

Ink-jet printing in the manufacturing of electronics, photonics, and displays

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ABSTRACT

Ink-jet printing technologies are now being developed and used across a wide spectrum of optoelectronic and microelectronic manufacturing applications, because they provide opportunities both for significant cost reductions in existing components and for new component and device configurations. Examples of cost reductions in existing component configurations include printing of optical epoxies to fabricate precision microlens arrays for micro-mirror-based MEMS optical switches and fluxless printing of solder bumps for flip-chip BGA, μ BGA and CSP (chip-scale package) manufacture. The most widely recognized, relatively new application of ink-jet printing has arisen in the manufacturing of PLED (Polymer-LED) displays. Potential uses of these technologies for creating new device and package configurations that provide both higher performance and lower cost include microlens printing directly onto VCSELs or the tips of optical fibers for increasing the efficiency of coupling and solder ball printing for making right-angle electrical connections, in order to enable further miniaturization of optoelectronic packages. Example of new device configurations which may be fabricated using these capabilities include chip-level optical switches, transceivers, transmitters and receivers.

Keywords: ink-jet printing, solder bumping, micro-optics, polymer LEDs, displays

1. INTRODUCTION

Interest in utilizing digital ink-jet printing technologies for optoelectronic and microelectronic manufacturing has increased in recent years due to the advantages it provides in increased automation, materials and labor cost reductions, and environmental friendliness.^{1,2} Ink-jet printing is also now being viewed as an enabling technology for new types of device and packaging configurations not readily achievable or as cost-effectively by conventional methods. Examples here include the manufacture of PLED displays³ and new, potentially higher performance, optoelectronic devices and packages⁴. After giving a brief background review of ink-jet printing methods we will present examples of their use in micro-dispensing of organic formulations and solder alloys for optoelectronic device fabrication and packaging. Then we will present concepts for utilizing these technologies as enabling processes in the development of new datacom and telecom devices such as chip-scale transceivers, transmitters and detectors. Finally we will review briefly the use of these technologies for flat panel display manufacturing.

2. INK-JET PRINTING BACKGROUND

In piezoelectric-based, drop-on-demand (DOD) ink-jet printing systems the application of a voltage pulse to a piezoelectric transducer that is coupled to the fluid induces a volumetric change in the fluid within a printing device that causes pressure/velocity transients to occur in the fluid, which are directed to produce a droplet from the orifice of the device.⁵ The process of droplet formation and ejection from the orifice of a DOD device is indicated in the time-sequenced photos of Figure 1. The volume of the elements printed at target locations are

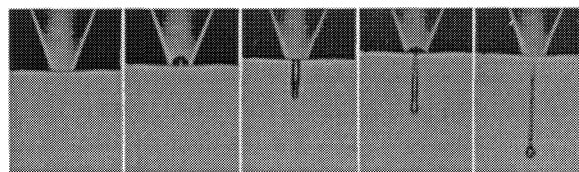


Figure 1. Sequence (left-to-right) of formation and ejection of a 50 μ m diameter droplet from a drop-on-demand microjet device.

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determined by the size (20-100 μm) and number of dispensed droplets. Their shapes are determined by surface tension and the wetting of the substrate surface by the material. Polymeric formulations remain liquid until solidified by UV irradiation, whereas solder alloy droplets printed at slightly above their eutectic temperatures freeze upon contact with the substrate. Print heads for dispensing these materials consist of a printing device attached to a fluid reservoir, both of which are typically heated to maintain the fluid at the DOD jetting threshold of ≤ 40 centipoise for polymer jetting, or slightly above the eutectic point in solder alloy printing. The printing devices are of two configurations, single and multiple jet, where the latter may consist of ganged single jets or monolithic array devices. The single-jet devices, as shown in Figure 2, typically consist of a cylindrical piezoelectric (PZT) element attached to a glass capillary tube with an orifice formed by heating. Array print heads, as exemplified in Figure 3, may be fabricated by sawing channels in a block of PZT, laminating a cover and attaching an orifice plate. The single-jet devices may be operated at temperatures up to 300°C, e.g., for dispensing of SnAu solder, although most of the development work to date has been with 63Sn/37Pb solder. Current uses of the array print heads include PLED display and biomedical printing. Droplets may be dispensed at frequencies up to 10,000 drops/sec, utilizing either step-and-print or print-on-fly modes. A microjet printing platform that can utilize any of these device configurations and dispense polymeric, solder or biomedical materials is shown in the photograph of Figure 4.

