitor characteristic is a low leakage current (and a complete absence of short circuits). This suggests that the capacitor dielectric is preferred to have a bulk resistivity in the range of 10^{14} to 10^{15} Ω-cm.

Conductors

The actual resistance of printed wires will be a function both of the resistivity of the ink used, the resolution of the printing process, and the thickness at which the ink can be deposited. For displays, small and / or slow displays, the wire conductivity requirements can be quite modest, but for large and/or fast displays, near-metallic conductivity will be required.

Printed conductors are usually characterized in terms of sheet resistivity *Rs*. For a display, the maximum row rate will be roughly given by

$$f \sim \frac{w}{\mathrm{dpl}\, D^2 R_s C_p} \qquad \text{Eqn. 1}$$

where *D* is the full width of the display, *w* is the width of the printed select line, and dpl (dots per length) is the number of optical pixels per whatever unit of length is used for *w* and *D*. *Cp* is the parasitic capacitance per pixel (due the crossing of the select and data lines and from the gate to the drain of the transistor).

For inductive RFID applications, the antenna must be printed with a near bulk metallic conductivity in order to have sufficient gain to power the device. For internal circuitry, excess resistivity in interconnects will result in power dissipation, reducing the distance from the reader at which the device can operate. The key figures of merit for passive devices and their critical functional attributes are listed in Table 21.

Table 21 Key figures of merit for passive devices

Device	Parameters
Interconnects, Conducting traces, Transmission Lines, and Microstrips (Metallic/ Conducting Polymer)	• Conductivity (> 100 S/cm) • Characteristic impedance (50Ω for special applications such as RFID)
Resistors	• Resistivity (Ω-cm) or sheet resistivity (Ω / square) • Nominal value tolerance (5%, 10%) • Terminating resistors (50 Ω +- 5%) • Power dissipation capability (application dependent : Bias Resistors, RLC cells, Terminating Resistors)
Capacitors	• Dielectric permittivity as a function of frequency ($K > 40$, $\Delta K/K$ 100 Hz – 100 kHz < 5%) • Capacitance density conductivity (> 1 nF/cm^2) • Nominal value tolerances (5% to 10 %) • Thermal coefficient of capacitance (TBD)
Inductors	• Conductivity of the conducting coil (> 100 S/cm)

Active Devices

Active devices generally refer to switching devices such as transistors; however light-emitting diodes, diodes, and photovoltaic devices may also be placed in this category. As indicated previously, printed active devices are in the developmental stage while printed passive devices have been used in high volume consumer electronics products e.g. mobile devices. The diverse application space makes it increasingly likely that a range of electronic materials will find use; some overlapping with materials used in passive device fabrication, notably insulators and conductors. Process development and cost, compatibility with the application platforms, the performance of the available electronic materials, and the performance required for entry-level systems will largely determine the application space addressed first by organic & printed electronics.

Large differences in performance requirements between electronic systems (and even between some technologies for a particular system) make the development of general / global performance requirements across systems inappropriate. Rather, appropriate metrics and standards must be defined or developed for a particular system and associated technology. A useful example illustrating this point is display technology, where active matrix displays make use of thin film transistors to control pixel elements. For emissive displays, the thin film transistor performance requirements (operation and reliability) differ greatly depending on whether the transistor is providing current to charge the capacitance of a liquid crystal light valve, or providing current to drive a light emitting device (OLED or PLED). Large differences in thin film transistors performance requirements also exist for reflective displays depending on the reflective cell material (for example, electrophoretic ink or polymer dispersed liquid crystal material). Factors such as the display size, resolution, and refresh rate (*i.e.*, e-book or video applications) place additional constraints on the thin film transistor performance.

In general, mobility serves as a key parameter for switching applications. It provides a first estimate for transit time (time required for charge to traverse the channel) and cut-off frequency (time required to charge the channel and parasitic capacitances) based on a given printable feature size. Upper frequency limitations (given by the transit time) for thin film transistor may be estimated by taking practical values for printing resolution and overlay tolerance (for example, 10 micrometers), operating voltage (for example, 10 V), and field-effect mobility (for example, 1 cm^2/Vs). Using these parameters, one arrives at a maximum switching speed of 10 MHz. Most often it is the charging of the channel and parasitic capacitances that limit the operating frequency. Thus, a transistor switching frequency greater than 10 MHz will require significant improvements in printing techniques and semiconductor mobility, or the use of large bias voltage.

To define useful near-term system performance limitations (and target performance) it is most appropriate to first define the material and device parameters needed to construct reliable circuit models, from which organic & printed electronic systems will be designed. Key figures of merit are identified for the set of active circuit elements and serve as input parameters (along with the physical device dimensions) to device and circuit simulators such as PSPICE. The active devices and their critical functional attributes are listed in Table 22.

