MEMS-Based Inkjet Drop Generators from Plastic Substrates

Kathleen M. Vaeth, Deborah DeMejo, Emmanuel Dokyi, Mark Evans, Joseph Jech, Maria Lehmann, Robert Link, and John Sechrist; Eastman Kodak Company; Rochester, NY/USA

Abstract

We report fabrication of a functional inkjet drop generator from plastic substrates exclusively using MEMS-based processing steps. Polyimide and poly(ethylene naphthalate) sheets laminated to a silicon carrier wafer are investigated as the drop generator substrate, and the MEMS processing methods used and associated challenges are discussed in detail. Successful generation of drops in a 600 npi array as small as 2.4 pL in volume (16.5 μm in diameter) at drop velocities of 15.5 m/s is realized with these devices.

Introduction

Applications of microelectromechanical systems (MEMS) range from sensory components, such as accelerometers for car airbags, to full systems such as lab-on-a-chip devices. The dominant material for fabrication of these devices is silicon and its related inorganic compounds. However, as the potential applications for MEMS technology have expanded, so too have the materials used for device fabrication, driven by increasing demands on the substrate optical properties, surface properties, and ruggedness, as well as the desire for low-cost rapid prototyping and fabrication. One popular alternative class of materials for MEMS is elastomeric resins such as poly(dimethyl siloxane), which can be molded against a master form [1, 2]. These materials offer the advantage of substrate transparency and rapid fabrication, but are somewhat limited in minimum feature size and preciseness, often fairly absorbent of moisture and other liquids, and more challenging to integrate with electronics or other sensors. An alternative to moldable polymers are polymer sheets fabricated by solvent casting or extrusion in roll form, such as polyimides, polyacrylates, polyesters, polycarbonates, and polysulfones [3]. These materials generally have better mechanical properties than moldable polymers, and in some instances, superior resistance to solvent and moisture uptake. Sheets of polymers such as polyimide have been used as the orifice for inkjet printers for years, but the nature of the fabrication process (laser drilling of the micrometer-sized features) does not lend itself easily to integration with other MEMS and electronic processing, thereby limiting the amount of functionality that can be incorporated onto the device substrate [4].

One class of commercial devices that utilizes MEMS for fabrication are inkjet print head drop generators. Generally, MEMS-based drop generators are fabricated from silicon substrates. However, use of silicon does limit some important characteristics of the drop generator, such as nozzle array width and mechanical robustness, which motivates exploration and development of alternate substrates for the device that provides more flexibility in these properties. In this paper, we report fabrication of a functional inkjet drop generator from plastic substrates exclusively using MEMS-based processing steps.

Device Design and Fabrication

An overhead view of a single nozzle is shown in Fig. 1A, and a cross-section of the nozzle is shown in Fig. 1B. The drop generator consists of a plastic substrate, in which the ink chamber is formed, a silicon nitride (SiN) membrane, which contains an embedded tantalum silicon nitride (TaSiN) annular heater around the bore, and aluminum electrical leads. In this device, drop generation is based on fluid breakup controlled by low energy pulses (<10 mW) applied periodically to a heater situated around the jet orifice [5–8]. The ink chamber is an oval 120 × 30 μm in dimension set at a pitch of 42 μm, corresponding to a 600 nozzles per inch (npi) array. The SiN membrane was 2.5 μm in thickness, the bores 10 μm in diameter, and the annular heaters 11 μm in inner diameter, 2 μm wide, 600 Å thick, and 100 Ω/□ in sheet resistance. To avoid high-density electrical connections in this feasibility study, 31 of the nozzles were electrically tethered together on the device and driven from the same power and ground electrodes (Fig. 1C). The aluminum (Al) electrical leads were 8000 Å in thickness, and the bond pads for the leads were 520 × 600 μm in size. For the purposes of this substrate feasibility study, the total length of the nozzle array was approximately one inch, corresponding to 640 nozzles in the array.

