The Current Situation and Future Applications of the Inkjet Industry

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Abstract

Several applications for inkjet technology are being developed based on the concept of a micro-liquid process. First, active-matrix thin-film diode liquid-crystal displays (TFD-LCDs) equipped with color filters are manufactured by using pigmented inkjet printing. Fundamental technologies have been optimized, including pigment-dispersed solvent inks, bank materials deposited on a metallic black matrix, a piezoelectric drop-on-demand inkjet head, an original inkjet machine, a drying process for color layers, and the fabrication of LCD panels. Applications in organic light emitting diodes (OLEDs), organic thin film transistors (TFTs), micro-lenses, metal wiring processes and other areas are planned, and visionary industrial inkjet applications for the future are presented.

Introduction

Inkjet methods are broadly classified as being either continuous systems, which continuously eject ink droplets, or on-demand systems, which selectively eject ink droplets. The latter are used extensively as PC printers. On-demand systems that use piezo elements are able to deposit uniform, well-formed spherical droplets of ink in targeted locations. This ability, combined with an increasingly wide selection of inks, has made on-demand systems a promising target for researchers bent on developing industrial applications. Focusing on recording applications, Epson has been using on-demand systems that employ piezo elements to achieve high image quality of printed output. Epson has pushed resolution all the way to 1,440 dpi (a 17. 6-micron pitch) and realized systems that render images with ink droplets as small as 2 picoliters, thus minimizing interference between dots. In addition, Epson has evolved multi-size dot technology (MSDT).[1] Three sizes of ink droplets—large, medium, and small—can be ejected from the same nozzle by changing the driving waveform. Enabling different droplet sizes to be used according to the image to be output has enabled Epson to boost printing speed. The optimum droplet sizes are set for each resolution. For example, a 1,440 dpi image is composed of droplets that are 4, 7, and 11 picoliters, while a 720 dpi image is composed of droplets that are 6, 10, and 20 picoliters. Six colors of ink are normally used to enable realistic rendering of tonal gradations. Variation in droplet volume from one nozzle to the next and a lack of color consistency when the head changes lines had been problems. Epson was able to solve these problems by introducing MSDT and error variance processing. Micro-patterning technology was originally acquired in the pursuit of photo-realistic output. The following is a detailed discussion regarding six key basic technological developments that led to the further evolution and growth of micro-patterning technology into a direct-draw patterning technology for industrial product production processes. LCD color filter fabrication[2] is used as an example. The six key basic technologies developed were as follows:

1. Techniques for precisely controlling ink menisci
2. A bank structure enabling liquid droplet self-alignment
3. A print head
4. A special-purpose inkjet printer
5. Substrate technologies
6. Drying and film-formation technologies

Precision Control of Menisci

The method used to control inkjet droplets, i. e. the design of the waveforms applied to piezo elements, is crucial. Uniform, well-formed ink droplets must be ejected at high frequency and on a straight path to produce a high-definition display at high speed. Moreover, the droplets must be extremely small (micro-liquids) if high resolution is to be obtained. To obtain such micro-droplets, it is essential to precisely and accurately control the behavior of the ink—and particularly of the ink menisci at the tips of nozzles—throughout the entire droplet ejection process. We thus investigated ejection waveforms that would take advantage of the properties of piezo elements and enable menisci to be controlled precisely and at high speed. A three-stage waveform driving method was developed as a result. First, a gentle pulling motion is applied to the ink menisci by the waveform, keeping all menisci the same shape before droplet ejection. Next, with the menisci in this state, a forceful eject motion is applied. The eject motion is immediately followed by another pull motion so as to control the vibrations of the ink menisci. In other inkjet systems meniscus vibrations are generally controlled by optimizing the shape of the supply ports located on the opposite side of the nozzles. However, ink needs to be resupplied rapidly if responsiveness is to be improved, which means that supply ports must be designed in a way that is not conducive to meniscus vibration control. The key to the new driving method lies in using the motion of the piezo elements to forcefully dampen meniscus vibrations. A schematic view of this method is shown in Fig. 1. The technology for precisely controlling the menisci enabled the stable, high-frequency ejection of ink droplets that have a uniform shape.

