Materials and Processes for High Speed Printing for Electronic Components

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Abstract

Printing methods already familiar to the graphic arts industry can be used to apply carefully designed electronic materials at high speed and low cost. Processes such as offset lithography, gravure, flexography and inkjet are being used to manufacture electronic components. Each method has advantages and disadvantages in terms of process capabilities, and differences in material properties required to run. For both historical and pragmatic reasons, the patterning and layering capability of high-speed printing has been limited to suit the resolving power of the human eye. Experiments have been conducted to benchmark existing capability of these processes and materials on flexible substrates. Such experiments will provide a foundation for exploring the viability of existing printing infrastructure for the mass production of commercial products. In addition, improvements in these electronic materials and the mechanics of printing processes may provide significant advancement of future application capability.

Introduction

While I realize that this conference is devoted to "Non Impact Printing", I appreciate the invitation that the organizers have extended to talk about alternative methods of printed electronics manufacturing, for there are a number of advantages to the traditional "impact" printing methods. Printing, in any form, makes good sense as a manufacturing method for complex electronic designs. Electronic components are typically made up of layers of various materials, much as graphic arts products are made up of layers of various colors. It is not so much of a stretch to replace CMYK with conductor, semiconductor, dielectric, and, well, something else such as phosphor. And commercial printing of electronics would offer many advantages in ease and speed over traditional fabrication methods of silicon-based components: instead of being carried out in clean rooms, at high vacuums and temperatures, in relatively small batches, printing electronic components means the processes can be carried out at room temperature and pressure in a continuous manner. As an example, a flexographic press running at 10 meters/second with stock 1meter wide, printing components 1 mm on a side, can print 3.6 billion components per hour. Of course there are trade-offs for these high speeds: commercial printing processes, having been developed to provide no greater precision than the human eye can resolve, cannot approach the incredibly tiny feature sizes possible with today's photolithography methods. Printing also imposes some fundamental limitations on material selection; to start, materials must be able to be dissolved or suspended in a liquid carrier. The amorphous or particulate nature of the materials involved differs greatly from the single-crystal and sputtered materials of solid-state electronics. This paper will discuss some of the other considerations that go into developing materials suitable for printable electronics.

And while much of the current research in printable electronics makes use of the high precision and small feature sizes available with ink-jet technology, for large-scale, high-volume commercial printing has some undeniable advantages.

High Speed Commercial Printing Processes

Flexography is a relatively simple method in which a raised image area on a flexible plate (hence "flexography") is inked and then pressed onto the substrate. The inking process is accomplished through an anilox cylinder, which is engraved all over its surface with cells of a given size; it is the size of these cells that controls the amount of ink transferred to the image plate. It can achieve line speeds of up to 1500 feet per minute, and a minimum feature sizes are quoted in the literature at 40-75µm.[1,2] Inks used in this process tend to have viscosities in the range of 25-100 cP. Various materials are available for the flexible plate and the chosen type should be resistant to the solvent blend of the ink to minimize deterioration over the length of the print run.

In gravure printing, the image is created by engraving tiny cells within the image area on a metal plate (see Figure 1). Ink is applied to the plate and wiped off the non-image areas with a doctor blade, and then the stock is pressed onto the plate with a rubber impression roller, drawing out the ink. In some cases an electrostatic charge may be applied to the impression roll to enhance this process. The advantage of gravure is that the surfaces in contact with the ink are metal, and so very durable and very stable; it is often used for long-run applications such as magazine publishing. Gravure presses can run at speeds up to 3000 feet per minute and achieve minimum feature sizes of 15-50µm.[1,2] Gravure inks tend to be a bit thinner than flexo inks; generally toward the lower end of the 25-100cP range.

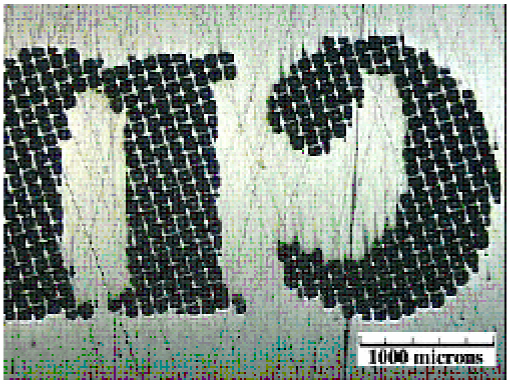

Figure 1. Engraving on a gravure plate.

Offset lithography can offer finer feature sizes than the other processes though developing a material for it can also be more technically challenging. On a typical press, ink is transferred from the well through a number of metering rollers until it is finally applied to the image plate. This plate is treated in such a way that the image areas are hydrophobic and the non-image areas hydrophilic; before inking it is dampened with an aqueous fountain solution which prevents the non-image areas from accepting ink when contacted with the inking roller. The image plate then transfers the ink to an offset blanket, which transfers it to the substrate. Press speeds vary depending on whether they are sheetfed or web, and whether they have drying capability or not; the fastest can run up to 3000 feet per minute. Lithography can offer feature sizes as small as 25μm^2, but lays down a relatively thin layer of ink. The inks used are very high in viscosity (2,000-100,000 cP) and must be able to emulsify a certain amount of the fountain solution.

