Improved mechanical reliability of MEMS electret based vibration energy harvesters for automotive applications

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Abstract. Current commercial wireless tire pressure monitoring systems (TPMS) require a battery as electrical power source. The battery limits the lifetime of the TPMS. This limit can be circumvented by replacing the battery by a vibration energy harvester. Autonomous wireless TPMS powered by MEMS electret based vibration energy harvester have been demonstrated. A remaining technical challenge to attain the grade of commercial product with these autonomous TPMS is the mechanical reliability of the MEMS harvester. It should survive the harsh conditions imposed by the tire environment, particularly in terms of mechanical shocks. As shown in this article, our first generation of harvesters has a shock resilience of 400 g, which is far from being sufficient for the targeted application. In order to improve this aspect, several types of shock absorbing structures are investigated. With the best proposed solution, the shock resilience of the harvesters is brought above 2500 g.

1. Introduction

With the purpose of enhancing driving safety, tire pressure monitoring systems (TPMS) are legally mandatory for all newly produced passenger cars in the US. Similar legislation will soon pop-up in Europe and Asia. Actual TPMS solutions are mounted on the valve of the tire. Future TPMS may be embedded in the inner liner of the tire. This would represent a first step towards the concept of intelligent tire. Additional features of intelligent tire may include monitoring of the forces between the road and the tire for future active safety systems [1]. Sensors placed in the inner liner of a tire require compact and long lasting electrical power sources that do not need to be replaced during the lifetime of the tire. While electrochemical batteries remain an option, their limited lifetime can be an issue. These considerations combined with the abundance of mechanical vibrations in the tire makes vibration energy harvesting a promising alternative.

Our group previously demonstrated fully autonomous TPMS powered by MEMS fabricated electret based vibration harvesters [2]. The harvester is described in Figure 1a. It consists of a stack of three bonded wafers. The central wafer contains a mechanical resonator made of a proof mass and springs etched in silicon. An illustration of the design for the silicon mass spring system is given in Figure 1b. The dimensions of the mass are 10×10×0.65 mm^3. The mass is connected to the frame by folded silicon beams. The springs on both sides of the mass are linked by a truss for increased stability of the oscillating structure. The maximum displacement of the mass is defined by the gap between the anchors of the springs. It is equal to ±100 µm. The proof mass supports a corrugated electret on its bottom side, obtained by Corona charging of a SiO_2/Si_3N_4 stack. The bottom wafer is made of glass and supports a set of two metallic electrodes that are connected to a load circuit. The top glass wafer is used as capping to protect the device and to allow vacuum encapsulation. With external vibrations, the mechanical resonator oscillates and an electric current is induced between the electrodes on the bottom wafer.

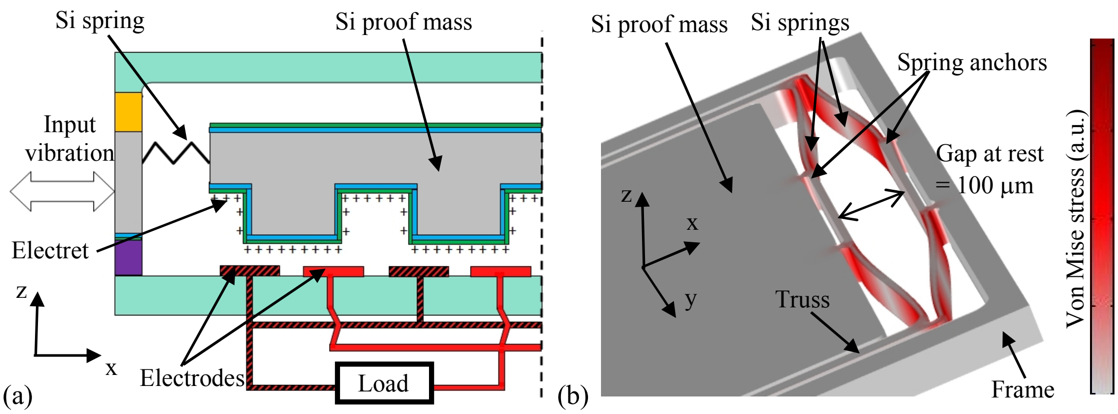


Figure 1. (a) Side-view schematic of the electret based harvester. (b) Top view schematic of the mass spring system.

