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FLEXIBLE SOI-BASED PIEZOELECTRIC MICROMACHINED ULTRASOUND TRANSDUCER (PMUT) ARRAYS

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ABSTRACT

A flexible pMUT multi-array structure is realized based on Silicon-on-Isolator (SOI) technology. Six rigid islands of pMUT arrays are connected together by means of silicon springs (acting as hinges), which are fabricated by Deep Reactive Ion Etching (DRIE). This enables unseen ultra-miniaturization. Each island consists of a 3×3 pMUT array. Arrays are electrically connected through metal tracks on top of the hinges. Each single pMUT is $410 \mu\text{m}$ in diameter with a resonance frequency of 426 kHz in air. The fabricated flexible array was wrapped around a $5 \times 5 \text{ mm}$ 3D printed cube to create an omnidirectional transducer.

KEYWORDS

Piezoelectric micromachined ultrasound transducer (pMUT), PZT, Deep Reactive Ion Etching (DRIE)

INTRODUCTION

Ultrasound transducers have already been used in many applications, such as biomedical imaging, non-destructive diagnosis, and more recently, underwater sensor networks [1], [2]. With the introduction of piezoelectric micromachined ultrasound transducers (pMUT), many new applications were launched. In this regard, finger print sensors, ultrasonic range finder in Internet of Things (IoT) devices, and miniaturized 2D ultrasound probes with complex wiring scheme can be referred to [3].

Moreover, flexible ultrasound transducers can broaden the application areas of ultrasonic sensors and actuators in our daily life. In a flexible configuration, pMUT arrays can be used in brain stimulation, intravascular imaging by wrapping it around a catheter, wearable ultrasound devices, and small sensor nodes with complex geometries. However, up to date, making pMUT arrays flexible (i.e. conformable) remains a challenge. Previously reported flexible MUT arrays can be divided in two categories: MUTs on a Si substrate [4] and MUTs on a polymer substrate [5]. Flexible MUTs on a Si substrate are small Si islands that are thinned-down ($< 50 \mu\text{m}$) and connected to each other by a polyimide carrier. The thinned-down substrate increases the fabrication cost significantly, since it reduces the reliability of handling the wafers or devices. Furthermore, in this technology the cross-talk between MUT elements cannot be neglected and reduces the resolution for imaging applications. MUTs based on a polymer substrate typically obtain a much lower output pressure than MUTs on Si substrate. Indeed, in order to operate at the same resonance frequency, a polymer membrane, due to its low flexural rigidity, requires a much smaller size than a Si membrane.

In this paper, we introduce a novel Silicon-on-Isolator

(SOI) based flexible pMUT array. Different pMUT arrays were fabricated on silicon islands without having to thin down or any further process that would degrade its performance. At same time, the islands were connected together by means of silicon springs that serve as hinges. As a proof of concept, 6 islands were connected together by the silicon hinges. Each island has a dimension of $3 \times 3 \text{ mm}$ and includes a 3×3 pMUT array with a resonance frequency of around 426 kHz. A central island provides the external electrical connection (bond-pads) and links electrically to all the pMUTs islands over the spring hinges. Finally, the six islands structure was wrapped around a $5 \times 5 \text{ mm}$ cube.

MATERIAL AND METHODS

Design of the flexible structure

Evidently, the silicon substrate in which the pMUT array is made, is not flexible. Therefore, flexible hinges need to be fabricated in between them. The design is based on a serpentine spring [6]. An illustration is shown in Fig. 1. By doing so, the complete fabrication of the pMUT array and the interconnections can be carried out with standard rigid wafer processing tools. The last step in the fabrication is the etching of the hinges, which releases the devices from the bulk silicon at the same time. The hinges serve a second function next to providing flexibility in an otherwise rigid structure. They also provide electrical interconnectivity between the different pMUT arrays. This is made possible by a double layer of metal interconnects on top of the hinges.

Figure 1: Graphical illustration showing the concept of the flexible pMUT array

The design of hinges was optimized to minimize the stress in the silicon upon bending the hinge up to 90° , which was necessary to fold the device around the cube into its final form. As such, the probability of failure is minimized [7].

Since a serpentine-shaped hinge is a repetitive structure consisting of multiple identical beams, it generally suffices to focus on one beam only. In principle, there are three design parameters: width (W), height (H)

and length (L). Such a beam is mainly loaded under torsion. Equation (1) shows the relationship between maximum stress (τ_{max}) and twist angle (θ) when loaded under torsion.

$$\tau_{max}/\theta = G \cdot \alpha \cdot W/L \quad (1)$$

This equation is only valid as long as $H \geq W$. G is the shear modulus of the material and α is a parameter that varies between 0.6 and 1 depending on the ratio H/W . To minimize stress for a given twist angle, the length (L) of the beams should be maximized, while the width (W) should be minimized. On the other hand, a minimal width is still required for a sufficiently low resistive metal interconnect. Therefore, a tradeoff exists between electrical resistivity and mechanical flexibility. The complete hinge is modeled and analyzed with FEM-software to optimize the links of the different beams and their connection with the islands. Different designs were fabricated with widths ranging between 60, 70, 80, and 90 μm . The length was maximized at 3 mm, to match them to the pMUT island width. The height does not affect equation (1) and is therefore 300 μm , which equals the wafer thickness.

