MICRO-DROPLET GENERATORS

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Introduction

Micro-droplet generators are becoming an important research area in MEMS (Micro-Electro-Mechanical-Systems), not only because of its historical valuable marketing device: inkjet-printhead, but also many other emerging applications in precise or micro amount fluidic control. There have been a long history of the development of micro-droplet generators since the inception of the ideas by sweet (1964, 1971) using piezo actuation, and HP as well Cannon corporation [Nielsen et al., 1985] in late 1970's using thermal bubble actuation. Tremendous research activates regarding inkjet applications have been devoted in this exciting field since then. Recently, with the emerging applications in biomedicine, fuel injection, chemistry, pharmaceutics, electronic fabrication, micro optical device, IC cooling, and solid free form, micro-droplet generators regain lots of research interests. Thus, many new operation principles, designs, fabrication processes, and materials related to micro-droplet generation were explored and developed during the last decade supported by the micromachining technology.

In this chapter, the micro-droplet generators are defined as droplet generators generating micro-sized droplets in a controllable manner, i.e., droplet size and number can be accurately counted and controlled. Thus, atomizer, traditional fuel injector or similar droplet generation devices without the aforementioned manner are not discussed.

Micro-droplet generators usually employ mechanical actuation to generate high pressure to overcome liquid surface tension and viscous force for droplet ejection. Depending on the droplet size, the applied pressure is usually higher than several atmospheres. The operation principles, structure/process designs, and materials often play key roles in the performance of droplet generators.

The applications of micro-droplet generators, in addition to the well-known application of inkjet printing, have a wide spectrum on various fields, such as direct writing, fuel injection, solid free form, solar cell fabrication, LEPD fabrication, packaging, micro optical components, particle sorting, micro dosage, plasma spraying, drug screening/delivery/dosage, micro propulsion, integrated circuit cooling, and chemical deposition. Many of them may become key technologies for integrated micro systems in the near future.

This chapter provides the reader an overview of the operation principles, physical properties, design issues, fabrication process and issues, characterization methods, and applications of micro-droplets generators.

Operation Principles of Micro-droplet Generators

There have been many attempts to generate controllable micro droplets [Myers et al., 1984, Buehner et al., 1977, Twardeck et al., 1977, Carmichael et al., 1977, Ashley et al., 1977, Bugdayci et al., 1983, Darling et al., 1984, Lee et al., 1984, Nielsen et al., 1985, Bhaskar et al., 1985, Allen et al., 1985, Krause et al., 1995, Chen et al., 1995, Tseng et al., 1996, Hirata et al., 1996, Zhu et al., 1996]. Most of these methods have employed the principle of creating pressure differences, either by lowering the outer pressure of a nozzle or increasing the inner pressure, to push or pull liquid out of the nozzle to form droplets. Typical examples are: pneumatic, piezoelectric, thermal bubble, thermal buckling, focused acoustic wave, and electrostatic actuations. The basic principles of those droplet generators are introduced in the following sections. An ejection method by acceleration is also included in the last section, in which inertial force is employed for droplet generation.

Pneumatic Actuation

Spray nozzle is one of the most commonly used devices for generating droplets nowadays in the applications of airbrush or sprayer. Two types of spray nozzles are shown in Figure 1. Figure 1a shows that the air brush generates lower pressure at the outer of the capillary tube by blowing air across the tube end, which forces liquid to move out of the tube and form droplets. The second one, a sprayer, shown in Figure 1b, employs high pressure to push liquid through a small nozzle to form droplets. Typical sizes of the droplets generated by spray nozzle are around tens to hundreds of ?m in diameter. The device can be fabricated in micro size by micro-machining technology. However, it is hard to control each nozzle separately in an array format.

Piezoelectric Actuation

The droplet ejection by a piezoelectric actuation was invented by Sweet in 1964. Based on the piezoelectric technology, there are two types of piezoelectric devices. One is called continuous inkjet [Buehner et al., 1977, Twardeck et al., 1977, Carmichael et al., 1977, Ashley et al., 1977]. Figure 2a schematically shows the operational principle of this type of inkjet. Conductive ink is forced out of the nozzles by pressure. The jet would break up continuously into droplets with random sizes and spacing. The size and spacing of the droplets can be controlled uniformly by applying an ultrasonic wave with fixed frequency to the ink through a piezoelectric transducer. The continuously generated droplets pass through a charge plate, and only the desired ones would be charged by the electric field and deflected to printout, while the non-desired ones are collected by a gutter and recycled. One piezoelectric transducer can support multiple nozzles, so the nozzle spacing can be as small as desired for high-resolution arrays. However, the complication of the droplet charging and collecting system is the major obstacle to practice this device.

The other device, called droplet-on-demand inkjet, utilizes piezoelectric tube or disc for droplet ejection only when printing a spot is desired [Bugdayci et al., 1983, Darling et al., 1984, Lee et al., 1984]. Figure 2(b) shows a typical drop-on-demand drop generator. The operational principle is based on the generation of an acoustic wave in a fluid-filled chamber by a piezoelectric transducer through the application of a voltage pulse. The acoustic wave interacts with the free meniscus surface at the nozzle to eject a single drop. The major advantage of drop-on-demand method is that complex system for droplet deflection and collection is not required. However, the main drawback is that the size of piezoelectric transducer tube or disc, in the order of sub mm to several mm, is too large for high-resolution applications. It was reported that the typical frequency for a stable operation of piezoelectric inkjet would be tens of kHz.