Table 22 Key figures of merit for active devices

Device	Parameters
Diodes (*p*-*n* junction or Schottky)	• Built-in potential or barrier height (eV, magnitude is based on application voltage) • Ideality factor (no units) • Reverse saturation current density (A/cm^2) • Rectification ratio (no units) • Parasitic series resistance (ohms-cm) - for large forward bias this might be best associated with space-charge limited current
Light emitting diodes (OLED or PLED)	• Current efficiency (Cd/A) • Luminance efficiency (Lumens/W) • CIE coordinates (*x*,*y*) • Rectification ratio (no units)
Photovoltaic cells	• Fill-factor (%) • Quantum efficiency (%) • Spectral Responsivity (A/W) • Short-circuit current density (A/cm^2) • Open-circuit voltage (V)
Thin film transistors	• Field-effect mobility (cm^2/Vs) • Threshold voltage (V) • Sub threshold swing (V/decade) • On/Off current ratio (no units) • Parasitic series contact resistance (ohms-cm) • Parasitic overlap capacitance (F/cm^2) • Hysteresis and threshold stability

Transistors

Specifying the dynamic performance requirements for transistors is heavily application dependent, and depends on a large number of design specific parameters and materials properties. Nonetheless, it is possible to provide some broad guidelines. For display backplanes, a key performance attribute is the pixel charging rate

$$f \sim 1/RC_{pix}, \qquad \text{Eqn. 2}$$

where *Cpix* is the capacitance which must be charged or discharged to change the optical state of the pixel element, and *R* is the transistor "on" resistance given by

$$R \equiv \frac{V_{DS}}{I_D} = \left(\frac{1}{\mu C_i} \frac{1}{(V_g - V_d - V_T)} \right) \frac{L}{W}. \qquad \text{Eqn. 3}$$

μ is the semiconductor mobility, *Ci* is the capacitance per unit area of the gate dielectric, and *L* and *W* are the channel length and width, respectively. *VT* is the transistor threshold voltage.

Assuming a pixel capacitance of 1 pF, we can find the required 'on' resistance for displays of different performance levels, as summarized in Table 23.

Table 23 Application Dependent Transistor Performance for Displays

Display Performance	Charging Rate (Hz)	Transistor On Resistance (Ω)
Low	1,000	$\sim 10^9$
Medium	10,000	$\sim 10^8$
High	100,000	$\sim 10^7$

A low performance display might be used for signage or a point-of-sale display that is updated only a few times per day. An electronic book reader requires a moderate level of performance in order to update the page in a fraction of a second. Video rate displays require higher performance transistors.

For RFID applications the analysis is mathematically identical, but is typically phrased somewhat differently since the capacitance to be charged is the typical channel capacitance in the transistors:

$$f \sim \mu V / L^2 \quad , \qquad \text{Eqn. 4}$$

where V is the operating voltage of the device, L is the transistor channel length, and μ is the semiconductor mobility. Table 24 summarizes the transistor performance requirements for various RFID applications.

Table 24 Application Dependent Transistor Performance for RFIDs

	μ/L^2 (cm^2/Vs per micron^2)	
Application	**Rectified voltage = 10 V**	**Rectified voltage = 1 V**
Clock/Data (20 kHz)	2×10^{-3}	2×10^{-4}
Modulation (125 kHz)	1.2×10^{-2}	1.2×10^{-3}
Modulation (13.56 MHz)	1.4	0.14

For all of these applications, the threshold voltage should be as small as possible, although consistency from device to device is more critical. The on/off ratio for most applications is typically desired to be 10^6 or higher although several printed electronics developers have shown that 100 to 1000 is adequate for some circuits.

Gaps and Showstoppers

Process Definition and Process Simulators:

There are few documented standard processes, or sets of processes, available in the public domain for fabrication of electronic devices by printing (company proprietary). Since device performance and design is a strong function of the fabrication process, it can only be discussed in the most general terms at this early stage. This presents a particular challenge for the design of complex devices. Modern device layout uses process-dependent design rules for error-checking and analysis. Since the processes for printed electronics are still under development, design rules are not mature or ready for wide-spread deployment. In several cases, design rules are proprietary to a company attempting to commercialize printed electronics products. Fundamental physics based process simulations, similar to those used for monolithic IC modeling, are essentially non-existent.

Modeling Parameters:
Most semiconductor design packages can be adapted to the design and layout of printed electronics. These tools have built-in SPICE modeling packages which could, in principle, be used to model printed electronic circuit designs. The accuracy of this modeling will be limited by the fact that there are few microscopic models for the physics of carrier transport (including defects and traps) in the semiconductors typically used in printed electronics.

