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A 2D Capacitive Micromachined Ultrasonic Transducer (CMUT) Array with Through-Glass-Via Interconnects Fabricated Using Sacrificial Etching Process

Oluwafemi J. Adelegan
Electrical and Computer Engineering
NC State University
Raleigh, USA
ojadeleg@ncsu.edu

Zachary A. Coutant
Electrical and Computer Engineering
NC State University
Raleigh, USA
zacotan@ncsu.edu

Xiao Zhang
Electrical and Computer Engineering
NC State University
Raleigh, USA
xzhang35@ncsu.edu

Feysel Yalcin Yamaner
Electrical and Computer Engineering
NC State University
Raleigh, USA
fyyamane@ncsu.edu

Ömer Oralkan
Electrical and Computer Engineering
NC State University
Raleigh, USA
ooralka@ncsu.edu

***Abstract*—A two-dimensional (2D) transducer array is an integral part of a three-dimensional (3D) ultrasound imaging system as well as a compact ultrasound system for neurostimulation to steer and focus the beam in a volume. In this paper, a sacrificial etching-based fabrication process for implementing a 16x16-element 2D CMUT array on a glass substrate with through-glass-interconnects is described in detail. Across the fabricated 256 elements of the 2D CMUT array, the mean resonant frequency is measured as 4.76 MHz with a standard deviation of 46.6 kHz. The fabricated 2D CMUT array shows a 100% element yield in fabrication and excellent uniformity in device performance. The process offers the advantages of developing 2D CMUT arrays on glass substrates that do not need to be compatible with anodic bonding.**

Keywords*—*CMUT, 2D Arrays, Glass substrate, Through-Glass-Vias (TGV), Sacrificial release process.

I. Introduction

Focused ultrasound has been proposed as a promising noninvasive or minimally invasive technique for neurostimulation with high spatiotemporal resolution, and relatively large penetration depth [1], [2]. Ultrasound is also widely used for imaging. A 2D transducer array enables a real-time 3D image and efficient beamforming and steering to focus ultrasound energy at the targeted location for therapy. Considering the associated challenges with the implementation of 2D arrays using piezoelectric technology, CMUT technology offers advantages such as the flexibility of fabricating complex array configurations and the potential for integrating arrays with supporting electronics [3]. Previous methods such as through-silicon-vias (TSV) [4] and trench-isolated interconnects [5] have been used to develop 2D CMUT arrays for hybrid integration but both methods increase the fabrication process complexity, and device reliability can be an issue.

There have been previous efforts in fabricating CMUTs on a glass substrate [6]–[8]. Reduced parasitic capacitance and series resistance are some of the advantages of using a glass substrate with a metal bottom electrode. Also, through-glass-vias (TGV) have been previously used for advanced electronic packaging and assembly [9]. Using a glass substrate helps reduce the electrical coupling between through-wafer interconnects in comparison to TSVs, and the need for additional insulation layer on the sidewalls of the via holes during fabrication is avoided.

We have previously reported a fabrication process for implementing vacuum-sealed CMUTs on a borosilicate glass substrate using anodic bonding [10]. We have also demonstrated the fabrication of vacuum-sealed 2D CMUT arrays on a glass substrate with copper through-glass-via interconnects using anodic bonding [11]. This process requires the use of an anodic bonding compatible glass substrate. So, in this work, we demonstrate an alternative fabrication process for fabricating 2D CMUT arrays on a glass substrate with through-glass-vias interconnects. This sacrificial etching based fabrication process is compatible with any glass substrate.

In the following section, the detailed fabrication process flow for fabricating 16x16 2D CMUT arrays is discussed. We then present the characterization results from the fabricated 16x16-element 2D CMUT array. The high yield in fabrication and uniformity in functionality are demonstrated by measuring the resonant frequency distribution across the 256 elements of the 2D CMUT array.

