

# ON-DEMAND PICOLITER-SCALE DROPLET GENERATION USING SURFACE ACOUSTIC WAVES

David J. Collins<sup>1</sup>, Tuncay Alan<sup>1</sup>, Kristian Helmersen<sup>2</sup> and Adrian Neild<sup>1\*</sup>

<sup>1</sup>Laboratory for Micro Systems, Department of Mechanical and Aerospace engineering, Monash University, Clayton, VIC, AUSTRALIA and

<sup>2</sup>School of Physics, Monash University, Clayton, VIC, AUSTRALIA

## ABSTRACT

Droplets are a versatile platform for performing chemical reactions, detection and compartmentalization. When a droplet is in a two-phase device droplet-based processes can be performed without the need for fluid handling, with small reaction volumes reducing the need to perform separate mixing steps and reducing reaction times. While techniques exist to produce continuous trains of water-in-oil droplets, it has been difficult to produce individual droplets on-demand, a prerequisite for more complex programmable microfluidic devices. Here we present a novel method for integrating a pressure source on-chip, producing picoliter scale water-in-oil droplets on-demand using surface acoustic waves.

**KEYWORDS:** Microfluidics, droplet, acoustic, surface acoustic waves

## INTRODUCTION

The production of microfluidic droplets is fundamental for reliable droplet-based chemical reactions. The production of these droplets has been predominantly in T-junctions [1] and flow-focusing systems [2], where a continuous fluid flow of two immiscible fluids (most often oil and water) is required, with a constant stream of monodisperse droplets resulting from the combination of these two fluid streams. Technologies used to drive these flows, most often peristaltic pumps or syringe pumps, are poorly suited to manipulation of fluid volumes in the sub-nanoliter range, making on-demand production of individual droplets difficult to control. Further, in most microfluidic devices the pressure source is located distances away that are orders of magnitude greater than the length scales of the device, introducing time delays, additional fluid volumes and additional pressure gradients and resistances proportional to the length of the connecting tubing.

To address these shortcomings, several methods have been used to create pressure gradients on-chip, including surface acoustic waves (SAW). SAW is readily applicable to droplet generation, given the ability for a SAW to act directly on a fluid-fluid interface [3] with the wavelength of a typical SAW device ( $5 \mu\text{m} < \lambda_{\text{SAW}} < 300 \mu\text{m}$ ) encompassing the range of length scales found in most microfluidic devices. SAW has been used previously for mixing, concentration [4], pumping [5], jetting [6] and atomization [7], where (in the last two cases) SAW was used to act on the fluid-air interface to produce droplets with diameters as small as a few micrometers.

A SAW is produced using a series of interdigital transducers (IDTs) arrayed on a piezoelectric substrate and driven at a frequency  $f = c_s/\lambda_{\text{SAW}}$ , where  $c_s$  is the sound velocity in the piezoelectric substrate, resulting in a Rayleigh wave which will travel on the surface unattenuated. A SAW is substantially different from other methods of piezoelectric actuation, with bulk of the displacement concentrated within a few wavelengths from the substrate surface, resulting in efficient energy transfer from the substrate to a fluid placed on top of it, with the angle at which the acoustic wave propagates into the fluid given by the Rayleigh angle,  $\theta_R = \sin^{-1}(c_l/c_s)$ .

In this paper we report a novel method to produce individual picoliter-scale droplets on-demand, using focused SAW to act upon a water-oil interface to eject water droplets into a continuous oil phase. Further, we elucidate the mechanism by which a Rayleigh SAW acts upon a water-oil interface in order to produce movement in the direction of SAW propagation.

## THEORY

Acoustic radiation pressure, the time-averaged pressure on an interface placed in the path of an acoustic beam, arises as the result of the nonlinear propagation of the acoustic wave across a material discontinuity. In the case of an acoustic beam produced using SAW acting on an oil-water interface (as in Fig. 1b), there is no method, aside from interface movement, to transfer the isotropic pressure induced by the SAW to the oil side of the interface. The Rayleigh pressure acting on an interface is then given by [3]