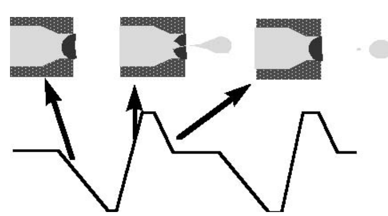

Figure 1. Meniscus control.

Similarly important are the properties of the medium ejected in inkjet processes—the ink. Ink parameters such as viscosity, surface tension, and drying speed must be carefully controlled. Color resists for color filters have been optimized for the conventional photolithography process to provide color reproduction in finished displays, but they had to be further optimized so that they could be ejected by an inkjet machine. Optimization of the ink formulation and ejection waveform enabled ink droplets ranging in volume from 4 to 20 picoliters to be ejected at a speed of approximately 7 meters per second with pigment-dispersed solvent inks for color filters. Ink was always stably ejected at between 1 to 28. 8 kHz. Figure 2 is a stroboscopic photograph of ejected ink droplets.

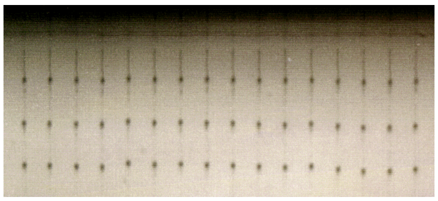

Figure 2. Observation of ink ejection.

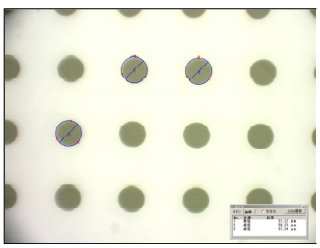

Figure 3. Ink droplet landing pattern on paper (with meniscus control).

The shape and location of these ink droplets after landing is shown in Fig. 3.

The liquid, forming beautiful spheres, lands on the substrate. For comparison purposes, the landing pattern when the menisci are not controlled is shown in Fig. 4. Without meniscus control, the main droplets are accompanied by numerous smaller satellites of liquid. In device fabrication these satellites are distributed between pixels, causing colors to mix and making it impossible to fabricate a high-definition display.

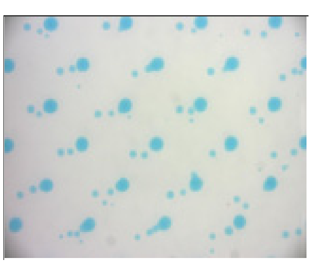

Figure 4. Ink droplet landing pattern on paper (without meniscus control).

Using a Bank Structure for Droplet Self-Alignment

A 400 mm × 500 mm substrate was patterned, and the positional accuracy of the dots over the entire surface of the substrate was measured. The positional accuracy was found to be ±15 microns. This level of accuracy is insufficient for producing high-definition displays. The accuracy with which inkjet head nozzle holes were processed, the alignment accuracy between the head and stage that carries substrates, the straightness of the ink droplets, and other factors were verified again. The verification results led to the conclusion that further improvements in structural accuracy would be very difficult with existing technologies. In lieu of structural modifications to improve accuracy, therefore, we developed substrate surface treatment and thin-film formation process technologies. Banks comprising an organic material are formed on the black-matrix regions of substrates so that each pixel is surrounded. The banked substrates are then plasma-treated in an oxygen gas atmosphere in a first step, followed by a second step in which they are plasma-treated in a fluorine atmosphere. When performed in this order, the plasma treatment causes oxygen, which has low surface tension, to adhere to the surface of the glass, making it lyophilic. Meanwhile, the fluorine bonds with the surface of the organic banks, making the banks lyophobic. A droplet containing a red, green, or blue colorant is deposited by an inkjet machine in the bank-enclosed pixel regions. The volume of the droplets is controlled so that an appropriate amount of colorant will remain after the droplets dry. Ejected droplets that land on the glass region of a pixel wet the surface and spread at a low contact angle before stabilizing. Ejected droplets that land on the lyophobic top layer of banks have a high contact angle. They slide down the banks to the glass region of the pixel. The banks thus prevent contact between droplets ejected into adjacent pixels and the running of droplets into an adjacent pixel. After the liquid dries, the RGB colorants comprise a flat film. The use of these banks allows the formation of color filters wherein the final droplet positions are accurate to about 1 micron.

