Inkjet Printhead Developments

The inkjet printing process involves many essential components including ink and fluids, and their delivery systems, substrates, coatings, driver boards and software. The inkjet printhead sits in the center of the process, delivering ink or other fluids to their print receiver. The characteristics and capabilities of the printhead determine the resolution, accuracy, speed, chemistry and viscosity of deposited materials.

Some inkjet printhead manufacturers have employed micro-electro-mechanical systems (MEMS) to fabricate parts of inkjet for almost four decades. HP* used MEMS techniques to fabricate parts of its early thermal inkjet printheads (TIJ). Other early TIJ makers including Canon*, Lexmark, and Olivetti* adopted MEMS techniques to make components for their heads. A number of manufacturers of industrial and high-performance inkjet printheads — including piezo inkjet (PIJ) manufacturers such as Fujifilm Dimatix*, Xaar*, Konica-Minolta, Epson* and Ricoh* — have joined TIJ OEMs in incorporating MEMS components into their industrial PIJ heads.

The growth of competition for printhead manufacturing is advancing development to match market applications' requirements. Competition among manufacturers has stimulated research and development for ways to overcome issues that have limited inkjet's capabilities. MEMS manufacturing techniques have enabled printhead manufacturers to produce the higher resolution, print speed and accuracy that meet the requirements of a growing number of applications. They have advanced the performance of inkjet to be able to compete successfully with analog printing methods for print speed, reliability, minimal environmental impact and cost effectiveness.

The entry into the world of the extremely small with the use of micro- and nano-electro-mechanical-systems has also required manufacturers to refine their quality controls even beyond Six-Sigma standards.

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This report describes how MEMS techniques work to make inkjet printheads. It describes new inkjet printhead models and the advantages of using MEMS manufacturing methods.

MEMS & Inkjet Printhead Developments

MEMS, is technology that fabricates small devices at the micrometer scale, i.e. technically creating detail from a micrometer or micron (µm) to a millimeter (mm) in size. In practice, MEMS manufacturing processes are yielding more densely packed transistors, sensors and printheads with sub-micron feature sizes smaller than 500 nanometers (nm), and thus may carry the label NEMS, nano-electro-mechanical systems. Photolithography, a.k.a. optical lithography, used in some MEMS/NEMS processing can define features as small as 10 nm.[1] The ability of photolithography and other MEMS/NEMS techniques to produce very small parts can yield advantages that smallness can provide, such as greater nozzle density, improved sensitivity, response speed and resonant frequency performance.

MEMS is used to make nozzles for inkjet nozzle plates, holes, manifolds and channels that are part of inkjet head structures. MEMS inkjet heads may use some of the MEMS techniques including photolithography, laser ablation, molding and plating, modified semiconductor fabrication technology, wet etching and dry etching, and electro discharge machining (EDM).[2] MEMS/NEMS technologies machine a number of materials for inkjet printhead manufacture including silicon, nickel, stainless steel and other metals.

MEMS fabrication techniques[3] include:

- Bulk Micromachining: A substrate (typically silicon) is selectively etched to yield a microstructure.[4]
  - ◊ Anisotropic wet etching (AWE) is orientation dependent and is typically applied to a silicon wafer creating a cavity below the areas on the unmasked areas of the silicon's surface, to which the etch is applied. The orientation of the silicon's crystalline structure will inform the shape of the cavity. Miller indices describe the orientation of crystalline structures using numbers in parenthesis to indicate crystalline structure orientation configuration.[5] Anisotropic wet etching of a silicon wafer with a (100) orientation will yield a cavity with a trapezoidal cross-section, with walls angled at 54.7° to the surface of the silicon wafer. On the other hand, anisotropic wet etching of a silicon wafer with a (110) orientation can yield a cavity with vertical walls. (AWE may also penetrate below the mask at times as with isotropic wet etching.) Some of the anisotropic wet etching agents for silicon are potassium hydroxide (KOH), ethylenediamine pyrocatechol (EDP), and tetramethylammonium hydroxide (TMAH). Anisotropic wet etching is often used in conjunction with Deep Reactive Ion Etching (DRIE) with silicon (100), where the AWE creates the top surface etch and the DRIE forms the vertical walls of the etched cavity.
  - ◊ Isotropic wet etching is not dependent on the crystalline orientation of the silicon wafers. Typically, a mixture of hydrofluoric acid, nitric acid, and acetic acid (HNA) is the isotropic wet etchant solvent for silicon.[6] Silicon dioxide or silicon nitride usually serves as the masking material to resist the HNA etchant. The isotropic wet etchant removes the silicon both downward into the material and laterally. It will also typically undercut the masking materials somewhat.
- Surface Micromachining: Several layers of structural and sacrificial material are deposited, typically by vacuum techniques, and often at high temperatures, then the sacrificial material is etched.
- Wafer Bonding
- Deep Reactive Ion Etching (DRIE) of Silicon[7]
- Deep Reactive Ion Etching (DRIE) of Glass
- LIGA ("Lithographie Galvanoformung Adformung" in German): A thick photoresist is exposed to energetic X-rays from a synchrotron and developed, metal is plated into cavities in the resist and the resist is removed (the metal can then be used for molding polymers).
- Hot Embossing
- XeF2 Dry Phase Etching

