Optimization of the geometry of MEMS Piezoelectric Energy Harvester cantilevers

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1. Introduction

The rapid growth of microfabrication techniques is ameliorating the progress in the low-cost, low-power, multi-function (ICs) such as independent Wireless Sensor Nodes (WSNs). Thus an independent battery-less device, that could harness energy from ambient environment vibration is a feasible way to supply continuous power to the WSNs.[1]. The direct piezoelectric effect can be utilized to harvest energy from the ambient vibrations as enough mechanical strain can be generated inside the piezoelectric material during the vibration. Cantilever beam based transducer (unimorph or bimorph) is the most commonly employed architectures in Piezoelectric Energy Harvester (PEH), since the resonance frequency of the fundamental modes of cantilever is lower than those of the other configurations such as plate or membrane. [2, 3] This research focuses on a micro-scale vibration energy harvester, applicable to powering a micro-scale sensor node. A cantilever beam configuration was chosen for its simplicity, compatibility with MEMS manufacturing processes, and its low structural stiffness. The designed structure work in the bending mode in which top layer of the film is in tension and the bottom layer in compression and generate voltage based on the direct piezoelectric effect. The preliminary optimization of the transducer is carried out using using Finite element analysis in COMSOL. Previous studies on harvester geometry so far focused on tailoring cantilever geometries involving length [2] nontraditional tapered structures[4], using multi-stack piezoelectric layers [5], using different shapes[6] in order to to improve the PEH performance but little on the optimal thickness of the piezoelectric layer. Here we optimize the geometry: proof mass length Lm to total length L, thickness of the piezoelectric material (T_p) to total cantilever thickness (T) for obtaining the maximum stress distribution (S_{max}), output voltage (Vout) and power performance (P_{out}) of the unimorph Cantilever beam based PEH. The study also shows that the length of proof mass and the stress has a dominant effect on the magnitude of the electromechanical output of the transducer. The Piezo layer to silicon substrate thickness ratio is important and may be tailored to optimize the electromechanical coupling or voltage. The results can be used to form a set of design guidelines for the performance optimization of MEMS/NEMS piezoelectric membrane generators.

2. Piezoelectric MEMS Cantilever geometry

Here we investigate d31 mode of operation. The goal was to design a thin, compact vibration energy harvester able to generate optimum power from a 3 × 3 mm^2 device electrode area with a maximum substrate thickness of 10 µm when subjected to low frequency vibrations and low accelerations (1g).

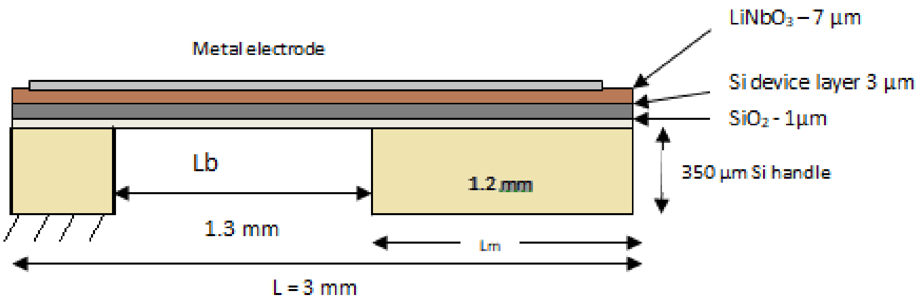


Fig.1: Cross section Schematic of the device under study

The design under study was a unimorph MEMS structure (Fig. 1) with different piezoelectric material such as Lithium Niobate (LN) and Lead zirconate titanate (PZT)stack placed on a silicon (Si) cantilever based on SOI wafer on 350 µm handle layer and 1 µm oxide layer. The harvester thickness is optimized by choosing an optimal piezoelectric layer and silicon wafer layer. Coupled 1-D and modal (beam structure) electromechanical models are presented to predict performance, especially power, from measured low-level ambient vibration sources. Lm is the length of proof mass and L is the length of the cantilever beam.

3. FEM Modelling

Physics Involved in the modelling includes solid mechanics, electrostatics and AC-DC module in the COMSOL Multiphysics. The substrate is assumed to be linear elastic material that bends according to the stress produced.

Mechanical Boundary conditions applied: Body Load was applied to the whole system, assuming a constant force per unit volume, i.e. acceleration equal to 1g. Fixed Constraint this is the second boundary condition where the one end of the beam is fixed so that the other end can vibrate about the mean.

Electrostatics boundary conditions: The following equations were applied to determine the charge distribution and the output voltage determination from the material:

