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MEMS meander harvester with tungsten proof-mass

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Abstract. Using current battery technology the life-time of a leadless pacemaker is approximately 6-10 years, with a large portion of the pacemaker occupied by the battery. This paper investigates the possibility to use a MEMS piezoelectric harvester as a complementary energy source in leadless pacemakers. The challenge is to combine the low resonance frequency required to harvest energy from a heartbeat with the small volume of 20×4×3 mm^3 available, with the corresponding harvester displacement restricted to 2 mm. Due to the displacement restriction the selected structure was a double clamped bridge in order to reduce the mass displacement, with various meander-type designs simulated to reduce resonance frequency. To further reduce resonance frequency large proof-masses of tungsten were attached by gluing. Two types of tungsten proof-masses were added to four different harvesters, 16.4 mg and 16.6 mg on sample 1 and 2 and 502 mg and 492 mg proof-mass on sample 3 and 4. The structures have 2 µm patterned PZT (deposited by sol-gel technique) and Pt metal electrodes for d_{31} mode harvesting. The power output measured from one of the two PZT/electrodes was 0.13 nW with 50 µm deflection at 100 kΩ optimal load resistance and 9.1 mV_{pp} at 232 Hz.

1. Introduction

In 1958 the first pacemaker was implanted and was followed by a 20-year long struggle to find a suitable energy source [1]. The first pacemakers relied on the patient to recharge the nickel-cadmium battery inductively with only a few days between recharges. In the early 1960s the zinc-mercury battery prolonged the lifetime to about 1-2 years but was unpredictable and the battery required venting. To reach a longer lifetime the battery was replaced with thermoelectric energy harvesters powered by a Pu-238 core [2]. This nuclear energy harvester increased the pacemaker lifetime substantially with patients still having their original nuclear pacemaker 30 years later. The obvious disadvantage of this nuclear harvester is the handling of plutonium, both during manufacturing and destruction. However, the nuclear pacemaker was discontinued shortly after it hit the market, with the arrival of the lithium-iodine battery which realized up to 10 years of lifetime without the need to handle toxic plutonium [1].

The pacemaker has its electronics and battery in the chest of the patient, with leads going to the heart through a large vein. This makes it possible to replace the pacemaker with a less invasive procedure and connecting the new pacemaker (with the new battery) to the existing leads. However, the leads going to the heart are one of the big issues with pacemakers and complications arise both during initial operation and over the lifetime of the patient [3].

In recent years, with increasingly efficient electronics and higher energy density batteries, it is now possible to produce pacemakers without leads and implanting the entire pacemaker into the heart. Changing the battery is therefore more invasive and the struggle to find a suitable energy source is once again in progress. One method is to harvest energy from the heartbeat and power the pacemaker from the patient's own heart. Zurbuchen et al. experimented with a prototype consisting of a stripped self-winding wristwatch mechanism sutured on the heart of a pig [4]. This method requires no leads and no battery replacement.

A recent commercial solution is to insert a small leadless pacemaker into the heart through the groin, which make the procedure of implanting a pacemaker easier [5]. However, with a size of only 25 mm×⌀ 6 mm this leadless pacemaker is an energy storage challenge, currently with a lifetime of only 6-10 years before the battery runs out [5, 6, 7]. Replacing parts of the battery with an energy harvester could improve the total life-time of the pacemaker substantially. This paper investigates the possibility to use a MEMS piezoelectric harvester as a complementary energy source to the battery inside the leadless pacemaker.

The maximum available size for the harvester is 20×4×3 mm^3 to have room also for emergency battery, supercapacitor, and pacemaker electronics. Harvesting energy from heartbeats requires a harvester working at low resonance frequency, 10 Hz to 50 Hz, and low excitation amplitudes, 0.5g to 1g [6, 7, 8], typically requiring a harvester size outside the allowed design space. Small size and low frequency harvesting ability can be obtained by using a large bandwidth resonator (e.g. mechanically converting low frequencies into higher frequencies) [9, 10] but this increases the size (even if MEMS manufactured), by using a very compliant structure such as meander bridge [11], or by attaching a tungsten proof-mass to the silicon resonating structure [12].

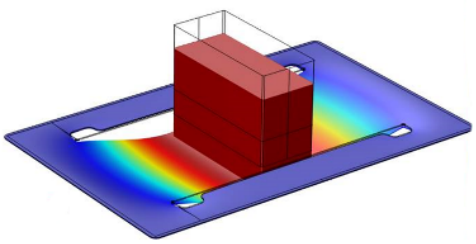

Figure 1. Simulation of bridge harvester with large tungsten mass. The size and shape of the proof-mass affects the resonance frequency and the modes.

2. Method

The first part of this project was to simulate and design a MEMS piezoelectric harvester for the challenging restraints on low displacement and low resonance frequency. Single clamped cantilevers were ruled out because of the large displacement. Due to the 2 mm displacement restriction the selected structure was a double clamped bridge, see figure 1. The size and shape of the proof-mass affects the resonance frequency and with larger proof-mass also the resonance modes.