Print Head

For the inkjet print head, a MACH (Multi-layer Actuator Head) system manufactured by Seiko Epson was used. MACH heads are an on-demand type system equipped with multiple nozzles that can be driven at high speed. The basic ejection frequency is 32 kHz. The structure of a MACH head is shown in Fig. 5.

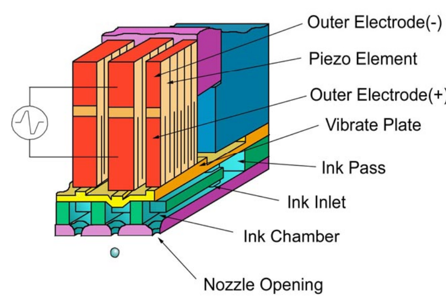

Figure 5. Head structure.

The ink droplet ejection reliability of the MACH head was secured, and the volumetric values required for color filter performance were obtained by optimizing the electrical waveform signals sent to the piezo driving elements as described above, and by reviewing and modifying the head assembly process to ensure that all nozzles eject the same volume of ink.

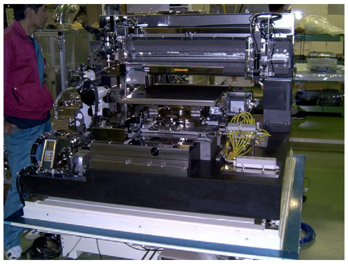

Figure 6. Special-purpose inkjet printer.

In addition, the materials used in the head were exhaustively reviewed from the perspective of solvent resistance, because an organic solvent is typically selected for liquefying and dispersing the polymer material used to form color filters and other layers. Reliability studies confirmed that, with the head specialized for this type of industrial application, neither the size of ejected droplets nor their traveling speed change, even after ejecting in excess of 2.5 billion droplets per nozzle.

Special-Purpose Inkjet Printer

Generally speaking, the limit for absolute positioning accuracy on media (normally paper) is only about 100 microns even for commercially available 1,440 dpi, high-resolution printers. The dots spread on the media to between 60 and 80 microns in diameter, and the location accuracy of droplet edges cannot be controlled. Moreover, commercially available printers are not adequately solvent resistant to withstand extended use with solvent inks. Epson thus developed an original inkjet machine (Fig. 6) specifically for fabricating color filters. This special-purpose inkjet machine is equipped with a high-precision stage and an auto-alignment mechanism for the substrate and head. The ejection control system was modified to allow the machine to eject droplets in a given location and at a given pitch during operation. The absolute landing accuracy of ink in a given location on a substrate measuring 400 mm × 500 mm is ±15 microns. Another difference between this inkjet machine and a commercially available printer is the level of reliability required. In industrial applications, a machine may run continuously 24-hours a day and must operate stably the entire time. To achieve stable operation, therefore, this industrial inkjet machine was configured with an inkjet head maintenance structure unlike anything seen in a commercial printer. A wet-type maintenance mechanism is used to maintain the cleanliness of the nozzle plate. An original sequence prevents an increase in the viscosity of ink at the nozzles. A droplet flight and landing measurement function monitors nozzle clogging and the straightness of the flight path. And, an ejection volume measuring apparatus and feedback control system control and maintain the volume of ejected droplets at a fixed level.

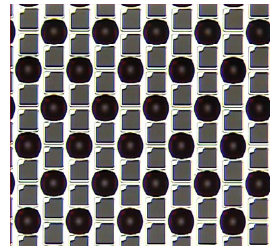

Figure 7. Ink droplets on glass.

