Printing Processes for Functional Electronic Manufacture

Robert H. Detig and Dietmar C. Eberlein, Chief Engineer, Electrox Corp., Denville, New Jersey, USA

Abstract

In this paper, I will review the requirements for the printing of functional electronic parts.

The ideal process for electronic printing should be fast, inexpensive and offer high performance. I will show examples of serial vs. massively parallel printing processes. Inexpensive means an additive process rather than the traditional print/then etch subtractive process. Finally, whether electronic addressability is important, or even affordable, will be considered as part of the "ideal process".

Introduction

Important issues for electronic manufacture are:

1. What thermal processing is required and its impact on substrate dimensional stability?
2. Is aqueous processing allowed?
3. What specifications on overlay accuracy are required (i.e. alignment with previous layers)?

Philosophical Issues

Since inks are liquids, one could ask, "Why can't I find an organic precursor of material X, then print it by one of the traditional means and finally react (or reduce it) to X; yielding a finished product?" The answer is that these approaches have been extensively studied and have been found "wanting"! These approaches suffer from a yield problem. The fraction of useful material in the precursor is too small. I refer to this as the Functional Fraction (FF), with the remainder called the Process Burden material. A second point is the issue of do I want a "serial" or massively parallel printing process; and this, of course relates to print speed and productivity. The answer is easy, speed is good but don't dismiss serial processes (like ink jet) which have carved out huge chunks of market share. Furthermore it's productivity is enhanced by multiple print heads in parallel (some times several hundred).

Its important to remember an event from the 15th century; up until then, scholars recorded data (text) by hand, serially. A fictitious Brother Dominic took one year to scribe one complete Bible. Johannes Gutenberg (1397-1468) produced 150 sets of the Bible on paper (2 volumes), and 60 on vellum (animal hide). This is probably a 1000X improvement in productivity.

A third point is electronic addressability or printing directly from a data file (ie tool-less manufacture). To those from the copier or printer industry, this may seem to be a moot point. But it is not so obvious in a manufacturing environment (an Indigo printer could produce 2 million RFID antenna in a 20 hr. day), and all of them identical. Addressability depends upon the market. A printed wiring board shop that produces from 50 to 100 pieces of an 8 to 12 layer board will be greatly enhanced by tool-less mfgr. But flat panel display manufacturers will produce 100's of thousands of panels before a design change occurs.

An example of the cost of electronic addressability is seen below:

Electronic Addressability

HP/Indigo Printer

- Width 300 mm wide, Theta scan limited
- Process Speed 600 mm/sec, polygon speed limited
- Resolution 100 micron feature, spot size limited
- Productivity 0.18 m2/sec

Electrostatic Printing Plate Based Machine

- 1 m/wide, industry standard
- 1m/sec process speed, industry standard
- 10µ feature
- 1 m2/sec productivity
- 5x productivity increase
- 10x feature size improvement

The fourth point, is it an additive vs subtractive process? Which is the better solution? The answer is that it depends on the economic restraints (not just overall cost) and a host of other factors. Our company position is that additive processes are the winners in "niche" markets but photolithography (print & etch) will be around a long time. What follows shows five different schemes for printing conductive traces.

Printing Conductors for Electronic Products

- Subtractive
  - o Cu or Al foil coated PET, Photolithography; print etch resist toner, etch metal, then strip resist
- Additive, with electroless followed by electroplating
  - o Print catalyst toner
  - o Electroless Cu or Ni
  - o Finish with electroplate Cu
- Additive (no electroless)
  - o Print conductive layer
  - o Finish with Cu electroplate
- Additive (one step)
  - o Print conductive (silver filled) resin
- Additive Resinless, one step
  - o Print MOD coated metal particle (metallo-organic decomposition)
  - o Heat Process to sintered metal (Paralec LLC technique)[1]

Survey of the Printing Landscape

The traditional graphic arts processes are:

