

# Surface Acoustic Wave Driven Microfluidics – A Review

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**Abstract:** This paper presents a systematic overview on the recent works on surface acoustic wave (SAW) driven microfluidics. SAW microfluidics is based on acoustic streaming induced by leaky SAW radiation into a liquid. The development of this field attracts attention from microfluidic research community due to its rapid actuation, programmable capability, simple and yet efficient operation. In our paper, SAW microfluidic applications are categorized into droplet-based applications and continuous-flow applications. Droplet is actuated into unique behaviours depending on the applied SAW power. A wide range of droplet based applications have been employed utilizing these behaviours. In continuous-flow system, applications are further categorized based on the interaction of travelling SAW and standing SAW with the bulk liquid. Finally, future perspectives of SAW driven microfluidics are discussed.

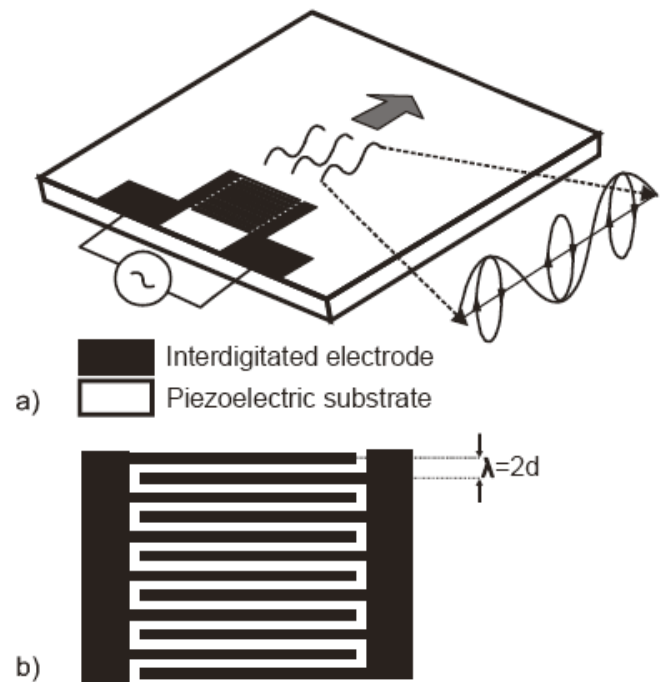
**Keywords:** Surface acoustic wave, microfluidics, droplet-based, continuous-flow, mixing, sorting, pumping, concentrating.

## 1. INTRODUCTION

Over the past few decades, surface acoustic wave devices have been successfully employed in various applications. Common usage of SAW ranges from radio frequency (RF) communication [1] to chemical and biochemical sensors [2] to optical modulators [3]. In recent years, SAW has been attracting attentions from microfluidics research communities. SAW microfluidic working mechanism is based on the efficient energy transferred from the megahertz (MHz) wave into a liquid, which is due to the mismatch of sound velocities in the substrate and fluid. Compared to other actuation mechanisms in microfluidics such as surface gradient [4], thermo capillarity [5], electrowetting [6], magnetism [7], the apparent advantages of SAW are large force, fast operation and simple electrodes network. Current technologies make the fabrication of SAW devices relatively cost-effective. Moreover, the simple integration of SAW devices into microscale system promises an excellent solution for fluid miniaturization platforms. Many works have been reported in the literature on SAW microfluidics. Reviews on these works were published recently by Yeo and Friend *et al.* [8], Fu *et al.* [9] and Wixforth *et al.* [10]. However, the main focus of the above papers is SAW droplet-based microfluidics. Other works on SAW based continuous-flow applications have not been discussed in depth.

Recent developments of SAW microfluidics are systematically discussed throughout this paper. Generally, SAW devices consist of interdigitated electrodes (IDT) patterned on a piezoelectric substrate as shown in Fig. (1a). Upon applying a RF signal to the IDT, the piezoelectric substrate contracts and expands due to the redistribution of charges. Continuous deformations lead to the launching of SAW, which has both longitudinal and transverse vibrations along the propagation of the waves. The combined effect causes the point near the surface to move in an ellipse which is in the plane normal to the surface and parallel to the wave propagation. SAW wavelength is determined by the

transducer pitch  $\lambda = 2d$ , (Fig. (1b)). The central frequency  $f_0$  of the SAW is determined by the relation:  $f_0 = c_s / \lambda$ , where  $c_s$  is the wave propagation speed of SAW in the substrate. These electrodes are fabricated onto the substrate using standard lithography and lift off/wet etching process. Different piezoelectric materials are used in traditional SAW devices. In SAW microfluidic application, single crystal lithium niobate ( $\text{LiNbO}_3$ ) substrate, however, is preferred due to the relatively high electromechanical coupling coefficient.

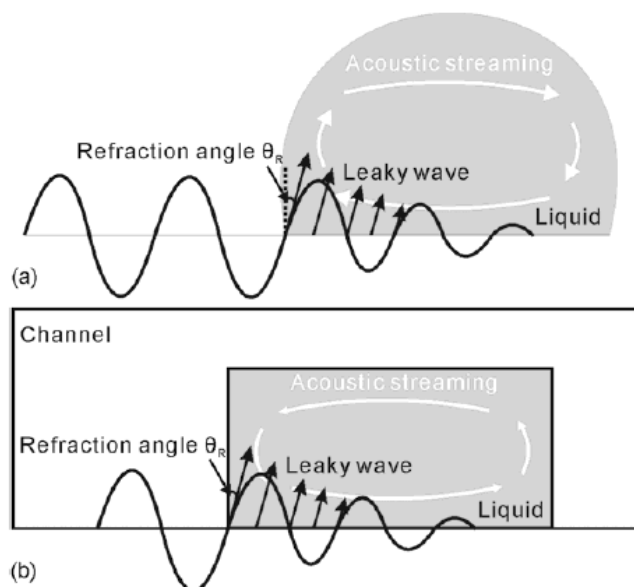


**Fig. (1).** SAW device principle: (a) SAW generation and coupled surface movement; (b) interdigitated electrode concept.

