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Electrostatic energy harvesting device with out-of-the-plane gap closing scheme[☆]

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ABSTRACT

In this paper, we report on an electrostatic energy harvester with an out-of-the-plane gap closing scheme. Using advanced MEMS technology, energy harvesting devices formed by a four wafer stack are batch fabricated and fully packaged at wafer scale. A spin coated CYTOP polymer is used both as an electret material and an adhesive layer for low temperature wafer bonding. The overall size of the device is about 1.1 cm × 1.3 cm. At an external load resistance of 13.4 MΩ, a power output of 0.15 μW is achieved when vibration at an acceleration amplitude of 1 g (~9.8 m/s^2) is applied at a low frequency of 96 Hz. The frequency response of the device is also measured and a broader bandwidth is observed at higher acceleration amplitude.

1. Introduction

Recently, energy harvesting devices have attracted more and more attention from both academia and industry. Many micro energy harvesters have been developed based on electromagnetic [1–3], piezoelectric [4,5] and electrostatic [6–13] transduction principles due to their potential to replace batteries used in wireless sensor network (WSN) technology [14]. Based on the Faraday's law of induction, electromagnetic energy harvesting devices can generate electric power when a number turns of a coil cut across a magnetic field. The piezoelectric effect is utilized to harvest energy when piezoelectric materials are subjected to mechanical strain. The electrostatic devices typically use a variable capacitor structure, whose capacitance changes when the overlap area varies in response to an external vibration source [6–10]. As a result, induced charge moves back and forth through an external load resistance, and electric power is generated when the proof mass-spring structure resonates in response to the vibration source.

The capacitance of an ideal parallel-plate capacitor is $C = \varepsilon_r \varepsilon_0 A/g$, where ε_r is the relative permittivity of the dielectric (e.g. air), ε_0 the permittivity of vacuum, A the electrode overlap area, and g the air gap between the two electrodes. According to this equation, there is another scheme to change the capacitances in addition to the above-mentioned scheme by changing the overlap area. The capacitances can also be changed by changing the gap distance between the two electrodes of the capacitor [11,12]. This scheme can be achieved by out-of-plane vibration of the proof mass to change the air gap, as demonstrated in a prototype device [13], where a cantilever based structure was developed for an electret energy harvester, and 50 μW was harvested from an active chip size of 4.2 cm^2. However, the fabrication process of the prototype device is neither practical for mass production nor compatible to integration with wireless sensor nodes. In this paper, we will present an energy harvesting device with an out-of-the-plane gap closing scheme, which can be fabricated at wafer level. Thanks to the compatible processes, the devices may be fabricated and packaged together with the sensors and the CMOS circuits in the future.

2. Design and modeling

As shown in Fig. 1(a), the energy harvesting device consists of a four wafer stack where CYTOP polymer is used both as an electret material and adhesive layers for low-temperature wafer bonding. This device consists of a proof mass which is suspended

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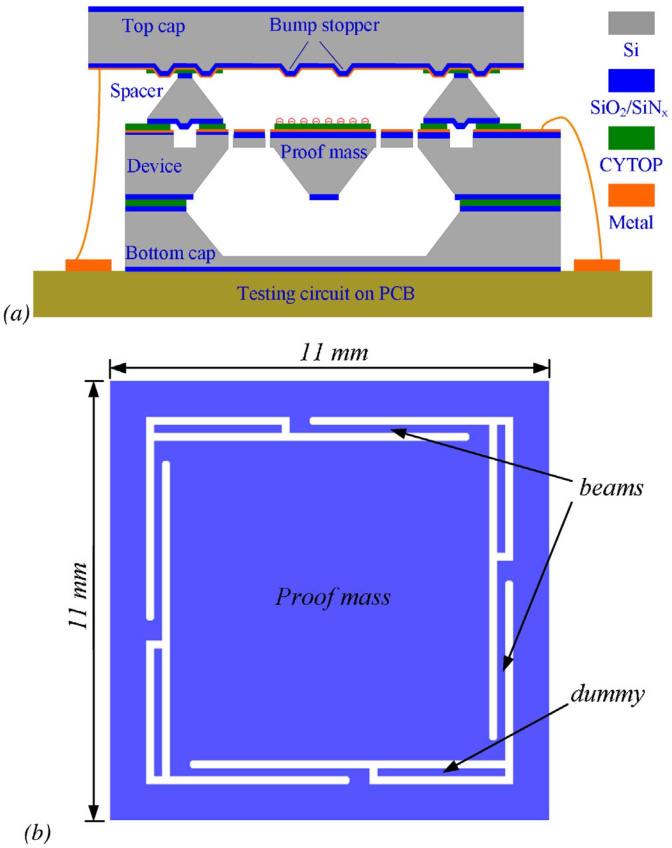

Fig. 1. (a) Cross-sectional scheme of the energy harvester. The device is composed of four wafers stack, namely, *Top cap*, *Spacer*, *Device*, and *Bottom cap*. The four wafers are bonded by at low temperature using a thermo-compression bonding technique with adhesive polymer CYTOP. (b) Layout for the device structure with proof mass suspended by beams.

