LINEAR SELF-FOCUSING ACOUSTIC TRANSDUCER

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ABSTRACT

This paper describes a linear self-focusing acoustic transducer (SFAT) capable of ejecting liquid droplets and asymmetric and heavy semiconductor chips from a liquid surface. The linear SFAT is designed to have multiple distributed focal points to generate an ejection force on multiple points at a liquid surface and is shown to be capable of ejecting a single liquid droplet in the center, two droplets out of its distributed side peaks, or tall water columns from the three pressure peaks, depending on how the transducer is electrically actuated. In addition, a linear SFAT (designed for a focal length of 5mm), when actuated at its thickness mode resonance at 1.955MHz with sinusoidal pulses of 173V_{pp} for 10.2ms with a duty cycle of 1.0%, is shown to eject a silicon chip of 12× 4×0.4 mm^3 (45mg) up to 9cm height from a liquid surface, one chip per pulse.

KEYWORDS

Acoustic Droplet Ejection, Chip Ejection, Microfluidic Manipulation, Focused Ultrasonic Transducers

INTRODUCTION

In semiconductor manufacturing, robotic pick-and-placement [1] is commonly used to assemble components, including integrated circuit chips and micro-LEDs on a printed circuit board or a large display panel [2]. As the robots mechanically pick, move, and place the components through nozzles, the assembly technique has inherent issues with high cost, frequent failure and maintenance [3], and limited minimum size of the components.

Acoustic droplet ejectors are capable of ejecting droplets of liquids such as water [4], ink [5], liquid metal [6], biological reagents [7 - 8], and solid pieces [10]. For droplet ejection, acoustic waves are focused through an acoustic lens [10, 5] formed on the surface of a piezoelectric transducer that generates acoustic waves.

Self-Focusing Acoustic Transducers (SFAT) focus ultrasound through annular electrode rings (of Fresnel Half-Wave Bands) patterned on a piezoelectric transducer [11]. Instead of the annular patterned electrodes, similar annular ring patterns of air cavities can be formed on a piezoelectric transducer [12]. The focused ultrasound can overcome the liquid surface tension and eject a droplet from the liquid surface. Most SFATs [13 – 14] have been designed to generate focused ultrasound at a single focal point and are not effective for ejecting asymmetric solid objects, as illustrated in Fig. 1. The ultrasound focused on a single point makes the flying trajectory of the ejected object non-perpendicular to the liquid surface, unless the object is precisely aligned.

A linear SFAT generates a line of focal points with three primary zones, one centered and two positioned on either side of the central focal point (Fig. 1b). The acoustic pattern generated by the linear SFAT extends over a relatively large area, enabling it to eject large rectangular chips from a liquid surface for assembly at a collection site (Fig. 2).

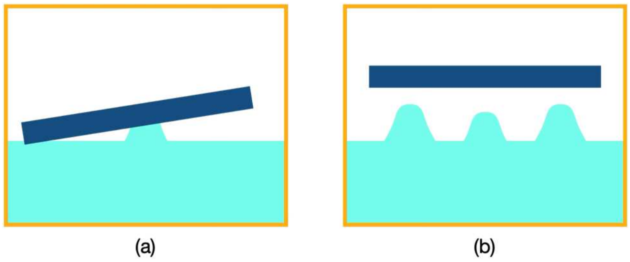

Figure 1: Cross-sectional views of ejecting a rectangular silicon chip out of a liquid surface, with an ultrasound focused on (a) a single point and (b) distributed multiple points.

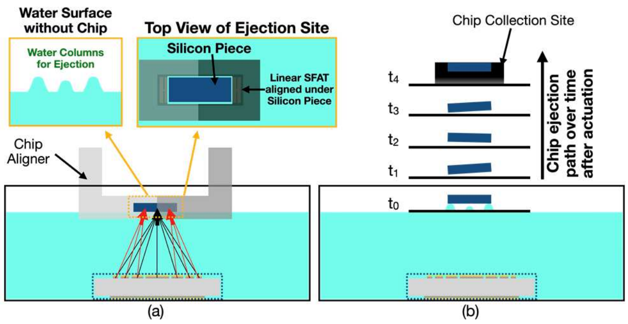

Figure 2: (a) Setup for ejection of a large rectangular chip with the linear SFAT and (b) a pick-and-placement of a chip through the ejection by the linear SFAT.