Complimentary Logic:
Low power consumption applications (*e.g.*, RFID) require complementary logic. While there are adequate, stable organic *p*-type semiconductor inks, compatible *n*-type semiconductor inks have lagged in performance - although recently several claims of new higher performance organic *n*-type semiconductor inks have been made by researchers. In the case of thin-film inorganic semiconducting materials the inverse is typically true, with *n*-type devices readily available and corresponding *p*-type devices difficult to realize.

Transistor Design:
Most printed transistors follow the design for a standard thin-film transistor. Some applications, however, will require more sophisticated designs. For example, an RFID that can accept data from the base station for internal storage will require some kind of EPROM memory. Conventional tunneling based EPROM memories with floating gate transistors are unlikely in printed electronics, and such memory will require a printable floating gate transistor, or some other method of semi-permanently programming the state of a transistor.

FLEXIBLE ELECTRONICS: TECHNOLOGY REQUIREMENTS

Needs
Based upon some of the aforementioned disadvantages, the primary needs to bring flexible (i.e., plastic) electronics to the market, at appropriate price points, are the following - reference:[76] 1) materials (substrates, barrier layers, semiconductors, dielectrics, metal or polymer conductor, and passivation coatings), 2) process technology & equipment (*e.g.*, flexo or micro-gravure printing, web based traditional vacuum coating and photolithography, 3D lithography or imprinting and ink jet technologies), 3) device design, and 4) product design for flexible substrates. New concepts in electronics reliability will also need to be created based on applications and field and use environments.[94]

Gaps and Showstoppers
A recent study concluded that a combination of high costs and poor availability of production tools are hindering the adoption of R2R manufacturing.[95] The study suggests that there is a "chicken-and-egg" syndrome wherein tooling companies are waiting for product designers to try to identify products that are to be made in R2R, while the designers (*e.g.*, display makers) feel that the tool manufacturers should be able to build custom tooling.

In addition to the limited production tooling availability, the foreseen / existing hurdles in R2R flexible electronics processing are the following: 1) damage due to handling, 2) particle generation, 3) impurity due to contact, 4) yield management, and 5) linear processing. These hurdles, if / when surpassed may not be the biggest showstoppers. Flexible electronics, at least for the consumer, will not be successful unless the cost to manufacture R2R is on par, or significantly less, than traditional silicon wafer-based electronics and packaging and assembly.[76]

ELECTRICAL DESIGN, LAYOUT, AND SIMULATION TOOLS: TECHNOLOGY REQUIREMENTS

Needs

It is critical that design and layout tools are developed that provide design rule check (DRC) and electrical continuity check operations to ensure circuit electrical functionality prior to circuit printing. Commercially available graphic arts software tools manipulate circuit designs as graphic images and therefore are not able to provide these electrical functionality checks that are commonly available in the microelectronics design tools. It has been observed that during the conversion process from an electrical design file to a graphic arts design file, mistakes occur during the manual extrapolation of imaging data which subsequently leads to incorrectly printed circuits.

In the near future, standards for data conversion between electrical design tools to graphic arts design tools must be agreed upon. Moreover, the electrical design data conversion and graphic arts image information extrapolation must be automated to enable quick design to product cycles. Also, the embedding of design rule and electrical functionality check software operations into the graphic arts software will further streamline the process.

Gaps and Showstoppers

Since printed circuits today are relatively simple in complexity, the lack of a dedicated software tool for layout, conversion and circuit check has not impacted the industry. However, as circuit complexity increases, a standard software package incorporating consensus based conversion algorithms must be established for high volume manufacturing and organic & printed electronics industry growth.

Another gap concerns the lack of printed circuit design rule based software tools. The techniques for printed circuit layout are taken directly from legacy silicon design methods, which in general are inadequate. Since the focus has been on developing devices that conform to silicon design rules, in the near future design rules based on the unique attributes of printed transistors must be established and integrated into designer-friendly software tools.

RELIABILITY: TECHNOLOGY REQUIREMENTS

Needs

Reliability needs vary based on the application and product use environment. Consumer electronics, automotive electronics, point-of-purchase / point-of-sales applications, medical / bio-sensors / monitors and flexible displays have different operating conditions and product specific requirements. Table 25 lists the reliability and operating requirements for two printed electronics based products, printed displays and RFID tags. The most commonly mentioned applications for printable electronics have two similar attributes: 1) low cost and 2) short product life cycle. Since product level reliability testing is performed using Accelerated Life Testing (ALT) methods, the specific reliability testing parameters that will be used are determined based on modeling of the product life cycle. In many instances, commercially available modeling software is used to identify the required reliability testing conditions based on the product life cycle and the various components (substrate, functional inks, etc) used to build the product.

