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Research Paper

Design and simulation of MEMS P(VDF-TrFE) cantilevers

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Abstract

This paper presents design and simulation of micro-electromechanical systems (MEMS) based piezoelectric cantilevers and beams. Poly (vinylidine fluoride-trifluoroethylene) (P (VDF-TrFE)) co-polymer was chosen as the piezoelectric material which has better piezoelectric properties than other polymers. These piezoelectric co-polymer cantilevers form the main elements as low level and low frequency energy harvesters or vibration sensors. P (VDF-TrFE) cantilevers and beams were designed to take advantage of unimorph d_{33} mode. The design has an active P(VDF-TrFE) layer, Cr/Au electrode of interdigitated pattern for power/signal output. The design is to be implemented on 2 inch diameter, <110> silicon base, bulk micro-machined using TMAH etchant. P(VDF-TrFE) cantilevers and beams were simulated using Comsol Multiphysics simulation software with dimensions in the range 100-400μm width, Length 200-2000μm and all having thickness of 2.5μm. The mechanical and electrical properties of cantilevers were analyzed during the simulation. The results show that the fundamental resonance frequency varied from 6.483 kHz for 100 (W) x 200 (L) μm^2 to 63.328 Hz for 400 (W) x 2000 (L) μm^2 cantilevers. Similarly, the fundamental resonance frequency varied from 41.98 kHz for 100 (W) x 2000 (L) μm^2 to 410.76 Hz for 400 (W) x 2000 (L) μm^2 for beams. Hence, it is clear from the simulation results that, as the length of cantilever/beams increases fundamental resonance frequency decreases.

Keywords: Microelectromechanical systems, P(VDF-TrFE) cantilevers, beams, energy harvesters, vibration.

1 Introduction

With the advancement of technology in electronic systems such as wireless sensors, mobile phones, external wearable medical devices etc, researchers have focused on advancement of smaller volume and durable power sources. Batteries as a conventional power sources have some limitations due to its higher volume and a limited lifetime [1, 2]. To reduce the energy sources issue, energy harvesting is an attractive way to extract energy from environmental renewable energy sources such as solar, wind, tidal and geothermal [3]. Furthermore, ambient mechanical vibration can be recycled to generate electrical energy for wireless sensor networks, chemical sensors [4] and health monitoring [5]. Vibration based energy harvesters efficiently convert vibration energy into electrical energy using three electromechanical transduction processes: electrostatic, electromagnetic, and piezoelectric [6-8]. Among those transduction methods, piezoelectric transducers have attained much attention due to the simplicity in configuration and higher conversion efficiency [9, 10].

In piezoelectric transduction there are some piezoelectric materials namely, Lead Zirconate Titanate (PZT), Polyvinylidene Fluoride (PVDF) and their co-polymers [11], and Aluminium nitride (AlN) [6]. When those piezoelectric materials are configured for mechanical energy, then electrical energy will be generated and vice versa as shown in Figure 1 [12].

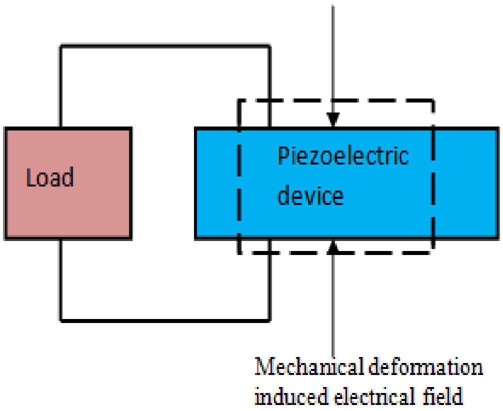

Figure 1: Piezoelectric effect of piezoelectric materials.

Ambient mechanical vibration sources generally provide lower frequencies (< 1000 Hz); in order to utilize ambient vibration properly, resonant frequency of piezoelectric energy harvester should be in the range of vibration. Moreover, maximum energy can be harvested efficiently when energy harvester is driven at the resonant frequency [13]. However, there is a limited choice of piezoelectric materials suitable for low frequency resonator designs. PVDF is an attractive piezoelectric material for harvesters owing to its low elastic stiffness allowing the design of resonators with the fundamental mode of vibration below 1000 Hz. Recently it has been reported that Poly (vinylidine fluoride-trifluoroethylene) (P(VDF-TrFE)) has better piezoelectric properties than PVDF. Due to flexibility, lower resonant frequency and high stress generation, cantilever geometry is more preferred for energy harvesting. In this paper, unimorph (which is having one piezoelectric active layer) d_{33} mode P (VDF-TrFE) single cantilevers and beams of different dimensions were analyzed to realize desirable mechanical and electrical properties.