- Electro-Discharge Micromachining
- Laser Micromachining
- Focused Ion Beam Micromachining

Besides inkjet printheads, MEMS fabrication applications include the manufacture of pressure sensors, accelerometers for industrial, automotive and medical markets, gyros for automotive, displays, fiber optic switches, alignment and attenuators, radio frequency relays and components, drug delivery, and DNA sequencing and chemical analysis devices for the biomedical industry.[8]

MEMS can make inkjet printheads with smaller features, less weight, greater precision and lower cost than other manufacturing methods. MEMS can fabricate printheads that deliver smaller volume drops with greater uniformity among the hundreds to thousands of head jets. Its advantages have driven printhead manufacturers to adopt it for their head manufacture. MEMS also enables denser nozzle placement, higher-resolution prints, and higher-frequency drop generation that results in faster printing speeds.

MEMS evolved from the development of photolithography and etching for fabricating semiconductors and integrated circuits (IC). Also, discoveries of materials, such as silicon and germanium, supplied the raw ingredients for many MEMS applications.

The use of MEMS to fabricate inkjet printheads begins when Hewlett Packard (HP) adopted MEMS techniques for the manufacture of the nozzle plates and silicon dies for their early thermal inkjet (TIJ) printheads beginning with its printhead research and development in 1977 and 1978. Since then, HP has generated the most revenue from its MEMS manufacturing than any other MEMS user. Yole Development estimated that for 2015 HP TIJ printheads represented 57 percent of all MEMS inkjet heads and that thermal inkjet heads represented 85 percent of the MEMS printhead market.[12] HP now uses MEMS to make virtually all of its latest PageWide TIJ technology. Similarly, MEMJet and Canon with its FINE (full lithography nozzle engineering) system, and Funai (which acquired Lexmark inkjet in April 2013) use MEMS to construct their TIJ heads. Kodak builds its continuous inkjet (CIJ) heads with MEMS. Epson's PrecisionCore piezo inkjet (PIJ) and Fujifilm Dimatix's Samba PIJ heads are MEMS fabricated. Epson produced 8 percent of MEMS built heads and Fujifilm Dimatix produced 2 percent in 2015 according to Yole

MEMS Development Timeline

- 1750s: First electrostatic motors (Benjamin Franklin, Andrew Gordon)
- 1824: Silicon discovered (Berzelius)
- 1927: Field effect transistor patented (Lilienfield)
- 1947–8: Invention of the germanium transistor at Bell Labs (W. Shockley, J. Bardeen and W. Brattain)
- 1954: "Piezoresistive effect in Germanium and Silicon," Physical Review, 94.1, April 1954 (C.S. Smith)
- 1958: First integrated circuit (IC) (J.S. Kilby 195 /Robert Noyce 1959)
- 1958: Silicon strain gauges commercially available
- 1959: "There's Plenty of Room at the Bottom" (R. Feynman)
- 1959–61: First silicon pressure sensor demonstrated (Kulite)
- 1967: Anisotropic deep silicon etching (H.A. Waggener et al.)
- 1967: Invention of surface micromachining (H. Nathanson, et al. Resonant Gate Transistor, Westinghouse, patented 1968)
- 1970: First silicon accelerometer demonstrated (Kulite)
- 1971: The invention of the microprocessor (Intel 4004)
- 1977: First capacitive pressure sensor (Stanford)
- 1977: Texas Instruments begins development of DLP display technology
- 1977: HP and IBM micro-machine an inkjet nozzle[9]
- 1977–1978: Hewlett Packard (HP) begins its thermal inkjet (TIJ)development and MEMS research
- 1980: "Silicon Torsional Scanning Mirror", IBM J. R&D, v24, p631, 1980 (K. E. Petersen)
- 1982: "Silicon as a Structural Material", (K. E. Petersen)
- 1982: LIGA process (KfK, Germany)
- 1982: Disposable blood pressure transducer (Foxboro/ICT, Honeywell, $40)
- 1982: Active on-chip signal conditioning
- 1983: Integrated pressure sensor (Honeywell)
- 1983: First polysilicon MEMS device (Howe, Muller)
- 1983: "Infinitesimal Machinery," (R. Feynman)
- 1984–1985: HP introduces its ThinkJet TIJ printer with printheads constructed using MEMS technology
- 1985: Sensonor Crash sensor (Airbag)
- 1985: The "Buckyball" discovered
- 1986: Atomic force microscope invented (IBM)
- 1986: Silicon wafer bonding (M. Shimbo)
- 1987: Nova Sensors ships MEMS built blood pressure sensors costing about $5
- 1988: Batch fabricated pressure sensors with wafer bonding (Nova Sensor)
- 1988: Rotary electrostatic side drive motors (Fan, Tai, Muller)
- 1989: Lateral comb drive (Tang, Nguyen, Howe)
- 1991: Polysilicon hinge (Pister, Judy, Burgett, Fearing)
- 1991: Carbon nanotube discovered
- 1992: Grating light modulator (Solgaard, Sandejas, Bloom)
- 1992: SCREAM process bulk micromachining (Cornell)
- 1992: MCNC starts MUMPS foundry service
- 1993: Ikuta and Hirowata report stereolithography used for MEMS fabrication
- 1993: Texas Instruments ships DLP displays
- 1993: First surface micro-machined accelerometer shipped to Saab (Analog Devices, ADXL50)
- 1994: Xenon Difluoride (XeF2) used for MEMS
- 1994: Bosch process for deep reactive ion etching is patented
- 1996: Richard Smalley develops method for making uniform diameter carbon nanotubes
- 1999: Optical network switch (Lucent)
- 2003: Steve Nasiri founds InvenSense to manufacture three-axis gyroscopes with MEMS
- 2009: InvenSense generates revenue of $100M
- 2009: Knowles Acoustics ships 1 billionth Sisonic MEMS microphone in seventh year of sales[10,11]