The ultimate product reliability performance depends on the intrinsic thermo-mechanical properties and environmental sensitivity of the functional inks, interfaces between functional inks, and the low cost flexible substrate. The specific reliability test and testing parameters are established based on historical benchmark data and modeling results. Initially, most industry members will rely on using reliability criteria established for commercially available disposable (and single-use) electronic products to determine reliability requirements for printed electronics based products. As reliability data is accumulated and reliability performance trends are observed, specific reliability methodology for printed electronics based products will be established and adopted product developers.

Table 25 Reliability tests and testing parameters for example printed electronics based products.

Product	Operating Conditions	Storage Conditions
Printed display	Temperature: 0 to 60 °C Humidity: 10 to 70 %RH Cold/Heat Shock: yes	Temperature: -30 to 80 °C Humidity: 50 %RH Cold/Heat Shock: none
RFID	Uses/day: 10 Temperature: -10 to 32 °C Humidity: 10 to 100 %RH Cold/Heat Shock: yes UV light: yes Bending: 10 flexures/day	Temperature: 25 °C Humidity: 50 %RH Cold/Heat Shock: none UV light: none

Gaps and Showstoppers

Two potential showstoppers for printed electronics commercialization are: 1) the materials do not meet product operating/reliability requirements and 2) the materials are not environmentally friendly. In both cases, materials must be rigorously assessed to ensure that they will not be categorized in the aforementioned groups.

Once transitioning from product development to product manufacturing, product level reliability testing can be used to optimize the material design and manufacturing process to further mitigate the occurrence of a showstopper. The low temperature processing attribute that is unique to printed electronics does not contribute additional stresses to the finished product. However, the final product assembly process/conditions and final product operational conditions will be restricted to the processing temperature attributes of the materials. As mentioned previously, it is strongly felt that new reliability testing conditions and procedures will be established for the different printed electronics enabled products.

STANDARDS: TECHNOLOGY REQUIREMENTS

Needs

The existing standards build a strong base for characterization and reporting of electrical properties of devices and circuits. Needs include primarily non-electrical test and quality control standards for printed electronics:

- Materials storage and batch-to-batch consistency standards
- Mechanical / rheological testing and reporting standards for functional inks, substrates, and printed products
- Standardized layout and design rules for each dominant print process

Gaps and Showstoppers

Some identified areas that would benefit from standardized processes and reporting may have technical gaps which need to be addressed before standards may begin, including:

- Software interoperability, particularly software interfaces between electrical design and printing equipment

A potential threat to cohesive standards development would be competing standardization efforts, which would create confusion and potentially hinder adoption of standardized characterization techniques. Competing standards efforts typically result in multiple standards for the same topic (for example, several methods to characterize a printed transistor, perhaps with very minor differences between each). If such a situation were to arise, the main objective of the current standards efforts, which is to clarify the techniques used and to standardize reporting practices, would be severely compromised.

To date, no significant competition between standards organizations has been identified for printed electronics. In fact, standards development has been a relatively unified effort under the IEEE umbrella, with active international participation and subsequent adoption of each standard.

It is recommended that, due to the established work at IEEE, that standards road mapping and development be continued under the IEEE umbrella. However, partnerships with other standards bodies would likely be beneficial, such as JEDEC for reliability testing standards, but such efforts should be formally synchronized. It is strongly encouraged that recruitment efforts for the working groups be ramped up, particularly for encouraging increased participation from the printing industry and equipment manufacturers.

CRITICAL INFRASTRUCTURE ISSUES AND PARADIGM SHIFTS

Several critical infrastructure issues must be addressed to ensure successful commercialization of organic & printed electronics enabled products. The three infrastructure issues that should be addressed in the near-term are: 1) integrated printing platform suppliers, 2) in-line characterization equipment suppliers, and 3) functional ink suppliers.

The paradigm shifts listed in Table 26 will enable the integration of electronics in consumer products that were previously non-electronics based to provide:

- Product differentiation
- Product personalization
- Information and content access anywhere

Table 26 Paradigm shifts for organic & printed electronics

Paradigm Shift	Comments
Vacuum to solution processing	• Low cost process
Batch to R2R	• High throughput, large area electronics manufacturing
Rigid substrate to flexible substrate	• Novel product form factors
Component assembly for product manufacturing to complete integration of device, circuit, and component assembly on a roll-to-roll manufacturing line	• Novel electronic product manufacturing process leveraging novel electronic inks and roll-to-roll processes

ORGANIC & PRINTED ELECTRONICS TECHNOLOGY NEEDS AND POTENTIAL SOLUTIONS

The most pressing technology needs and potential solution are given in the next few sections.

