30 Microdroplet Generators

30.1 Introduction

Microdroplet generators are becoming an important research area in microelectromechanical systems (MEMS), not only because of the valuable marketing device—inkjet printhead—but also because of the many other emerging applications for precise or micro-amount fluidic control. There has been a long history of development of microdroplet generators ever since the initial inception by Sweet (1964, 1971), who used piezo actuation, and by Hewlett-Packard and Cannon [Nielsen et al., 1985] in the late 1970s, who used thermal bubble actuation. Tremendous research activities regarding inkjet applications have been devoted to this exciting field. Emerging applications in the biomedical, fuel-injection, chemical, pharmaceutical, electronic fabrication, microoptical device, integrated circuit cooling, and solid freeform fields have fueled these research activities. Thus, many new operation principles, designs, fabrication processes and materials related to microdroplet generation have been explored and developed recently, supported by micromachining technology.

In this chapter, microdroplet generators are defined as droplet generators generating microsized droplets in a controllable manner; that is, droplet size and number can be accurately controlled and counted. Thus, atomizer, traditional fuel-injector or similar droplet-generation devices that do not offer such control are not discussed here.
Microdroplet 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 greater than several atmospheres. The operation principles, structure/process designs and materials often play key roles in the performance of droplet generators.

The applications of microdroplet generators, in addition to the well-known application of inkjet printing, cover a wide spectrum of fields, including direct writing, fuel injection, solid freeform, solar cell fabrication, light emitting polymer display (LEPD) fabrication, packaging, microoptical components, particle sorting, microdosage, plasma spraying, drug screening/delivery/dosage, micropropulsion, integrated circuit cooling and chemical deposition. Many of these applications may become key technologies for integrated Microsystems in the near future.

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

### 30.2 Operation Principles of Microdroplet Generators

Many attempts have been made to generate controllable microdroplets [Buehner et al., 1977; Twardeck, 1977; Carmichael, 1977; Ashley et al., 1977; Bugdayci et al., 1983; Darling et al., 1984; Lee et al., 1984; Myers and Tamulis, 1984; Nielsen, 1985; Bhaskar and Aden, 1985; Allen et al., 1985; Krause et al., 1995; Chen and Wise, 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 or increasing the inner pressure of a nozzle, 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.

#### 30.2.1 Pneumatic Actuation

The spray nozzle is one of the most commonly used devices for generating droplets nowadays for airbrush or sprayer applications. Two types of spray nozzles are shown in Figure 30.1. Figure 30.1a shows that the air brush generates lower pressure at the outer edge of the capillary tube by blowing air across the tube

![Figure 30.1](image_url)

**FIGURE 30.1** Operation principle of airbrush and sprayer. (After Tseng, 1998.)
end, which forces liquid to move out of the tube and form droplets. The sprayer shown in Figure 30.1b employs high pressure to push liquid through a small nozzle to form droplets. Typical sizes of the droplets generated by the spray nozzle range from tens to hundreds of microns in diameter. The device can be fabricated in microsize using micromachining technology, however, it is difficult to control each nozzle separately in an array format.

30.2.2 Piezoelectric Actuation

The droplet ejection by piezoelectric actuation was invented by Sweet in 1964. Based on the piezoelectric technology, there are two types of piezoelectric devices. One is called the continuous inkjet [Buehner et al., 1977; Twardeck, 1977; Carmichael, 1977; Ashley et al., 1977]. Figure 30.2a shows the operation principle of this type of inkjet. Conductive ink is forced out of the nozzles by pressure. The jet breaks up continuously into droplets with random sizes and spacing. Uniformity of the size and spacing of the droplets can be controlled 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 are charged by the electric field and deflected to printout, while the nondesired ones are collected in 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 complexity of the droplet charging and collecting system is a major obstacle to practical use of this device.

The other device, called droplet-on-demand inkjet, utilizes a 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 30.2b 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 the drop-on-demand method is that a complex system for droplet deflection and collection is not required. However, the main drawback is that the size of the piezoelectric transducer tube or disc, on the order of submillimeters to several millimeters, is too large for high-resolution applications. It has been reported that the typical frequency for stable operation of a piezoelectric inkjet would be tens of kilohertz [Chen et al., 1999].