While the functionalities of the harvester have been demonstrated, its mechanical reliability, particularly in terms of shock resilience, remains a challenge. Our objective is to make harvesters that survive half sine shocks with amplitude in the range of 2500 g and duration of 0.6 ms, which would be within safety margins of the standard requirements of the automotive industry [3]. As discussed in [4], our first generation of devices do not meet this requirements so that solutions for improving the shock resilience needs to be found. Inspired by the work of Yoon [5], solutions are found in the form of mechanical stoppers. Different types of stoppers, illustrated in Figure 2, are investigated.

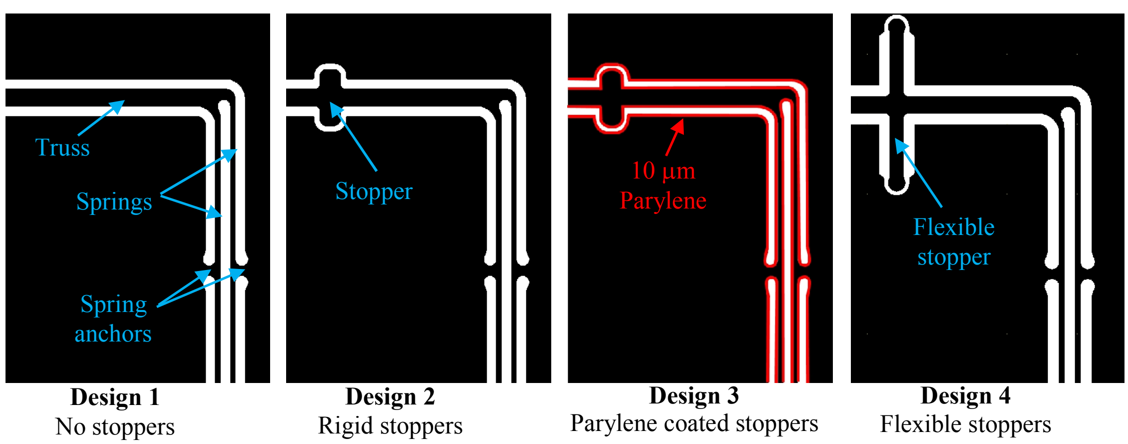
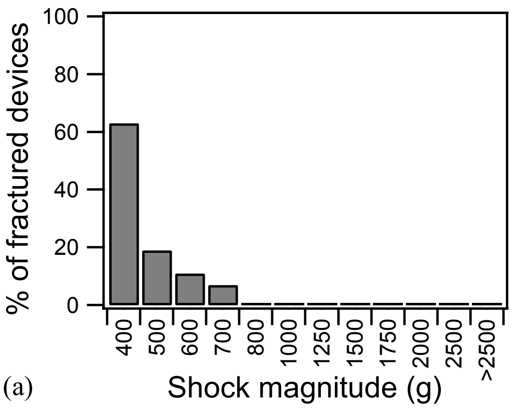


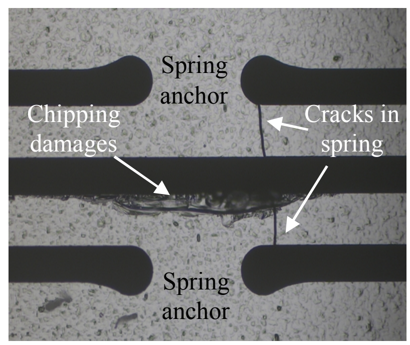
Figure 2. Illustration of the different mechanical stoppers investigated in this article.