Development. MEMS forms their piezo actuator, ink channels and nozzle plates using semiconductor wafer level micro-machining techniques. Ricoh, Konica Minolta, HP Scitex (X2), Panasonic and Fujifilm Dimatix employ silicon micro-machining for making parts for models of their printheads, such as the piezo actuators, nozzle plates and ink channels.

MEMS fabricates the different layers that are subsequently assembled into inkjet printheads. MEMS printhead manufacture first requires a MEMS foundry where printhead layers, actuators, nozzle plates and other parts are micro-machined. Following foundry processing, the printhead manufacturer aligns and adheres the layers and connectors. MEMS foundries include ST Microelectronics, Rohm Semiconductor, Silicon Sensing (SSS), Silex Microsystems in addition to Canon, Ricoh, Konica Minolta and Epson that operate their own foundries. SPGPrints's sister company, Stork Veco B.V. reportedly is "the world's leading manufacturing company of two-dimensional, high accuracy Metal Precision Products"[13] offering spin coating of photo resists and electro forming, photo etching and laser cutting for micro-machining of inkjet nozzle plates among other MEMS applications.

MEMS fabrication of inkjet printheads requires the removal of all contamination from the surfaces to receive the masking and photo resists. Typically, a hydrogen peroxide or similar type liquid cleanses the surface. The surface material is heated to about 150°C to evaporate any residual moisture. The photolithographic process then deposits a photo resist coating on the silicon or metal plate using spin coating or other coating methods. After the photo resist is baked, it is photographically or projection masked while exposed to UV light. The process develops the photo resist, etches the surface and removes the residual photo resist. This photolithographic process forms precise geometric patterns that have enabled the production of nozzle plates and printhead layer components.

A method Stock Veco employs features a base metal support (mandrel) to receive the photo resist pattern for its nickel (Ni) electroforming process. The electroplating process deposits Ni on the mandrel where the photo resist has not covered it. As it builds above the height of the resist layer, the Ni can overflow onto the top of the resist.

For all its advantages, MEMS fabrication techniques also have a few disadvantages. They require flat substrate surfaces to begin. They are not useful for creating shapes that are not flat. They also require clean room environments free of dust and dirt in order to achieve the yield rates for acceptable performance printheads. A minimum clean room standard of Class 10 FED STD 209E is generally recommended. Class 10 is equivalent to the ISO 4 clean room standard. It requires that no more than 352 particles equal to or greater than 0.5µm in the largest dimension can be in any cubed meter of the clean room.