$$p_r = \langle p - p_0 \rangle + \langle \rho v^2 \rangle, \quad (1)$$

where  $v$  is the instantaneous fluid particle velocity and  $\langle \rho v^2 \rangle$  is simply  $\langle E \rangle$ , the energy density in the fluid. To a first order approximation the fluid particle velocity  $v \approx v_0$ , where  $v_0 = \zeta \omega$  is the substrate velocity,  $\zeta$  is the surface displacement and  $\omega$  is the angular frequency. If the substrate velocity is oscillating sinusoidally, the time average  $\langle \rho v^2 \rangle$  is nonzero, resulting in a nonzero pressure term for an interface in the path of the acoustic beam. The static pressure term  $\langle p - p_0 \rangle$  arises from the nonlinear propagation of the acoustic beam through the fluid itself. Both the static and interfacial pressure contribute to the production of droplets in the system presented in Fig. 1.

## EXPERIMENTAL

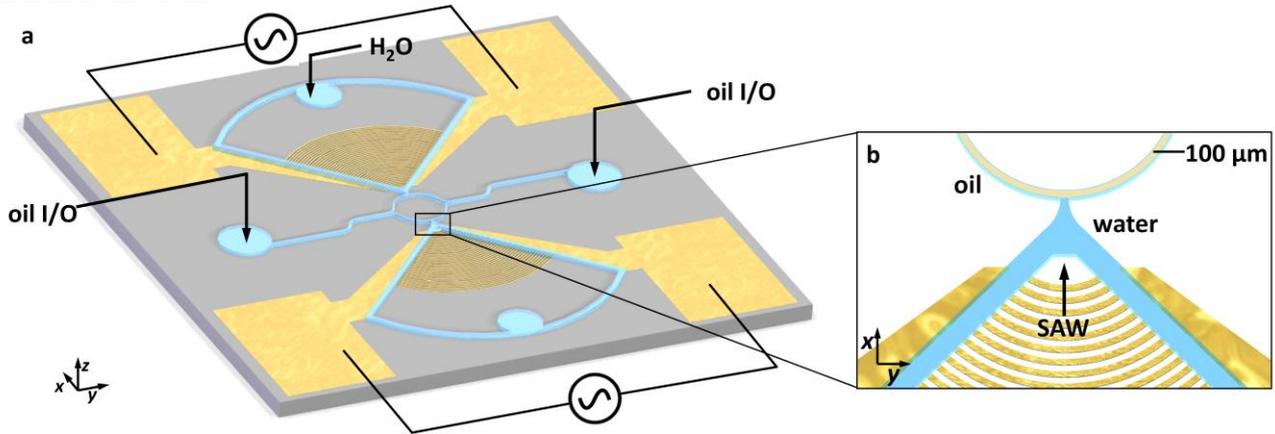


Figure 1: (a) Diagram of the SAW-based picoliter-scale droplet production system. A continuous and constant fluid phase of oil is injected in either symmetric oil I/O port. (b) Applying a short-duration SAW pulse (on the order on 100ms) focused at the water-oil interface is used to produce a single picoliter-scale water-in-oil droplet on-demand. The preferred SAW propagation direction is in the  $x$ -direction, as per the coordinate systems in (a) and (b). Figure is adapted from [8].

We employed 40 μm/80 μm wavelength focused SAW devices, comprising 90/45 finger-pairs of 90° circular focused interdigital transducers (FIDTs) on a 0.5 mm thick, single side polished 128°  $Y$ -cut,  $X$ -propagating lithium niobate (LN) substrate. The 10 nm chrome/200 nm aluminium FIDTs were aligned on the substrate symmetrically with respect to the preferred propagation direction on the LN. With the exception of the electrode pads, the devices were further coated with 70 nm of evaporation-deposited SiO<sub>2</sub> to promote adhesion with polydimethylsiloxane (PDMS), which was bonded after exposure to an activated air plasma. In the device setups considered the PDMS (~ 2 mm height) was either bonded directly to the IDTs (as in Fig 1) or delineated a water filled chamber around the IDTs (Figs. 2,3). Results from the two systems are comparable, though marginally higher powers are required to produce comparable droplets in the first case due to PDMS-loaded SAW attenuation.

Olive oil was injected into the using a syringe pump (KD Scientific 210, Holliston, MA, USA) whereas water (Milli-Q 18.2 MΩ.cm, Millipore, Billerica, MA) was manually manipulated using a 1 mL syringe until a steady-state oil-water interface was achieved. A signal generator/amplifier (BelektroniG F10, Freital, Germany) was used to power the device.

