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Freestanding piezoelectric rings for high efficiency energy harvesting at low frequency

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Energy harvesting at low frequency is a challenge for microelectromechanical systems. In this work we present a piezoelectric vibration energy harvester based on freestanding molybdenum (Mo) and aluminum nitride (AlN) ring-microelectromechanical-system (RMEMS) resonators. The freestanding ring layout has high energy efficiency due to the additional torsional modes which are absent in planar cantilevers systems. The realized RMEMS prototypes show very low resonance frequencies without adding proof masses, providing the record high power density of $30.20 \mu\text{W mm}^{-3}$ at 64 Hz with an acceleration of 2g. The power density refers to the volume of the vibrating RMEMS layout. © 2011 American Institute of Physics. [doi:10.1063/1.3551725]

Over the past few years, the development of energy harvesting devices for different ambient energy sources has been the subject of intense investigation. Among the others, mechanical vibrations are easily exploitable through microelectromechanical-system (MEMS) technology.^{1–5} Mechanical vibration energy can be converted into electric energy by piezoelectric transducers, which are preferable to electromagnetic and electrostatic transducers due to their higher energy density.⁶ Piezoelectric mechanical transducers are based on the mechanical deformations undergone by bimorphic structures (piezoelectric/structural layer) induced by the internal stress generated in the piezoelectric material. Among the possible piezoelectric thin films, $\text{Pb}(\text{Zr},\text{Ti})\text{O}_3$ (PZT), ZnO, and AlN are the most used in piezoelectrically actuated mass sensors.^{7–14} Despite the lower piezoelectric coefficient, AlN is very attractive for micromechanical energy harvesting due to the simple manufacturing process and easy integration with complementary metal-oxide semiconductor (CMOS). So far, several vibration harvesting devices have been reported,^{2,3,15–21} based on schemes and interface electronics. In this work we develop a new MEMS architecture based on a freestanding molybdenum/aluminum nitride/molybdenum (Mo/AlN/Mo) ring obtained by exploiting the AlN built-in strain property and controlled by the deposition process. The ring-MEMS (RMEMS) [see Figs. 1(a)–1(c)] has high mechanical flexibility, designed to obtain piezoelectric resonances at low frequencies. By virtue of the excellent elastic property and of the addition of the torsional degree of freedom the RMEMS exhibits very high power density resulting in an unprecedented efficiency at low frequency and for low vibration forces.

In the typical configuration of Mo/AlN/Mo layers (grown by dc magnetron sputtering), the AlN thin film (400 nm thick), sandwiched in two Mo electrodes, is grown on a substrate consisting of a thin SiO_2 sacrificial layer on a thick (100) silicon substrate. Molybdenum has been chosen as the

electrode material because of its threefold properties: (i) it promotes a preferential (002) orientation of the AlN film, (ii) low resistivity, and (iii) it can be easily etched by H_2O_2 , thus reducing the complexity of device fabrication. The control of the deposition parameters related to the Mo and AlN layers, such as bias and N_2/Ar pressure ratio, allows the control of the residual stress.^{22,23} The fabrication of the rings and the electric contacts requires a few steps of optical lithography and well-controlled wet etching. In order to open windows reaching the Mo bottom layer after a lithographic patterning, the upper Mo layer is chemically etched in a H_2O_2 -based solution; then a wet chemical etching in a H_3PO_4 -based solution of the AlN layer is performed. Afterward, the sample is dipped into the H_2O_2 -based solution for etching the bottom Mo layer. Finally a HF-based solution is used to remove the SiO_2 sacrificial layer, allowing the release of the rings from the substrate.²² The high residual stress of the layered structure leads to the rolling up of the realized strips forming the RMEMS. By assuming the layer configuration of Fig. 1(a) the obtained rings have a diameter of about 200 μm .

Now we present and discuss the experimental results obtained from the characterization of a RMEMS chip prototype for vibration energy harvesting purposes. The chip is composed of five different RMEMSs having an average radius of 85 μm . For measuring the performances of the realized AlN-based RMEMS chip, we arranged the dedicated experimental setup shown in the inset of Fig. 2(a). As shown in the inset of Fig. 2(a) vibrations have been provided through an

FIG. 1. (Color online) (a) Ring layout: particulars of the Mo/AlN/Mo growth. (b) Scanning electron microscope (SEM) image of the Mo/AlN/Mo RMEMS and torsional moments of the tip. (c) Top view SEM image of a vibrating RMEMS of the energy harvesting chip.

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FIG. 2. (Color online) (a) Open-circuit voltage V_{oc} generated by the RMEMS excited at different accelerations. Inset (a): experimental setup used for RMEMS characterization. (b) Output power P_{out} provided by the RMEMS with $R_{L,opt}=11\ \Omega$ for different accelerations.

electrodynamic platform shaker, which is the Data Physics V400 /M8/VI with a DSA1-2K amplifier. The RMEMS chip is fixed to the vibrating platform of the shaker, which provides a d_{31} excitation. The vibration, frequency, and acceleration are controlled by means of the SignalStar Vector Vibration Controller software, which allows a very fast and precise control of the shaker oscillations thanks to the accelerometer feedback signal required to monitor the effective shaker platform acceleration. The voltage generated by the excited RMEMS is measured by means of a SRS SR530 analog lock-in amplifier (LIA). The LIA synchronization signal is provided by an accelerometer fixed to the shaker platform.

