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Fabrication Techniques for Improving the Performance of PVDF-on-Silicon Ultrasonic Transducer Arrays

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***Abstract*— A PVDF-on-Silicon 8-element ultrasound transducer array (1mm×1mm and element spacing of 1mm) is fabricated and characterized. To improve the performance of the transducer, new CMOS-compatible fabrication technologies are introduced. These include: 1) micro-contact printing on non-radiating areas, and 2) glass microspheres (7-20µm in diameter) embedded low melting temperature alloy (LMA) material for backside electrical connection. The first improvement removes the impedance mismatching of adhesive layer (e.g., lower sensitivity) between the PVDF and backside contact while the second one improves the pulse-echo signal quality by eliminating reflections at the backing/water interface. The fabricated array elements are tested in a water tank and their pulse-echo response are recorded. The central frequency of each element is 25MHz with a 100% measured 6-dB bandwidth (60% 3-dB bandwidth).**

I. INTRODUCTION

High-frequency (>20MHz) ultrasound is an attractive modality for imaging fine tissue structures with promising applications in ophthalmology, dermatology, and intravascular imaging [1, 2]. Recent advances in transducer materials and micromachining technology have increased interest in high frequency transducer arrays for such applications. Several different transducer materials/technologies are being investigated for use in high-frequency ultrasound imaging. These include lead zirconate titanate (PZT), polyvinylidene fluoride (PVDF), and capacitive micromachined transducers (cMUT). PVDF, which is a piezoelectric polymer, offers several unique advantages compared to other materials. These include lower acoustic impedance, larger bandwidth, lower cost, and mechanical flexibility [3, 4]. However, it has a lower sensitivity as compared to PZT. This can be overcome by integration of PVDF with active electronics. Micromachined PVDF arrays with active electronics on-board can be used in intra-vascular imaging with distinct advantages mentioned above. Several groups have reported on the fabrication of micromachined PVDF transducers, mostly attaching a PVDF film on the metallized (used for the bottom electrical contact) silicon substrate using epoxy and removing the silicon on the backside to improve sensitivity and reduce the cross talk [5, 6].

Several fabrication challenges need to be overcome to integrate PVDF with silicon substrate and active electronics. These include: 1) suitable backing material, 2) attachment methods to the substrate at low-enough temperatures (typically < 70°C in order to retain the piezoelectricity), and 3) avoiding organic solvents during the process (these damage the PVDF film). For PVDF transducers, the most common backing material has been conductive/silver epoxy [7]. More recently, some investigators have experimented with tungsten powder filled epoxy in order to improve the backing performance (higher attenuation) [8].

In this paper, we present new fabrication methods for high-frequency wideband ultrasonic transducer array that uses an epoxy stamped front surface for the attachment of a thin (9µm) PVDF film and glass microspheres embedded low melting alloy (LMA) backing. The developed methods have several unique advantages including: 1) front-side patterning of adhesives using micro-contact printing, 2) batch scale backside contact using LMA microspheres, 3) low processing temperatures, 4) increased scattering at the backing/water interface due to the irregular geometry using glass microspheres, and 5) scalability through creating small LMA microspheres (~100-300µm diameter).

II. DESIGN AND FABRICATION

A general description of the array structure and fabrication process is given in this section. Figure 1 shows a schematic of the PVDF ultrasonic array structure and components used in the fabrication of the transducer. These include: 1) a silicon substrate with KOH-etched holes representing the array elements, 2) a PVDF film coated with a thin gold layer on one side, 3) LMA spheres for backside electrical contact, and 4) glass microspheres for modifying the backing surface geometry.