HP

Since 1977–1978, HP has lead the development of Thin Film and MEMS technology for the manufacture of inkjet printheads. HP uses the TIJ printheads it developed in its print solutions for consumer desktop, office, graphic arts and industrial production applications. HP continues to invest in and advance its TIJ, as well as its HP Scitex X2 PIJ, printhead technologies, resulting in higher resolution, greater durability and printer reliability. In February 2015, HP introduced its MEMS built High Definition Nozzle Architecture (HDNA), which features, according to HP, "a 2,400 dot-per-inch, dual channel, thermal inkjet (TIJ) print head capable of speeds up to 800 feet per minute. This top speed is 33 percent higher than the 600 fpm of the previous HP TIJ heads, and the resolution is twice the previous 1,200 dpi. This fourth generation of print heads is made using MEMS (Micro-Electro-Mechanical Systems) technology that is widely used in silicon-based electronics manufacturing. MEMS has gained acceptance in print head manufacturing because it allows for increased nozzle density (i.e., higher resolution) and permits the creation of integrated print head circuitry."[14]

The HDNA heads are a first step toward addressing the inability of TIJ to print grayscale as many PIJ heads can. HP incorporated two nozzle sizes into these heads to produce two drop sizes and three gray levels for higher apparent resolution and perceived print quality. The head's dual parallel channel configuration enables higher print speeds or nozzle redundancy at half speed. Each channel can also print a different ink color from the other channel. HP is beginning to use its HDNA heads in single-pass print systems for applications from office CAD to production corrugated packaging printing.

HP is using its HDNA printheads on its new Inkjet Web Press T series systems, including the HP T200, T300 and T400 Inkjet Web Presses. HP's single-pass Page Wide Web Press series for book, newspaper, direct mail and corrugated packaging printing are also using the HDNA printheads. HP has committed to developing its next generation heads on the same modular form factor so as to be able to upgrade its existing Inkjet Web Presses with coming head improvements. HP indicated in 2015 that the installed base of its Inkjet Web Press T Series devices produced about four billion A4 equivalent pages per month. It claimed that the volume of pages grew at a 34% CAGR since 2010 when the first production unit was placed.

In addition to its Inkjet Page Wide systems, HP advanced its Latex printing systems with its third generation ink strategy a few years ago that greatly improved print durability, while reducing energy consumption and temperature required for curing. Reportedly, HP Scitex has resolved initial issues with its X2 PIJ printhead and is advancing its High Dynamic Range (HDR) PIJ grayscale printing for sign, display and corrugated packaging applications.

Fujifilm Dimatix

In their 2004 IS&T NIP20 paper on "MEMS Solutions for Precision Micro-Fluidic Dispensing Application", Chris Menzel, Andreas Bibl and Paul Hoisington discussed how, "customer demands for increased performance within the precision micro-fluidic markets, including high image quality printing" led their Spectra team to develop "piezoelectrically actuated inkjet printhead modules with single crystal silicon micro-electro-mechcanical manufacturing processes."[15] While the paper focuses on Spectra's use of MEMS in the fabrication of its M-Class PIJ heads, which were not commercially successful, it illustrates the compelling drivers for adopting MEMS for printhead fabrication, which subsequently led Spectra and its successor Fujifilm Dimatix to embrace MEMS for its Dimatix Material Cartridge single-use head and other heads for its DMP material deposition printers and Samba PIJ head. The paper points to the potential MEMS offers to approach higher firing frequencies. It noted that, "Pumping diaphragm natural frequencies are in the 2–3MHz range. System natural frequencies (with ink) are in the 100–150 kilohertz (kHz) range. Firing frequencies up to 40 kHz are routinely achieved with the M-Class prototypes and higher firing frequencies are expected from the current design as development continues."[16] Fujifilm currently rates the maximum frequency of its Samba PIJ MEMS head at 100 kHz.

Fujifilm Dimatix recently fine-tuned its MEMS built Samba printhead with its G3L model. It features native 1200 dpi resolution and 2048 nozzles per modular head. It jets 2-picoliter (pl) primary drops with the ability to generate grayscale larger drop sizes with its VersaDrop™ wave form control. It also features fluid recirculation in the printhead manifold. Since Dimatix designed the Samba head to be readily stacked in print bar arrays, it has found application in single-pass printers, including the SPGPrints Pike and Javelin industrial textile printer and Fujifilm Jetpress 720 commercial printer among others.

Konica Minolta

On July 23, 2015, Konica Minolta (KM) announced that it developed three industrial piezo inkjet (PIJ) printheads using MEMS manufacturing methods and that it would begin production of these heads in the spring of 2016.

All three heads contain 1024 nozzles per head with independent ink channels that can tolerate all typical inkjet ink types, including aqueous, UV, solvent and oil-based inks. The ME130H head offers a print width of 21.65 mm/0.85 inches (in), 1200 nozzles per inch (npi), eight gray levels with a primary drop volume of 3 pl, and a maximum drive frequency of 100 kHz. The MC160H and MC160L offer a print width that is twice as wide at 43.3 mm (1.7 in), only a binary drop volume of 6 pl and a maximum drive frequency of 70 kHz. The MC160H has 600 npi for one-color printing, while the MC160L can print two ink colors using 300 npi each.