### 30.2.3 Thermal-Bubble Actuation

The thermal bubble jet was developed by Hewlett-Packard in the U.S. and by Canon in Japan in the early 1980s [Nielsen, 1985; Bhaskar and Aden, 1985; Allen et al., 1985]. There are also many other designs reported in the literature [e.g., Krause et al., 1995; Chen and Wise, 1995; Tseng et al., 1996; Tseng, 1998]. Figure 30.3 shows the cross section of a thermal bubble jet. Liquid in the chamber is heated by a 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 the meniscus for 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 the H-P ThinkJet 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

![Diagram of a thermal-bubble-actuated droplet generator](image-url)
600 dpi [Krause et al., 1995] and 1016 dpi [Chen and Wise, 1995]. The typical operational frequency for the contemporary thermal bubble jets is from several to tens of kilohertz.

30.2.4 Thermal-Buckling Actuation

Hirata et al. (1996) employed a buckling diaphragm for droplet generation. Figure 30.4 shows the basic operation principle. A composite circular membrane, consisting of silicon dioxide and nickel layers, is fixed on the border with a small gap between it and 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 microseconds. 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-µm-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.

30.2.5 Acoustic-Wave Actuation

Figure 30.5 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 an on-chip Fresnel lens was employed to generate and focus acoustic waves on the air–liquid interface for droplet formation. The actuation comes from excitation of a piezoelectric film under a burst of radio-frequency (RF) signal. The device does not require a nozzle to define droplets, thus reducing the troublesome clogging problem occurring in most of the droplet generators employing nozzles. Droplet size can also be controlled by acoustic waves with specific frequencies, however, due to vigorous agitation of the 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 at a stable level. The applied RF ranges from 100 to 400 MHz and the burst period is 100 µs. The power consumption for one droplet is around 1 mJ, which is high compared to other principles. The droplet size ranges from 20 to 100 µm, depending on the RF. The reported size of the device is $1 \times 1 \text{mm}^2$, which is much larger than other droplet generators mentioned in the previous sections.
30.2.6 Electrostatic Actuation

The electrostatically driven inkjet printhead was first introduced by Seiko–Epson Corp. [Kamisuki et al., 1998, 2000] for commercial printing purposes. As shown in Figure 30.6, the actuation begins by application of a dc voltage between the 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 was developed for use in electric calculators, as it offers low power consumption of less than 0.525 mW/nozzle. The driving voltage for a SEAJet™ is 26.5 V and the driving frequency can be up to 18 kHz with uniform ink ejection. A device with 128 nozzles/chip with 360-dpi pitch resolution has also been demonstrated to have high printing quality (for bar coding), high-speed printing, low power consumption, a long lifetime under heavy-duty usage (lifetime more than 4 billion ejections) and low acoustic noise. However, the fabrication comprises complex bonding processes among three different micromachined pieces. Besides, the pressure plate requires a very precise etching process to control the accuracy and uniformity of the thickness. Due to the deformation limitation of solid materials and alignment accuracy required in the bonding process, the nozzle pitch may not easily be reduced further for higher resolution applications.

FIGURE 30.5 Operation principle of an acoustic-wave-actuated droplet generator. (After Zhu et al., 1996.)

FIGURE 30.6 Operation principle of an electrostatic-actuated droplet generator. (After Kamisuki et al., 1998.)
30.2.7 Inertial Actuation

Inertial droplet actuators apply high acceleration to the nozzle chip for droplet ejection. Such an apparatus is shown in Figure 30.7 [Gruhler et al., 1999]. The print module consists of large reservoirs on the top plate, which connects to the nozzles on the bottom plate. The print module is mounted on a long cantilever beam with a piezo–bimorph actuator for acceleration generation. It requires 500 µs to generate 1 nl of droplets from 100-µm-diameter nozzles. Twenty-four liquid droplets of different solution types were demonstrated to be ejected simultaneously from the nozzles in a 500-µm-pitch. The smallest droplet claimed to be generated is 100 pl from 50-µm-diameter nozzles. This principle provides a gentle ejection process for bioreagent applications. However, the ejection of smaller droplets may encounter strong surface tension and flow drag forces at the microscale that are much larger than the droplet inertial. Also, the droplets cannot be selectively and individually ejected from the desired nozzles which limits its applications.

30.3 Physical and Design Issues

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

30.3.1 Frequency Response

The frequency response of droplet generators is an important measure for assessing the performance of a device. The reported typical frequency response for thermal bubble jets, piezo jets, thermal buckling jets, acoustic wave jets and electrostatic and inertial jets ranges from a kilohertz to tens of kilohertz. Piezo and acoustic wave jets typically have higher frequency responses than the others. Recently, the novel design by Tseng (1998) improved the frequency response of thermal bubble jets by about three times (35 kHz), which is comparable to the speed of piezo jets. Higher speed devices (in the range of hundreds of kilohertz) are currently under development by major inkjet printer makers and further breakthroughs will follow in the next few years.