Thermal-Bubble Actuation

Thermal bubble jet has been developed by HP in USA, and by CANON in Japan since early 1980's [Nielsen et al., 1985, Bhaskar et al., 1985, Allen et al., 1985]. There are also many other designs reported in the literature [for example, Krause et al., 1995, Chen et al., 1995, Tseng et al., 1996, 1998]. Figure 3 shows the cross-section of a thermal bubble jet. Liquid in the chamber is heated by pulse current applied to the heater under the chamber. The temperature of the liquid covering the surface of the heater rises to around the liquid critical point in microseconds, and then a bubble grows on the surface of the heater, which serves as a pump. The bubble pump pushes liquid out of the nozzle to form a droplet. After the droplet is ejected, the heating pulse is turned off and the bubble starts to collapse. Liquid refills the chamber by surface tension on the free surface of meniscus for its recovery to the original position. The second pulse starts again to generate another droplet. The energy consumption for ejecting each droplet is around 0.04 mJ for HP Think Jet printhead. Because bubbles can deform freely, the chamber size of the thermal bubble jet would be smaller than that of other actuation means, which is important for high-resolution applications. The resolution reported in the literature ranges from 150 to 600 [Krause et al., 1995] and 1016 [Chen et al., 1995] dpi. The typical operational frequency for the contemporary thermal bubble jets is around several to tens of kHz.

Thermal-Buckling Actuation

Hirata et al. (1996) employed Buckling diaphragm for the droplet generation.

Figure 4 schematically shows the basic operation principle. A composite circular membrane, consisting of silicon dioxide and nickel layer, is fixed on the border and remains a small gap to the substrate. A heater is placed at the center of the composite membrane and electrically isolated from it. Pulsed current is sent to the heater and then the membrane is heated for several ?s. When the thermally induced stress is greater than the critical stress, the diaphragm buckles up abruptly and ejects a droplet out of the nozzle. The power required to generate a droplet at a speed of 10 m/s is around 0.1 mJ for a 300-?m-diameter diaphragm. The power consumption and the device size of buckling membrane inkjet are much larger than those of the thermal bubble jet. The reported frequency response of membrane buckling jet ranges from 1.8 to 5 kHz depending on the desired droplet velocity.

Acoustic-Wave Actuation

Figure 5 schematically shows a lensless liquid ejector using a constructive interference of acoustic waves to generate droplets [Zhu et al., 1996]. A PZT thin-film actuator with the help of on-chip Fresnel lens was employed to generate and focus acoustic waves on the air-liquid interface for droplet formation. The actuation comes from the excitation of a piezoelectric film under a burst of RF signal. The device does not need a nozzle to define droplets, reducing the troublesome clogging problem occurring in most of the droplet generators employing nozzles. Droplet size can also be controlled by the acoustic wave with specific frequencies. However, due to the vigorous agitation of acoustic wave in the liquid, it is difficult to maintain a quiet interface for reliable and repeatable droplet generation. As a result, a "nozzle area" is still desired to maintain the interface in a stable level. The applied RF frequency ranges from 100 to 400 MHz and the burst period is 100 ?s. The power consumption for one droplet is around 1mJ, which is high compared to other principles. The droplet size ranges from 20 to 100 ?m, depending on the RF frequency. The reported size of the device is 1?1 mm^2, which is much larger than other droplet generators mentioned in the previous sections.

Electrostatic Actuation

Electrostatically driven inkjet print head was first introduced by Seiko Epson corporation [Kamisuki et al., 1998, 2000] for commercial printing purpose. As shown in Figure 6, the actuation starts by applying a DC voltage between electrode plate and pressure plate to deflect the pressure plate for ink filling. When the voltage turns off, the pressure plate reflects back to push the droplet out of the nozzle. This device is developed for the use in electric calculators due to its low power consumption, less than 0.525mW/nozzle. The driving voltage for a SEAJet^{TM} is

26.5 V and driving frequency can be up to 18 kHz with uniform ink ejection. The 128 nozzles/chip with 360 dpi pitch resolution has also been demonstrated. This device was claimed with high printing quality (for bar code), high speed printing, low power consumption, and long life time under heavy duty usage (life time more than 4 billion ejections) and low acoustic noise. However, the fabrication comprises complex bonding process among 3 different micromachined pieces. Besides, the pressure plate needs very precise etching process to control the accuracy and uniformity of the thickness. Due to the deformation limitation of solid materials and alignment accuracy in the bonding process, the nozzle pitch may not easily go further down for higher resolution applications.

Inertial Actuation

Inertial droplet actuators apply a high acceleration to the nozzle chip for droplet ejection. The apparatus is shown in Figure 7. The print module consists of large reservoirs on the top plate, which connects to the nozzles on the bottom one. The print module is mounted on a long cantilever beam with a piezo-bimorph-actuator for acceleration generation. It requires 500 ?s to generate 1 nl droplets from 100-?m-diameter nozzles. Twenty-four liquid droplets of different solution types were demonstrated to be ejected simultaneously from the nozzles in a 500-um-pitch.

The smallest droplet claimed to be generated is 100 pl from 50-?m-diameter nozzles. This principle provides a gentle ejection process for bio-regent applications. However, the ejection of smaller droplets may encounter strong surface tension and flow drag forces in micro scale, much larger than the droplet inertial. Besides, that the droplets can not be selectively and individually ejected from the desired nozzles limits its applications.

Physical and Design Issues

The sequence of droplet generation involves wide ranges of physical issues and design concerns, including micro fluid flow, heat transfer, wave propagation, surface properties, material properties, and structure strength. The following sections discuss frequency response, thermal cross talk, hydraulic cross talk, overfill, satellite droplets, puddle formation, and material issues, commonly seen in micro-droplet generators.

Frequency Response

Frequency response of droplet generators is one of the important measures to assess the performance. The reported typical frequency response for thermal bubble jets, piezo jets, thermal bulking jets, acoustic wave jets, electrostatic and inertial jets, ranges from kHz to tens of kHz. Piezo and acoustic wave jets typically have higher frequency response than others. Recently, the novel design by Tseng et al., (1998) greatly improved the frequency response of thermal bubble jets by about three times (35 kHz), which is compatible with the speed of piezo jets. Higher speed devices (in the range of hundreds of kHz) are currently under development by major inkjet printer makers and will have further breakthrough in the next few years.