When SAW comes into contact with a liquid along its path, the leaky SAW, with decaying amplitude, is launched into the bulk liquid. The refraction angle of the radiated wave could be calculated based on Snell's law:  $\theta_R = \sin^{-1}(c_l / c_s)$ , where  $c_s$  and  $c_l$  are the sound speeds in the substrate and in the liquid, respectively. Acoustic radi-

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ance pressure is also built up inside the liquid and results in internal streaming following the wave propagation. However, internal flow circulation depends on the nature of the experimental setup. As shown in Fig. (2), the circulation is in a clockwise direction [10] for droplet and a counter clockwise direction for liquid in a confined channel [11]. This so-called acoustic streaming effect is the foundation for application of SAW in microfluidics. In this review paper, SAW microfluidics is categorized and discussed according to droplet-based and continuous-flow applications. In the discussion of droplet-based applications, reported works are further categorized based on droplet behaviour in different power regimes. Continuous-flow based applications are discussed under the categorization of travelling SAW and standing SAW.

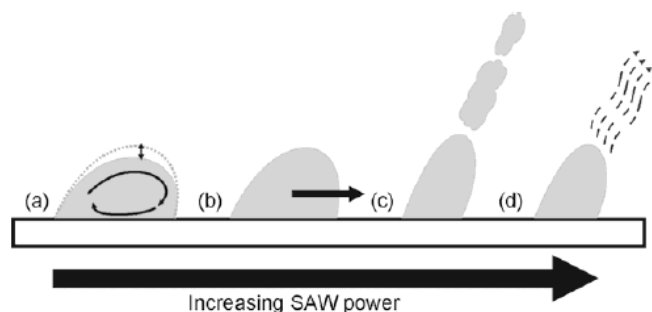


**Fig. (2).** Acoustic streaming in (a) droplet and (b) in a confined channel.

## 2. SAW DROPLET-BASED APPLICATIONS

Under different power load, behaviours such as droplet vibration, droplet motion, droplet jetting and droplet atomization are observed. In this section, published works on SAW-based droplet manipulation are reviewed according to the different droplet behaviours. As shown in Fig. (3), when the RF power is applied, acoustic streaming is induced due to leaky wave radiated into the droplet. At low power, the droplet vibrates at its position, (Fig. (3a)). Wide range of applications utilizing this effect includes droplet mixing, droplet heating, particle patterning and particles concentration. Increasing the power makes acoustic streaming strong enough to result in a significant inertial force and drive droplet in the wave propagation direction (Fig. (3b)). Droplet actuation has been used for pumping, sample collecting and sample dispensing. Several methods for droplet positioning are proposed for a well controlled SAW droplet platform. Further increasing the power makes acoustic streaming so violent that the liquid is jetted into the air as shown in Fig. (3c). Droplet jetting is suitable for ink-jet printing applications. When the applied power is too high, strong capillary waves

at the droplet surface overcome capillary stress and result in atomization of droplet (Fig. (3d)). This effect has been exploited to synthesize arrays of nanoparticles.



**Fig. (3).** (a) Droplet vibration (b) Droplet actuation (c) Droplet jetting (d) Droplet atomization.

## Droplet Oscillation and Its Applications

### Active Droplet Micromixer

When the RF input power is lower than a critical value, pressure gradient is still generated inside the droplet. However, this gradient is not strong enough to move the droplet but still induces acoustic streaming in the liquid. Flow patterns and circulation are formed as shown in Fig. (4a). When SAW is launched to the liquid from the right side, circulation direction follows a clockwise direction as seen from the side view. From the top view, the left portion of droplet has a counter clockwise circulation as opposed to a clockwise circulation formed in the right portion of the droplet and the directions of the flows are in the same direction with the wave propagation.

Mixing of reactant inside a droplet is important in many biological applications. However, mixing is difficult and slow due to the relatively low Reynolds number in micro-scale systems. Electrowetting on dielectric (EWOD) based droplet mixers has been reported in the literature [12]. This method involves splitting and merging a droplet to generate flow advection and thus can enhance mixing. Alternative method is to employ the internal streaming generated by SAW. Rapid mixing inside a droplet based on this internal flow has been achieved and reported in the work of Frommelt *et al.* [13] and Wixforth *et al.* [14]. The mixing efficiency was found to be high for droplet with diameters larger than the SAW wavelength. This is due to the fact that acoustic power would couple more effectively into such a droplet to induce a stronger flow. Active droplet mixers based on SAW generally offer a very fast and effective solution. Mixing rate could be controlled simply by adjusting the input power from a single IDT compared to a more complicated electrode network in EWOD based mixer.

