

Direct-Write Technologies for Rapid Prototyping Applications: Sensors, Electronics, and Integrated Power Sources

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Introduction to Direct-Write Technologies for Rapid Prototyping

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1. Direct-Write Technologies
 2. Electronics
 3. Biomaterials
 4. Miscellaneous Application Areas
 5. Conclusions

1. DIRECT-WRITE TECHNOLOGIES

The ability to deposit and pattern different thin-film materials is inherent to the fabrication of components and systems such as those found in electronic devices, sensors, MEMS, etc. The trend toward miniaturization has been led by developments in lithography techniques, equipment, and resists materials. But with increased capabilities comes limited flexibility as well as increased complexity, time, and cost. Today there remains, and will remain in the future, applications for rapid prototyping thin film material patterns with CAD/CAM capabilities. A wide range of different direct-write technologies is being developed to satisfy this need. They differ in resolution, writing speed, 3-D and multimaterial capabilities, operational environment (gas, pressure, and temperature), and basically what kinds of final structures can be built. Direct-write technologies do not compete with photolithography for size and scale, but rather complement it for specific applications requiring rapid turnaround and/or pattern iteration, for minimizing environmental impact, for conformal patterning, or for prototyping and modeling difficult components, circuits, subassemblies, etc. (1).

The area of electronic components might be the greatest driver for the development of new direct-write technologies and materials with special emphasis on electronic material quality, writing speeds, and processing temperatures. In particular, there is a strong need in industry for rapid prototyping and “just in time methods” (JITM), materials, and tools to direct write passive circuit elements on various substrates, especially in the mesoscopic regime, that is, electronic devices that straddle the size range between conventional microelectronics (sub-micron range) and traditional surface-mount components (10-mm range). Integral passives and high-density interconnects are important and listed on the National Electronics Manufacturing Initiative (NEMI) roadmap. The need is based, in part, on the desire to: (1) rapidly fabricate prototype circuits without iterations in photolithographic mask design, in an effort to iterate the performance on circuits too difficult to accurately model; (2) reduce the size of PCBs and other structures ($\sim 30\text{--}50\%$ or more) by conformally incorporating passive circuit elements into the structure; and (3) fabricate parts of electronic circuits by methods that occupy a smaller production scale footprint, that are CAD/CAM compatible, and that can be operated by unskilled personnel or totally controlled from the designer's computer to the working prototype. The savings in time is especially critical to the quick-changing electronics market of today. The novel direct-write approaches described in this book will contribute to new capabilities satisfying next-generation applications in the mesoscopic regime.

There is no single book that summarizes the different direct-write technologies available and emerging today. This is due, in part, to the advances made only recently in the different approaches in this field, such as ink jet printing, laser forward transfer techniques, laser chemical vapor deposition (LCVD), matrix-assisted pulsed-laser evaporation direct write (MAPLE-DW), and Micropen (2). As an example of the relevance of these technologies, it is useful to consider the size of a few markets on which direct-write tools are expected to have an impact. For example, the development of the next generation of sensors for medical applications hinges on the ability to further miniaturize their size as well as tailor their response to controllably varying analytes. The market for biomedical sensors exceeds several billion dollars. In the area of electronic devices and systems, direct-write technologies could play a pivotal role in such markets as Smart Cards, with a global sales exceeding a billion dollars. The development of new multilayer circuit board assemblies, where current technologies are reaching global sales of 30 billion dollars, will also be improved. These examples do not take into consideration the potential for new opportunities and further growth that a new technology, such as direct write, would offer, in which case the market size will grow faster. The goal of this book is to provide a platform to introduce ideas and approaches that are fundamental to direct-write technologies, to present in a

similar format a cross-section of some of the conventional and exciting new direct-write techniques, and lastly to objectively discuss the spectrum approaches for patterning materials where direct writing is a subunit.

Electronics and biomaterials are two areas that offer the greatest opportunity and at the same time the greatest challenges for the development, implementation, commercialization, and impact of direct-write processes. The remainder of this chapter uses these two areas to introduce and discuss different direct-write techniques, material issues, and potential for future applications.

2. ELECTRONICS

There are numerous direct-write technologies in existence today and they are of increasing importance in materials processing—enabling, for example, the simplification of printed circuit-board manufacture at reduced costs (3). Other exciting areas for direct-write applications include chemical and biological sensors, integrated power sources, and 3-D artificial tissue engineering. Figure 1 gives a representative sample of some of the different direct-write techniques that exist today. Each of the techniques in Fig. 1 are different in the way they direct write material and each has advantages and disadvantages with respect to a given metric of direct-write ability. There exists no universal tool with which to direct-write all materials, so it may be necessary to combine two or more disparate approaches in order to achieve a direct-write tool capable of a wide range of materials and structures. With a direct-write approach, 3-D structures can be built directly without the use of masks, allowing rapid prototyping, product development, and cost-effective small-lot manufacturing. As materials and processing challenges are being met with increasing success—low processing temperatures and high write speeds, for instance—direct-write techniques move toward an even wider range of possible applications. Passive electronic components (e.g., capacitors, resistors, ferrite-core devices) and conducting interconnects with properties comparable to conventional thick-film approaches (e.g., screen printing and tape casting) have been made by direct-write techniques using a variety of materials. In a parallel development demonstrating the new capabilities of different approaches, direct writing of heterogeneous biomaterials (proteins, DNA, living cells) is being used for tissue engineering and array-based biosensors.

To optimize different direct-write techniques for electronic device fabrication, high-quality electronic starting materials must be developed and tailored for each processing method, transfer method, and required final electronic (or other) device performance. Many different approaches exist to direct-write or transfer-patterned materials as shown in Fig. 1 and each technique has

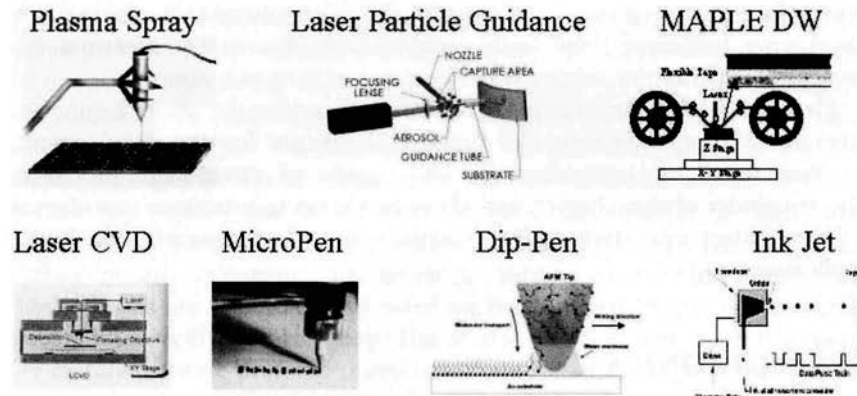


FIGURE 1 To compare different direct-write techniques, a schematic picture of some approaches that are commonly used in commercial or research institutions today is shown. Note the wide range of approaches used to transfer the material and the subsequent effect on material properties, the flexibility to adapt to other material systems, as well as feature resolution.

strengths and shortcomings in terms of ultimate capabilities. The techniques include plasma spray, laser particle guidance, matrix-assisted pulsed-laser evaporation (MAPLE), laser chemical vapor deposition (CVD), Micropen, ink jet, e-beam, focused ion beam, and several novel liquid or droplet microdispensing approaches (4–11). These techniques differ in the way that they transfer, deposit, or dispense materials and they are compared principally in terms of cost, speed, resolution, flexibility to work with different materials, final material properties, and processing temperature.

While the direct-write techniques of Fig. 1 are wide ranging, they are a subset of a larger research-and-development area called rapid prototyping. The classic definition of rapid prototyping is “a special class of machine technology that quickly produces models and prototype parts from 3-D data using an additive approach to form the physical models” (12). The length scales of common rapid prototyping techniques such as solid freeform fabrication (SFF), stereolithography (SLA), selective laser sintering (SLS), fused deposition modeling (FDM), and computer numerical controlled (CNC) milling are centimeters to meters—macroscopic—and extend visibly in three dimensions. Typically they are only to-scale models and are structural as opposed to functional. When viewing the evolution, current status, and future potential for direct-write techniques, it is useful to consider the lessons learned from rapid prototyping. The key aspect of solid freeform and additive fabrication is the ability to deposit or build up material only where it is required to produce finished parts. Novel materials combined with the additive nature of these

processes leads to tremendous flexibility in the shape and complexity of parts that can be fabricated. The choice of starting materials and the specific rapid prototyping technique will produce unique microstructures that impact final performance, especially of macroscopic parts. The ability to do point-wise deposition of one or more materials provides the opportunity for fabricating materials with novel microstructural and macrostructural features such as micro-engineered porosity, graded interfaces, and complex multimaterial constructions.