Screen printing is not generally considered a high-speed process but has and will continue to play a role in electronics printing due to its other advantages, the foremost being its ability to put down thick layers of ink over large areas. To create the image area, a steel or polyester mesh of a given thread diameter and mesh opening is covered with a photosensitive emulsion. A mask of the image area is placed over the emulsion, and then exposed to UV light to harden. The unexposed areas are then washed out, allowing ink to be pressed through these open areas with a rubber squeegee during printing. Film thickness is controlled by the size of the mesh openings, which also has an impact on the line resolution achievable. Web-fed rotary screen presses can run at speeds around 500 feet per minute, but generally run in the 100-200 feet per minute range. Minimum feature size depends on mesh size, which may in turn depend on the particle size of the pigments to be used in the ink. Viscosities of screen inks are higher than those for flexo and gravure, generally 500-5000 cP. This can often allow for the printing of more highly-loaded materials at higher film builds than the other processes can tolerate.

Printed Electronic Materials

The demand for materials that can be easily and cheaply applied to flexible substrates to make low-cost electronics was clearly demonstrated at this year's spring meeting of the Materials Research Society, where there was a four-day track of lectures on Flexible Electronics and two and a half days on Printing of Materials for Photonics, Electronics, and Bioinformatics.[3]

Today's solid state electronics are very good at what they do. High purity, highly ordered, stable materials allow for very high performance and ultra-miniaturization. The lack of grain boundaries, inclusions, or other interfaces allow for highly efficient charge transport and fast device speed in service. On the other hand, growing a single crystal of silicon large enough to slice wafers from, and the mask-image-wash-deposit-etch process for adding subsequent layers of material are labor- and time-intensive processes and results in relatively large amounts of waste materials. In situations where blazing device speed and miniscule size are not critical, being able to quickly produce large numbers of low-cost devices with "good enough" performance is quite attractive.

Research into flexible electronics is looking towards the use of amorphous silicon as well as organic thin-film transistors, with an eye toward the manufacture of large-scale flexible displays especially. Reel-to-reel processing is the ultimate goal in order to maximize manufacturing productivity, but many of the materials in use still need to be applied by high-temperature vapor deposition or in inert atmospheres.

Much of the high-end research into printable electronics is being done with ink-jet deposition of conductive polymers. This is an attractive process for microelectronics due to the small feature sizes it can produce, as well as the enclosed nature of the system which minimizes contamination of sensitive materials. Much of the focus is on the use of these polymers as semiconducting materials, and the printing of all-polymer thin film transistors.

However, as conductors, polymers are still significantly less conductive than materials containing pigments such as carbon or metals. And due to constraints on particle size of the pigments and viscosity of ink-jetted materials, much of the research being done with conductive pigmented materials for ink-jet involves the use of low-viscosity dispersions of metallic nanoparticles. These are relatively expensive materials, and the processes often involve burning out the binder and sintering the particles at elevated temperature after the printing step to leave, effectively, a bulk-metal material behind.

An alternative to this scenario, which can be used with high-speed commercial printing processes, is to rely on particle-to-particle contact in inks highly loaded with metal pigments. This approach allows the formulator greater latitude in choice of binders, including many which are used in graphic arts inks today. This in turn allows for the use of solvents which are known to be acceptable for use on existing printing equipment. The main concern then becomes balancing the amounts of resin, pigment, and solvent so that it prints well, and that when the ink dries there is enough resin to hold the pigment flakes together, but not so much as to isolate the particles from each other. Figure 2 shows an SEM picture of a cross-section of a dried ink film in which the orientation and contact of individual silver flakes are visible.

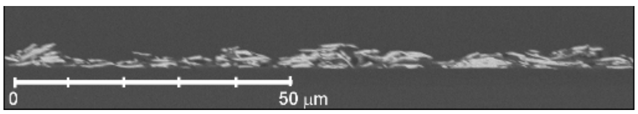

Figure 2. Backscatter SEM o f silver flakes in dried ink film.

Materials of this highly-filled nature are being used for conductive traces, resistors, antennas, contacts and electrodes in printable batteries, and backplanes for displays, depending on the choice of pigment and loading levels. These variables can, in turn, have an effect on which process is chosen for manufacturing. For example, in some printed batteries, the cathode material is consumed as the reaction progresses, and the amount of cathode material applied during printing has a direct effect on the lifetime of the battery. To maximize this parameter, the ink is loaded as highly as possible with pigment, resulting in a high-viscosity material. This, combined with the ability to deposit very high film thicknesses, makes screen printing the method of choice for this application.