### Droplet Heater

The interaction of SAW and liquid could be used as a heating mechanism. Heating of a droplet by SAW is caused by heating of the piezoelectric substrate by the wave propagation and by radiated SAW energy into the liquid. Beyssen *et al.* [15] demonstrated a droplet heating system based on such mechanism. In this work, a 10  $\mu$ L water droplet was heated from an initial temperature of 18°C to 30°C under an applied SAW power of 1.5 W. At low input power, the effect

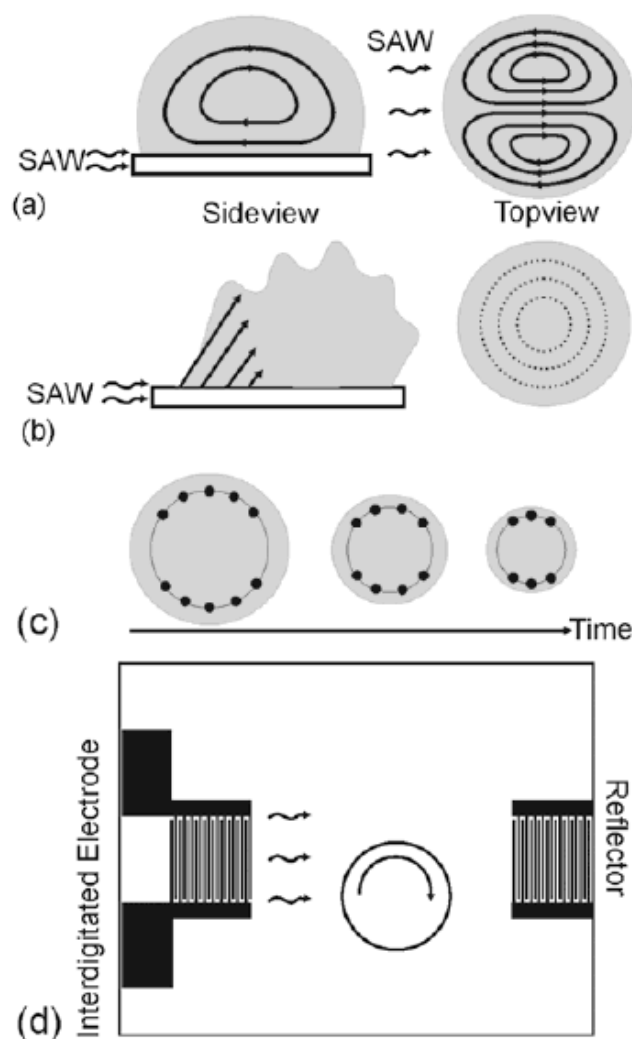
of substrate heating is inferior to that of radiated energy. The viscosity of the liquid is also a parameter that influences the droplet heating. A glycerol droplet of  $10\ \mu\text{L}$  has successfully undergone three heating cycles of  $55^\circ\text{C}$  peak with an input power of  $1.6\ \text{W}$ . Heating with SAW could be a potential concept for polymerase chain reaction (PCR) applications where no droplet movement through three temperature zones is required.

### Droplet Particle Patterning

If the droplet contains nanoparticles, unique particle assembly patterns are observed inside the droplet. These unique patterns depend on the power input of the SAW and the droplet diameter as reported by Li *et al.* [16]. In this experiment, the frequency of the applied input was  $20\ \text{MHz}$ . Under a low applied power, the pattern had a ring shape with the distance between the rings to be half of the SAW wavelength (Fig. (4b)). A laser Doppler vibrometer (LDV) was used to confirm the vibration at the free liquid surface at a very small amplitude. This surface vibration was believed to form a standing wave on the droplet surface and drove the particles to the pressure nodes which created ring like structure in the experiment. Upon increasing the input power, low frequency capillary-viscous vibrations of  $1\ \text{kHz}$  strongly interfered with the surface standing wave and formed point wise colloid islands in the circular nodes. The number of colloidal islands formed at intersection points between the  $20\ \text{MHz}$  nodal lines and the  $1\ \text{kHz}$  circular nodal ring decreased with time as shown in Fig. (4c). The reason was the evaporation of droplet with time which leads to the change in the number and the positions of colloid islands. If the input power was further increased, significant circulation flow was presented and the pattern of colloid islands was disturbed. A transient metastable state was established in which continuous cycle consists of colloid erasure and colloid islands formation took place subsequently. At even higher power, the internal streaming became dominant, permanent particle dispersion in bulk droplet was observed.

### Droplet Particle Concentration

Particle concentration at small scale is not an easy task since large radial force is needed to overcome the surface tension and to focus the particles in the droplet. Such radial force could be generated using SAW through symmetry breaking of the acoustic wave propagation across the substrate. By placing the droplet asymmetrically in the propagation line of SAW (Fig. (4d)), Li *et al.* [17] demonstrated asymmetric pressure fluctuations inside a droplet which gave rise to a unidirectional flow circulation, and hence, the suspended particles. Once the particle concentration was sufficiently high within a particular streamline of the acoustic streaming convective flow, the shear-induced migration gave rise to an inward radial force that concentrated the particles at the centre of the droplet. Other methods to create such asymmetric pressure were to introduce a diagonal cut of the substrate or to absorb half of the acoustic wave. Shilton *et al.* [18] intensified the circulation by introducing focusing interdigitated transducer electrode (FIDT) to generate a higher amplitude surface wave. Exploiting four FIDTs, concentration of fluorescent polystyrene particles of  $0.5\ \mu\text{m}$  in diameter was achieved rapidly after few seconds.



**Fig. (4).** (a) Flow pattern of induces acoustic streaming under effect of SAW; (b) Surface vibration and ring-like pattern formed inside droplet; (c) Point wise patterning formed inside droplet with increasing time (d) Symmetry breaking of SAW leads to unidirectional flow circulation.

