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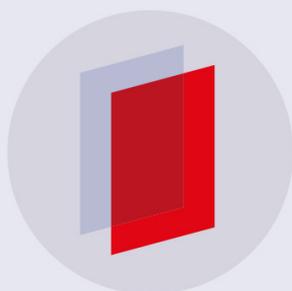
Non-Linear Vibration Electret-Harvester with Optimized Curved Beam for Low-Frequency Operation

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NON-LINEAR VIBRATION ELECTRET-HARVESTER WITH OPTIMIZED CURVED BEAM FOR LOW-FREQUENCY OPERATION

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Abstract In this study, we report the design and fabrication results of an optimized curved beam structure for low frequency, under one-hundred Hz, and non-linear operation of MEMS (Micro-Electromechanical Systems) vibration energy harvester. The optimization procedure for shape and dimension of the curved beam were established combining a FEM and a numerical analysis. Simulated curved beam with bi-stable motion was evaluated for wide bandwidth operation of a vibration energy harvester and preliminary fabrication process was confirmed.

1. Introduction

Wireless sensor nodes (WSNs) become more important to monitor environmental parameters of human activities [1]. A typical WSN consists of many components e.g. sensors, integrated circuit, power management component, and battery. The battery is the largest problem for the spreading of WSNs. The energy harvesting technologies are expected to convert variety of environmental energy to electrical energy. We focused on vibration energy sources generated from a motor rotation and industrial equipment. It is difficult to apply typical resonant type energy harvester for environmental vibrations, because these vibrations have low frequency spectrum under 100 Hz and vibrate irregularly. In our previous device, a linear resonator structure with silicon-based MEMS (Micro Electromechanical Systems) processing was demonstrated [2]. The high mechanical quality factor of silicon MEMS structure is not only advantageous for sensors and actuators but also for energy harvesting devices for real vibration sources. In order to utilize the irregular vibration sources, we developed a bi-stable spring by MEMS fabrication [3]. The spring can collect energy from random vibration sources by using its nonlinearly. Most bi-stable harvesters are developed and studied at the mesoscale [4], but not at the MEMS scale. We reported the MEMS type bi-stable spring with curved parallel leaf spring and the combination of bi-stable and linear spring structure for low acceleration operation [5]. In this study, we established the optimization method by using the combination of two simulation software for our targeted applications.



2. Simulation and modelling of bi-stable spring

The mesoscale bi-stable spring is usually realized by applying an axial compression force to a clamped-clamped beam. However, it is difficult to apply such a force on MEMS devices. Thus, we investigate a bi-stable phenomenon in an initially curved beam design of a MEMS structure with various parameters. Figure 1 shows a half beam model of the proposed design in FEM analysis software (ANSYS workbench R17.0). The left-end is the clamped point and the right-end is a guided point for the half model. The snap-through force of the bi-stable spring is affected by the beam shape (*width*) and the initial deflection of the guided point (*amplitude*).

Figure 2 shows design optimization procedure by using ANSYS and a numerical simulation software (MATLAB2017a). By applying initial parameters e.g. beam length, width and deflection amplitude generated by MATLAB, ANSYS calculates the non-linear spring stiffness as a function of the deflection. Then the computed non-linear stiffness is automatically transferred to MATLAB SIMULINK where the frequency response of the harvester is computed when a 120 mg mass is attached between two non-linear springs. From the frequency response corresponding to a frequency sweep-up operation, the integrated area of the beam vibration amplitude and the frequency is output and can be used as an index of the bandwidth. SIMULINK also computes and outputs the number of equilibrium points as an index of bi-stability. An iterative and automatic simulation is performed to find the optimal design.

