MICROMACHINED ACOUSTIC-WAVE LIQUID EJECTOR

Xu Zhu, Eddie Tran, Weichih Wang, Eun Sok Kim and Soo Young Lee*

Department of Electrical Engineering
University of Hawaii at Manna
Honolulu, HI 96822

*Tektronix, Inc.
Beaverton, OR 97077

ABSTRACT

This paper describes a micromachined Acoustic-Wave Liquid Ejector (AWLE) array on silicon wafer for ink jet printing and microfluidic systems. The AWLE focuses acoustic waves (generated by piezoelectric ZnO thin film) through a constructive interference without any lens. Initial results show that the AWLE ejects ink liquid of 20 μm diameter size when driven by a 260 MHz sinusoidal wave for 100 μsec .

INTRODUCTION

Affordable, high quality and reliable printers are in great demand with the booming of personal computer industry. Currently, two most dominant printing methods are laser printing and ink jet printing. Laser printing produces high quality images. However, the technological complexity in laser printing has resulted in an expensive machine. In contrast, printers using ink ejection are relatively inexpensive due to their simple printing process.

Various methods have been employed to eject ink droplets for ink-jet printers. Among them are techniques using physical vibration through piezoelectric actuation [1,2] and thermal induced actuation [3]. Non-vibration based printers use electrostatics [4], vapor bubbles [5] and focused acoustic waves [6]. Most of these printers eject ink droplets through small nozzles onto a paper to form an image. The small nozzles are difficult to construct with good uniformity, and also tend to be clogged. Ink ejection without the use of small nozzles is thus desired.

Figure 1. Liquid ejector using acoustic lens to focus acoustic waves.

Nozzleless liquid ejection has been shown with a high inten-

sity focused acoustic beam [7]. A high intensity burst of acoustic energy focused to a diffraction-limited spot at a free-liquid surface (Fig. 1) can result in droplet ejection from the surface. Liquid ejection using a focused acoustic beam is capable of ejecting liquid droplets as small as a few μm in diameter which are stable in size and directionality. This technique, when applied to ink jet printing, can provide excellent quality printing with good reliability.

The liquid ejector shown in Fig. 1 requires an acoustic lens to focus the acoustic waves. Additional processing steps required to construct any physical lens in an IC process are not desirable. Spherical acoustic lens would be especially difficult to implement using planar IC processing. Thus, we came up with a self-focusing planar transducer.

THEORY

Based on the concept of constructive interference of acoustic waves, we have developed a self-focusing liquid ejector shown in Fig. 2. When the transducer is excited with a burst of RF signal,

Figure 2. Lensless liquid ejector using a constructive interference of acoustic waves.

it generates acoustic waves that propagate in the liquid toward the liquid/air interface. If the electrodes of the transducer are properly designed, the acoustic waves will add in-phase at the focal point.

Our lensless design borrows its concept from optical Fresnel lens which blocks certain area of light to get intensity enhancement. We make only certain areas of the piezoelectric film generate acoustic waves, which arrive at a focal point in phase. The other areas (that would have generated waves with a phase difference of π at the focal point) are designed not to generate any acoustic wave.

This is what we call Half-Wave-Band sources. Figure 3 shows the acoustic wave transducer with several annular sources. The acoustic waves generated by the successive annular sources are designed to arrive at the focal point (f) with finite delays (equal to multiples of the wavelength) by ensuring that the radii r_n satisfy the following relation [7]:

$$\sqrt{r_n^2 + f^2} - f = \frac{n\lambda_w}{4}. \quad (1)$$

Figure 3. Focusing acoustic waves by half-wave-band sources.

Solving Eq. 1 for r_n results in $r_n = \sqrt{\frac{n\lambda_w}{2} \left(f + \frac{n\lambda_w}{8} \right)}$, where $n=1,3,5,\dots,2n+1$; λ_w is the wave length of acoustic wave in liquid.

If we use an isotropic medium, such as water, where the particle displacement u associated with the longitudinal waves can be defined as the gradient of a potential $u = \nabla\phi$, the potential ϕ at any point in the water for a half-wave-band source shown in Fig. 3 is obtained as

$$\phi(x, y, z) = -\frac{1}{2\pi} \int_s u_z(x', y', 0) \frac{e^{-jkR}}{R} ds' \quad (2)$$

where $k = \frac{2\pi}{\lambda}$; R is the distance between a half-wave-band-source and the focal point; s' is the surface area of the transducer at $z = 0$; and s is the active surface area at $z > 0$. The potential along the z -axis due to n numbers of half-wave-band sources can be expressed as

$$\begin{aligned} \phi_z &= -u_0 \left[\int_{r_1}^{r_3} \frac{e^{-jkR}}{R} r' dr' + \int_{r_5}^{r_7} \frac{e^{-jkR}}{R} r' dr' + \dots \right] \\ &= \frac{u_0}{jk} \left(e^{-jk\sqrt{r_3^2 + z^2}} - e^{-jk\sqrt{r_1^2 + z^2}} + e^{-jk\sqrt{r_7^2 + z^2}} \right. \\ &\quad \left. - e^{-jk\sqrt{r_5^2 + z^2}} + \dots \right) \end{aligned} \quad (3)$$

where $u_z(r, 0) = u_0$ is assumed to be uniform over the transducer and zero outside it.