The three important time constants related to the frequency response of microdroplet generators are actuation, droplet ejection and liquid refilling, as shown in Figure 30.8.

The typical time constant from heating to bubble formation in a thermal bubble jet is around 5 to 10 µs for a chamber size ranging from 20 to 100 µm [Tseng, 1998]. Thermal buckling and electrostatic microdroplet generators have actuation times of tens to hundreds of microseconds (estimated from Hirata et al., 1996), due to the large actuation plate required for sufficient displacement for droplet formation. The inertial type required even longer actuation time (estimated from Gruhler et al., 1999), typically hundreds to thousands of microseconds, due to the large cantilever structure necessary for generating large droplets with sufficient inertial force to overcome liquid surface tension and viscosity. The actuation
time for piezo or acoustic wave types of generators may be shorter [Darling et al., 1984; Zhu et al., 1996], around one microsecond to tens of microseconds.

After application of actuation pressure to the liquid, the droplet starts to eject. The ejection sequence usually takes a couple to hundreds of microseconds for a droplet volume of 1 pl to 1 nl [Tseng, 1998], 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 by three orders of magnitude (e.g., from less than 10 µs to over 1 s), depending on the length and geometry of the refilling path. In most of the commercial inkjet printhead designs, a chamber neck [Nielsen, 1985], elongated chamber channel [Neilsen, 1985] or physical valve [Karz et al., 1994] is 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; 1998b; 1998c) introduced the concept of a virtual chamber neck to speed up the refilling process of thermal bubble jets and to suppress cross-talk. The virtual neck consists of vapor bubbles that provide sealing pressure while the droplet is ejecting and opens up to reduce flow resistance while liquid is refilling, thus increasing the frequency response. The concept is shown in Figure 30.9.

For simulation of droplet actuation and the formation sequence, much work [Curry and Portig, 1977; Lee, 1977; Levanoni, 1977; Pimbley and Lee, 1977; Fromm, 1984; Bogy and Talke, 1984; Asai et al., 1987; 1988; Asai, 1989; 1991; 1992; Mirfakhraee, 1989; Chen et al., 1997a; 1997b; 1988a; 1988b; 1999; Rembe et al., 2000] has been conducted on the bubble formation sequence, droplet generation, and aerodynamics of droplets traveling in the atmosphere for thermal bubble as well as piezo jets. Interested readers can refer to those works for details.

### 30.3.2 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 a pressure wave from the firing chamber to the neighboring chambers, as shown in Figure 30.10. 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 the thermal bubble jet, is the phenomenon of thermal energy transportation from the 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 of 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 illustrated in Figure 30.11.
These issues stem from the fact that there is not enough flow compliance among nozzles. One of the solutions developed by IBM [Nielsen, 1985] is to increase the channel length for each chamber. However, the increased serial compliance of the lengthened channel between the reservoir and chamber increases the flow resistance and inertia significantly, increasing the liquid refilling time.

HP tried to solve this problem by using either a parallel compliant (reservoir) or a chamber neck. Figure 30.12 shows a slot used as a reservoir beside the nozzles to store energy while the bubble is exploding and to release energy while the bubble is collapsing [Nielsen, 1985]. Figure 30.13 shows the second approach by narrowing the inlet of the chamber to form a chamber neck [Buskirk et al., 1988].

The effects from the aforementioned methods were simulated by Buskirk et al. (1988). Figure 30.14 shows the simulation results of the meniscus position of the firing chamber and neighboring chamber for various 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 fluctuations. 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 rising response among the three methods.

In contrast to fixed chamber neck design, Xerox [Karz et al., 1994] has used a flexible plate as a valve to address the cross-talk issue. However, this design may suffer from low frequency response and material...
Tseng et al. (2000) used a novel design of a virtual chamber neck, employing the 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 30.9. Their work demonstrated that the bubble has faster response and more reliable operation performance in the microscale than do solid valves.

In addition to hydraulic cross-talk, thermal cross-talk, in Tseng’s work, was also reduced by placing the heater on the chamber top of a thin film with low thermal conduction, instead of leaving it 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.