II. Fabrication Process

The fabrication of these arrays requires six (6) masks. The process started by cleaning the substrate to remove the organics and contaminants on the wafer surface. The substrate was a SGW3 (Corning) glass wafer with a thickness of 0.5 mm and a

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diameter of 100 mm with incorporated copper through-glass-via interconnects (Fig. 1a). The substrate was cleaned using N-Methyl-2-pyrrolidone (NMP), a non-acidic based solvent at 70ºC for 30 minutes. After the wafer cleaning, we defined a metal stack of 20-nm titanium as an adhesion layer, 250-nm gold, and 20-nm titanium using e-beam evaporation and lift-off as the bottom electrode for the devices. After the lift-off, using plasma enhanced chemical vapor deposition (PECVD), a 100-nm silicon nitride (Si_3N_4) was deposited as a passivation layer (Fig. 1b). We then patterned and deposited 250-nm chromium by e-beam evaporation to serve as the sacrificial layer. Then, another 1.2-µm silicon nitride was deposited as part of the vibrating plate (Fig. 1c). We then created etch holes by photolithography and dry etching to access the sacrificial layer. Using a chromium etchant (Chromium Cermet Etchant TFE, Transene Electronic Chemicals, Massachusetts, USA) with good selectivity, we etched the chromium sacrificial layer.

After etching the sacrificial layer, we then deposited 1-µm conformal silicon nitride to seal the devices in vacuum (Fig. 1e). After confirming that the devices are vacuum-sealed, we then patterned and deposited 20-nm chromium and 280-nm gold by e-beam evaporation to serve as the top electrode. Also, a metal stack of 20-nm chromium, 280-nm copper, and 220-nm gold was deposited by e-beam evaporation and patterned by liftoff for backside metallization to provide the under-bump metallurgy (UBM) that is required for flip-chip bonding (Fig. 1e). This completes the fabrication process. Optical images showing the front side of the fabricated 16x16-element 2D CMUT array and a zoomed image to one of the elements are shown in Fig. 2.

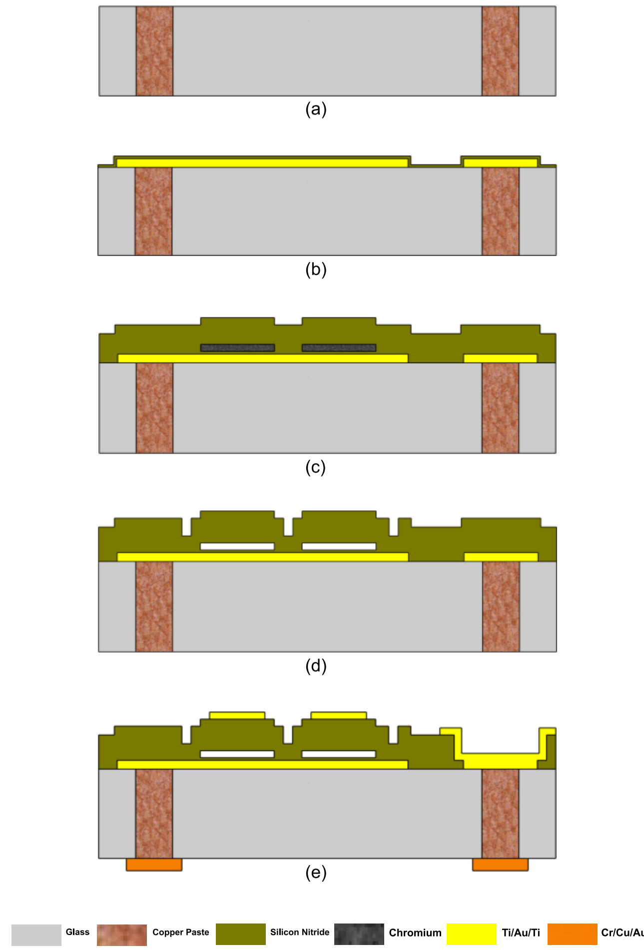

Fig. 1: Fabrication process flow: (a) Glass substrate with TGVs; (b) Bottom electrode deposition and lift-off followed by silicon nitride passivation layer deposition; (c) Sacrificial chromium deposition and PECVD silicon nitride deposition; (d) Etch hole patterning, sacrificial chromium etch, and sealing silicon nitride deposition; (e) Top electrode and backside metal deposition.

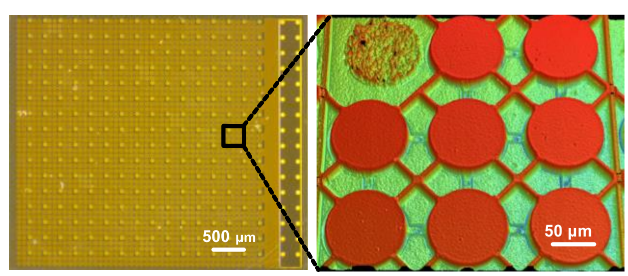

Fig. 2: Front side of the fabricated 16 x 16-element 2D CMUT array with a zoomed image of one of the elements.