There is a thread of continuity between all direct-write prototyping techniques: their dependence on high-quality starting materials, typically with specially tailored chemistries and/or rheological properties (e.g., viscosity, density, and surface tension). The starting materials, sometimes termed "pastes" or "inks," may consist of combinations of powders, nanopowders, flakes, surface coatings, organic precursors, binders, vehicles, solvents, dispersants, and surfactants. These materials have applications as conductors, resistors, and dielectrics and are currently being developed specifically for very low-temperature deposition (< 200 to 400°C). Low-temperature processing will allow fabrication of passive electronic components and radio-frequency devices with the performance of conventional thick-film materials, but on low-temperature flexible substrates, such as plastics, paper, and fabrics. The desired final electronic materials may be silver, gold, palladium, and copper conductors or alloy conductors; polymer thick film and ruthenium oxide-based (cermet) resistors; and silicate glass and metal titanate-based dielectrics.

Figure 2 shows a schematic diagram outlining the evolution and future of rapid prototyping technologies and materials development as it applies to direct writing. Today, most rapid prototyping techniques involve depositing single materials and they are typically not electronic materials with the exception of some limited metals. To expand this capability to multiple materials will principally involve developing the rapid prototyping tool. New techniques or approaches are needed to address the issues with handling different materials such as the compatibility of multimaterial, multifunctional components and the co-firing of multifunctional, multimaterial systems. Subsequent to the rapid prototyping of multiple materials will be the expansion of applications to flexible polymer or other low-processing temperature substrates. Research in this area is ongoing and is centered on novel approaches to processing materials at lower temperatures. One popular approach is the use of laser surface sintering, because under the right conditions (e.g., wavelength, fluence, pulse width) it allows the surface of the direct-written material to achieve temperatures far beyond the decomposition temperature of common polymer substrates. That is, the heat-affected zone does not penetrate significantly beyond the penetration depth of the laser.

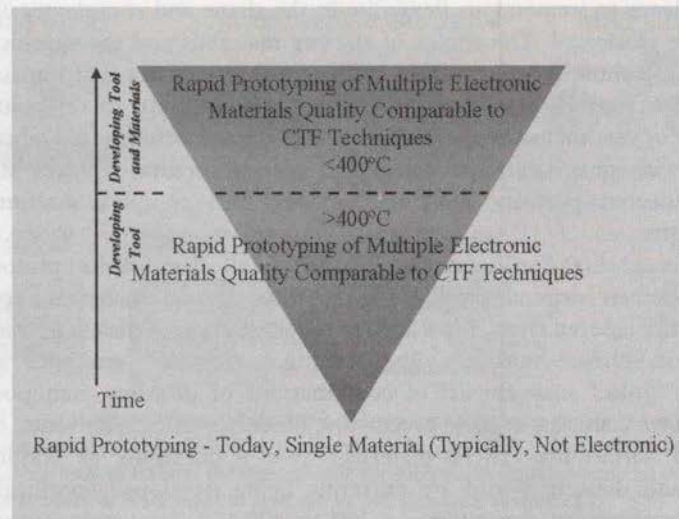


FIGURE 2 A schematic diagram is shown outlining the evolution of rapid prototyping technologies and materials development compared to conventional thick film (CTF) techniques. The dotted line indicates the approximate maximum processing temperature for the polymer substrate Kapton.

Figure 3 shows a schematic diagram of the approximate temperature scales associated with direct-write processing. In order for direct-write techniques to increase their area of applications and compatibility with almost any type of substrate, most all direct-write processing needs to occur in an ambient atmosphere at room temperature. Fabrics can only withstand temperatures of about 200 °C and Kapton about 400 °C. Chemical precursors react over a large temperature range with minimum temperatures of about 200 °C. For high- k ceramic dielectrics, the thermal sintering temperature and atomic-diffusion-distances-per-unit time increases with temperature and with noticeable changes starting at about 500 °C. The ambient increase in the surface temperature by laser sintering can be estimated for a given set of conditions, but a conservative estimate of best case sintering is approximated at about 200 °C. In Figure 3, we show this increase against two possible ambient laser-sintering temperatures: one at which proteins denature and another that is the maximum temperature at which Kapton can be processed. Ceramic materials used in conventional thick-film approaches typically require sintering at temperatures around 900 °C for 1 hour that would be catastrophic for temperature-sensitive plastic substrates. For infrared laser wavelengths (1 to 10 μm), the penetration depth is very dependent on laser and material

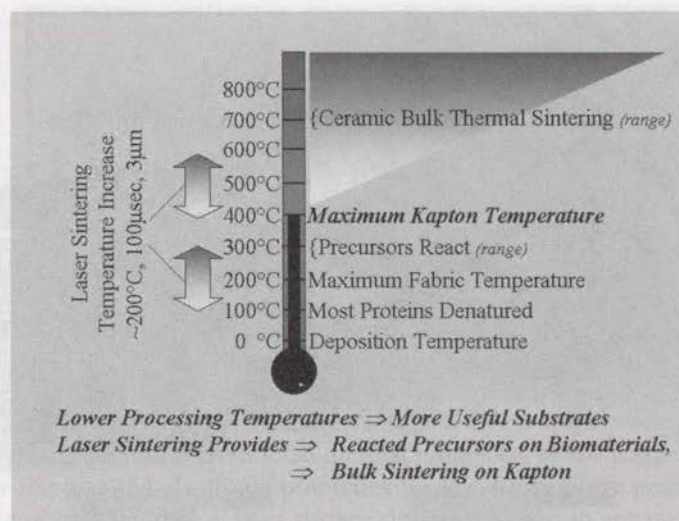


FIGURE 3 A schematic diagram is shown of the approximate temperature scales associated with direct-write processing as well as the approximate improvement due to laser sintering.

properties, but for most combinations good, localized surface absorption is achieved between 1 and 10 micrometers. Annealing just the surface brings with it the benefits of higher temperature processing on thermally sensitive, but technologically important, plastic or paper substrates.

Serious technological problems occur for the fabrication of high-quality crystalline materials, required for state-of-the-art electronic performance of the final device, because it is nearly impossible at these processing temperatures ($\leq 400^\circ\text{C}$) even with laser sintering. That is, high-quality crystalline ceramic processing of refractory materials is synonymous with high temperatures for long times as required for atoms to diffuse and defects to be annealed (see Fig. 3). Consider, for example, dielectrics for high- k , low-loss capacitors applications. The highest possible packing density for spherical powders is $\sim 74\%$ for the face-centered cubic structure and it is even lower ($\sim 64\%$) for random close packing (13,14). This means that there is at least 26% air in the structure. According to the logarithmic mixing rule for dielectrics, 26% air reduces the effective dielectric constant by almost an order of magnitude, highlighting the importance of reducing the porosity in transferred materials (15). Figure 4A illustrates the difficulty involved in forming a high-density coating with spherical powders alone. Significant particle-particle bonding does not occur at low processing temperatures. One approach to overcoming the porosity problem is with a poly-dispersed powder, that is, spherical powders of different

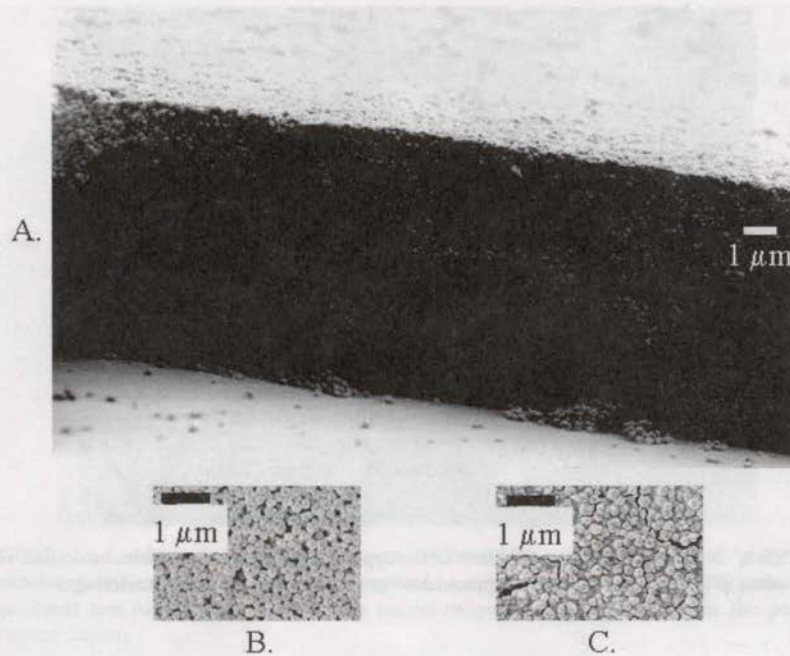


FIGURE 4 Scanning electron micrographs of a fracture cross-section (A), and surface images (B and C) demonstrate the extremely uniform and optimized packing of BaTiO_3 nanopowders.

particle sizes. Furthermore, porosity is a source of dangling bonds and adsorbed moisture, neither of which lends it to either low loss in the microwave or to the millimeter frequency regime.