30.3.3 Satellite Droplets

Satellite droplets result from the breakdown 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 breakdown. The droplet ejection sequence captured from a commercial inkjet reveals the detailed steps of satellite droplet formation, as shown in Figure 30.15 [Tseng et al., 1998c]. When applied to printing, the quality is degraded from the occurrence of satellite drops, as revealed in Figure 30.16. 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; 1988; Asai, 1989; 1991; 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 the drop-on-demand inkjet, Fromm (1984)
FIGURE 30.15  Droplet ejection sequence of HP 51626A printhead. (After Tseng et al., 1998c.)

FIGURE 30.16  A printed vertical line smeared by satellite droplets. (After Tseng et al., 1998c.)
and Chen et al. (1997a; 1997b; 1998a; 1998b; 1999) solved the Navier–Stokes equation to predict the droplet formation, and showed the process of satellite droplet formation. Pimbley and Lee (1977) and Chen et al. (1997b) demonstrated the evolution of the 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.

Various efforts have been made to eliminate satellite droplets from the commercial product. In piezo droplet generators, triangular waves were used to eliminate satellite drops [Chen et al., 1999]. For thermal bubble jets, Tseng et al. (1998a; 1998c; 2000) proposed a novel method employing the bubble as a trimmer to cut off the long droplet tail to eliminate satellite droplets, as shown in Figure 30.17. The tail of the liquid column, shortened by the bubble trimmer in Tseng’s work, is drawn back by surface tension into the main droplet, thus eliminating satellite drops.

30.3.4 Puddle Formation

A liquid puddle forms when liquid is pushed to flow outward and accumulates on the outside surface of the nozzle. Puddles impose a great blocking force on droplet ejection, causing distortion or even disruption of droplet ejection. One of the major causes of puddle formation is the hydrophilic nozzle surface. When it comes into contact with working fluid from the chamber, the liquid accumulates on the outer surface of the nozzle. It was observed by (Tseng, 1998) that the puddle appears after several continuous operations; that is, the chamber surface does not acquire a puddle until getting wet after several runs. If the operation of droplet ejection stops, the puddle is drawn back into the chamber by surface tension. However, once the chamber surface becomes wet, puddle formation always occurs when operation starts again. Figure 30.18 shows the formation of a puddle during the running of a microinjector [Tseng, 1998]. Notice that the droplet ejection position is away from the nozzle, due to distortion by the liquid puddle.

One way to eliminate puddle formation is to coat the chamber outer surface with a nonwetting material to prevent the wetting process of the working fluid, the inner surface of the chamber must remain hydrophilic.
for liquid refill. Even with the coating, however, there is still no guarantee that the puddle will not form. More research is under way to fully understand the mechanism of the puddle formation process.

30.3.5 Material Issues

Material issues, including stress, erosion, durability and compatibility, are very complex issues in the design of microdroplet generators. Material compatibility, stress and durability problems are commonly discussed from the processing perspective. Material compatibility issues result from the processing temperature, processing environment (oxidation, reactive gas, etc.), etching method used and adhesion ability; stress issues are usually a result of processing temperature as well as doping conditions; material durability issues either are material intrinsic properties or are due to the mechanical forces induced during the process (i.e., fluid flow force, surface tension force, vacuum forces or handling force). Lots of care needs to be taken in the process flow design to eliminate the material issues, such as compensating material stress during or after the fabrication process, conducting the high-temperature process earlier than the low-temperature material, finishing aggressive wet etching before metal film deposition or using low-temperature bonding material and processes to protect integrated circuit and microdevices.

From the operation aspect, durability, stress and erosion issues are the major concerns. Due to the cycling nature of the droplet generation process, the materials chosen for actuation face challenges not only from stress but also from fatigue. HP reported that possible reasons for failure of the heater passivation materials are cavitation and thermal stress [Bhaskar and Aden, 1985]. 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 preventing the material from cracking by eliminating stress concentration points. Moreover, the erosion of structure materials from the working fluid is another serious issue. Lee et al. (1999) reported the erosion of spacer material in a commercial inkjet head when diesel fuel was used as the working fluid. In contrast, materials, including silicon and silicon nitride, used by Tseng et al. [Tseng et al., 1998c; Tseng, 1998] and Lee et al. (1999b) in the microinjector are free of this problem and can be applied to a 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.
30.4 Fabrication of Microdroplet Generators

The common structures in most of the microdroplet generators include a manifold for liquid storage, microchannels for liquid transportation, microchambers for holding liquid, nozzles for droplet size and direction definition and actuation mechanisms for droplet generation. Occasionally, droplet generators may not have nozzles but instead use energy focusing as a means to generate droplets locally, such as acoustic wave droplet generators [Zhu et al., 1996]. Before micromachining processes became popular, most of the fabrication processes of microdroplet generators stemmed from the same 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 pose severe alignment, yield, material and integrated-circuit compatibility problems. Also, 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 to fabricate high-resolution integrated circuit droplet generators have become very important. In the following sections, examples of different fabrication means are introduced.