There are three important time constants related to the frequency response of micro droplet generators, including actuation, droplet ejection, and liquid refilling, as shown in Figure 8.

The typical time constant from heating to bubble formation in a thermal bubble jet is around 5-10 ?s, for the chamber size ranging from 20 to 100 ?m [Tseng et al., 1998d]. Thermal bulking and electrostatic type micro-droplet generators have the actuation time around tens to hundreds of ?s [estimated from Hirata et al., 1996], owning to the large actuation plate required for sufficient displacement for droplet formation. Inertial type required even longer actuation time [estimated from Gruhler et al., 1999], typically hundreds to thousands of ?s, due to its large cantilever structure for generating large droplets with sufficient inertial force to overcom liquid surface tension and viscosity. The actuation time for piezo or acoustic wave type may be shorter [Darling et al., 1984, Zhu et al., 1996], around ?s to tens of ?s.

After the application of actuation pressure to the liquid, the droplet starts to eject. The ejection sequence usually takes couple to hundreds of ?s for the droplet volume from 1 pl to 1 nl [Tseng et al., 1998d], which does not vary much for different operation principles.

The liquid refills back automatically by surface tension force after the droplet ejection. Liquid refilling time can vary in 3 orders of magnitude, e.g., from less than 10 ?s to over 1 s, depending on the length and geometry of the refilling path. In most of the commercial inkjet printhead designs, chamber neck [Nielsen et al., 1985], elongated chamber channel [Neilsen et al., 1985] or physical valve [Karz et al., 1994] are used to prevent hydraulic cross talk and maintain a high pressure in the firing chamber. However, those designs, if not arranged properly, may greatly increase the refilling time causing a reduction in the frequency response. As a result, how to prevent the hydraulic cross talk without sacrificing the device speed becomes an important issue in the design of super high speed and high-resolution droplet generators. Tseng et al.(1998a, b, c) introduced a concept-virtual chamber neck-to speed up the refilling process of thermal bubble jets and suppress cross talk. The virtual neck, consists of vapor bubbles, forms for pressurization while droplet is ejecting, and opens up to reduce flow resistance while liquid is refilling, thus increases the frequency response. The concept is shown in Figure 9.

In the simulation of droplet actuation and formation sequence, much work [Curry et al., 1977, Lee et al., 1977, Levanoni et al., 1977, Pimbley et al., 1977, Fromm et al., 1984, Bogy et al., 1984, Asai et al., 1987-1992, Mirfakhraee et al., 1989, Chen et al., 1997-1999, Rembe et al., 2000] has been conducted on the bubble formation sequence, droplet generation, and aerodynamics of droplet traveling in the atmosphere for thermal bubble as well as piezo-type jets. Interested reader can refer to those works for details.

Thermal/hydraulic Cross Talk and Overfill

When nozzle pitch becomes small, two types of cross talk, hydraulic and thermal (for thermal bubble jet), become significant in multiple-nozzle droplet generators. Hydraulic cross talk relates to the transportation of pressure wave from the firing chamber to the neighboring chambers, as shown in Figure 10. The vibration of the meniscus of the neighboring chambers may result in poor droplet volume control, or even worse, unexpected droplet ejection. Thermal cross talk, which only appears in thermal bubble jet, is the phenomenon of thermal energy transportation from firing chamber to neighboring chambers, resulting in poor droplet volume control. After droplet ejection, the refilling process of liquid sometimes causes meniscus oscillation, posing another issue-overfill. Overfill, similar to cross talk, increases the waiting time for the next droplet ejection and even causes undesired droplet ejection. The phenomenon of overfill is schematically illustrated in Figure 11.

These issues stem from the fact that there is not enough flow compliance among nozzles. One of the solutions by IBM Inc. [Neilsen et al., 1985] is to lengthen channel length for each chamber. However, the increased serial compliance by the lengthened channel between the reservoir and chamber increases the flow resistance and inertia significantly, increasing the liquid refilling time.

HP Inc. tried to solve this problem by either using a parallel compliant (reservoir) or a chamber neck. Figure 12 shows a slot used as a reservoir beside the nozzles to store energy while bubble is exploding, and to release energy while bubble is collapsing [Neilsen et al., 1985]. Figure 13 shows the second approach by narrowing down the inlet of the chamber to form chamber neck.

The effects from the aforementioned methods were simulated by Buskirk et al. (1988). Figure 14 shows the simulation results of the meniscus position of firing chamber and neighboring chamber for different chamber designs. In the first figure, without any design of flow compliance, the meniscuses on both the firing chamber and the neighboring chamber show huge fluctuation. Doubling the channel length (series compliance) damped down some of the fluctuation, but not completely. Only the chamber neck design almost completely damped down the meniscus fluctuation, however, it has the slowest response among the three.

In contrast to fixed chamber neck design, Xerox corp. [Karz et al., 1994] used a flexible plate as a valve to address the cross talk issue. However, this design may suffer from low frequency response and material reliability problems. Moreover, Tseng et al. (2000) used a novel design of virtual chamber neck, employing bubble as a virtual valve, to reduce the cross talk problem while maintaining the high frequency response of the droplet generator, as shown in Figure 9. Their work demonstrated that bubble has faster response and more reliable operation performance in micro scale than solid valves.

In addition to hydraulic cross talk, thermal cross talk, in Tseng’s work, was also reduced by placing heater on the chamber top of a thin film with low thermal conduction, instead of leaving on the thick substrate through which heat can be conducted to the neighbors [Tseng et al., 1998c, 2001a]. It is clear that as the nozzle pitch becomes closer, the cross talk problem becomes more severe in the operation of very high resolution and high-speed droplet generators.

