DESIGN AND FABRICATION OF MEMS ELECTROSTATIC ENERGY HARVESTER WITH NONLINEAR SPRINGS AND VERTICAL SIDEWALL ELECTRETS

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Abstract: This paper reports the design and fabrication of a MEMS electrostatic energy harvester with nonlinear springs and vertical sidewall electrets based on silicon MEMS fabrication technology. A SPICE model shows that the harvester can work in a wide bandwidth of 540 Hz under white noise acceleration at a level of 76.5 x 10^{-4} g^2/Hz. The harvester is fabricated using an SOI DRIE process. The sidewall angle of our 150 µm silicon device thickness is typically 89.1^0 for the nonlinear spring and 89.7^0 for the capacitor fingers. The SiO_2/Si_3N_4 electrets layer on the sidewall capacitor finger has a thickness of about 700 – 800 nm.

Keywords: MEMS energy harvester, nonlinear springs, vertical electrets

INTRODUCTION

Traditional vibration energy harvesters are designed as linear resonating structures [1]. They have a very narrow bandwidth and operate efficiently only when the excitation frequency is very close to the resonant frequency of the harvesters. These resonant harvesters are limited in their application in real-world environments with stochastic or varying vibration spectra. There have been several attempts to overcome this limitation by tuning the resonant frequency or widening the bandwidth of the harvesters [2]. Several authors have exploited nonlinear suspensions, often created with magnets, to extend the bandwidth of the harvesters by hardening [3-5] and/or softening nonlinearities [6-8]. Electrostatic energy harvesters have been developed as a preferred choice for silicon MEMS fabrication technology [8-9]. An issue with electrostatic energy harvesters is the need for a bias or priming voltage. Electrets provide a viable means for self-bias of electrostatic energy harvesters [10], even for the vertical structures of in-plane gap closing or overlap varying transducers [11-12].

In this paper, we will present the design and fabrication of a MEMS electrostatic energy harvester with nonlinear springs and vertical sidewall electrets. The nonlinearity of springs is obtained purely by mechanical design.

DESIGN AND SIMULATION

Nonlinear spring design

Figure 1 shows the shape of a nonlinear spring at its equilibrium position. The un-deformed spring shape is constructed equal to the deformed shape of a straight clamped-guided spring with a tip displacement of y_0 [13]. The spring force vs. displacement for different y_0 is shown in Figure 2. Clearly, the behavior of the nonlinear spring is different depending on y_0. When the guided end moves in the positive direction, the spring appears increasingly stiffer. If it moves in the opposite direction, it becomes more compliant until it ultimately stiffens again at large displacements. For large enough initial displacement y_0, e.g. y_0 = 40 µm and y_0 = 50 µm in Figure 2, the force is zero at three points representing two stable local minima and one local maximum of the corresponding potential energy. By varying y_0, the nonlinear spring design can thus be varied continuously from linear to asymmetrically bi-stable. This design degree of freedom can be used to shape an energy harvester's spectrum. In particular it can be used to design for large bandwidths [8, 13].

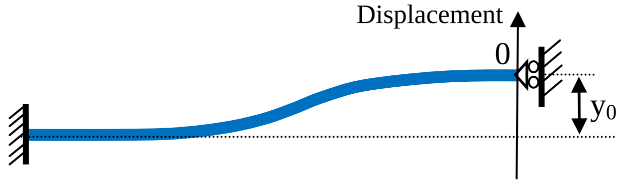

Figure 1: The shape of the nonlinear spring at its equilibrium position.

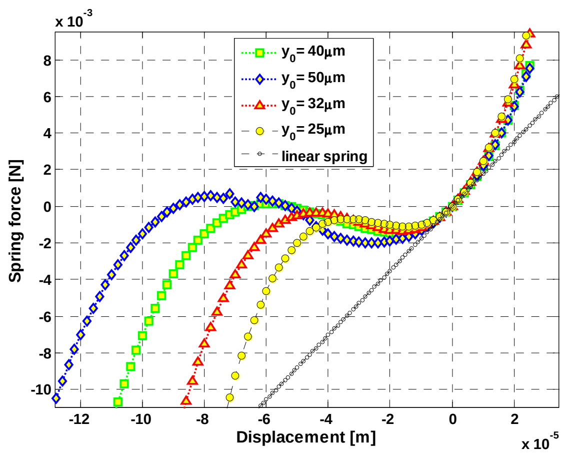

Figure 2: Spring force vs. displacement for different initial displacements y_0, calculated by the finite element method.

