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Fabrication and Characterization of Capacitive Micromachined Ultrasonic Transducers Integrated on Ultra-thin and Flexible Substrates

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***Abstract*— Polymer-based microfabrication approaches have been recently proposed as a low-cost alternative to traditional Capacitive Micromachined Ultrasonic Transducers (CMUT) fabrication methods. In most of the CMUT structures fabricated using such approaches, the electrodes passivation is achieved by a spin-coated polymer layer, with dielectric properties typically unsuitable to withstand the high in-cavity electrical fields. Moreover, typical layer thicknesses achievable by spin-coating bring to a significant increase of the effective gap height, inducing a very high collapse voltage and thus the need to use unpractically high operating voltages. In this paper, we investigate a process aimed at fabricating flexible CMUTs, potentially enabling high-performance, low-cost, curved, and ultra-miniaturized transducer configurations. In the proposed process, CMUT fabrication is carried out on an ultra-thin Polyimide substrate spun on a silicon wafer. The electrodes passivation is achieved by a thin SiO_2 layer with excellent dielectric properties. A thin layer of SU-8 is used for the membrane fabrication and for sacrificial etch holes sealing. The devices are mechanically peeled-off from the wafer at the end of the process.**

***Keywords*— CMUT, Flexible, SU-8 polymer, Polyimide**

I. Introduction

Capacitive Micromachined Ultrasonic Transducers (CMUTs) have been introduced in the nineties, and represent a valid alternative to piezoelectric transducers in many application fields. Indeed, CMUTs are generally preferred for their higher bandwidth and efficiency [1-2], as well as for their lower cost, especially in devices characterized by stringent miniaturization and high-volume manufacturing requirements.

Traditionally, MEMS-based ultrasonic transducers are fabricated on silicon using complex and expensive microfabrication processes. Recently, polymer materials with good mechanical properties, such as SU-8, have been considered as viable alternatives [3-4]. The possibility to fabricate polymer-based flexural plates is opening new opportunities in the manufacturing of flexible and even stretchable CMUT-based ultrasonic devices. Until now, many challenges need to be solved such as materials intrinsic softness, polymers shrinkage issues, metallization robustness on plastic, etc. We believe that many issues can be overcome by integrating the expertise acquired from flexible electronics fabrication processes [5].

In this paper, we present a low complexity, sacrificial-release-based microfabrication process, in which SU-8, a well-known polymer used in microelectronics, is used as the CMUT plate material. After introducing the novel process, we report on the fabrication of CMUT test devices and show the first characterization results. We then discuss the strengths and weaknesses of the current process and propose an improved flow aimed at solving the observed issues.

II. Materials and Methods

A. Microfabrication Process

The main steps of the microfabrication flow, described in Fig. 1, consists in photolithography processes with lift-off and wet etching, which contribute to minimize the costs and the fabrication effort. The metals used for electrodes and sacrificial layers were obtained by evaporation and patterned with lift-off processes with a 2D-pattern resolution in the order of few microns. We used SU-8 3003 in order to obtain 3μm-thick CMUT plates. For the removal of the sacrificial metal layer, we opened three etch-holes per cell in the SU-8, by a photolithography process, in order to permit the sacrificial metal etching solution input. The CMUT microfabrication is carried out on a silicon wafer, on top of which a flexible substrate,

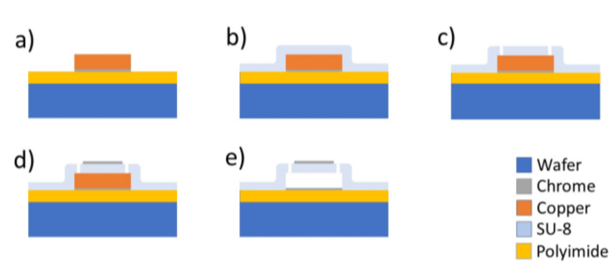

Fig. 1. Fabrication scheme for CMUT test device: a) Bottom electrode and sacrificial layer evaporation; b) SU-8 deposition; c) SU-8 development (etc-holes opening for copper removing); d) Top electrode evaporation; e) Copper etching

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consisting in a 5µm-thick layer of Polyimide PI2611 is previously spun. Polyimide is a polymer that, once deposited on a wafer, can be mechanically peeled off from the support together with the structures on it, thus obtaining fully flexible devices.

