Inkjet Printing of Functional Materials

Henning Sirringhaus and Tatsuya Shimoda, Guest Editors

Abstract

This article introduces the November 2003 issue of *MRS Bulletin* on Inkjet Printing of Functional Materials. The issue is devoted to the emerging non-graphic-arts uses of inkjet printing as a technique for depositing and patterning functional materials in the liquid phase onto a substrate. The articles provide an overview of a selected range of representative applications in the field of structural ceramics, polymer electronics, and protein chips, and address some of the key challenges that face the broad scientific and industrial community as it attempts to apply a mature and well-developed graphic arts printing technique to the deposition of functional materials.

Keywords: *functional materials, inkjet printing.*

There are a growing number of applications that require the delivery of small quantities of functional materials with specific electrical, optical, chemical, biological, or structural functionalities into well-defined locations on a substrate. In many cases, these materials are most suitably processed from a liquid solution, dispersion, or melt, rather than from the vapor phase. Many functional materials, such as polymers or large biomolecules, are not amenable to vacuum deposition techniques. The need for solution processing may also be dictated by the nature and properties of the substrate; the need to distribute the materials over a large substrate area, or only to certain locations of the substrate and not to others (e.g., to induce a local chemical reaction); or simply to keep the material in a liquid environment at all times, such as for some biological applications. This issue of *MRS Bulletin* is devoted to the emerging non-graphic-arts uses of inkjet printing as a technique for depositing and patterning functional materials in the liquid phase. The articles provide an overview of representative applications in the field of structural ceramics, polymer electronics, and protein chips, and address some of the key challenges that face the broad scientific and industrial community as it attempts to apply a mature and well-developed graphic arts printing technique to the deposition of functional materials.

Inkjet printing has become one of the most widespread printing techniques in the home and office desktop printing market. Advances in inkjet technology now allow the printing of full-color, high-resolution photographs. In the commercial printing arena, inkjet technology is widely used for digital proofing prior to running a print job on a press; for short-run, wide-format digital printing such as posters for outdoor advertising; and for applications that require printing onto nonpaper substrates such as rigid display boards. Inkjet printers are being developed for integration with offset presses to print customized information in magazines, such as tailored advertising. In industry, inkjet technology is the dominant technology for printing variable information such as "sell-by" dates or product identification codes, as part of production or packaging processes.

Since the original observation by Lord Rayleigh in 1878 that a liquid stream is unstable and tends to break up into individual droplets, a large number of inkjet technologies have been developed. Continuous inkjet (CIJ) technology is based on inducing an electrical charge to the liquid by ejecting a jet of conductive ink from an orifice through a region with an external electric field. After the jet breaks up into isolated droplets, the charge remains on the droplets and can be used to deflect them either toward the substrate or into an ink collection and recirculation system. In drop-on-demand (DOD) inkjet technology, ink droplets are formed only when required. The two dominant techniques in this area are thermal and piezoelectric DOD printing. In thermal DOD printing, droplets are generated by heating the wall of the ink chamber, causing the formation of vapor bubbles and the ejection of droplets though a nozzle orifice. In piezoelectric DOD printing, a pressure wave in the ink chamber is generated by applying a voltage pulse to a piezoelectric stack or plate, resulting in the formation of droplets at the nozzles. (For a more extensive review of these and other inkjet technologies and their applications in graphic arts printing, see, for example, Reference 1.)

The application of inkjet technology to the delivery of functional materials poses a range of important challenges in terms of ink formulation, print head and print system design, substrate choice and preparation, and control of solvent evaporation. The inks need to be formulated in a narrow viscosity range compatible with the specific print head used. In many cases, the additives that are routinely used in graphic arts printing to modify, for example, ink viscosity, cannot be used for functional materials, as they will adversely affect the materials' performance. It is necessary to ensure that the ink does not in any way chemically interact with or dissolve any of the components inside the print head or the ink feed system. Nor should the ink's properties degrade under the high mechanical shear of a piezoelectric head or the high-temperature conditions of a thermal inkjet head. The ejection of droplets from the array of nozzles needs to be stable and reliable. Nozzles can become clogged by the evaporation of ink on the nozzle plate or the presence of particulates in the ink. Fluctuations in droplet volume can lead to undesirable variations in the amount of material deposited onto the substrate. For many applications, the velocity and direction of the droplets ejected from the array of nozzles must be highly uniform in order to ensure highly accurate positioning of a large number of droplets in well-defined substrate locations. For many nontraditional inkjet applications, the requirements for droplet positioning accuracy are significantly more demanding than for graphic arts printing. Finally, the spreading and drying of ink droplets on the substrate must be carefully controlled in order that the droplets arrive at the desired position and the desired structure and profile of the material on the substrate are achieved.

Solving these challenges through the design of specialized print heads and ink formulation is not made easier by the fact

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that inkjet technology is still regarded by many experts in the field as "black magic." Although several groups have attempted to model theoretically the hydrodynamical processes occurring in the ink chamber and at the nozzle plate (e.g., see Reference 2), in many cases ink formulation and print head design are still based on empirical experience and trials. A better theoretical understanding of the inkjet process would be of great help to print head designers and ink formulators. Similarly, a theoretical understanding of the process of spreading and drying of a microliquid deposited onto a substrate is challenging because a microliquid exhibits specific size effects arising from its high surface-to-volume ratio, such as different drying kinetics, that are not observed for bulk liquids.