Energy harvester design

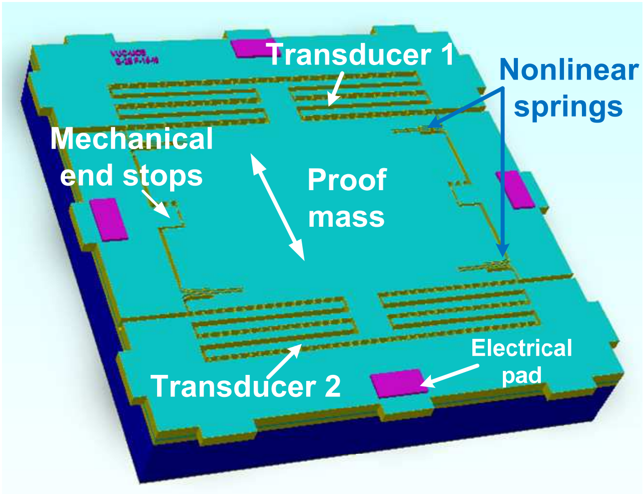

Figure 3: Schematic drawing of electrostatic energy harvester using nonlinear springs.

Table 1: Design parameters for the harvester

Symbol	Description	Value
S	Die size	10 mm x 10 mm
t	Thickness of device structure	200 µm
m	Proof mass	16.58 mg
K_1	Linear spring stiffness	770 N/m
K_2 K_3 K_4 K_5 K_6 K_7	Coefficients of the nonlinear spring stiffness	2.43×10^7 Nm^{-2} 1.34×10^{11} Nm^{-3} 8.62×10^{14} Nm^{-4} 5.03×10^{19} Nm^{-5} 5.24×10^{23} Nm^{-6} 1.68×10^{27} Nm^{-7}
f_0	Resonant frequency at very small acceleration	1080 Hz
b	Damping coefficient (estimate)	7.5×10^{-4} Nms^{-1}
g_0	Capacitor gaps	15 µm
x_{01}	Overlap, transducer 1	22 µm
x_{02}	Overlap, transducer 2	100 µm
N	Number of capacitor pairs per transducer	315
C_{01}	Transducer 1 capacitance	1.64 pF
C_{02}	Transducer 2 capacitance	7.43 pF

The electrostatic energy harvester using nonlinear springs is designed to work in a wide vibration frequency range of 400 Hz – 1000 Hz at sufficiently high levels of acceleration. Figure 4 shows the schematic drawing of the device. It is an in-plane overlap varying type with two asymmetric transducers. To increase the coupling of the energy harvester, there is a large number of electrodes on each transducer. The device layout is fit within a 1-cm^2 area. Because the aspect ratio of deep reactive ion etch (DRIE) and the vertical sidewall electrets could potentially be affected by the device thickness, the prototypes are made with a variety of device thicknesses (125 µm, 150 µm and 200 µm). The prototypes are also designed with variety of initial displacements y_0 (25 µm, 32 µm, 40 µm and 50 µm). Typical parameters of the energy harvester with y_0 = 40 µm is shown in Table 1.

We built a lumped model for SPICE simulation as in our previous works [7-8] to simulate the harvester's responses under sinusoidal accelerations and white noise accelerations. Figure 5 shows the response of the harvester (y_0 = 40 µm) under the increasing and decreasing frequency sweeps at constant acceleration amplitudes of 1 *g* and 1.2 *g*. The softening spring effect is clearly exhibited with the widening frequency response for decreasing frequency sweeps. The output power spectral density (PSD) under white noise acceleration is shown on Figure 6. At the white noise level of 76.5×10^{-4} g^2/Hz, a wide bandwidth of about 540 Hz is obtained.