Another way to overcome this liability, which most of the aforementioned techniques can use to some extent, is to begin with a high-density packed powder of differing particle sizes combined with chemical precursors that form low-melting-point nanoparticles *in situ*, welding the powder together chemically (16). The precursor chemistries used are diverse and include various thermal, photochemical and vapor, liquid, and/or gas coreactants. The precursor chemistries carefully avoid incorporation of carbon and hydroxide (which would cause high losses at microwave frequencies) and chemistries that are incompatible with other fabrication line processing steps. Part of optimizing the materials for different direct-write processes will be to find the ideal ratios of powders, nanopowders, and chemical precursors to produce the most dense film with the desired electronic properties. Figure 4B,C demonstrate two cases in this optimization. In Fig. 4B there is a low precursor/powder ratio as is clear from the porosity in the micrograph. In Fig. 4C the ratio is closer to ideal since

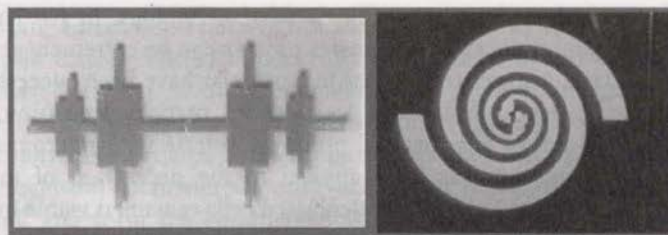


FIGURE 5 An example of a loaded dipole antenna and log-periodic fractal antenna fabricated by direct-write methods.

the voids observed in Fig. 4B are filled with reacted precursor. Also in Fig. 4C, cracking is present due, in part, to the thermal reaction of the precursor. Figure 4 shows examples for conventional thermal processing at low temperatures. To further improve the electronic properties for low-temperature processing, especially of oxide ceramics, laser surface sintering is used to enhance particle-particle bonding and reduce porosity.

In most cases, individual direct-write techniques make trade-offs between increasing particle bonding to help the transfer process and optimizing direct-write properties such as resolution or speed. The resolution of direct-write lines can be on the micrometer scale, speeds can be greater than 200 mm/s, and the electronic material properties are comparable to those of conventional screen-printed materials. The use of electronic materials that have been optimized for direct-write technologies results in deposition of finer features, minimal process variation, lower prototyping and production costs, higher manufacturing yields, decreased prototyping and production time, greater manufacturing flexibility, and reduced capital investments.

An excellent example of the application of direct writing to low-cost product development is the rapid prototyping of multiband antennae. Examples of two of these antennae are shown in Fig. 5. The direct writing of these antennae is accomplished in minutes with the commercial, purchased software that produces the design file, whereas conventional lithographic mask fabrication, patterning, and process development would take days. Furthermore, selective dielectric loading to enhance particular band performance can be done without resorting to complicated photolithographic lift-off techniques.

3. BIOMATERIALS

Materials advances have driven advances in the direct writing of electronic materials. In contrast, recent advances in the direct writing of biomaterials

have been driven by advances in the transfer technology, in particular, the recognition that in some cases the transfer process can be extremely gentle and selective. Two laser transfer techniques in particular have been successful with novel biomaterial depositions. First, laser-guided particle deposition has the ability to deposit almost any material on any substrate with micrometer-scale accuracy. This technique has been applied to the deposition of individual “living” neural cells (see Fig. 6). The deposited cells remained viable in spite of being exposed to the laser transfer process (17,18). Micrometer-scale patterns of viable cells and the methods to manufacture them are required for next-generation tissue engineering, fabrication of cell-based microfluidic biosensor arrays, and selective separation and culturing of micro-organisms. (No current technology is capable of writing adjacent patterns of different viable cells.) Second, at the Naval Research Laboratory, patterns of viable *Escherichia coli* bacteria, as well as of various types of eukaryotic cells, proteins, enzymes, and antibodies have been transferred onto various substrates with a laser-based forward transfer technique (19). These techniques are covered in depth later in the text.

With these new computer-controlled tools, we are now in a position to physically manipulate living and structural life-supporting biomaterials from their natural environment. In particular, we can create three-dimensional mesoscopically engineered structures of living cells, biocompatible cell scaffolding, proteins, DNA strands, and antibodies as well as cofabricate electronic devices on the same substrate to rapidly generate cell-based biosensors and

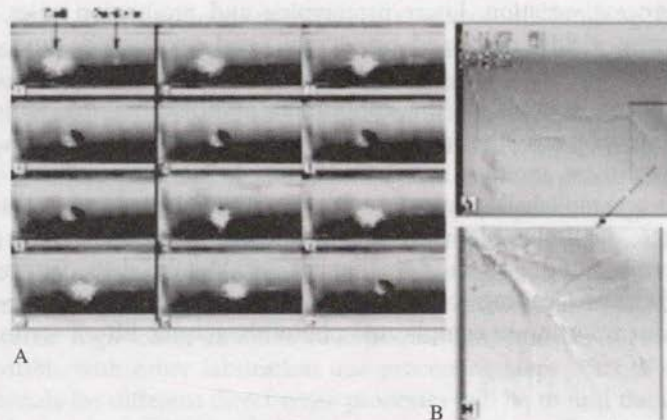


FIGURE 6 An individual neuron cell (embryonic chicken spinal cord) was deposited by laser guidance in a hollow-core fiber. Inner diameter of the fiber: 30 μm ; cell diameter: $\sim 9 \mu\text{m}$. Time lapse between images: 0.3 s. (A) and (B) illustrate cell viability after guidance with normal adhesion and neurite growth. Image width in (B): $\sim 30 \mu\text{m}$ [Adapted from (17)].

bioelectronic interfaces. This will, for example, allow us to probe intercellular signaling in cancer cells or to construct tissue-based biosensors. An exciting application of direct writing biomaterials is a computer-controlled (i.e., bioCAD/CAM) system that will be able to help identify a human wound or tissue abnormality, prompt human input in order to three-dimensionally map the heterogeneous biomaterial profile needed for repair (i.e., cell/biomolecule structure), and form the complementary tissue or organ structure designed from the input. These systems could potentially be used in battlefield, hospital trauma, and general surgical applications to speed diagnosis, the repair process, and recovery. Furthermore, these techniques have the unique ability to construct tissue cell by cell. Different cell types can easily be placed adjacently or in multilayers by changing the culture from which we perform the transfer. This ability will enable us to create miniature organs that are engineered to mimic natural tissues. These methods represent an important advance in biomaterial processing and the manipulation of natural systems.

4. MISCELLANEOUS APPLICATION AREAS

Direct-write technologies also have potential in the medical device markets with the fabrication of micromechanical components, labeling, and biocompatible and active coatings. UV micromachining, a subtractive direct-write process, has already shown the ability to reduce the size and improve the performance of a number of medical devices (20).

Various direct-write methods could be utilized for efficient assembly of components in the display and interconnect industry. For example, the "drop on demand" ink-jet approach has shown itself to be an outstanding path for the microdeposition of organic light-emitting polymers and phosphors, solder bumps, spacer balls, electrical interconnects, and adhesive sealant/bond lines in the manufacture of display panels. Some of the advantages of this route to fabrication include low cost, high speed, noncontact, and environmentally friendly processing.

5. CONCLUSIONS

In this chapter, we introduced the direct writing of electronic materials of biomaterials, and of other miscellaneous materials, and discussed some of the issues surrounding their use in future applications. Direct writing is a subset of the larger field of rapid prototyping and has experienced significant growth recently through the development of new transfer methods and improved materials that react at lower temperatures. The impact these advances should

have on the field of direct writing will make many of the approaches commercially viable for rapid prototyping and small-lot-size manufacturing. For electronics, these technologies offer opportunities in both manufacturing improved discrete electronic devices on flexible substrates and rapid prototyping machines with increased flexibility. Furthermore, as a research tool, direct writing is already breaking new ground in the computer-controlled three-dimensional construction of biological materials. Direct writing breaks the paradigm outlined in the first paragraph in this chapter: the assumption that increased capabilities must come with limited flexibility. Instead, there are advantages of lower cost with increased flexibility of manufacturing, enhanced process integration, and reduction in environmental impact (21,22).

Because this is the first edited textbook on this subject, we organized the chapters in such a way that we hope will provide a strong foundation for understanding the many issues common to most direct-write approaches. Care was taken to also include information not only about conventional approaches to direct writing, but also about novel ones. It was our goal to have each author (or team of authors) be as objective as possible in comparing techniques and to list both a technique's strengths and its weaknesses. The value of this text to the general reader will be in its comprehensive overview of the field and the stimulation of ideas for new application areas of continued research.

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Role of Direct-Write Tools and Technologies for Microelectronic Manufacturing

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1. Introduction
 2. Direct-Write Technology in the Microelectronics Industry
 3. Next Generation System
 4. Technology Diffusion in Microelectronic Industry
 5. Conclusions

1. INTRODUCTION

The rapid prototyping, miniaturization, substrate versatility, and three-dimensional (3-D) fabrication capabilities of direct-write (data-driven materials deposition) technologies have gained increased interest from the electronics industry. This growing attention is propelling the development of a number of candidate direct-write systems. These technologies offer the potential for low-cost small-batch manufacturing and unparalleled levels of integration and density that are essential to advanced telecommunications applications. The microelectronics manufacturing industry is evaluating these technologies because they offer the potential for highly compact, ultra-lightweight assemblies. In addition, they can offer rapid product introductions and enhancements, which are becoming increasingly critical to maintain leadership in the accelerating electronics products market. Moreover, it is important to establish an industry standard technology with multiple vendors to ensure a continuous, reliable, long-term source of supply.