Functional Inks

Silver nanoparticle conductive inks continue to improve performance with respect to reduced curing temperatures, increased conductivity, and ease of use. Additional improvement is expected. The recent success and commercial promise of silver conductive ink have led to additional investments in manufacturing infrastructure. These investments may lead to reduced manufacturing costs and ultimately, lower prices. Several technology needs and potential solutions for functional inks are provided in Table 27.

Table 27 Technology needs and potential solutions for functional inks

Technology Needs	Potential Solutions
Higher performance semiconductor ink theoretical models	To increase the performance of the semiconductor inks, a fundamental understanding of the mechanisms that limit the charge carrier mobility is needed. This understanding will aid in the design of new molecules and processing steps that improve the performance.
Material degradation mechanics	The mechanisms of material degradation need to be determined to provide insight into ways to increase the stability. The results of these studies can then be used to develop inks that maintain both performance and stability.
Higher performance interconnects, traces and antennas	Conductive inks that enable higher resolution printing Enhanced intrinsic ink conductivity for ultra high frequency operations

Packaging/Barriers

Aluminum foil is often referenced as a standard barrier film. It is virtually impervious to moisture, gas and light (if thickness > 25 µm). However, its metallic nature does not allow Al foil to be used in conjunction with printed electronics. Direct lamination or even pressure sensitive adhesion of Al foil can result in coupling capacitance or even shorts, leading to device malfunction or failure. As a result, a non-metallic barrier film is preferred. Many manufacturers offer families of products that offer high moisture and oxygen barrier without use of Al foil. They use Al_2O_3 and SiO_x barrier coatings to meet the most demanding requirements, again at a premium price.

Standardization of flexible substrates for printed electronics applications, and compatible sealants should be established. Pressure sensitive adhesive (PSA) materials do not require high lamination temperature. They can be easily applied using current graphic arts infrastructure equipment. However, the major concern with PSA films is water absorption along the sealant layer. Water and oxygen molecules can penetrate through the sealant layer. So in that case not only penetration through the barrier film is a concern, but the sealant layer as well. Another issue with PSA films is their chemical / electrical interface compatibility in contact with functional materials. This could become a concern for devices with high sensitivity functional ink (e.g. semiconducting ink) that is exposed to various chemistries that are present in the PSA. More emphasis should be placed on the development of PSA film with excellent adhesion / barrier properties that are compatible with commercially available semiconducting materials. Several technology needs and potential solutions for packaging / barriers are provided in Table 28.

Table 28 Technology need and potential solutions for packaging/barriers

Technology Needs	Potential Solutions
Low cost barrier	Cost could be reduced in response to greater demand created by volume commercialization of organic & printed electronics products.
Improved Water Vapor Transfer Rate (WVTR) and Oxygen Transfer Rate (O_2TR) barrier properties for non-metallic films	Enhancements in manufacturing processes and new barrier system designs (multiple layers) could result in more robust structures with improved barrier properties.
Improved PSA adhesives	Preferred/qualified flexible substrate materials for printed electronics applications would allow formulators to develop sets of optimal sealants to satisfy reliability requirements.
Chemical compatibility	Need for a stronger fundamental understanding of commercially available semiconducting inks to provide barriers that have engineered interfacial properties.
Hybrid systems	Some industry leaders have suggested that a hybrid system that combines a barrier film, a conformal coating and/or vacuum deposited material, may improve barrier properties.

Printing Platforms

With improved process techniques and material science developments, more accurate delivery of semiconductor, conductor and dielectric functional inks will allow smaller feature sizes in commercially printed electronics. Developments continue in the area of 'functional inks' suitable for printing electronic components. Metal and polymer based inks, along with advances in nanoparticle technology will continue to produce materials that not only perform electrically, but also lend themselves to the economics of the manufacturing process. These materials must provide suitable physical characteristics to provide for the delivery and curing constraints of high speed production. The manufacturing process will also continue to see advancement. More accurate placement, reduced feature size, and tighter registration will allow higher density electrical circuit designs. Improved techniques in material spraying, stamping, photochemical assembly and self-assembly may also play a roll along with conventional printing methods. Several technology needs and potential solutions for printing platforms are provided in Table 29.