30.4.1 Multiple Pieces

Figure 30.19 shows the traditional fabrication of microdroplet generators by the bonding of fabricated structure pieces [Tseng, 1999]. Actuation plates are fabricated separately from the nozzle plates. In the thermal bubble jet, heaters are usually sputtered or evaporated and then patterned with an integrated circuit on the bottom plate, while piezo, thermal buckling, electrostatic and inertial actuators consist of

![Diagram showing conventional fabrication process flow of microdroplet generators.](image-url)
more complex structures, such as piezo disc, 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 is 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 by 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 of 4 µm (10% of the nozzle pitch) is difficult to achieve. 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. The bonding materials (mostly polymers) chosen may not be suitable for the application environments and working fluids. Also, the bonding process, involving heat, pressure, high voltage or chemical situations, restricts integrated circuit integration with the droplet generators which is essential for large-array and high-resolution applications.

### 30.4.2 Monolithic Fabrication

In order to address the aforementioned issues, monolithic processes utilizing micromachining technology have been widely employed since the early 1990s. Two major methods have been introduced: One is the combination of bulk and surface micromachining and the other is the use of bulk micromachining and deep-ultraviolet (UV) lithography associated with electroforming (or UV lithography only).

For example, Tseng, (1998) combined surface and bulk micromachining to fabricate a microdroplet 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 a fluid-handling system that included a manifold, microchannels and microchambers. Surface micromachining was used for heater, interconnection line and nozzle fabrication. The whole process was finished on (100)-crystal-orientation silicon wafers. Figures 30.20 and 30.21 show the three-dimensional structure of the microinjectors and the monolithic fabrication process, respectively. The ejection of 0.9-pl droplets has also been demonstrated by Tseng et al. (2001b) for high-resolution microinjectors. The structure materials used in the microinjector are silicon silicon nitride and silicon oxide, durable in high temperature and suitable for various liquids (even some harsh chemicals). Integrated circuits can be easily integrated with this device on the same silicon substrate.

The second case can be found in Lee et al.'s (1999a) work. In this design, the multi-exposure and signal development (MESD) lithography method was used to define microchannel and microchamber structures

**FIGURE 30.20** Schematic three-dimensional structure view of microinjectors. (After Tseng et al., 1998c.)
(using a photoresist as the 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 demonstrated compatibility with the very-high-resolution array and integrated circuit process. Another method, using a photoresist as the sacrificial layer and polyimide as the structure layer, was introduced by Chen et al. (1998b) for applications compatible with high-resolution and integrated circuit applications.

### 30.5 Characterization of Droplet Generation

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

#### 30.5.1 Droplet Trajectory

Droplet trajectory visualized by utilizing a flashing light on the ejection stream, as shown in Figure 30.22, was introduced by Tseng et al. (1998a). The white dots in Figure 30.23 indicate the droplet stream. The visualized droplet trajectory follows an exponential curve, very different from the parabolic one expected for normal-size objects with 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:

\[
Y = U_{\infty} \left[ t - \frac{U_{\infty}}{g} \left( 1 - e^{-\frac{6\mu r_0}{m}} \right) \right] \\
X = \frac{U_{Ho} m}{6\pi \mu r_0} \left( 1 - e^{-\frac{6\mu r_0}{m}} \right)
\]

(30.1)

(30.2)

where \( g \) is the acceleration due to gravity, \( t \) is the time, \( m \) is the mass, \( r_0 \) is the radius of the droplet, \( \mu \) is the viscosity of air, \( U_{\infty} = \frac{mg}{6\pi \mu r_0} \) is the droplet terminal velocity, and \( U_{Ho} \) is the initial horizontal velocity.
The trajectory is drawn in Figure 30.23 with the experimental result and fits the visualized trajectory well except at the end, suggesting an interaction among droplets. From this simple analysis, the maximum flying distance of a droplet with a known diameter can be estimated as:

\[
X_{\text{max}} = \frac{U_{0}m}{6\pi \mu r_{0}} = \frac{2\rho_{\text{liquid}}}{9\mu_{\text{air}}}(U_{0}r_{0}^{2}), \quad \text{when } t \sim \infty
\]  

(30.3)

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

### 30.5.2 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 control droplet direction.

### 30.5.3 Ejection Sequence/velocity and Droplet Volume

To characterize the detailed droplet ejection sequence, a visualization system [Chen et al., 1997b; Tseng et al., 1998c], as shown in Figure 30.24, 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 30.15. Droplet volume can be determined from the images by assuming the droplet is axisymmetric or by weighing certain numbers of droplets. Droplet velocity can be estimated by measuring the flying distance difference of the droplet fronts in two successive images.

