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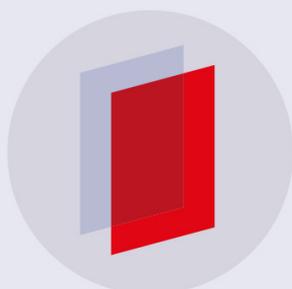
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Comparison of Five Topologies of Cantilever-based MEMS Piezoelectric Vibration Energy Harvesters

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Abstract. In the realm of MEMS piezoelectric vibration energy harvesters, cantilever-based designs are by far the most popular. Despite being deceptively simple, the active piezoelectric area near the clamped end is able to accumulate maximum strain-generated-electrical-charge, while the free end is able to accommodate a proof mass without compromising the effective area of the piezoelectric generator since it experiences minimal strain anyway. While other contending designs do exist, this paper investigates five micro-cantilever (MC) topologies, namely: a plain MC, a tapered MC, a lined MC, a holed MC and a coupled MC, in order to assess their relative performance as an energy harvester. Although a classical straight and plain MC offers the largest active piezoelectric area, alternative MC designs can potentially offer higher average mechanical strain distribution for a given mechanical loading. Numerical simulation and experimental comparison of these 5 MCs ($0.5 \mu\text{AlN}$ on $10 \mu\text{Si}$) with the same practical dimensions of $500 \mu\text{m}$ and $2000 \mu\text{m}$, suggest a cantilever with a coupled subsidiary cantilever yield the best power performance, closely followed by the classical plain topology.

1. Introduction

Cantilever-based topologies are the incumbent design of choice within the field of piezoelectric vibration energy harvesting (VEH), especially for MEMS harvesters [1]. This is primarily because the active piezoelectric area near the clamped end is able to accumulate strain energy, while the free end can house a stiff proof mass without significantly compromising the effective area of the piezoelectric generator since it experiences minimal strain anyway.

While a number of different examples of micro-cantilever (MC) designs for MEMS piezoelectric vibration energy harvesters have been previously explored [1], the most popular design is based on the classical rectangular plain MC topology [2] with variations in design usually driven by process constraints rather than design objectives. Nonetheless, alternative designs such as tapered cantilevers [3] have been explored in an attempt to achieve equal distribution of strain along the cantilever length. This paper demonstrates that systematic modifications in the specific topology of piezoelectric MEMS cantilever energy harvesters can result in significant differences in the output power response. Five different cantilever-based topologies are numerically and experimentally compared in order to rank the effectiveness and power performance of each design for the purpose of VEH.

2. Apparatus

Five different topologies implemented using an aluminium nitride (AlN)-on-silicon micromachining process with the same overall practical dimensions (2 mm by 0.5 mm) were investigated,



as shown in figure 1, in an attempt to compare their relative power performance for vibration energy harvesting. Apart from the plain and the tapered designs, the other topologies included: a primary MC coupled with a subsidiary MC based on [4], a MC with etched holes throughout the surface as a means of stiffness reduction inspired by [5], as well as a MC formed by multiple parallel thin beams strongly coupled at the end.