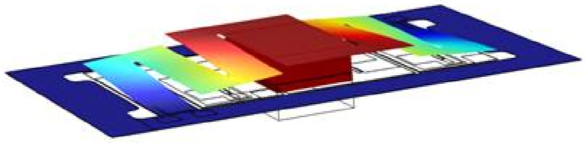

Figure 2. 10 mm long MEMS Meander structure with small proof-mass and 3 meanders.

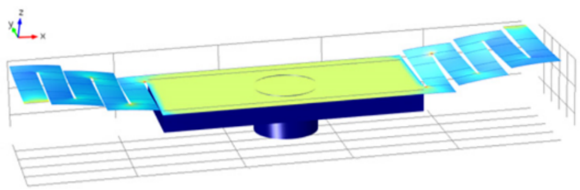

Figure 3. 10 mm long MEMS Meander structure with large proof-mass and 5 meanders.

To reach the displacement requirement and a low resonance frequency various meander-type designs were simulated, see figure 2 and 3. The five-meander harvester in figure 3 includes an extra proof-mass of tungsten. The tungsten mass is manually glued on the silicon proof-mass, see figure 4.

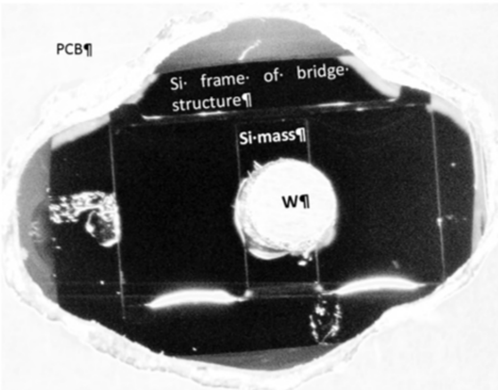

Figure 4. Image of a MEMS bridge harvester with manually glued tungsten extra proof-mass (16 mg).

To MEMS fabricate the structures simulated in figure 2 and 3 with reasonable yield is difficult. The large tungsten proof-mass is needed to reach even lower resonance frequencies but complicates the fabrication method (especially when intended for batch fabrication). Two different types of tungsten proof-masses were added, one smaller mass of approximately 16 mg and one large cylindrical block of tungsten weighting around 500 mg.

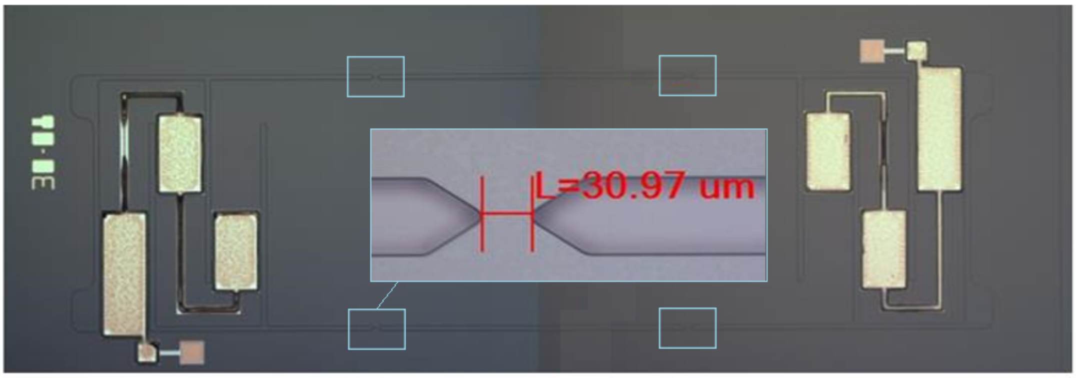

Figure 5. Meander-type harvester with 3 meanders and large proof-mass area. Four support bridges are located on the proof mass with a width of approximately 30 μm.

Because of the fragile meander structures and the choice of gluing the tungsten proof-mass in place, a method was developed to handle this difficult procedure. To protect the structures during the fabrication processes, handling/transport and the addition of proof-mass, each big Si proof-mass was reinforced with four small support bridges, figure 5. The support bridges were removed with focused ion beam (FIB) milling, figure 6, before measurements with Laser Doppler Vibrometer and shaker were performed. The samples need to be properly connected to ground to decrease the charging as much as possible as well as controlling the power during FIB milling process such that no debris are deposited on the sample, see figure 6b.