PMUT design parameters

Lead zirconate titanate (PZT) was used as the piezoelectric thin-film in the design and fabrication of the pMUT arrays. Each individual pMUT in the array has a measured resonance frequency of 426 kHz in air. The pMUT element has a diameter of 410 μm , silicon thickness of 6 μm , and a PZT thickness of 800 nm. In this paper, two types of pMUT arrays were realized; (i) pMUTs with only one center top electrode and (ii) a two electrode version, comprising a ring and a center electrode on the membrane. As explained previously, actuating the center and ring electrodes with 180° phase shift improves the response of the pMUT membrane [8]. In the case of a single center electrode, the width of electrical interconnects on top of the hinges was chosen to be 50 μm , while for center/ring electrodes two metal tracks with a width of 30 μm each were placed next to each other on top of the hinges.

The pMUTs in the array had a pitch of 490 μm , realizing a highly dense array, to produce an omnidirectional beam pattern underwater. All pMUTs on the islands were electrically connected. As a result, the final wrapped device around the cube works as a spherical-omnidirectional ultrasound transducer.

FABRICATION PROCESS

The fabrication process of a single pMUT is explained in [9]. One of the main problems of pMUTs is the large parasitic capacitances (C), which, in combination with the parasitic resistance (R), forms a low-pass filter with a 3dB bandwidth that can be lower than the mechanical resonance frequency. Actually, the RC time constant of a pMUT acts as a low-pass filter and degrades the applied input power significantly. Basically, the parasitic RC consumes most of the input power to charge and discharge the capacitor, so only a small

fraction of input electrical power is transferred to the mechanical-acoustical domain. This problem is more pronounced in the proposed flexible structure, since the PZT layer is sandwiched between the top and bottom electrodes that conduct over the hinges. Each spring-shape hinge in between two islands has a total length of about 27 mm. This is a long metal track and increases the parasitic capacitance and resistance, significantly. In order to overcome this problem, Ti / Ag / Ti / Pt stack metal layers were used as the top electrode with the thicknesses of 20 nm/300 nm/20 nm/150 nm, respectively, to reduce the resistivity of the top electrode. Furthermore, a SiO₂ layer was deposited on top of the PZT layer, except for the regions where the pMUT membranes are located, with a thickness of 250 nm to reduce the parasitic capacitance.

Fig. 2 shows the fabrication process of the flexible pMUT array. First, a SiO₂ 500 nm/Ti 20 nm/Pt 200 nm layer was deposited on top of a SOI wafer to serve as the bottom electrode. The Ti/Pt layers were patterned by a lift-off process to provide room for the spring-shaped hinges fabrication at a later stage. Thereafter, the SiO₂, that was exposed where no Ti/Pt was left, was reactively dry etched in CHF₃ plasma with a 30 sccm gas flow, 160 W RF power, and 20 mTorr working pressure. The etching of the SiO₂ layer is necessary, since the hinges will be realized by performing a DRIE process on the topside of the wafer.

Figure 2: Fabrication process of the flexible SOI-based pMUT array; (a) SiO₂/Ti/Pt (bottom electrode) deposited and lifted off to realize the spring hinges later, (b) PZT deposited by sol-gel process and pattern to access to the bottom electrode and realize the hinges later (c) SiO₂ sputtered and lifted off as isolation layer, (d) Ti/Ag/Ti/Pt (top electrode) deposited and lifted off, (e) DRIE on the backside of the wafer and BOX removal to release the membranes, (f) topside DRIE to release the hinges.

An 800 nm PZT layer was deposited by a sol-gel process [9]. The PZT was patterned to access to the bottom electrode and also to realize the hinges at a later stage. A SiO₂ layer was sputtered and lifted off everywhere except on top of pMUT membranes and the areas that need to be exposed to the DRIE to realize hinges. The sputtered SiO₂ was used to reduce the parasitic capacitance.

Afterwards, the Ti / Ag / Ti / Pt layers, as the top electrode, were deposited and patterned by a lift-off process. At the end, the membranes were released in a two steps process. First, a DRIE was performed on the backside of the wafer to reach to the Buried Oxide (BOX) layer. In this process the hinges and membranes were etched at the same time. Due to the different dimensions of the hinges and membranes, the etch rate is different. For our case, the hinges were etched slower than

membranes. Consequently, in order to reach the BOX layer where hinges were etched, the membranes tend to be over-etched, which results in a notching effect. Choosing a highly conductive device layer in the SOI wafer can diminish the notching effect, because the accumulated charges at the bottom of the etched trenches can be released faster. The second step in releasing the membrane was removing the BOX layer in a HF vapor etcher. Fig. 3 shows the released membrane without notching.