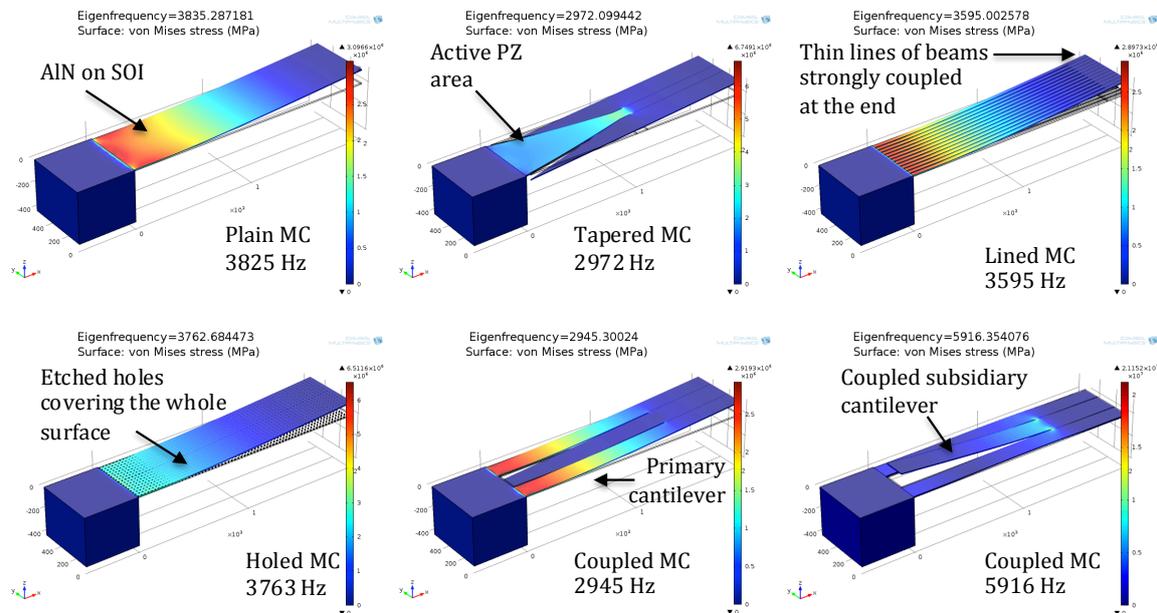


Figure 1. Designs of the five topologies of micro-cantilevers (MC), with the relevant resonant frequency information. Overall dimensions are the same: 2000 μm length and 500 μm width.

A summary of the 5 topologies and the employed acronyms are listed as the following,

- MCI: plain micro-cantilever (MC) with 2000 μm length and 500 μm width
- MCT: tapered MC with trapezium of 500 μm and 100 μm sides, and 1000 μm height.
- MCL: lined MC with 30 μm wide lines separated by 10 μm gap.
- MCH: holed MC with 5 μm square holes separated by 25 μm gap in both length and width.
- MCC: coupled MC with 1375 μm long and 180 μm wide subsidiary cantilever coupled onto a primary cantilever with 150 μm wide side beams.

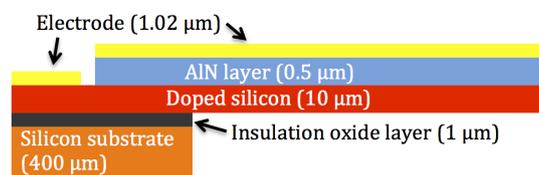


Figure 2. Stack of material used in the fabrication of the MEMS piezoelectric micro-cantilevers.

The experimental prototypes were manufactured using the material stack shown in figure 2 and the micrographs of the fabricated devices are presented in figure 3. For topologies with fine design features such as the MCL and the MCH, piezoelectric area is further reduced due to the need to provide clearance between the silicon, piezoelectric and the metal layers as well as over-etch of some of the small features during fabrication. Therefore, the actual sandwiched piezoelectric area is noticeably smaller than the silicon area for these designs.

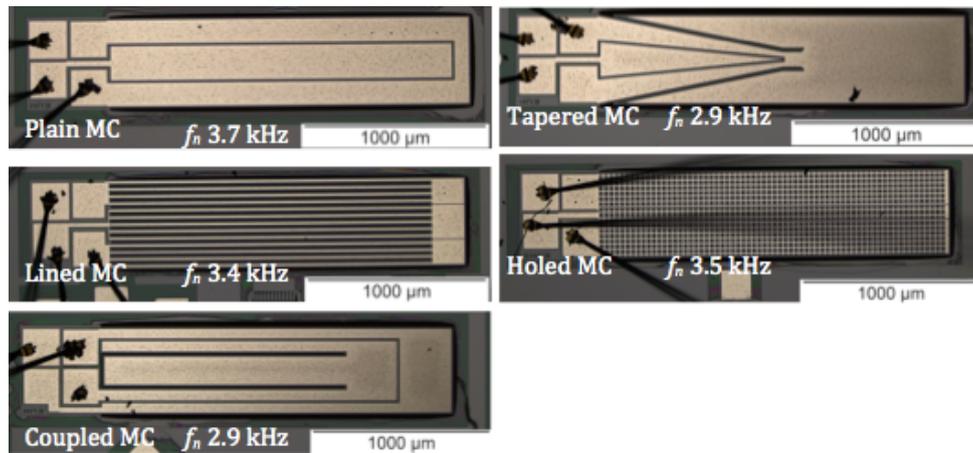


Figure 3. Micrographs of the 5 micro-cantilevers

3. Result

3.1. Simulation and calculation

COMSOL finite element analysis was used to evaluate the strain distribution of the 5 designs for a given loading. Figure 4 illustrates the strain distribution across the length of the active region of the MCs. The average strain of this distribution is shown in figure 5, demonstrating that the plain MCI fares the worst in terms of accumulating mechanical strain energy. It can be noted that MCT is the only one to have approximately constant strain distribution long the active piezoelectric area, while all others have a steady decreasing strain along the cantilever length.