The KM MEMS heads avoid the limitations of KM's earlier Xaar licensed shared-wall shear mode PIJ inkjet technology. While KM had designed its independent ink channel versions of shared wall shear mode for its KM 1024i and KM 1800i, enabling them to print aqueous inks for textile and other applications, they still suffer from jetting frequency and nozzle packing limits of the shared wall shear mode design. Its new MEMS inkjet printheads achieve higher resolution and drop placement accuracy as well as superior jetting characteristics over its earlier printheads.

Like Epson, Konica Minolta manufactures its heads with its own MEMS thin film systems and also assembles them robotically.

Memjet Printhead — Full-Shot Angle

Memjet Printhead — Full-Width

Memjet

Silverbrook Research labs in Australia originated Memjet* technology with the mission of finding a better way to print color documents. The company developed over 3,500 international patents and a number of printhead designs. Silverbrook Research formed a business partnership with Taiwan Semiconductor Manufacturing Company and MEMS fabricated and tested over 1,000 nozzle designs. The resulting MEMS TIJ printer design envisioned a page-wide single-pass system using MEMS built inkjet printheads. It targeted 1600 dpi resolution because its image quality would be photographic and beyond the human eyes ability to perceive the pixel artifacts of the print process. The printhead design proposed generating 1-pl volume drops and a minimum of 54,400 ink nozzles per A4/letter sized printhead.

In March of 2007, the group demonstrated a Memjet printing system that integrated printheads, controller chips, ink and software. Since Memjet does not manufacture printers, but does make the printheads, controllers, ink and software, in 2009 it began licensing its technology to OEM printer manufacturers that began bringing Memjet powered label and office printers to the market in 2011 and wide-format printers in 2012. OEM companies offering printer using the Memjet technology include Xante*, Colordyne, Afinia*, Canon, Canon Oce, Xerox*, Rena, Gongzheng Group, Rigoli s.r.l. , Beiren, Delphax, Digikett GmbH, Halm Industries, IPT digital LLC, New Solution, Super Web Digital, and Trojanlabel.

Funai

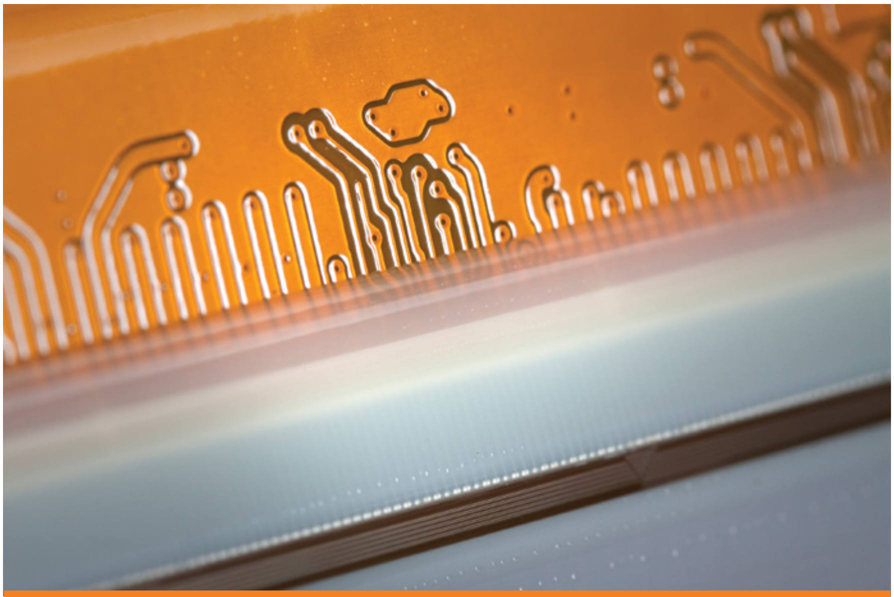
On April 1, 2013, Funai Electric Co. Ltd. of Japan announced its acquisition of Lexmark's inkjet related technology and patents, primarily concerning thermal inkjet, and its production facility in the Philippines. Consequently, Funai manufactures TIJ heads with MEMS micro-machined nozzle plates like those on Lexmark TIJ heads. Funai research has continued to develop and advance its TIJ technology and has filed a number of patents related to inkjet printheads. Funai Electric also manufactures Televisions for Philips, Magnavox, Emerson, Sanyo and inkjet printers for Kodak. It manufactures the Kodak Verité line of desktop color TIJ printers that print documents and photos, copy and scan. The Verité line offers resolution up to 4800 x 1200 dpi and prints with dye-based inks for its CMY process colors and pigmented ink for black.