Improved component tolerances and unique patterning capabilities have been claimed for many direct-write technologies. Presently, many of these technologies are being evaluated to determine whether each is capable of the requisite reproducibility, robustness, and accuracy. This is necessary for reliable production of complex electronic products containing hundreds of passive and active components and very high densities of interconnects. As the microelectronics industry has learned in the past, a promising and mature research and development technology does not necessarily translate directly to a factory-ready manufacturing process. Several comprehensive evaluation programs are under way within the industry to identify the most promising direct-write equipment and materials systems.

The direct-write technologies under development must be evaluated by fabricating a statistically significant number of test vehicles that are subsequently subjected to a series of factory standard evaluations. This will enable the identification of candidate direct-write equipment, processes, and materials that offer the greatest near-term potential for real manufacturing. The selected solutions must meet microelectronic industry standards for quality, yield, reproducibility, and product reliability in rugged environments. Predictions have been made that direct-write technologies will allow manufacturers to eliminate dedicated chemical vapor deposition systems, sputtering chambers, photolithographic techniques and materials, and enable electronic device and component fabrication in a high-volume factory environment under ambient conditions. The ultimate goals of these development efforts are to build and qualify direct-write technologies and materials systems to manufacture low power, lightweight, robust electronic devices (e.g., flexible Bluetooth modules) at low temperatures on 3-D nonplanar substrates.

The development of materials and direct-write processing technologies will allow the technology developers to gain a competitive advantage within their respective microelectronic infrastructure segments. Initially, these companies will maintain an economic advantage through licensing agreements with competitors and having established the in-house technology capabilities. Due to the competitive environment within the microelectronic industry, the economic benefits to the developers will be short because their competitors will become proficient in the technologies and will begin to implement internally developed technologies enhancements. Irrespective of the total economic benefits achieved by the individual companies, the developed technology will renew growth in the U.S. microelectronics industry and will initiate a paradigm shift in microelectronics manufacturing.

The technology developers must initiate discussions with members of the microelectronics infrastructure in an effort to expose engineers and designers to this new technology. They must provide documentation as well as engineering support to companies that decide to evaluate the developing technology. In addition, the developers must give external presentations to interested

suppliers and offer support during the early technology transfer period. If this technology transfer is conducted efficiently, the materials suppliers, equipment developers, and original equipment manufacturers (OEMs) will maintain the momentum and continue to recommend the usage of the advanced direct-write microelectronic manufacturing technology to their customers. Presently, several potential partnerships exist and this list will increase with the introduction of several new suppliers into the microelectronics infrastructure sector.

2. DIRECT-WRITE TECHNOLOGY IN THE MICROELECTRONICS INDUSTRY

Current computer aided design/computer aided manufacturing (CAD/CAM) direct-write processes are limited by the substrate thermo-mechanical material properties. These limitations (e.g., glass transition temperature) reduce the number of potential microelectronic devices and components, which one can fabricate.

- ✓ Presently, several developing commercial systems offer unique manufacturing advantages. Although each system developer may use a different description or acronym for their technology, the authors decided to group and classify the systems into four general technology categories: (1) microdispensing, (2) laser-assisted transfer, (3) electrostatic assisted transfer, and (4) jetting.

The microelectronics industry has the vision to integrate these systems onto a reel-to-reel platform, which will enable rapid, high-volume manufacturing using flexible plastics as substrates. The compliant nature of the substrate layer(s) will enable the design and fabrication of a truly conformal electronics system. Product assembly line pulse rates will increase and will enable manufacturers to benefit from economies of scale. Furthermore, the substrate type will provide a significant reliability advantage over a nonflexible system. In particular, the strain generated by thermal expansion mismatch of the materials will be more readily dissipated in the flexible system while the strain generated in a "rigid" system will not have a mechanism by which to relax the strain.

2.1. DIRECT-WRITE TECHNOLOGIES

A representative list of the CAD/CAM direct-write tools and the various direct-write materials is given in Table 1. This table identifies materials and tools to fabricate various microelectronic devices and components. Table 2 lists components that can be manufactured by direct-write techniques along with

TABLE 1 Potential Components Fabricated by Direct-Write Technologies and Materials

Components	Direct-write materials	Direct-write technology	Final processing
Capacitors	Metallo-organic materials	Micro-dispensing, jetting	Thermal
	Filled polymer thick films	Micro-dispensing, electrostatic	Thermal, UV, microwave
	Polymer-based dielectric materials	Micro-dispensing, jetting, electrostatic	Thermal, UV
	Ceramics dispersed in an organic binder	Micro-dispensing, jetting	Thermal, microwave, laser
	Ceramic dielectric nano-materials	Laser-assisted transfer	Thermal, laser
Resistors	Donor material films	Laser-assisted transfer	Laser
	Filled polymer thick films	Micro-dispensing	Thermal
	Metallo-organic materials	Micro-dispensing, jetting	Thermal
Inductors	Donor material films	Laser-assisted transfer	Laser
	High μ materials	Micro-dispensing	Thermal, laser
	Donor material films	Laser-assisted transfer	Laser
Batteries	Metallo-organic materials	Micro-dispensing, jetting	Thermal, laser
	Metallo-organic materials	Micro-dispensing, jetting	Thermal, laser
	Electrolyte materials	Micro-dispensing, jetting	Thermal, laser
Antennas	Metallic materials	Laser-assisted transfer	Thermal, laser
	Metallo-organic materials, conductive polymers	Micro-dispensing, jetting	Thermal, laser
Conductors	Metallic nanomaterials	Micro-dispensing, jetting	Thermal, laser
	Donor material films	Laser-assisted transfer	Laser
	Conductive polymers	Jetting, micro-dispensing	Thermal, laser, microwave
	Metallo-organic materials	Jetting, micro-dispensing	Thermal

TABLE 2 Representative Component Values and Tolerances for a Consumer Product

Components	Range of values	Tolerances
Inductors		
Decoupling	1–10 μ H	$\pm 30\%$
Filter	10 nH–0.56 μ H	$\pm 10\%$
Capacitors		
Decoupling	0.01–100 nF	$\pm 30\%$
Filter	0.4–5,600 pF	$\pm 10\%$
Resistors		
Termination	25–100 Ω	$\pm 10\%$
Logic	1k–1 M Ω	$\pm 20\%$
Filter	5–250 Ω	$\pm 5\%$
Antenna	Controlled impedance	$\pm 5\%$

their respective operating range and tolerances. In some cases, a single direct-write tool may have a competitive advantage for a greater variety of electronic devices and components that can be fabricated. However, at present many of these tools have not been subjected to high-volume manufacturing studies that evaluate their applicability toward microelectronics device fabrication. In addition, several of the tools, at this time, have not demonstrated the required attributes necessary to be accepted by manufacturing (e.g., long mean time to failure, short mean time to repair, small footprint, low processing cost environment, and fewer required number of operators, engineers, and technicians). A brief description of the different technologies is presented in the following sections.

2.1.1. Micro-Dispensers

Several different micro-dispensing technologies are currently commercially available: (1) rotary screw, (2) positive displacement piston, and (3) needle valve (1–3). Several companies offer production-ready systems for in-line manufacturing of electronic components and products. Today these systems can cost between \$125 K and \$250 K, require approximately 9.3 m² of floor space in a manufacturing microelectronic environment (30 °C/60%RH), and are the most mature of the four tool categories. However, repeatability and precision of the volume of material deposited is related to the dispensing technology. Micro-deposition systems are sensitive to the material rheology formulation because fine features are obtained by using small gauge dispensing tips. In addition, the optimal linear velocity depends on the properties of the material that is being dispensed. Dispensing studies have shown that viscosity, surface tension, needle gauge and length, and flow rate are all critical for dispensing uniform structures. Although the micro-dispensing systems are capable of dispensing materials having a wide range of viscosity, the settling viscosity of thick films must be monitored with an optical imaging system or a feedback weight control loop to observe the morphology of the printed features. The range of dimensions for repeatable traces that these tools have demonstrated are 25 to 300 µm wide and 1.3 to 51 µm thick. Figure 1 is an example of micro-dispensed circuitry. In general, width and thickness (height) are material dependent while “straightness” is machine dependent. In addition, the distance between the dispensing needle orifice and substrate affect the pattern features. For example, too great of a distance will affect the straightness of the line.

Of the commercially available micro-dispensing systems, the displacement piston system is currently used for depositing electronic-grade materials to fabricate integrated, multilayer passive components through a layer-by-layer build-up process that also combines multiple materials within a single layer.