B. Test Device Design and Fabrication

We developed a first set of masks to define single test structures composed by seven cells arranged in a honeycomb configuration (Fig. 2). Different cell diameters have been designed ranging from 50 µm to 150 µm with the intent of obtaining an oscillation frequency in the range of few MHz. The fabrication of these first test devices was performed at the clean rooms of the Rome Unit of the Institute for Microelectronics and Microsystems (IMM) of the National Research Council of Italy (CNR) using the proposed three-mask process, in which chrome is used for the electrodes and copper for the sacrificial layer. The electrodes and the sacrificial layer have been obtained by lift-off, and the sacrificial layer removal, that is the most critical step in the process, has been successfully completed by wet etching for all the different types of structures, including the ones characterized by the largest cell diameter, without experimenting stiction. As can be seen in Fig. 3, the progressive removal of the sacrificial layer has been calibrated by observing a control structure, which consists in a "dummy" cell including only the bottom electrode and the sacrificial layer.

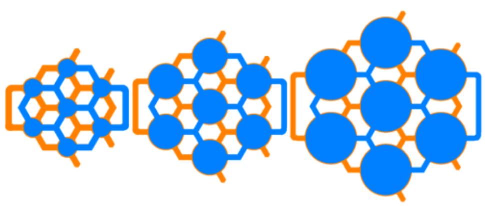

Fig. 2. Single device structure composed by seven cells arranged in a honeycomb configuration. From left to right: 50 µm, 100 µm and 150 µm plate diameter.

C. Characterization

In order to evaluate the SU-8 robustness during operation, basic electromechanical characterization in air-coupled conditions was carried out on fabricated CMUT test devices before peeling them off the wafer, using a Polytec MSV-300 (Polytec PI Inc., Auburn, MA) Laser Doppler Vibrometer (LDV). We acquired LDV displacement spectra of the seven cells centers of a CMUT test device biased with 20 V and excited with a sinusoidal signal of 1V rms amplitude, in the 1-10 MHz range (Fig. 4). A mean resonance frequency of 6.5 MHz was estimated.

Finally, the fabricated CMUT devices were successfully peeled-off from the wafer (Fig. 5) reaching a final thickness of about 10 µm.

III. Results and Discussion

The displacement measurements of Fig. 4 showed that all the membranes oscillate with a resonance frequency in the order of few MHz and confirm the possibility to fabricate polymer-

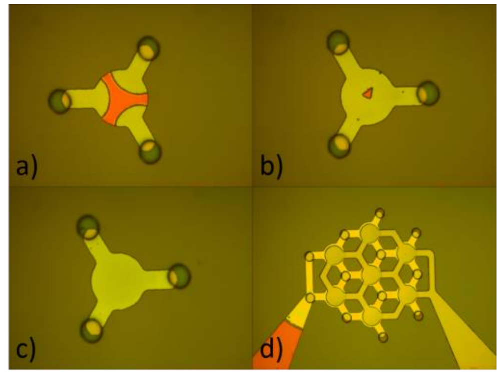

Fig. 3. Control structure during the sacrificial metal etching process; the time is ordered from a) to c). Complete SU-8 array of 50µm CMUT plates on image d).

based CMUTs using SU-8. Even though the proposed fabrication process was demonstrated to be solid and reproducible, some issues were observed.