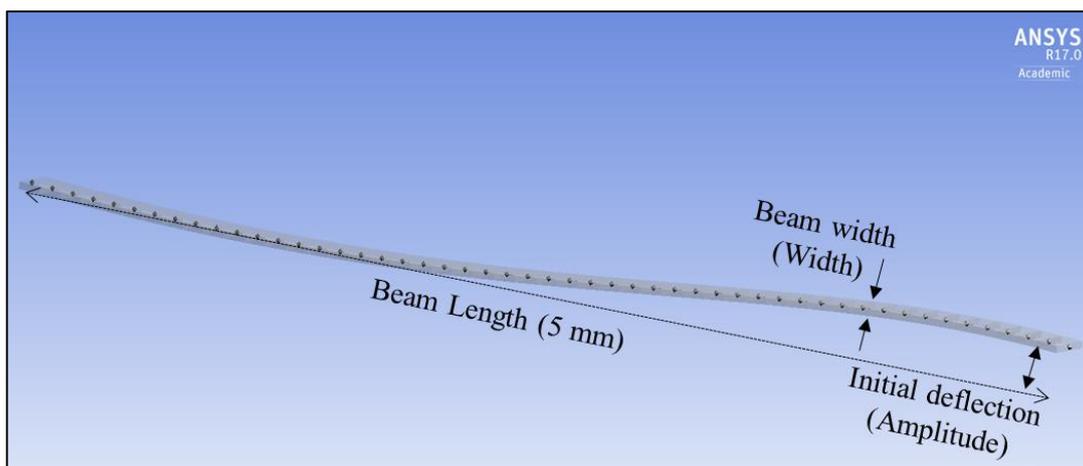


Figure 1. The simulation model of proposed curved beam in FEM software

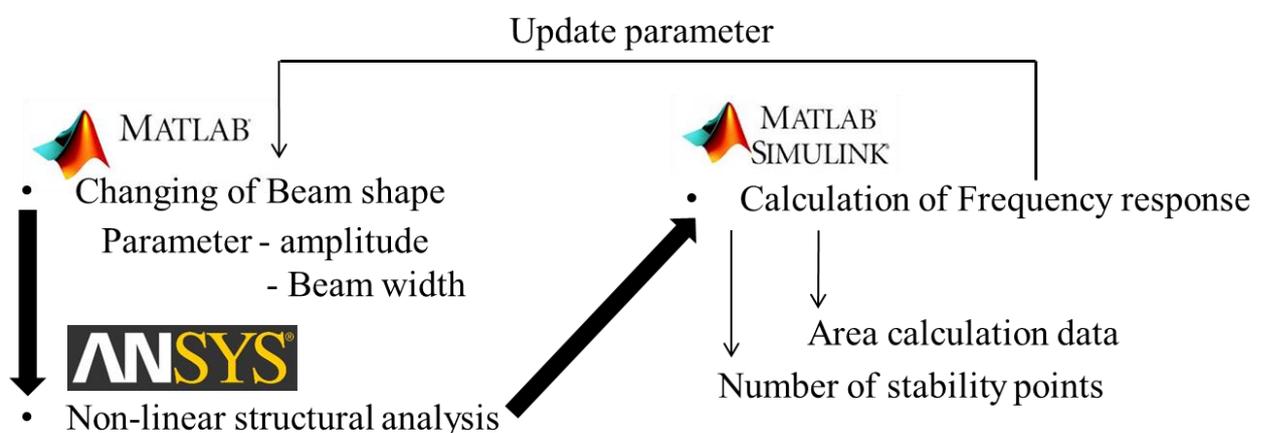


Figure 2. Computing for optimized design with ANSYS and MATLAB software

3. Simulation results

We set a target acceleration at $1 G_{p-p}$ for bi-stable motion. The considered beam widths range from 20 to 50 μm with 5 μm step, the deflection amplitudes range from 50 to 500 μm with 50 μm step. The other parameters e.g. the total beam length of 10 mm, the beam thickness of 200 μm were fixed. The integrated area of the frequency response is shown in Fig. 3. The area size indicates easiness of bi-stable motion on specific acceleration of 1 G. The 150 μm amplitude and 30 μm width correspond to the peak value of the area. Figure 4 shows the number of equilibrium points in the nonlinear spring. The bi-stable motion has three equilibrium points (two stable, one unstable), and corresponds to the case where the spring can hold two stable different shapes after any external force is unloaded. The blue, where only one equilibrium exists corresponds to a mono-stable behaviour. By a combination of both simulation results, the optimized dimension is obtained as 150 μm in amplitude and 30 μm in width.

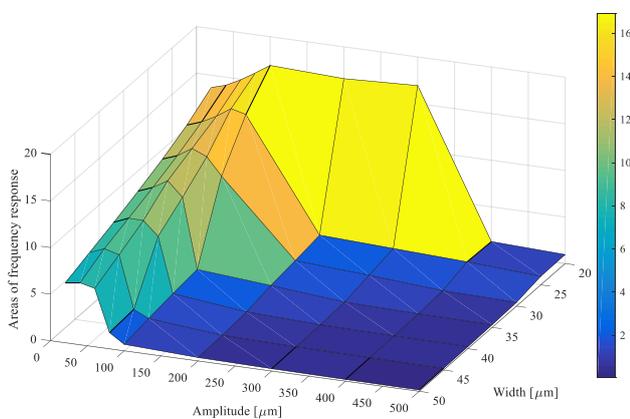


Figure 3. Integrated area of frequency responses for amplitude vs. width.

