A flat-panel-display compatible ultrasound platform

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Abstract

We present a thin-film piezoelectric micromachined ultrasonic transducer (PMUT) technology compatible with flat-panel manufacturing methods. Using the developed flow which is based on a low temperature AlScN piezoelectric layer, we fabricate large area 48x48 element PMUT arrays on glass. Beam steering and ultrasound medical imaging are demonstrated. The developed transducer technology can be combined with a TFT backplane and has the potential of direct integration on top of display size glass sheets, expanding the boundaries of ultrasound application domains.

Author Keywords

Piezoelectric transducers; ultrasonic transducers; large-area; thin-film; microelectromechanical system (MEMS).

1. Background and context

The use of ultrasound is widely spread in our daily life, from park assistant sensors to echography for fetal growth monitoring. The most common ultrasound sensors use thick piezoelectric layers. By applying a high voltage across this piezo layer, thickness modulation is achieved. This displacement creates disturbances in the ambient pressure level and an ultrasound wave can be emitted (or detected). Next generation ultrasound devices make use of piezoelectric micromachined ultrasound transducers (PMUT), where the displacement is generated by a thin piezo layer (500 nm – 2 um) on top of a membrane, vibrating at resonance. Using photo-lithographic patterning techniques, dense arrays with a pitch around $\lambda/2$ (half acoustic wavelength) are achievable, which makes this technology ideal for applications where more complex beam-forming PMUT arrays, both in transmit or in receive mode, are required. An additional benefit is the optional tight integration with electronics, enabling circuitry below each PMUT element.

Most available PMUT arrays are produced using silicon semiconductor facilities, limiting the process size to 6"/8"/12", depending on the facility. This contrasts with the flat panel display production, where large glass sheets are processed for screens. The combination of PMUT with processing on glass sheets would enable unique applications that require large (10 – 100 cm²) PMUT arrays. The combination with existing FPD process blocks such as thin-film circuitry or flexible substrates further broadens the application domains (Figure 1). Haptic mid-air feedback requires air-born focused ultrasound with a high focal pressure point to generate a touch sensation; while the current technology consists of large arrays of discrete transducers (~1 cm³ each), a large area thin-film approach will enable tight integration on flat or even curved surfaces. The same holds for non-camera-based gesture recognition: surfaces can become aware of their environment. Ultrasound based fingerprint detection is currently limited to small silicon chip sizes; display size fingerprint (or palm) detection requires an FPD technology. Using modulated focused ultrasound waves, large directional speakers can be fabricated. A last example, and the focus of this work, is the use of large ultrasound arrays for medical imaging.

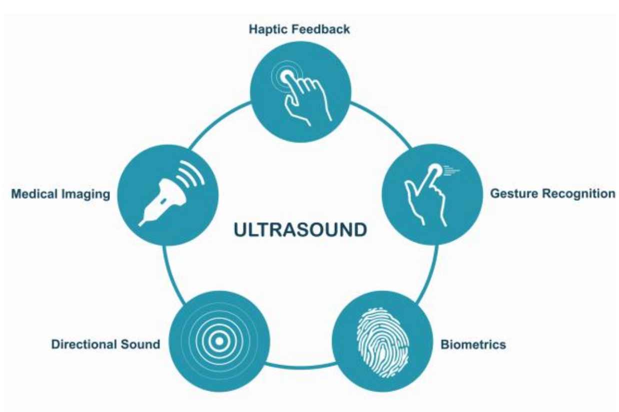

Figure 1. Example application domains for large area ultrasound arrays.