Substrate Preparation and Handling

Kapton HN (125 μm thick) and Kapton VN (75 μm thick) polyimide sheets from DuPont, and poly(ethylene naphthalate) (PEN) sheets from DuPont Tejin Films (90 μm thick) were investigated as the nozzleplate substrate in this study. The coefficient of thermal expansion (CTE) for the Kapton VN and PEN at the highest processing temperature for the nozzleplate fabrication (~150 °C) was measured to be ~25 ppm and 110 ppm, respectively. A glass transition temperature (T_g) of 124 °C was measured for the PEN, but no significant thermal transition was observed for the Kapton. Water absorption of the polymer sheets was not measured, but is typically reported to on the order of 2–3% for Kapton, and 0.6% for PEN [9].

In order to handle the plastic substrates in 6-inch wafer tools, the polymer sheets were attached to a silicon carrier wafer using a laminate. Because both front and backside processing must be performed on the substrate, facile, clean release of the plastic from the laminate/carrier wafer stack was critical. For the studies presented here, a solid silicone-based film laminate manufactured by Gel-Pak (Gel-Film DGL-80-X4) was used. To achieve the best adhesion of the laminate to the carrier wafer, the silicon was treated with an oxygen plasma just prior to laminate application.

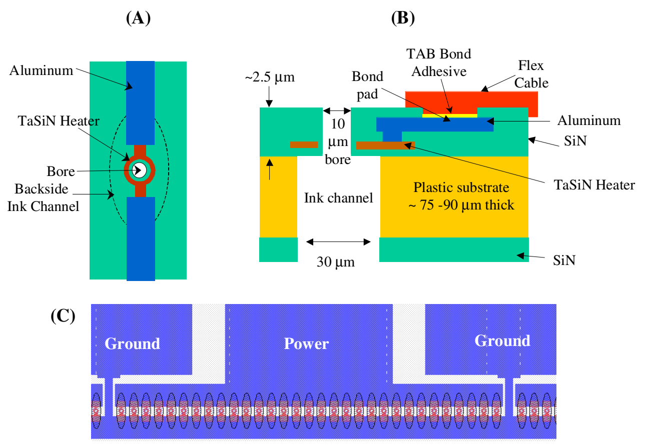

***Figure 1**. (A) Overhead view and (B) cross-sectional view of a single nozzle from the plastic CIJ drop generators. (C) Overhead view of a bank of tethered nozzles*

In order to help stabilize the plastic substrate against water absorption during processing, both sides of the film were coated with a thick layer of low-stress SiN (5 mPa compressive stress). On the backside of the wafer, the SiN membrane (2 μm) was also used as a hard mask for the ink chamber etch into the plastic substrate. On the frontside of the wafer, the SiN layer (1 μm) also served as part of the device membrane, in which the bore and associated electronics were formed. It is worth noting that the plastic substrates could be laminated and delaminated from the carrier wafer without damaging the SiN membranes. In addition, the stress of the SiN membrane on the single- and double-coated plastic wafers was low enough such that the delaminated substrates showed very little curl.

Process Flow

The full process flow used for nozzleplate fabrication is shown in Fig. 2. The overall process was designed to have a nominal maximum temperature of 150 °C, set by the deposition temperature of the SiN, in order to be compatible with a wider range of plastic substrates. The ink channels were etched into the polymeric substrate first (backside processing), followed by definition of the heaters, bores, and associated electronics (frontside processing). SiN deposition was performed via plasma-enhanced chemical vapor deposition in an STS Pro-PECVD chamber at 150 °C. Backside lithography was performed using a Karl Suss MA/BA-6 1x aligner, and a Canon FPA-2500 i2 5x stepper was used for the frontside lithography, all with FujiFilm OiR 906-17 photoresist. Etch of the backside SiN was performed in a LAM Etcher 4520XL using CHF_3/CF_4 chemistry at a power of 600 W, and the SiN and TaSiN etch on the frontside of the wafer was performed with SF_6/Ar chemistry in an Oxford F PlasmaLab 100 at 100 W RF. It was found that the lower process power had to be used for the frontside SiN etch because the conductive TaSiN acted as a floating electrode during the etch process, and caused the plastic substrate to arc, overheat, and burn at the higher process power. The same low-power SF_6/Ar chemistry was used to etch the TaSiN layer. The ink chambers were etched into the plastic substrate with an oxygen-reactive ion etch (RIE) in an Oxford F PlasmaLab 100 unit (60 sccm O_2, 5 mTorr chamber pressure, 170 W RF, 2000 W ICP unless otherwise stated). The TaSiN was deposited by DC sputtering and the Al by RF sputtering using a CVC Connexion-6. Although the laminated stack was very robust to immersion in wet processing baths, dry processes were used whenever possible in order to minimize cracking of the inorganic layers on the plastic substrate. Wet processes were only used for the Al metal etch (nitric, phosphoric, and acetic acid bath, 25 °C), the cleaning step after the ink chamber etch, and resist removal after the TaSiN etch.