Satellite Droplets

Satellite droplets result from the break down of the long ejected liquid column by the interaction among surface tension, air drag force, and inertial force. The velocity mismatch along the liquid column, resulting from the variation of actuation velocity, promotes the break down. The droplet ejection sequence captured from a commercial inkjet, reveals the detail steps of satellite droplet formation, as shown in Figure 15 [Tseng et al., 1998c]. When applied for printing, the quality is degraded from the occurrence of satellite drops as revealed in Figure 16. Satellite droplets also reduce the accuracy for precise liquid dispensing control.

A literature survey reveals that there have been many attempts to predict the droplet formation. Asai et al. (1987-1992) conducted both numerical simulation and experimental measurements to obtain the temporal variation of droplet length at a thermal bubble jet. However, the formation process of satellite droplets is not included. In drop-on-demand inkjet, Fromm et al. (1984) and Chen et al. (1997-1999) solved the Navier-Stokes equation to predict the droplet formation, and showed the process of satellite droplet formation. Pimbley et al. (1977) and Chen et al. (1997b) demonstrated the evolution of droplet as well as satellite droplet formation by flow visualization. However, the detailed method for eliminating the separation of satellite droplet from the main droplet was not discussed.

Different efforts have been tried to eliminate satellite droplets from the commercial product. In piezo droplet generators, triangular waves were used to eliminate satellite drops [Chen et al., 1999]. In thermal bubble jets, Tseng et al. (1998a, 1998c, 2000) proposed a novel method, employing bubble as trimmer to cut off long droplet tail to eliminate satellite droplets, as shown in Figure 17. The shortened tail of the liquid column, by the bubble trimmer in Tseng's work, is drawn back by surface tension into the main droplet, thus eliminates satellite drops.

Puddle Formation

Liquid puddle forms when liquid is pushed to flow outward and accumulates on the nozzle outside surface. Puddle poses great blocking force on droplet ejection, causing the distortion or even the stop of droplet ejection. One of the major reasons of puddle formation is because of the hydrophilic nozzle surface. When touching with working fluid from the chamber, the nozzle outer surface accumulates liquid puddle. It was observed by Tseng et al. (1998d) that the puddle appears after several continuous operations, i.e., the chamber surface does not accumulate puddle until it gets wet after several runs. If the operation of droplet ejection stops, puddle is drawn back to chamber by surface tension. However, once the chamber surface becomes wet, there is always a puddle formation when operation starts again. Figure 18 shows the formation of puddle during the running of the microinjector [Tseng et al., 1998d]. Notice the droplet ejection position is away from the nozzle, due to the distortion by liquid puddle.

One way to eliminate puddle formation is to coat the chamber outer surface with a non-wetting material to prevent the wetting process of the working fluid. The inner surface of the chamber needs to remain hydrophilic for liquid refill. However, even with the coating, there is still no guarantee that the puddle will not form. More researches are underway to fully understand the mechanism in the puddle formation process.

Material Issues

Material issues, including stress, erosion, durability and compatibility, are very complex issues in the design of micro droplet generators.

In the processing aspect, material compatibility, stress, and durability problems are commonly discussed. Material compatibility issues result from the processing temperature, processing environment (oxidation, reactive gas, etc…), etching method used, and adhesion ability; stress issues are usually from processing temperature as well as doping condition; material durability issues are either material intrinsic properties or from the mechanical forces induced during the process, i.e., fluid flow force, surface tension force, vacuum forces or handling force. Lots of care need to be taken in the process flow design to eliminate the material issues, such as compensating material stress during or post fabrication process; progressing high temperature process earlier than the low temperature material; finishing aggressive wet etching before metal film deposition; or using low temperature bonding material and process to protect IC and micro devices.

In the operation aspect, durability, stress, and erosion issues are the major concerns. Due to the cycling nature of droplet generation process, the materials chosen for actuation face the challenges not only from stress, but also from fatigue. The HP corp. reported that the possible failure reasons of the heater passivation material are cavitation, and thermal stress [Bhaskar et al., 1985]. As a result, silicon, low stress silicon nitride, silicon carbide, silicon dioxide, and some metals, are usually used to overcome the aforementioned problems. In addition to proper material selection, reducing sharp corners in the design is also an important key to prevent material from crack by eliminating stress concentration points. Moreover, the erosion of structure materials from working fluid is another serious issue. Lee et al. (1999) reported the erosion of the spacer material in a commercial inkjet head while using diesel fuel as working fluid. In contrast, the materials, including silicon and silicon nitride used by Tseng et al. (1998c, 1998d) and Lee et al.(1999) in the micro injector, are free of this problem and can also be applied to wide variety of fluids, including solvents and chemicals. Selecting materials wisely, arranging them correctly in process, and properly designing the materials in the microstructures are the three important concepts in reducing material issues.

Fabrication of Micro-Droplet Generators

The common structures in most of the micro droplet generators include: manifold for liquid storage, micro channels for liquid transportation, micro chambers for liquid holding, nozzles for droplet size and direction definition, and actuation mechanisms for droplet generation. Occasionally, droplet generators may not have nozzles but they use energy focusing means to generate droplets locally, such as acoustic wave droplet generators [Zhu et al., 1996]. Before micromachining process becomes popular, most of the fabrication processes of micro droplet generators stem from the similar concept: nozzle plates, fluid handling plates and actuation plates are manufactured separately, and then integrated into one final device. However, as the nozzle resolution becomes finer, bonding processes pos severe alignment, yield, and material as well as IC compatibility problems. On the other hand, interconnection lines may not have enough space to pull out individually from each chamber when nozzle resolution is higher than 600 dpi. As a result, monolithic ways for the fabrication of high resolution, IC integrated droplet generators become very important. In the following sections examples of different fabrication means are introduced.