**FIGURE 30.24** Experimental setup for droplet ejection sequence visualization.
30.5.4 Flow Field Visualization

To better understand flow properties such as cross-talk, actuation sequence, liquid refill and droplet formation inside microdroplet generators, flowfield visualization is one of the most direct and effective ways. Flow visualization at a small scale has some difficulties that do not occur at a large scale, such as limited viewing angles, hard-to-apply light sheet reflection from the particles trapped on the wall, short response time and small spatial scale. Meinhart and Zhang (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. The spatial as well as temporal resolutions of the image velocimetry were found to be 5 to 10 µm and 2 to 5 µs, respectively. The four primary phases of the injection operation, including infusion, inversion, ejection and relaxation, were clearly captured and quantitatively analyzed.

30.6 Applications

More than a hundred applications have been explored employing microdroplet generators. This section provides a summary of some of the applications.

30.6.1 Inkjet Printing

Inkjet printing involves arranging small droplets on a printing medium to form texts, figures or images and is the most well-known application. The smaller and cleaner the droplets are, the sharper the printing is, however, smaller droplets cover a smaller printing area and thus increase the printing time. Therefore, in printing applications, high-speed microdroplet generation with stable and clean microsized droplets is desired for fast, high-quality printing. The printing media can be paper, textile, skin, cans or other surfaces that can adsorb or absorb printing solutions. Inkjet printing generated a more than $10 billion worldwide market in 2000 and continues to grow.

30.6.2 Biomedical and Chemical Sample Handling

The application of microdroplet generators to biomedical sample handling is an emerging field and is drawing much attention. Much research effort has been focused on 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, for mass spectrometry. Figure 30.25 shows the design of the injectors, which are utilized to generate submicron- to micron-sized bioreagent droplets for sample separation and analysis in a mass spectrometer, as shown in Figure 30.26. Lugnbuhl et al. (1999) employed silicon bulk micro-machining to fabricate a silicon nozzle plate and Pyrex® glass actuation plate, while Wang et al. (1999)
employed the combination of surface and bulk micromachining to fabricate a droplet generator. These injectors are part of the lab-on-a-chip system for incorporating a microchip with a macro-instrument.

Microdroplet generators were also used by Koide et al. (2000), Nilsson et al. (2000), Goldmann and Gonzalez (2000) and Szita et al. (2000), for the accurate dispensing of biological solutions. Piezo- and thermal-type injectors were used in this research for protein, peptide, enzyme or DNA dispensing. In those applications, the operation principles of the employed devices are similar to those for inject printing. A 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 bioreagents can be further bioprocessed for high-throughput analysis.

Continuous-jet-type droplet generators were reported by Asano et al. (1995) to effectively focus and sort particles by electrostatic force. The experimental setup is shown in Figure 30.27. A syringe pump pressurizes the sample fluid containing the particles, which pass through a nitrogen sheath flow for focusing. The sample is then ejected from a piezoelectric-transducer-disturbed nozzle to form a droplet. The droplets containing the desired particles are charged at the breakup point and deflected into collectors. The reported separation probability for 5-, 10-, and 15-µm particle can be as high as 99%. However, the
inner jet diameter limits the particle size for separation. Other than solid particle separation, this method can potentially also be applied to cell sorting for biomedical applications.

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

### 30.6.3 Fuel Injection and Mixing Control

Microdroplet generators can be used for fuel injection to dispense controllable and uniform droplets, important for mixing and combustion applications. Combustion efficiency depends on the mixing rate of the 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 and Huang, 1982) or passively (Ho and Gutmark, 1987). The effectiveness of controlling large-scale vortical structures by 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, a significant challenge in combustion research is to improve the small-scale mixing and to reduce the evaporation time of the liquid fuel.