### Droplet Motion and its Applications

Increasing SAW input power beyond a critical value causes the pressure gradient inside the droplet to be larger than the surface tension, and thus results in the droplet motion along the wave propagation direction. Due to the fact that piezoelectric ceramics substrate is naturally hydrophilic, and wetting area of a droplet is large, the device requires a higher input power to drive a droplet compared to a hydrophobic surface. To improve the performance of droplet actuation, surface treatment to make the substrate hydrophobic is needed. Different materials have been reported in the literature [19,20]. Polyvinylidene fluoride (PVDF) offers the lowest surface friction of  $85\ \mu\text{N}$ . Teflon also offer a good hydrophobic surface with the contact angle larger than  $100^\circ$ . A thin  $\text{CF}_x$  hydrophobic layer could be achieved by using an expensive plasma deposition process. However, self assembly mono-layer (SAM) of octadecyltrichlorosilane (OTS) is found to be the better solution in SAW droplet based microfluidics due to its simple and cost-effective coat-

ing process [21, 22]. A sufficiently thin hydrophobic layer with a thickness in the range of tenths to hundredths of nanometres can couple the SAW into the droplet more efficiently than the generally thicker films coated by other methods.

### **Droplet Actuation**

In many biological applications, droplet actuation is an important task. One popular method is EWOD driven digital microfluidics. Drawbacks of this method are the low driving force and the slow processing time. Acoustic streaming induced by SAW move the droplet with a large force and at a higher speed. Droplet actuation schemes driven by SAW have been proposed in the literature [23,24]. The speed of the droplet motion achieved was in the range of cm/s. For improved control of the droplet path, hydrophilic tracks on a hydrophobic piezoelectric surface were exploited in order to guide the droplet more accurately. The tracks could be easily fabricated by a lift-off process or by an etching process. Renaudin *et al.* [25] used a simple hydrophilic track on a silanized LiNbO<sub>3</sub> substrate to precisely deliver the droplet to a point of interest. Thalhammer *et al.* reported a SAW platform for two dimensional actuation of droplets [26]. Droplet actuation and merging have been successfully operated in some applications such as PCR, hybridization [27]. A potential microfluidic SAW processor could be attractive in various applications.

### **Droplet Particle Collecting**

In various biological applications such as environmental monitoring, particles such as fungi, bacteria, etc need to be collected by a carrier at an expected concentration. Tan *et al.* [28] exploited droplet movement and the internal streaming for particle collecting. In this work, dry particles were collected by an actuated water droplet along a hydrophilic track, (Fig. (5a)). The leaky force makes its more effective to sweep up particles from the surface into the bulk liquid. The collection process only took a few second per run, much faster than collection based on electrowetting. In this work, pollen has been reported to have a collection efficiency of 45-68%, and the efficiency is 61- 69.8% for bacteria.

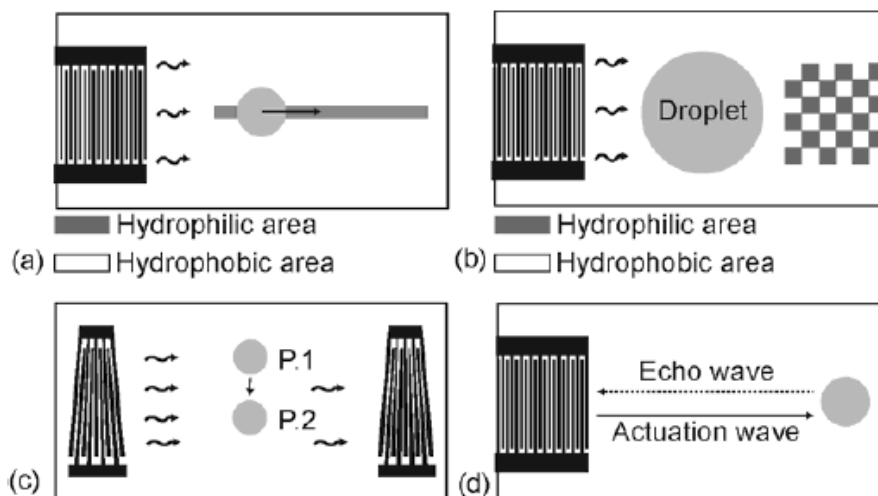
### **Droplet Sample Dispensing**

Strobl *et al.* [29] has demonstrated a cost-effective method to dispense droplet at nano and pico liter range using SAW. An array and a single passive sample SAW driven dispenser was introduced. This method is achieved elegantly by utilizing hydrophilic area on the silanized LiNbO<sub>3</sub>. A hydrophilic checker box consisting of 65  $\mu\text{m}$  size squares pattern was formed on the substrate (Fig. (5b)). When the water droplet was driven to pass the area, it left behind small amount of water in the hydrophilic squares. An array of droplet was formed with estimated droplet volume of around 50 pL. In single SAW dispenser, a fluid reservoir was formed by a large hydrophilic spot, and the amount of fluid dispensed is based on a small hydrophilic spot anchored next to the reservoir. One IDT actuated the fluid to cover the anchor. Upon turning off the signal, the fluid retracted back and left the anchor area wet. The dispensed droplet was subsequently moved to other location by another transducer. The spot in the experiment had a diameter of 300  $\mu\text{m}$  and the droplet volume was about 2 nL. These array and passive dispenser worked fast, reliable without expensive external control system.

### **Droplet Detection**

Besides traditional methods, SAW has been used to detect droplet as well. The working principle of detecting droplet using SAW is based on the strong attenuation in intensity of the transmitted wave. Bennes *et al.* [30] has demonstrated the improvement in detection by exploiting the step-by-step displacement of the droplet with a pair of uniform IDT. Instead of a continuous RF signal, a pulse modulated RF signal was applied to the input of the transmission IDT to drive a droplet in a step-by-step motion. With the modulation frequency of 5 Hz, pulse duration of 30 ms, a 0.4  $\mu\text{L}$  droplet could be actuated and detected with the resolution of 100  $\mu\text{m}$ . This method has accuracy higher than a tenth of the acoustic aperture.