Table 29 Technology need and potential solutions for printing platforms

Technology Needs	Potential Solutions
Flexible functional ink delivery equipment	Gravure and Flexography inking systems provide the best delivery today. Ink usage and recovery are efficient. Gravure (and Intaglio) provides the most direct delivery to a substrate. Flexography provides limited printing on conformal surfaces . This could also prove to be an advantage.
Nanoparticle technology based suspensions, polymer solutions, etc.	Ink formulation can easily include nanoparticles in place of the pigments used today. This is already the case is some copier toners and conductive inks for antenna and “chip-less RFID”. Nanoparticle based “ink” in combination with control UV and Infrared do deliver uniform drying thickness.
Reduced printed feature sizes	Today’s laser imaging can deliver fine features to cylinders and plates. Substrates, inks, press speeds and control need full spectrum testing on state-of-the-art press equipment to determine thresholds. One company claims an Intaglio press with 3µm features and registration.
Improved layer-to-layer registration	Modulate press speed testing relative to conductive inks and substrates. Slower press speeds to give servo guidance units more time to control. Increase resolution of camera imaging equipment or lower area scanned to accommodate 10 µm resolution image capture.
Improved layer thickness control	Flexography Anilox roll or Gravure cylinder laser imaging cell size to a match ratio of specific particle size in functional ink. Use Gravure electrostatic ink release in combination with ink formulation to modulate more precise thickness control.
Improved ink placement control	This is relative to both plate or cylinder resolution and layer-to-layer registration on press. Higher resolution surface imaging materials on plates and cylinders to enable finer features.
Low temperature curing/annealing systems	Flash applied UV curing. Reflective indirect infrared. Temperature control of ink systems.

New curing methods are in development that may offer improvements in the performance of functional inks while also reducing system costs by enabling the use of inexpensive, nonthermally stable substrates. Thermal curing (via convection or IR ovens) is the dominant approach for curing most functional inks. A major drawback of thermal curing is that some inks require high temperatures and / or long curing times to reach adequate cure. This forces the use of expensive thermally stable substrates. Various low-temperature curing technologies offer potential solutions:

- UV radiation curing is one of several potential solutions for processing/curing inks, but it requires incorporation of photo-initiators raising potential materials compatibility issues. The attractiveness of a UV curing process has increased its adoption into several product manufacturing platforms e.g. composite substrate manufacturing, automobile components manufacturing. Currently, UV curable metallic-based inks are in development that will enable organic & printed electronics based products to further benefit from the economies of scale offered by high throughput roll-to-roll manufacturing.
- Laser and e-beam curing technologies are also being explored for printable electronics. Laser based systems can cure a large variety of inks, but the systems are expensive and have low throughput. E-beam systems cure a limited number of inks, but have high throughput, and are very industrial.
- Photonic curing is a new curing technology for curing metallic inks that require sintering.[96] The approach uses a brief (~1 ms), intense pulse of light from a xenon flash lamp to selectively heat and sinter the metal nanoparticles - without heating the substrate. Photonic curing is similar to laser based systems, but much cheaper and higher in throughput. Since the nanoparticles preferentially absorb the radiation, the process can be broadcast in nature thus eliminating the need for precise registration. Photonic curing has been successfully demonstrated with various silver and copper nanoparticle conductive inks on substrates such as polyester, paper, polycarbonate, polyimide, polyethylene, and polystyrene. In addition to conductive inks, ongoing research is investigating the applicability of photonic curing to semiconductive, dielectric, resistive, and other inks and coatings.

In-line Characterization Tools

It is important to develop manufacturing platforms offering microelectronics manufacturing related in-line characterization tools to ensure that organic & printed electronics based products can benefit from the economies of scale offered by printing platforms. One of the technical hurdles is the real-time, quality control monitoring of the printed electronics products during production. Attributes of printed electronics such as dimensions and electrical continuity require constant monitoring to ensure high product yield during high throughput printing. Several technology needs and potential solutions for in-line characterization tools are provided in Table 30.

Table 30 Technology need and potential solutions for in-line characterization tools

Technology Needs	Potential Solutions
Registration/defect detection at very fine resolution	Scanning laser / white-light interferometry
Optical testing	Scanning high-speed video imaging
Electrical testing	Backplane / Backpanel electrical test systems

In-line systems for printed electronics should draw from both print manufacturing and fab manufacturing. Examples:

- There exists a register system that can maintain a 25 µm register. It automatically and simultaneously detects and corrects both circumferential and lateral register errors as small as 0.0254 mm. Also, it accurately electronically pinpoints and automatically removes imperfect product via a divert gate.
- Another system provides inspection and registration camera systems up to 6000dpi (2 µm). This system is primarily designed for use with central impression flexographic presses. The system reliably and consistently adjusts mis-registration with accuracy down to 15 µm, depending on press performance and also has automated quality/defect inspection options as add-on modules
- One other system is configured with scientific imaging, press registration and defect detections systems. The vision system is capable of pixel resolutions to 6.45 µm x 6.45 µm and is applicable to Offset, Gravure or Flexography.
- Other systems can operate in both process recipe adjustments and as a real-time monitor of thin-film deposition.

