Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

Design and Fabrication of Flexible and Transparent Piezoelectric Micromachined Ultrasonic Transducer Based on Mica Substrates

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***Abstract*—Piezoelectric micromachined ultrasonic transducers (PMUTs) with features of flexibility or transparency have excellent prospects for curved surface imaging, biological sensors and wearable electronics. In the paper, a flexible PMUT based on unique mica substrate has been fabricated by thermal release transfer printing technique. In this fabrication process, a three-dimensional PMUT structure was picked up and transferred onto a mica substrate without using additional sacrificial layer or suspended architectures. The preliminary experimental results demonstrate that the proposed mica based PMUT has excellent flexibility and high transparency.**

***Keywords*—PMUT, flexibility and transparency, mica substrate**

I. Introduction

Piezoelectric micromachined ultrasonic transducers (PMUTs) have attracted lots of interest because of their advantages of lower working voltage, higher sensitivity, and better matching to electronic circuits. They have been widely used in many applications such as consumer electronics, medical and industrial devices, etc [1-2]. However, conventional PMUTs are commonly based on silicon or glass substrates. These rigid substrates are appropriate for standard micromachining fabrication techniques, but prevent PMUTs from being used on curved, soft, elastic surface. Flexible and transparent electronics, with their excellent mechanical properties and electrical performance, are superior candidates for a new generation of implantable or wearable devices [3]. There is no doubt that PMUTs with the features of flexibility and transparency will have a broad application prospect.

Some feasible strategies were available for fabricating PMUT based on flexible or transparent substrates. One of them is flexible bonding technique. In the method, the Cu/PZT/Pt piezoelectric stack was deposited and patterned onto silicon-on-insulator (SOI) wafer and released from backside using DRIE, afterwards the structures were bonded on PDMS and diced to separate each PMUT element. With this fabrication method, a PMUT array bonded on a flexible PDMS substrate was developed to study ultrasound brain stimulation [4]. The other is transfer printing technique called “FlexMEMS technology”, which was proposed to fabricate flexible MEMS devices [5-6]. In the technique, a PDMS stamp was used to pick up prepared PMUT structure from a donor substrate and to transfer the PMUT to a receiver substrate. Because of the larger interfacial adhesion force between PMUT and receiver substrate, the PMUT was eventually remained on the receiver substrate. The transfer printing technique is normally considered to be a better option to fabricate flexible and transparent PMUTs because of its extensive adaptability and simplified procedures. But the technique still has some drawbacks. For instance, in order to decrease the adhesion force of the interface between device and the donor substrate during transferring, an additional sacrificial layer was usually employed to form a suspended structure. Extra steps of depositing and etching the sacrificial layer will increase the cost and risk of the fabrication process. Besides, additional surface treatments such as UV exposure or O_2 plasma were used to increase the interfacial adhesion force between the device and receiver substrate so as to separate device from PDMS stamp and remain it on receiver substrate. These complex treatments may impact the cost and convenience in manufacture process.

In this paper, a thermal release transfer printing technique for fabricating PMUT based on flexible and transparent mica substrate is proposed to simplify the transfer printing process and improve the stability of the whole micromachining fabrication process. In this approach, a thermal release tape (TRT) was used to pick up prepared three-dimensional PMUT directly and to transfer PMUT onto flexible and transparent mica substrate without additional complex treatments. The PMUT bonded on a mica substrate was mounted on a cylinder with 10 mm curvature radius and wrapped around finger to perform the excellent flexibility.

II. Design and Modeling

A typical PMUT structure consists of a supporting layer and a piezoelectric stack which composed of a piezoelectric layer sandwiched by top and bottom electrodes. An air cavity beneath PMUT is necessary in order to suspend the upper composite diaphragms. The schematic cross-section of our proposed PMUT structure is shown in Fig. 1. Mica is used as a substrate in this structure. The thickness of the top Al electrode, piezoelectric ZnO layer, bottom Al electrode and PI supporting

The work was financially supported by National Natural Science Foundation of China under Grant Number of 51675278 and the Project of Key Research and Development Plan of Jiangsu Province under Grant Number of BE2017730.

layer is 100 nm, 1μm, 100 nm, and 3 μm respectively. The air cavity beneath PMUT is 80 μm in diameter and 3.5 μm in depth.

