Printed MEMS-based self–contained piezoelectric-based monitoring device for smart grids

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Abstract. In this work, screen-printed piezoelectric PZT films are printed on a meandering-shaped 301SS stainless steel substrate to harvest power from current-carrying wires by piezo-electromagnetic transduction. Process optimization lead to good adhesion of the PZT on the stainless steel substrate and minimum bending of the multilayer {electrode/PZT/electrode/stainless substrate}. A permanent magnet is integrated on the substrate tip for electromagnetic coupling. A power of 0.05 µW is harvested from 1 A of current flowing in a wire 12.5 mm from the tip mass. The normalized power is comparable to other available MEMS-based technologies in the literature. The development of a wireless sensor network for real time electricity monitoring application is also discussed.

1. Introduction
An emerging application of piezoelectric microstructures is in the field of vibration energy harvesting for the Internet of Things and wireless sensor networks. Our objective is to develop a low cost MEMS-based self–contained piezoelectric-based monitoring device for smart grids. The MEMS is based on a piezo-magnetic Energy Harvester (EH) operating through interactions of a tip magnet with the AC electromagnetic field around a wire carrying an AC current. Then, the induced magnetic force results in vibrations in the MEMS where a piezoelectric material is integrated and consequently in an induced voltage in the piezoelectric layers. This harvested power can be used to power a sensor in a self-contained system for electricity monitoring applications. For the maximization of the electromechanical coupling, thick piezoelectric layers of tens of micrometers are required. The low-cost screen-printing process is well adapted to this films scale. Screen-printed piezoelectric thick-films are usually implemented on silicon substrates suitable for further electronics integration [1-2]. Nevertheless, use of metallic substrates (stainless steel platforms, aluminum or copper) instead of silicon substrates has already confirmed their excellent performances such as flexibility, toughness and high-efficiency of power generation [3-5]. Zhu et al have obtained a power of 240 µW harvested at 66.2 Hz with an acceleration $g=2.8$ m.s$^{-2}$. In this work, the energy harvester MEMS is made of a stainless substrate supporting the piezoelectric printed layers. This choice is justified by the low Young’s modulus of the stainless steel substrate compared to alumina substrates classically used in thick film technology, or to silicon wafers. Finally, despite the RoHs restriction, the PZT (PbZrTiO$ _3$) piezoelectric material is selected because of its outstanding electromechanical properties. This paper reports the fabrication and the optimization of the low-frequency cantilevered-zigzag energy harvester designed in a previous work [6] and the experimental testing of the piezoelectromagnetic energy
harvester for current monitoring applications. Details of the wireless sensor network developed for real time electricity monitoring application is also presented.

2. Energy harvester processing
For the processing of the MEMS piezo-magnetic energy harvester, PZT layers sandwiched between two electrodes are integrated by screen-printing on the top of a stainless steel substrate. This substrate is first laser micromachined into a meandering shape which allows maximum strain under vibrations at the expected resonance frequency of 60 Hz [6].

2.1. Screen-printing, firing and polarization
Commercial pastes from Electroscience Laboratory or home-made pastes are respectively used for the deposition of the gold electrode layers and the piezoelectric PZT layers. The selected 301SS stainless substrate withstands the high temperature necessary for the PZT densification. The PZT piezoelectric paste is prepared with the PZT: LBCu powder blended with an organic binder. After manual mixing in a mortar, the particle dispersion is optimized using a three-roll mill to achieve good viscosity [7]. The EH fabrication then consists of subsequently printing of Au, PZT and Au layers on the 301SS substrate, with a drying step at 120 °C between each deposition (Figure 1 a and b). The layers are then isostatically pressed at 40 MPa before their co-firing at 900 °C in air to improve densification and thus piezoelectric properties [8]. The final PZT’s thickness is ~60µm. In addition, compared to previous results [6], adhesion is clearly improved with the co-firing of all the printed layers. Slight bending of the multilayer is also observed because of an adapted PZT thickness leading to good compensation between the respective expansion’s coefficients. Finally, to to achieve the desired piezoelectric properties, the fired PZT layers are wire-bonded and poled under 200V applied at 280°C, just below the Curie temperature (Figure 2). The beams named bi+ or bi- are polarized in opposite directions as in bimorph configurations according to their tension or compression under vibration.

