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An Umbrella-Shaped Topology for Broadband MEMS Piezoelectric Vibration Energy Harvesting

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Abstract. While cantilever topologies offer high power responsiveness for MEMS vibration energy harvesting (VEH), they are less robust than multiply clamped or membrane topologies. This paper attempts to address this topological optimisation dilemma by attempting to achieve both high power density and robustness. The proposed umbrella-shaped topology constituents of a single central anchor while the membrane area extends outwards and is further enclosed by a ring of proof mass. Implemented on a 0.5 µm AlN on 10 µm doped Si process, a fabricated device (121 mm^2 die area) recorded a peak power of 173 µW (1798 Hz and 0.56 g). The normalised power density compares favourably against the state-of-the-art cantilever piezoelectric MEMS VEH, while not sacrificing robustness. Furthermore, this device offers a broadband response, and it has experimentally demonstrated over 3 times higher band-limited noise induced power density than a cantilevered harvester fabricated using the same process.

1. Introduction

The development of MEMS vibration energy harvesting (VEH) has the potential to provide an on-chip self-sustaining power solution for microelectronics and embedded systems. Applications include autonomous sensing for tracking or condition monitoring, wearable consumer devices and medical implants. Piezoelectric cantilever topologies [1] has been a popular design of choice due to the relatively high energy density and scalability of piezoelectric transducers, as well as the good power responsiveness [2] of cantilevered devices towards an input excitation.

However, cantilevers are also easily prone to failure as they attain relatively large travel and accumulation high stress concentration around the anchored edge. Therefore, for practical applications, impulse or high acceleration fracture failure of MEMS cantilevers are of a major concern, especially given the brittle nature of silicon. While clamped-clamped beams [3], membrane devices [4] and other multiply anchored topologies offer greater robustness, their power responsiveness is typically far from what cantilevers can achieve. This paper reports a new umbrella-shaped topology for MEMS VEH, which aims to address the robustness issue of cantilevers while not compromising on power responsiveness.

2. Design and device

The proposed design, illustrated in figure 1, is made up of a circular centre anchor with a ring of membrane extending outwards and it is further enclosed by a continuous proof mass. This inverted membrane structure utilises the wafer die as the proof mass, which allows the device to house a relatively large proof mass as compared to other MEMS topologies of similar dimension.

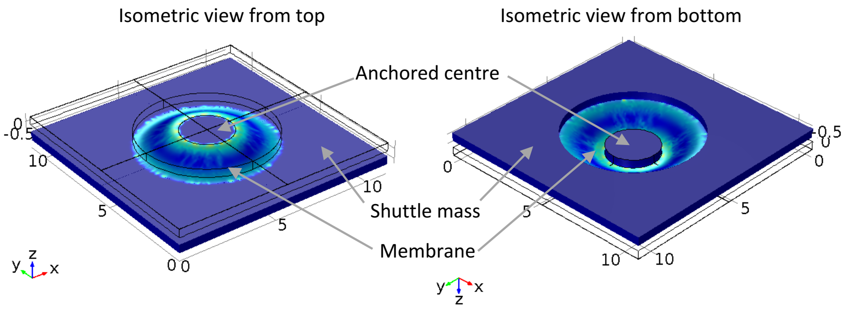

Figure 1. Finite element model view of the proposed umbrella-shaped oscillatory device for MEMS VEH. The device is an inverted membrane with the anchor at the centre.

Devices were fabricated using an AlN-on-SOI process outlined in figure 2. The centre anchor measured 1.25 mm in radius, the membrane had a radius of 3.25 mm measuring from the centre point of the anchor and the die itself is a square of 11 mm. The un-etched regions of substrate serve as the anchor (inner region) and shuttle (outer region) while the etched regions of the substrate act as the flexural link.

Figure 3 presents a micrograph of the fabricated umbrella device. Two rings of top electrodes were deposited the AlN layer in order to harness the opposing strain polarity induced during oscillation. Al wire bonds are used to route out the electrical output. A small circular metal pedestal beneath the die is used to elevate the centred anchor on a ceramic chip carrier. The die, pedestal and carrier are all held in place by an adhesive epoxy. Therefore, the centre of the harvester is fixed while the remainder of the chip vibrates as a shuttle.

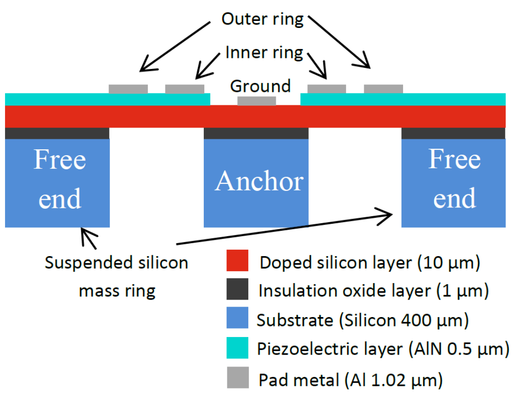

Figure 2. Cross-sectional view of the stack of material of the AlN-on-SOI MEMS process.

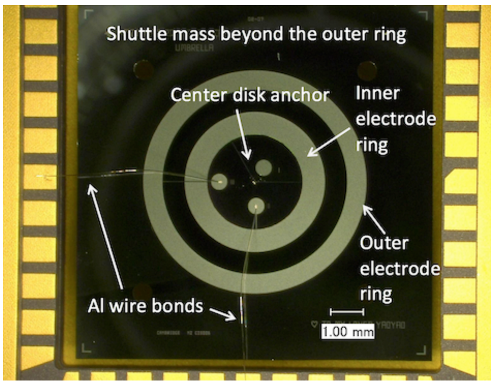

Figure 3. Micrograph of the umbrella-shaped MEMS AlN vibration energy harvester within a leadless chip carrier.