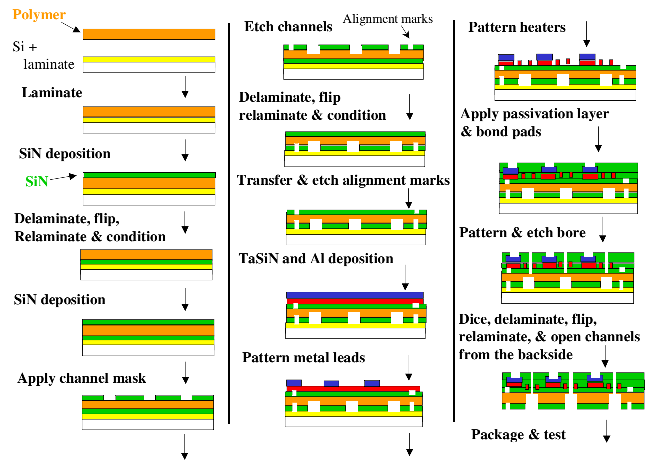

***Figure 2**. Process flow for fabrication of plastic CIJ drop generators*

Backside Processing

Once the SiN encapsulation was deposited on both sides of the plastic wafer, the lithography for the backside ink channels was performed using a 1x mask, and the pattern was etched into the SiN using CHF_3/CF_4 chemistry, stopping on the plastic substrate. The wafers were then placed in an oxygen RIE to transfer the ink channel pattern into the substrate, with etch rates of 1.6 µm/min and 1.2 µm/min observed for PEN and Kapton films, respectively. The quality of ink chamber sidewalls formed in the plastic substrate could be controlled by the power and pressure used in the RIE chamber. For both Kapton and PEN substrates, higher chamber pressures and lower powers resulted in sloped sidewalls and connected ink chambers (Fig. 3A), while higher powers and lower chamber pressures resulted in straighter sidewalls and discrete ink chambers (Figs. 3B-D). Note in particular the contrast in sidewall straightness between Figs. 3A and 3B at the end of the ink chamber array. The final power chosen for the RIE (170 W) was a balance between the ink chamber feature quality and overheating of the substrate during the etch process.

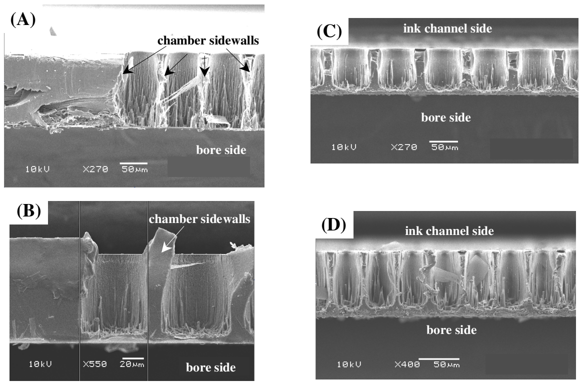

***Figure 3**. SEM cross-section of the ink chamber etch through a Kapton substrate at (A) 10 mTorr, 80 W RF power, and (B) 5 mTorr, 170 W RF power. Note that 300 npi test structures were used in the etch development shown in (A) and (B). (C) Cross-section of 300 npi and (D) 600 npi ink chambers etched at 5 mTorr and 170 W RF power*

With the Kapton HN substrate, posts of residual polymer capped with small knobs were observed after the ink channel etch. It is believed that these features are a result of debris in the polymer film, which mask removal of material during the highly directional conditions of the RIE. These features were not observed with the lower CTE Kapton VN, nor with PEN. Therefore, Kapton HN was discarded as a candidate substrate for the plastic nozzleplates.