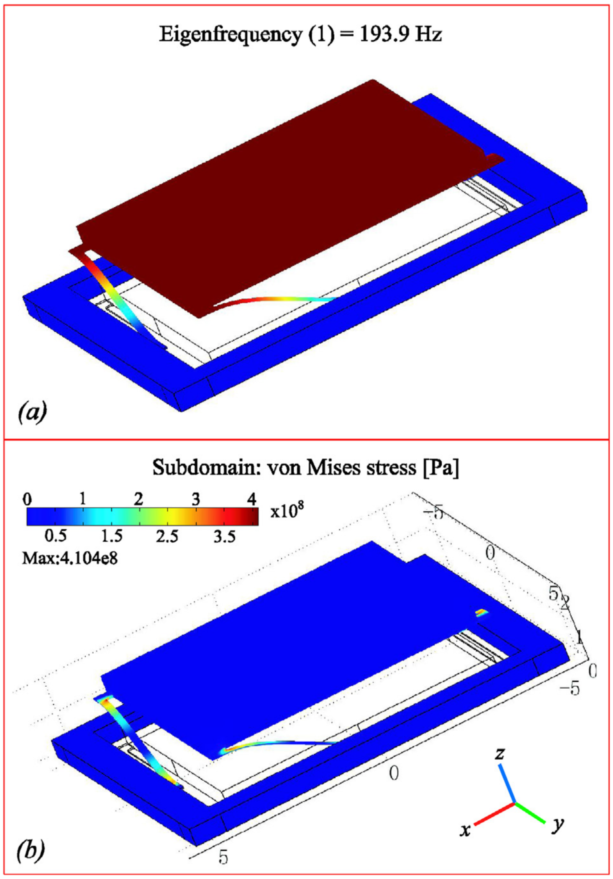

Fig. 2. Finite element modeling. (a) Eigenfrequency and eigenmode study and (b) strain–stress study. The maximum stress at the corner of the beam structure is about 400 Mpa when the *z*-axis displacement of the proof mass is 300 µm.

to a fixed frame through spring structures. When the proof mass is driven by an ambient vibration source, the capacitance between the top (on the *Top cap* wafer) and the bottom (on the *Device* wafer) electrodes changes as the gap distance varies. Therefore, induced charge moves back and forth between the two electrodes, which causes a current through an external load. Unlike the previously reported prototype energy harvesting devices [6–8,13], the device presented here is a fully packaged device which can be fabricated at a wafer level. The gap between the electrodes is well controlled and limited by bump stopper structures, which avoids the risk of the pull-in effect during the movement of the proof mass.

Fig. 1(b) shows the layout of the proof mass structure suspended by four beams. Dummy structures are designed to keep a uniform trench width in the deep-RIE silicon etching. The dummy structures improve the uniformity of the etching and high yield can be achieved during the process. Fig. 2 shows results of 3D simulations using COMSOL finite element modeling (FEM) to determine the resonant frequency of the device (Fig. 2a) and the stress distribution in the beams (Fig. 2b). It is well known that the resonant frequency f_0 of a beam-mass system is dependent on the beam geometry and the proof mass, $f_0 \propto (\mathrm{wh}^3/\mathrm{mL}^3)^{1/2}$, where m is the proof mass, w, h, and L are the width, thickness and length of the beam, respectively. By optimizing the width and the length of the beams, the resonant frequency of the device can be easily tuned from tens to hundreds hertz. Table 1 lists four devices with different geometry and the simulation results for them. The resonant frequency ranges from 50 Hz to 200 Hz here, but a lower resonant frequency down to 10 Hz is also possible using a longer beam length or a heavier proof mass. The simulation shows a maximum stress of 400 MPa across the beam when the displacement of the proof mass is 300 µm. The maximum stress is far smaller than the fracture limit of the single crystal silicon, which may be up to 7 GPa [15]. The overall device size is designed to be as small as a button battery, which makes it compatible with the state-of-the-art WSN technology.

Fig. 3 shows the principle of the energy conversion with the coupling between the mechanical and the electrical domains. The mechanical behavior of the mass-spring-damper system is governed by

$$m(\ddot{x}+\ddot{y})+c\dot{x}+kx+mg-F_t=0 \quad (1)$$

where m is the proof mass, x the relative displacement of the proof mass and y the external vibration driving the device; the term c is

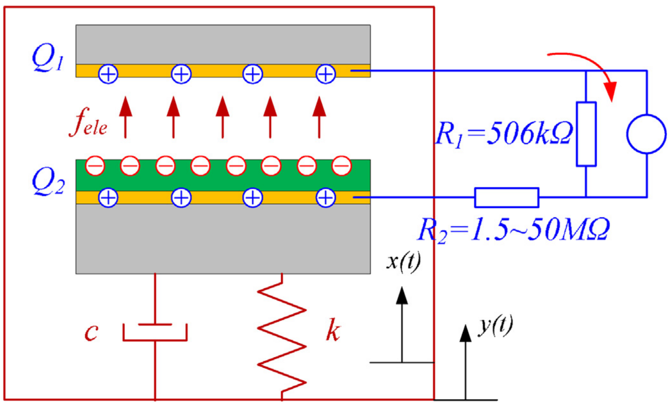

Fig. 3. Energy transduction between the mechanical system and the electric circuit with external resistance load.