Substrates

The substrates patterned by this industrial inkjet machine differ from ordinary printer output in that they are nonabsorbent. The shape of a functional liquid after landing on the surface of a glass substrate is determined by the characteristics of the liquid itself, as well as by the surface conditions of the substrate (Fig. 7). The bank structure and the glass surface that comes into contact with the liquid were optimized so as to control the final shape of a pattern. The banks were designed to strongly repel ink solvents, either by the inclusion of a fluorinated polymer or by modification of the bank surface. The banks are formed on top of an opaque layer of metal (a black matrix). The surface of glass is normally lyophilic. However, the adhesion of organic matter and so forth can cause irregularities in lyophilic properties. To provide uniform lyophilic properties, therefore, the glass was surface-treated under normal atmospheric pressure using an original technology developed by Epson.

Drying and Color Filter Formation

Figure 8 shows the process for fabricating color filters using an inkjet method.

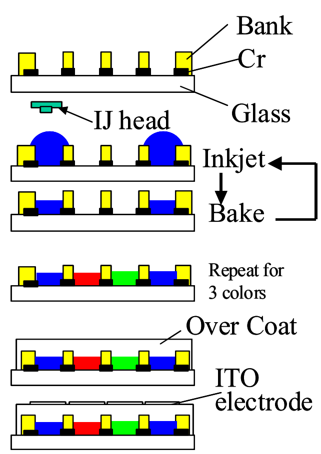

Figure 8. Color Filter Fabrication Process.

Even if the ink drifts over to a bank, the bank's ink-repelling properties cause the ink to contract and gradually settle to within the pixel opening inside the bank structure. This phenomenon is dependent on more than just the optimization of bank shape; it is also greatly affected by drying conditions such as time and temperature.

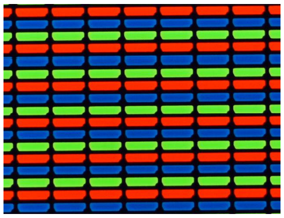

Figure 9. LCD pixel photograph.

Hence, these drying conditions were also optimized. In the process of optimizing the drying conditions, it was found that the initial shape of the liquid prior to drying is important, so a concurrent effort was made to verify the best conditions for the arrangement of dots during inkjet printing (processing techniques for things such as ink droplet landing position and error variance). With the establishment of the above two drying and film deposition technologies, variation in the uniformity of the thickness of the color layer was narrowed to within ±1. 25% within each pixel, chips and substrate. With this level of uniformity color variations cannot be detected by the eye when an LCD is on (Fig. 9)

Potential Applications for Inkjet Technology

This technology is basically suited to high-mix, low-volume production. Pattern designs can be modified for a variety of different models simply by altering digitally processed electronic CAD data. In addition, the production system platform is the same even when fabricating devices that differ structurally as much as, say, color filters and organic LEDs, and a new manufacturing line can be built merely by changing the functional material that is supplied. A facility that was used to fabricate color filters one day can operate as an organic LED fabrication facility the next. The recently developed inkjet film deposition production technology is not limited to flat panel display applications. The applications being developed for this technology at Seiko Epson are shown in Table 1.

Table 1: Applications in Flexible Devices

Device	Application Process
Display panels	LCD color filter formation
	Organic LED formation
	LCD liquid crystal coating
	LCD alignment layer coating
	LCD spacer formation
	LCD electrode formation
	Organic TFT device formation
Wired substrates	Printed circuit board wiring formation
	Printed circuit board silk screening
	Printed circuit board resistor formation
	Printed circuit board capacitor formation
	Printed circuit board coil formation
Other	Micro-lens formation
	Bio (DNA) chips
	Bio protein synthesis

Applications in Deposited-Type Electronic Devices

The formation of thin film transistors using organic materials[5] and the results of functional evaluations have been reported outside Japan. But a method of printing directly on substrates can also be used to form devices such as plasma display buses,[6] metal wiring patterns on circuit boards, resistors built into substrates as a part of conventional chips, and functional devices such as capacitors, diodes and transistors. In circuit fabrication, this technology shows potential for achieving unprecedented levels of integration. The potential for deposited-type electronic devices fabricated using inkjet technology is expected to grow moving forward.

