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Modeling and Analysis of PMN-PT Silicon-Integrated Micro-Actuator

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Abstract

Generally MEMS are Silicon capacitive devices. The described research provides the means for approaching towards different concepts combining silicon technology with piezoelectric materials into Piezo-MEMS systems. The present technology is based on the bonding and patterning of bulk PMN-PT Piezoelectric material on a Silicon wafer rather than Spitting thin piezoelectric films On the other hand bulk piezoelectric materials are more suited for micromanipulation actuators or energy harvesters. The advantage of PMN-PT piezoelectric material with respect to the PZT ceramics is presented in the context of the latest works. The technology and some results for actuation and energy harvesting are shown in the paper.

Keywords: PMN-PT(X=0.32); PZT-5H; MEMS.

Introduction

During the last decade a noticeable interest can be found in (1-x)$Pb(Mg_{1/3}Nb_{2/3})O_3$–(x)$PbTiO_3$(PMN–PT) “F. Wang et al.[1]”. Initially used as a ceramic, then grown into single crystals by modified Flex technique or the solid-state single crystal growth, PMN-PT have become commercially available. Those materials exhibit outstanding piezoelectric properties (e.g.d_{33}=3500 pC/N, d_{13}=-1200 pC/N, k_{33}=0.95etc.) that considerably surpass the PZT ceramics by a factor of 4 to 5 “I.A.Ivan et [2]”. The current numbers of reports on PMN-PT increases and diversify, with potential or existing applications in high frequency bulk and surface resonators and filters, sensors and actuators, ultrasonic transducers or energy harvesters. Most applications, which will not be detailed here, apply to the classical mechanical machining (saw dicing, ultrasonic cutting, lapping, polishing, etc.) of bulk material while others document very recent MEMS micro-devices, mainly on “S.Tadigadapa & K.Mateti [3]”. The use of high piezoelectric factor monocrystalline materials like PMN-PT which possess better piezoelectric and electromechanical coupling properties than the classical PZT-5H ceramics are thus the first advantage. Another advantage, in fact even more important than the former, is that the proposed solution is compatible with the Silicon micromachining processes. In consequence the miniaturized devices will be able in the future, like an example, to integrate not only the harvesting stage, but also to embed a part of the analogical electronic circuit.

There are already some very recent reports of using this material for actuators, ultrasonic transducers or energy harvesters, but by using classical structures like stacks and benders. However, we target a notable reduction in sizes and an integration of the active elements into a silicon wafer. For instance, such devices containing arrays of flexural beams will allow in the future energy harvesters with significant bandwidth increase.

This work is organized as follows: Section-2 presents the micro-manufacturing technology and provides references to some recent works. Section-3 discusses the material re-polarization and a micro-actuator design. Section-4 presents comparative results between PMN-PT and PZT-5H as energy harvesters. Section-5 concludes the paper.

Micro Modeling

The technology steps are as follows:

- Lapping and chemical cleaning of the PMNPT wafer.
- Chrome-Gold sputtering on both PMN-PT and Silicon sides – see Fig. 1.b. Gold thickness: >300nm. Gold layer

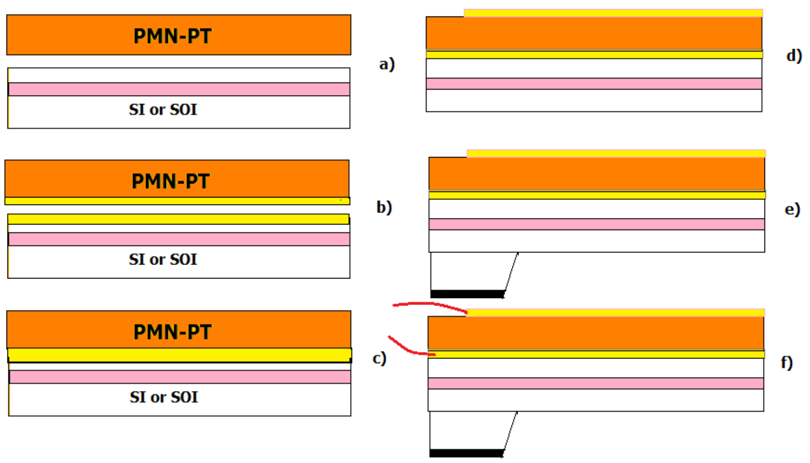

Figure 1: Micro-actuator's flowchart: a) initial PMN-PT and Silicon wafers; b) Cr-Au sputtering at interface; c) copper bonding; d) top electrode (Cr-Au) and bottom mask (Cr-Al) sputtering; e) saw dicing into individual beams followed by DRIE; f) wire bonding and external poling. As in "I.A.Ivan et al. [4]".