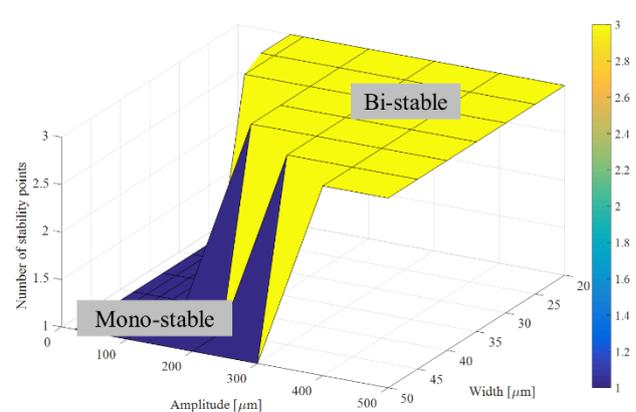


Figure 4. Number of equilibrium points for amplitude vs. width.

4. MEMS fabrication for the proposed beam

We fabricated the proposed curved beam in silicon MEMS process. The designed beam are included in a the electret-part of an electrostatic energy harvester. Figure 5 shows the fabrication process flow of the electret mass with curved spring. We used 200 μm thickness, 4 inch diameter single crystal silicon as a starting material. (1) The SiO_2 film is formed and patterned for mass and spring shape. (2-3) Aluminium film is deposited and patterned for electrodes. (4) The CYTOP for electret part is spin-coated and patterned. (5) Finally, the spring-mass structure is fabricated by Deep-RIE. The completed devices were picked up from substrate. Figure 6 shows fabricated device wafer (Fig. 6a), the close-up view of single chip (Fig. 6b) and the curved beam (Fig. 6c). The proof mass has a size of $12 \times 10 \text{ mm}^2$. The curved beam has a width of 30 μm and an initial deflection of 150 μm .

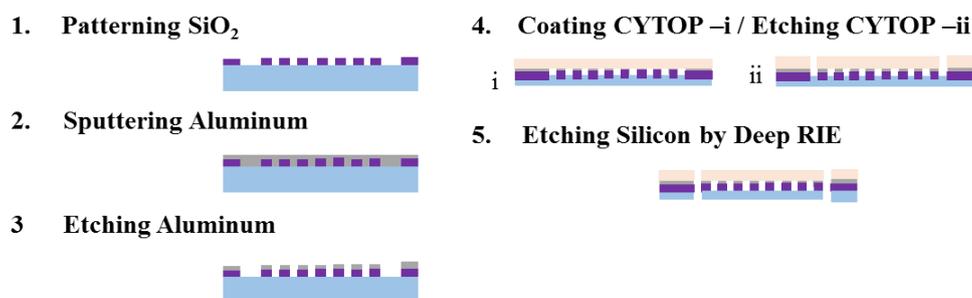


Figure 5. Processing flow of electret parts for the harvester

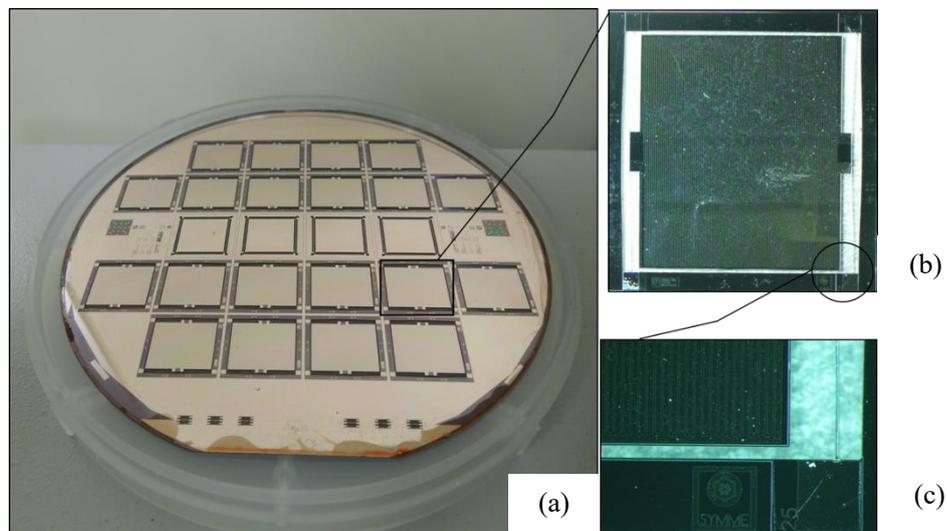


Figure 6. (a) Completed wafer after processing (b) The fabricated electret parts
(c) Enlarged parts in the edge of the spring

5. Conclusion

We established the combination analysis method that can be effectively used to find the optimal geometry of a bi-stable spring. Samples for harvesting are being fabricated for experimentally verifying the proposed concepts.

Acknowledgement

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