In water, the pressure p is isotropic, and is equal to $p = \omega^2 \rho \phi$ where ρ is the liquid density. The average intensity of an acoustic beam is

$$I = \frac{|p|^2}{2\rho V_a} = \frac{\omega^4 \rho |\phi|^2}{2V_a} \quad (4)$$

where V_a is the acoustic wave velocity in liquid. Thus the intensity along the z -axis is

$$I(z) = I_0 \left| \left(e^{-jk\sqrt{r_3^2 + z^2}} - e^{-jk\sqrt{r_1^2 + z^2}} + e^{-jk\sqrt{r_7^2 + z^2}} - e^{-jk\sqrt{r_5^2 + z^2}} + \dots \right) \right| \quad (5)$$

where I_0 , the intensity at the transduce (i.e., at $z = 0$), is equal to

$$I_0 = \frac{\rho V_a \omega^2 u_0^2}{2} = \frac{p_0^2}{2\rho V_a}. \quad (6)$$

At the focal point, $\sqrt{r_1^2 + z^2} = f + \frac{\lambda}{4}$; $\sqrt{r_3^2 + z^2} = f + \frac{3\lambda}{4}$; ..., in which case Eq. 5 simplifies to

$$I_f = I_0 \left| \left[e^{-j2kf} (2nj)^2 \right] \right| = 4n^2 I_0. \quad (7)$$

Therefore, the half-wave-band sources effectively increase the intensity at the focal point by a factor of $4n^2$.

DEVICE STRUCTURE AND FABRICATION

We use silicon bulk micromachining to produce a 1×1 mm² membrane and a liquid cavity in the AWLE (Fig. 2). Low-stress LPCVD silicon nitride (0.5 μ m thick) is used to support 10 μ m thick piezoelectric ZnO film and 0.5 μ m thick Al electrodes. The segmented bottom electrode and the ZnO film act as half-wave band sources as shown in the photograph of the fabricated transducer (Fig. 4).

Fig. 4 Top View photograph of lensless acoustic-wave liquid ejector. Bottom Al electrode and ZnO are patterned with annular rings and a tailed circle, respectively. Lightly shaded square area represents the 1×1 mm² thin membrane.

An array of transducers is fabricated on a silicon wafer with the following 4-mask process. After depositing and patterning 0.5 μ m thick LPCVD low-stress silicon nitride, we remove silicon with KOH to form 1×1 mm² membranes, on which 0.3 μ m thick Al is evaporated and patterned for an annular bottom electrode. Then a 10 μ m thick ZnO is sputter-deposited in Ar/O₂ environment from a ZnO target, followed by 0.5 μ m thick Al evaporation and

delineation for a top electrode.

RESULTS AND DISCUSSION

The fabricated devices are tested with the set-up shown in Figure 5. A continuous sinusoidal wave (in the range 100 - 400

Figure 5. Schematic representation of the test apparatus for liquid ejection.

MHz) from a signal generator is fed into a high speed switch which is turned on/off with a modulating pulse duration set at, in this case, 100 μ sec. The RF power amplifier then amplifies the RF burst to 10 Watts level before feeding it to the transducer.

Figure 6. Experimental data on spot size of ejected ink versus driving RF frequency.

We use color methanol mixed with tin solution as the liquid for (1) low surface tension for an ejection with a relatively small power and (2) low boiling point for a relatively fast change in the liquid level so that the exact focal plane can gradually be reached without any elaborate apparatus. The ejected droplets are detected by a piece of a paper placed over the chamber area. The droplet formation is made possible by a series of high power RF pulse (with single-frequency sinusoidal waves) fed to the piezoelectric transducer which in turn generates focused acoustic waves at the focal plane. Initial results show that ink spots roughly around 20 - 100 μ m in diameter have been ejected around the thickness-mode resonant frequency (260 MHz) of the piezoelectric transducer (Figure 6). The largest ink spot of 100 μ m is observed at the resonant frequency (260 MHz) where the output acoustic wave is at its maximum. The smallest pulse duration for any visible liquid ejection is 100 μ sec during which a sinusoidal wave ranging from 100 - 400 MHz is applied to the transducer. The power out of the power amplifier is kept constant at 10 Watts.

When the pulse duration is much longer (e.g., >100 msec), sporadic ink ejection is observed due to thermal evaporation

and also large thermal-induced deflection of the membrane. The flexural deflection of the membrane occurs due to thermal expansion differences in the films employed for the transducer as the membrane temperature gets high. The temperature on the transducer is measured to be a function of the sinusoidal frequency and the pulse duration. When the transducer is driven continuously by a sinusoidal wave in a frequency range 100-400 MHz, the temperature measured above the liquid chamber over the transducer appears to peak as the frequency approaches the thickness-mode resonant frequency.

CONCLUSION

An array of self-focusing acoustic beam transducers using a 0.5 μ m thick low-stress silicon-nitride membrane and a 10 μ m thick piezoelectric ZnO film has been fabricated on a silicon wafer, and shown to eject liquid of 20 μ m diameter size with 100 μ sec application of a 260 MHz sinusoidal wave. This technique of nozzleless liquid ejection may advantageously be applied to ink jet printing and microfluidic systems.

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