- Thermo-compression bonding of the copper layers; bonding is performed in vacuum, under a pressure of 2 MPa.as in Fig.2

Figure 2: Scanning electron microscope (SEM) image of a PMN-PT/Si small sample.[100µm]

- Chrome-copper or other metal deposition of the top electrode
- Photolithographies of the top electrode followed by wet etch. Lift-off could also be possible.
- Silicon bottom side DRIE-mask construction (SiO_2, Chrome-Aluminum etc.) (Fig1.d).
- DRIE etching of the bottom silicon side, see Fig1.e. If the silicon wafer is SOI (silicon-on insulator)type,there is the advantage of the oxide stopping barer to a fixed thickness. Otherwise, for a bulk Silicon wafer the etching time must be managed to reach the appropriate thickness.
- Conductive paste or copper wire bonding connection as in Fig. 1.f
- Final external re-poling of the PMN-PT material at room temperature and a constant 15 kV/cm field for over 20 minutes and testing of the device.

Piezoelectric Actuator [PMN-PT &PZT-5H]

PMN-PT Material Re-Poling The material has to be re-pulled due to the high pressure endured during bonding and due to high temperature during DRIE. The curves were recorded in a low frequency, high voltage sine wave form (+/- 250V, 4mHz or 600s). Re-poling of the PMN-PT material in both positive and negative field is reversible. Figure 3 shows the typical polarization shape. The first conclusion is that the piezoelectric strain vs. the external field (aka the “butterfly” curves) is not symmetrical, for reasons that have to be further investigated. The net stroke is higher in the original positive polarization.

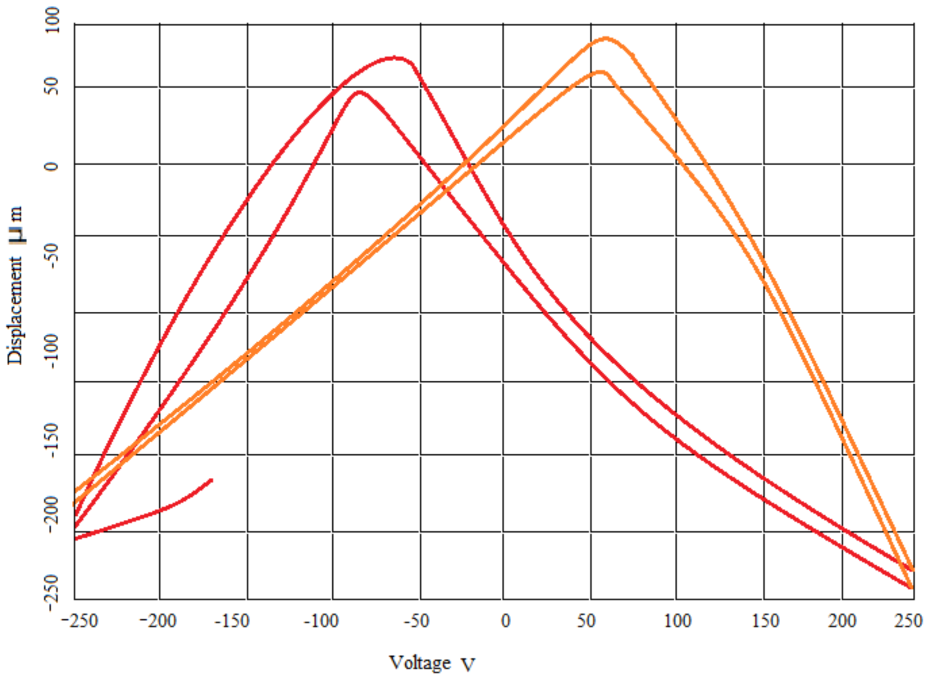

Figure 3: External re-poling curve of a PMN-PT/Si actuator

The coercive field of the PMN-PT is quite low compared to PZT, f -46V or 2.2 KV/cm which prevents large negative signal operation as in the case of PZT. Actuation and hysteresis properties The experimental results four types of PMN-PT / Si actuators as well as the PZT / Ni used as a comparison were confronted with the simulation results. There is certain dispersion in the values between different beams, at large and small voltages, either positive or negative The actuation capabilities results are compared to the ones of a classical PZT-ceramic actuator of equivalent size, demonstrating a 4 to 5 times net gain in terms of the displacement range of low voltage and 3 to 4 times at high voltage. The dynamics are improved by a factor of 2.7X for the same actuating range.