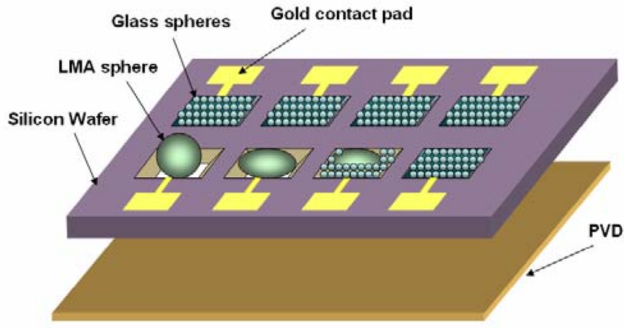

FIGURE 1. Schematic and components used in the fabrication of the transducer array.

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Figure 2 illustrates the cross section of the integrated ultrasonic transducer with a thin layer of glass microspheres covering the LMA backing surface. As will be discussed in Section III, the presence of glass microspheres increases the scattering at the backing/water interface and reduces the back reflection at the interface, hence improving the pulse-echo response of the transducer. The fabrication process starts with Low Pressure Chemical Vapor Deposition (LPCVD) of low-stress silicon nitride (Si_3N_4) on a p-type <100> silicon wafer. The nitride layer (~ 1µm in thickness) is used as a mask during the KOH etching process. After a standard lithography process (Mask # 1), the silicon nitride on the backside of wafer is patterned using a reactive ion etcher. After pattering silicon nitride, silicon wafer is etched throughout its thickness (500µm) in 45% KOH solution for 12 hours at 80ºC. Silicon nitride on the top and the backside is then stripped using a dry etcher. A Plasma Enhanced Chemical Vapor Deposition (PECVD) silicon nitride (3000Å in thickness) is deposited to cover the front, back, and sidewalls of the KOH-etched silicon wafer.

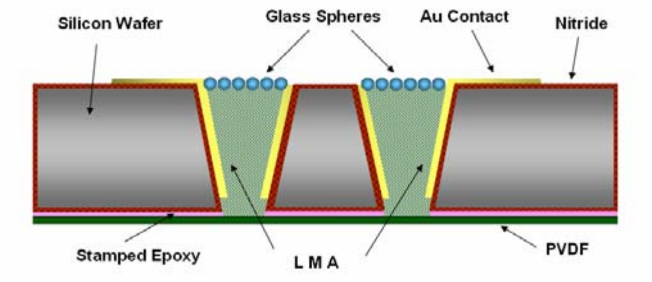
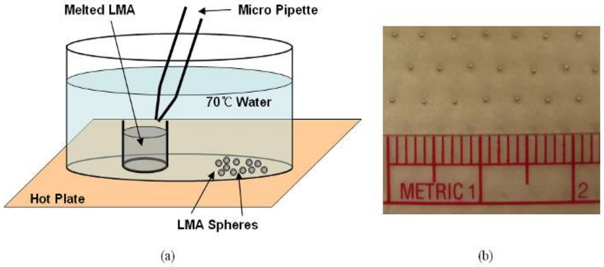


FIGURE 2. Cross section of the integrated transducer.

Next, a Ti/Au (300Å/3000Å) layer is deposited (E-beam evaporator) on the nitride coated backside of the wafer and patterned through a standard lithographic process (Mask #2) and wet etching. This layer is necessary in order to provide a better connection to the measurement system subsequent to the backside filling. The PVDF film is next attached to the front side of the silicon substrate using stamped epoxy as an adhesive layer. In this step, a one-side Ti/Au (100Å/1000Å) coated PVDF (9µm in thickness) film is prepared separately. The PVDF film is then bonded to the silicon substrate using a soft lithography stamping technique [9]. During this process, a polymeric stamp is first fabricated through spin coating and curing a PDMS (Sylgard 184, Dow Corning) film on a silicon wafer. Subsequently, the PDMS stamp is spin-coated with a thin adhesive layer (Eccobond 24, Emerson and Cumming Corp.), which is then transferred to the front side of silicon substrate. The PVDF film (non-metallic side) is subsequently bonded to the adhesive transferred side of the substrate. After attachment, the PVDF film is loaded into a vacuum chamber for 10 minutes and subsequently cured at room temperature for 24 hours.

