Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 47 (2012) 1434 – 1437

Procedia Engineering

www.elsevier.com/locate/procedia

Proc. Eurosensors XXVI, September 9-12, 2012, Kraków, Poland

Preliminary performance evaluation of MEMS-based piezoelectric energy harvesters in extended temperature range

R. Xu[a]*, L. M. Borregaard[a], A. Lei[b], M. Guizzetti[a], E. Ringgaard[a], T. Zawada[a], O. Hansen[b], E. V. Thomsen[b]

[a]*Meggitt A/S,* Hejreskovvej 20, *Kvistgaard 3490, Denmark*
[b] *Department of Micro- and Nanotechnology, Technical University of Denmark, Kongens Lyngby 2800, Denmark*

Abstract

In this work a batch of MEMS-based vibration energy harvesters consisting of a silicon/PZT thick film cantilever with integrated proof mass is characterized. The purpose of a vibration energy harvester is to convert low grade vibrations to useful electrical power. Optimally, the natural frequency of the harvester should match the frequency of the ambient vibration. The first step to achieve this is to evaluate the uniformity of the fabricated harvesters and understand the effects of temperature on the harvesters during operation. Therefore, the uniformity of 40 energy harvesters from one wafer has been evaluated. Thereafter the performance of the energy harvesters operating at temperatures between -30ºC to 100ºC was measured.

Keywords: Energy harvester; MEMS; piezoelectric; temperature range; performance

---

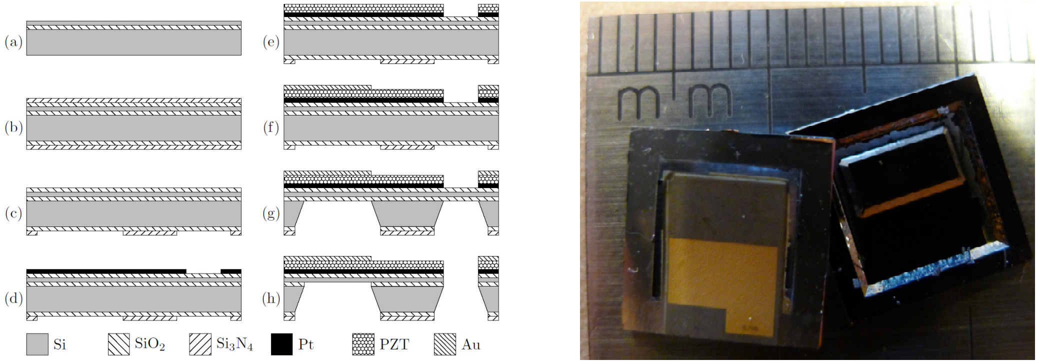
Introduction

The MEMS vibration energy harvesters have received significant attention in recent years. However, the effects of non-uniformity from the fabrication process and the influence of the operation temperature have not been the focus. For an optimal implementation of an energy harvester in any real vibrating environments, both the resonant frequency and the voltage output are vital parameters that should be understood. The resonant frequency of the energy harvester must match the available vibrating frequency from the environment to maximize the voltage output. The voltage output must then be sufficiently high for optimal operation of the power management circuitry. This paper evaluates the challenges related to frequency matching and variations in voltage output with respect to temperature for the presented MEMS-based piezoelectric energy harvesters [1].

doi:10.1016/j.proeng.2012.09.427

Fabrication

The piezoelectric energy harvesters were fabricated on 525 µm thick 4 inch silicon on insulator (SOI) wafers with a 20 µm device layer (Fig. 1(I, a)). A silicon oxide layer was thermally grown, followed by a deposition of stoichiometric low pressure chemical vapor deposition (LPCVD) silicon nitride (Fig. 1(I, b)). Backside windows in the nitride for a later KOH etch were defined using UV lithography followed by reactive ion etch (RIE) and then the front side nitride was removed in a RIE etch (Fig. 1(I, c)). A Pt bottom electrode, also serving as a diffusion barrier, was deposited using e-beam evaporation and patterned (Fig. 1(I, d)). On top of the bottom electrode a PZT thick film (InSensor® TF2100) was deposited using screen printing (Fig. 1(I, e)). An Au top electrode layer was deposited by e-beam evaporation (Fig. 1(I, f)). The silicon dioxide in the backside windows was removed in a buffered hydrofluoric acid (bHF) solution, and cavities were etched in a KOH solution (Fig. 1(I, g)). The PZT structures were covered with photoresist and the cantilevers released by an oxide etch in bHF followed by a RIE silicon etch (Fig. 1(I, h)). Finally, the wafers were diced (Fig. 1(II)) and the PZT film poled by applying an electric field between the top and bottom electrodes at elevated temperature.