Wu *et al.* [31] has employed the slanted inter-digitated transducers (SIDT) for droplet detection (Fig. (5c)). In this configuration, two SFIT were used for unidirectional detec-



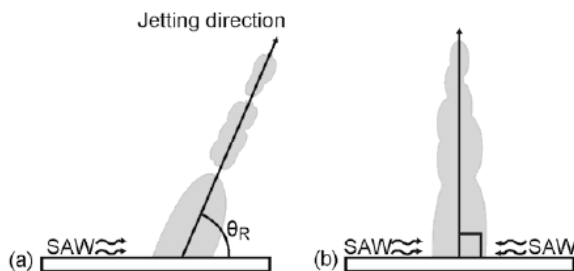
**Fig. (5).** (a) Droplet motion in a designate hydrophilic path; (b) Droplet array dispenser through checker hydrophilic area; (c) Droplet detection employing slanted IDT; (d) Droplet detection with a single IDT through echo wave.

tion with one as the transmitter and the other as the receiver. With the SFIT design, the centre frequencies varied within a passband according to the maximum and minimum of the finger pitch. When the droplet moved in the direction perpendicular to the IDT from location 1 and 2, its position could be tracked by monitoring the transmitted signal in the working passband of the device. The corresponding frequencies, where high transmission loss was observed, would indicate the positions of the droplet in the line. By varying the number of fingers and the size of the aperture, the passband and the amplitude of the wave could be adjusted. This design has the advantages over the uniform IDT in detecting droplets with size smaller than the aperture of the transducer. Nevertheless, the whole passband (in the range of few MHz) of the device requires continuous scanning in order to keep track of the droplet position.

Renaudin *et al.* [32] proposed another method to detect droplet in line with a single IDT using echo wave. A pulsed excitation RF signal was applied to actuate a droplet. A second pulse signal was sent afterwards and its corresponding reflected signal was recorded, (Fig. (5d)). Based on the time difference between the excitation signal and the reflected signal, the position of a droplet can be calculated. The reported device was able to receive the echo signal of the droplet as small as 0.2 nL. Furthermore, with the orthogonal detection being limited by the aperture size of the transducer pair, this method definitely provides much wider detection range compared to the above methods.

### Droplet Jetting and Its Applications

Current inkjet technology employs thermal and piezoelectric effects, where the ink is ejected perpendicular to the nozzle surface. With the application of SAW, a nozzle-free ink ejector could be realized [33]. When the applying power was larger than 1 W, the radiant force was strong enough to eject droplet from the bulk liquid in contact with the SAW substrate. The droplet was ejected at an angle  $\theta_R$  equivalent to  $22.6^\circ$  in the reported work (Fig. (6a)). This angle could be calculated based on Snell's Law with the propagation velocities of 3900 m/s and 1500 m/s in the substrate and in water, respectively. Tan *et al.* [34] demonstrated another method utilizing two opposite FIDTs at the ends of the substrate to drive the convergence of two SAWs at the point with a liquid drop as shown in Fig. (6b). The radiation from two sides of the droplet resulted in an elongated liquid column with an angle of about  $90^\circ$ . These SAW ejectors are free of nozzle head and offer a more cost effective solution as compared to the current ink ejector.



**Fig. (6).** (a) Droplet jetting induced by a single SAW; (b) droplet jetting induced by a pair of SAWs.

### Droplet Atomization and Its Applications

As the leaky SAW propagates in the fluid, capillary waves are generated at the liquid–air interface. If the applied power is sufficiently large, the acoustic stress dominates the capillary stress and destabilises the interface. Liquid atomization is induced, and continuous mist of droplets is evaporated in-flight. This technique has been used for biodegradable polymeric nanoparticles generation [35]. A polymeric excipient was dissolved into a solvent drop. This solvent droplet was then atomized by SAW and left behind solidified polymeric particles which are relatively monodispersed. With this technique, 150–200 nm spherical clusters were formed and comprised sub-50 nm particulates. Spatial ordering of periodic polymer has been patterned on a substrate by SAW atomization as well [36]. Droplet of a polymer solution was dispensed to a SAW track through a needle placing above the substrate. When this solution was in contact with the SAW, acoustic streaming displaced the droplet and left behind a trailing thin film layer of typically 10  $\mu\text{m}$  thickness. Due to the thin thickness, the film was quickly evaporated. The break-up of the film in both transverse and longitudinal directions produced evenly spaced solidified polymer droplets. It was observed that the longitudinal spacing was approximately half of the SAW wavelength while the transverse spacing was about half of this longitudinal value.

### 3. SAW CONTINUOUS-FLOW APPLICATIONS

Early applications of SAW in microfluidics mainly focus on droplet-based microfluidics. The integration of SAW on a channel microfluidic system has been researched more intensive recently. Applications in continuous flow such as pumping, mixing, sorting and patterning have been reported. The fabrication usually requires an additional step to fabricate the channel and to combine it with a piezoelectric substrate. On one hand, open channels can be fabricated by direct pattern transfer onto a SU-8 coated on the substrate. On the other hand, closed channel, usually made of PDMS, can be treated by oxygen plasma and bonded to the substrate. The applications are categorized according to interference of a single SAW or multiple SAWs which create standing surface acoustic wave (SSAW).

