MEMS FABRICATED ENERGY HARVESTING DEVICE
WITH 2D RESONANT STRUCTURE

Andrea Crovetto[1,2], Fei Wang[1*], Marco Triches[1,3], and Ole Hansen[1,4]
[1]DTU Nanotech, Technical University of Denmark, Kgs. Lyngby, Denmark
[2]Politecnico di Milano, Italy
[3]University of Padova, Italy
[4]CINF, Center for Individual Nanoparticle Functionality, NanoDTU, Denmark
(*Email: Fei.Wang@nanotech.dtu.dk*)

Abstract: This paper reports on a MEMS energy harvester able to generate power from two perpendicular ambient vibration directions. CYTOP polymer is used both as the electret material for electrostatic transduction and as a bonding interface for low-temperature wafer bonding. With final chip size of ~1 cm^2, an output power of 32.5 nW is reached with an external load of 17 MΩ, under a harmonic source motion with acceleration RMS amplitude 0.03 g (0.3 m/s^2) and frequency 179 Hz.

Keywords: MEMS, energy harvesting, polymer electret, CYTOP, wireless sensor networks, 2D vibrations

INTRODUCTION

Recently, energy harvesting devices have been developed based on electromagnetic, electrostatic, and piezoelectric methods [1-5] for their potential to replace batteries used in wireless sensor network (WSN) technology. Among them, electret-based energy harvesting devices can be fabricated and packaged together with the sensors due to their compatible fabrication processes.

As shown in Fig. 1, we have developed an energy harvester with a 4-wafer stack structure. The device includes a suspended proof mass that is confined within a fixed frame through spring structures. The springs are designed to provide a sharp resonance peak in the ambient vibration frequency range (less than 200 Hz). Two perpendicular in-plane vibration directions can drive the proof mass with this method. As the pre-charged electrets oscillate according to the vibration source, induced charges will move between the two types of electrodes on the counter part causing a current through the external load.

Similar to [2], the output nodes where the load is connected are located on the same side of the device and not across the gap. Moreover, moving parts and electrets are completely encapsulated to keep them dust- and moisture-free for better charge stability and overall performance. Unlike our previously reported prototype harvester [5], this is a packaged device entirely built at a wafer level. Also, the gap between electrets and counter electrodes is tunable in the fabrication phase. The small device size (1 cm × 1 cm × 0.15 cm) makes it compatible with WSN technology.

DEVICE FABRICATION

The energy harvesting device is built with standard MEMS fabrication techniques. Initially, the SiO$_2$ layer of an oxidized silicon wafer ("device wafer") is patterned on both sides. Then, the spring structures
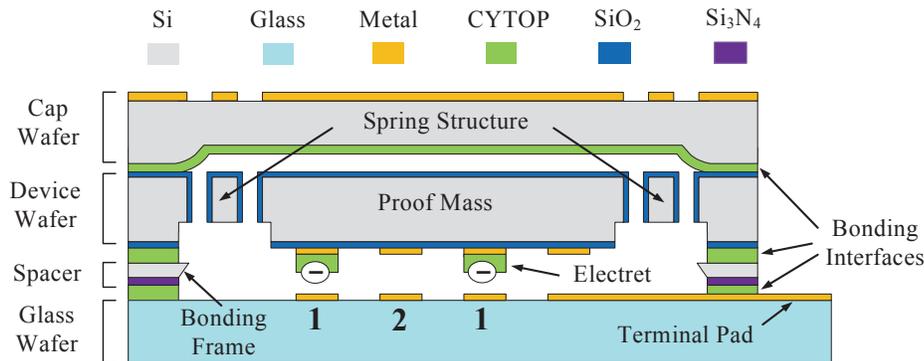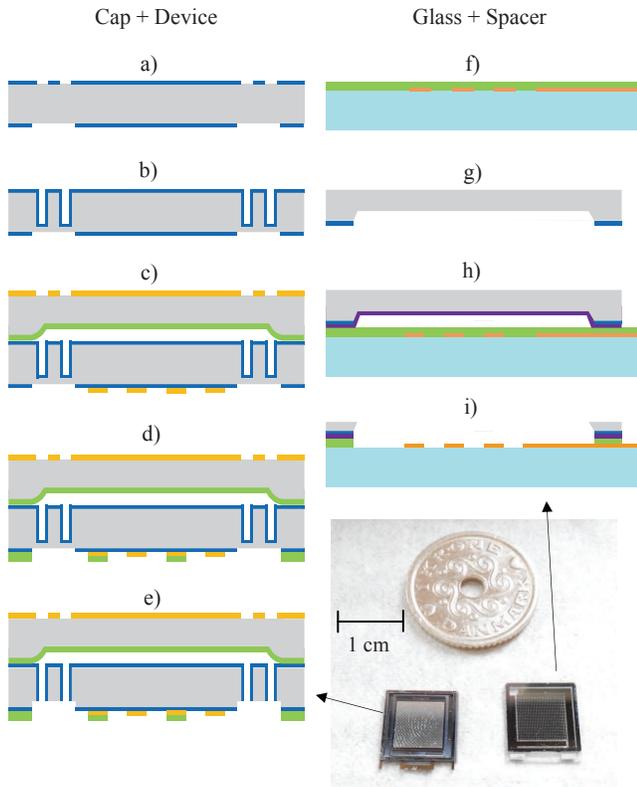