1. Letterpress (flexography)
2. Lithography

3. Gravure
4. Screen/Stencil

While the electronic processes include:
1. Ink Jet
2. Electrography
   a. Electrophotography
   b. Electrostatic Printing from a fixed image

Ink jet and electrophotography are electronically addressable; all others involve a fixed image configuration. The first important issues are ink thickness and print speed. They are:

	Web Speed	Ink Thickness
Letterpress	500ft/min	0.5-1.0μ
Litho	500ft/min	0.5-1.0μ
Gravure	1500-2000ft/min	0-10μ
Screen	300ft/min	100's of microns
Rotary Screen	500ft/min	100's of microns

Of more significance is the functional fraction (FF) of material in the ink that provides a useful functionality. Table 1 shows some representative examples. The inks for the traditional processes are all a result of decades of experience with 100-200 nm organic pigments. They could be much higher in FF in the case of gravure inks with 1-2μ dia metal in the ink. Silk screen inks can equal the FF of large particles toners as with the solder pastes that are routinely stencil printed to thick layers for solder bumping or ball grid arrays for electronic packaging.

Ink "Pathology"

Several objective conclusions can be drawn after careful reflection. The traditional thin profile inks (Letterpress, lithography) have problems producing thick layers and are restricted in their Functional Fraction (FF) to the 50-60% range. Gravure inks can produce thicker ink layers but are limited in solids content. Screen print inks seem unlimited (greater than 100u) in thickness but limited in Functional Fraction to about 60% (on a volumetric basis) Ink jet inks are very limited in solids content but even then can produce 300nm of sintered metal in one pass.

Finally, the toners (in this case liquid toners) have a FF of 97 to 99% FF (on a wt basis) for particle sizes over a range of 400x (50nm to 20 microns)! This is one of the important advantages of electrographic systems; the ability to print large particles with very high Functional Fraction (FF).

Conductivity Needed

The answer to this depends on the intended market and even the operating point within that market, like in RFID. The most demanding application is RFID, because the received radio signal is used to "power Up" the chip, data is accessed and retransmitted back. Electric rf field strengths are limited by human exposure standards, and long read range is desired so energy efficiency/ conservation considerations are paramount. Rule of thumb; make chips small and simple and provide efficient antennae. An engineering design standard for RFID substrates, depending on the frequency band; this is the amount of pure copper that is needed:

Freq.	t: microns pure copper: thickness
13.5 mhz	20μ
890 mhz	5μ
2.45 Ghz	2μ

Here it is important to remember the skin effect phenomenon; in AC systems electrical currents flow on the surface of conductors. The results for pure copper are:

Freq.	Skin depth (microns)
13.5 mhz	17.96
890 mhz	2.2
2.45 Ghz	1.32

Table 1: Constraints Placed on the Ink by the Printing Process

	Litho %	Gravure %	Flex %	Ink Jet %	Silver Toner	SN/PB (63/37)
Functional (pigment) Factions; FF by volume	60	25	35	10	97% by wt 90% by vol	99% by wt 70% by vol, for large particle size
Process Burden	40	75	65	90	3% organics d = 50 nm (1)	1% resin d = 15-25μ density 8.42 Wafer bump toner (2)

Roughly 90% of the current flows within 2 skin depths of the surface. Skin depth is proportional to resistivity to the ½ power, so a resistivity. of 16.9 micro ohm cm increases skin depth by a factor of the square root of ten.

For display panels, new rules apply, namely that frequencies are lower, there is no chip to power up and the conductivity needed depends mainly on what type of display technology your are making. Organic light emitters require much higher currents than electrophoretic displays (E ink type)

Some typical technologies are listed here:

Display Technology	Drive Current Density
OLED	5-10ma/cm^2
Electro-chromic(Dow/Aveso)	0.5ma/cm^2
Electro-phoretic(E Ink, Gyricon)	0.01ma/cm^2

Liquid crystal displays are close to the E Ink materials and plasma displays close to the electro-chromic.