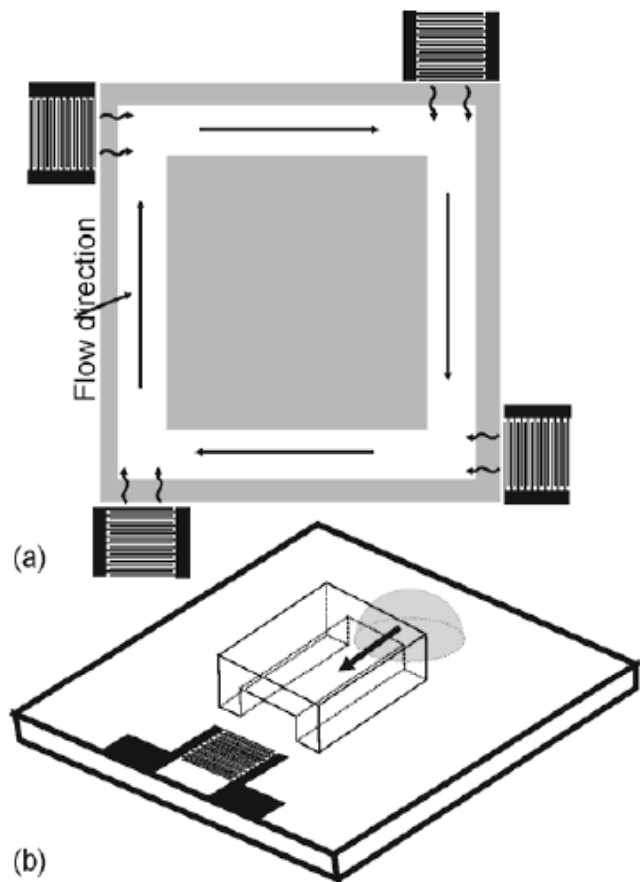
#### SAW Propagation and Its Applications

##### Micropump

Not only SAW was used as pump in droplet-based microfluidics, but also in continuous-flow microfluidics. Compared to other methods, SAW driven micropump is not in contact with the liquid, which can offer the diverse use of chemicals without affecting the electrode.

SAW pumping of liquid through an open-channel network has been demonstrated. Saiki *et al.* [37] pumped the fluid between two reservoirs through a channel of 1 mm width and 220  $\mu\text{m}$  depth with a flow rate of 4  $\mu\text{L/s}$ . The fluid velocity was proportional to the applied voltage. However there was a limited working range for the input signal. If the signal voltage exceeds 65Vp-p the fluid in the channel started to vaporize. Fukuoka *et al.* [38] used a similar setup to pump the liquid in a closed square loop channel (Fig.

(7a)). A mixture of dye and aluminium powder was used for visualization in the experiment. Relationship between the number of the fingers and comb pitch was characterized for optimal performance. A maximum flow velocity of 108 mm/s was achieved by using a 200  $\mu\text{m}$  comb pitch. Flow could be directed through positioning of the IDTs. Lindner *et al.* [39] proposed a micropump in which the piezoelectric transducer was attached to the bottom of the substrate with the channels. SAW was generated by the transducer, and the wave were radiated into the liquid through the substrate under the refraction angle  $\theta_R$ . This method is not limited to the size of the channel and offers more choices for the system substrate.



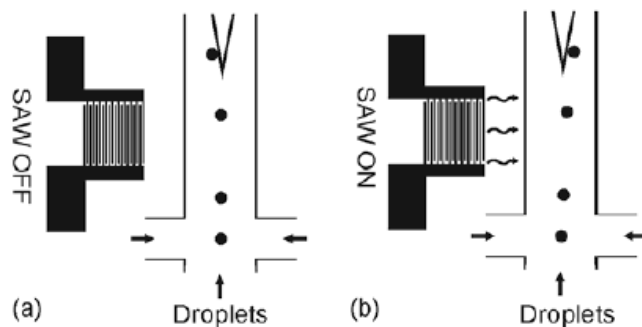
**Fig. (7).** (a) SAW pumping in an open SU-8 channel; (b) Fluid retraction through a closed PDMS channel.

Fluid could also be pumped through a closed microchannel [40]. A PDMS closed channel was mounted on the  $\text{LiNbO}_3$  substrate. The channel was aligned along the wave propagation. A drop of water was placed at one end of channel further away from the IDT as shown in Fig. (7b). The overall force balance at the liquid-solid interface system did not allow the channel to be filled. Upon switching on the transducer, the fluid is extracted to the other end through the microchannel by the liquid atomization and condensation. The process continued until the fluid reaches the opposite end. The velocity was observed up to 2.6 mm/s for water. This method provides an effective mechanism in withdrawing liquid for lab-on-chip applications. However, high input power (30 dBm) is required to achieve an efficient pump rate.

### Micromixer

Mixing in microchannel is a challenging task due to the natural laminar characteristics of flows. Rapid mixing of liquids inside a sealed microchannel could be achieved with the usage of SAW. Srithiran *et al.* [41] demonstrated a SAW mixer in a Y-shaped channel. The SAW device was placed directly under the junction of the inlets for a effective mixing effect. The wave propagation was designed to be perpendicular to the flow direction. The channel reported has 75  $\mu\text{m}$  in depth and 100  $\mu\text{m}$  in width. Water was filled in one inlet while fluorescent beads (1  $\mu\text{m}$  diameter) diluted in water was pumped to the other inlet. Different voltages were used to verify the mixing efficiency at a fixed flow rate of 250  $\mu\text{m/s}$ . Complete mixing state was achieved at a distance of 2 mm downstream, when SAW power was turned on, compared to a mixing fraction of 50% (purely due to diffusion) at the distance of 50 mm downstream.