Piezoelectric materials characterize the hysteresis and creep nonlinearities. The influence of these phenomena generally increased with the amplitude of the applied electric field. In this part, we characterize the small and large signal hysteresis of the developed PMN-PT/Si piezocantilevers. First, the small signal hysteresis of two PMNPT cantilevers (belonging to the two lots) is compared with the PZT/Ni beam. By small signal we mean voltages that provide symmetric shapes, like up to 40V. For that, a sine input U is applied of fixed amplitude and varying frequency, then the output y is reported and finally the curve (U, y) is plotted for each. As we can see in the Fig.4 the PMN-PT/Si performs a large stroke with an associated hysteresis larger than to the compared PZT beam.

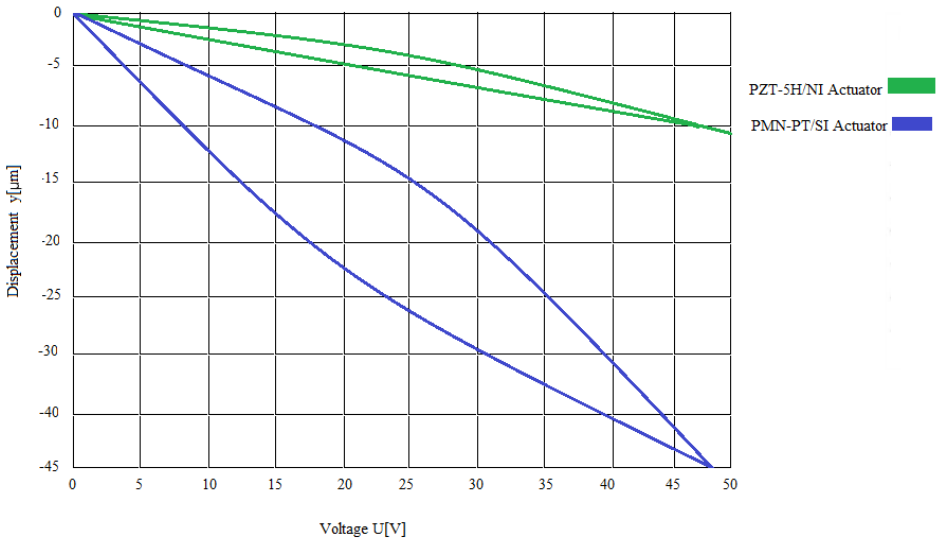

Figure 4: This figure 0V to 50V comparative actuator hysteresis characteristics of PMN-PT on silicon and of PZT on Ni. Sizes are 10.3mm long, 0.6 mm wide and 0.4 mm thick. The PMN-PT provides 5.5X the actuating range of the PZT.

The next experiment consisted in applying some large voltage signals (-45V to 250V) of low frequency (0.1Hz), the results being pictured in Fig.5. In the case of PZT we notice an increased actuation with the voltage, but with the cost of a much higher hysteresis. The PMN-PT hysteresis is significantly lower for large positive values, but nonlinear; from 50V we notice how the saturation starts occurring. As for the reverse fields, hysteresis shape is very large and asymmetric (Fig.5 left) The PMN-PT material may be driven theoretically until 400V but with the cost of an even increased nonlinear behavior.