Multiple Pieces

Figure 19 schematically shows the traditional fabrication way of micro droplet generators by the bonding of fabricated structure pieces [Tseng et al., 1999]. Actuation plates by this mean are fabricated separately from the nozzle plates. In the thermal bubble jet, heaters are usually sputtered or evaporated and then patterned with IC circuit on the bottom plate, while peizo, thermal bulking, electrostatic, and inertial actuators consist of more complex structures, such as piezo disk, thin plate structure, or cantilever beam. Parallel to the actuator fabrication, nozzles are fabricated by electroforming [Ta et al., 1988], molding, or laser drilling [Keefe et al., 1997]. The combination of those processed pieces are assembled either by using polymer spacer material as intermediate layers [Siewell et al., 1985, Askeland et al., 1988, Hirata et al., 1996, Keefe et al., 1997], or directly adhering several pieces through anodic bonding [Kamisuki et al., 1998, 2000], fusion bonding [Gruhler et al., 1999], eutectic bonding or low temperature chemical bonding. However, most of the bonding means are chip level, not wafer level processes, and face the similar challenges of alignment, bonding quality, and material/process compatibility. As the nozzle resolution becomes higher than 600 dpi, alignment accuracy is hard to approach 4 ?m (10% of the nozzle pitch). Higher alignment accuracy significantly increases the fabrication cost especially for the chip level process. Bonding quality is another important issue corresponding to the fabrication yield of large array and high-resolution devices. On the other hand, the bonding materials (mostly polymers) chosen may not be suitable for the application environments and working fluids. Besides, the bonding process, involving heat, pressure, high voltage, or chemical situations, restricts IC integration with the droplet generators, and the IC integration is an essential part for large array and high resolution applications.

Monolithic Fabrication

In order to address the aforementioned issues, monolithic processes utilizing micromachining technology have been widely employed since early 1990's. In those monolithic means, two major methods have been introduced: one is the combination of bulk and surface micromachining and the other is the usage of bulk micro machining and deep UV lithography associated with electroforming (or UV lithography only).

For example, Tseng et al. [Tseng et al., 1998d] combined surface and bulk micromachining to fabricate micro droplet generator array with potential nozzle resolution up to 1200 dpi (printing resolution can be 2400 dpi or higher). In this design, double bulk micromachining processes were utilized to fabricate fluid handling system, including manifold, micro channels and micro chambers. Surface micromachining, on the other way, were used for heater, interconnection line, and nozzle fabrication. The whole process was finished on (100) crystal orientation silicon wafers. Figures 20 and 21 show the three-dimensional structure of the micro injectors and the monolithic fabrication process, respectively. The ejection of 0.9 pl droplets has also been demonstrated by Tseng et al. (2001b) with the high-resolution micro injectors. The structure materials used in the micro injector are silicon, silicon nitride, and silicon oxide, durable in high temperature and suitable for various liquids (even some harsh chemicals). ICs can be easily integrated with this device on the same silicon substrate.

The second case can be found in Lee's (1999) work. In the design, multi-exposure and signal development (MESD) lithography method were used to define micro channel and micro chamber structures (photoresist as sacrificial layer) and the physical structures were constructed by electroformed metal. The manifold was manufactured from the wafer backside by electrochemical methods [Lee et al., 1995]. This device was also demonstrated the capability of very high-resolution array and compatibility with the IC process. Another method, using photoresist as sacrificial layer and polyimide as structure layer, was introduced by Chen et al. (1998) for high resolution and IC compatible applications.

Characterization of Droplet Generation

Droplet trajectory, volume, ejection direction, and ejection sequence/velocity are four important quantitative measures to assess the ejection quality of micro droplet generators. The following sections briefly introduce the basic methods for the testing of droplet generation.

Droplet Trajectory

Droplet trajectory can be visualized by utilizing flashing light on the ejection stream, as shown in Figure 22, introduced by Tseng et al. (1998a). The white dots in Figure 23 show the droplets stream from the visualization. The visualized droplet trajectory follows an exponential curve, very different from the parabolic one expected for the normal size objects with a similar initial horizontal velocity. The droplet trajectory was also estimated by Tseng et al. (1998a) by solving a set of ordinary differential equations from the force balance, in both horizontal and vertical direction, of a single droplet flying through air.

From the analysis, the vertical position Y and horizontal position X of the droplet can be expressed by the following equations:

$$Y \;?\; U_{v?}[t \;?\; \frac{U_{v?}}{g}(1 \;?\; e^{\frac{?6??r_0}{m}t})] \qquad (1)$$

$$X \;?\; \frac{U_{H0}m}{6??r_0}(1 \;?\; e^{\frac{?6??r_0}{m}t}) \qquad (2)$$

where g is the acceleration due to gravity, t is the time, m is the mass and r_0 is the radius of the droplet, ? is the viscosity of air, $U_{v?} \;?\; \frac{mg}{6??r_0}$ is the droplet terminal velocity, and U_{H0} is the initial horizontal velocity. The trajectory is drawn in Figure 23 with the experimental result, and fits the visualized trajectory well except at the end, suggesting the interaction among droplets. From this simple analysis, the maximum flying distance of a droplet with a known diameter can be estimated as

$$X_{\max} \;?\; \frac{U_{H0}m}{6??r_0} \;?\; \frac{2?_{liquid}}{9?_{air}}(U_{H0}r_0^2)\text{, when t ~ ?} \qquad (3)$$

Here the maximum distance is proportional to the droplet velocity and droplet radius to the second power. For droplet with different droplet sizes and the same initial velocity, the maximum flying distance is dropped very fast for smaller ones. To obtain 1mm flying distance, the droplet with 10 m/s initial velocity needs to have the minimum radius of 2.7 ?m. From the above estimation, droplet size should be maintained beyond certain value to ensure enough flying distance for printing. Printing with very fine droplets (diameter smaller than a couple of micrometers) needs either increasing the initial velocity of droplets or printing in special vacuum environment to overcome the resistant force from air drag.