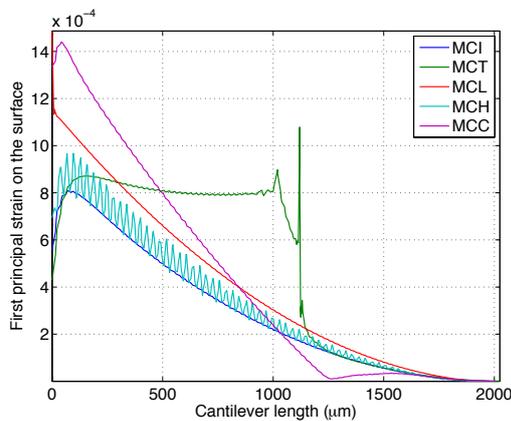


Figure 4. Strain distribution across the length of the 5 micro-cantilevers when subjected to a static loading of $1.5E-3$ N. The origin of the x-axis is the clamped end.

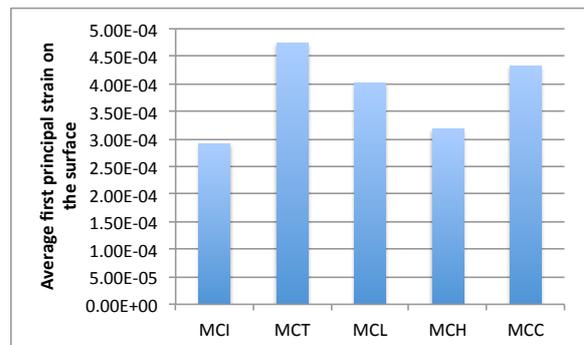


Figure 5. Average strain across the active transducer area of the cantilever length for the 5 micro-cantilevers when subjected to a static loading of $1.5E-3$ N. While MCI ranks the lowest on this metric, it has the largest active piezoelectric transduction area.

While mechanical strain maximisation across the cantilever surface for a given input forcing is an important design metric, there is a trade-off involved in sacrificing the active piezoelectric area to accommodate the additional design complexity. Although all of the 4 alternative MC topologies are able to experience a higher mechanical strain for a given mechanical loading, the plain MC have by far the largest active piezoelectric area as shown in figure 6.

Along with the strain information extracted from COMSOL, electrical charge generated and peak power output can be estimated by equations 1 and 2 respectively.

$$q = d_{31}\varepsilon_{av}Ea_{pz} \quad (1)$$

where, q is the charge generated, d_{31} is the piezoelectric charge constant in the 31 mode, ε_{av} is the average strain experienced by the piezoelectric transducer, E is the elastic modulus of the piezoelectric material and a_{pz} is the active piezoelectric area.

$$P = \frac{\omega q^2}{C} \quad (2)$$

where, P is the peak power generated, ω is the frequency and C is the capacitance of the piezoelectric layer. Figure 7 shows the power predications for the 5 MCs when subjected to the same loading. MCH is predicted to perform the worst despite having a relatively high average strain, while MCC is estimated to perform the best and is closely followed by the classical MCI design. Therefore, the systematic optimisation of the power performance is primarily a compromise between the average mechanical strain and the active piezoelectric area.

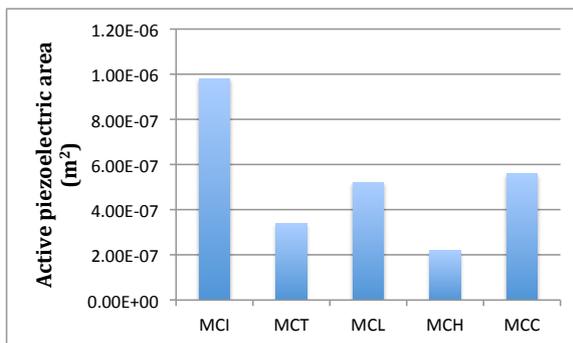


Figure 6. Calculated active piezoelectric area for the 5 micro-cantilevers when subjected to a static loading of $1.5\text{E-}3$ N.