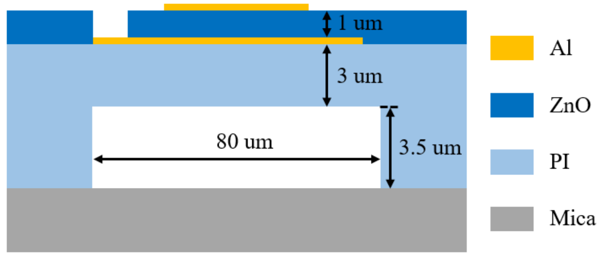

Fig. 1. The schematic cross-section of PMUT

When the electric field is exerted across the piezoelectric layer, the bending moment is generated through the piezoelectric effect. The natural vibration frequency of a circular plate with an edge-fixed condition can be computed from [7]:

$$\mathrm{f} = \frac{{\lambda_{mn}}^2}{2\pi r^2}\sqrt{\frac{\mathrm{D}}{\rho \mathrm{h}}} \tag{1}$$

$$\mathrm{D} = \frac{\mathrm{Eh}^3}{12(1-\mu^2)} \tag{2}$$

where r is the membrane radius, h is the thickness of the membrane, ρ is the density of the membrane, D is flexure rigidity, E is the Young's modulus, μ is the Poisson's ratio, and λ_{mn} is the natural frequency constant. The first three natural frequency constants for fixed edge boundary condition are given as follows: $\lambda_{00} = 3.196$, $\lambda_{01} = 4.611$, $\lambda_{02} = 5.906$ [8].

It is known that, all of the diaphragms including supporting layer and piezoelectric stack have contribution to vibration. In the case of composite diaphragms, the (1) and (2) have to be modified including material parameters for each layer, which will complicate the calculation procedure. Here, the finite element analysis (FEA) was carried out to predict the resonant frequency of the composite diaphragms. A simulation model of PMUT was established using COMSOL Multiphysics. A 2D axisymmetric model and piezoelectric devices multiphysics interface were chosen to be used. Fixed boundary conditions were applied to the both sides and bottom of model. The FEA simulation of bending mode shape at 1st resonant frequency of 2.32 MHz is shown in Fig. 2 (a), and the absolute value of admittance is plotted in Fig. 2 (b).

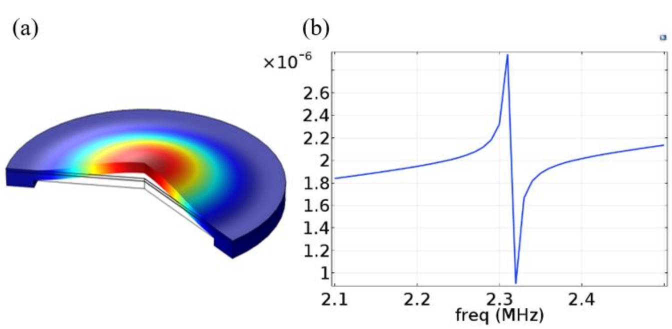

Fig. 2. The simulation results of PMUT. (a) Vibration mode shape at resonant frequency of 2.32 MHz; (b) plot of PMUT admittance.

III. FABRICATION

In this work, a PMUT was fabricated via standard bulk micromachining fabrication techniques and a thermal release transfer process. The schematic fabrication steps are illustrated in Figure 3. The fabrication started with a silicon mold that formed by standard photolithography and deep reactive ion etch (DRIE). Then, the polyimide solution (30% solid content) was spin-coated onto the Si mold at 4000 rpm and pre-baked on hot plate at 150 °C for 40 min to obtain a ~3 μm structure layer. A 100 nm thick Al film was deposited by magnetron sputtering and patterned by lift-off process to form the bottom electrode. Afterwards, 1 μm thick piezoelectric ZnO film was deposited on the bottom electrode using direct-current (DC) magnetron sputtering. The zinc target of purity 99.99% was employed for sputtering under a mixture gas of O_2 and Ar with a deposition pressure of 2 Pa. An access hole in ZnO was formed to create an electrical connection for bottom electrode by wet etching. After that, another 100 nm thick Al film was sputtered and patterned as the top electrode.

Whereafter, the mica substrate was spin-coated a thin layer of PDMS and baked at 75 °C for 20 min. The PDMS was partially cured and served as the adhesive layer. Then the structures above Si mold were picked up directly by TRT and transferred to the mica substrate. After that, a simple thermal treatment was carried out to fully cure the adhesive layer and to peel off the TRT simultaneously. Finally, mica was thinned to ~25 μm in thickness by mechanical exfoliation to achieve desired flexibility and transparency.