DESIGN AND FABRICATION

An SFAT is designed by forming annular rings of Fresnel Half Wave Bands (FHWB), where each ring radius is chosen to maximize the constructive interference at a focal point for focused ultrasound [10]. The linear SFAT is designed with rectangular electrodes rather than annular rings [11]. The Cr/Au electrode on top of a 1-mm-thick lead magnesium niobate-lead titanate (PMN-PT) substrate (whose thickness-mode fundamental resonant frequency is 2.0 MHz) is patterned into five pairs of rectangular electrodes (Fig. 3a). The widths of each symmetric electrode pair are designed into FHWB sources, with the distance from the n^{th} band boundary to the center line being

$$R_n = \sqrt{n\lambda \times (F_n + \frac{n\lambda}{4})} \qquad (1)$$

where λ is the wavelength in water at 2.32 MHz, while F_n is the focal length for the n^{th} Fresnel band. The regions that are not covered by the top electrode would have produced acoustic waves that would destructively interfere at the focal points (R_n<R<R_{n+1}, n=1,3,5,…), while the areas with electrodes (R_n<R<R_{n+1}, n=0,2,4,…) produce acoustic waves which interfere constructively at focal points.

The linear SFAT's cross-section resembles a regular SFAT, generating a focused ultrasound at a focal point at the center of the device. However, each rectangular electrode in the linear SFAT has its own focal point, resulting in many focal points in the case of the linear SFAT.

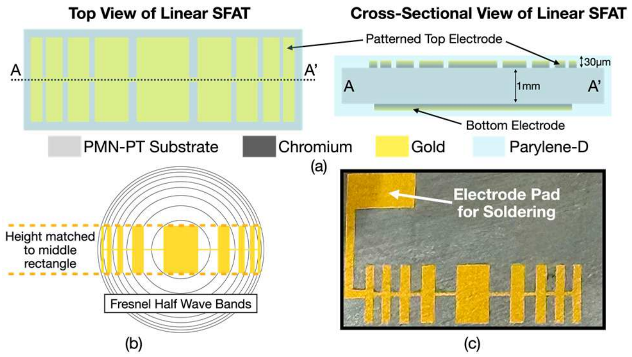

Figure 3: (a) Top view and cross-sectional view of the linear SFAT built on a lead magnesium niobate-lead titanate (PMN-PT) substrate, (b) design concept based on Fresnel half wave bands, and (c) top-view photo of the fabricated transducer.

The linear SFAT is designed to have a main focal length of 5mm with five pairs of rectangular electrodes on the top side of the piezoelectric substrate, while the electrode at the bottom side is patterned into a large rectangle. After being soldered with flexible wires, the SFAT is coated with 30µm thick Parylene-D for electrical insulation of the electrodes and wires.

DEVICE CHARACTERIZATION SETUP

A long-range microscope is connected to a high-speed camera (Photron Fastcam SA5) set to record 7,000 frames per second and is used to visualize the disturbance of the water surface under high-intensity illumination when the linear SFAT is actuated (Fig. 4). The SFAT is placed underwater so that the water level matches the designed focal height, and is actuated with a function generator whose signal is amplified with a power amplifier.

When a pulsed sinusoidal signal with the sinusoidal frequency matching the thickness mode fundamental resonance frequency (1.955MHz) is applied for a very short time, the disturbance of the water surface above the linear SFAT matches the acoustic pressure simulations at the designed focal plane using Finite Element Modeling (FEM) simulations in COMSOL, as shown in Fig. 5. With longer applied pulse width, the water surface profile changes due to fluid dynamics, depending on the applied voltage and the duty cycle for the applied signal. By altering the duration of the applied pulse, the device can be operated in various modes.

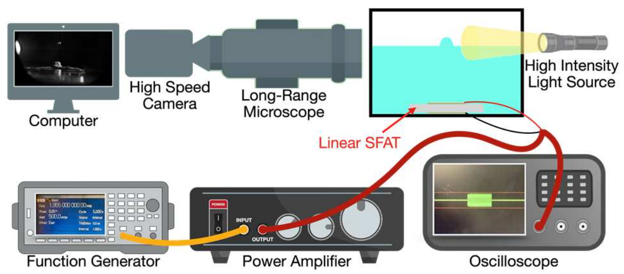

Figure 4: Setup for observing the liquid surface as the linear SFAT is actuated.