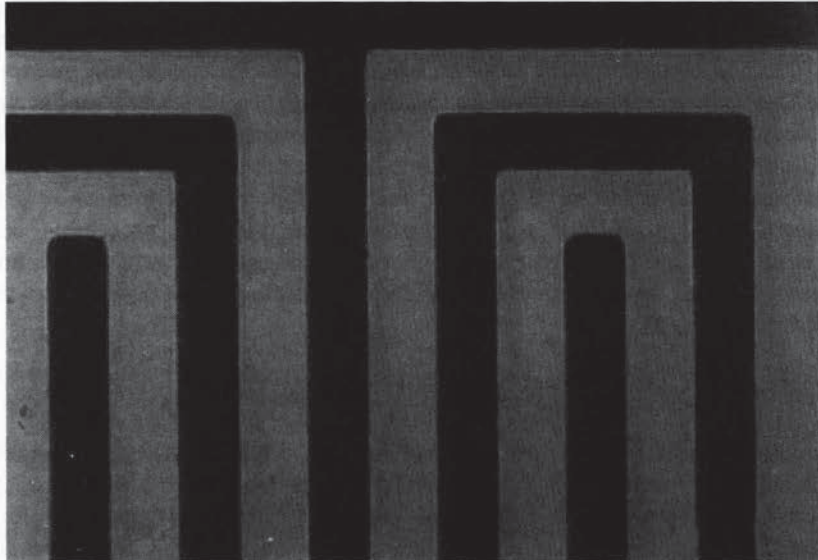


FIGURE 1 Electronic circuitry ($40\text{ }\mu\text{m}$ wide and $5\text{ }\mu\text{m}$ thick) fabricated using a micro-dispensing system.

The system is capable of depositing slurries and solutions that cover a wide range of viscosities, from $100\text{ mPa}\cdot\text{s}$ to $100,000\text{ mPa}\cdot\text{s}$. It has several attractive features: (1) an accuracy of roughly 2 to $3\text{ }\mu\text{m}$; (2) capability of writing line widths approaching $25\text{ }\mu\text{m}$; and (3) dimensional control of better than $\pm 0.5\text{ }\mu\text{m}$. In addition, the system has demonstrated the ability to fabricate band reject filters with 27 dB suppression at the reject frequency by achieving matched values for the capacitors and resistors. The developers have eliminated the requirements for high processing temperatures by working with polymeric-based conductors, resistors, and dielectrics, which ultimately lead to the capability for printing custom components on low-temperature substrates. Presently, this system is being modified to enable simultaneous multiple material deposition, enhanced adjustment features to fabricate finer-line features, and greater controlled start/stop features in an effort to improve the structure definition at the start/stop points.

A novel linear positive displacement piston pump micro-dispensing system is presently being used in high-volume manufacturing to dispense long lines of material to form resistors and traces on printed wiring boards (PWBs). The typical fluids, which are being used, have viscosities between $1,000$ and $500,000\text{ mPa}\cdot\text{s}$ and studies have suggested that highly thixotropic materials perform best for continuous line dispensing. The system has demonstrated

PWB line widths on the order of 300 μm using a 30-gauge dispensing needle. Studies suggest that the dispensing envelope is limited by the pressure the system can develop and the viscosity of the material.

A rotary screw equipped micro-dispenser has the ability to deposit materials having viscosities from 100 to 1,000,000 mPa-s using a 30-gauge needle. Resistive pastes can be used to fabricate between 125 and 300 μm wide line resistors. This system has a maximum linear velocity of 13 m/s. A next-generation system is being developed which can operate at velocities approaching 64 m/s over a 152×213 cm panel area. Current commercial systems can accelerate/decelerate in 5 milliseconds during negotiation of right angles, which enables the fabrication of structures with dimensional accuracy of $\pm 0.3 \mu\text{m}$. Presently, micro-dispensing developers are designing a device to dispense 10 to 20 μm line widths with a turret subsystem to enable dispensing of multiple materials.

Micro-dispenser technology is the most mature of the four technology groups and several systems have been integrated in high-volume microelectronic manufacturing for low-risk applications. The design of an assembly line based on these systems increases the risk level because they have not demonstrated circuitry and device design that address the microelectronics industry roadmap. The five greatest technical risks are as follows: (1) the ability of these systems to print fine lines requires an exact vertical alignment that is not available on current equipment; (2) a low-cost, reliable, repeatable means of needle-tip fabrication must be identified; (3) acceptable line definition when starting and stopping the needle motion will require improved system control and/or material property modification; (4) multiple pump block modules to improve the speed for simultaneous deposition of multiple materials has not been demonstrated; and (5) minimum demonstrated line width control and writing speed must be improved.

2.1.2. Laser-Assisted Transfer

The laser-assisted transfer technologies are diverse in nature and are currently in different stages of development. The designers of these systems have developed processes to transfer and deposit metals and other materials from donor films to substrates (4–8). Some systems are wafer fab compatible and are presently used by IC manufacturers while others are used in high-volume manufacturing for transferring gold onto pin connectors. Laser scanning techniques are well understood and precision scanning systems for high-volume microelectronics manufacturing are available (Fig. 2). Combinations of laser processes (transfer/sinter/cure/anneal) are being developed by using multiple wavelength lasers. Developers are evaluating the use of higher laser power and/or alternate wavelengths to locally heat regions of the substrate to

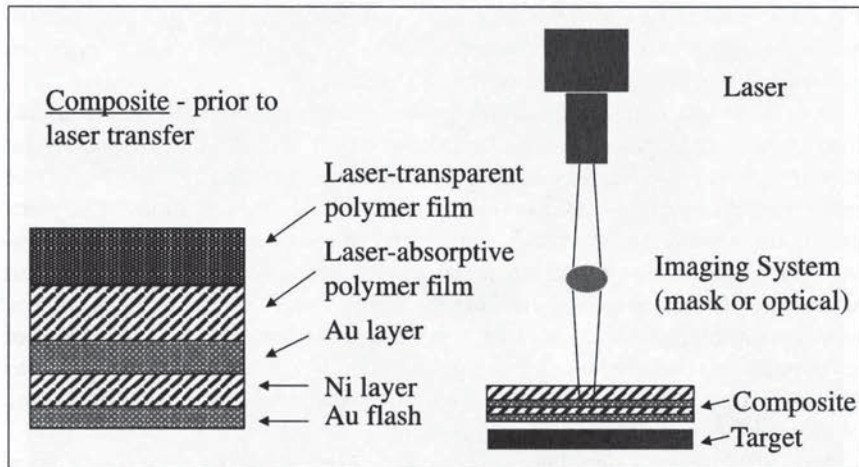


FIGURE 2 Schematic of laser-assisted transfer technology.

high temperatures for sintering and curing. However, care must be taken to ensure the region heated remains small to avoid melting of the substrate.

One laser-assisted transfer technology has demonstrated the ability to fabricate structures having dimensions less than $25\mu\text{m}$. The first studies were conducted in the late 1970s to evaluate the potential for laser-assisted transfer of metals from donor films onto receiving substrates in ambient conditions (5). These studies were performed to develop a low-cost deposition-transfer technique to fabricate metallurgical traces on ceramic and glass substrates using a yttrium aluminum garnet (YAG) laser having an $8\text{-cm} \times 8\text{-cm}$ stage, a repetition rate of $3,000\text{Hz}$, a current of 20A , and speed of 20mm/s . They demonstrated the fabrication of copper and aluminum traces having $100\text{-}\mu\text{m}$ widths on inorganic substrates when processing in ambient conditions. This technology can direct write passive components, conductors, and batteries by supplying materials on a ribbon or donor film. The donor film is comprised of several components—a laser transparent substrate, a thin polymeric film, which has a high optical coefficient of absorption to the wavelength of the laser, and a composite of metals. An example of a composite metal has approximately $120\text{\AA}$ of a gold flash deposited on $1.2\mu\text{m}$ of Ni, deposited onto $1.2\mu\text{m}$ of gold which is deposited on a $2.5\text{-}\mu\text{m}$ laser absorptive polymer film. This composite structure can be fabricated via evaporation, microwave sputtering, or arc deposition. The thin, high optical coefficient of absorption polymer film is deposited onto a flexible laser-transparent substrate (e.g., polystyrene, polyvinyl acetate, or polyethylene). During exposure to the laser the absorptive layer is vaporized propelling the metal composite toward

the substrate and forming a cold weld or pressure bond. Typical laser platforms as those mentioned require approximately 200 sq ft of floor space, and cost between \$300 K and \$1,000 K.

Another donor film based laser-transfer system uses a 2.2-W infrared (IR) laser source with a spot size of 12 μm , and a drum radius of 25 cm, to cover a 76-cm $\times$ 76-cm substrate in 25.4 min. Preliminary studies have suggested that increasing the power of the laser to 9 W will enable the coverage of the same print area in 6 min, thereby meeting one of many manufacturing specifications. The system developer has demonstrated the deposition of single and multiple layers of pure and composite materials. To date, the system is able to consistently fabricate 50- to 200- μm -wide copper lines on an epoxy/E-glass composite and polyimide, and the finest demonstrated features were 25 μm wide and 1 μm thick.