## RESULTS AND DISCUSSION

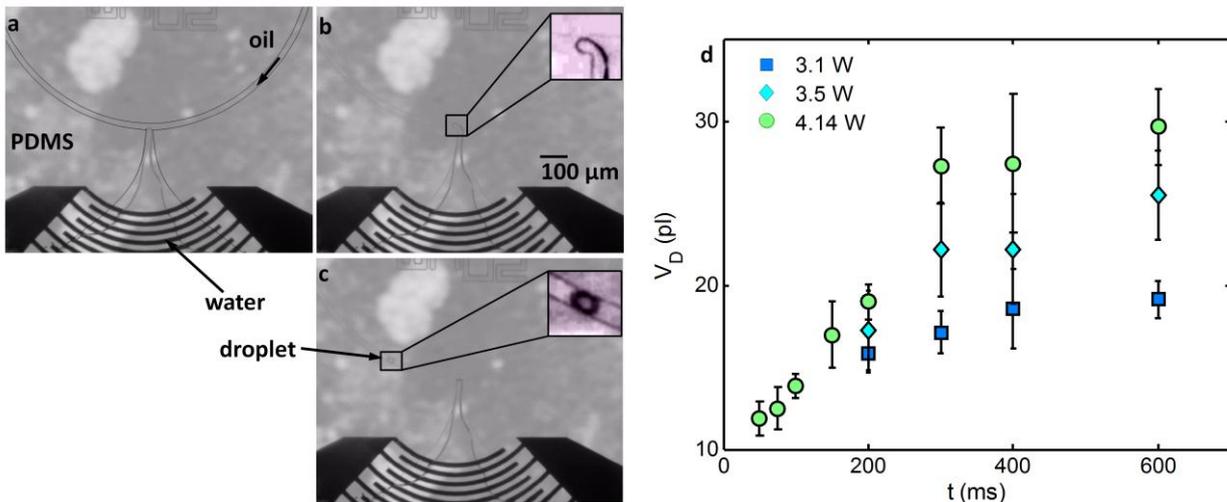


Figure 2: (a-c) Images of the production of an individual droplet and (d) the droplet volume  $V_D$  for different pulse durations and applied powers. The insets in (a-c) are contrast-enhanced for clarity. The orifice and channel width for (a-d) are 20 μm and 30 μm, respectively, both with a 30 μm chamber height, with a SAW wavelength of 80 μm and frequency of 48.4 MHz. The PDMS boundaries are highlighted in (a) for clarity. (d) Is adapted from [8].

In this work a focused SAW pulse is directed at an oil-water interface in a modified T-junction, where oil is the continuous and water is the disperse (droplet) phase. When the fluid interface is deformed sufficiently to bring the leading edge of the interface into contact with the opposing wall of the T-junction, the non-uniform pressure gradient on either

side of the nascent droplet resulting from the continuous fluid flow causes the neck at the orifice boundary to thin and finally break off, resulting in a water-in-oil droplet embedded in the oil phase [1]. Fig. 2a-c shows the interface movement and droplet break-off processes, with Fig 2d showing the observed droplet volumes, here encompassing a range of ~10-30 picoliters for SAW pulse durations from 50-600 ms. The SAW pulse must be of sufficient duration and power to deform the interface sufficiently to reach the opposing T-junction wall and produce a droplet; here pulses of lower powers (3.1, 3.5 W) require longer pulse times to initiate droplet production.

Wherever a discontinuity in acoustic properties exists an acoustic wave will be able to exert pressure on that interface – this is true for not only water-oil interfaces, but also any particles or cells that may exist in a medium exposed to an acoustic field. However, this force is greatly enhanced for higher frequencies and powers, with the force on the particle  $F \sim f^4$  (for radius  $\ll \lambda_{\text{SAW}}$ ). Increasing the SAW frequency to 95.4 MHz ( $\lambda_{\text{SAW}} = 40 \mu\text{m}$ ) it is possible to concentrate particles, here an analogue for cells, at the water-oil interface for subsequent simultaneous droplet production and particle encapsulation.