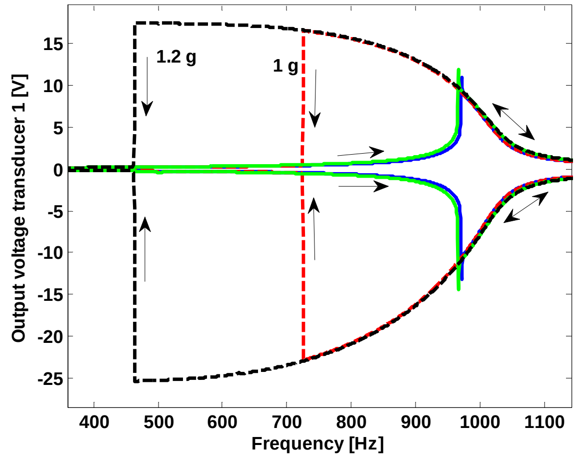

Figure 4: The increasing and decreasing frequency sweeps for many acceleration amplitudes. The bias is 150V, the load resistor of transducer 1 and transducer 2 is 20 MΩ and 21.2 MΩ respectively.

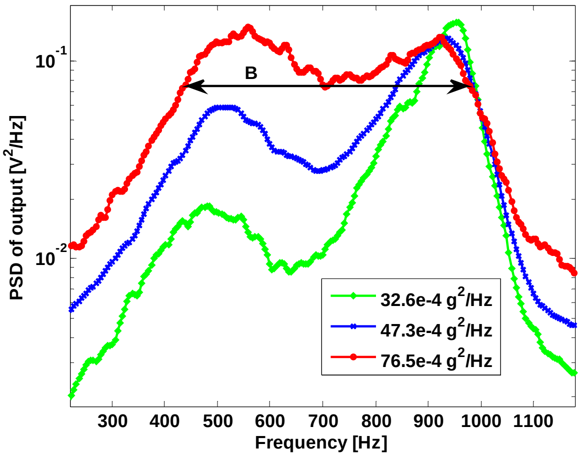

Figure 5: PSD of output voltage for few values of the white noise acceleration PSD.

FABRICATION

Fabrication process

The fabrication process aims to achieve high aspect ratio Si device structures by DRIE on silicon on isolator (SOI) wafers and SiO_2/Si_3N_4 electret layer on the vertical sidewalls of the capacitor fingers. The harvester is fabricated on 6 inch SOI wafers with 125 µm, 150 µm or 200 µm device layer thickness, 2 µm buried oxide and 500 µm substrate thickness. The process starts with deposition of titanium (Ti) for the electrical bonding pads. Ti is selected due to its high melting temperature (1668^{0}C) so that it can be allowed in the furnace for oxidation and low pressure vapor chemical deposition (LPVCP) in later steps. The Ti layer is then wet etched using Hydrogen peroxide plus a few percents of Ammonium hydroxide (step 1). In step 2, 200 - 300 nm silicon nitride (Si_3N_4) is deposited by LPCVD method as a passivation layer for local oxidation of silicon in later step. In the next step, the wafers are coated by spinning a thick SPR 220-7 photoresist (about 10 – 11 µm at 1800 revolutions per minute) as a mask for DRIE. In the lithography step, a multiple exposure process is used to avoid cracking of the thick photoresist in the development step. The wafers are then DRIE etched in a Surface Technology Systems Advanced Silicon Etch equipment. The (SF_6 + O_2) gas in the DRIE process will etch the thin Si_3N_4 layer and then the Si device layer. The etching process stops on the buried oxide layer (step 3).