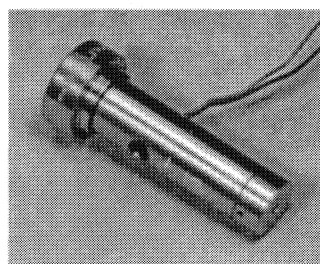


Figure 2. Single-jet, 33mm long, drop-on-demand device for micro-dispensing at temperatures to 300°C.

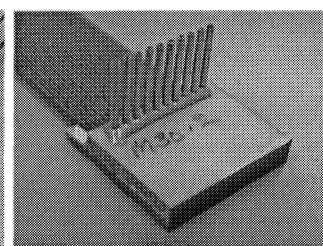


Figure 3. Array printing device, 1 inch wide, for micro-dispensing up to 10 different fluids.



Figure 4. Jetlab® printing station for direct writing from data files of patterns of micro-optical, adhesive, solder or biomedical elements, and consisting of print head(s), XYZ stages, drive electronics, software and pneumatic & temperature controls.

3. MICROLENS PRINTING

3.1 Microlens materials

The preferred class of materials for microlens fabrication is UV-curing optical epoxies, because of their superior thermal and chemical durability, compared to other optical-grade plastics such as acrylics and photoresists. For example, no changes in focal lengths of such lenslets, within our measurement resolution of 1-2%, were seen at elevated temperatures up to 100°C. Additionally, no significant change in focal length at room temperature has been seen for optical epoxy microlenses after either exposure to thermal aging for thousands of hours at 85°C or to 1-hr thermal cycles at temperatures as high as 200°C.

3.2 Microlens arrays

Arrays of microlenses, such as that shown in Figure 5, are currently being printed and shipped for use in coupling of arrays of in/out optical fibers in micro-mirror-based MEMS optical switches. By patterning the substrate with a low wet coating, the tolerances for lenslet placement and diameter may both be held to the order of 1 μm . Additionally, the focal lengths for

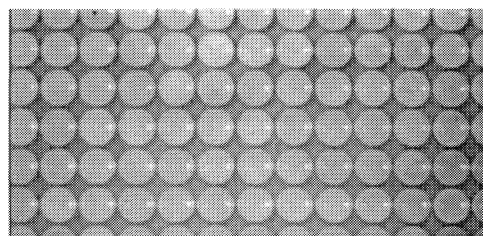


Figure 5. Printed array of 916 μm diameter microlenses on 1 mm centers with focal lengths of 1.10 ± 0.01 mm.



Figure 6. 700 μm diameter microlenses in profile with focal lengths of (left-to-right) of 850, 525, 430 and 405 μm , respectively.

printed microlenses, even within an array, may be varied over wide ranges, as illustrated in Figure 6, and with fractional micron resolutions. These capabilities are especially important in such devices requiring free-space optical interconnections over relatively long path lengths.

3.3 Microlenses on optical fibers

Ink-jet printing may be utilized to provide both cost reduction and increased efficiency in the coupling of light between diode laser sources or photodetectors and optical fibers.⁶ By printing a small spherical microlens onto the center of the tip of a single-mode fiber, as in Figure 7, one may increase the NA (numerical aperture) for acceptance of light from a diode laser source. Alternatively, the output beam from a fiber may be either collimated or focused at a design distance by printing a microlens which is offset from the fiber tip.⁷ In this case the fiber is inserted partway into a collet, the optical fluid is dispensed

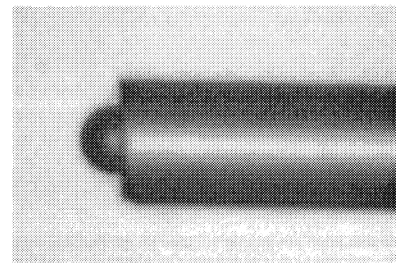


Figure 7. 70 μm diameter microlens printed onto the tip of a 125 μm diameter optical fiber to increase NA.

into the recess until a lenslet of the design geometry is built up on the end of the collet, as in Figure 8, and the optical formulation is UV-cured. The outer diameter of the collet determines the diameter of the printed lenslet, and the lenslet height, which determines the radius of curvature, may be adjusted at a fixed offset distance to achieve either collimation or focusing at a design distance, as shown in Figure 9.