Low melting temperature (47ºC) alloy spheres (~100-300µm diameter) are manufactured for backing and electrical connection to the ultrasonic transducer. These LMA spheres are fabricated through dispensing a specified amount of melted LMA (Bismuth 44.7%, Lead 22.6%, Tin 8.3%, Cadmium 5.3%, Indium 19.1%, Small parts Inc.) droplets into a hot water (70ºC) bath, Figure 3 (a). The water is then cooled down to the room temperature to solidify the spheres. Figure 3 (b) shows a photograph of manufactured LMA spheres which have a diameter of approximately 100-300µm.



(a) (b)

FIGURE 3. (a) Experimental set up for manufacturing LMA spheres. (b) Manufactured LMA microspheres.

The backside contact to the PVDF is achieved via filling the KOH-etched holes with these LMA spheres and melting them on a hotplate. In the melted state, glass microspheres (7-20µm in diameter, Sigma-Aldrich) are dispersed onto the surface of the melted alloy backing in order to modify/roughen the surface geometry, hence increasing the signal scattering at the backing/water interface. This is followed by cooling the device to the room temperature, hence solidifying the alloy and glass microspheres in place.

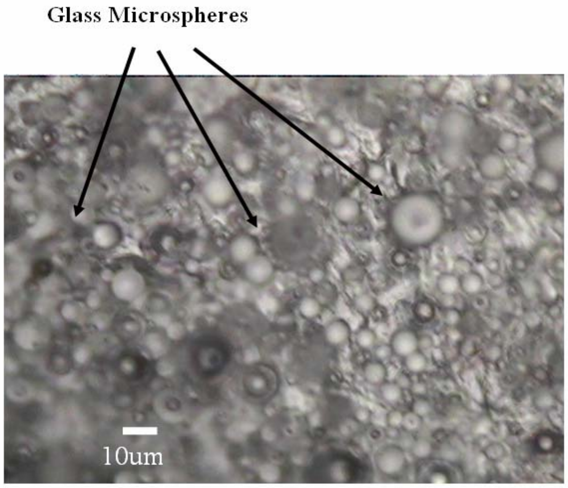


FIGURE 4. A photograph of LMA backing surface with embedded glass microspheres.

Figure 4 shows the surface of the glass microspheres embedded LMA backing. As can be seen, dispersed glass microspheres self-spread on the surface of the melted LMA backing. Figure 5 is a photograph of fabricated 8-element ultrasonic transducer array. Each element has a gold trace pad that is used to wire bond the array to the 8-channel diplexer board for measuring the pulse-echo signal.

FIGURE 5. A photograph of an 8-element transducer array

III. TEST RESULTS AND DISCUSSION

Figure 6 illustrates the experimental setup for measuring the pulse-echo signal. The measurement of the array elements was performed using a GE panametrics 5900 HF pulser-receiver. A thick (2cm) flat Plexiglas plate was immersed at various depths inside a large water tank. An 8-channel diplexer was used to select one of the 8-elements and a 1GHz Tektronix Gage digitizer was used to sample the receiver output. Figure 7 shows a pulse-echo signal of one of 8-elements in the time domain. The array element was excited by a broadband signal and pulse repetition rate was set to 1KHz. Trace (a) shows the response of a transducer array element without glass microspheres (only LMA backing), whereas (b) shows the pulse-echo response of an element with dispersed glass microspheres on the LMA backing surface. Figure 8 shows frequency domain echo responses of a single element without (a) and with glass micropsheres (b). Each element has 25MHz center frequency and a 6dB bandwidth of 100%.