The wafers are then thermally oxidized at 1000^{0}C to grow about 500-nm silicon dioxide on the sidewalls for the electret layer. Only the silicon on the sidewall is oxidized, since the silicon on the topside is passivated by Si_3N_4 on the topside (step 4). The Si_3N_4 is then subsequently removed using 160^{0}C hot phosphoric which has a good selectivity of etching Si_3N_4 over SiO_2 and Si (step 5). To make a thin Si_3N_4 layer on the SiO_2 forming a suitable structure for the sidewall electrets, a 300 – 400 nm Si_3N_4 layer is deposited by LPCVD (step 6) and subsequently removed from the top structure by an anisotropic plasma etch (step 7). The wafers are then DRIE etched from the backside. To etch the 500-µm silicon of the substrate layer, the wafers need to be bonded on a handle wafer using cool grease which is a high thermal conductivity material. As a mask for DRIE of the substrate, the thick photoresist is again used. The post-bake step lasts much longer (from 8 to 10 hours) to increase the selectivity of photoresist mask (step 8). Since the SiO_2 on the vertical sidewall is protected by the Si_3N_4 layer, Buffered Hydrofluoric is used to etch the buried oxide layer to release the proof mass.

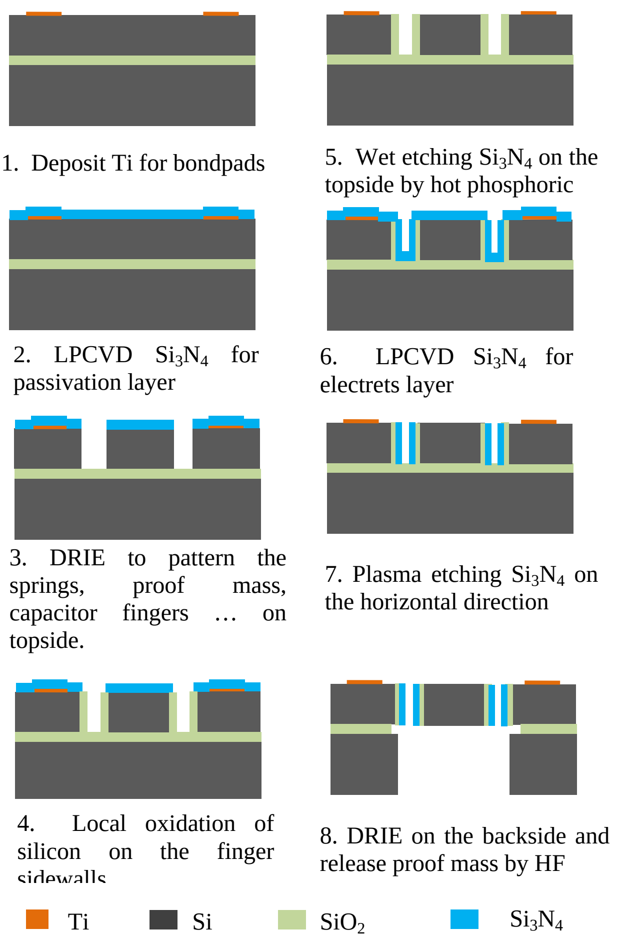

Figure 6: Fabrication process for MEMS electrostatic energy harvester with nonlinear springs and vertical sidewall electrets.

Fabrication results

Figure 8 shows the picture of the harvester die after fabrication. The backside view of the harvester with the nonlinear spring and the capacitor fingers is shown in Figure 9. Due to the non-uniform etching in the DRIE process – the fastest etching is near the rim of the wafer and gradually reduces towards the center. The sidewall profile of the nonlinear springs is somewhat different from die to die, depending on its position on the wafer. A typical sidewall angle of a nonlinear spring is about 89.1^0 for 150-µm Si device thickness. Figure 10 shows the cross-section view of the capacitor fingers. A profile angle of 89.7^0 is observed in this situation. The SiO_2/Si_3N_4 electret layer on the sidewall finger has a thickness of about 700 – 800 nm (Figure 11).