Canon

Canon is generally credited with having invented the TIJ printhead, which it called the Bubble Jet. It subsequently cross licensed its patented TIJ intellectual property with HP that had also developed a TIJ system soon after Canon. Canon uses thin film and MEMS techniques to fabricate its TIJ printhead nozzle plates. It also offers inkjet printers using Memjet MEMS fabricated printheads.

Epson

Epson's PrecisionCore MEMS built PIJ printhead resulted from two decades of printhead development and subsequent adoption of MEMS microfabrication techniques to machine submicron part features. Epson manufactures its MicroTFP print chips at its Suwa Minami Plant, in Nagano prefecture, Japan, and assembles its PrecisionCore heads at its two fully robotically automated manufacturing lines at Tohoku and Akita, Japan. Epson describes its process as follows, "Three silicon chips — a TFP actuator, an ink channel and a nozzle plate — are bonded together. Ink that enters through the ink flow path of the ink channel is ejected from the nozzles by pump-like action of the TFP actuator. Epson's innovative thin-film



Memjet Printhead — Close-Up

piezo technology is used to produce the TFP actuators; its innovative MEMS technology is used to make the chip components."[17] The thin film piezo (TFP) actuator element is formed as a 1-micrometer thick film on a silicon wafer, where it is sintered and crystalized. Epson uses its photolithography process for making the TFP actuators, ink channels and nozzle plates for the PrecisionCore.

Epson offers two types of PrecisionCore Thin Film Piezo print chips: TFP and Micro TFP. MEMS forms both of their all silicon ink paths and nozzle plates and they both can jet the full range of ink types, including aqueous, solvent, resin and UV curable. They both can jet a range of grayscale drops volumes from 1.5 to 32.5 pl at a maximum frequency of 50 kHz. The TFP nozzle line length is 25.4 mm (1 in) while the Micro TFP's is 33.8 mm (1.33 in). The TFP has 720 nozzles per inch, while the MicroTFP has 600 nozzles per inch. For its printers, Epson assembles these chips in a number of configurations.

Panasonic

In 2014, Panasonic* began to produce and supply its UH-HA800 series PIJ heads. It offered three versions of the head: UH-HA810, 820 and 840. Essentially, the 810 is a single module with 800 nozzles. The 820 consists of two 810 modules with 1600 nozzles and the 840 consists of four 810 modules with 3200 nozzles. The 810 module yields a resolution of 360dpi. It has a print width of 56.3 mm (2.2 in) with drop sizes of 3 to 30 pl, a maximum drop frequency of 100 kHz and drop speed of 8 to 10 m/sec. It includes an ink heater to maintain ink consistency and enable the printing of relatively high viscosity fluids. Reportedly, Panasonic used MEMS micro-machined parts for the UH-HA800 series, such as nozzle plates, to improve jetting straightness and dot placement accuracy, reduce satellite dots, produce perfectly circular dots for fine print detail and enable jetting of a wide range of inks, including aqueous-based, solvent, UV and resin inks.

Xaar

The Cambridge, UK headquartered printhead manufacturer introduced its MEMS produced XAAR 5601 MEMS PIJ head at drupa. It also launched the Xaar 1003 and Xaar 1201 thin film piezo head that incorporate MEMS fabricated parts.

The Xaar 1201 is a compact greyscale thin film PIJ printhead that can print user choice of one, two or four colors. It can jet aqueous and eco-solvent inks. It features 1280 nozzles jetting variable drop sizes for an apparent resolution of up to 1440dpi. Ricoh and Xaar partnered to develop the Xaar 1201. Ricoh released its version at drupa 2016. It also offers 1,280 nozzles in four rows of 320 producing 300dpi with each row and can jet up to four ink colors simultaneously. MEMS created the nozzle plate and thin film PZT actuators.