Yet another type of laser system is based on the melting of copper, gold, silver, and ceramic nanomaterials in-flight prior to contact with the substrate. The method of powder delivery impacts the achievable linear velocity. One powder delivery method allows a linear velocity of approximately 50 cm/s with large line dimensions, while the second delivery method is much slower limiting the linear velocity to 0.6 cm/s. Although the developers of the system have not demonstrated multiple material deposition, they are currently building a system that will have this capability. To date, this system has generated lines that were 250 μm wide and approximately 10 μm thick.

In summary, laser-assisted transfer is a promising technology that uses laser energy as either a precision thermal source or as high-energy photons to deposit a variety of electronic-grade materials. The resolution and speed should be more than adequate because of the small spot size and high energy possible with commercial laser systems assuming tool reliability is not an issue. The greatest risk is that the transferred material quality is not well suited for present low-cost characterization techniques.

Similar to micro-dispenser technology, some laser-transfer systems are presently used in the electronics industry. However, the specific applications are not as demanding in the fabrication of circuitry and devices for an electronic product. Further in-depth studies are required before the acceptance of this technology into low-cost, high-volume microelectronics manufacturing.

2.1.3. Electrostatic-Assisted Transfer

Electrostatic-assisted transfer is based on xerographic printing. Two companies offer electrostatic-assisted transfer technologies for the processing of micro-scale and macro-scale microelectronic structure feature dimensions (9,10). Several material properties are critical for an optimal toner, such as particle distribution, volume average particle size, particle charge/unit mass, bath

conductivity, dynamic mobility, Zeta potential, and electrophoretic mobility. The micro-scale processing system has demonstrated the ability to consistently deposit 30- μm line widths. However, the imaging portion of the tool has the ability to print features having 10- μm sizes by using a 10-facet polygonal scanner with a 3.5- μm spot size. The 10-cm wide scanner can achieve 500 rev/s and 28,300 spots/scan line with a scan error of $\pm 1 \mu\text{m}$, and imaging speeds of 2.5 cm/s can be obtained. The developers have shown that development, transfer, and fixing takes approximately 16 s for a 10-cm $\times$ 10-cm substrate. The footprint for this system is 9 m² and during its operation, it requires two system operators.

The commercially available macro-scale electrostatic-assisted transfer technology handles a 340-cm-width web. The technology is capable of reel-to-reel processing and can be used to apply charged organic and inorganic particles to the substrate to fabricate 200- μm features. The charge applied to the particles as well as their size and distribution are critical. The deposition of materials on both organic and metal substrates in high volume has been demonstrated. In addition, deposition onto porous and nonporous substrates that are nonplanar has been shown (see Fig. 3). This system can be miniaturized to accommodate a 30-cm web for typical microelectronic applications and can fabricate sub-100- μm features.

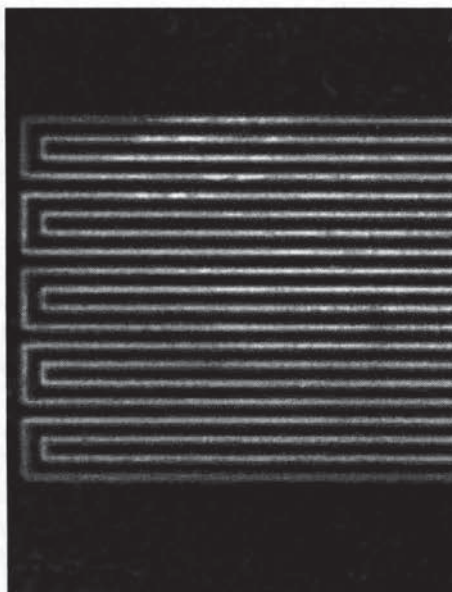


FIGURE 3 Electrostatic-assisted transfer fabricated test vehicle.

Although macro-scale electrostatic technology is well characterized and used in high-volume manufacturing for the fabrication of gross feature structures, a potential risk exists in the scaling of this technology to the micro-scale. Several nonmicroelectronic industries presently use macro-scale electrostatic-assisted transfer technology with no apparent technology related issues. The evaluated micro-scale technology appears promising and efforts were initiated to address the minimal structure feature resolution. This technology holds great promise provided that the developers are able to address the feature scaling related issues.

2.1.4. Jetting

Several jetting tool suppliers offer jetting systems for sale to OEMs and research and development groups (11–14). The suppliers have worked with a variety of commercial sectors (pharmaceutical, electronic, and automotive) to develop the processes for jetting unique materials. Jetting technology is a mature process capable of handling a variety of materials at elevated temperatures (e.g., 220 °C). One ink-jet printer technology consists of a thermally driven process and can only operate within a narrow range of ink viscosities. The material vaporizes readily and obtains sufficient momentum to exit the orifice to form a single droplet that impacts the printing surface. A more robust jetting technology uses a piezoelectric material to rapidly change the volume of the fluid delivery chamber to generate and deliver droplets to the substrate.

Both jetting technologies require a relatively low-viscosity fluid, typically below 100 mPa-s. In addition, there must be sufficient wetting of the jetted fluid on the substrate to promote adequate adhesion. Recently, micro-replication technology has been used for both controlling the flow of the jetted liquids and for increasing the adhesion by modifying the morphology of the substrate material. The overall size of the particles that can be jetted are limited by the nozzle exit orifice diameter and line width/thickness is determined by the jetted liquid properties and the orifice diameter. With a transport mechanism that allows the printhead to reciprocate across the substrate to be printed, it is possible to jet up to four different inks on top of one another. The jetting systems typically require materials having viscosities of 3 to 20 mPa-s, and surface tensions of greater than 35 dynes/cm. Figure 4 shows an example of a jetted pattern with 200- μ m trace widths. However, 37- μ m-wide traces have been demonstrated. Typical jetting systems require 19 m² of floor space and cost between \$200 K and \$400 K.

A jet printing system is used in manufacturing to deposit palladium oxide (PdO) to fabricate surface conduction electron emitter (SCE) cathodes for flat panel displays. This process uses a piezoelectric-excited device to deposit a dispersion of PdO nanoparticles suspended in a resin and solvent solution.

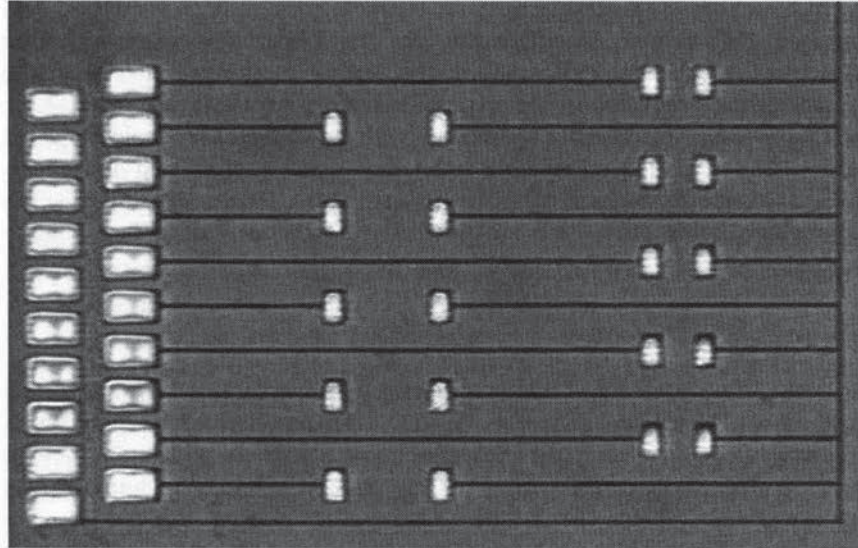


FIGURE 4 Circuitry fabricated with a jetting device: 200 μm line width on a polyimide film substrate.

They are able to achieve displays with high image quality, full motion, and full color pictures that are comparable in quality to those of cathode-ray tube displays. The piezoelectric device is trapezoidal shaped, 125 μm in length, and 62.5 $\mu\text{m} \times 50 \mu\text{m}$ and has the capability to deposit 100 to 130 picoliters per pulse. Presently, a higher voltage output system is being developed to enable the dispensing of higher viscosity and higher surface tension materials without heating the device. Alternatively, a heater can be integrated enabling the jetting of materials having high viscosities without requiring elevated excitation voltages.

A second jetting system developer offers a drop-on-demand platform that has a single-nozzle piezoelectric actuated device. The device can be driven at frequencies approaching 10 kHz to create droplets with diameters varying from 25 to 125 μm . Presently, no information has been reported although testing has shown that the operational lifetime of the piezoelectric device is between 24 and 720 hrs. Recently, the jetting device has been integrated on a manufacturing-ready platform to investigate the opportunity to deposit different materials: metalo-organic, filled epoxies, polyimide, fluxes, organic solvents, and phosphors. This system can achieve printing speeds of up to 51 cm/s.

Jetting is an attractive technology because of the perceived simplicity, high speed, and noncontact nature of the process. However, there are significant

technical risks in obtaining and formulating suspensions or solutions with optimal rheological and materials properties for jetting (e.g., viscosity, surface tension, density). The issues associated with developing formulations yielding high strengths of adhesion to the substrates present risks as well. Other potential risks concern spatial resolution of the jetted material and the deleterious production of satellites or secondary droplets, and the removal of the carrier or solvent fluid after droplet impact at the substrate to enable the formation of pinhole-free surfaces.