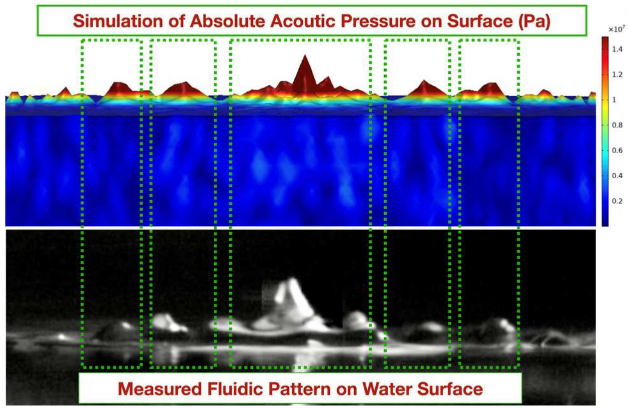

Figure 5: (Top) COMSOL-simulated acoustic pressure pattern generated by the linear SFAT at 5mm away from the transducer surface and (Bottom) photo of the water surface that confirms the simulated pressure pattern.

EXPERIMENTAL RESULTS

By optimizing the electrical signal applied to the linear SFAT, it is possible to eject a single liquid droplet from the center, two liquid droplets simultaneously (one from each of the side peaks), or a large, non-symmetric rectangular solid piece using all three high-pressure peaks.

Single Water Droplet Ejection

As the linear SFAT is designed to extend the functionalities of a conventional SFAT in terms of ejection capabilities while preserving its key performance characteristics, it generates one droplet per pulse without satellite droplets.

To achieve this, the operating conditions of the linear SFAT are optimized to prevent the side columns from generating excessive acoustic pressure that would result in unintended secondary droplets. This is accomplished by actuating the linear SFAT for a very short duration, ensuring that only a single pressure peak is formed at the center of the device. By precisely controlling the actuation parameters, the linear SFAT minimizes the risk of unwanted secondary pressure peaks.

Experimental results demonstrate that when the linear SFAT is operated at 225V_{pp} at its fundamental resonance frequency of 1.955MHz for a duration of 0.255ms, a single droplet of 1mm diameter is reliably ejected from the high-pressure peak at the center. Notably, this droplet formation occurs without satellite droplets, ensuring a clean and precise ejection, as shown in Fig. 6.

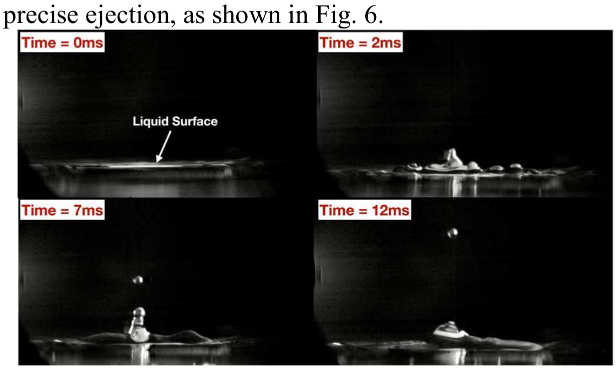

Figure 6: Sequential photos of a single droplet ejection (per applied electrical pulse) without any satellite droplet when the linear SFAT is actuated with pulses of 1.955MHz, 225V_{pp} sinusoidal signal for 0.255ms at 5Hz pulse repetition frequency (PRF).

Additionally, the linear SFAT is operated at a low Pulse Repetition Frequency (PRF) of 5 Hz to ensure single droplet ejection per pulse in a controlled and repeatable manner.

Multiple Water Column Formation

The primary obstacle in lifting non-symmetric large pieces from a liquid surface is overcoming the surface tension that naturally resists the upward movement of an object resting on the liquid. To successfully lift such objects, generating a substantial and well-distributed ejection force across the liquid surface is necessary to counteract the surface tension across the entire contact area of the object, ensuring a uniform lift without introducing any undesired horizontal displacement post-ejection.

The linear SFAT with multiple high-pressure zones arranged in a linear configuration is designed to generate a more significant lifting force that effectively distributes the ejection pressure over the entire object's surface. When the linear SFAT is activated for an extended duration, these high-pressure focal points on either side of the device gradually converge, ultimately forming three distinct high-pressure peaks - one at the center and two symmetrically positioned on either side of the central peak.

