A Silicon Ultrasonic Imager Probe for Minimally Invasive Diagnosis

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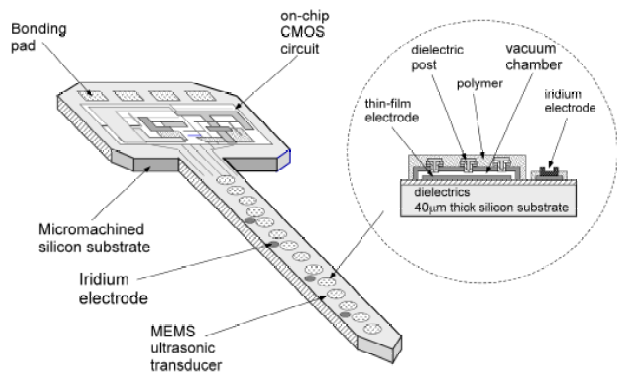
ABSTRACT

A probe-shaped MEMS ultrasonic transducer array with the probe cross-section smaller than the human's hair has been developed for invasive diagnosis and imaging. This device was fabricated using a two-layer polyslicon surface micromachining process, followed by a double-side deep silicon etching for substrate shaping. Such imager array is useful for invasive imaging of anatomical structure difficult to access by bulky traditional ultrasonic imager. It is especially useful for near-field imaging of cells and structures deep inside the tissue. Due to its submicron (typically 0.1-0.2μm) gap height under the suspended membrane, this device operates at low DC bias (<20V) in receiving mode and requires low (typically <35V) peak-to-peak voltage during transmission mode. Preliminary experiments showed the feasibility of this device as an ultrasonic imager.

Keywords: CMUT, ultrasonic transducers, medical imaging, B-mode imaging, implantable

1. Introduction

Ultrasound is longitudinal acoustic wave having a frequency higher than the human ear's audibility limit of about 20kHz. The application of ultrasound covers almost every field in our daily lives including nondestructive evaluation of materials and medical diagnosis and treatment. As a normally non-invasive diagnostic tool, ultrasound imaging has been widely used in exploring anatomical structures and other biological activities inside the body since early 1970s. Compare to other popular medical imaging approaches, including X-ray, MRI, and CT, the advantages of ultrasound imaging including real-time imaging, affordable apparatus cost, smaller device size, and a non-radioactive approach. Ultrasound has also been used in other medical applications including hyperthermia and ultrasound-enhanced drug delivery for cancer treatment. Traditional piezoelectric transducers have been the dominating technology for building the medical ultrasonic imager. Due to its unsatisfactory acoustic impedance match to fluids and difficulty in connecting electrical wires to transducers, alternative technologies are being explored. Among which the capacitive micromachined ultrasonic transducer (CMUT) [1] technology has attracted a lot of attentions due to its IC compatibility and better acoustic impedance match to fluids.



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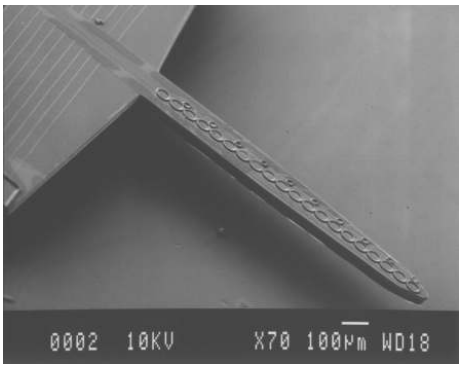

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Figure 1 (a) Schematic of a 1D ultrasonic imager array integrated on a micromachined silicon probe for ultrasonic imaging; (b) SEM photograph of the 1D ultrasonic imager array. The substrate thickness of this array is 40μm, while the width of the probe shank is 80μm.

CMUT was first introduced in early 1990s. It delivers a broader bandwidth and has a lower gain than its piezoelectric counterpart. It also has the potential for monolithic integration with front-end signal-processing

circuitry. The integration would reduce the parasitic capacitance and improve the image quality. CMUT devices use the deformation of a suspended membrane, fabricated using either a wafer-to-wafer bonding or a surface micromachining process, to transmit and receive ultrasounds. CMUT technology has made significant progress both in device and system levels since its first introduction. However, most of these development works reported so far centering on CMUTs integrated on a bulky substrate for non-invasive applications. In many medical diagnoses, close-range imaging of the tissue/organ is important for accurate identification of disease/disorder. Being close to the target, higher frequency ultrasounds can be applied and higher resolution can be achieved. In order to perform these close-range diagnoses, an invasive imager is needed and the size of the imager has to be miniaturized in order not to introduce significant disruption to the tissue.