III. Device Characterization

A. Characterization in Air

After fabrication, we diced the wafer to singulate the 2D CMUT arrays for device characterization. A 125-µm pitch coplanar microwave probe (Model ACP40-GSG-125, Cascade Microtech, Beaverton, OR, USA) connected to a network analyzer (Model E5061B, Agilent Technologies, Inc., Santa Clara, CA, USA) was used to measure the input impedance of the fabricated 2D CMUT array elements in air. Fig. 3 shows the real and imaginary parts of the electrical input impedance of one element of the 2D CMUT array. We measured an average open-circuit resonant frequency of 4.57 MHz at a bias voltage of 110 V.

B. Device Resonant Frequency Distribution

We characterized the yield and uniformity of the fabricated 2D CMUT array. A measurement of resonant frequency of the devices across the 16x16-element array at 40 V DC bias shows an average resonant frequency of 4.76 MHz with a standard deviation of 46.6 kHz which is 0.9% of the average resonant frequency (Fig. 4). These results show the viability of the proposed fabrication process flow with an excellent uniformity across the 256 elements of the 2D CMUT array.

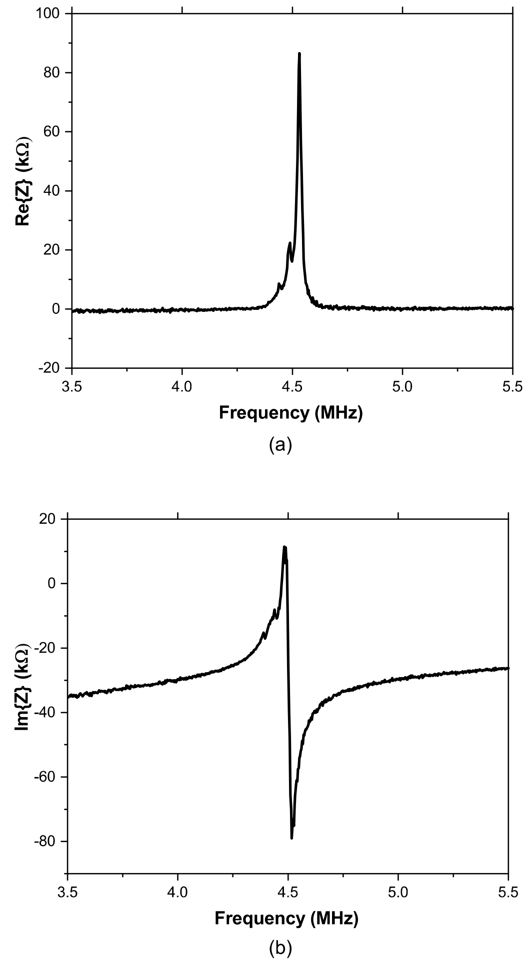

Fig. 3: The real part of the electrical input impedance at 110 V DC bias; (b) The imaginary part of the electrical input impedance at 110 V DC

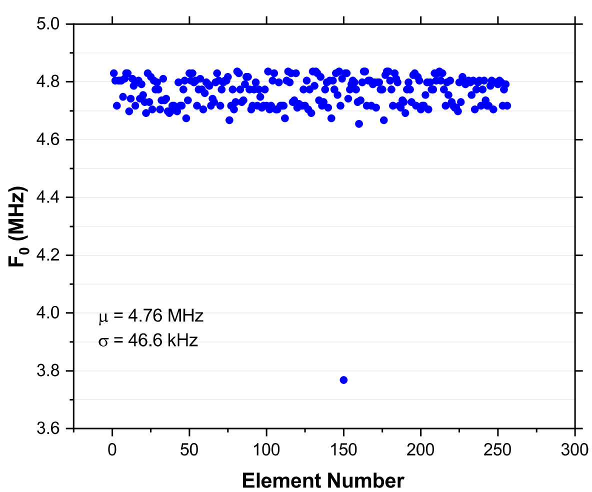

Fig. 4: Resonant frequency distribution of the fabricated 16x16-element 2D CMUT array.