Flexible Electronics

As described earlier, adoption of R2R may be hindered due to limited tooling and due to hurdles such as: 1) damage due to handling, 2) particle generation, 3) impurity due to contact, 4) yield management, and 5) linear processing. Efforts are underway to establish an R2R flexible electronics assembly process by the end of 2007 at a well financed technology development center.[97] With regards to tooling and other capabilities, current acquisitions are the following: substrate material cleaning, high vacuum coater-24", high vacuum coater-12", coat & bake (photoresist, planarization, etc.), high precision lithography stepper (expose), develop / mild etch, and wet etch / strip. The planned acquisitions are for the following pieces of equipment: particle / defect inspection, dry etch (silicon / oxides), and web storage/handling. Initial applications will focus on R2R processing that will aid development of emerging applications such as low-cost RFID tags, low-cost sensors, large-area OLED lighting, and other applications. While some of these applications will be fabricated using traditional silicon manufacturing equipment, the use of advanced printing technologies for manufacturing is considered as a pathway to inexpensive printed electronics. During the next several years, the center plans to develop processes based on offset lithography, printing and hybrid processes with initial efforts directed to develop display TFTs with 2-5 micron features using initially conventional batch vacuum deposition and photolithography processes but ultimately transferring these processes to web manufacturing. Several technology needs and potential solutions for flexible electronics are provided in Table 31.

Table 31 Technology need and potential solutions for flexible electronics

Technology Needs	Potential Solutions
Prototype tools	Feature Inspection, Low-precision / high-throughput Lithography (embossing, direct patterning, additive processes), ink-jet, screen printing, laser transfer metal dry etch, metal and OLED evaporation.
Demonstration of process feasibility	An R2R based wet cleaning system with throughput of 0.2 - 10 FPM A large high-vacuum deposition tool with five PVD sources capable to process 8”-24” wide substrates with a length of 1000 ft A photo lithography tool, capable of minimum resolutions of ≤4 microns line / width spacing with a throughput of 0.75 – 2.5 FPM An inline defect inspection tool, capable to detect defect sizes of 3 microns with a throughput of 2FPM

Data compiled from reference 98.

Standards

IEEE P1620.2 is currently a project under development. This focuses on block-level function characterization for printed wireless devices. Currently RF electrical testing standards for printed electronics are not well established, and could be a hindrance to further development of printed wireless devices. P1620.2 is focusing on the electrical characterization techniques for printed diode bridge structures, but may be applicable to other low-RF characterization needs. Several technology needs and potential solutions for standards are provided in Table 32.

Table 32 Technology need and potential solutions for standards

Technology Needs	Potential Solutions
Reliability Testing *Due to significant differences in materials, processing, substrate, and applications from conventional consumer electronics, reliability testing standards established for consumer electronics may not apply. Therefore, new testing standards for printed electronics need to be created.*	Tests to be considered include: • Liquid-to-liquid thermal shock • Air-to-air thermal cycling • Humidity/elevated temperature storage and operation • Bend testing • Crushing or folding testing • Barrier testing • Exposure to solvents, water, etc
Consumer Safety	Considering uses for printed electronics will include use in food packaging, toys, etc. Safety standards and testing need to be established.
Recycling or Disposal	Many printed electronic circuits will be single-use or short-term use. Standards on disposal and/or recycling may need to be established. Considerations for evaluating ability for incineration or recyclability through the existing waste management infrastructure in particular need to be standardized.

Devices and Circuits

The future of printable devices (active and passive) and circuits is dependent upon the development and qualification of several ink, processing, and design technologies. Several technology needs and potential solutions for devices and circuits are provided in

Table 33.

Table 33 Technology need and potential solutions for devices and circuits

Technology Needs	Potential Solutions
Printed ICs for power conversion, logic and memory	Designing and modeling using layout rules and CAD / CAM tools
Functional testing with parameterization	Inline testing capability
Device switching time < 10^{-7}s, operating voltage < 5V	Novel device architecture and materials

Organic & printed devices and circuits will cause a major shift in responsibilities from the custom manufacturer / assembler to the printer. Fabricators will now be responsible for delivering substrates with built-in passive components as well as certain electrical performance. The fabricators will have to develop new processes along with inspection tools for the new passive devices. Commercially available materials and newly developed materials need to be evaluated for compatibility with the existing circuit board fabrication, including fabrication processes, materials properties and reliability. Additional work needs to be done to fully commercialize and transfer the technology to the industry at large.