Xaar 5601

Xaar 1201

The Xaar 5601 3p0 is a thin film silicon MEMS fabricated eight gray level PIJ head that prints a primary drop of 3 pl and a maximum drop volume of 21 pl with a maximum drop generation frequency of 96 kHz. It offers a print width of 4.5 inches (116mm) and has a total of 5680 nozzles arranged in four rows that can jet up to six liters of ink per hour. Xaar indicates that the head's 1200 nozzles per inch and eight levels of gray can yield "apparent resolution greater than 2440dpi with high levels of productivity."[18] Xaar indicated that this water tolerant head would be available by the end of 2016. Xaar is targeting textile, laminate, commercial print, packaging and carton applications with this head. Its Xaar 5601 is the second Xaar head that can tolerate aqueous-based inks after the Xaar 001 designed for jetting large particle aqueous ceramic glazes. The Xaar 5601 opens opportunities for Xaar in the rapidly growing textile inkjet market, where aqueous inks, that its shared wall shear mode heads could not tolerate, are standard. Xaar claims that its AcuDrp Technology™ allows complete control over greyscale drop ejection that adjusts for inconsistencies among its nozzles with sub-drop tuning for every nozzle on every 5601 printhead print bar. The Xaar 5601 incorporates the company's TF Technology® that continuously recirculates its print fluids directly past the back of the nozzles to prevent fluid particles settling and maintain fluid temperature. Xaar designed the 5601 with built-in mounting to readily stack and align in print bar arrays for rapid maintenance with printhead removal and replacement. The Company partnered with its Cambridge UK neighbor, Global Inkjet Systems*, to develop the driver electronics board and ink delivery systems for the 5601.

Xaar developed its 1003 PIJ printhead as an upgrade for its Xaar 1001 and 1002 heads. Like its predecessor heads it incorporates Xaar's TF Technology® that recirculates its print fluids. Xaar offer three versions of its 1003: Xaar 1003 GS6, GS12 and GS40. All of these models have 1000 active nozzles arranged in two rows for 360 nozzles per inch (npi) and a print width of 70.5 mm (2.775 inches). The Xaar 1003 GS6 can print eight gray levels from a primary drop volume of 6pl up to 42 pl with a 6 kHz drop generation frequency. The Xaar 1003 GS12 also can print eight gray levels from a primary drop volume of 12 pl up to 84 pl with a 6 to 12 kHz drop generation frequency. The Xaar 1003 GS40 can print five gray levels from a primary drop volume of 40 pl up to 160 pl with a 5 kHz drop generation frequency. Xaar has employed its X-ACTTM MEMS manufacturing process to build parts for its 1003 line of heads, that improved their accuracy and scalability over their 1001 and 1002 predecessors.

Ricoh

On May 23, 2016, Ricoh announced its development of a new inkjet printhead for industrial applications using a thin film (PZT) piezo actuator. This is the same head as the Xaar 1201. Ricoh indicates that its Sol Gel process manufactured the head's high stiffness actuator, which "enables the application of high quality multi-drop control." Its MEMS technology also enables the new head "to realize 600 dpi resolution with 1,280 nozzles configured in 4 x 300 dpi rows. Additionally, the ink paths are isolated, enabling a single head to jet up to four ink colors."[19] Ricoh introduced its MEMS/thin film PZT head both on its own printers and a number of its partners' devices.

Kyocera

Kyocera has not disclosed details of its manufacturing processes. It holds its manufacturing methods as proprietary, but it does feature micron-level printhead alignment and simplified head design that suggest micro-machining of some type. In late 2015, Kyocera introduced three PIJ printheads. On Sept 17, 2015, Kyocera announced its 360 dpi KJ4C-0360 head with recirculation primarily for ceramic tile printing, but is also offering it for textile, carpet, apparel and pharmaceutical capsule printing applications. It prints up to 50 m/min with an effective print width of 109 mm and offers grayscale with a maximum drop volume of 84 pl. On October 6, 2015, Kyocera announced its four-color 150 dpi per color KJ4B-0150 head. It uses water-based ink and operates as fast as 76.2 m/min and features a print width of 112 mm. Kyocera is targeting the fashion apparel market with this 300 dpi head. On November 5, 2015, Kyocera launched its two-color 300 dpi KJ4B-0300-G06DS head with a maximum drive frequency of 30 kHz. The company designed this head primarily for textile printing. It features 112 mm print width. It can print grayscale with four drop volumes: 5, 7, 12, and 18 pl. Both KJ4B heads provide a total of 2,656 nozzles with 664 nozzles per color for the KJ4B-0150 head and 1,328 nozzles per color for the KJ4B-300.

Conclusions

MEMS and NEMS fabrication techniques are playing a dominant role in the way inkjet printheads are made. These processes have produced printheads with densely packed ink channels and nozzles that jet smaller drop volumes with greater uniformity. They can micro- and nano-machine durable materials, such as silicon, that resist chemical attack from the range of currently available inks and deposition fluids. Silicon is also hard and abrasion resistant and as a nozzle plate material can tolerate frequent wiping and withstand most head strikes. MEMS techniques can also fabricate metal nozzle plates and other inkjet parts. MEMS processing can significantly reduce the cost of printhead manufacture. Its lower costs have enabled HP to offer disposable printheads that are part of its ink cartridges, and Spectra-Fujifilm Dimatix to offer disposable one-time use heads for its DMP laboratory printers, while maintaining MEMS printhead cost competitiveness in spite of their improved performance and refinement.