Another micromixer utilizing SAW on a Y-cut 128 degree  $\text{LiNbO}_3$  was reported by Tseng *et al.* [42]. In this work, a Y-shaped PDMS channels were bonded directly onto the SAW substrate through an  $\text{O}_2$  plasma surface treatment process. Two schematic layouts parallel type (where the wave propagation is parallel to the flow direction) and the transverse type (the wave propagation is perpendicular to the flow direction) were investigated. Rhodamine B dyes and buffer solutions (sodium borate) were electrokinetically driven (100 V per cm) by a high-voltage power supply from two inlets of the channels. Mixing efficiency of more than 80% was reported at 2 mm downstream from the mixing junction. The parallel type mixer was reported to have a better mixing efficiency than the transverse type.



**Fig. (8).** Droplet sorting in channel by SAW: (a) SAW power is OFF, droplet flow to the left outlet (b) droplets are actuated by SAW to the right outlet.

### Sample Sorting

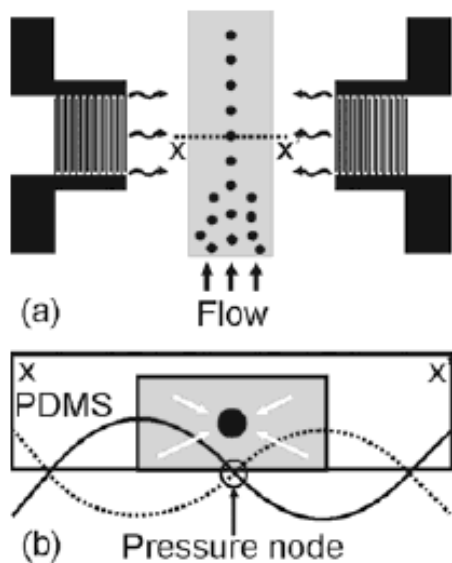
Droplet motion could be directed in a microchannel by SAW [43]. The microchannel was 50  $\mu\text{m}$  in depth and 100  $\mu\text{m}$  in width. Mono dispersed water droplet entered the channel from the bottom and flowed toward the left outlet based on PDMS channel design (Fig. (8a)). IDT was placed perpendicular to the left of the channel. When SAW power was turned on, acoustic streaming would drive the droplets to the right outlet, (Fig. (8b)). Individual droplets were actively directed along separate microchannel paths at high volume flow rates, which is useful for droplet sorting. Franke *et al.* [44] further improved this method to actively direct cell in a microchannel.

## SSAW and Its Applications

SSAW microfluidic devices exploit multiple IDTs on a piezoelectric substrate. The interference of waves generated by these IDTs created a standing wave with periodic distribution of pressure nodes and anti-nodes in the liquid medium contacting the substrate. Particles in the suspension liquid would be driven towards either the nodes or anti-nodes depending on the density and the compressibility of the fluid medium. Various applications have been demonstrated utilizing this particles redistribution.

### Particle Focusing

Particle focusing could be achieved by a few methods: 3D-hydrodynamics, dielectrophoresis and others. A new method is proposed by Shi *et al.* [45] employing standing surface acoustic wave to focus particle. The device consists of a pair of interdigitated transducers deposited on LiNbO<sub>3</sub> and a PDMS channel bonded between the transducers, (Fig. (9a)). A RF signal was applied to the transducers launching SAW from opposite directions into the microchannel and formed a SSAW. If the channel is designed to have the width of half the pitch, only one node (or antinode) appeared inside channel. Particles were pushed to this single node (antinode) due to acoustic force, (Fig. (9b)). A dilute solution ( $1.176 \times 10^7$  beads/mL) of 1.9  $\mu\text{m}$  diameter fluorescent polystyrene particles in water was used in the experiment. Stable focusing was achieved with a line width of 5  $\mu\text{m}$ . The method is frequency dependant, and the focusing width is inversely proportional to the frequency. SSAW based-focusing device provide a simple, fast method compared to other current focusing techniques.

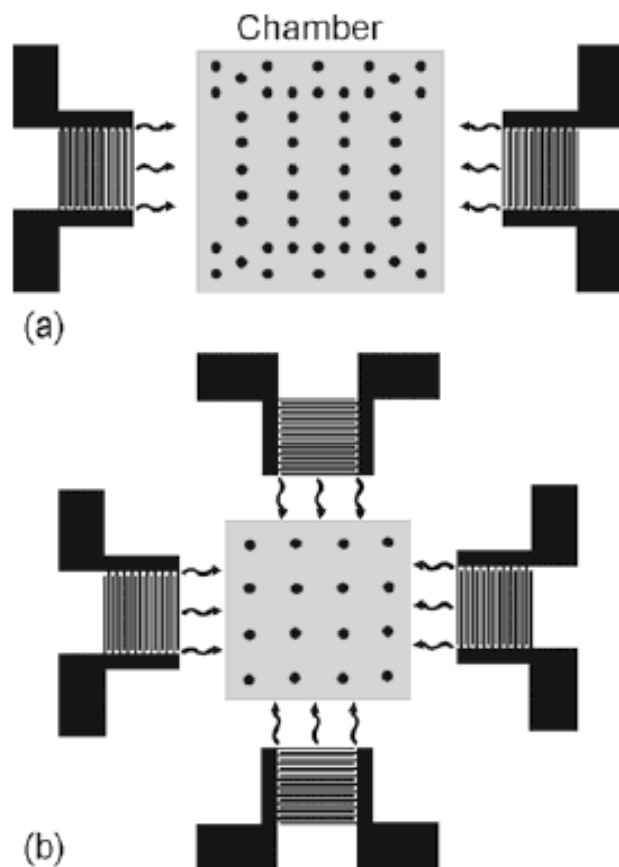


**Fig. (9).** (a) SSAW focus particles inside channel (b); A single pressure node (anti-node) is achieved when channel width is half of the SAW pitch.

