Ink-Jetting Polymers for Electronic, Optical and Biomedical Micro-Devices

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\section*{Introduction}

Ink-jetting has been used beyond the office desktop printer for a long time\cite{1}. Past and present efforts have pursued applications from bump bonding components and direct writing of active and passive elements in electronics, to lenslets on fibers and in arrays for optical communications, to 3D modeling, to arrays and other patterns for biological and medical tests and analyses, to controlled dispensing of aromatic substances for support of medical diagnostic, for fragrance manufacturing, and even for pest control in agriculture. The degree of commercial success to date in these fields is varied, but on nearly all fronts further development is very vibrant and expanding. The attractive features of ink-jet printing include constructive operation with little material waste, digital control and viability of small lot sizes. Combined with other processes, feature definitions to an accuracy of the order of one micron can be maintained. Below, we discuss examples of ink-jetting polymers in the manufacturing of displays, lenslets for optical communications, biological sensors, and, as an unconventional 3D example, conduits for nerve repair and regeneration.

\section*{Ink-Jetting}

Simple and efficient drop-on-demand devices are built as glass tubes with a shaped tip to form a narrow orifice. Typical diameters are 450 \(\mu\text{m}\) inner diameter for the main tube and 40-60 \(\mu\text{m}\) for the orifice; smaller orifices are possible. A PZT cylinder, equipped with electrodes on each its inside and outside surfaces, is glued onto the glass tube. Applying a voltage pulse makes the PZT cylinder deform in both length and thickness, allowing to impart a small but fast motion (tens to hundreds of microseconds) onto the glass tube walls, which in turn starts an acoustic wave in the fluid inside the glass tube. The first pressure maximum of this wave arriving at the orifice forces the fluid column far enough out to form a neck as a break-off point for a droplet when the wave front is finally reflected back up the tube (Figure 1). Velocity and volume of the droplets can be influenced by the shape of the voltage pulse applied to the PZT. The “natural” drop diameter for a device is close to its orifice diameter, but larger droplets can be consistently obtained.

Fig. 1: Droplet at break-off time.

Ink-jet devices of the glass tube design can
be built for operating temperatures from below room temperature to over \(300^\circ\text{C}\). This is important because it allows the use of materials that become fluid and/or show sufficiently low viscosities only at elevated temperatures. Also, the speed of evaporation for a solvent carrying the payload of interest (polymers in the present discussion) can be influenced this way. “Pure” polymer fluids are used for lenses (Figure 2) and other relatively voluminous objects, while polymers in solutions allow to produce submicrometer thick spots and films (Figure 3). A print station with a high-temperature print head mounted is shown in Figure 4.

**Fig. 4:** \(\text{jetlab}^{\text{R}}\) | print station with high-temperature head mounted.

**Fig. 2:** Lenses made from pure liquid polymer.

**Fig. 3:** Thin spot of light emitting polymer printed in solution.

**Fig. 5:** Printed pixels of light emitting polymer. Photo courtesy of DuPont Displays.

**Fig. 4:** \(\text{jetlab}^{\text{R}}\) | print station with high-temperature head mounted.

**Displays**

Organic light emitting polymers have become a very desirable material to make pixels of displays from. Typical applications for these materials presently address small displays, like for cell phones. Pixels are usually placed on a 300 \(\mu\text{m}\) pitch, which with 3 color subpixels require small areas of the order of 250 \(\mu\text{m} \times 50\ \mu\text{m}\) to be manufactured (Figure 5), using about 7 droplets per pixel. Quite commonly, the light emitting polymer solutions for the pixels are printed onto a prepatterned substrate, which by containing wells or some differentiation of hydrophilic versus hydrophobic surface regions will contain the deposited fluids in the desired places. Figure 6 shows a working ink-jet printed demonstration sample for a handheld passive matrix display. The display development presented here was performed by DuPont Displays of Santa Barbara, California, in 2001 and 2002[2].

In an active matrix TFT backplane for a flat panel display, there is a transistor for every subpixel. Plastic Logic Ltd. of Cambridge, England, has endeavored to apply this backplane largely by ink-jet printing[3]. The first step is a traditional photolithography process, defining hydrophilic and hydrophobic areas. Then the subpixels and, next to them, the sources and
drains for the transistors are printed. The source and drain leave a channel between them, on top of which a semiconducting polymer is printed with good contact areas to both sides. In the fourth step, everything is spincoated with a dielectric, and finally the gate electrodes and connecting lines are printed. Connections between conductive layers are achieved by printing a solvent to form a via (a rare intentional destructive process step by ink-jetting, for a change), which gets filled during printing of the conductive gate material.