This paper reports the development and results of preliminary image acquisition using a miniaturized ultrasonic transducer array. Different from traditional piezoelectric or CMUT ultrasonic transducers which generally use a bulky piece of substrate, this array is integrated on a 40μm-thick micromachined silicon substrate into a probe shape with a typical width of 50-80μm, as shown in figure 1. The length of this imager probe typically ranges from 4 millimeters to over one centimeter, depending on how many transducers are to be integrated on the probe for the specific application. Due to its miniature size, this array can be placed or implanted close to the target structure/tissue/organ and performs imaging or high-precision diagnosis/stimulation using high-frequency ultrasounds. This device is useful for near-field imaging for identifying minor disorders in anatomical structure of tumor or tissue. The issue of poor image resolution inherent from long-wavelength waves required for deeper penetration depth can therefore be resolved.

2. CMUT transducer design and fabrication

As shown in figure 2, several novel structures have been developed and used in the transducer design for preventing the shorting of the transducer drum to its counter electrode, and for minimizing the charging problem. For example, an array of dielectric posts is embedded in the polysilicon membrane such that when the membrane moves down during ultrasonic transduction, the protruded posts prevent direct touch of the membrane to the counter electrode. Different from traditional polysilicon surface micromachining process, as shown in figure 2, a thin (~250 angstroms) layer of LPCVD oxide is added between the lower polysilicon electrode and the floor nitride layer such that the conducting polysilicon microstructures are not in direct contact with the silicon nitride. In a similar arrangement the metal interconnects are separated from the silicon nitride layer by a thin layer of polymer. This design is important in reducing the charging problem and enhancing the reliability as well as prolonging the lifetime of the device.

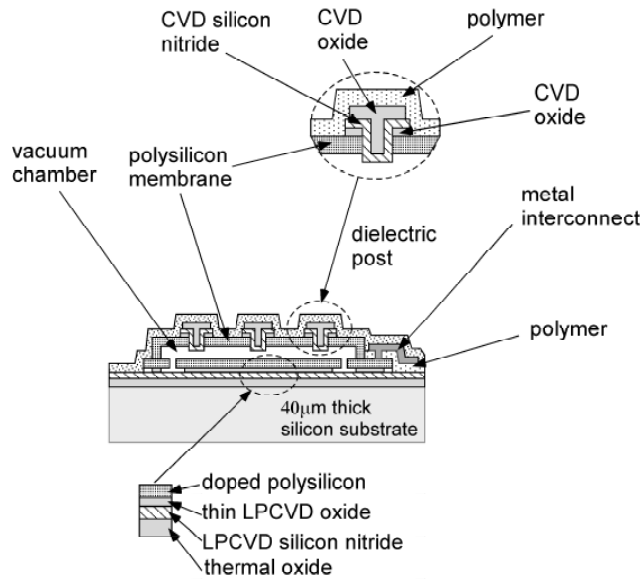


Figure 2: Cross section of the ultrasonic imager. An array of dielectric posts are embedded in the polysilicon membrane for preventing shorting of the membrane to its counter electrode. All the conducting thin films including doped polysilicon and metal are separated from silicon nitride by a thin layer of LPCVD oxide or polymer in order to minimize charging problem at the nitride-conductor interface.

After completion of the thin-film transducer structures, the substrate of the transducer is micromachined using a double-sided deep silicon etching process shown in figure 3. The substrate thickness is determined by the depth of the dry-etched trenches defined on the front side and can be controlled to within ±1μm. In addition to miniaturization, one of the advantages of micromachining the substrate thickness is reduction of cross talk from Lamb waves propagating in the substrate. This is important to improving signal-to-noise ratio and the image quality. According to theoretical calculation, the lamb wave-related crosstalk level is reduced by 2.3 dB if the substrate thickness is reduced from 550μm to 40μm as used in this device design.

3. Transducer characteristics

This miniature ultrasonic imager operates at a peak-to-peak voltage less than 35V and is able to transduce ultrasound waves of frequencies ranging from several hundred kHz up to 20MHz at different power level. Figure 4(a) is the ultrasound signal transmitted by a 46μm-diameter imaging transducer. The transducer was excited by a 35-volts peak-to-peak, 50ns-wide electrical impulse without DC bias. Its frequency response is shown in figure 4(b). All the measurement was performed in water.