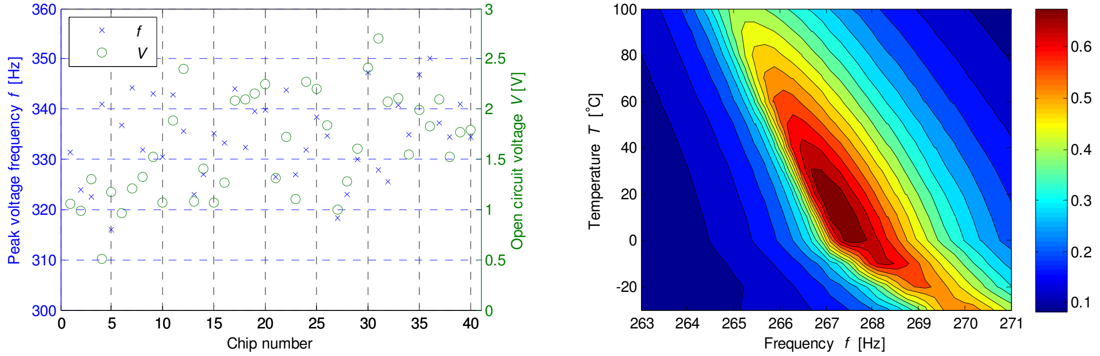
(I) (II)

Fig. 1. (I) Cross sectional view of the fabrication process; (II) Photograph of the fabricated energy harvesters, one is viewed from the front and another is viewed from the back.

Results and discussion

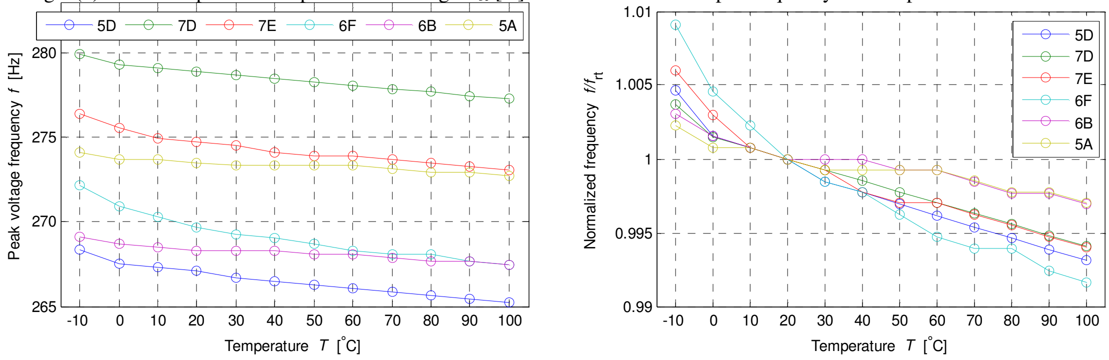
From one of the fabricated wafers 40 energy harvesters were characterized using a shaker setup to evaluate the fabrication uniformity. The open circuit voltage was measured as a function of the input frequency at 0.5 *g* RMS acceleration. The peak voltage frequency and the peak voltage for the 40 energy harvesters are shown in Fig. 2(a). The relative standard deviation of peak voltage frequency in the sample population was found to be 2.4% and relative standard deviation of peak voltage was around 30%. The frequency variation could be explained by variations in proof mass or cantilever spring constant due to variations in cantilever thickness; the fabrication process of the mass however is quite well controlled and thus the variation is presumably due to variations in cantilever spring constant.

From another wafer, 6 energy harvesters were characterized at 0.1 *g* RMS acceleration between temperatures from -30ºC to 100ºC in 10ºC increments using a climatic chamber integrated with the shaker setup. The measurements of one selected harvester are shown in Fig. 2(b) as a contour plot of the open circuit voltage V_{oc} as a function of frequency f and temperature T. Note, there is at clear break line at T=0ºC. This is believed to be caused by the condensation of water vapor and ice formation on the cantilever, which increases the effective thickness of the cantilever and hence the spring constant. In Fig. 3(a) the peak voltage frequencies of all 6 harvesters are plotted as a function of the temperature. Since the frequency variation between the harvesters is comparable to the effect of the temperature, the frequencies are normalized with respect to the room temperature (20ºC) value for better comparison as shown in Fig. 3(b). One can observed from Fig. 3 that the peak voltage frequencies decrease as the temperature increases, which has been also reported in [2]. This is caused by the decrease in Young's modulus of the cantilever materials, *i.e.* silicon and PZT, with temperature. The change in the peak frequency in the temperature range is around 2% as it is seen in Fig. 3(b). Even though the change is smaller than the frequency variation between the different harvesters, it is still a significant change compared to the harvester bandwidth (~2 Hz) and the often narrow frequency bandwidth of the vibrating source. Similarly, the peak output voltage is shown as a function of the temperature in Fig. 4(a) and the voltage normalized with respect to that at 20ºC is shown in Fig. 4(b). These measured results show that compared the peak voltage frequency the peak output voltage is highly dependent on the temperature, where the output voltage can drop below 60% of its original value at 20ºC. The variation with temperature seems to cluster in two classes, four devices with high output voltage show almost identical behavior at temperatures above 0ºC (the differences below 0ºC could be caused by differences in ice formation), while two devices (7E and 6F) have a significantly lower output voltage and a smaller variation with temperature.