Overlay Accuracy of One Layer Over Another

Figure 1 shows a cross section of an organic field effect transistor (FET). The critical dimensions in the first layer (metal layer) are the gap between the source/drain electrodes, called the gate length; the shorter this is the faster the transistor. Next is the printing of the semi material and this can be quite large and need not be carefully overlaid. So too is it with the gate dielectric which is really a conformal coating. The fourth layer, the metal gate must be carefully aligned to the source/drain gap for proper transistor function. With the desire to print on flexible substrates like PET & PEN, and with aggressive thermal processing (125-150°C, 15 to 30 min) there is considerable substrate "movement" so overlay accuracy becomes a significant issue. Proposal solutions include:

1. Innovative transistor design
2. Adaptive printing processes for the gate (serial & speed limited)
3. Self alignment techniques to solve the dimensional stability of the substrate

Examples of these will be shown.

Implications of Large Features in a Printed IC

Let us postulate that the following technologies have been achieved:

1. We have a successful self-aligning process.
2. We can print 3 micron features (lines and spaces).
3. We have developed organic materials with properties equal to those of single crystal silicon.
4. We will reverse engineer the Hitachi Mu chip and produce it using the new organic semi-conducting technology, at 3 micron features.

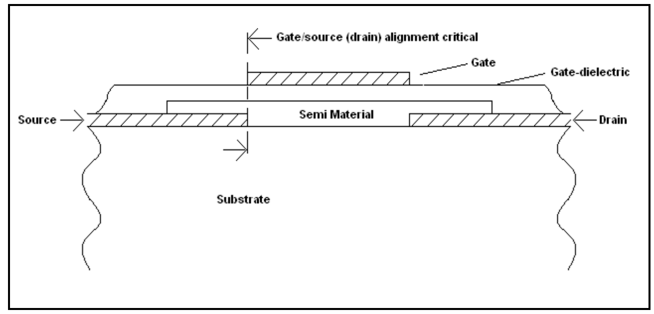

Figure 1

The Hitachi Mu chip is made with 0.3 micron features and has a size of 400 micron by 400 micron. This means our final chip will be 10X larger or 4mm by 4mm, a 100X increase in area. A first order design rule is that the chip power requirements are proportional to chip area, so our new organic chip will require 100X the power to feed it! But with innovative design improvements like slowing the clock rate, etc.; we can cut that power by a factor of 10. Now our new chip requires only 10X the power of the Hitachi chip. In some RFID applications like warehousing, distribution centers, etc. where long read range is required, this can have disabling consequences. Since power density captured by the antenna drops by the square of the distance from the transmitter, our read range with the new organic chip is only 30% of that of the almost identical Hitachi silicon chip. I must emphasize that these considerations apply only to a sub-set of the RFID market, that requiring long read range. For other applications, like display backplanes and RFID markets that are contact machine read; organic transistors offer a new approach to inexpensive manufacture.

Conclusions

We have reviewed the printing technology landscape and identified important differences in ink functionality, and serial versus parallel processes. Also the implications of electronic addressability were considered. Conductivity and current density requirements were presented for various applications, some more severe than others. Finally, the details of printing an organic transistor, with the implications of printing a "large" one were presented.

References

1. US 6,153,348
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Author Biographies

Robert H. Detig founded Electrox Corporation in 1992 to apply electrographic imaging to technology as a manufacturing tool for various industries. He has pioneered the concept of functional toners made of high-density materials like metals and glasses; to be used in a manufacturing process. He was awarded a PhD in Electrical Engineering from Carnegie Mellon University in Pittsburgh, Pennsylvania.

Dietmar C. Eberlein is Chief Engineer and principal of the Electrox Corp. He has broad experience in all aspects of electrophotography. He worked for Savin, Olivetti USA and Minox Camera. He has a BS in Mechanical engineering.