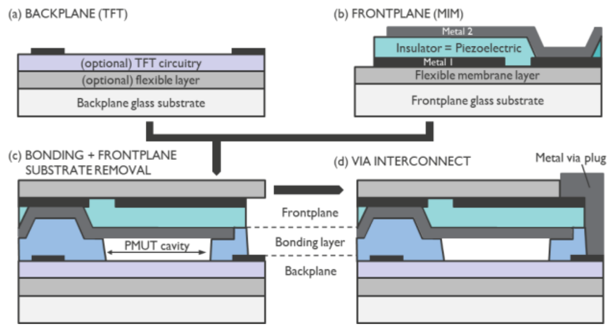

Figure 2. Schematic cross-sections of a PMUT process flow: (a) backplane substrate with optional TFT and/or flexible layer; (b) frontplane substrate with metal-insulator-metal stack; (c) bonding of frontplane to backplane and removal of frontplane substrate; (d) metal via interconnect for electrical connection between front- and backplane.

Here we present a novel large area PMUT (LAPMUT) technology that is compatible with flat panel manufacturing methods. The piezoelectric stack, fabricated on glass, utilizes a thin AlScN-based actuation layer in combination with a polyimide membrane. The transducer cavity is formed by adhesive bonding to a glass substrate mimicking a TFT backplane. By using a high crystallinity scandium doped AlN piezo-layer we achieve large membrane displacements, which are exceeding the ones previously reported for large area PMUT solutions based on un-doped AlN or PVDF [1,2]. By combining multiple transducer elements, a large 48x48 array is fabricated operating at 2.4 MHz frequency range which is suitable for medical imaging applications. To demonstrate this, we successfully perform ultrasound image acquisition and beam steering from ±16-degree angles and up to 10 cm distance with

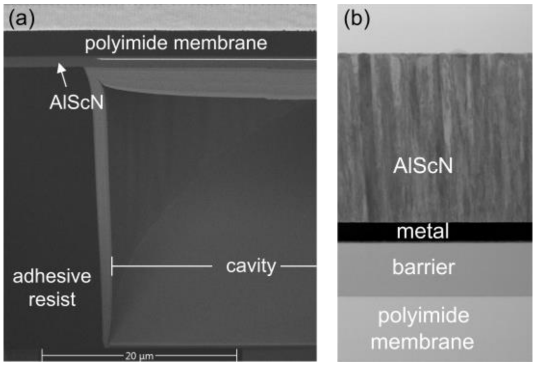

Figure 3. (a) SEM cross-section of a PMUT device. The light gray layer that outlines the cavity is caused by re-deposition of the sputtered material against the edges of the cavity during the FIB; (b) TEM picture showing crystalline AlScN on glass substrate

pressures above 7 kPa/V in water. The presented technology offers a competitive solution for large area ultrasound applications allowing the fabrication of large and high-density arrays.

2. Flat-panel compatible PMUT technology

To fabricate the LAPMUT device a frontplane piezoelectric stack is combined with a backplane through adhesive bonding (Figure 2). In this work, as backplane we have used a glass wafer without any circuitry which mimics a TFT stack. The frontplane consists of a patterned metal-insulator-metal (MIM) stack where the insulator layer is a piezoelectric material. The stack is deposited on top of a glass wafer coated with a 3 µm polyimide layer serving as the transducer membrane. In the next step an adhesive photoresist is coated and patterned on top. The role of this layer is two-fold. First, it forms the PMUT cavity and second, it allows the bonding of the piezoelectric stack with the backplane as shown in Figure 2(c). After the bonding, the initial glass wafer is released from the polyimide membrane. In the case of a full TFT integration a via interconnect opening can be envisioned which is then plugged with a metal for the electrical connection between front- and backplane Figure 2(d). The final PMUT stack is shown in the inset of Figure 5. A Focused Ion Beam Scanning Electron Microscopy (FIB SEM) image of the cross-section reveals the well-formed cavity and the sharp edges of the adhesive layer

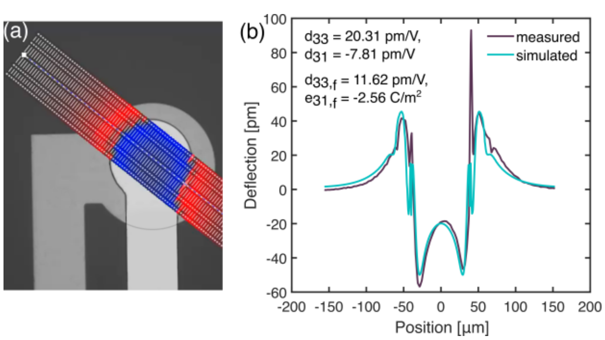

Figure 4. Characterization of AlScN piezoelectric properties. (a) microscopy picture of the MIM stack with the deflection profile highlighted; (b) measured deflection data and corresponding FEM simulation for d_{33} and d_{31} extraction.

below the frontplane stack (Figure 3(a)).