Fig.1: Cross-sectional drawing of the 2D harvester

Fig. 2: Fabrication process flow and photograph of the two detached device components. (a) double-side patterning of SiO₂ layer on oxidized silicon wafer. (b) deep etching of silicon (DRIE) and re-oxidation. (c) metal deposition/lift-off and bonding with cap wafer. (d) electret patterning (RIE). (e) release of spring structure (DRIE) and charging of electrets. (f) metal deposition/lift-off and CYTOP spin-coating. (g) SiO_2 patterning and silicon etching (KOH). (h) SiN_x deposition and spacer-glass wafer bonding. (i) release of bonding frames (KOH) and CYTOP etching (RIE). Last steps: final bonding and dicing.

are pre-etched with a DRIE process down to the desired thickness. This step enables tuning of the device's resonance frequency to a frequency peak of the target vibration source. Metal electrodes are
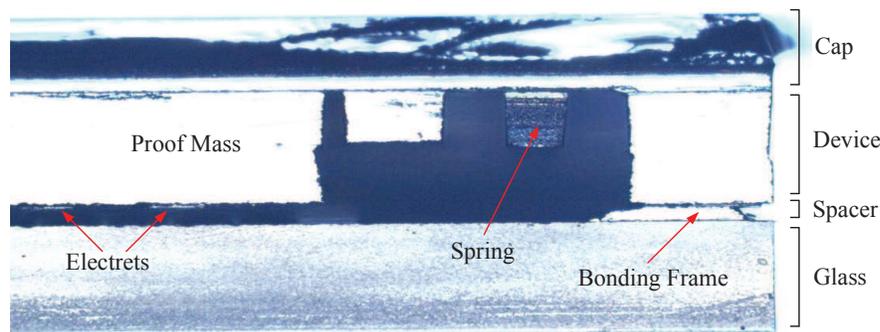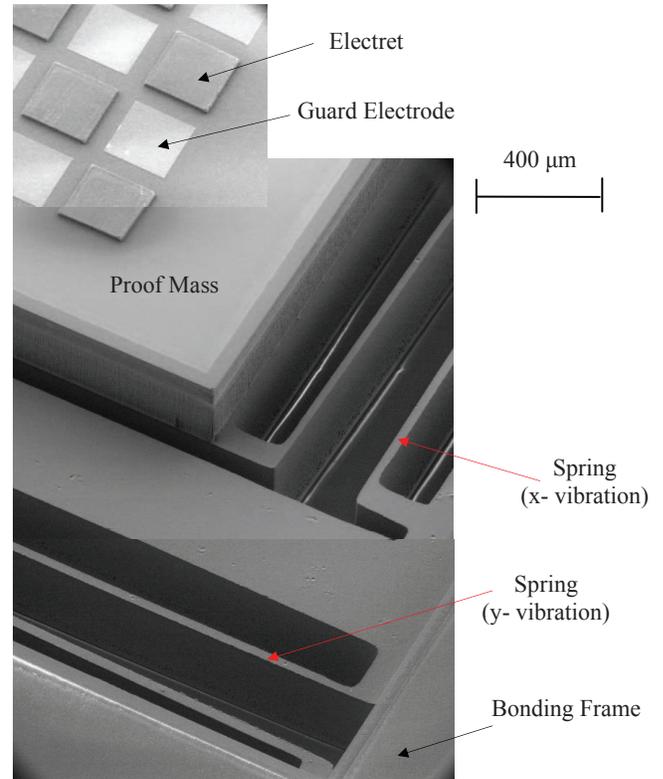