Traditional injectors with a nozzle diameter of tens to hundreds of microns can neither supply uniform microdroplets for reducing evaporation time and fine-scale mixing nor eject droplets which can be controlled individually to modulate vortex structure [Lee et al., 1999b]. To overcome those limitations, Tseng et al. (1996) proposed a microdroplet injector array fabricated using micromachining technologies for fuel injection. The droplets ejected from microinjectors are uniform and the size can be one to tens of microns in diameter, which is close to the microscale of low-turbulence eddies. The fine-scale mixing can be carried out by the reaction of the low-turbulence eddies directly with the microdroplets. The evaporation time is also greatly reduced by increasing the evaporation surface from the reduced and unformed droplet size. In addition, appropriate selection of microinjectors distributed around the nozzle of a dump combustor (Figure 30.28) 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 the injection. If the ejecting phases of the

![FIGURE 30.28](image_url) Control of mixing and fuel injection by microdroplet generators. (After Tseng et al., 1996.)
microdroplets along the azimuthal direction are the same, the mode zero instability (Brown and Roshko, 1974) is enhanced. When a certain defined phase lag is imposed on these microinjection, higher mode instability (Brown and Roshko, 1974) waves are generated which are usually beneficial for mass transfer enhancement. Because about a 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 microinjection brings forth fine-scale mixing.

30.6.4 Direct Writing and Packaging

Microdroplet generators offer an alternative to the lithography process for electronics and optoelectronics 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). Materials used with this process include adhesives for component bonding, filled polymer systems for direct resistor writing and oxide deposition and solder for solder-bumping of flip-chip ball grid arrays (BGAs), printed circuit boards (PCBs), and chip-scale packages (CSPs) [Teng et al., 1988; Hays et al., 1999]. In these printing applications, the temperature should be elevated to 100 – 200°C, and the viscosity of fluids should be around 40 cps; in some cases, an inert process environment, such as nitrogen flow, is required to prevent oxidation of the materials.

Direct writing by inkjet printing can eliminate the fabrication difficulty inherent in photolithography or screen-printing processes for solar-cell metallization and light-emitting polymer (LEP) deposition of light-emitting polymer displays (LEPDs). In solar-cell metallization, metallo-organic decomposition (MOD) silver ink is used to inkjet print directly onto solar-cell surfaces for avoidance of p–n junction degradation under the traditional screenprinting method requiring 600 to 800°C for firing process. Inkjet printing also allows formation of a uniform line of film on rough solar-cell surfaces [Tang and Vest, 1988a; 1988b; Somberg, 1990] which is not easily achieved by traditional photolithography.

Organic light-emitting devices that require deposition of many organic layers to perform full-color operation face similar problems. Due to the solubility of those organic layers in many solvents and aqueous solutions, conventional methods such as photolithography, screen printing and evaporation, which require a wet patterning process, are not suitable [Hebner et al., 1998; Shimoda et al., 1999; Kobayashi et al., 2000]. Thus, direct writing of organic materials by inkjet printing has become a promising solution to provide a safe, patternable process without a wet etching procedure. However, due to pinholes appearing on the patterned materials, high-quality polymer devices may not be easily inkjet printed. Yang’s group proposed a hybrid way of combining an inkjet-printed layer with another uniform spin-coated polymer layer to overcome the problem [Bharathan and Young, 1998]. In such a system, the uniform layer serves as a buffer to seal the pinholes and the inkjet-printed layer contains the desired patterns [Bharathan and Young, 1998].

30.6.5 Optical Component Fabrication and Integration

Integrated microoptics has become a revolutionized concept in the optics field, as it provides the advantages of low cost, miniaturization, improved spatial resolution and time response and reduction of the assembly process on optical systems, which is not possible by traditional means. As a result, fabricating and integrating miniaturized optical components with performance similar or even better than traditional components are critical issues in integrated microoptics systems. Standard bulk or surface micromachining provides various ways to fabricate active/passive micromirrors, wave-guides and Fresnel lenses, but fabrication of refractive lenses with curved surfaces is not easy. Compared to photolithography, which utilizes patterned and melted photoresist columns as lenses, the inkjet printing method provides more flexibility as far as the process, material choices and system integration. Cox et al. [Cox et al., 1994; Hays and Cox, 1998] employed inkjet printing technology to eject heated polymer material to fabricate a microlenslet array. 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- to 150-µm-diameter lens with a density greater than 15,000/cm² has been successfully fabricated and
has focal lengths between 50 and 150 µm. Besides the lens, wave-guides have also been demonstrated by Cox et al. (1994) using inkjet technology.

Because the optical components can be selectively deposited onto the desired region with varying properties, integration of those components with fabricated integrated circuit or other devices is possible and efficient.