**Lenslets and VCSELs**

Ink-jetting polymers to build microlenses provides significant improvements in light coupling efficiency and relaxed alignment requirements from submicrometer to the order a few micrometers. The preferred optical material here is actually a monomer, which is cross-linked only in the curing process, building the polymer in its final service location. A good example for the desired effect is placing a lenslet onto the end of a fiber (Figure 7) to produce a tight focal spot at some distance (Figure 8) where placing a receiving component is relatively easy to accomplish[4]. Light coupling thus occurs through an air gap and is thus optically quite stable. In the example of Figure 7, the height of the lens above the front face of the collet, and with it the radius of the lens surface, can be tuned to better than 1 µm resolution, with 1.7 nL or on the order of 10-20 droplets needed for a 1 µm change.

**Fig. 6: Handheld demonstration display. Photo courtesy of Dupont Displays.**

**Fig. 7: Fiber (4.3 µm core, 125 µm total Ø) with lens on, and filling cone inside, a collet.**

**Fig. 8: Effect of lens height on location and diameter of focal point.**

**Fig. 9: Set of 4 VCSELs located with a MEMS clamper.**

This concept can be applied to VCSELs (vertical cavity surface emitting lasers), which are useful in optical computing and communications.
Implementation of VCSELs in optical components provides another example of ink-jetting combining with photolithography techniques. To provide accurate location of the lenslets, cylindrical posts are built over the VCSEL apertures by photolithographic means. The edge of the post then confines the location of the lens, built from a number of droplets. Small sets of VCSELs thus equipped are cut from a wafer and placed onto the optical device substrate (Figure 9). Precise location of it can be accomplished by building a clamper onto the substrate[5], which in turn gets to hold the VCSELs. The electrical connections can be made easily by ink-jetting solder balls and reflowing them. Figure 10 shows one of the 4 VCSELs on our development device being fired. In both electronic and optical respects, the performance characteristics of the manufactured devices meet requirements and do not suffer any degradation of performance from the ink-jetting processes, in particular the heating and curing processes involved (Figure 11).

Bio-Sensors

Printed lenslets also find use as optical biosensors, where they allow the integration of multiple individual sensors with a single fiber bundle. Such composite sensors can produce useful assays from small amounts of fluid in tight spaces, like in periodontal pockets, salivary ducts or wounds. In a project lead by a group at Lawrence Livermore National Laboratory[6], a set of 7 lenslets in a 6-around-1 pattern was printed on the end of a fiber bundle (Figure 12), with a fluorescein-doped optical polymer. This could be done with high accuracy: The center lens was placed off of the center of the fiber bundle by only 2 µm, the drop diameters averaged out to 93.3±2.2 µm, and the roundness (difference of largest and smallest diameter over average) was 0.00072±0.00023.

The sensor is exposed to the target substance, usually a fluid, and the indicator chemistry embedded in the sensor lenslets reacts by specific changes. By illuminating the sensor, fluores-
Fluorescein will occur in the lenslets characteristic of the tested target and can be read out at the other end of the bundle. The test sensor shown in Figure 12 showed less than 2% variation in intensity both from fiber to fiber within a lens and from lens to lens.

**Nerve Conduits**

Our last example for ink-jet printing polymer is the manufacturing of conduits to support the (re)growth and healing of nerves. While in the other examples the manufacturing process placed the polymer on some support substrate as its final location, here a free-standing structure is built wholly by ink-jetting, and is inserted at its place of work only afterwards. The polymer is biodegradable, and it can be loaded with supporting substances like nerve-growth factors[7].

The sample conduits that have been printed to date are about 1 mm in diameter (Figure 13). The polymer is dispensed onto a steel mandrel (Figure 14) and then slipped off. The overall environment for the printing process can be controlled by inserting the print station under a sterile hood in a dedicated room (Figure 15). As a demonstration that gradients of loading along the conduits are possible, we simply dunked one conduit into water containing a fluorescing dye (Figure 16). This step will ultimately be done by ink-jet printing onto the conduit, which allows fine tuning of the gradient. We are cur-
Currently working on improving all process steps in order to move closer to biological viability of the printed conduits.

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References