Applications in Flexible Devices

To date, flat panel displays have been fabricated on rigid glass substrates. Glass is used largely because it can withstand the high temperatures reached in conventional manufacturing processes and also for reasons relating to things such as production accuracy and liquid crystal principles of operation. However, this inkjet machine is also highly amendable to the direct drawing of micro-patterns on flexible materials such as plastic films. Reel-to-reel manufacturing processes can be built and will lead to the emergence of extremely thin information devices. Whether glass or plastic is used, the structure wherein an inkjet head travels back and forth over a substrate without touching it is the same. The application of inkjet technology to flexible devices can be expected to bring about never before seen, novel applications that promise to change and enrich lives. For example, very few homes, especially in Japan, have the space to accommodate a large-screen television. However, an ultra-thin, flexible display could be placed just about anywhere. Such a display would also erase concerns about injury from a heavy TV in the event of a major earthquake. Moreover, in the near future, flexible displays will free up the wasted space currently occupied by information equipment within the home.

Other

Direct patterning with liquid droplets also presages the emergence of new industrial products. For example, an inkjet head could be mounted on the end of a robot arm and used to directly print micro-patterns on three-dimensional objects, promising the advent of innovative new devices.

Economic Impact

The transition to flat panel displays (FPDs) is not unique to Japan, either, but is steadily picking up speed, especially among the affluent, in Europe, America and Southeast Asia. This generational shift is due in part to the space-saving advantages offered by thin, lightweight FPDs, but the biggest reason for the shift is that consumers recognize dramatic improvement in FPD picture quality; the picture looks real. Against this backdrop, new product plans based on inkjet production technology have been formed. The plans involve the commercialization of organic light-emitting diode (OLED) displays, considered to be the ultimate display for enabling a more realistic picture. Epson was the first to recognize that its inkjet technology could be used to form patterns made from light-emitting polymer (LEP) materials and thus has continued research in this area.[7] Epson has set its sights on developing a commercial high-definition, full-color OLED display by developing special-purpose inkjet printers and inks containing LEP materials, low-temperature polysilicon TFTs, and technologies for treating the surface of substrates equipped with banked structures. In May 2004, these efforts lead to the announcement that Epson had produced the world's first 40-inch OLED display prototype. If a large-sized, 40-inch OLED display can be fabricated, then, obviously, the technology can be applied to panels of smaller sizes. Medium and small panels that reproduce realistic moving images in broadband environments have come a reality. According to estimates that came out in the first half of 2005, the global FPD market is expected to grow to $100 billion, total, in 2010. Large-sized displays will account for half, or $50 billion, of the total market. This compares to a total FPD market of $40-billion in the year 2000, of which large-sized displays accounted for $3 billion. OLED displays offer basic performance that is superior to that of either liquid crystal or plasma. Their emergence on schedule could thus further drive up these estimates. In fact, it is estimated that OLED displays could account for 1/4 to 1/2 the estimated total market in 2010, so the potential for a fierce restructuring of the industry on a global scale is easy to envision.

Reliability

Inkjet heads, the key device in this technology, pattern the surface of a substrate by separating a liquid into microscopically small droplets and then depositing them at high speed and high accuracy. Variations in the amount of ink ejected are so slight as to be imperceptible—and not only variation within a single nozzle but variation among all the nozzles on the same head. In addition, the head cycle-life exceeds 2. 5 billion shots per nozzle, and the flight accuracy of the ink droplets that are formed is such that each can be placed inside a 5-micron circle at a distance of 0. 5 mm from the nozzle surface to the recording medium. This level of reliability was achieved largely because the structure of the inkjet machine itself is exceedingly simple, the amplitude of the actuator that controls the motion of the menisci is a miniscule 1 micron or less, and the system operates in accordance with the fundamental laws of motion for liquids. In addition, there is a highly linear correlation between the amount of change in the piezo elements, which serve as head actuators and which convert electrical energy to kinetic energy, and the volume of ink droplets ejected from the nozzles. Given this intrinsic reliability and the use of controllable inkjet technology, this production technology has acquired high reliability in the fabrication of devices.