OEM manufacturers and their foundries are using MEMS technology for making all or some of their print head parts. MEMS PIJ heads, including the Fujifilm Dimatix Samba, Xaar 5601, Epson PrecisionCore, and Konica Minolta ME130H, MC160H and MC160L, are configured as bend mode and can jet a wide range of fluids. These drop-on-demand heads have advanced to generate drops at frequencies as high as 100 kHz for each independent ink channel-nozzle. HP has led in using MEMS technology for making TIJ head nozzle plates and component parts. Memjet, Canon and Funai also use MEMS to make their TIJ heads. Kodak uses MEMS for its Stream CIJ heads. The competition among these companies with large R&D budgets and R&D teams are continuing to overcome technical printhead hurdles that have limited inkjet application. MEMS techniques has helped these teams accomplish their goals. The limitations of the past have provided opportunities for future advances.

As a set of platform building techniques, MEMS provides advantages over other fabrication methods for overcoming inkjet printhead limitations and realizing new application opportunities. These advantages include the ability to precisely define, locate and replicate jetting nozzles on their plates, create tightly packed and integrated printhead structures, and chemically inert parts that can flow and deposit the range of available jetting fluids, all while reducing the cost of manufacture. MEMS and NEMS technologies and the competition among its practitioners are illuminating the path to future printhead improvement.

***SGIA members in order of mention:**
Canon, since 2006
Olivetti, since 2009
Fujifilm Dimatix, since 2004
Xaar, since 2007
Epson, since 2006
Ricoh, since 2014
Xante, since 2016
Afinia, since 2013
Xerox, since 2013
Panasonic, since 2007
Global Inkjet Systems, since 2014

References

- Elwenspoek and Jansen, Silicon Micromachining, Cambridge
- Hoath, Stephen D. (editor), Fundamentals of Inkjet Printing: The Science of Inkjet and Droplets, Wiley
- Keller, Microfabricated High Aspect Ratio Silicon Flexures, MEMS Precision Instruments
- Kovacs, Micromachined Transducers Sourcebook, McGraw-Hill
- Madou, Marc J., Fundamentals of Microfabrication, CRC Press
- Madou, Marc J., Microfabrication and Nanotechnology Volume 1, Solid-State Physics, Fluidics, and Analytical Techniques in Micro- and Nanotechnology, CRC Press
- Maluf, An Introduction to Microelectromechanical Systems Engineering, Artech House
- Ristic, Sensor Technology and Devices, Artec House
- Senturia, Microsystem Design, Kluwer
- Sze, Semiconductor Sensors, Wiley

[1]http://www.memscentral.com/overview_of_mems.htm Overview of MEMS by MEMSCentral and Chang Liu
[2]http://www.silversheen.com/pdf/Introduction to Inkjet Technology.pdf
[3]https://www.mems-exchange.org/MEMS/fabrication.html
[4]http://mems.isi.edu
[5]For more detail on Miller conventions & indicesfor silicon see: http://www.cleanroom.byu.edu/EW_orientation.phtml

[6]http://web.ece.ucdavis.edu/~anayakpr/Papers/Wet and Dry Etching_submitted.pdf
[7]U.S. Patent US20030024897, (2003) D. Milligan & T. Weber, assigned to HP
[8]http://robotics.eecs.berkeley.edu/~pister/245/Notes/Intro.pdf
[9]Petersen, K. E. 1982. Silicon as a Mechanical Material. Proceedings IEEE 70:420-57
[10]http://scme-nm.org/files/History%20of%20MEMS_Presentation.pdf
[11]http://robotics.eecs.berkeley.edu/~pister/245/Notes/Intro.pdf
[12]http://www.yole.fr: Yole Inkjet Printhead Market and Technology Trends, March 2016
[13]http://www.azooptics.com
[14]http://www8.hp.com/us/en/commercial-printers/web-presses/hdna.html
[15]Chris Menzel, Andreas Bibl & Paul Hoisington, MEMS Solutions for Precision Micro-Fluidic Dispensing Application, IS&T NIP20: International Conference on Digital Printing Technologies, Salt Lake City, UT; October 2004; p. 169-175; ISBN / ISSN: 0-89208-253-4
[16]Ibid, p. 169
[17]http://global.epson.com/innovation/engineer/precisioncore.html
[18]http://www.xaar.com/en/media-centre/xaar-sets-a-new-inkjet-standard-with-the-xaar-5601-thin-film-silicon-mems-high-resolution-printhead-family
[19]https://www.ricoh.com/release/2016/pdf/0523_IJE.pdf

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