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# Magnetoelastic Vibrational Energy Harvester with Enhanced Robustness

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The need to power wearable devices and wireless sensor systems increases the demand on small-scale power sources. Miniaturized cantilever-based vibrational energy harvesters (VEHs) capable of transforming energy from the mechanical domain, i.e. vibrations, into energy in the electrical domain have recently received considerable interest [1-4]. Most ambient vibrations are characterized by a low frequency range [2]. In order to tune in to the low frequencies the common approach is to increase the cantilever length and reduce its thickness, which leads to very fragile structures. This fragility generates an upper limit to the maximum acceleration at which the harvesters can operate. Furthermore, it has been previously demonstrated that the harvested power increases as the square of the acceleration [3]. Therefore, it becomes of utmost importance to develop procedures for increasing the robustness of the cantilevers. A five-step strengthening process, which consisted of a set of steps that included spray coating and a dry etching of a pattern of holes on the backside of the cantilever, proved to increase the structure robustness while at the same time reducing the resonance frequency [4].

This work presents a magnetoelastic piezoelectric-based vibrational energy harvester where a two-step and lithography-free process is implemented to increase the cantilever's robustness. This enhancing process consists of growing a layer of $SiO_2$ once the cantilever's shape has been defined, directly followed by a strip of the whole oxide layer. The entire fabrication process of the cantilevers, including the piezoelectric layer and electrodes, consists of a set of steps. First, a KOH etch is performed to define the cantilevers, Fig. 1.a, where a 3000 nm thick oxide layer is used as a mask. This layer is stripped and a 1100 nm oxide layer is grown to round the sharp corners created during the KOH etch. Then, the oxide is stripped, Fig. 1.b-c. This is followed by a deposition of the bottom electrode, piezoelectric layer, top electrode and resist, Fig. 1.d. After this, the top electrode is defined, Fig. 2.e. and the three-stack layer together with the silicon is etched through, Fig. 2.g. Then, the bottom electrode used as contact node is deposited on the backside of the low-resistivity wafer, Fig. 3.i. Finally, ferromagnetic foil is attached to both sides of the beam and two magnets are incorporated to the system, Fig. 3.g. The oxide growth in step b reduces the stress concentration at the anchoring point, which is achieved by a corner rounding mechanism based on the different growth rates of $SiO_2$ depending on the silicon crystal orientations that are revealed at the surface after the KOH definition of the beams. The rounding effect was studied by carrying out simulations using the Silvaco Athena process simulation software. Fig. 4 shows the effect of rounding the sharp corners by growing the oxide layer. The dimensions of the fabricated cantilevers are shown in Tab. 1. SEM images of a cantilever with and without the corners rounded are shown in Fig. 5 and 6, respectively.

The mean resonant frequency for the regular and enhanced cantilevers is 301.4 ± 3.0 Hz and 277.7 ± 5.9 Hz, respectively. This difference in resonant frequency is the result of different beam thicknesses due to the combination of three effects: the inhomogeneity of the KOH etching, the corner rounding oxide growth and the magnetic foil position alongside the beam. The procedure followed to test the devices was to excite them at their resonant frequency for increasing accelerations until they eventually broke. The sinusoidal signal was generated from an Agilent 33220A waveform generator and amplified by a Pioneer VSX-405RDS MkII amplifier, which is connected to a B&K Minishaker 4810, the direct excitement source for the devices. The experimental results obtained are shown in Table 2. It can be seen that the mean acceleration at which the enhanced beams broke is around twice as much as their counterparts mean value, which are 5.6g and 3.0g, respectively. This increased tolerance clearly improves both the handling of the device and the in situ operation, enabling also larger deflections in magnetoelastic VEHs.

[1] A. Erturk, et al. A piezomagnetoelastic structure for broadband vibration energy harvesting. Applied Physics Letters, 2009, vol. 94, no 25, p. 254102.
[2] L. Tang, et al. Toward broadband vibration-based energy harvesting. Journal of Intelligent Material Systems and Structures, 2010, vol. 21, no. 18, pp. 1867-1897.
[3] Kamel, T. M., et al. Modeling and characterization of MEMS-based piezoelectric harvesting devices. Journal of Micromechanics and Microengineering, 2010, vol. 20, no 10, p. 105023.
[4] F. Guido, et al. A new architecture of high performance AlN vibrational energy harvester, MNE 2016, Wien, 2016.


Figure 1. Steps followed to round the corners once the beam has been defined (a-c), three-stack and resist deposition (d).

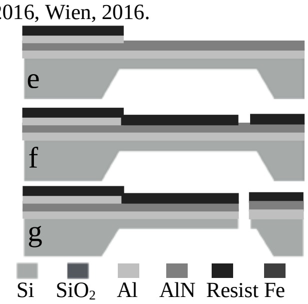


Figure 2. Steps followed to define the top electrode (e) and releasing the beam (f-g).

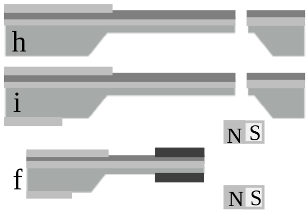


Figure 3. Beam released and bottom electrode deposition (h-i). Ferromagnetic foils and magnets are incorporated (f).

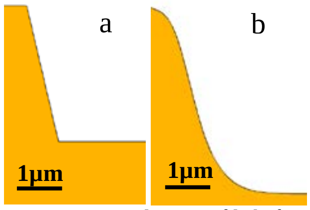


Figure 4. Cantilever profile before (a) and after (b) corner rounding simulated by Silvaco Athena software.

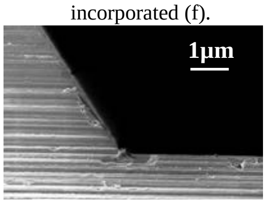


Figure 5. SEM image of cantilever without corners rounded.

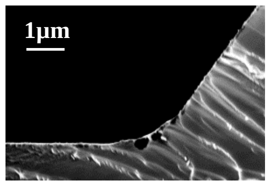


Figure 6. SEM image of cantilever after corners are rounded.

Table 1. Cantilever dimensions together with ferro magnetic foil and magnets specifications.

| | Dimensions |
|---|---|
| Length | 6.5 mm |
| Width | 6.0 mm |
| Thickness | ~ 40µm |
| Area | 39 mm$^2$ |
| Foil thickness | 150 µm |
| Foil Length | 3.25 mm |
| Magnet length | 1 mm |
| Magnet thickness | 1 mm |

Table 2. Acceleration (acc.) tolerances and resonant frequencies ($f_0$) for both regular and enhanced cantilevers.

| Enhanced | | Regular | |
|---|---|---|---|
| $f_0$ [Hz] | acc.[g] | $f_0$ [Hz] | acc.[g] |
| 269.6 | 3.3 | 302.4 | 2.4 |
| 283.0 | 2.4 | 284.5 | 3.5 |
| 291.9 | 5.1 | 302.6 | 2.0 |
| 276.7 | 7.4 | 306.2 | 3.1 |
| 264.4 | 6.1 | 299.4 | 3.1 |
| 268.6 | 7.0 | 269.9 | 3.8 |
| 285.8 | 5.5 | 310.9 | 3.5 |
| 281.3 | 8.3 | 335.5 | 2.9 |
| Mean values | | | |
| 277.7 | 5.9 | 301.4 | 3.0 |
| Standard deviations | | | |
| 9 | 1.8 | 19 | 0.5 |