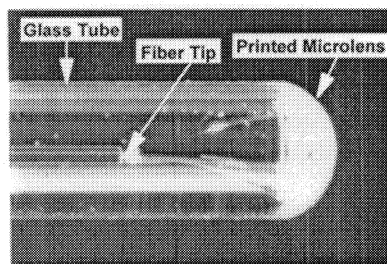


Figure 8. Single mode fiber collimator fabricated by ink-jet printing a 900 μm diameter microlens onto the tip of a glass tube into which the fiber has been partially inserted.

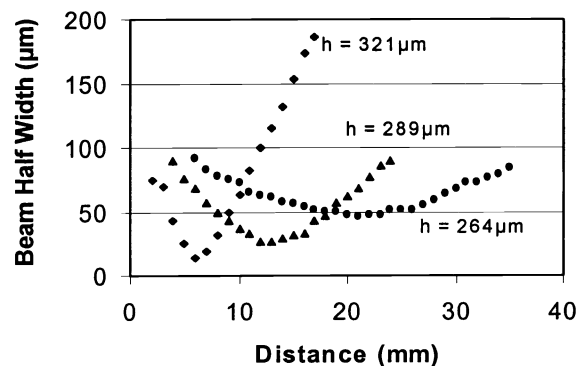


Figure 9. Output beam half-width (at 13.5% of peak intensity) along beam path as a function of printed lenslet height for 3 fibers fabricated as in Fig. 8.

3.4 Microlenses on arrays of VCSELs and/or photodiodes

Reductions in packaging costs and improved performance may be achieved in the coupling of output beams from VCSELs into optical fibers by the use of ink-jet printing to form microlenses directly over the VCSEL emitters.^{7,8} Since only spherical-section (versus ball) microlenses may be ink-jet printed, one must provide an offset of the lenslet from the emitter plane. One way of achieving this in VCSEL array packaging is to print an array of microlenses onto a glass substrate, where the thickness of the substrate is matched to the radius of curvature of the lenslets such that their back focal points will be at the emitter plane. Then the glass substrate is placed over the VCSEL wafer and microlenses and emitters are aligned.^{9,10} However, such alignment may be eliminated by

forming individual pedestals of optically transparent material on top of each emitter, then printing a microlens on top of each pedestal, as shown in the photograph of Figure 10. The radius of curvature

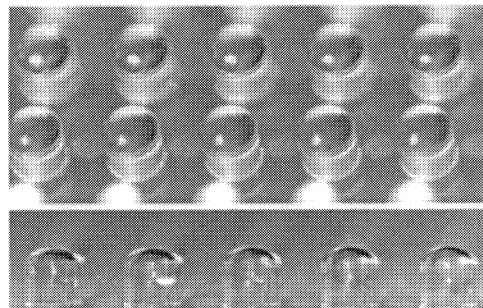


Figure 10. 150 μm diameter microlenses printed onto an array of 90 μm high posts of optical material on 250 μm centers, in order to put back focal point of lenslets at the emitter plane.

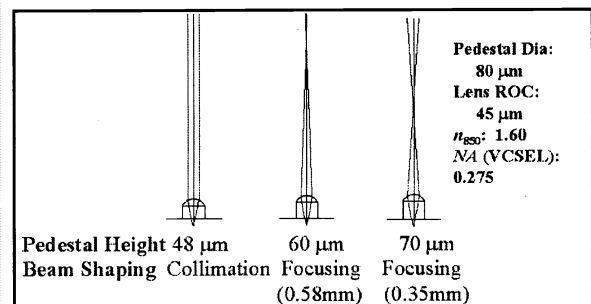


Figure 11. Optical modeling results for microlenses printed onto posts of optical material deposited onto a VCSEL emitter, demonstrating tailoring of the optical properties for collimation or focusing at a design distance.

of the deposited microlenses may be varied over a wide range by varying the number of printed droplets, since the pedestal perimeter stops the fluid flow to a degree determined by the surface tension of the optical material. Optical modeling of this configuration shows, as in Figure 11, that either collimation or focusing of the VCSEL beams at a design distance from the microlenses may be achieved by adjusting pedestal diameter & height and lenslet radius of curvature, taking into account VCSEL NA, and refractive indexes of the pedestal and lenslet materials.

