MUSIC™: Micromachined UltraSound Integrated Circuit

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ABSTRACT

Here, we present a novel ultrasound transducer which can be considered as a micromachined ultrasound integrated circuit in which a combination of micromachined dome-shaped piezoelectric resonators arranged in a unique flexible architecture. By mixing these basic cells and modifying their dimensions by lithography, adjustable frequency spectrum can be achieved similar to a radio frequency integrated circuit (RFIC). Unique features such as high sensitivity (more than 100kPa/V), adjustable wide-bandwidth frequency response, CMOS-compatible low transmit voltage (2V-40V), intrinsic acoustic impedance match to water and reliable monolithic fabrication process are demonstrated. We envision that this technology can be implemented as a desirable solution in high performance 3D/4D, low-power portable and in-vivo imaging systems.

Keywords: MEMS, Piezoelectric, Ultrasound, Wide Bandwidth, Dome

1 INTRODUCTION

MEMS based ultrasound transducers have recently emerged as an alternative to bulk piezoelectric transducers aiming to offer advantages such as increased bandwidth, flexible geometries, natural acoustic match with water, reduced voltage requirements, mixing of different resonant frequencies, and potential for integration with supporting electronic circuits especially for miniaturized high frequency applications [1, 2].

Capacitive micro-machined ultrasound transducers (CMUT) technology introduced in 90s has offered promising results such as better acoustic matching, a broader bandwidth, size reduction and the possibility to be integrated with the front-end electronics on the same wafer. Nevertheless, CMUTs suffer from serious issues, including low transmit sensitivity (~10kPa/v), very large drive and bias voltage requirements (up to 200V), difficult fabrication, long-term device reliability, electrical safety issues, acoustic cross-talk, and high electrical impedance as a result of limited capacitance [3].

In theory, piezoelectric micro-machined ultrasound transducers (PMUT) have been sought as a solution that can be actuated at much lower voltage levels and provide much lower electrical impedance per area even in comparison with conventional bulk piezoelectric transducers. However, difficulties in fabricating thin-film piezoelectric MEMS structure combined with technical issues such as very low electromechanical coupling and small bandwidth have prevented PMUT to become a viable and practical solution [4-9].

Hereby, we are presenting a novel micro-machined ultrasound technology aiming to address the aforementioned issues [10]. Analogous to RFIC and MWIC technologies, MUSIC™ can be seen as a monolithic integrated ultrasonic circuits manufactured by lithography with three main advantages over bulk piezoelectric transducers: cost, performance and miniaturization capability. In this paper, the design and testing results of a wideband 5MHz linear array are presented and discussed as an example; however, transducers in a wide range of frequencies (1MHz-40MHz) have been successfully fabricated in the same wafer by changing the element dimensions.

2 DESIGN

2.1 Thin-film PZNT

The lack of a reliable process to deposit high-quality piezoelectric films has been one of the biggest difficulties in developing high performance and reliable PMUTs in the past. Our proprietary thin-film PZNT technology has been one of the main enabling technologies implemented in this work [11]: a reliable and repeatable highly-doped PZNT sputtering process to deposit dense and high performance piezoelectric film which results in a ~70% higher piezoelectric coefficient than sputtered PZT films previously reported. As shown in Fig. 1, the x-ray diffraction patterns of the PZNT film demonstrate that film is in a perovskite phase with predominantly (100) orientation which partly accounts for its high piezoelectric performance ($\varepsilon_{31,f} = -23C/m^2$). One of the unique properties of the PZNT film is that the hysteresis loop is shifted toward the positive electric field direction. Consequently, the polarization axes have been aligned in a certain direction beforehand, making a post-deposition polarization process unnecessary.
2.2 Dome-shaped structure

As shown in Fig. 2, the basic resonating cell consists of active piezoelectric film in the form of a three dimensional (3D) dome with thin metallic top and bottom electrodes. The pre-shaped structure of the dome eliminates the stiff silicon membrane layer otherwise required for the traditional bending mode. Electrical energy is efficiently converted via piezoelectric effect to elastic energy through the “stretching” mode in addition to the typical “bending” mode [12]. Subsequently, the elastic energy is converted into the desired acoustic energy through the interaction of the dome and the medium. Consequently, a significant electromechanical coupling, as high as 45%, and strong acoustic sensitivity are achieved.

Figure 2 Cross-section of three-dimensional dome-shaped piezoelectric membrane: Schematic (left) and scanning electron microscope image (right)

Semi-spherical membranes cells vibrate at various modes which are the solutions of Bessel functions. Considering that the piezoelectric excitation of the semi-spherical dome is almost independent of the angle $\theta$, the preferred mode shapes are $(0, 1)$ mode, $(0, 2)$ mode, $(0, 3)$ mode in which the number of nodal diameter is 0. Fig 3 shows the simulated acoustic intensity sensitivity generated by a single dome with the cavity diameter of 75$\mu$m as a function of frequency up to 20MHz. The mode shapes of the single dome are measured by laser Doppler vibrometer (MSA-500 Micro System Analyzer by Polytec). $(0, 1)$ mode and $(0, 2)$ modes with corresponding acoustic intensity of 0.15mW (RMS) and 0.13mW (RMS) at 1V can be identified which translate into impressive acoustic power density of 3W/cm$^2$ and 2.6W/cm$^2$ at 1V excitation level. However, the corresponding bandwidth of 15% and 9.5% is too narrow for ultrasound imaging applications.