The presence of organic binder between pigment particles and the particulate nature of the conductors themselves will necessarily result in conductivities significantly lower than that of the conductive materials in bulk form. It is important to distinguish, however, between material properties and device performance. There are cases in which printable electronic materials, though they may have different properties than those used in traditional fabrication methods, will still give acceptable device performance.

One example, which is in commercial use today, is printed antennas for Radio Frequency Identification (RFID) tags. Passive RFID tags typically consist of a metallic antenna and a silicon-based microchip. The microchip contains the identifying information for the container on which it is placed, whether this be simply a unique number, or a more complex set of data such as the time-temperature history of the container. The chip itself, however, cannot interact directly with the radio frequency readers; an antenna is necessary to receive the energy from the reader and reflect it back. The size and shape of the antenna is determined by a number of factors, including the frequency range at which it operates, customer requirements for read range and footprint size, and the type of material to which it will be applied. Printing these antennas offers a more flexible, faster, and less expensive alternative to etching or stamping the antennas out of a metal foil. But will the difference in conductivity of the materials affect the performance of the final product? Figure 3 shows a comparison between the read ranges obtainable with stamped copper antennas vs. some printed in the same size and shape on 80# coated paper with silver-filled ink on a lab-scale flexographic press. To make a functional RFID tag, a microchip from Alien Technologies was applied to each, and the minimum distance necessary to get a stable reading on a 915 MHz reader was measured. As can be seen from the figure, the printed antennas generated approximately the same read range as the metal foil antennas.

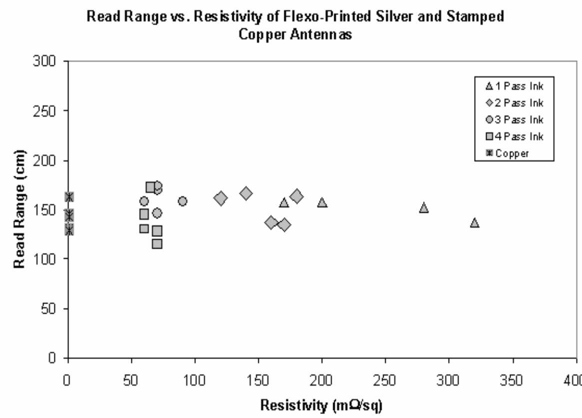

Figure 3.

Another experiment looked further into the effect of various printing variables on the performance of printed antennas. This time the antennas were printed on a full size, 11-station flexo press; variables included the number of layers of ink, speed of the web, and heat of the dryers. The sheet resistivity of the ink at each press condition was measured, and the read range was evaluated. To remove the possible variability between microchips, a single microchip was attached to a stationary jig, and each antenna was clamped to it during the read range measurement. It was found that the print speed and drying conditions had a negligible effect in the range that they were varied. Number of layers of ink had a greater impact on read range than did any other factor. Again, the results shown in Figure 4 indicate that a large difference in resistivity does not necessarily correlate directly to device performance in this application.

It should be noted that at RFID tags designed to work in higher frequency ranges work on a fundamentally different electronics principle, where conductivity is much more closely tied to device performance. It is therefore imperative to understand the application before deciding on what metric to use in material evaluation!

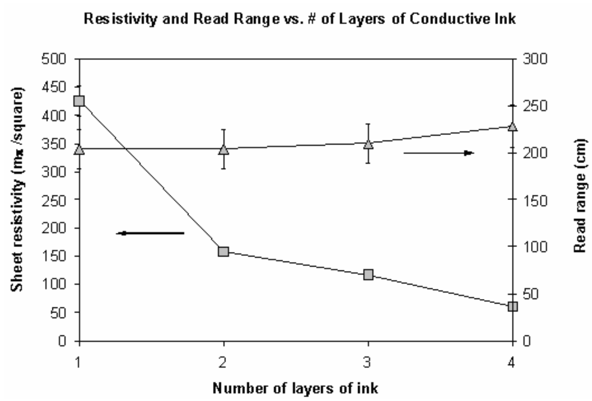

Figure 4.

Conclusion

Many commercial printing processes can be used in the manufacture of certain electronic components today. They provide an opportunity for high speed, low cost manufacturing, though they impose certain limitations on material selection and minimum size. Materials must be selected and developed with an eye toward viscosity, particle size, drying, and how material properties relate to final device performance to take full advantage of the opportunities these processes offer.

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Biography

Jennifer Rigney holds a master's degree in materials science from the University of Michigan and a bachelor's degree from the Massachusetts Institute of Technology. Before joining Precisia in September 2003, she spent 6 years as a formulation chemist in the Industrial Coatings division of PPG Industries, followed by 3 years in the R&D group of Serigraph Inc., an industrial screen print provider in West Bend, WI. Her work has comprised optimizing the performance and application properties of a wide range of coatings: anti-corrosive primers, graphic arts inks, and electronic materials.