Ejection Direction

Droplet direction can be decided by the visualized trajectory. Many parameters, including nozzle shape, roughness, aspect ratio, and wetting property as well as actuation direction and chamber design, affect droplet direction. In general, symmetric structure design and accurate alignment can help on the control of droplet direction.

Ejection Sequence/velocity and Droplet Volume

To characterize the detailed droplet ejection sequence, a visualization system [P.-H. Chen et al., 1997b, Tseng et al., 1998c], as shown in Figure 24, has been widely used. In this system, an LED was placed under the droplet generator to back-illuminate the droplet stream. Two signals, synchronized with adjustable time delay, were sent to a microinjector and an LED, respectively. Droplets were ejected from a droplet generator continuously, and the droplet images were frozen by the flashlight from the LED at specified time delays, as shown in Figure 15. Droplet volume can be determined from the images by assuming the droplet is axi-symmetric, or from weighing certain numbers of droplets. Droplet velocity can be estimated by measuring the flying distance difference of the droplet fronts in success two images.

Flow Field Visualization

To better understand the flow properties, such as cross talk, actuation sequence, liquid refill, and droplet formation, inside micro droplet generators, flow field visualization is one of the most direct and effective ways. Flow visualization in small scale has some difficulties that do not occur in large scale, such as limited viewing angles, light sheet impossible, reflection from the particles trapped on the wall, short response time, and small spatial scale. Meinhart et al. (2000) adopted a micrometer resolution particle image velocimetry system to measure instantaneous velocity fields in an electrostatically actuated inkjet head. In the setup, 700-nm-diameter fluorescent particles were introduced for flow tracing, and the spatial as well as temporal resolutions of the image velocimetry are 5-10 ?m and 2-5 ?s, respectively. The four primary phases of inject operation, including infusion, inversion, ejection, and relaxation, were clearly captured and quantitatively analyzed.

Applications

More than a hundred applications have been explored employing Micro droplet generators. This section gives a summary to some of the examples of the applications.

Inkjet Printing

Inkjet printing involves arranging small droplets on printing medium to form texts, figures or images, and is the most well-known application. The smaller and the cleaner the droplets are, the sharper the printing is. However, smaller droplets cover smaller printing area and thus increases the printing time. Therefore in the printing application, high-speed micro-droplet generation with stable and clean micro sized droplets are desired for fast and high quality printing. The printing media can be paper, textile, skin, can or other surfaces that can adsorb or absorb printing solutions. Inkjet printing generated more than US$10 billions worldwide market in 2000 and keeps growing in the future.

Biomedical and Chemical Sample Handling

The application of micro droplet generators on biomedical sample handling has been an emerging field and drawing much attention since the past few years. Many research efforts have been focused on the droplet volume control, droplet size miniaturization, compatibility issues, variety of samples, and high-throughput parallel methods.

Luginbuhl et al. (1999), Miliotis et al. (2000), and Wang et al. (1999) developed piezo and pneumatic type droplet injectors, respectively, for the mass spectrometry purpose. Figure 25 schematically shows the design of the injectors. Those injectors are utilized to generate sub-micron to micron sized bio-reagent droplets for sample separation and analysis in a mass spectrometer, as shown in Figure 26. Lugnbuhl et al. (1999) employed silicon bulk micromachining to fabricate silicon nozzle plate and Pyrex glass actuation plate, while Wang et al. (1999) employed the combination of surface and bulk micromachining for fabricating the droplet generator. Those injectors are part of the lab-on-the-chip system for incorporating microchip to macro instrument.

Micro-droplet generators were also used by Koide et al. (2000), Nilsson et al. (2000), Goldmann et al. (2000), and Szita et al. (2000), for the accurate dispensing of biological solutions. Piezo and thermal type injector were used in those researches for protein, peptide, enzyme, or DNA dispensing. In those applications, the operation principle of the employed devices are similar to inject printing, in which single biological droplet can be precisely dispensed and deposited onto a desired medium, and the dispensing of droplet arrays can also be carried out. The arrayed bio-regents can further be bioprocessed for high throughput analysis.

Continuous jet type droplet generators were reported by Asano et al. (1995) to effectively focus and sort particles by using the electrostatic force. The experimental set up is shown in Figure 27. A syringe pump pressurizes the sample fluid containing those particles to pass through a nitrogen sheath flow for focusing, and then the sample is ejected from a piezoelectric transducer disturbed nozzle to form droplet. The droplets containing desired particles were charged at the breakup point and deflected into collectors. The reported separation probability for 5, 10, and 15 ?m particle can be as high as 99%. However, inner jet diameter limits the particle size for separation. Other than solid particle separation, this method can potentially be applied to cell sorting for biomedical applications.

In addition to biomedical reagent handling, micro droplet generators were widely used in chemical handling. For example, Shah et al. (1999) used inkjet to print catalyst patterns for electroless metal deposition. In their system, a Pt solution was employed and ejected by commercial inkjet printhead as seed layer for Cu electroless plating. The lines produced by this method were reported to be 100 ?m wide and 0.2-2 ?m high.

Fuel Injection and Mixing Control

Micro droplet generators can be used for fuel injection for the ability of dispensing controllable and uniform droplets, which are important for mixing and combustion applications.

Combustion efficiency depends on the mixing rate of reactants. The reactants in a shear flow are first entrained by large vortical structures (Brown and Roshko, 1974) and then mixed by fine scale eddies. The entrainment can be greatly enhanced by controlling the evolution of large-scale vortices either actively (Ho et al., 1982) or passively (Ho et al., 1987). The effectiveness of controlling large-scale vortical structures on increasing the combustion efficiency has also been experimentally demonstrated (Shadow et al., 1987). Although much work has been done on improving the mixing efficiency in combustion chambers, it still poses a great challenge in combustion research to improve the small scale mixing and reduce the evaporation time of liquid fuel.