Finally, the hinges were realized by another DRIE process from the top side of the wafer. Four different width of hinges ($60\ \mu\text{m}$, $70\ \mu\text{m}$, $80\ \mu\text{m}$, $90\ \mu\text{m}$) were fabricated to compare their out of plane spring constant. Fig. 4 shows the SEM image of the realized hinges connecting to the pMUT array islands.

Fig. 5 shows the backside and the front side of the fabricated flexible pMUT array prior to folding. Fig. 6 shows the folded pMUT array around a $5\times 5\ \text{mm}$ 3D printed cube. As shown, the island with bond-pads was glued to a UFL connector by means of conductive epoxy.

Figure 3: Released pMUT membrane without any notching after the DRIE and HF vapor etching.

Figure 4: SEM image of the realized hinges connecting two pMUT array islands.

RESULTS AND DISCUSSION

The fabricated flexible pMUT array was characterized statically, mechanically, and dynamically. The static characterization was performed by measuring the parasitic resistance and capacitance. Table 1 lists the R and C values. The resistance of the top electrode metal tracks was measured between the bond-pad (central island) and either one further island or two further island. The resistance of the top electrode between the bond-pad and one further island and two further island were measured to be $31.7\ \Omega$ and $67\ \Omega$, respectively, for the $50\ \mu\text{m}$ width metal track and $62\ \Omega$ and $124\ \Omega$,

respectively, for the $30\ \mu\text{m}$ width metal track. The parasitic capacitance of the 3×3 pMUT array on each island by considering the center and ring electrode separately was about $5.8\ \text{nF}$ and $5.2\ \text{nF}$, respectively.

Figure 5: Frontside (a) and backside (b) of the fabricated flexible pMUT array prior to folding.

Figure 6: folded pMUT array around a $5\times 5\ \text{mm}$ 3D printed cube.

Figure 7: Measured out of plane spring constants for the four different serpentine used designs. The spring constant increases, as expected, with increasing width.

Table 1: Measured parasitic resistance and capacitance of the flexible pMUT array

	Value
Resistivity between the bond-pad and one further island ($60\ \mu\text{m}$ width wire)	31.7
Resistivity between the bond-pad and two further islands ($60\ \mu\text{m}$ width wire)	67 Ω
Resistivity between the bond-pad and one further island ($30\ \mu\text{m}$ width wire)	62 Ω
Resistivity between the bond-pad and one further island ($30\ \mu\text{m}$ width wire)	124 Ω
Capacitance of a 3×3 array with the center electrode	5.8 nF
Capacitance of a 3×3 array with the ring electrode	5.2 nF

The mechanical characterization was performed by measuring the force displacement characteristics of the hinges with different widths, as shown in Fig. 7. From this measurement, the spring constant was calculated. As expected, the wider springs are stiffer, and thus the probability of failure upon bending the hinge up to 90° increases.

A Laser Doppler Vibrometer (LDV) (Polytec MSA-500, Waldbronn, Germany) was used to characterize the pMUT arrays dynamically. The frequency response of one singular pMUT is shown in Fig. 8. All pMUTs had a resonance frequency of 426 kHz with less than 2.8% variation among different pMUTs in the whole wafer. The resonance frequency deviation among different pMUTs in one flexible pMUT array was less than 0.25%.

Fig. 9 shows the time domain response of a single pMUT by actuating the ring electrode, center electrode, and both center/ring electrodes with 180° phase shift. The actuation of the ring electrode alone resulted in the minimum displacement of 1.6 $\mu\text{m}/\text{V}$, due to its low electrical to mechanical coupling factor. However, the actuation of the center electrode and center/ring electrode resulted in a displacement of 2.27 $\mu\text{m}/\text{V}$ and 3.4 $\mu\text{m}/\text{V}$, respectively. During the whole LDV measurement process, the pMUTs were actuated by a 30 mV_{p-p} sinusoidal signal.

Figure 8: Frequency response of one singular pMUT measured by a LDV. (Inset) measured first mode of vibration of two pMUTs in an array.

Figure 9: Time domain response of a single pMUT by actuating different configuration of the top electrodes with 30 mV_{p-p} sinusoidal signal.

The measured first mode of vibration of two pMUTs

in an array by the LDV is shown in the inset of Fig. 8. Due to the limited field of view of the LDV's objective, it was not possible to measure more than two pMUTs at the same time.

CONCLUSION

A novel flexible SOI-based pMUT array was designed and fabricated. The proposed flexible pMUT array was realized by connecting several rigid array islands with spring shape silicon hinges, where the metallic interconnects between islands were deposited. The silicon hinges were fabricated by a DRIE process. The proposed flexible pMUT array benefits from a reliable SOI-based fabrication process without losing the performance of the pMUT elements in comparison with polymer based flexible pMUT arrays.

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