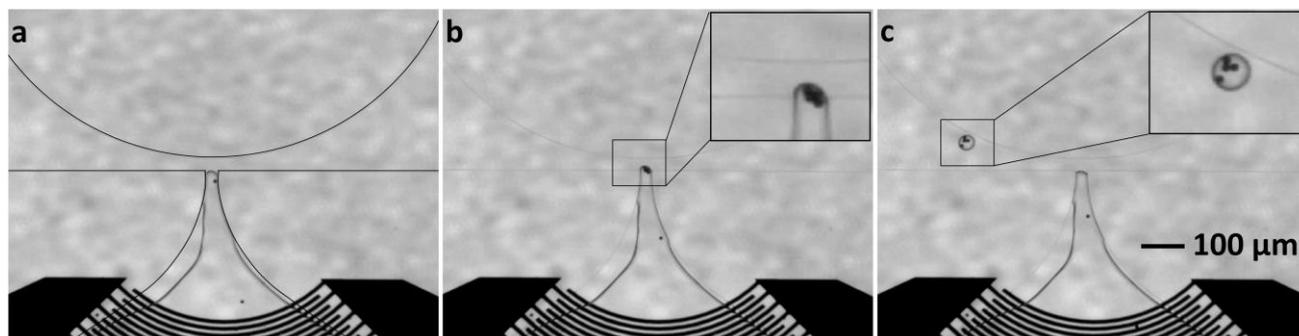


Figure 3: Simultaneous on-demand droplet production and particle encapsulation using SAW. (a) The water-oil interface at rest is (b) subjected to low power, high-frequency 95.4 MHz SAW to concentrate  $10 \mu\text{m}$  particles in a dilute mixture at the interface. Applying a short duration, high power SAW pulse results in an individual water-in-oil droplet encapsulating the concentrated particles. The PDMS boundaries are highlighted in (a) for clarity. Figure is adapted from [8].

## CONCLUSION

We have developed a novel system for on-demand production of water-in-oil droplets on a microfluidic platform using SAW. This system combines separate steps of particle concentration, encapsulation and droplet production, where the picoliter-scale droplet size produced can be reliably determined as a function of applied power and SAW pulse duration. We expect this system to find application in high-throughput serial analysis systems requiring programmable, on demand droplet production.

## ACKNOWLEDGEMENTS

Fabrication work was performed at the Melbourne Center for Nanofabrication.

## REFERENCES

- [1] G.F. Christopher, N.N. Noharuddin, J.A. Taylor, and S.L. Anna. Experimental observations of the squeezing to-dripping transition in t-shaped microfluidic junctions. *Physical Review E*, 78(3):036317, 2008.
- [2] A.M. Gañán-Calvo and J.M. Gordillo. Perfectly monodisperse microbubbling by capillary flow focusing. *Physical Review Letters*, 87(27):274501, 2001.
- [3] R.T. Beyer. Radiation pressure: the history of a mislabelled tensor. *The Journal of the Acoustical Society of America*, 63(4):4, 1978.
- [4] R. Shilton, M.K. Tan, L.Y. Yeo, and J.R. Friend. Particle concentration and mixing in microdrops driven by focused surface acoustic waves. *Journal of Applied Physics*, 104(1):014910-014910, 2008.
- [5] M. Cecchini, S. Girardo, D. Pisignano, R. Cingolani, and F. Beltram. Acoustic-counter flow microfluidics by surface acoustic waves. *Applied Physics Letters*, 92(10):104103-104103, 2008.
- [6] M.K. Tan, J.R. Friend, and L.Y. Yeo. Interfacial jetting phenomena induced by focused surface vibrations. *Physical Review Letters*, 103(2):024501, 2009.
- [7] D.J. Collins, O. Manor, A. Winkler, H. Schmidt, J.R. Friend, and L.Y. Yeo. Atomization off thin water films generated by high-frequency substrate wave vibrations. *Physical Review E*, 86(5):056312, 2012.
- [8] D.J. Collins, T. Alan, K. Helmersson, A. Neild. Surface acoustic waves for on-demand production of picoliter droplets and particle encapsulation. *Lab on a Chip*, 13:3225-3231, 2013.

## CONTACT

\*A. Neild, tel: +61 3 990 54655; adrian.neild@monash.edu