2.2. Characterization
The electromechanical properties are strongly influenced by the densification. The previous work showed a better densification and reproducibility of PZT thick films when using the PZT powder mixed with the eutectic LBCu instead of borosilicate glasses [8]. The µm particle size of the different powders (<10µm) also helps to improve densification. The porosity of the layers are analysed through SEM cross-sections by using ImageJ analysis software (Figure 3). The evaluated porosity of PZT on the stainless substrate (24%) is comparable with that on layers fired on alumina substrates. This porosity is nevertheless higher than that observed for PZT free-standing layers, because of the binding with the substrate reducing the lateral shrinkage. Electromechanical characterization, with conductance and susceptance measurements, confirm the success of the polarization step with a main resonance peak at 321 kHz for the polarized bi+ beams (Figure 4).
3. Device tests

3.1. Energy harvester tests

Once polarized, tests under vibration without tip-mass are carried out using a shaker to confirm the good electromechanical coupling. Voltage output in an open circuit state is taken across the top and bottom electrodes of the b+ beams (Figure 5a). The acceleration is fixed at 0.4g and the frequency is swept around the resonance vibration of the EH MEMS. With this configuration, the maximum RMS voltage produced by the harvester without tip mass is 242 mV with a natural frequency of 209 Hz. This value, similar to that obtained during previous tests [6], confirms the good reproducibility of the process. For further tests under magnetic field, all b+ and b-beams are connected in parallel and a neodymium magnet (dimension 12.7x3.2x3.2mm³) is finally epoxied to the substrate’s tip. With the addition of this magnet the resonance frequency is reduced down to 60 Hz. Then, a magnetic field is created by a 1A current flowing in an AWG10 wire (Figure 5b). The harvested power is finally measured with different load resistances. For a distance of 12.5 mm between the magnet and the wire’s surface, a maximum power of 0.05 µW is measured for a 1.8 MΩ resistor. With the volume of 169.7mm³ of the EH, the normalized power 0.053µW/mm³ is comparable to other available MEMS-based technologies in the literature [9-10].

Figure 2. Wiring bonding of the beams bi+ and bi- for the PZT polarization of each adjacent beam

Figure 3. SEM image of the cross-section of the multilayer SS substrate Au/PZT/A

Figure 4. Conductance G and susceptance B measured for all the b+ beams connected

Figure 5. EH tests (a) Experimental open-circuit voltage of the EH without tip mass at 0.4g (b) Experimental set-up of the EH with magnetic tip-mass and harvested power for different load resistances
3.2. Electronics
Piezo-electromagnetic harvesters using simple cantilever beam structures have already been integrated with power management and wireless communication circuits to form an individual node in a wireless sensor network for electricity grid monitoring (Figure 6) [11]. With its innovative lower power circuit design and dynamic power management scheme, the system is fully self-contained and non-invasive. With the simple cantilever beam EH attached at 6mm away from an electric wire carrying currents in the range of 7.6A to 30A, the state-of-the-art electronic system can achieve a read-transmit duty cycle from <1min to 2.5min and capable of reading a 60 HZ AC sensor signal with a peak voltage in the range of 100 mV to 900 mV with an accuracy of 91.4% [11]. The integration of the electronic system is in progress.

![Figure 6. System diagram for the sensor node for electricity grid monitoring](image)

4. Conclusion
In summary, a fully printed piezo-electric energy harvester was successfully fabricated, with a symmetric cantilevered zig-zag geometry. Adhesion of the thick printed layers (~60µm) on the selected 301SS stainless steel substrate is improved and bending of the multi-layer has been reduced. A power of 0.05 µW, harvested from 1 A of current flowing in a wire 12.5 mm from the tip mass, is comparable to other available MEMS-based technologies in the literature. Tests are under progress to integrate this EH in a system for electricity monitoring applications.

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