For the characterization of the RMEMS prototypes, we measured both the open-circuit voltage and the maximum power provided by the RMEMS varying both vibration frequency and acceleration. The vibration frequency range considered spans from 20 to 100 Hz since this range includes the typical vibration frequencies in environment and industrial applications.^{18–33} Open-circuit voltages measured on the RMEMS chip prototype excited with different accelerations are plotted versus frequency in Fig. 2(a). We do not consider acceleration values higher than 2.0g ($g=9.807\text{ m/s}^2$), as they are very rare in environment and industrial applications. As shown in Fig. 2(a), the highest value of the open-circuit voltage V_{oc} generated by the RMEMS occurs at ~ 64 Hz independent of the excitation acceleration, indicating that the main resonance frequency of the RMEMS is $f_0=64$ Hz. The maximum open-circuit voltage is $V_{oc}=236\ \mu V$ with a 2.0g acceleration. Moreover, two lower V_{oc} peaks occur at lower

frequencies, i.e., at 40 and 48 Hz, probably due to torsional vibration mode of the ring structure of the MEMS transducer.

The quality factor of the RMEMS piezoelectric transducer ($Q=f_0/\Delta f$) decreases slightly at higher accelerations, dropping from 24 to 17 with acceleration levels going from 0.5g to 2g, respectively. This is due to the air-damping, which is a well known mechanical loss factor.³² In order to evaluate the maximum output power provided by the RMEMS chip, we derived the output impedance satisfying the power matching conditions.³³ Thus, we measured first the output impedance of the RMEMS transducer, $R_{MEMS} \sim 18\ \Omega$. Surprisingly, the capacitive part of the RMEMS impedance is negligible compared to the resistive one, R_{MEMS} . The device resistance (impedance) turns out to be quite low, in the range of tens to hundreds of ohms depending on frequency and sample size. We believe that such a low resistance value is primarily due to molybdenum interdiffusion across the thin polycrystalline AlN layer having a columnar structure. A trade-off between thin layers for optimal strain release and thick layer for resistance optimization has to be found in order to optimize yield of the RMEMS. Work is underway in our laboratories to assess this issue.

An optimized load impedance was employed in order to measure the RMEMS output power, which is shown in Fig. 2(b) at different frequencies and for different accelerations. The power generated by the RMEMS is 1.3 nW at the resonance frequency under 2.0g excitation acceleration. By normalizing the power to the total volume of the rings arranged in the chip we obtain a maximum power density of

TABLE I. Comparison among piezoelectric vibration energy harvesting devices.

Author	Year	Device	f (Hz)	A (g)	Power density ($\mu\text{W}/\text{mm}^3$)
Glynne-Jones (Ref. 30)	2001	d_{31} PZT cantilever	80	4.0	0.017
Marzencki <i>et al.</i> (Ref. 24)	2005	d_{31} AlN cantilever	204	0.5	0.01
Fang <i>et al.</i> (Ref. 29)	2006	d_{31} PZT cantilever	608	1.0	10.84 ^a
Renaud <i>et al.</i> (Ref. 25)	2007	d_{31} PZT cantilever	1.8k	1.9	21.68 ^a
					<3.57 ^a
Marzencki <i>et al.</i> (Ref. 26)	2007	d_{31} AlN cantilever	1.3k	4.0	
Shen <i>et al.</i> (Ref. 17)	2008	d_{31} PZT cantilever	462.5	2.0	3.27
Kim <i>et al.</i> (Ref. 28)	2008	d_{31} PZT cantilever	870	8.0	0.30
Renaud <i>et al.</i> (Ref. 18)	2008	d_{31} AlN cantilever	320	0.02	0.22
Isarakorn <i>et al.</i> (Ref. 27)	2008	d_{31} PZT cantilever	70	1.0	2.50
This work	2009	d_{31} AlN ring	64	0.5	2.09
This work	2009	d_{31} AlN ring	64	1.0	8.11
This work	2009	d_{31} AlN ring	64	1.5	17.45
This work	2009	d_{31} AlN ring	64	2.0	30.20

^aEstimated from data in reference.

30.2 $\mu\text{W}/\text{mm}^3$. Such a value is very high, indicating the excellent performance of the RMEMS compared to those recently reported in the literature (Table I). The measured power density of RMEMS chip is more than two orders of magnitude higher than AlN piezoelectric micropower generators at low frequency and significantly higher than the best PZT micropower generator reported in the literature.²⁷ The great advantage of the proposed AlN-based solution is mainly due to its ring structure, which allows achieving a very low resonance frequency compared to other solutions, thus opening new perspectives for piezoelectric MEMS energy harvesting applications.

In this letter we presented a novel Mo/AlN/Mo vibration energy harvester RMEMS fabricated by micromachining technique. Its microscale dimensions and compatibility with silicon-based technology are ideal for large scale production and for the integration of different arrays of integrated RMEMS on the same chip. The combination of high control of sputtering parameters with micromachining technology allows us to obtain integrated vibration energy harvesting systems working at very low frequencies with a very high power density. By means of the freestanding property, the proposed RMEMS chip exhibits an excellent high power density of 30.2 $\mu\text{W}/\text{mm}^3$ at 64 Hz, when excited with a 2.0g acceleration. The proposed RMEMS is suitable for multi-axis energy harvesting systems. Spiral energy harvesting layouts are under investigations.

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