Figure 3 Simulated acoustic intensity spectrum (bottom) of a single dome at 1V excitation level shows two modes of vibration. The simulated acoustic pressure sensitivity (in kPa/\text{v}) distribution (top) and their mode shapes measured by laser Doppler vibrometer (middle).

2.3 Architecture

Unlike a bulk piezoelectric transducer in which the resonant frequency is fixed by the thickness of the ceramic, the resonant frequency of a micro-machined dome-shaped element is mainly determined by its dimensions as defined by lithography. Therefore, an array of domes may be constructed as a network of resonators in which the resulting frequency response can be adjusted by modifying the dimensions of the domes by lithography. Basically, the process is very similar to the design of RF and microwave band-pass filters using microstrips [13].

The architecture of a 64 channel 5MHz linear array is optimized to achieve a wide fractional bandwidth (>64%)
desired for a good imaging axial resolution. Fig 4 shows the optical image and also the scanning electron microscope image of the fabricated device exploiting 5 different dome sizes with cavities ranging from 74µm to 90µm diameter.

The bandwidth broadening and sensitivity improvement have been achieved through a number of complex interaction mechanisms. Similar to a coupled-resonator optical waveguide [14] or a microstrip loop resonator [15, 16], the strong coupling between elements caused by the acoustic loading induces degenerate mode splitting for similar dome sizes. In addition, using multiple domes in a row increases the effective width of the channel to approximately one wavelength. It causes a significant improvement in the effective acoustic impedance and the real acoustic power which results in further increase of sensitivity and bandwidth. Finally, exploiting different dome sizes in an optimized order and architecture creates a wide composite bandwidth by overlapping the frequency spectrum of multiple resonators similar to a 5th order linear filter.

3 MEASUREMENT AND RESULTS

The frequency spectrum of the transducer has been measured by a swept-sine network analyzer (Agilent E5061B-3L5) to achieve a better accuracy especially at low-amplitude regions of the signal. The low-frequency (LF) output of the gain-phase test port was amplified by a broadband solid-state class A power amplifier (325LA by E&I) to excite the transducer. The realized underwater acoustic pressure was measured by a hydrophone (HGL-1000 by ONDA Corp.) followed by a 20dB pre-amplifier (AH-2010 by ONDA Corp.), and was fed back to the network analyzer. As shown in Fig. 5, the S11 parameter and the pressure frequency response of the 5MHz transducer (which contains 5 different dome sizes) were measured in air and in water at 30mm depth. The integration of 5 different dome sizes in the transducer design results in 5 distinct pairs (one per mode) of high-Q peaks of the S11 parameter measured in air. These peaks merge together when measured in water as a result of the strong acoustic damping caused by water also the resulting acoustic coupling between the domes and generates a response similar to a wide-band resonator. Exploiting the 5th order filter design, the transducer generates two wide bands: 1st and 2nd modes centered at 5MHz (-3dB bandwidth of 55%) and 10.6MHz (-3dB bandwidth of 34%) and a peak sensitivity of 85kPa/V and 115kPa/V, respectively.

To measure the pulse-echo response, the transducer was excited by a train of 100ns pulses generated by an arbitrary function generator (Tektronix AFG3102) amplified by the 325LA amplifier. By transmitting a pulse width of 100ns, the 1st mode is exclusively excited while higher modes, including the 2nd mode, are suppressed. Fig. 6 depicts the resulting acoustic pulse echo and its corresponding FFT spectrum of a single channel reflected from a stainless steel reflector at 15mm depth. Strong sensitivity and wide bandwidth (64.5%@-6dB and 78.1%@-10dB) is demonstrated.

Figure 5 (top) S11 measurements show 5 distinct high-Q peaks per mode in air which become merged and well-damped in water indicating a wide achieved bandwidth and strong acoustic coupling. (Bottom) Transmit pressure sensitivity vs. frequency measured at 30mm by hydrophone.

Figure 4 Optical and SEM images of a 64 channel 5MHz linear array
Figure 6 Measured pulse-echo response and its corresponding FFT spectrum measured at 15mm depth. Single channel excitation by 100ns pulse train.

4 CONCLUSION

This 5MHz linear array, as an example of a 3D-MEMS piezoelectric ultrasound transducer, demonstrates unique features such as high sensitivity (more than 100kPa/V), adjustable wide-bandwidth frequency response (65%), CMOS-compatible low transmit voltage (2V-40V), low electrical impedance (less than 50 Ohms), efficient electromechanical coupling (greater than 45%), and reliable monolithic fabrication. Exploiting its small form-factor, high sensitivity, low voltage level and low impedance well matched to micro-coaxial cables, the transducer can be incorporated into high performance ultrasound catethers including EUS, TEE, ICE and IVUS applications. Besides in-vivo imaging, it can enable high performance, low-power, low-voltage and portable 3D/4D sonography and an affordable 3D Ultrasound Stethoscope.

REFERENCES