2. Stoppers free structures (design 1)

As detailed in [4], shock tests are performed using a drop machine. For each shock amplitude, 3 successive shocks are applied. The status of the devices is checked after each shock. A first series of experiments suggested that the *x* direction in Figure 1a is the most critical. Therefore, we focused on investigating the reliability of the harvester with shocks applied along the *x* direction. In order to limit the manufacturing efforts necessary to provide a sufficient quantity of test samples, the subsequent shock tests were not performed on fully functional harvesters but on simplified test devices. The test devices are made of FR-4 boards on which the central wafer in Figure 1, i.e. the mass spring system of the harvester, is glued. The distribution of the shock amplitude leading to failure for structures with design 1 is given in Figure 3a. Failure of the samples is observed in the form of fracture of the silicon springs. This results from the spring anchors impacting each other. A close up picture is given in Figure 3b. It can be seen that more than 60% of the 27 tested samples fail for 400 g shocks and that 100% of the samples are broken at 700 g. This result is clearly not satisfying.



(a)

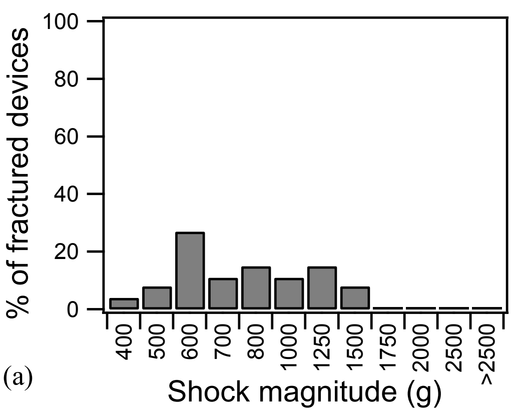


(b)

Figure 3. (a) Distribution of the shock resilience for the stoppers free devices (27 samples). (b) Picture of the broken area.

3. Rigid stoppers structures (design 2)

In order to avoid contact between the anchors of the springs, rigid stoppers are introduced in design 2. The stoppers are designed in such a way that, when they contact, there is still some distance between the anchors of the springs. As shown in Figure 4a, the shock resilience is improved compared to the stoppers free design. However, the median shock survival rate is about 700 g which remains unsatisfying. Failure of the springs occurs when the stoppers themselves are fractured by the impact. In this case, contact between the anchors of the springs is not avoided and the springs break.



(a)

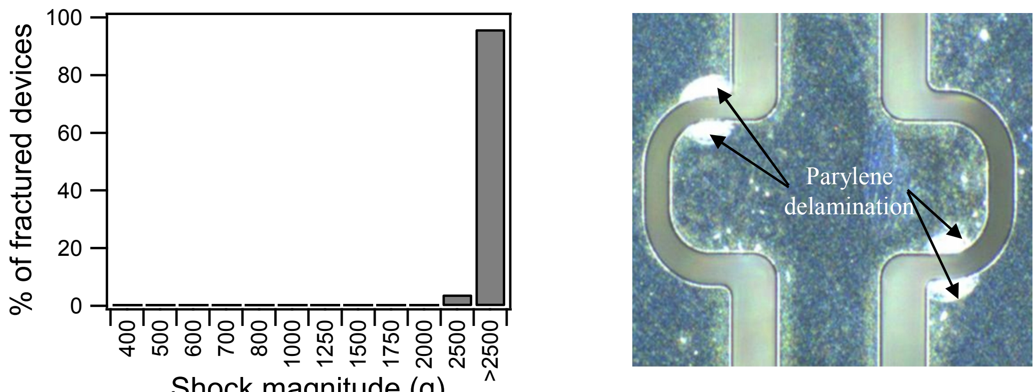
(b)

Figure 4. (a) Distribution of the shock resilience for the rigid stoppers devices (26 samples). (b) Picture of a broken stopper.

4. Parylene coated stoppers (design 3)

In order to avoid damaging the stoppers and, ultimately, to avoid contact between the spring anchors for ensuring the survival of the springs, the amplitude of the contact force during impact should be reduced. This can be done by increasing the compliance of the contact surfaces. It is possible to do so by coating the rigid stoppers of the last section with a layer of compliant material. Parylene is not only a compliant material but is also conformal and non-brittle. It is therefore a good candidate. Note that, for manufacturing simplicity, the whole test samples are covered with 10 μm Parylene. The layout of the devices is adjusted so that the maximum displacement of the mass in the coated devices remains 100 μm.