### Particle Patterning

Particle manipulation and patterning have potential applications in biological micro array, tissue engineering or bio sensor array. An active method utilizing SSAW for particles patterning has been proposed. Particles would be attracted

toward pressure nodes or anti-nodes formed in a fluid channel/chamber. Particles alignment was achieved into lines inside a fluid chamber with a pair of IDTs positioned opposite each other's, (Fig. (10a)) [46]. The distance between these lines could be adjusted by changing the working resonance frequencies. SSAW two-dimensional (2D) particles patterning could be formed by rearranging the position of multiple IDTs. Wood *et al.* [47] used two pairs of SAWs with the chamber positioned at the centre, (Fig. (10b)). The standing wave would drive particles into an array with spacing equal to half of the SAW wavelength (or half of the pitch). Inside a chamber of diameter 1.2 mm, 456 nodes are reported to form an array of particles. Shi *et al.* [48] retrieved similar results with only 2 transducers arranged in the orthogonal direction. The spacing of the array could be adjusted by manipulating the SAW frequencies. The so-called "SAW tweezers" offer advantages of high speed, low power consumption and easy integration into a miniaturized system.

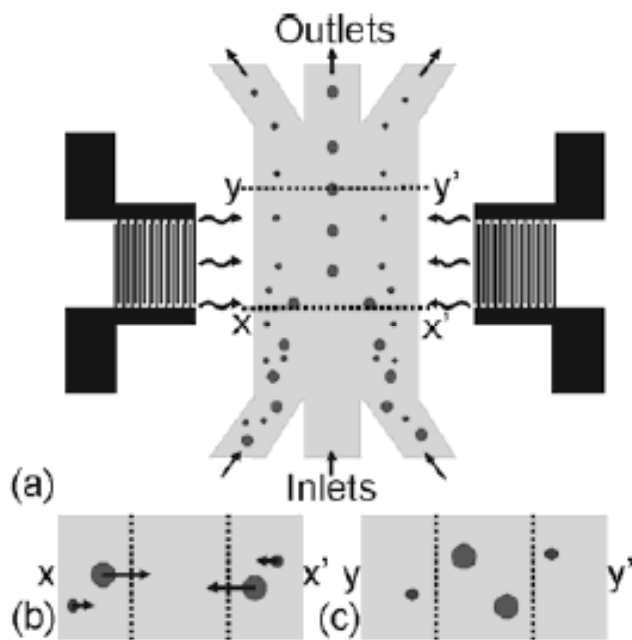


**Fig. (10).** (a) Particles alignment in a fluid chamber with a pair of IDTs; (b) 2D array patterned of particle with two pairs of IDTs.

### Particle Sorting

Effective particle sorting system is crucial for applications in medical diagnosis and biological research. The sorting mechanism is based on either particle size or particle physical properties. Besides its applications in focusing, patterning, SSAW also provides an active, fast, simple and high throughput mechanism for sorting particles [49]. The device consisted of a pair of IDT with a PDMS channel bonded and positioned between them. The mixture of particles with different sizes was seeded into the two outer sheath flows of a

three-streams laminar flow system, (Fig. (11)). Upon activating the two transducers, a SSAW was formed on the piezoelectric surface. Based on the channel design, only one pressure node (antinode) was formed inside the channel. The particles could be attracted to this pressure point only if the acoustic force is larger than the shear force. Sorting area was the intersection of the microchannel and the SAW aperture. Fluorescence particles of two diameters  $4.17\ \mu\text{m}$  (green) and  $0.85\ \mu\text{m}$  (red) were used. For the green particles of a larger diameter, the acoustic force is large enough to push them into the middle flow, while the red particles remained in the outer stream, (Fig. (11)). With a flow speed of  $2.5\ \text{mm/s}$ , the separation time of the green fluorescence only took 360 ms. The paper reported an efficiency of 80% of large particles migrating to the central stream, which is comparable or higher than other reported techniques.



**Fig. (11).** (a) Outline of the SSAW sorting experiment; (b) Cross section of microchannel before the working zone; (c) Cross section of microchannel after the working zone and particle separation was achieved.

## CONCLUSIONS

This paper reviews the state of the art of SAW driven microfluidics. The apparent advantages of SAW microfluidics are the strong motion, fast operation and especially the programmability. The fabrication process is established based on the already matured SAW technology. Surface treatment and integration of microfluidic components on piezoelectric substrate are proven to be simple and cost-effective. Various applications of SAW in the literature can be categorized based on the nature of the fluid namely droplet-based and continuous-flow systems. Depending on the droplet behaviour under an applied SAW power, suitable applications have been exploited. Besides the influence of acoustic streaming from a single source, standing SAW has delivered promising concepts for continuous-flow microfluidics. However, much of the works in SAW microfluidics are still open to be investigated. Firstly, the nonlinear interaction between SAW, liq-

uid and particles is yet to be studied in depth. There are still lack of quantitative studies and numerical works on this aspect. Secondly, the liquid used in most of SAW applications reported is of a single phase. Multi-phase SAW platforms could be of interest in many applications and worth of further exploitation. Evaporation of droplet over time is the main hindrance in some system where long sample processing time or heating are required. SAW applications in continuous flow still have room for such applications.

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