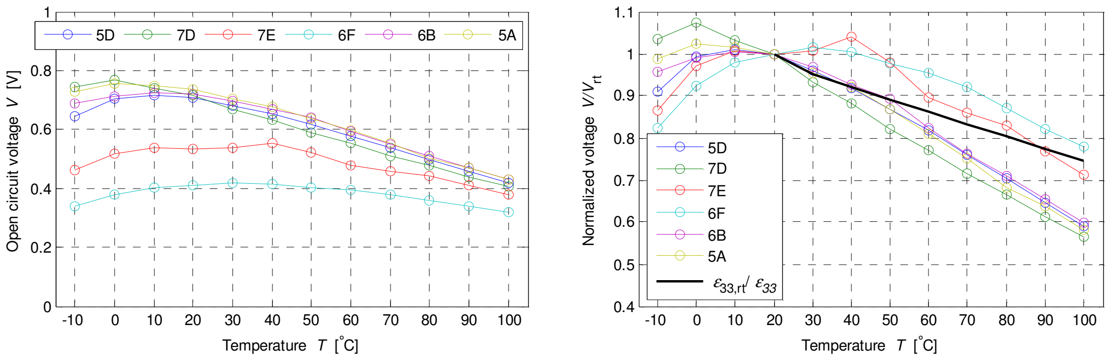
(a) (b)

Fig. 2. (a) The performance of 40 chips from one wafer in terms of peak output voltage frequency and peak open circuit output voltage. (b) A contour plot of the open circuit voltage V_{oc} [V] as a function of the input frequency and temperature.



(a) (b)

Fig. 3. (a) The peak output voltage frequency as a function of the temperature at 0.1 *g* RMS acceleration; (b) The peak output voltage frequency normalized to that at room temperature shown as a function of the temperature.



(a) (b)

Fig. 4. (a) The peak open circuit output voltage as a function of the temperature at 0.1 *g* RMS acceleration; (b) The peak open circuit output voltage normalized to that at room temperature shown as a function of the temperature. The normalized reciprocal dielectric constant in the temperature range 20ºC to100ºC is also shown for comparison.

Since the piezoelectric coupling coefficient is relatively low for the fabricated energy harvesters (~0.2), the output voltage will be roughly proportional to d_{31}/ε_{33}, where d_{31} is the piezoelectric coefficient and ε_{33} is the dielectric constant of the PZT thick film. The dielectric constant was measured at temperatures in the range 20-100ºC, and the reciprocal value normalized with respect to its value at 20ºC is shown in Fig. 4(b) along with the normalized voltages. Fig. 4(b) shows that the reciprocal dielectric constant decreases at a lower rate than the voltage, which indicates that the change in the dielectric constant is not the only contributing factor to the decrease in voltage. However, the voltage decrease is not believed to be caused by d_{31}, since d_{31} is expected to increase with increasing temperature [3]. The aforementioned decrease in Young's modulus of the PZT material and the increased mechanical damping at higher temperature observed in [2] are two other contributing factors to a decreasing voltage output.

Conclusion

The presented results indicate that temperature has a significant effect on the resonant frequency as well as the output voltage of the energy harvesters, which is of high practical importance.

Acknowledgements

This research is part of the ELBA project, which is funded by the Danish National Advanced Technology Foundation.

References

[1] Lei A, Xu R, Thyssen A, Stoot A C, Christiansen T L, Hansen K, Lou-Moller R, Thomsen E V, Birkelund K. MEMS-based thick film PZT vibrational energy harvester. *IEEE MEMS 2011.* 2011, p. 125-128

[2] Barker S, Vassilevski K V, Wright N G, Horsfall A B. High Temperature Vibration Energy harvester System. *IEEE Sensors 2010.* 2010, p. 300-303

[3] Wolf R A, Trolier-McKinstry S. Temperature dependence of the Piezoelectric response in lead zirconate titanate films *Journal of applied physics*. 2004, **95**, nr. 3, p.1397-1406