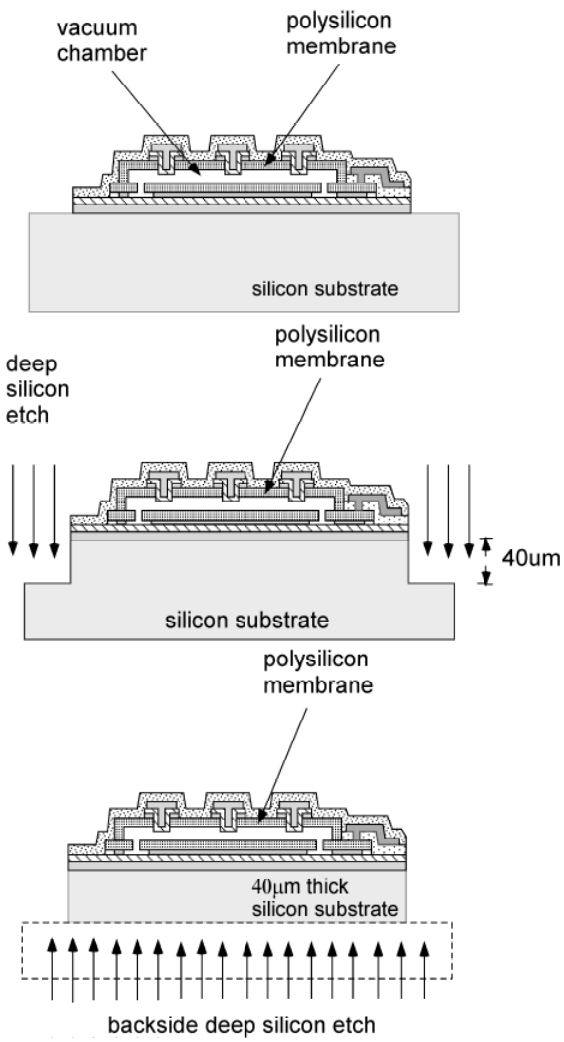
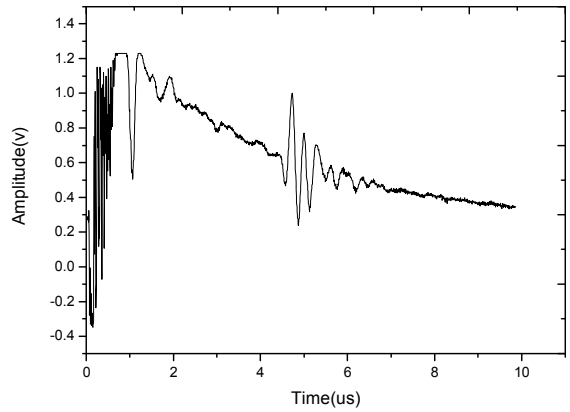


Figure 3: Micromachining the silicon substrate using a double-sided dry etching process.

4. B-mode imagng

The experimental setup for image formation is shown in figure 5. A section of metal wire was soaked in water as the target to be imaged. Instead of a motor positioning system, a manual positioning system is used to avoid electromagnetic interference. The 1D transducer array and a 1 MHz ultrasound transducer (Panametrics V302, Waltham, MA) are fixed on two ends of an L-shape holder. A ceramic plate (LiNbO3) is placed at the focus of the 1 MHz transducer as a acoustic reflector. The pulser/receiver (Panametrics PR5072, Waltham, MA) transmits a short pulse to drive the transducer. Then, the reflected wave is received by the needle array. The echoes are amplified by 59dB using the same pulser/receiver before being digitized by an oscilloscope. (Tektronix TDS 3054B, Tokyo, Japan). To improve signal-to-noise ratio, signal averaging of 1024 times at each holder is performed before the holder is moved to the next step position. The step size between two scan positions is 100 μm. Signal processing is performed and displayed on a computer using MATLAB (MathWorks, Natick, MA).



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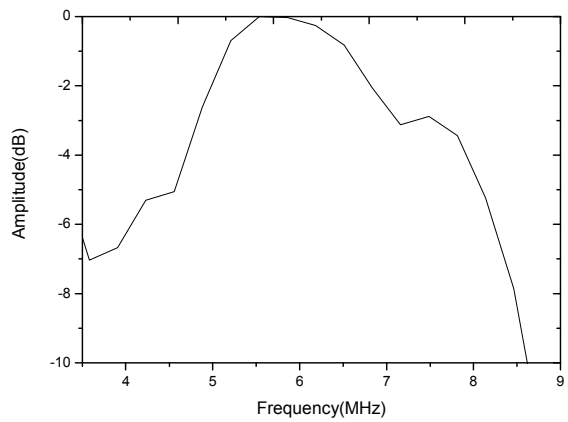

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Figure 4: (a) Ultrasound signal generated by a 46μm-diameter ultrasound transducer in water. The transducer was excited by a 35-volts peak-to-peak, 50-nanosecond wide electrical impulse. (b) Frequency response of the 46μm-diameter ultrasound transducer. The major resonant frequency of this transducer is 6.0MHz.