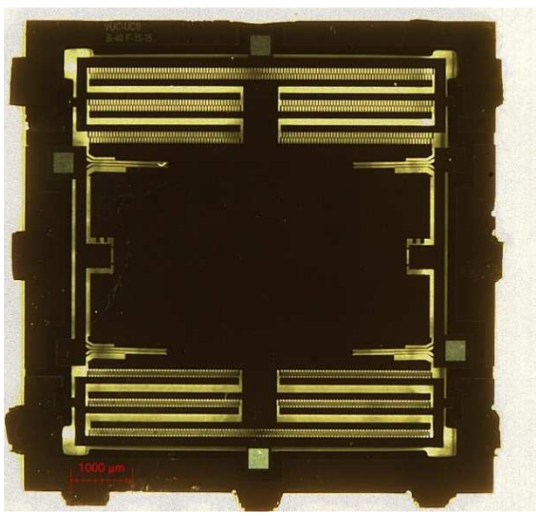

Figure 7: The picture of the harvester after fabrication

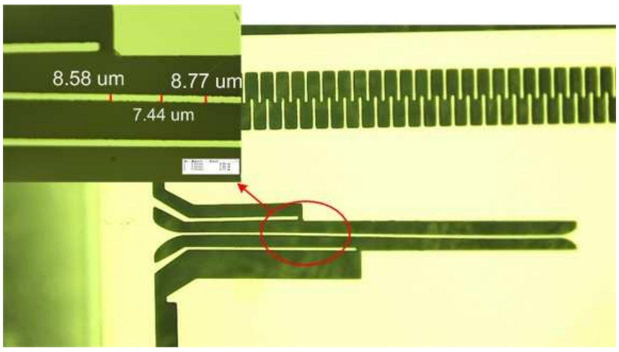

Figure 8: The back side view of the nonlinear spring and the capacitor fingers.

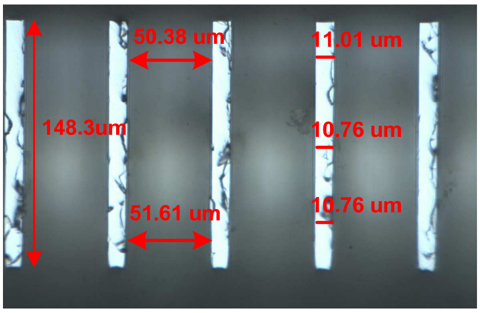

Figure 9: The cross-section view of the capacitor fingers.

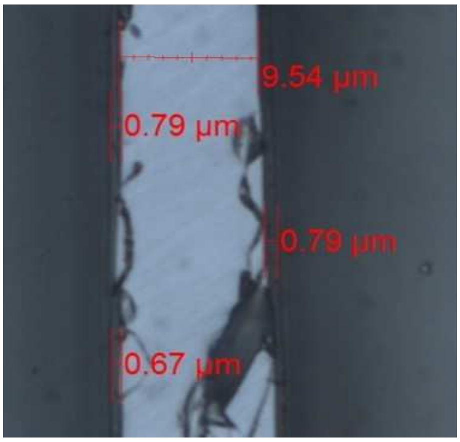

Figure 10: The cross-section view of a capacitor finger with SiO_2/Si_3N_4 electret layer.

CONCLUSION

We have presented the design and fabrication of a MEMS electrostatic energy harvester with nonlinear springs and vertical sidewall electrets based on SOI DRIE fabrication technology. Simulations indicate that a wide bandwidth of 540 Hz can be achieved by this design under white noise acceleration at a level of 76.5 $\times$ 10^{-4} g^2/Hz. The harvester is fabricated using an SOI DRIE process. The sidewall angle of our 150 µm silicon device thickness is typically 89.1^0 for the nonlinear spring and 89.7^0 for the capacitor fingers. The SiO_2/Si_3N_4 electret layer on the sidewall capacitor fingers has a thickness of about 700 – 800 nm. Charging of the vertical sidewall SiO_2/Si_3N_4 electrets and characterization of the nonlinear-spring energy harvester will be pursued in the future.

ACKNOWLEDGEMENT

The authors grateful thank to Sia Parsa (Marvell Nanolab) and Antwi Nimo (IMTEK) for the useful and stimulating discussion on the fabrication. This work is supported by The Norwegian Centre for International Cooperation in Higher Education (SIU) contract no. MNA-2008/10004 and the Research Council of Norway (RCN) Grant no. 191282. The devices were fabricated at the U.C. Berkeley nanofabrication facility.

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