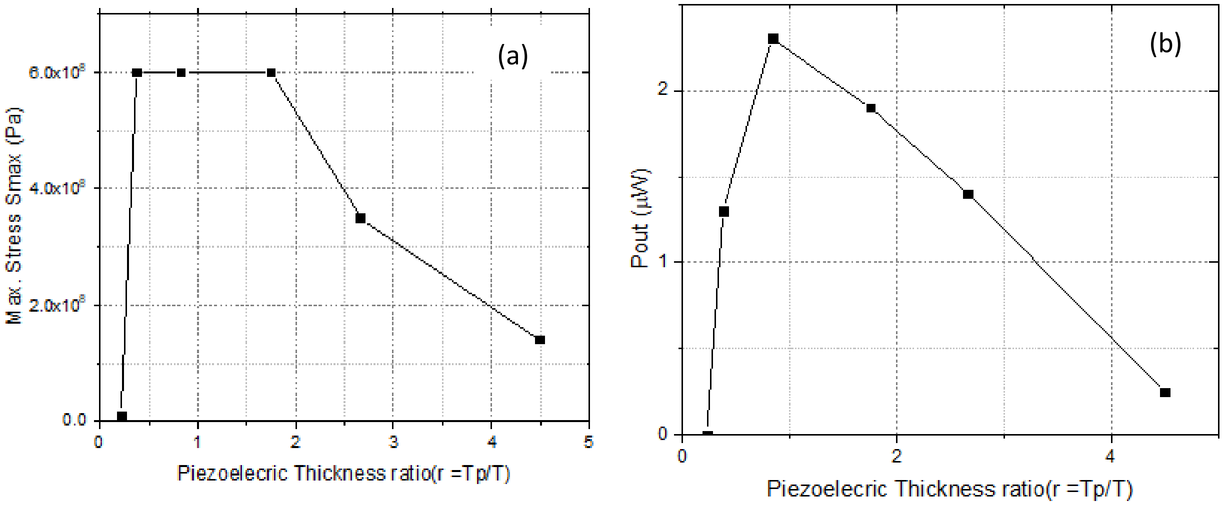
$$\nabla \cdot \mathbf{D} = \rho_v$$

$$\mathbf{E} = -\nabla V$$

Charge Conservation is necessary to define the boundary of the piezoelectric material. The charges reside only on the surface of the metal electrode as well. Zero Charge is specified for the ground so that no charge resides on it, and the potential therefore is zero. Charge Conservation is necessary to be specified for the piezoelectric material because there is the spontaneous polarization inside the material on the application of strain. Then a ground is specified to one of the electrode to define a zero reference potential, V=0. Terminal is defined to obtain the output voltage from the upper electrode, generally terminal voltage is considered as the output voltage wrt. ground. Triangular Mesh is used throughout, that helps to reduce the voids.

4. Result and Discussion

Fig. 2 shows the optimal thickness (r) for the (a) maximum stress (b) maximum power (c)maximum cantilever displacement as well as the (d)maximum output voltage (Voc). Tp is the thickness of the piezoelectric material and T is the total cross sectional thickness including the piezoelectric material and the substrate (piezo+substrate-Si/SiO2).



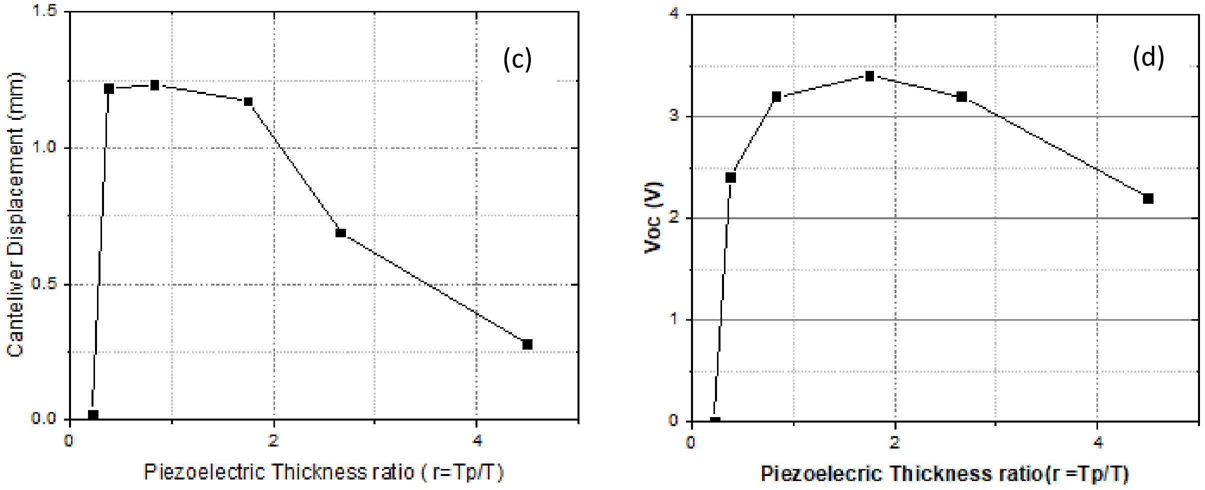


Fig.2: Dependence of the (a) Maximum stress (S_{max})and (b) Output power (P_{max}) (c) Cantilever displacement (d) Open circuit Voltage (Voc) with the piezoelectric thickness ratio (r=Tp/T)

The maximum output power (Pout) was obtained at the Lm/L ratio ~ 0.4. Also, it was obtained that the maximum stress developed inside the beam is near the root of the beam when the ratio r= Tp/T is close to 1 to 2. The maximum output power (Pout) is obtained from the PEH at the maximum strain induced at the optimum ratio r =1 as evident from the Fig. 2 (b and c). Similarly, the Open circuit voltage (Voc) generated across the electrodes were plotted against the optimal thickness Tp/T ratio. It was observed that the maximum Voc is generated when the Tp/T ratio is close to 2.

5. Conclusion:

We have determined the optimal ratio of the piezoelectric material to the substrate thickness to obtain the maximum stress, power, cantilever displacement and the output voltage respectively. This study therefore throws insight on optimal thickness of the piezoelectric material relative to the substrate to obtain a maximum electromechanical coupling for a given geometry and therefore the electrical outputs namely the voltage and power of the harvester.

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