Design Flexibility

The substrate to be patterned using this inkjet machine should be flat, but, other than that, the nature of the substrate material does not matter. The material can be solid, like a glass or silicon wafer, or flexible, like a plastic film. Nor is the size of substrates particularly limited. Micro-patterns can be formed as long as the substrate allows an inkjet head to travel over it. This lack of limitations enhances the flexibility with which manufacturing systems can be laid out. In addition to production systems that are installed level with the floor, vertical configurations that are inclined to the floor are also possible. Using the system layout that is best suited to the device to be manufactured will enable the optimization of factories and maximize investment productivity. For example, in the coming ubiquitous network society, computers will be built into a vast array of goods, giving the things around us—our furniture, home appliances, stationery and more—the functions of an information and communication device. To achieve this vision, it will be essential to make smaller, lighter circuit boards that offer greater performance and to increase the size of displays while giving them a slimmer profile. Inkjet machines will make it possible to produce lightweight, wall-mounted devices inexpensively and, moreover, with a lower consumption of energy. They will enable the realization of thin, lightweight, truly wall-mountable TVs, for example. OLED displays fabricated on plastic substrates will be achievable, and paper-like flexible displays will materialize. Ultra-large displays that cover entire walls are expected to creep into homes, revolutionizing the living space. There will be a commensurately dramatic increase in the design options for key devices used in homes, transportation, clothing, food packaging, distribution, communication means and much, much more. Technology will thus enhance our lives.

Practical Implementation

Epson organized an Inkjet Industrial Applications Project team in October of 2000. The team's charter is to develop direct-draw inkjet micro-patterning technology into a core technology of the company. Additionally, to promote joint development with partners, Epson began rolled out operations globally, setting up the Suwa Minami Open Laboratory in June of 2002, followed in October of the same year by the Cambridge Inkjet Open Laboratory, in Cambridge, England. In May 2004, Epson unveiled the world's first prototype large-screen (40-inch), full-color OLED display fabricated using inkjet technology and announced its intention to bring the display into mass production in 2007. This news reverberated throughout the flat panel display industry, which had finally crossed over to the growth phase for liquid-crystal and plasma TVs, and awakened high expectations for continuous development of the industry in Japan. In November of 2004 Epson announced that it had succeeded in developing the world's first ultra-thin 20-layer circuit board manufactured by using an inkjet machine to alternately draw patterns and form layers on the board using an ink containing a dispersion of silver micro-particles and an insulator ink. On April 27, 2005, Epson announced that it had used inkjet technology to form liquid-crystal alignment layers for LCDs, marking the first example of the actual implementation of inkjet technology in an industrial application.

Conclusion

Revolutionary production technology has been developed and implemented for the formation of thin films in products such as flat panel displays and semiconductors. Inkjet technology has been introduced to realize groundbreaking levels of energy savings and efficiency. The development of this production technology required all of the following to be optimized: ink, surface treatments for substrates to be patterned, a piezo-driven on-demand inkjet head, an industrial printer, a drying process for functional materials, and a device assembly process. This inkjet production technology expands the application of direct-draw micro-patterning into the realm of industrial production. Moreover, it shows potential for use in a radical new manufacturing process that at once solves the serious drawbacks inherent in photolithography and vacuum deposition processes: mass consumption of materials, and the maintenance of massive and expensive fabrication facilities. The promulgation of the Kyoto Protocol makes the introduction of low-energy manufacturing processes like this more important than ever. And, as for cost savings and CO_2 transactions, we firmly believe this is the most effective means for conserving the global environment.

References

1. T. Kitahara, Japan Hardcopy ‘99, 335 (1999).
2. H. Kiguchi et. al., Proceedings of Asia Display/IDW’01, 1745 (2001).
3. T. Shimoda et al. SID 99 Digest, 376 (1999).
4. T. Takahashi, Proceedings of IS&T 17th International Conference on Digital Printing Technologies, 323 (2001).
5. T. Kawase et. al., Tech. Digest of IEDM, 623 (2000).
6. M. Furusawa and H. Kiguchi et. al. SID01 Digest, 753 (2002).
7. T. Shimoda and H. Kiguchi et. al. , MRS BULLETIN, 28,821-827 (2003).

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