The key component of the frontplane is the piezoelectric material. Thin-film piezoelectric MEMS typically use PZT, AlN or ZnO [3]. Among those, PZT is widely adopted in PMUT devices fabricated on silicon due to its high piezoelectric constant $e_{31,f}$ [4]. However, PZT requires high annealing temperatures (500-800°C) which make it incompatible with FPD processes. Until now PVDF (polyvinylidene fluoride-co-trifluoroethylene) has been the only suggested candidate for large area display compatible PMUT arrays [5], though its performance capabilities are limited. Recently, it has been shown that scandium doping of AlN can drastically enhance its piezoelectric coefficients, making it competitive to PZT [6,7]. The advantage of AlScN is that it can be deposited at temperatures as low as 150ºC providing high flexibility for integrating it in thin-film process flows. For this work, AlScN with a scandium concentration of 30% is deposited by reactive sputtering on top the polyimide coated glass wafer. Platinum is used as the bottom metal of the MIM stack, acting also as the seed layer for AlScN, ensuring its high crystallinity (Figure 3(b)). The stack is finalized by a top Al metal layer.

3. Transducer performance

Prior to cavity definition, the MIM stack is characterized in terms of the AlScN performance. By applying a low-frequency single-tone electrical excitation to the electrodes, the voltage-induced intrinsic piezoelectric displacement is measured through Laser Doppler Vibrometry (LDV) (Figure 4(a)). The obtained deflection profile is then fitted with a finite element model (FEM) for the extraction of the piezoelectric constants. The results are plotted in Figure 4(b), showing good agreement between the measured and simulated data. Large piezoelectric coefficients with values of 20.31 pm/V for d_{33} and -7.81 pm/V for d_{31} are achieved which are on par with the state-of-the-art values reported in literature for AlScN deposited on silicon substrates [8]. This confirms the high quality of the AlScN deposited on

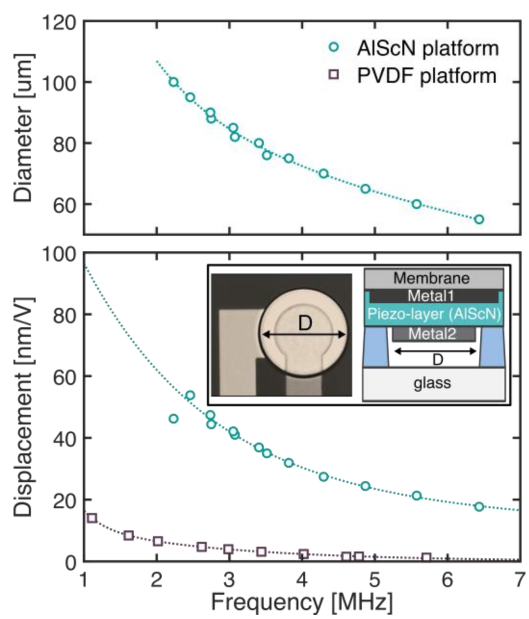

Figure 5. Resonance frequency of PMUT elements with variable cavity diameter (top) and corresponding membrane displacement amplitude (bottom). The inset shows a microscopy image of the fabricated PMUT and a corresponding cross-section across the cavity.

glass and its suitability for LAPMUT devices.