CONCLUDING REMARKS AND RECOMMENDATIONS ON PRIORITIES

During the 1980s and 1990's, organic & printed electronics technology was largely the domain of traditional players within the microelectronics industry, involving semiconductor companies, research laboratories, and government organizations. The advancement of this nascent field included contributions from chemists, materials scientists, electrical engineers, physicists, and many other professions. The print industry which shaped much of the Second Millennium, joined the organic & printed electronics quest in 2000. This seemingly unlikely marriage of the microelectronics and graphic print industries shows incredible promise to spawn an entirely new method of electronics manufacture for large consumer electronic product markets.

Organic & printed electronics technology is maturing rapidly with the advent of higher performing electrically functional "inks". These functional inks have enabled the use of low-cost printing platforms, such as inkjet, flexographic, gravure, offset, and screen printing, which are traditionally used for printing books, packaging, and newspapers. Since product price is a strong function of the materials and manufacturing costs, such graphic arts printing platforms and engineering expertise promise to greatly reduce the cost of organic & printed electronics e.g. displays, sensors, and simple wireless products (such as RFID tags).

In 2003, the printed electronics industry experienced a catalyst for growth as high volume printing of RFID antennae became a reality. Companies driven to meet RFID deployment goals established by Wal-Mart and the Department of Defense gained greater visibility in the printing industry as the printing of RFID antennae became the manufacturing process of choice. The increased activity by members of the printing industry accelerated the development of functional ink and printing process development. As more companies became involved, the number of potential functional ink systems and printing processes increased, therefore accelerating printed electronics development.

As the organic & printed electronics industry is being established, it is critical to identify the gaps / needs based on the present status of the enabling technologies and supply chain. This iNEMI Organic & Printed Electronics Roadmap identified several barriers. Listed below are those that are deemed most critical:

- One technical barrier concerns the development of in-line manufacturing quality control equipment. To benefit from the economies of scale that printing offers, systems must be developed and qualified for testing of the printed circuits.
- A second technical barrier that is necessary to expand the number of product opportunities for printed electronics is the development of higher performance solution processable semiconducting inks. The recent increase in visibility for printed electronics has seen the introduction of several new participants in the

semiconducting ink development field (both organic and inorganic inks) that will attempt to address this need.

- A third technical barrier is that a dedicated, hybrid printing / manufacturing platform must be developed. Industry members envision that a printing / manufacturing platform combining several printing technologies (e.g. flexography, gravure and micro dispensing) is required to enable realization of the market potential for printed electronics based products.
- A fourth technical barrier is the lack of organic & printed electronics simulation tools and software platforms that provide a robust interface between microelectronics design software and graphic arts image design software. The simulation tool must consider the unique characteristics of printed electronics devices and circuits, i.e. high impedance, high operation voltage, etc. The interface software platform is critical to enable graphic arts manufacturers to print circuits / products and should have features such as electrical continuity and design rule checks. These features are necessary for final evaluation before on-press printing to ensure electrical functionality and high yield of printed electronics products.

One non-technical barrier is the lack of pull by the customers for printed electronics based products. Although, early opportunities such as RFID and flexible displays have been mentioned for the past five years, several products could reach the market sooner. It is important that companies identify early opportunities that do not need the stringent reliability and performance requirements that RFID and flexible displays demand. At recent conferences and workshops, presentations have been made suggesting that if the industry waits for printed RFID and / or displays, many opportunities and potential sources of revenue will be overlooked.

The authors of this iNEMI Organic & Printed Electronics Roadmap provide an overview of the status and requirements of the different technologies that are required before full market potential will be realized. This roadmap is not a static document but one that will grow in value as it is continually updated by business and technical experts in the industry.

GLOSSARY

Below several acronyms and terms are defined.

Al_2O_3	Aluminum oxide
COC	Cyclic olefin copolymers
EVOH	Ethylene vinyl alcohol
FPM	Feet per minute
HDPE	High density polyethylene
IEEE 1620-2004™	Standard for Test Methods for the Characterization of Organic Transistors and Materials.
IEEE 1620.1-2006™	Standard for Test Methods for the Characterization of Organic Transistor-Based Ring Oscillators.
LCD	Liquid crystal display
LCP	Liquid crystal polymers
LDPE	Low density polyethylene
OLED	Organic light emitting diode
oPET	Oriented polyester
OPP	Oriented polypropylene
O_2TR	Oxygen transmission rate
PAR	Polyarylate
PCTFE	Polychlorotrifluoroethylene
PE	Printed electronics technology
PEN	Polyethylene naphthalate
PET	Polyethylene terephthalate
PSA	Pressure sensitive adhesive
PVC	Polyvinyl chloride
PVdC	Polyvinylidene chloride
R2R	Roll to Roll
RFID	Radio frequency identification
SiO_x	Silicon dioxide
WVTR	Water vapor transmission rate

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