2.2. MATERIALS SYSTEMS

Several commercially available materials systems exist as do a variety of experimental systems that are being developed specifically for the direct-write tools. The commercially available systems are offered in large batch quantities and have demonstrated attributes required for high-volume manufacturing.

A large supplier and developer of metallic materials offers a variety of nanoparticle metals and mixed metal oxide dielectric systems for laser-assisted transfer for plastic, glass, metal, and ceramic substrates. The tape-like materials are composed of the materials dispersed in a binder and applied to a backing material. The material manufacturer also offers aqueous-based materials having the rheological properties suitable for jetting and micro-dispensing systems.

Another supplier of materials for direct-write systems offers metal-filled organic conductive, carbon-filled resistive, and inorganic-filled dielectric materials. These materials are compatible with polyester, polyimide, paper, and epoxy glass substrates. The typical thermal cure schedule is 5 to 15 minutes at 140 °C to yield a bulk material having optimal electrical and mechanical properties. The materials have a minimum shelf life of 6 months if stored at ambient conditions (23 °C/60%RH) and have a pot life in an ambient electronic manufacturing environment (30 °C/60%RH) of approximately 8 hours.

Yet another supplier of materials offers metallo-organic solutions, pure metals, metal compounds, and metal-oxide films on high-temperature substrates (e.g., polyimide and ceramic substrates). The thermal-processing temperatures for the materials range from 300 to 850 °C and the processing time at peak temperature is approximately 15 minutes. The materials can be applied to the substrates by micro-dispensing, jetting, or laser-assisted transfer. The typical shelf life of the materials ranges between 3 months to 1 year while their pot life is dependent on factory environment and specified by a change in viscosity.

The composite ribbons used for laser-assisted transfer during high-volume manufacturing are not widely available. Typically, companies have relied on

internal efforts for developing proprietary composite ribbons for in-house manufacturing use. Other donor films have been developed although their specific compositions and dimensions are proprietary.

Dispersed ultra-fine copper, gold, and silver nanoparticle suspensions are available in high-volume quantities. The manufacturer of the suspensions offers materials having high viscosities (10 to 20 Pa-s) for micro-dispensing and low viscosities (1–100 mPa-s) for jetting systems. The shelf life of the suspensions is 3 months when the materials are stored at 22 °C and 6 months when they are stored at 0 °C. Meanwhile, the pot life is specified by a maximum allowable change in viscosity.

Several technical risks must be addressed prior to acceptance of the materials systems in high-volume manufacturing. Novel materials systems must be identified having acceptable manufacturing attributes (e.g., viscosity, electrostatic charge, adhesion, ease of handling, low cost, long pot life and shelf life, ease of cleaning, low toxicity, processing in ambient environments).

The direct-write process will be an accepted manufacturing technology provided that materials are developed having the aforementioned attributes. In addition, certificates of compliance containing material specifications for acceptance and the methods for evaluation of the materials to ensure material quality must be generated by the vendors.

3. NEXT GENERATION SYSTEM

The value of direct-write systems to the microelectronics industry depends on many manufacturing-related parameters. The acceptance and long-term market diffusion of direct-write technology are based on several variables (capital costs, materials, manufacturing line pulse rate, etc.). Also, even if these systems demonstrate the capabilities to fabricate structures having the desired electrical performance and dimensions, these systems will not be accepted by the microelectronic infrastructure if cost targets are not achieved.

Product designers were asked to identify an example product and corresponding bill of materials in an effort to perform a series of cost-modeling studies to determine the cost advantages of a direct-write tool. An electronic product was selected and for the cost modeling the corresponding components, physical dimensions, ranges of components, values, and tolerances were taken into consideration. In an effort to compare direct-write systems to conventional manufacturing processes, a cost model was developed based on a cost estimator tool (15). The model was validated and used to calculate the cost involved in the assembly of modules and the manufacture of circuit boards. The model was sensitive to several categories of manufacturing parameters. Table 3 lists the four categories of inputs: (1) general factory

TABLE 3 Direct-Write Cost Model Input Data

General factory data	Equipment	Materials	Processing parameters
Desired throughput	Number	Ag PTF (\$/g)	Duration (min)
Hours per month worked	Cost (\$/tool)	Carbon (\$/g)	Set-up (min)
Labor cost for production operators	Space (m ²)	Substrate (\$/cm ²)	Set-up quantity (#)
Labor cost for production technicians	Utilities (\$/hr)		Material cost (\$/part)
Labor cost for production engineers	MTBF (hr) ^a		Yield (%)
Additional staff costs	MTTR (hr)		Operators (#)
Additional factory costs			Technicians (#)
Facilities costs			Engineers (#)
Equipment cost depreciation cycle			

^a MTBF, mean time between failure; MTTR, mean time to repair.

data (throughput based on a portable electronic product front-end assembly line), (2) equipment, (3) material, and (4) processing parameters.

Figure 5 shows the direct-write process flow used in the cost model. The data generated by the model was for the fabrication of a 4-layer PWB with embedded passives on a flexible substrate. The data from the cost model was compared to the quoted cost for the product with surface mount technology (SMT) components at medium volume production rates. The key assumptions for processing the PWB are listed in Table 4 (e.g., materials and substrate costs were obtained from vendor quotes based on medium quantity purchasing). The linear direct-write velocity was the speed associated with dispensing of materials while the mean writing speed was calculated by dividing the writing length by the time required for board completion. The completion time was a function of linear writing speed, writing pattern design, and the system motion control optimization scheme.

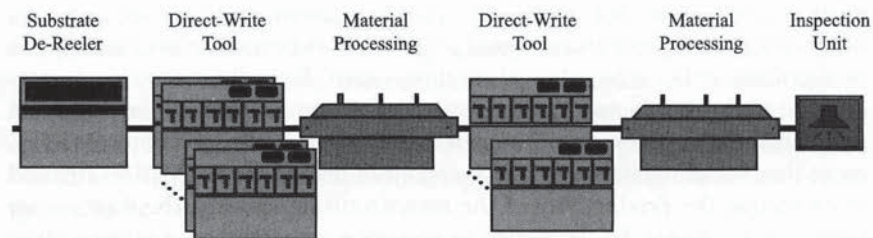


FIGURE 5 Direct-write process flow.

TABLE 4 Assumptions Used in the Cost Analysis

Characteristic	Unit of measure
Board size	cm ²
Board density	cm/cm ²
Resistors	#/products unit
Print head	#
Throughput	items/year
Conductive paste	\$/g
Resistive paste	\$/g
Flexible substrate	\$/m ²
Direct-write linear speed	m/min
Mean writing speed	cm/min

Based on commercially available system-processing parameters, the cost for fabricating a 58-cm² populated PWB was 3 times the present cost for the board using mature PWB fabrication technologies. The material cost per item was less than 2% while the cost for the equipment and labor was more than 81% of the total cost. Although there are limitations for further improving writing speed due to the material properties, a multiple-device system is envisioned for the future. This advanced system can provide parallel writing operations thereby increasing manufacturing throughput. The cost reduction associated with using a multiple-device system is shown in Fig. 6 and the cost reduction observed, in this case, is approximately proportional to the number of print heads used.

3.1. DIRECT-WRITE PLATFORM

The next-generation system should have all the attributes of present high-volume microelectronics manufacturing systems. The system would be expected to have a de-reeler that feeds the substrate to the assembly equipment, a direct-write tool, a material processing oven, a test station, and a re-reeler or a packing unit that is based on whether the manufactured item is the final product or is a submodule of another system. Typically, several parameters are used in the development and selection of equipment that will be integrated in the manufacturing system. Parameters such as mean time to failure (MTTF), mean time between failures (MTBF), and mean time to repair (MTTR) are used to determine the productivity of the manufacturing system. The direct-write tool platform should be developed to provide a repeatability of about 0.5 μ m in the x and y plane of travel and about 0.001 degrees in theta. These

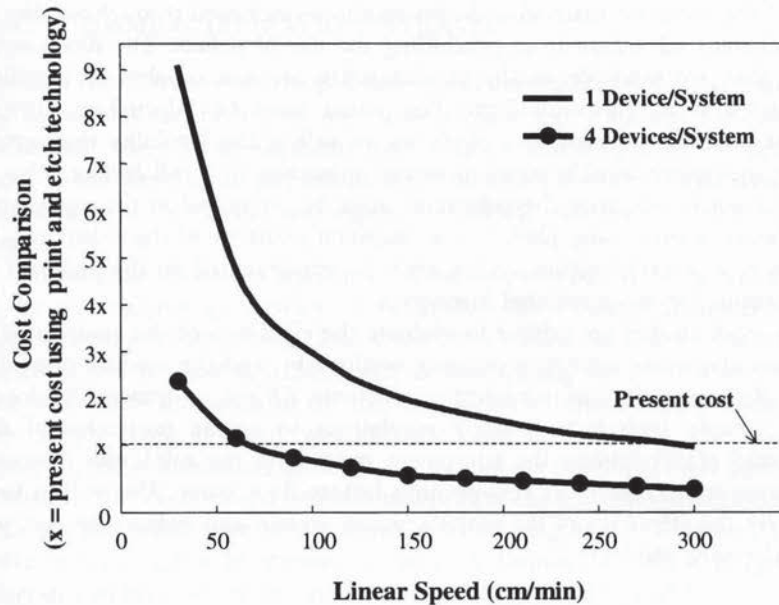


FIGURE 6 Cost reduction as function of device linear velocity and number of devices per system.

characteristics will enable the tool to operate accurately even while writing at high speeds associated with high-volume manufacturing. It is expected that the platform will have multiple devices each operating with a linear speed of at least 200 cm/min. This linear velocity should enable the direct-write platform to achieve a product pulse rate acceptable to high-volume manufacturing. Also, flexibility must be built into the equipment to achieve multitasking through communication with other equipment in the manufacturing system, off-line programming, and upgradeable system hardware and software to facilitate system enhancements.