Traditional injectors with nozzle size around tens to hundreds of ?ms in diameter can neither supply uniform micro droplets for reducing evaporation time and fine scale mixing, nor eject droplets which can be controlled individually to modulate vortex structure [Lee et al., 1999]. To overcome those limitations, Tseng et al. (1996) proposed micro droplet injector array fabricated by micromachining technologies for fuel injection. The droplets ejected from micro injectors are uniform and the size can be ?m to tens of ?ms in diameter, which is close to the micro scale of small turbulence eddies. The fine scale mixing can be carried out by the reaction of the small turbulence eddies directly with the micro-droplets. The evaporation time is also greatly reduced by increasing the evaporation surface from the droplet size reduction and uniformity. In addition, an appropriate selection of the micro injectors distributed around the nozzle of a dump combustor (Figure 28) provides spatial coherent perturbations to control the large vortices. Two types of coherent structures, i.e., spanwise and streamwise vortices, can be influenced by imposing subharmonics of the most unstable instability frequency of the air jet. Control of the spanwise vortices can be accomplished by applying temporal amplitude modulation on injection. If the ejecting phases of the micro droplets along the azimuthal direction are the same, the Mode zero instability (Brown et al., 1974) is enhanced. When a certain defined phase lag is imposed on these micro injectors, higher mode instability (Brown et al., 1974) waves are generated, which are usually beneficial for mass transfer enhancement. Since about thousand injectors are placed around the nozzle, the spatial modulation in the azimuthal direction can perturb the streamwise vortices. The interaction of streamwise and spanwise vortices by micro injectors brings forth fine scale mixing.

Direct Writing and Packaging

Micro droplet generators offer an alternative to the lithography process for electronics and opto-electronics manufacturing. This approach has the advantages of precise volume control of dispensed materials, data driven flexibility, low cost, high speed, and low environmental impact, as mentioned by Hayes and Cox (1998). The materials have been demonstrated for process including adhesive for component bonding, filled polymer systems for direct resistor writing and oxide deposition, and solder for solder bumping of flip-chip, BGA (Ball grid arrays), PCB (printed circuit board), and CSP (chip-scale-package) [Hays et al., 1999, Teng et al., 1988]. In those printings, temperature is desired to elevate to 100~200 ?C, and the viscosity of fluids need to be around 40 cps, and in some of the cases, inert process environment, such as nitrogen flow, is required to prevent the materials from oxidation.

Through direct writing by inkjet printing, the fabrication difficulty from photolithography or screen-printing process for solar cell metallization and LEP (light emitting polymer) deposition of LEPD (light emitting polymer displays) can be easily eliminated. In solar cell metallization, metalo-organic decomposition (MOD) silver ink was used to directly inkjet print onto solar cell surfaces for avoidance of p-n junction degradation under traditional screen printing method requiring 600-800 °C for firing process. Inkjet printing also provides the formation of uniform line film on rough solar cell surfaces [Tang et al., 1988a, 1988b, Somberg et al., 1990], which is not easy to be achieved by traditional photolithography way.

On the other hand, organic light emitting devices, requiring the deposition of multi organic layers to perform full color operation, face similar problems. Due to their solubility in many solvents and aqueous solutions, conventional ways, such as photolithography, screen printing and evaporation which need wet patterning process, are not suitable for them on the same substrate [Hebner et al., 1998, Shimoda et al., 1999, Kobayashi et al., 2000]. Thus direct writing of organic materials by inkjet printing becomes one of the promising solutions to provide a safe patternable process without wet etching procedure. However, owing to the pinholes appearing on the patterned materials, high quality polymer devices may not be easily inkjet printed. Yang's group proposed a hybrid way combining inkjet printed layer with another uniform spin coated polymer layer to overcome the problem [Bharathan et al., 1998]. In such a system, the uniform layer serves as a buffer layer to seal the pinholes and the inkjet-printing layer consists the desired patterns [Bharathan et al., 1998]. .

Optical Component Fabrication and Integration

Integrated micro optics has become a revolutionized concept in the optics field, since it provides the advantages of low cost, miniaturization, improved spatial resolution as well as time response, and reduction of assembly process on optical systems, which is not possible by the traditional means. As a result, how to fabricate and integrate miniaturized optical components with the performance similar or even better than traditional ones are critical issues in integrated micro optics systems.

Standard bulk or surface micromachining provides various ways in the fabrication of active/passive micro mirrors, wave-guides, and Fresnel lens, but not easy in refractive lens with curved surface. Compared to the photolithography mean which utilizes patterned and melted photoresist column to be lens, the inkjet printing method provides more flexibility on process, material choices, and system integration. Cox et al. employed inkjet-printing technology to eject heated polymer material to fabricate micro lenslet array [Cox et al., 1994, Hays et al., 1998]. The shape of the lens was controlled by the viscosity of the droplets at the impact point, the substrate wetting condition, and the cooling/curing rate of the droplets [Hays et al., 1998]. A 70-150 ?m diameter lens with density greater than 15,000/cm^2 has been successfully fabricated and has the focal lengths between 50 and 150 ?m. Beside the lens, wave-guides have also been demonstrated by Cox et al. (1994) using inkjet technology.

Since the optical components can be selectively deposited onto the desired region with varying properties, integration of those components to the system with fabricated IC or other devices are possible and efficient.