In the following step, the cavity is formed and the PMUT devices are characterized. By monitoring the membrane deflection with LDV while actuating the device at different frequencies, the resonance frequency and the membrane velocity are extracted. Figure 5 shows the results of several individual PMUT elements with varying diameter from 50 to 100 µm. The corresponding resonance frequency ranges from 2 to 6.5 MHz. Large membrane displacements are measured with 18 nm/V for the smallest transducers and 58 nm/V for the largest one. These values are the highest reported for a large area thin film PMUT and an order of magnitude higher than respective devices based on a PVDF piezoelectric layer. By combining individual PMUT elements of a specific size in an array configuration, different ultrasound applications can be targeted. The proposed technology offers tremendous flexibility on the array size, form factor and pixel density.

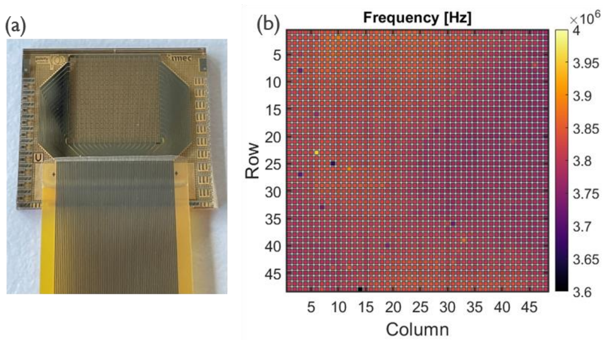

Figure 6. PMUT array (a) fabricated device with flexible connector to a PCB and (b) measured array resonance frequency map in air.

4. PMUT arrays

To obtain sufficient output pressure and allow beam steering, single PMUT devices are combined in square arrays. Targeting 2.4-MHz operation in tissue, the PMUT diameter is fixed at 76 µm. The devices are organized as a 48x48 element matrix with a 200-um pitch. After fabrication and dicing, flexible PCBs are bonded to the contact pads using an anisotropic conductive adhesive (Figure 6(a)).

The characterization of a full array starts with a mechanical measurement using laser Doppler vibrometry. The frequency

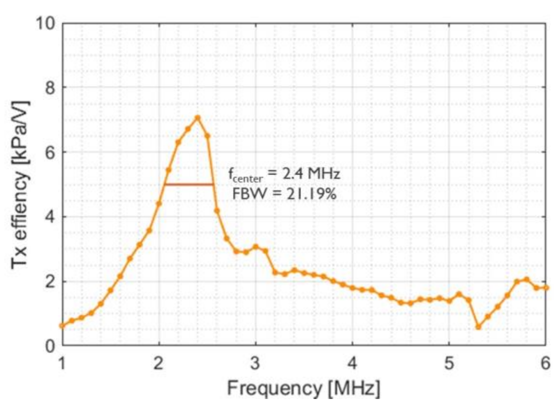

Figure 7. Acoustic frequency response of a LAPMUT array in water.

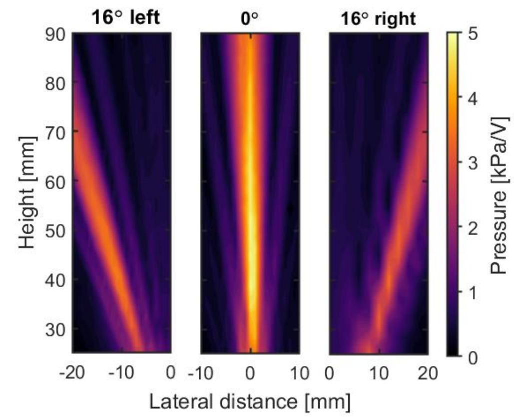

Figure 8. Beam steering demonstration from ±16-degree angles and up to 10 cm distance.

response of each single PMUT is measured to determine its resonance frequency. As demonstrated in Figure 6(b), the frequency uniformity across a complete array is excellent. In air, an average of 3.8 MHz is reached, with a standard deviation of only 25 kHz and a (mechanical) bandwidth of 100 kHz.

After the initial mechanical characterization, a uniform 700-nm layer of Parylene C is deposited onto the die, to serve as a protective barrier between the electrodes and aqueous medium during acoustic measurements. The added layer shifts the PMUT frequency up, while the change in medium shifts it down, resulting in an optimum around 2.4 MHz. Figure 7 illustrates the acoustic frequency response at 50 mm from the center of the array, where a fractional bandwidth of 21% is reached.