First of all, the position of the SU-8 layer in the material stack i.e. between the electrodes, is disadvantageous since it increases the effective gap and, consequently, the CMUT collapse voltage. Second, once evaporated, the sacrificial copper layer surface doesn't show a smooth profile but instead, shows a big number of spikes in the order of hundred nanometres of height. This surface roughness is transferred to the bottom surface of the CMUT plates thus compromising the uniformity. Finally, the etch holes used to remove the copper sacrificial layer are still open at the end of the manufacturing process. This issue is responsible of air damping and stiffening effects which make the behaviour of these devices difficult to predict.

We addressed the abovementioned issues by establishing an improved version of the SU-8 based CMUT process, schematically reported in (Fig. 6). The improved process flow uses five masks and has been tested by fabricating the same devices previously described. Starting from the same masks design, we added two additional masks, one for pattering an additional passivation layer (in the improved version, both the electrodes are inside the cavity), and one for closing the etch holes.

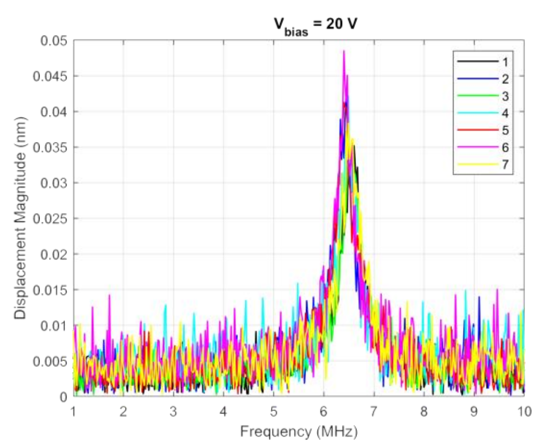

Fig. 4. Displacement spectra measured by LDV of the 7 cells at 20V DC bias and AC sinusoidal signal of 1V rms amplitude in the range 1-10 MHz.

Fig. 5. Flexible strip of CMUT devices after peeling off from the silicon wafer.

The fabrication process flow is practically the same of the previous version with the addition of two additional steps. The first one consists in deposition of a 100nm-tick passivation layer of SiO_2 with excellent dielectric properties, i.e. reduced charge injection and high breakdown field [6]. This thin Silicon Oxide layer is deposited at low temperature by Electron Cyclotron Resonance (ECR) / Plasma Enhanced Chemical Vapor Deposition (PECVD) and is patterned using a Reactive Ion Etching (RIE) process. The second additional step consists in deposition and developing of an additional SU-8 film, useful to close the etch holes after the sacrificial layer removal. Moreover, we changed the metals used to fabricate the electrodes and the sacrificial layer. We used titanium for the electrodes, because of the reduced stress in comparison with chrome and because of its biocompatibility, i.e. a desired requirement for biomedical applications. We also replaced copper with aluminium for the sacrificial layer in order to eliminate the roughness problem of the copper surface; in fact, the aluminium surface roughness is typically one magnitude order lower as compared to copper.

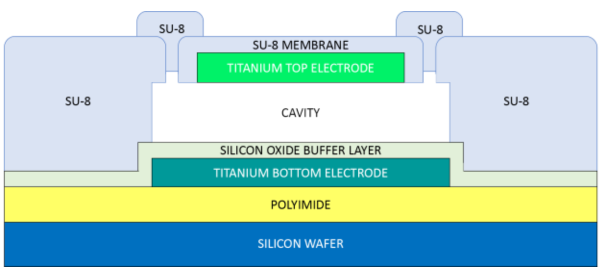

Fig. 6. Cross-sectional view of a second-generation SU-8 based CMUT device.

IV. Conclusion

A novel polymer-based CMUT process, aimed at fabricating flexible ultrasonic devices, was investigated. The process was demonstrated to be solid and reproducible, and the measurements performed on fabricated test devices showed CMUT operation in the MHz range. The issues observed in the first implementation have been discussed and addressed by proposing an improved process flow. Current work is devoted to the characterization of test devices based on the improved process. In conclusion, the investigated process opens the way to a new generation of high-performance, low-cost, curved, ultra-thin and ultra-miniaturized transducers, with high potential in novel ultrasonics applications.

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