4. SOLDER PRINTING

4.1 Solder pad bumping

The process for ink-jet printing of solder alloys differs somewhat from that employed to print micro-optics in two respects. Firstly, higher dispensing temperatures are required, e.g., $\sim 200^{\circ}\text{C}$ & $\sim 300^{\circ}\text{C}$ for SnPb and SnAu alloys respectively. Secondly, the dispensing devices must be constructed so as to provide a co-flow of inert gas around the printing trajectory, in order to keep the solder droplets from oxidizing before they solidify on the substrate.¹¹ For Au-plated or clean Cu substrates, no flux is required to obtain good adhesion. A primary use of this technology in optoelectronic and microelectronic device manufacturing and packaging is for in-situ placement of ball grid arrays, the ball volumes of which are digitally controlled, for flip-chip and VCSEL bonding and self-aligning, as illustrated in the micrographs of Figure 12.¹² For such applications ink-jet printing is competitive with conventional plating methods from a throughput perspective, since pad bumping rates of 400 bumps/sec may be achieved in the print-on-the-fly mode. It also offers the cost and environmental advantages of an additive deposition process.

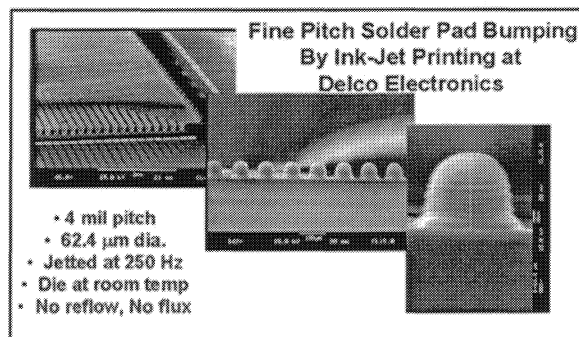


Figure 12. Micrographs of 62 μm diameter solder balls ink-jet printed on 100 μm pitch. (Courtesy of Delco Electronics)

4.2 Solder vias and right-angle electrical interconnects

One unique capability provided by this SolderJet® technology is the fabrication of vertical vias, as exemplified in Figure 13, which could be utilized for making vertical electrical connections in multilayer boards and device structures.

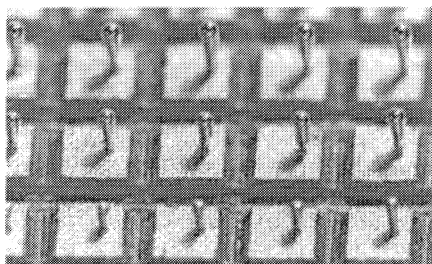


Figure 13. Array of 63/37 Sn/Pb solder towers, 300 μm tall, 60 μm wide, printed onto metal pads.

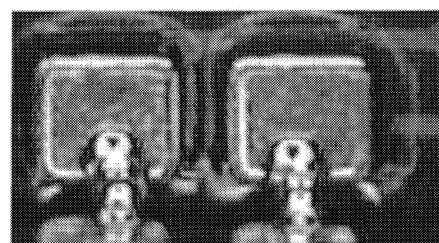


Figure 14. Two sets of pads oriented at right angles which were electrically connected by printing 90 μm diameter solder balls onto the intersection lines.

Another is the formation of right-angle electrical bonds, as illustrated in Figure 14. Here the part is oriented such that the solder balls

hit the juncture lines at an angle of 45° relative to the two pads. This orthogonal bonding capability may be utilized for both mechanical and electrical joining, and it is a potential enabler for new and more compact device and packaging configurations.

5. ADHESIVES PRINTING FOR PACKAGE ASSEMBLY

In many optoelectronic component assembly and packaging applications significant labor cost savings may be realized via process automation by utilizing ink-jet printing for dispensing the adhesives.¹³ By this method droplets as small as 10 picoliters may be precisely placed in a design pattern on a substrate, and the size of the features may be varied within the same pattern, as illustrated in Figure 15. Either thermal or UV curing adhesive may be dispensed, and bond lines on the order of 1 μm have been achieved.

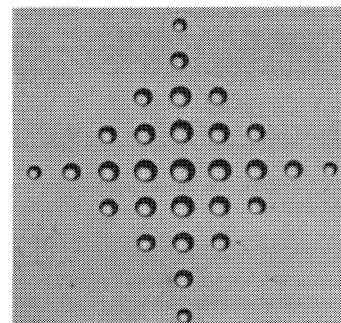


Figure 15. Printed adhesive pattern with spot sizes ranging from 80 to 200 μm .