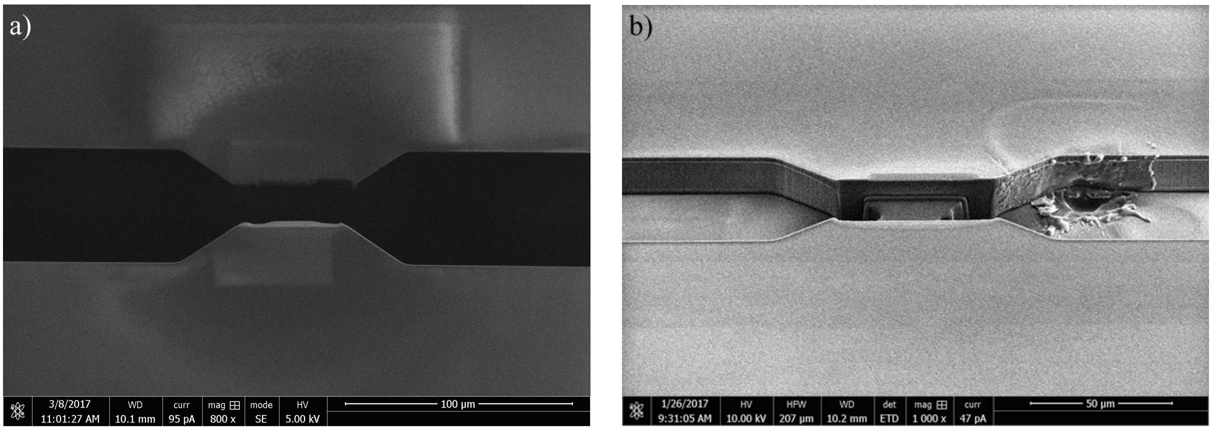

Figure 6. Pictures of the support bridges removed with focused ion beam (FIB). (a) Top view with support-bridge completely removed. (b) At 52° angle support-bridge partly removed. Debris deposition to the right of the support bridge caused by poor connection to ground.

3. Results and Discussions

The two different tungsten proof-masses were added to four different harvesters, 16.4 mg and 16.6 mg proof-mass on sample 1 and 2 and 502 mg and 492 mg cylindrical proof-mass on sample 3 and 4. As expected, the resonance frequency dropped when extra mass was added, see figure 7. For sample 1 and 2 the resonance frequency dropped from 220 Hz and 240 Hz to 140 Hz and 170 Hz respectively. For sample 3 and 4 the resonance frequency dropped substantially more from approximately 240 Hz to 61 Hz.

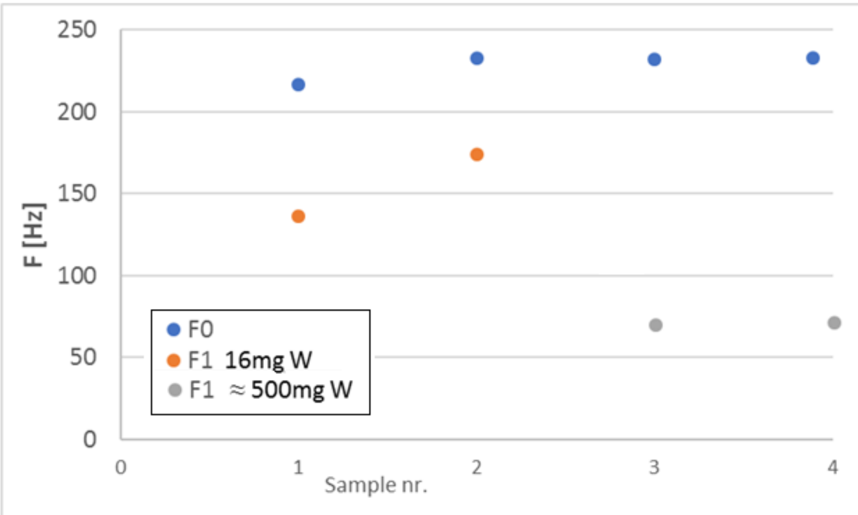

Figure 7. The first resonance frequency before (F0) and after attaching tungsten (F1, F2) as extra proof mass to MEMS harvesters.

The structures have 2 µm patterned PZT (deposited by sol-gel technique) and Pt metal electrodes for d_{31} mode harvesting. The power output measured was limited to a deflection of 50 µm because when the structure deflected more than 100 µm it tended to stick to the PCB board on which it was mounted. Due to bonding issues only one electrode worked, meaning that only one PZT volume provided output power. A power output of 0.13 nW was obtained at 100 kΩ optimal load resistance and a voltage of 9.1 mV_{pp} at 232 Hz, which is much lower (very small PZT volume) than the few microwatts needed.

Future research is needed to increase the fabrication yield, to reduce the resonance frequency of the harvester and to increase the power output. Using focused ion beam to release the support-bridges is also a slow and expensive procedure and could be improved.

4. Conclusion
Different meander type MEMS piezoelectric energy harvesters were simulated. The double clamped bridge design was deemed necessary to manage the 3 mm vertical space. The fragile meander harvester in combination with a large proof-mass was successfully fabricated by incorporating four support-bridges, on the large Si proof-mass, that was later removed with focused ion beam. The power measurement could only be conducted on one sample, one PZT and with 50 µm displacement and yielded a power output of 0.13 nW at 232 Hz. The design does however show the feasibility to incorporate large proof-mass and to keep a low displacement for small size device applications.

Acknowledgments
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