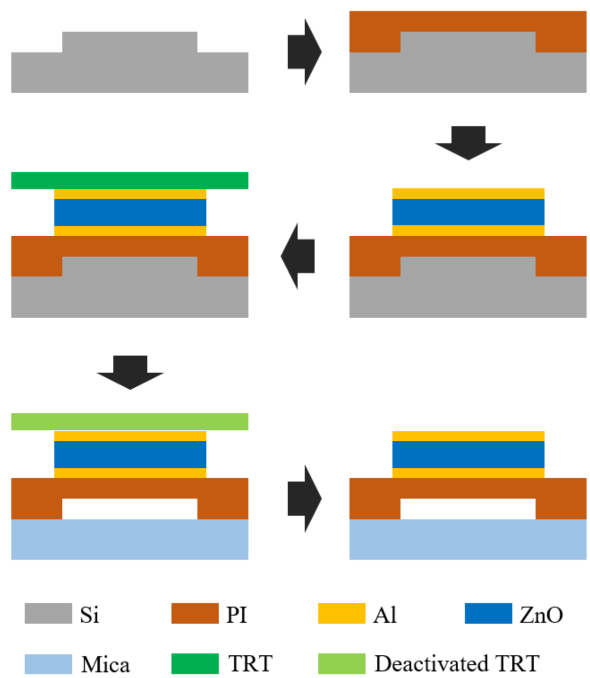

Fig. 3. The schematic illustration of the fabrication process for PMUT on flexible and transparent mica substrate using standard bulk micromachining fabrication techniques and thermal release transfer technique.

IV. Results and Discussion

Fluorophlogopite mica, used as a flexible and transparent substrate here, has advantages of low cost, excellent surface roughness, high thermal stability, and good transparency. Furthermore, mica has the two-dimensional layer structures and can be thinned to tens of micrometer by mechanical exfoliation due to the weak bonding force between potassium ions and aluminosilicate layers [9]. The bonding force between two layers is strong enough to make mica rigid during the micromachining fabrication process and can be eliminated easily by mechanical exfoliation. Fig. 4 shows the mica peeled off to ~25 μm indicates excellent flexibility and transparency.

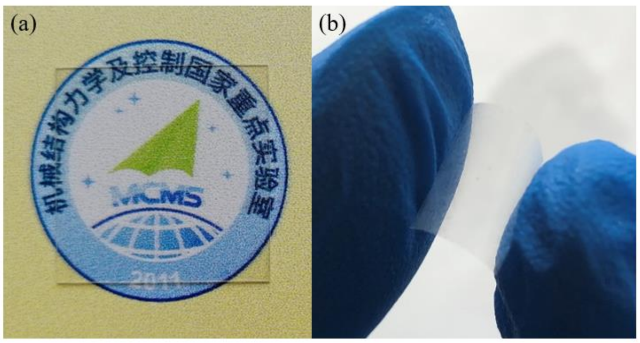

Fig. 4. The Photographs of mica substrate show (a) high transparency and (b) excellent flexibility.

Based on the proposed thermal release transfer printing technique, PMUT with a cavity was peeled off completely and transferred to mica substrate. Step profiler was used to measure the contour of the cavity. From Fig. 5 we can see that the surface of the air cavity is smooth and the sidewall is conformal after PMUT was peeled off from Si mold. PMUT was mounted on a cylinder with 10 mm curvature radius and wrapped around a finger. These results indicate that the PMUT on mica substrate is flexible and transparent, and the back image can be clearly seen. If indium tin oxide (ITO) or Al-doped ZnO (AZO) are used as electrodes, the device will become completely transparent.

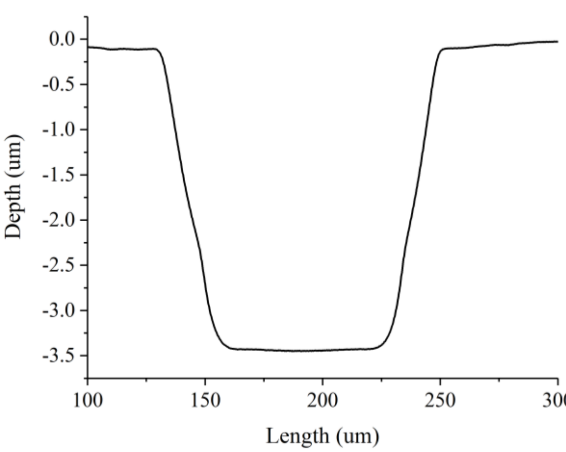

Fig. 5. The contour profile of the air cavity of PMUT after peeled off.

V. Conclusion

In summary, a thermal release transfer printing technique was demonstrated to fabricate flexible PMUT. The thermal release tape (TRT) which substitutes conventional transfer printing stamp has been used in this technique to pick up a complete three-dimensional PMUT structure. Mica was served as not only a rigid substrate during the fabrication process but also a flexible and transparent substrate after thinned due to its unique two-dimensional layer structures. Finite element analysis was carried out to predict the resonant frequency of composite diaphragms. The proposed PMUT based on mica substrate has exhibited excellent flexibility and transparency both on a finger and curved surface indicating great potential applications in microsystems and wearable devices.

Acknowledgment

We would like to thank Nanofabrication facility in Suzhou Institute of Nanotech and Nano bionics (CAS) for providing relative processing equipment to support in developing flexible and transparent PMUT based on mica substrate.

The work was financially supported by the National Natural Science Foundation of China [Grant no. 51675278] and the Project of Key Research and Development Plan (Social Development) of Jiangsu Province (No. BE2017730).

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