6. HYBRID ASSEMBLY AND NEW DEVICE & PACKAGE CONFIGURATIONS

The unique capabilities provided by ink-jet printing of micro-optical and solder elements may be utilized for fabrication of both conventional and new configurations of optoelectronic devices and packages. For example, one may potentially employ these capabilities to assist in the fabrication of chip-level optical switches, transceivers, transmitters and receivers.¹⁴ This would involve patterning offset pedestals over the emitters of a 1D VCSEL and/or photodiode array and printing microlenses onto them, as illustrated in Figure 10, in order to provide interconnection to optical fibers. Then one could singulate the arrays and mount them on edge onto a substrate using printed solder balls to provide electrical connection from the emitter/detector pads to pads on the substrate, as illustrated conceptually in Figure 16. Here silicon circuitry on the substrate could provide any number of functions, from A/D conversion to switching (which would require a VCSEL and photodetector array on the same chip). Since the printing technologies are compatible, one could also achieve a high level of process integration by utilizing a common printing platform having both polymer and solder printing heads.

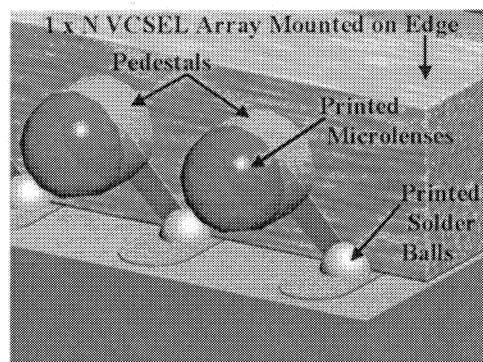


Figure 16. Concept (patent pending) of the use of OpticsJet® and SolderJet® ink-jet printing technologies to fabricate a chip-level optoelectronic device using 1D arrays of VCSELs and/or photodiodes.

7. POLYMER LED DISPLAY PRINTING

Ink-jet printing methods have been discussed and demonstrated over the last few years for a variety of applications in the manufacture of flat panel displays, including the printing of spacer balls and color filters for liquid crystal displays, along with printing phosphor particle elements for inorganic electroluminescent devices.¹⁵ With the recent rise of interest in polymer-based, color LED displays, ink-jet printing has come to the forefront as potentially the lowest cost and most capable manufacturing technology for such displays due, among other aspects, to its additive and non-contact characteristics. Commercial fluids used currently to fabricate the light emitting layers of PLEDs are readily dispensed by ink-jet printing due to the ability to utilize formulations with low solids content, which translates into low viscosity. However, care must be exercised in selecting a solvent blend, in order to satisfy both the rheological demands of the printing process and the requirements of the polymeric LED structure.¹⁶ One example of the printing of such fluids (a Dow Chemical polyfluorinated light-emitting polymer formulation) is shown in Figures 17 & 18, where it can be seen that the printed spots take on a pancake-like geometry when printed onto a substrate uniformly coated with a hole-transport layer. In three-fluid color display printing, researchers are now printing the droplets into micro-wells formed by barriers on the substrate surface, which insures uniform element shape, while the ink-jet process provides uniformity of volume.¹⁷

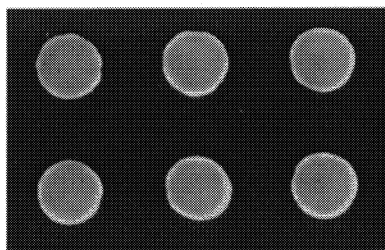


Figure 17. Array of 250 μm diameter spots of a light-emitting polymer printed on 600 μm diameter centers onto a Baytron-P coated substrate, shown under UV illumination.

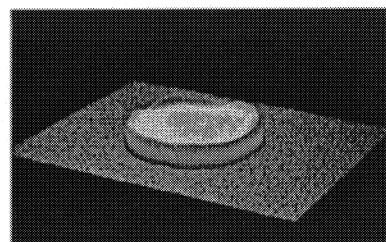


Figure 18. 3D image of a spot from array of Fig. 17 made with a Veeco interferometric system (courtesy of Jan Bernkopf and Yijian Shi of Alien Technology).

8. CONCLUSIONS

We have shown how drop-on-demand ink-jet printing technologies have been utilized to achieve inherent cost reductions and flexibility in the fabrication of: (a) high-precision microlens arrays, e.g., for MEMS devices; (b) lensed optical fibers, e.g., for transceivers and other free-space optical interconnect applications; and (c) solder bumps for BGAs. At the

laboratory development level ink-jet printing has also become the technology of choice for the fabrication of color PLED displays. Finally, we have demonstrated the requisite capabilities and provided specific concepts for combining OpticsJet® and SolderJet® processes to create new, lower-cost, small-size and higher-performance optoelectronic components and packages, including chip-scale optical switches, transceivers, transmitters and detectors.

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