To demonstrate beam steering and medical imaging capabilities, an array is connected to a Verasonics 64 LE high frequency system, driving each of the 16 PMUT pixel columns at the appropriate phases to obtain ultrasound beam angles. All PMUT rows are connected to ground. First, a Precision Acoustics 0.5 mm needle hydrophone connected to a 3D stepper motor was used to map the far field ultrasound pressure in a plane perpendicular to the array, along the center row. Figure 8 depicts the results for steering under three distinct angles. Subsequently, an imaging demonstration is performed using a CIRS Model 055A 3D Wire

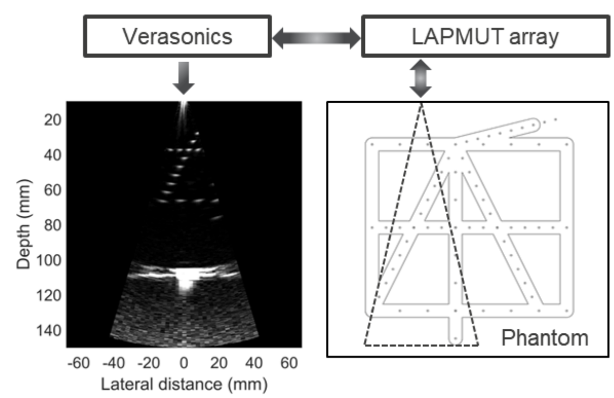

Figure 9. Ultrasound imaging demonstration (left) is performed using a CIRS Model 055A 3D Wire Test Object (right).

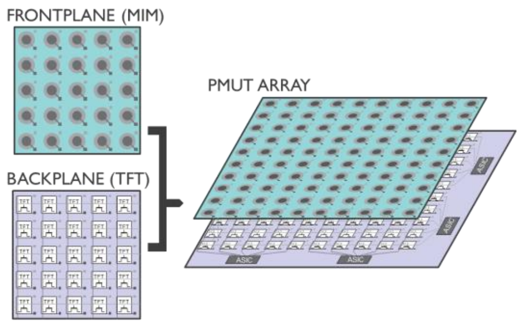

Figure 10. Towards a fully acoustic display, by adding local TFT circuitry to each PMUT element and ASICs for row-column addressing.

Test Object (Figure 9). For this, the beam angle is dynamically swept between -16° and +16° at 2° intervals.

5. Conclusions and impact

Micromachined ultrasound transducers are enabling device component for a broad range of applications. Key for these applications are a small element pitch (ideally <λ/2) and the possibility to probe a large 3D volume with ultrasound. This is where the MEMS and display industry can team up to create display-sized ultrasound arrays. Our presented platform aims to bridge this gap and enables the production of PMUT arrays on glass. The demonstrated LAPMUT elements and arrays demonstrate a 10X increase in mechanical displacement compared to previous fully glass based PMUT arrays (see Table 1). Further development is ongoing, to expand the frequency range and by combining the LAPMUT platform with existing FPD building blocks, such as flexible substrates or local TFT circuitry, towards a real acoustic display (like an optical display, Figure 10). This opens possibilities to apply large ultrasound arrays on curved surfaces (e.g. a human body or a car dashboard), and to locally address a single PMUT element for more complex ultrasonic beam-forming (holographic ultrasound projection) or local amplification of the received signal.

Table 1. Performance and benchmark overview. Displacement is given for membrane vibration in air at around 2.5MHz.

	This work	**Jeong et. al.** [5,9]	**Luo et. al.** [2]	**Sun et. al.** [10]
Piezoelectic material	AlScN	P(VDF-TrFE)	AlN	AlN
Freq range (MHz)	2.2-6.5	0.2-5.7	3-18	2.6
Displacement (nm/V)	50	5	3.5	30
Array size (px)	48x48	16x16	23x23	1
Beamforming demonstrated	Y	Y	N	N

6. References

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