Fig. 4: Multiple SEM images of device wafer's bottom side after final release of spring structure. (re-edited for better illustration.)

obtained from a lift-off process on a Cr/Au/Cr multilayer. A "cap wafer" is bonded on the device wafer in order to protect electrets and fragile structures from external agents. Here and for the rest of the process flow, the bonding technique involves a CYTOP layer as an adhesive material at the bonding interface, which allows for a relatively low process temperature of 120ºC. After bonding, CYTOP is spin-coated multiple times on top of the electrode pattern to reach a 10 μm thickness. It is then patterned into a 2D array of 200 μm × 200 μm electrets using RIE with a photoresist mask [6]. The springs are subsequently released in another DRIE process from

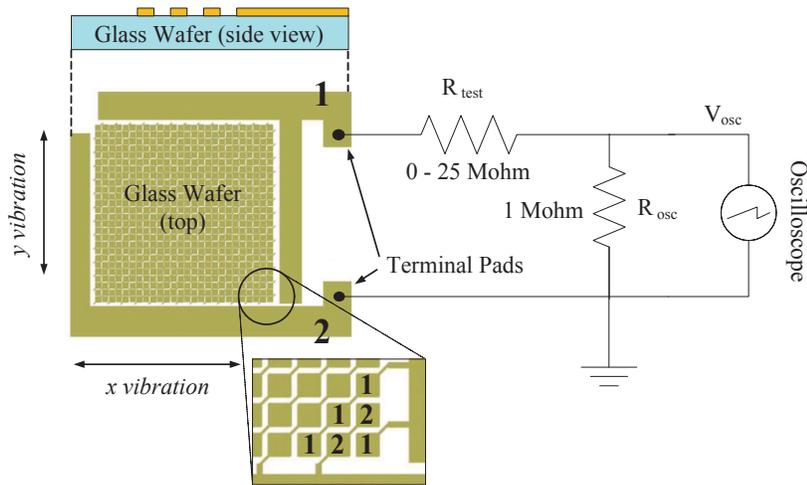Fig. 3: Microscope view of a device cross-section.

Fig. 5: *Schematic view of test setup. Rows of counter electrodes '1' and '2' are connected to terminal pads '1' and '2' respectively. The voltage V_{osc} is measured for different R_{test} to obtain an output power vs. load curve.*

Fig. 6: *Device mounted on a piezoelectric shaker with the test circuit connected.*

Fig.8: *Harvested RMS power in the total external load $R_{tot} = R_{osc} + R_{test}$*

charging performance and uniformity. Stable surface potentials up to -100 V were achieved with patterned electrets.