For both Kapton and PEN substrates, it was noted that a thin, fibrous mat was deposited on the sidewalls of the ink chamber, starting at the SiN hard mask and extending downward (Fig. 4A).

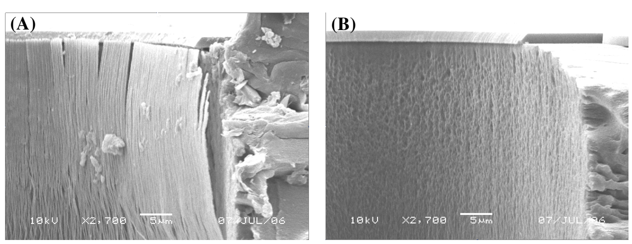

***Figure 4.**. SEM of PEN ink chamber sidewall (A) before and (B) after strip with EKC265 at 70 ºC. Note the fibrous mat of material in Fig. 4A.*

Formation of this mat was also observed when an aluminum hard mask was used. EDAX analysis of the ink chamber array showed an enhancement of silicon and oxygen in the areas where the mat had been deposited in the chambers, suggesting that the fibrous mat was formed by chemistry involving sputter removal of the hard mask, followed by reaction with oxygen and redeposition on the ink chamber sidewalls. It is worth noting that when aluminum was used as the hard mask for the RIE etch, an enhancement of aluminum and oxygen was observed in the areas where the mat was deposited. However, it was found that this layer could be removed easily by adjusting the wafer cleaning conditions after the etch step.

Frontside Processing

After the ink channels had been formed, the substrate was delaminated from the carrier wafer, flipped, and relaminated to a fresh Gel-Film/silicon substrate. Delamination was done by gently peeling the polymer substrate off the carrier wafer by hand. In general, very little cracking of the SiN membranes was observed during this step in the broad areas of the wafer. However, severe, catastrophic cracking of the membrane suspended over the ink channels was observed when the ink channel was etched down to the SiN membrane during backside processing. This cracking could be avoided if the ink channels were not etched completely through the substrate, leaving 5−10 µm of the plastic substrate under the SiN membrane as a support for the delamination/relamination process. This layer of polymer could be removed from the backside of the drop generator with an oxygen RIE after the heaters and bores had been integrated into the membrane (see Fig. 2).

Once the wafers had been flipped for frontside processing, the Al electrical leads, TaSiN heaters, bondpads, and bores were defined using 5x stepper lithography. This step required alignment of the frontside lithography to the backside features. Although the alignment marks on the backside of the plastic could be seen through the substrate, the stepper encountered some difficulty recognizing these buried features, and it was necessary to transfer these marks to the frontside SiN membrane. This was done using three 1x masks, each covering a vertical third of the wafer, which were aligned to the backside and exposed separately in order to minimize the effects of any substrate distortion that occurred during the delamination, flip, and relamination process. Further compensation for substrate distortion was achieved by programming the stepper to align to a localized region of the wafer, and only exposing a portion of the wafer around the alignment marks. The best alignment of frontside and backside features was obtained by performing an alignment and exposure for each 20 mm × 25 mm die on the wafer (die-by-die alignment). This approach was used for all frontside 5x stepper levels.

After the metal etches, another layer of low-temperature SiN was deposited on the substrates (1.5 µm), and the bond pads were defined and etched. The bore level was then patterned and etched, stopping on the plastic substrate. Resist strips for both of these levels were done using an oxygen RIE. The substrate/Gel-Film/silicon laminate structure was then diced, and the individual drop generators were inspected for the quality of ink channel/frontside feature alignment, and for heater/bore alignment. Those selected were delaminated from the carrier wafer, flipped, and laminated to a fresh carrier wafer with Gel-Film for removal of the polymer support layer underneath the SiN membrane with an oxygen RIE. Optical and SEM images of the completed drop generator are shown in Fig. 5.