Solid Free Forming

Not only can two-dimensional patterns, but also three-dimensional solid structures be generated by micro-droplet generators. Orme et al. (1993) and Marusak et al. (1993) reported the application of molten metal drops for solid free form fabrication. Evans' group demonstrated the application of continuous and drop-on-demand inkjets for ceramic printing to fabricate 3-D structures as well as functionally graded materials [Blasdell et al., 2000, Mott et al., 1999]. Yamaguchi et al. (2000) used metal jet to print functional three-dimensional microstructures, and Figure 29 shows the operation principle. To print an overhanging structure, employing multi jets for structure and sacrificial material deposition was also proposed by Yamaguchi et al. (2000), while Fuller et al. (2000) used laminated PMMA film as the supporting material for ejection of metal cantilever beams. The fabrication principle is shown in Figure 30.

Manufacturing Process

Droplet generators also provide novel ways for material process. For example, sub-micron ceramic particles can be plasma sprayed, introduced by Blazdell and Juroda, for surface coating [Blazdell et al., 2000]. The operation principle is shown in Figure 31. A continuous jet printer was used for droplet formation from ceramic solution. The produced ceramic stream was delivered into the hottest part of the plasma jet, and then sprayed onto the working piece. Those splats by the plasma spray are claimed similar in morphology to those produced using conventional plasma spraying of a coarse power, but significantly smaller in size, which may provide unique characteristics such as extension of solid state solubility, refinement of grain size, formation of metastable phases and high concentration of point defects [Blazdell et al., 2000].

IC Cooling

Conventionally, blowing fan and fins are widely used for IC chips, especially CPU, cooling. Recently as the heating power increases greatly with the increasing CPU size, more advanced methods, such as heat pipes, CPL, and impinging air jets, were introduced for quick heat removal. However, no matter how the designs improve, the limitation of heat removal ability for those devices is in the order of tens of W/cm^2. In addition, the detection of hot spot and selectively removing the heat only from hot regions to preserve energy are highly desired, but not easy to perform by traditional ways, as chip become large. As a result, using the concept of transportation of large latent heat through the droplet evaporation process is the promising new way. This method can in principle remove three to four order more heat than the conventional ones. Besides, the cooling spot can be selected and monitored through the integrated micro temperature sensor and IC array. The conceptual design by Tseng (2001c), as shown in Figure 32, used a 2-Dimensional array of micro injectors to selectively deposit liquid droplet onto the chip surface. The applied droplet frequency and numbers can be adjusted to keep a dry chip surface with constant temperature. The estimated maximum heat removed by this device is around 300,000 W/cm^2, more than 1000 times larger than the conventional ways. Temperature sensors as well as control circuit can also be fabricated on the same chip to form a self-contained smart system.

Concluding Remarks

Droplet generator is one of the important fluid handling devices in precise liquid dosing control. MEMS technology makes the micro sized droplet generators possible and popular for many applications. Various ways for droplet generation, including piezoelectric, thermal bubble, thermal buckling, focused acoustic wave, electrostatic, and inertial actuation, have been employed in the micro droplet generation. Compared to other methods, thermal bubble way has larger actuation deformation, simpler design/fabrication and less limitation on the chamber volume, but has the drawback of the temperature sensitivity and influence to liquid properties. Piezo type jet has the advantage of high frequency response, controllable droplet size, and free of satellite drops, but has the limitation of finite actuation deformation thus limiting the chamber volume from miniaturization. Electrostatic and thermal bulking jet has similar size limitation to the piezo ones. Despite the former one has the benefit of low power consumption, both have limited frequency response due to the size limitation. Acoustic wave droplet generator, on the other hand, is not mature and stable enough for commercial applications, while inertial actuation method has limitation on miniaturization from operation principle. More types of micro-droplet generators are under developing, they may one day replace the ones we have been using for decades.

Physical properties, design issues as well as manufacturing aspects are important concerns in the design and fabrication of micro droplet generators. The associated issues including frequency response, cross talk, satellite droplets, puddle formation, material selection, and integration, require a lot of cares in different design and fabrication levels. MEMS technology provides some of the key solutions to those practical issues.

Many aspects of the applications make micro droplet generators important and exciting since its inception. Inkjet printing is the traditional application field and has generated as well as will continuously produce huge amount of revenue in the printing market. Moreover, hundreds of applications have been emerging, including bio-reagent handling, fine chemical handling, drug delivery, direct writing, solid free-form, IC cooling, and fuel injection, showing promising results and possible markets. Many exciting applications of micro-droplet generators are yet to be discovered.

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Figure Captions

Figure 1: Operation principle of airbrush and sprayer, after Tseng (1998d).

Figure 2a: Operation principle of a piezoelectric-actuated continuous droplet generator, after Buehner (1977).

Figure 2b: Operation principle of a piezoelectric-actuated droplet-on-demand droplet generator, after Lee (1984).

Figure 3: Operation principle of a thermal-bubble-actuated droplet generator, after Allen (1985).

Figure 4: Operation principle of a thermal-buckling-actuated droplet generator, after Hirata (1996).

Figure 5: Operation principle of an acoustic-wave-actuated droplet generator, after Zhu (1996).

Figure 6: Operation principle of an electrostatic-actuated droplet generator, after Kamisuki (1998).

Figure 7: Operation principle of an inertia-actuated droplet generator, after Gruhler (1999).

Figure 8: The sequence of droplet generation.

Figure 9: Operation principle of virtual chamber neck, after Tseng (1998c)

Figure 10: Cross talk among neighboring micro-chambers

Figure 11: Overfill phenomenon.

Figure 27: Particle sorting using droplet generators, after Asano (1995)

Figure 28: Control of mixing and fuel injection by micro droplet generators, after Tseng (1996).

Figure 29: Operation principle of three-dimensional structure fabrication by micro droplet generator, after Yamaguchi (2000).

Figure 30: Fabrication of three-dimensional structures by droplet ejection and polymer lamination, after Fuller (2000).

Figure 31: Operation principle of plasma spraying by micro droplet generators, after Blazdell (2000).

Figure 32: Conceptual design of IC cooling by micro droplet injections.