The "glass wafer" features diagonal rows of linked counter electrodes ending up in two larger terminal pads, i.e. the output nodes where the external load is connected (Fig. 5). The desired electret-counter electrode gap is set by a silicon "spacing wafer" that is first etched to the target gap using KOH and then covered with a thin SiN_x layer. These two wafers are bonded together and KOH-etched again to release the spacing frames. The inset photo in Fig. 3 shows the "cap+device" and the "glass+spacer" wafer pairs having a small chip size of ~ 1 cm^2. Finally, the two wafer pairs are bonded together. Here, the low bonding temperature of 120ºC is crucial in order to minimize charge losses. Figures 3 and 4 show the fabricated chip with more details. In particular, the 4-wafer stack is clearly seen from the cross-sectional view in Fig. 3; electrets and springs are seen in Fig. 4.
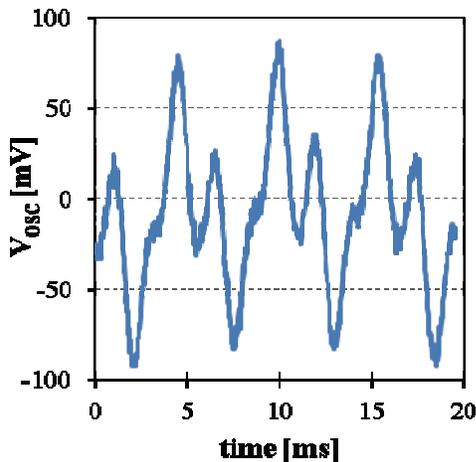

Fig. 7: *Example of oscilloscope output voltage signal at resonance.*

the back side. Finally, electrets are charged quasi-permanently to the desired charge density by a controlled corona discharge. Floating guard electrodes on the device wafer (Fig. 4) are designed to improve
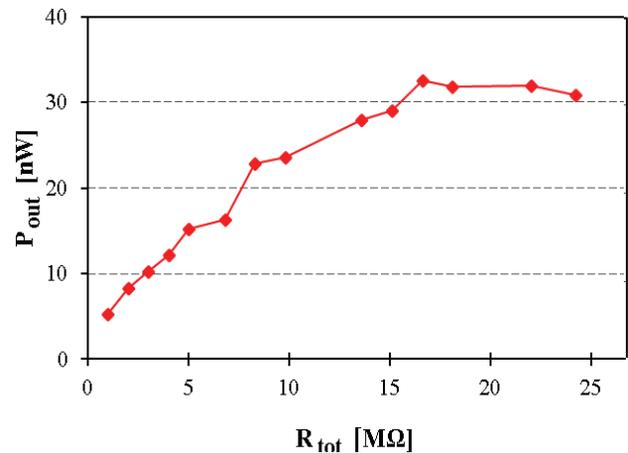
TESTING AND DISCUSSION

As shown in Fig. 6, the energy harvesting device is mounted on a piezoelectric shaker and driven to its mechanical resonance frequency along one of the two allowed vibration directions. A scaled output signal is read by an oscilloscope in series with a variable test resistance (Fig. 5). Such a test setup yielded a maximum output power of 32.5 nW with an external load of 17 MΩ and a harmonic source acceleration amplitude of 0.03 g (~0.3 m/s^2) at frequency 179 Hz (Fig. 7, Fig. 8). Furthermore, it was observed that comparable output powers were extracted from two perpendicular vibration directions. The normalized power density for our device, defined as power/volume/acceleration^2 in [1], is as high as 1.8 kg·s/m^3, which compares favorably to 1.0×10^{-6} kg·s/m^3 and 0.013 kg·s/m^3 from [2] and [3], respectively.

CONCLUSION

A 2D electret-based energy harvesting device was fabricated with a MEMS-compatible process flow. The device was packaged as a ~1 cm^2 chip using CYTOP as an electret material and as a bonding interface between wafers. Electrical power was generated from two perpendicular vibration directions as the proof mass was driven to its resonance frequency.

In a simple test setup, a maximum output power of 32.5 nW was achieved with an external load of 17 MΩ, under a harmonic source motion with an acceleration RMS amplitude of 0.03 g (0.3 m/s^2) at a frequency of 179 Hz.

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