This issue of *MRS Bulletin* is organized in the following way. The first article, by Creagh and McDonald, is devoted to the design of specialized piezoelectric DOD print heads for non-graphic-arts applications, in particular, for manufacturing flat-panel displays based on light-emitting polymers. Although inkjet techniques such as CIJ or thermal DOD have many attractive attributes, a lot of the nontraditional inkjet printing to date has been done with piezoelectric DOD. This is at least partly due to the ability of piezoelectric DOD to deposit a broad range of water- and solvent-based inks, as well as both conductive and nonconductive inks. The article discusses some of the design principles for high-performance piezoelectric DOD print heads. It presents the state of the art of piezoelectric DOD print head technology in terms of droplet volume, variations of droplet volume between nozzles, achievable uniformity in droplet speed and directionality, and materials compatibility.

The second article, by Derby and Reis, is devoted to the formulation of jettable inks with a focus on the important class of particulate suspensions. Concentrated liquid suspensions of powders need to be printed in a range of applications, such as suspensions of metallic particles for the printing of high-conductivity metallic interconnects. Suspensions of ceramic particles are needed for the deposition of high-performance dielectrics and for printing three-dimensional objects formed from structural ceramics (e.g., for rapid-prototyping applications). The article reviews the requirements for the rheology of such suspensions to be printable by inkjet technology and shows how basic fluid dynamics properties affect droplet formation and droplet spreading upon impact. The authors discuss in particular the requirements for inkjet printing of alumina ceramic suspensions for the fabrication of three-dimensional objects.

The next three articles are devoted to representative applications of inkjet printing in the area of displays, microelectronics, and biology, respectively.

The article by Shimoda et al. is devoted to the development of a microliquid manufacturing process based on inkjet technology and its application to the fabrication of full-color emissive-polymer displays. In such applications, inkjet technology is used to pattern the red, green, and blue emissive polymers, as well as charge injection and transport layers, into the respective pixel locations of the display. The article focuses on the effects of key process parameters such as the droplet positioning accuracy and the drying mode on the performance of inkjet-fabricated polymer light-emitting diodes (PLEDs). It also describes the inkjet-based manufacturing process for active-matrix PLED displays on top of polycrystalline silicon transistor active-matrix arrays.

The article by Burns et al. focuses on the use of inkjet printing in the solution-based manufacturing of integrated circuits for thin-film transistors (TFTs). This application is characterized by the need to integrate a range of different materials, including solution-processable conductors, polymer semiconductors, and polymer dielectrics, into multilayer assemblies with good control of interfaces. It also has very stringent requirements for printing resolution, droplet volume, and droplet-placement accuracy in order to achieve critical feature sizes (of several micrometers) and high uniformity of transistor performance. The article describes the use of surface-energy-assisted inkjet printing to enable transistor devices with channel lengths of micrometer and even submicrometer dimension with high device uniformity. The application of this inkjet-based manufacturing process to the fabrication of polymer-dispersed liquid-crystal and electronic paper displays driven by an active matrix of printed TFTs is discussed.

The last article, by Zaugg and Wagner, reviews the fabrication of protein biochips, which have recently gained a lot of attention as emerging bioanalytical tools for clinical diagnostics as well as drug development. The creation of such devices was possible by merging scientific approaches and methodologies in microfabrication, organic interface chemistry, biochemistry, and—last but not least—advances in depositing minute amounts of protein-containing solutions precisely onto small micron-sized areas of biochip substrates. The extremely fragile nature of the biomolecules in these solutions (which ultimately become the active ingredients on the biochips) imposes special demands on the design of the corresponding arraying technology that are very different from standard inkjet printing applications. This article presents a comparison of different DOD and alternative arraying technologies that are currently under development or already commercialized.

The articles in this issue have been selected to provide a representative, but in no way comprehensive, overview of the many important applications that inkjet technology is finding outside the graphic arts printing field. Important application areas such as textile printing, printing of photoresist layers, patterning of printed circuit boards, and the delivery of liquids to induce local chemical reactions had to be omitted. All of these areas constitute important fields of research and development and provide a broad spectrum of interesting scientific challenges for a wide range of functional materials. Similarly, due to space limitations, no attempt has been made to include alternative, viable printing techniques capable of controlled delivery of small fluid volumes to well-defined locations. Techniques such as microdispensing, screen, offset, and gravure printing, and spray and aerosol coating using small nozzles, have many attractive attributes that rival those of inkjet technology and make them viable alternatives for many applications.

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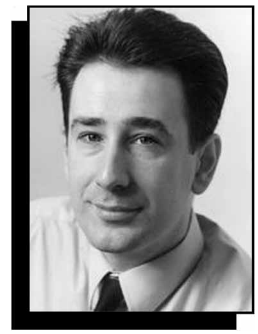

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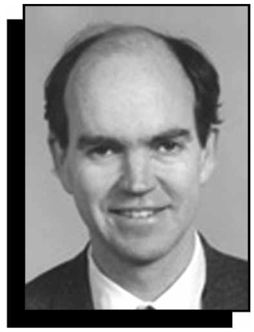

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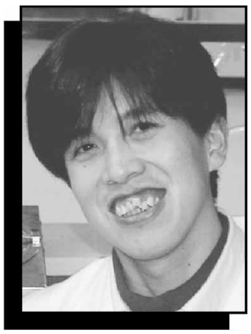

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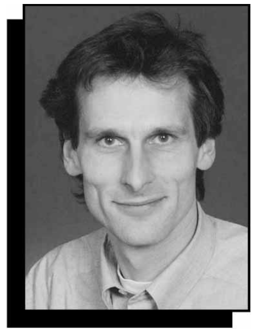

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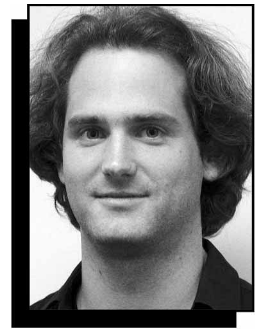

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