3. Results

The umbrella devices were characterised on a mechanical shaker both in air and in a vacuum chamber. The results were compared with previous data from a comparable membrane device [4] and a cantilever device [2] (not shown here). FEA simulation showed that both the umbrella and membrane devices exhibited similar stress concentration factor, while the cantilever device recorded a higher value as summarised in table 1. Coupled with the high responsiveness of cantilevers, this makes them vulnerable to exceeding the failure stress limit for silicon, whereas umbrella designs are potentially more resilient.

Table 1. FEA simulated stress concentration factor K_c (ratio of peak stress to average stress) comparison of various topologies for comparable designs.

	Cantilever	Umbrella	Membrane
K_c	2.33	1.94	1.92

Figure 4 presents the impedance matched power response in the frequency domain of the umbrella harvester at an average acceleration of 0.2 g. It can be seen that a very strong spring hardening Duffing nonlinearity can be observed, with the resonant peak bend spanning several hundreds of hertz. At this acceleration level, the Duffing resonant peaks were measured at 1390 Hz and 1546 Hz for air and vacuum cases respectively. However, the FEA simulated resonant peak was supposed to be around 500 Hz. At higher acceleration levels, the resonant peak bends towards even higher frequencies.

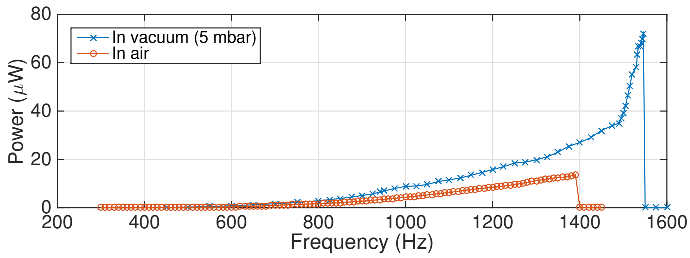

Figure 4. Frequency domain average power response of the umbrella-shaped MEMS harvester across a matched load when subjected to average acceleration amplitude of 0.2 g in both air and vacuum. Matched load in air is 100 kΩ and in vacuum is 70 kΩ.

Figure 5 shows the Duffing resonant peaks of the umbrella device in both air and vacuum. A highest peak of 173 µW was measured in vacuum at 0.56 g and 1798.4 Hz. Higher sine wave acceleration levels were not scanned due to the limitation of the small shaker system employed that was able to be accommodated into the vacuum chamber.

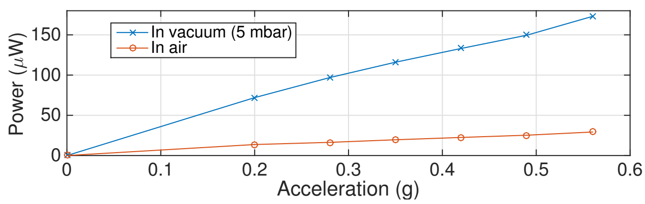

Figure 5. Average power response of the umbrella-shaped MEMS harvester across a matched load for varying levels of acceleration at the resonant peak frequency in both air and vacuum.

The reported power densities compare favourably against some of the state-of-the-art AlN-based piezoelectric cantilever MEMS VEH devices reported in the literature as shown in table 2. Furthermore, leveraging from both a lower quality factor and the nonlinear bandwidth of umbrella devices, it performed over 3 folds better than the comparable cantilever device when subjected to band-limited white noise excitation as illustrated in figure 6. Therefore, the umbrella device is able to outperform cantilevers in terms of both power density and frequency bandwidth when subjected to the same acceleration, despite being more topologically robust.

Table 2. The umbrella MEMS AlN VEH device measured in both air and vacuum, compared with other state-of-the-art cantilever-based AlN VEH devices reported in the literature.

Ref.	Power (µW)	Volume (mm^3)	Acceleration (g)	Frequency (Hz)	NPD ($\mu W\, mm^{-3}\, g^{-2}$)
In air	13.69	36	0.20	1390	9.55
In vacuum	72.0	36	0.20	1546	50.25
[5]	128	12.6	1	58	10.16
[6]	0.63	1.3	0.2	214	12.12
[7]	489	3.3	4.5	1011	7.32
[8]	165	347	0.18	155	14.68

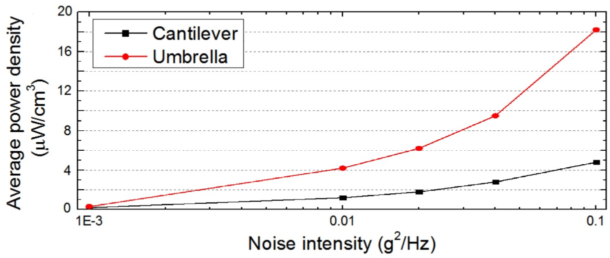

Figure 6. Power densities of comparable cantilever and umbrella-shaped devices fabricated using the same AlN-on-SOI process, subject to band-limited white noise (100 Hz to 2 kHz).

Conclusion

This paper proposed a new umbrella-shaped topology for piezoelectric MEMS VEH. The design is able to offer both the high power responsiveness advantage of cantilevers, as well as good robustness merits of multiply clamped devices. Prototypes implemented on an AlN-on-SOI process has experimentally demonstrated over 3 times higher normalised power density compared with some of the state-of-the-art AlN cantilever VEH, while also outperforming comparable cantilever devices by over 3 times when subjected to band-limited white noise. Therefore, the proposed topology offers both sufficient power output as well as robustness and reliability for practical applications.

Acknowledgement

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