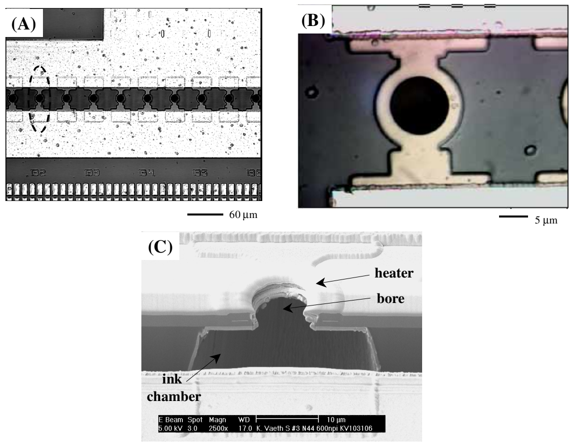

Figure 5. (A) Optical image of 600 npi drop generator (backside ink channel highlighted with dashed line). (B) Optical image of 600 npi bore and heater, and (C) SEM of FIB cross-section of a 600 npi nozzle

It is worth noting that only the drop generators made from PEN substrates survived the full process. Kapton drop generators showed catastrophic cracking of frontside membrane when exposed to wet processes, particularly at elevated temperatures. Because the PEN has a higher CTE than Kapton, but lower water absorption properties, this suggests that water absorption is more critical than thermal expansion for substrate selection with the drop generator when using the SiN membrane, presumably below a certain threshold level of thermal expansion. (Note that the CTE of low-temperature PECVD SiN is typically on the order of 1–3 ppm/°C [10], compared to ~15 ppm/°C for Kapton VN and ~30 ppm/°C for PEN.) Conversion to all-dry processing steps would likely make the Kapton substrate viable in this general process flow. Alternatively, the device membrane could be further engineered to compensate for the stress experienced during the wet processing steps.

Release, Packaging, and Electrical Bonding

After processing was complete, the drop generator was then attached to a stainless steel manifold using a bead of epoxy glue along the edges of the die. Reasonable flatness of the packaged part could be realized with this method, with the surface of the nozzleplate exhibiting a slope of 0.01 µm/inch. However, the flatness of the packaged device was sensitive to the uniformity of the epoxy bead—nonuniformities lead to distortion and buckling of the part. A flex cable was then attached to the nozzleplate using tab-automated bonding with a Z-conductive anisotropic adhesive (3M-5460R).

Device Characterization

As discussed previously, nozzles on the plastic drop generator were ganged into groups of 31 for the 600 npi devices and driven as a bank array. Typical operating conditions for the drop generator were heater bank resistances of 20–30 ohms, fluid pressures of 30–45 psi, drop velocities of 15–17 m/s, breakoff lengths of ~400 µm, and a heater pulse frequency of 100–400 kHz. A schematic of the experimental setup for observing drop generator operation is shown in Fig. 6, and a side-view picture of drop generation from a PEN drop generator at 360 kHz is shown in Fig. 7, corresponding to a drop diameter and volume of 16.5 µm and 2.4 pL, respectively. Note that drop generation characteristics are reasonably uniform across the array—the residual variability is likely due to nozzle-to-nozzle etch and heater variations. It is worth noting that, aside from nozzle-to-nozzle uniformity issues, the drop formation characteristics of the drop generators fabricated from plastic substrates are consistent with the characteristics of silicon drop generators of similar geometry.

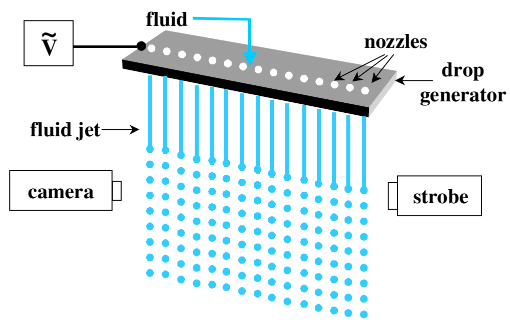

Figure 6. *Schematic of the experimental setup used for testing the plastic continuous inkjet drop generators*