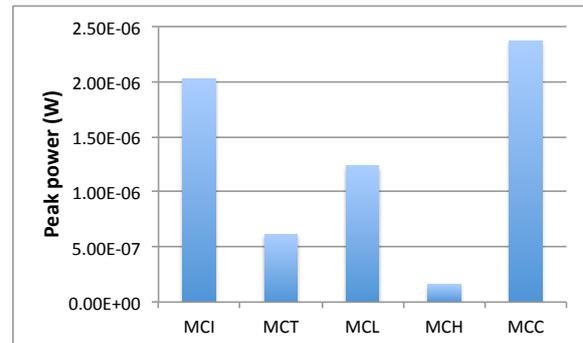


Figure 7. Calculated peak power for the 5 micro-cantilevers when subjected to a static loading of $1.5\text{E-}3$ N.

3.2. Experiment

Experimental verification was carried out by electrically driving the piezoelectric transducers and measuring the mechanical motion by a laser doppler vibrometer (figure 8) to characterise the electrical-to-mechanical responsiveness, as well as exciting the prototypes on a mechanical shaker and measuring the voltage output across matched resistive loads at their resonant frequencies (figure 9) to determine the mechanical-to-electrical responsiveness.

The experimentally measured power output at 3 g of input acceleration for the 5 devices are: 1.01 nW for MCI, 0.45 nW for MCT, 0.7 nW for MCL, 0.03 nW for MCH and 1.35 nW for MCC. From figure 9, power values for MCH driven at lower acceleration levels were experimentally not measurable. The matched load resistance and natural frequencies for the various prototypes are: 0.3 M Ω at 3688 Hz for MCI, 1 M Ω at 2938 Hz for MCT, 0.6 M Ω at 3375 Hz for MCL, 1.2 M Ω at 3531 Hz for MCH and 0.6 M Ω at 2891 Hz for MCC.

The experimental results agree with the simulated predication of a relatively superior responsiveness from the MCC, closed followed by the MCI. MCH fares the worst, with MCL and MCT taking the 3rd and 4th positions respectively. The precise order of this power performance ranking is in agreement with the simulated results. Additionally, the MCC further benefits from

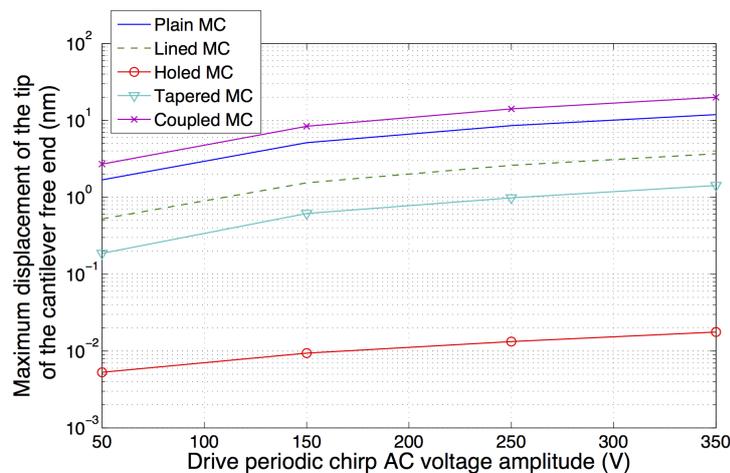


Figure 8. Laser vibrometer measured electrical-to- mechanical response (displacement). The coupled MC yielded the largest response.

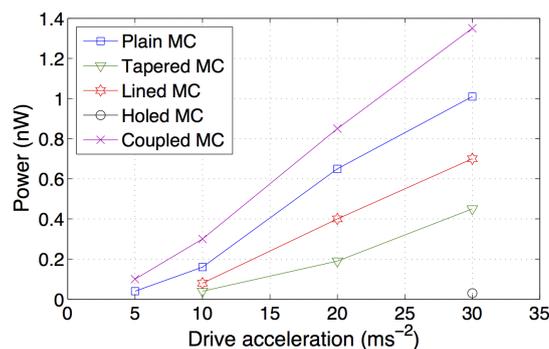


Figure 9. Experimentally measured power response of the mechanical-to-electrical response of the 5 MC. MCC produced the highest power responsiveness, with MCH being the worst.

dual frequency band sensitivity (from both its primary and subsidiary cantilevers), whereas the other 4 MCs only possess a single fundamental transverse mode.

Conclusion

Five cantilever-based topologies have been investigated for the purpose of vibration energy harvesting. Coupled micro-cantilevers ranked the highest in terms of power performance and was closely followed by the classical plain cantilever topology. While the tapered, lined and holed cantilevers all experienced higher average mechanical strain than the plain cantilever for a given loading, they performed worse due to the smaller active piezoelectric area. Therefore, a compromise is required while optimising designs between the maximisation of mechanical strain energy accumulation and the total active piezoelectric area.

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