The distribution of the shock amplitude leading to fracture of the springs is given in Figure 5a. Only one of the 28 tested samples has damaged springs, showing that the Parylene coating is a very good solution to improve the shock resilience of the harvesters. As shown in Figure 5b, signs of impact are visible on the bumpers of the tested devices. The Parylene is locally delaminated by the impact force. To check if this could become an issue after a large quantity of repeated impacts, some samples were tested under a series of 30 shocks with 2500 g amplitude. None of them showed signs of failure.



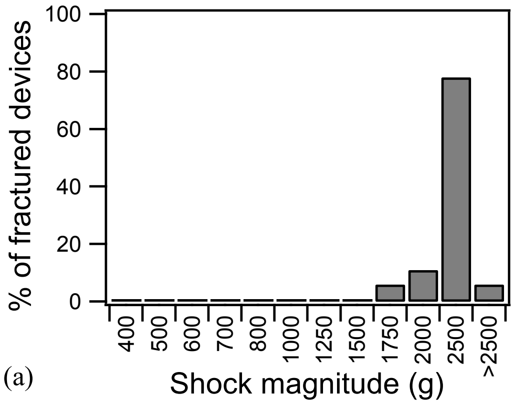
(a) (b)

Figure 5. (a) Distribution of the shock resilience for the devices with rigid bumpers coated with Parylene (28 samples). (b) Picture of a stopper with delamination of Parylene resulting from impact.

While the Parylene coating is a very effective solution to enhance the shock resilience of the test devices, it is not straightforward to integrate it in the manufacturing process of the complete harvester. Therefore, a silicon only solution to improve the shock resilience is considered in the next section.

5. Flexible stoppers (design 4)

In the previous section, the impact force on the stoppers was reduced by increasing the compliance of the contact surfaces with a layer of Parylene. Another solution to reduce the impact force is to make the bumpers structurally flexible [5]. Several variations of flexible stoppers with different stiffness are investigated. Theoretical considerations for the various considered dimensions are given in [4]. We observed that the more flexible are the stoppers, the higher is the median shock resilience. The distribution of the shock amplitude leading to fracture of the springs for the most flexible tested stoppers is given in Figure 6a. The flexible stoppers concept is convincing as the median shock resilience of the test samples is brought up to 2500 g. This result can be enhanced further by making the stoppers even more flexible. One drawback of this approach is that the area occupied by the stoppers increases as they are made more flexible. This is detrimental for the total footprint of the harvester.



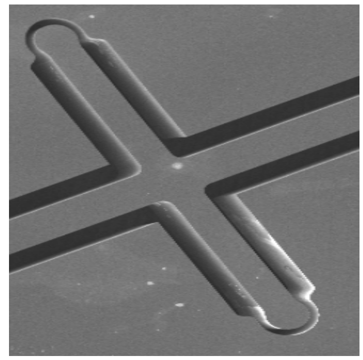


Figure 10. (a) Distribution of the shock resilience for the devices with flexible stoppers (27 samples). (b) SEM pictures of a pair of flexible stoppers.

6. Conclusion

Wireless TPMS powered solely by MEMS fabricated electret based vibration energy harvesters have been demonstrated by our group in previous articles. To attain the grade of commercial product with the devices, the mechanical reliability of the harvester has to be improved. Indeed, the tire environment is harsh, particularly in terms of mechanical shocks. Devices designed for this environment should survive shocks with amplitudes exceeding 2500g. It is shown in this article that our first generation of harvesters had a shock resilience of 400 g which was clearly not sufficient. For improving this aspect, several types of mechanical stoppers are considered. Rigid stoppers are first studied. They allow increasing the median shock resilience to 700 g which remains unsatisfying. Parylene covered stoppers is the second considered option. It gives very good results. 96% of the tested devices were not broken with 2500 g shocks. However, the integration of Parylene in the process flow of the harvesters is not straightforward. Therefore, a silicon only solution would be preferred and the concept of flexible stoppers is investigated. The concept is convincing, as we could bring the shock resilience of the tested samples to 2500 g. It is possible to enhance further this number by increasing the flexibility of the stoppers.

Acknowledgements

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