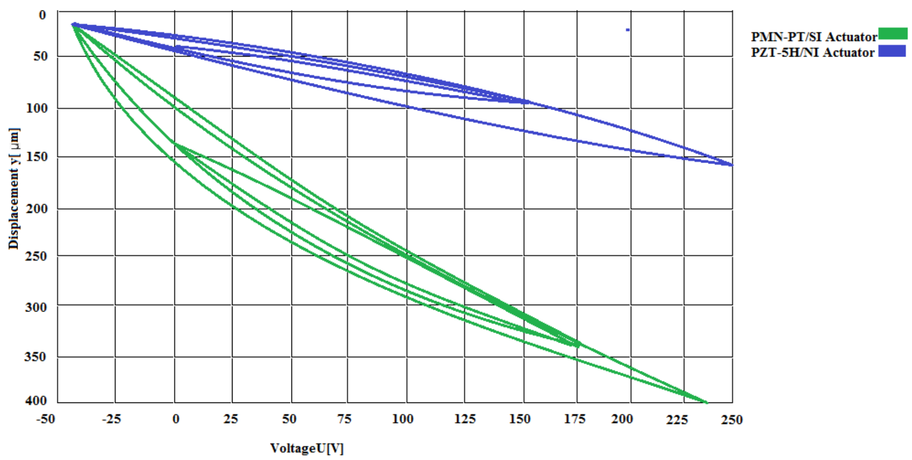

Figure 5: -45V to +250V large voltage hysterical behavior of PMN-PT on SI and of PZT on Ni. Sizes are 10.3mm long, 0.6mm wide and 0.4mm thick. The PMNPT actuator provides 3X more actuating than the range of the PZT.

Energy Harvesters [PMN-PT &PZT-5H]

The PMN-PT and PZT-5H materials were also tested as energy harvesters. Two identical cantilevers 20 mm long (active areas) and 5 mm wide were submitted to out of plane vibrations by means of a shaker. Vibration levels were imposed to ±1g amplitude.

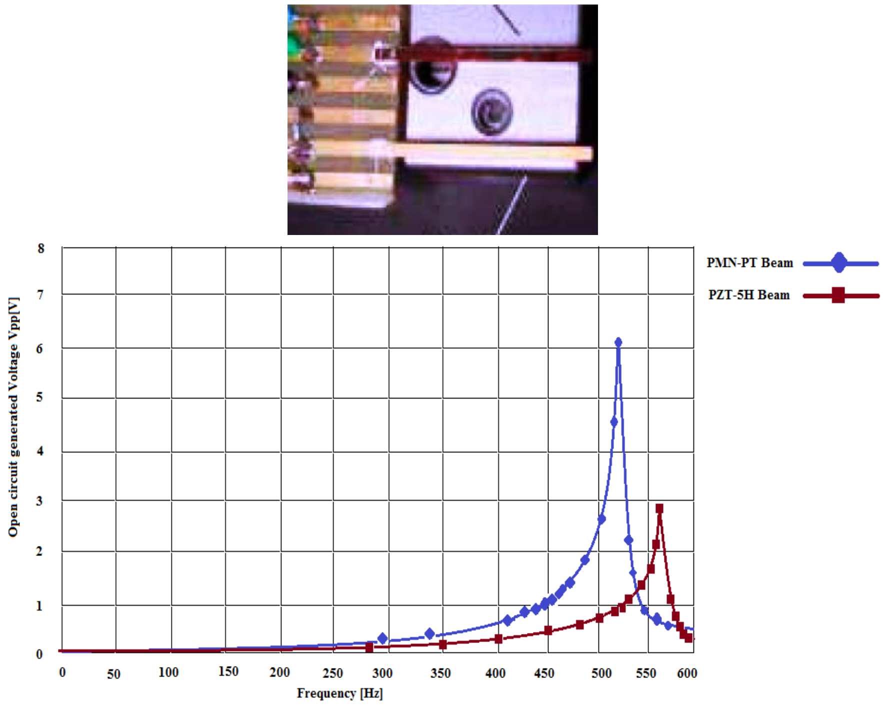

Figure 6: PZT and PMN-PT energy harvesting.The open circuit voltage corresponding to 1g peak-to-peak acceleration amplitude. The beams are 20 mm long.

The comparative results of Fig. 6 show a net improvement in terms of open circuit voltage generated by PMN-PT, by a factor of 2. This fact is particularly important for devices intended to scavenge low amounts of ambient vibration.

Conclusions

The overall intentions of the described works consisted in advancing the research limit, Towards more integrated and more autonomous piezoelectric devices such as microactuators or energy harvesters. These preliminary results were presented showing successful PiezoMEMS applications based on bulk PMN-PT on silicon substrate. The electro-mechanical characterization clearly shown a net performance improvement with respect to the classical designs based on PZT ceramics.

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