The development efforts should focus on achieving the lowest possible equipment set-up time and maintenance time which will subsequently improve the productivity of the manufacturing system. Moreover, the "actual" equipment performance will be determined from the data collected through statistical process control (SPC) software, and will be compared with vendor specifications. A manufacturing system that increases productivity through a closed loop failure reporting system complete with a corrective action system must also be developed.

To meet the desired cost targets, the proposed manufacturing system must have the ability to handle substrates in a roll format. This allows for increased

use of the substrate material and also results in increased throughput due to the inherent advantage from precluding the use of pallets. The direct-write tools that are available in the market today are not capable of handling substrates in a roll-to-roll form. Equipment must be selected to provide robust hardware and software platforms as well as the flexibility that would allow equipment modifications to accept substrates in a roll format. Also, a mechanism to planarize the substrates must be integrated in the equipment and between processing platforms to maintain planarity of the substrates. In addition, a powerful vision system must be implemented on the platform to compensate for any positional inaccuracies.

In-depth studies are critical to evaluate the efficiency of the equipment in the manufacturing system, processing bottlenecks, and the amount of equipment that is required to maximize productivity. All the equipment developed must comply with factory safety regulations to ensure protection of the personnel. Furthermore, the equipment must have the minimum footprint necessary to maximize the cost-per-unit factory floor space. This will in turn improve the efficiency of the manufacturing system and reduce the cost per manufactured product.

4. TECHNOLOGY DIFFUSION IN MICROELECTRONIC INDUSTRY

A cohesive strategy based on standard microelectronics program-management tools must be created to ensure successful commercialization of the technology. The technology developers must work in tandem with representatives from the microelectronics infrastructure because all will play important roles during the commercialization of these revolutionary technologies.

Once a design has been selected team members should be chosen to integrate all of the elements needed to successfully introduce and transfer direct-write technology to the microelectronic community. By minimizing the number of participants, customer/vendor interactions will be enhanced and meetings with key personnel should be easier to arrange. This will enable the progress, the processing issues, and any potential solutions to be quickly integrated into the program. Companies should plan to have at least quarterly review meetings with the principal program managers from each facility. In addition, direct contact between the appropriate technical members at each facility, face-to-face meetings, and onsite evaluations should be scheduled when appropriate. These meetings and experimental evaluations should be enhanced by the use of video conferencing, e-mail, and voice-mail.

4.1. COMMERCIALIZATION STRATEGY

Focused efforts to identify the potential market segments for the integration of the technology can be helpful for the development of a strategy for commercialization. Three broad segments exist which could benefit by the development of the direct-write technologies: (1) materials developers and suppliers, (2) equipment developers and suppliers, and (3) electronic product assemblers.

The ultimate success is dependent on the commercializing strategies as well as on the technology developers to modify the existing microelectronics manufacturing value chain. The commercialization and licensing of the materials and processing technologies created during the technology evaluation will enable alteration of the existing microelectronics supply chain. The new supply chain structure will shift the value creation to a new segment. However, the commitment made by the technology developers will ultimately determine the level of success. Establishing alliances and teaming relationships with the end users prior to the commercial offering of the developed direct-write system cannot be stressed enough. A teaming approach is typically suggested in microelectronic industry technology transfer models.

Strategies to advertise the technologies and to gain credibility within the microelectronics industry should be developed. Documentation as well as engineering support to those companies willing to evaluate the technology must be made available prior to the sale of the technology. After company "buy-in" is obtained, teams must form technical support organizations, which should both be flexible and have the ability to relocate to the prototype factory to work with its personnel until a desirable level of confidence is established.

The developers can expedite the commercialization of the technologies by establishing relationships with OEMs by offering them quick-turn delivery of fabricated passive-device-populated substrates. The technology developers should begin marketing the technology in the microelectronic market. Entrance into additional markets will be based on revenue and experience gained from the initial efforts. As the systems are transferred to the beta platform, team members will use established procedures to make recommendations to incorporate this technology in future assembly lines and factories. Team members may be met with some resistance, but as the technologies demonstrate their ability to perform in the manufacturing environment, external partners for technology transfer (e.g., material suppliers, equipment developers, and OEMs) will carry the project's momentum forward through recommendation of the technologies' use to their customers.

Past experience suggests that a multistage commercialization strategy can increase the chances for technology commercialization success. The strategy's three general phases are as follows.

4.1.1. Phase 1: Technology Introduction

It is critical to introduce the technology to the microelectronic industry as quickly as possible to enable product design engineers the opportunity to modify existing standard practices. The developers should attend several of the well-attended microelectronic conferences and give presentations discussing the benefits of the technologies such as cost, flexibility, size, etc.

4.1.2. Phase 2: Demonstrate Technology

It is recommended that developers offer beta-level systems to OEMs to generate a database for the direct-write system. While building the beta-level system, frequent update reports should be sent to the industry committee members. The developers should select an OEM site (or sites) for the testing of the system which is representative of a typical manufacturing environment, for instance, 30 °C/60%RH, no clean room facility. This activity will give the developers the opportunity to receive first-hand feedback from the customer. In addition, the developers will receive exposure to the manufacturing environment.

4.1.3. Phase 3: Technology Market Diffusion

During this phase it is suggested that the developers prepare a Design-to-Manufacturing (DTM) Evaluation Questionnaire to help them prepare the platform for the microelectronics manufacturing market. An example questionnaire is given in Fig. 7. It contains questions regarding the six key areas for DTM systems which enhance the rate of diffusion by ensuring that the technology meets the criteria set by manufacturing companies. Also, as technology diffusion will also depend on the economic variables, the technology sales and engineering teams should hold discussions with the OEM purchasing and manufacturing engineering groups to discuss the terms of the agreement for purchase of the system. Standard terms should be used as should customary warranty and technical support terms.

General Use Capabilities		Ease of Use	
Question		Question	
Import/Export Capabilities:		Is there a window-based, graphical user interface?	
List CAD packages with import capabilities		How many separate software applications does the user need to run?	
Import from existing machine programs?		Is on-line help provided?	
General Setup Capabilities:		Are there default settings and a default execution procedure?	
Is a graphical product viewer with report generation capability included?		Architecture	
Can product be viewed after CAD translation and prior to production?		Question	
Is a line balancer included?		Platform / OS support:	
Is there revision control or date/time stamps to identify program versions?		UNIX / AIX	
General Work -In-Process Capabilities:		Minimum System Requirements:	
Are colored overlays generated depicting the product and process?		UNIX, PC / Windows / Windows NT?	
Is real-time data collection and reporting, e.g., yields and alarms, possible ?		Code Design:	
What machine data collection protocols are supported?		Of how many separate software applications does the complete system consist?	
Are both manual and automated defect tracking supported?		Cost	
Can defect routes be documented from initial incident to corrective action?		Question	
Can program files be downloaded directly to the machines?		Licensing:	
Is there a unique security password level for program transmission in addition to program generation?		What is the per-seat cost?	
		What licenses are available?	
		Training/ Maintenance Cost:	
		What is the training cost?	
		What is the cost of on-site support?	
		What is the annual fee (maintenance, etc.)?	
		Support and Training	
		Question	
		Product Support Issues:	
		Is on-site installation / user support available 7X24 hours?	
		Is support at the same level, regardless of the location, e.g., U.S., Europe, Asia, etc.?	
		Is a product WWW site available?	
		Product Enhancement Issues:	
		What is the procedure for distributing product updates?	
		What is the procedure for bug submission and tracking?	
		What is the procedure for user requirements/enhancements submission and tracking?	
		Training Issues:	
		Are training classes available for installers/users?	

FIGURE 7 A sample of the questions for the design-to-manufacturing evaluation.

5. CONCLUSIONS

The microelectronics manufacturing industry is presently evaluating different direct-write tools for integration into next-generation manufacturing platforms. Several promising tools and complementary materials systems are in different stages of development. The systems developers have demonstrated fine feature structure fabrication as well as lot-to-lot consistency. A few of these tools are enhancements to existing tools presently used in low-volume production of electronic product.

The required system parameters to enable high-volume manufacturing compatibility were discussed. Also, the strategy required for introduction of this technology into the manufacturing industry segment was presented.

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