IV. Conclusion

In this paper, we presented a fabrication process for implementing vacuum sealed 16x16-element 2D CMUT arrays on a glass wafer with through-glass-via interconnects using sacrificial release process. This proposed fabrication process is compatible with most glass substrates even when the substrate is not compatible with anodic bonding. We recorded a mean resonant frequency of 4.76 MHz with a standard deviation of 46.6 kHz across the 256 elements of the 2D CMUT array. These results show excellent uniformity in performance and 100% element yield in the fabricated array.

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References

[1] M. D. Menz, Ö. Oralkan, B. T. Khuri-Yakub, and S.A. Baccus, "Precise neural stimulation in the retina using focused ultrasound," *J. Neurosci.,* vol. 33, no. 10, pp. 4550-60, Mar. 2013.

[2] X. Wu, M. Kumar, and Ö. Oralkan, "An ultrasound-based noninvasive neural interface to the retina," in *Proc. IEEE Ultrason. Symp.,* pp. 2623-2626, Sep. 2014.

[3] Ö. Oralkan, M. Karaman, U. Demirci, K. Kaviani, T. H. Lee, and B. T. Khuri-Yakub, "Capacitive micromachined ultrasonic transducers: Next-generation arrays for acoustic imaging?," *IEEE Trans. Ultrason., Ferroelectr.,Freq. Control,* no. 11, pp. 1596-1610, Dec. 2002.

[4] I. O. Wygant, Z. Zhuang, D. T. Yeh, Ö. Oralkan, A. S. Ergun, M. Karaman, and B. T. Khuri-Yakub, "Integration of 2d cmut arrays with front-end electronics for volumetric ultrasound imaging," *IEEE Trans. Ultrason., Ferroelectr.,Freq. Control,* vol. 55, no. 2, pp. 327-342, Mar. 2008.

[5] X. Zhuang, A. S. Ergun, I. O. Wygant, Ö. Oralkan, and B. T. Khuri-Yakub, "Integration of trench-isolated through-wafer interconnects with 2d capacitive micromachined ultrasonic transducer arrays," *IEEE Trans. Ultrason., Ferroelectr.,Freq. Control,* vol. 138, no. 1, pp. 221-229, Mar. 2007.

[6] M. Bellaredj, G. Bourbob, V. Walter, P. L. Moal, and M. Berthillier, "Anodic bonding using soi wafer for fabrication of capacitive micromachined ultrasonic transducers," *J. Micromech. Microeng.,* vol. 24, no. 2, pp. 25009, Jan. 2014.

[7] R. Mukhiya, K. Prabakar, M. Raghuramaiah, J. Jayapandian, R. Gopal, V. K. Khanna, and C. Shekhar, "Fabrication of capacitive micromachined ultrasonic transducer arrays with isolated trenches using anodic wafer bonding," *IEEE Sensors J.,* vol. 15, no. 9, pp. 5177-5184, May. 2015.

[8] N. Toan, S. Hahng, Y. Song, and T. Ono, "Fabrication of vacuum-sealed capacitive micromachined ultrasonic transducer arrays using glass reflow process," *Micromachines,* vol. 7, no. 5, pp. 76, May. 2016.

[9] M. Töpper, N. Ivan, E. Robert, B. Lars, N. Nissen, S. Henning, Y. Hidefumi, T. Guido, and R. Herbert, "3-d thin film interposer based on tgv (through glass vias): An alternative to si-interposer," in *Proc. IEEE Electr. Comp. Tech. Conf.,* pp. 66-73, Jun. 2010.

[10] F. Y. Yamaner, X. Zhang, and Ö. Oralkan, "A three-mask process for fabricating vacuum-sealed capacitive micromachined ultrasonic transducers using anodic bonding," *IEEE Trans. Ultrason., Ferroelectr.,Freq. Control,* vol. 62, no. 5, pp. 972-982, May. 2015.

[11] X. Zhang, F. Y. Yamaner, and Ö. Oralkan, "Fabrication of vacuum-sealed capacitive micromachined ultrasonic transducers with through-glass-via interconnects using anodic bonding," *J. Microelectromech. Syst.,* vol. 26, no. 1, pp. 226-234, Dec. 2016.