### 30.6.6 Solid Freeforming

Two-dimensional patterns and three-dimensional solid structures can be generated by microdroplet generators. Orme and Huang (1993) and Marusak (1993) reported the application of molten metal drops for solid freeform fabrication. Evans’ group demonstrated the application of continuous and drop-on-demand inkjets for ceramic printing to fabricate three-dimensional structures as well as functionally graded materials [Mott and Evans, 1999; Blasdell and Evans, 2000; Yamaguchi et al. 2000] used a metal jet to print functional three-dimensional microstructures, and Figure 30.29 shows the operation principle. Employing multijets for structure and sacrificial material deposition to print an overhanging structure was also proposed by Yamaguchi et al. (2000), while Fuller and Jacobson (2000) used laminated poly(methyl methacrylate) (PMMA) film as the supporting material for ejection of metal cantilever beams. The fabrication principle is shown in Figure 30.30.

### 30.6.7 Manufacturing Process

Droplet generators also provide novel material processing. For example, submicron ceramic particles can be plasma sprayed, as introduced by Blazdell and Juroda, for surface coating [Blazdell and Kuroda, 2000]. The operation principle is shown in Figure 30.31. 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. The splats produced by the plasma spray are similar in morphology to those produced using conventional plasma spraying of a coarse powder but are 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 a high concentration of point defects [Blazdell and Kuroda, 2000].

### 30.6.8 Integrated Circuit Cooling

Conventionally, blowing fans and fins are widely used to cool integrated-circuit chips, especially for central processing unit (CPUs). Recently, as the heating power has increased greatly with increasing CPU size, more advanced methods, such as heat pipes, CPL and impinging air jets, have been introduced for quick heat removal. However, no matter how the designs improve, the limitation of heat removal ability
for those devices is on the order of tens of watts per square centimeter. In addition, being able to detect hot spots and selectively remove the heat only from hot regions to preserve energy is highly desired but not easy to perform by traditional ways. As a result, the concept of transporting latent heat through the droplet evaporation process holds promise. This method can, in principle, remove three to four orders more heat than conventional methods. Also, the cooling spot can be selected and monitored through the integrated micro-temperature sensor and integrated circuit array. The conceptual design by Tseng (2001), as shown in Figure 30.32, used a two-dimensional array of microinjectors to selectively deposit liquid droplets onto the chip surface. The applied droplet frequency and numbers can be adjusted to maintain a dry chip surface with constant temperature. The estimated maximum heat removed by this device is
around 300,000 W/cm², more than 1000 times greater than by conventional means. Temperature sensors as well as a control circuit can also be fabricated on the same chip to form a self-contained smart system.

### 30.7 Concluding Remarks

The droplet generator is an important fluid-handling device for precise liquid-dosing control. MEMS technology makes micorsized droplet generators possible and popular for many applications. Various methods of droplet generation, including piezoelectric, thermal bubble, thermal buckling, focused acoustic wave, electrostatic and inertial actuation, have been employed. Compared to other methods, the thermal bubble approach has greater actuation deformation, simpler design/fabrication and less limitation on the chamber volume, but it has the drawbacks of being temperature sensitivity and influenced by liquid properties. The piezo-type jet has the advantage of high frequency response, controllable droplet size, and no satellite drops, but it has the limitation of finite actuation deformation, thus limiting miniaturization of the chamber volume. The electrostatic and thermal buckling jets have size limitations similar to the piezo type. Despite the electrostatic generator having the benefit of low power consumption, both have limited frequency response due to size limitations. The acoustic-wave droplet generator, on the other hand, is not mature and stable enough for commercial applications, while the inertial actuation method offers limited miniaturization due to its operation principle. More types of microdroplet generators are under development and may one day replace the ones we have been using for decades.

Physical properties, design issues and manufacturing aspects are important concerns in the design and fabrication of microdroplet generators. The associated issues, including frequency response, cross-talk, satellite droplets, puddle formation, material selection and integration, require great care at the various design and fabrication levels. MEMS technology provides some of the key solutions to those practical issues.

Many aspects of the applications have made microdroplet generators important and exciting ever since their inception. Inkjet printing is the traditional application and has generated a significant amount of revenue in the printing market. Moreover, hundreds of applications are yet emerging, including bioreagent handling, fine chemical handling, drug delivery, direct writing, solid freeform, integrated circuit cooling and fuel injection, which show promising results and many potential markets. Many exciting applications of microdroplet generators are yet to be discovered.
References