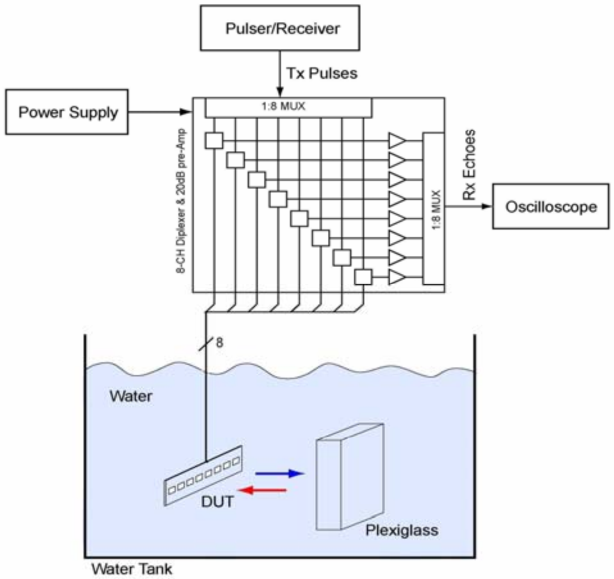


FIGURE 6. Schemetic of the experimental setup used for pulse-echo signal measurement

The speed of sound in the LMA was measured using a transmission technique in which an acoustic wave is passed through an LMA plate (510μm in thickness). By comparing the delay (~ 140nsec) between the sound source and detector with and without the LMA sample, one can easily calculate the speed of sound in the LMA. The acoustic velocity in LMA (C_L) can be given by:

$$C_L = \frac{C_0 \times Th}{Th - (\Delta T \times C_0)} \tag{1}$$

where C_0 is the speed of sound speed in water (1540m/sec), Th is a thickness of the LMA sample (510μm), and ΔT is the time delay (140nsec). The measured acoustic velocity of the LMA (C_L) is 2670m/s. The acoustic impedance of the LMA can be calculated using $Z_L = \rho \times C_L$ to be 24.45MRayl, where ρ is a density of the LMA (9160kg/m^3). Measurement results reveal several important properties of these transducers. As can be seen from Figure 8, the center frequency of the transducer is around 25MHz. Due to the rigidity of the backing material, each element resonates in a λ/4 mode ($f_{\lambda/4} = \frac{v_l}{4l}$, where v_l is the sound velocity in PDVF and l is its thickness). The calculated center frequency for a 9μm thick PVDF transducer at this mode is 62.5MHz (speed of sound in PVDF is ~ 2250m/s). The resonant frequency reduction observed here is due to the internal impedance of pulser/receiver, the capacitance of cables used to connect the transducer to measuring equipment, and the inductance of bond wires.

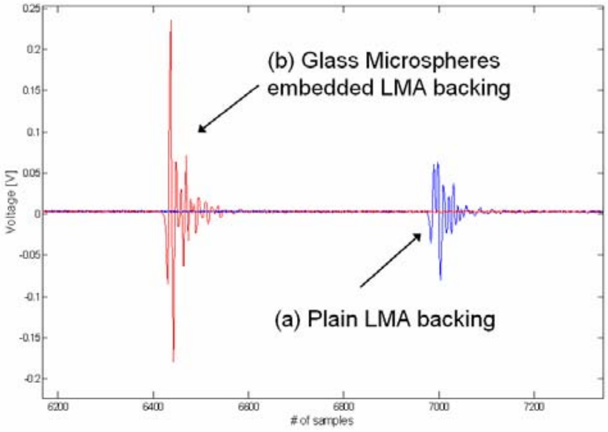


FIGURE 7. Measured pulse-echo signals

A good backing material for wideband transducers should have matching acoustic impedance to that of the transducer material while simultaneously having a large absorption coefficient. In the case of PVDF/LMA interface the reflection coefficient (R) due to the acoustic mismatch can be calculated using:

$$R = \left| \frac{Z_0 - Z_L}{Z_0 + Z_L} \right| = 0.7 \tag{2}$$

where Z_o is the acoustic impedance of PVDF (~ 4MRayl) and Z_L is that of the LMA. Acoustic impedance of tungsten-filled-epoxy is between 6 to 36MRayl depending on the loading ratio [3]. As can be seen, the LMA can have an unfavorable impedance matching property compared to that of conductive epoxies. However, the BW and sensitivity of the PDVF transducers reported in the literature using conductive epoxies are comparable to that of our LMA backing [10]. Another reflection happens at the LMA/water interface. Due to the limited thickness of the LMA backing (500μm) compared to the larger conductive epoxy elements, certain fraction of wave is reflected from the LMA/water interface. The reflection coefficient at this interface is ~ 0.88. Almost the entire incident signal is reflected from the boundary between the LMA and water resulting in the destructive interference signal loss at harmonics corresponding to integer multiples of the wavelength in the LMA (see Figure 8-a).

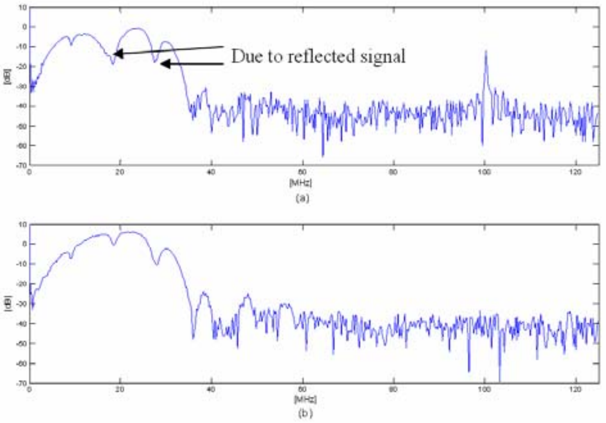


FIGURE 8. Frequency domain echo response (a) LMA backing (b) glass microspheres embedded LMA backing

These dips in the spectrum occur at wavelengths-thickness corresponding to:

$$T = 2n\lambda, \qquad n=1, 2, 3. \qquad (3)$$

where T is thickness of backing (~500μm) and λ (= c/f) is wavelength. The calculated destructive interference frequencies (10, 21 and 32MHz) corresponds accurately to the measured frequency dips in the spectrum. This power loss can have a detrimental effect on the transducer performance resulting in its lower sensitivity as is noticed in Figure 7. Irregular LMA/water interface geometry, due to the dispersed glass microspheres, enhances signal scattering and reduces direct back reflection at this interface.

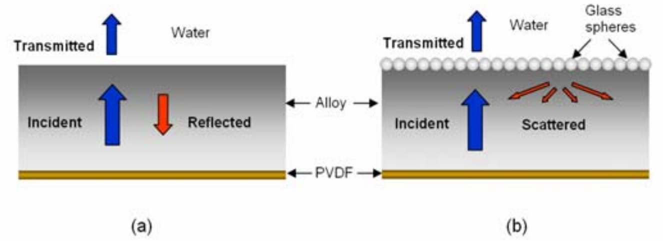


FIGURE 9. Schematic of the acoustic propagation (reflection, transmission, and scattering) (a) plain LMA backing, and (b) glass microspheres embedded LMA backing

Figure 9 illustrates signal propagation and reflection in (a) plain LMA backing and (b) glass microspheres embedded LMA backing. The echo signal of glass microspheres embedded LMA backing transducer shows greater amplitude than the plain LMA backing one, Figure 7. In addition, as can be seen in Figure 8-b the harmonic dips in the spectrum are significantly reduced in the glass microspheres embedded LMA backing transducer.

IV. Conclusion

CMOS-compatible and scalable fabrication technologies were presented to manufacture integrated PVDF wideband transducers for high frequency imaging applications. The reflected signal interference at backing was obviously reduced by adding glass microspheres. The transducer with glass microspheres embedded LMA backing having irregular surface geometry showed larger amplitude (higher sensitivity) in the time domain and less power loss at interfering harmonic frequencies. Although our array elements were rather large, we successfully fabricated 100μm LMA microspheres which can be used to fill $100\times100\mu m^2$ array elements using template-assisted self-assembly methods [11].

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