This configuration ensures that the lifting force is distributed over a significantly larger area, facilitating the effective and stable lifting of objects without unwanted lateral movement. This enables lifting much larger and heavier objects as compared to a conventional SFAT.

When the linear SFAT is operated with a sinusoidal signal of 173V_{pp} at a frequency of 1.955MHz for a duration of 2.05ms, the formation of the three high-pressure peaks becomes highly prominent and visibly distinct on the liquid surface. As illustrated in Fig. 7, these peaks highlight the effective force distribution across the surface.

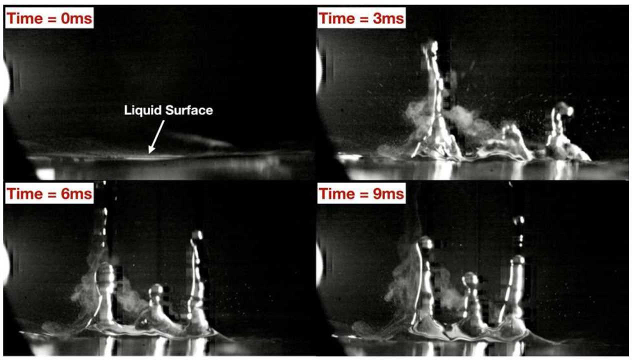

Figure 7: Sequential photos of water column formation (for lifting and ejecting a rectangular chip) when the linear SFAT is actuated with pulses of 1.955 MHz, 173V_{pp} sinusoidal signal for 2.05ms at 1Hz PRF.

Chip Ejection Experiment

The chip ejection capability of the linear SFAT is tested in a setup illustrated in Fig. 2. A silicon piece of 12×4×0.4 mm^3 is precisely positioned on the water's surface, directly above the linear SFAT, to ensure optimal interaction with the generated acoustic waves. When the linear SFAT is actuated at 173V_{pp} with a driving frequency of 1.955MHz for 10.2ms, the acoustic radiation forces generated by the SFAT eject the silicon piece out of the water surface into the air, against gravity, as high as 9 cm, as can be seen in Fig. 8.

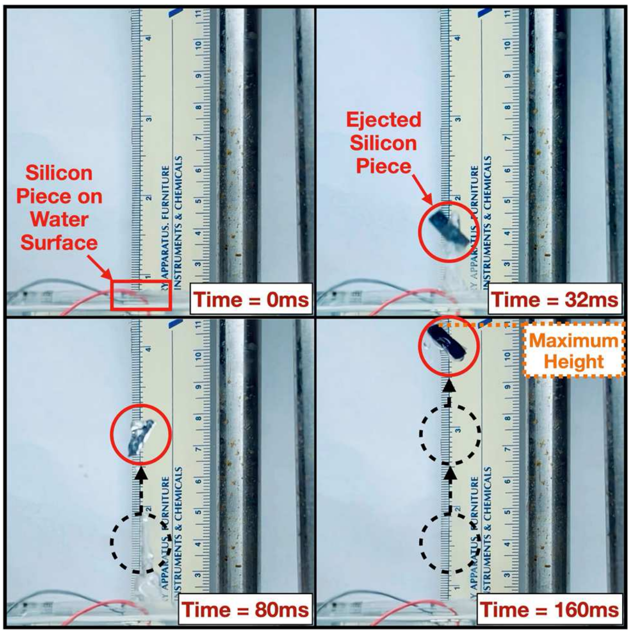

Figure 8: Sequential photos of the ejection of a rectangular silicon chip (12 x 4 x 0.4 mm^3) with the linear SFAT, which is actuated with 1.955MHz, 173V_{pp} sinusoidal signal for 10.2ms, showing the ejected chip traveling 9cm before falling due to gravity.

CONCLUSION

This paper presents a cost-effective solution that can be used as a replacement for traditional robotic pick-and-placement in semiconductor manufacturing assembly lines. The ejection (followed by collection) of chips is based on acoustic droplet ejection with focused ultrasound, in which the focal points are distributed over multiple points at a focal plane. Such distributed multiple focal points are obtained with a linear Self-Focusing Acoustic Transducer (SFAT) based on Fresnel Half Wave Bands (FHWB). The fabricated device is used to eject single droplets (like a conventional SFAT-based droplet ejection), multiple water droplets (from all the high-pressure peaks), and large silicon chips from a liquid surface.

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