5. Conclusions

Capacitive micromachined ultrasonic transducer (CMUT) array is widely considered as a promising alternative to the piezoelectric transducers for medical imaging. Traditional CMUT devices are integrated on a regular silicon substrate with a thickness thicker than 550μm, and are generally packaged as box-sized imager for operation from outside-of-the body. This paper reports the development of a miniaturized CMUT array integrated on a micromachined

silicon probe with a diameter smaller than the human's hair for invasive imaging. It is especially useful for near-field imaging of cells and structures deep inside the tissue. Due to the small gap under the suspended membrane, this device operates at low DC bias (<20V) in receiving mode and low (typically <35V) peak-to-peak voltage during transmission mode. Preliminary experiments showed the feasibility of this device for ultrasonic imaging.

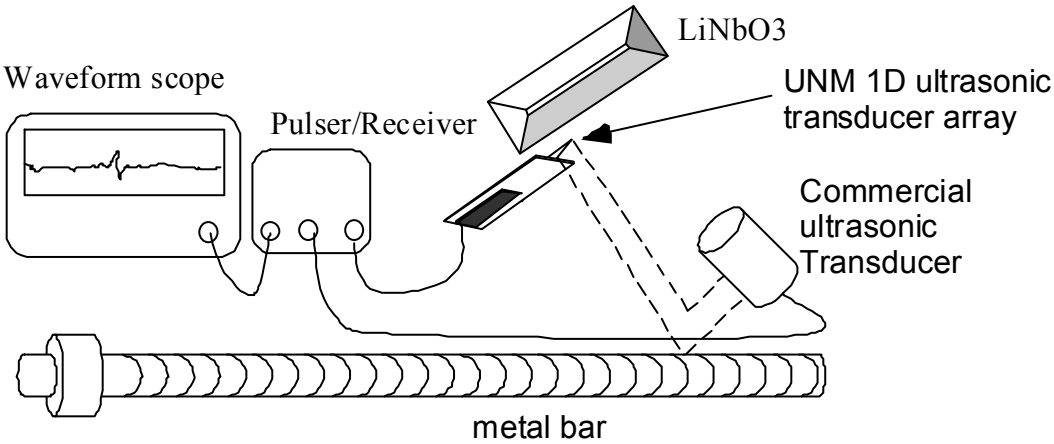
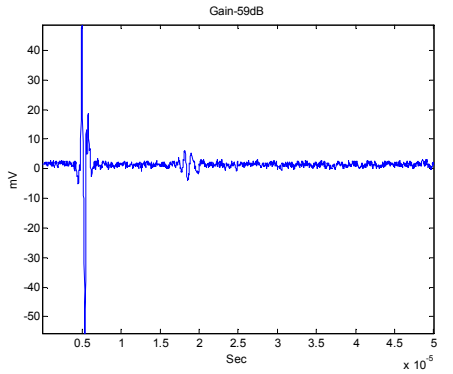


Figure 5: Setup for image acquisition of a metal wire using the 1D silicon ultrasonic imager array.



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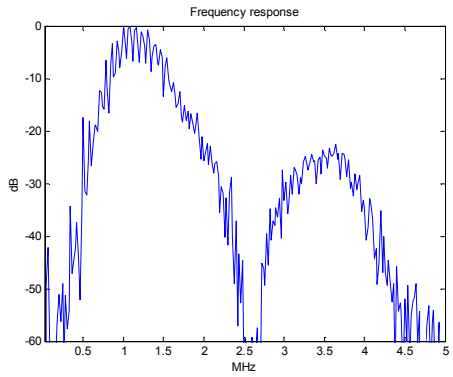

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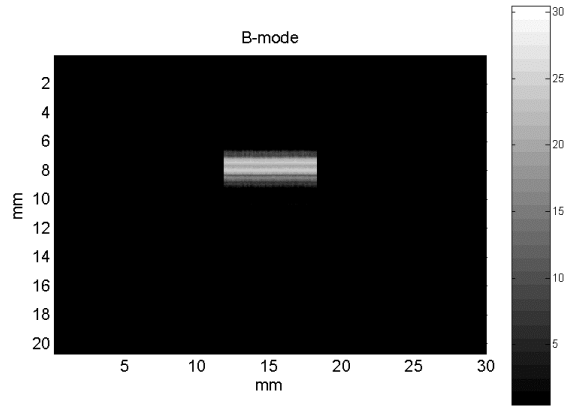

(c)

Figure 6: (a) Ultrasonic signals received by an array of 56μm-diameter imagers; (b) frequency response of the received signals; (c) B-mode image of the metal wire.

REFERENCE

[1] Davide T. Yeh, Ira O. Wygant, Butrus T. Khuri-Yakub, "3-D Ultrasound imaging using a forward-looking CMUT ring array for intravascular intracardiac applications." IEEE trans Ultrason., Ferroelect., Freq. Contr. Vol.53,pp1202-1211, August 2006.