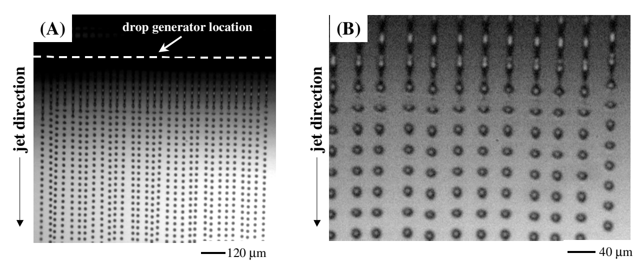

Figure 7. Drop formation from 600 npi PEN drop generator. 10 µm nozzle orifice, (A) and (B) 360 kHz, 3 V, 30% duty cycle, 35 psi, 15.5 m/s drop velocity, 16.5 µm drop diameter, 2.4 pL drops. Note that these images are a side view of the device operation—the drop generator is at the top of each image, as highlighted by the white dashed line in 7A, with the nozzles distributed horizontally across the frame. The jet direction of the device is from the top to the bottom of the frame

Conclusions

This study demonstrates the feasibility of fabricating a functional inkjet drop generator from plastic substrates exclusively using MEMS processing steps. Although there are clearly issues with jet-to-jet uniformity with the plastic drop generators, the drop generation characteristics of the plastic device are consistent with those of a silicon drop generator with similar geometry. Future work should include a more detailed study of the operational stability of the plastic drop generators, including printing, as well as further optimization of the overall process. Ultimately, integration of plastic drop generator fabrication with the installed base of the flat-panel display industry, which boasts motherglass substrate sizes of ~73 × 86 inches (Gen 7), or with the developing field of roll-to-roll fabrication of displays and associated electronics, could enable efficient fabrication of drop generators from plastic substrates.

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Author Biography

Kathleen Vaeth received her B.S. in Chemical Engineering from Cornell University, and her M.S. and Ph.D. in Chemical Engineering from MIT, where she was a Hertz Fellow. She joined the Research Laboratories at Eastman Kodak Company in Rochester, NY in 1999, and has worked in the areas of inkjet drop generator design and fabrication, OLED displays, flexible displays, and photothermographic X-ray film. She is also an adjunct faculty member in the Chemical Engineering Department at Cornell University.

Deborah DeMejo received her B.S. in chemistry from Gannon College. Since then she has worked for Eastman Kodak Company in Rochester, NY. Her work in the MEMS fabrication facility focuses on developing photolithography processes, utilizing new materials or current materials for novel applications.

Emmanuel Dokyi received his B.Sc. in physics from Cape Coast University, Ghana, and his M.S. from Clarkson University, Potsdam, NY. Since then he has worked in the field of process development, device integration and design in fabrication of CCD arrays, and inkjet drop generators.

Joseph Jech received his B.S. in Microelectronic Engineering from Rochester Institute of Technology. Since then he has worked in the Research Laboratories at Eastman Kodak Company in Rochester, NY. His work has focused on process development of semiconductor and MEMS devices, particularly in the areas of thin-film deposition, lithography, and plasma etching.

Maria Lehmann received her B.S. in Chemistry from the State University of New York at Brockport and her M.S. in Materials Science and Engineering from the Rochester Institute of Technology. Since then she has worked in the Research Labs at Eastman Kodak Company in Rochester, NY. As part of Kodak's Image Science Career Development Program she had the opportunity to work in various aspects of the research community, and upon completion of the program she has since been concentrating her efforts in the area of MEMS process development.

Robert Link has a B.S. in physics from SUC at Oneonta, NY, a B.S. in electrical engineering from the University of Buffalo, and a M.S. in electrical engineering from the Rochester Institute of Technology. Since then he has worked at Eastman Kodak Company. He is presently working in the area of inkjet drop generator device characterization and process development..

John Sechrist Received his A.A.S. in Electrical Engineering Technologies from MCC in. Since then he has worked at Eastman Kodak Company in the Research Labs lab supporting the integration of MEMS devices into fluidic and optical devices. This work includes the development of consumer and commercial print heads as well as CMOS devices for imaging products.