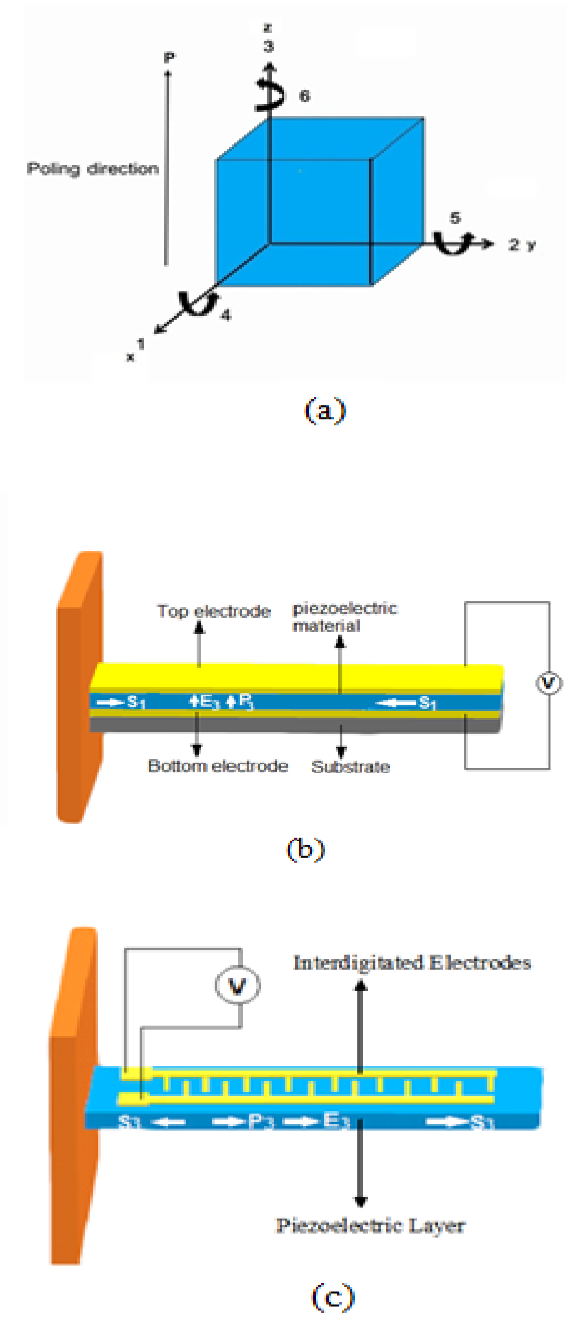

Figure 2: (a) Dielectric displacement direction of stress and polarization (b) d_{31} mode cantilever (c) d_{33} mode cantilever.

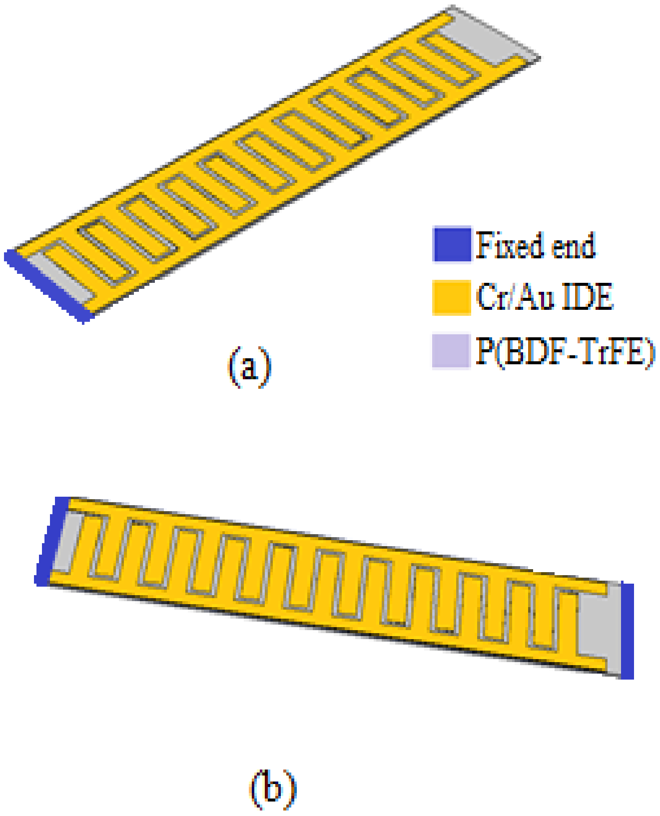

Figure 3: Model of unimorph d_{33} mode P(VDF-TrFE) (a) Single cantilever, (b) Beam.

2 Theory

In piezoelectric effect, if piezoelectric material is physically deformed by vibration, pressure or force, then it will create induced electrical field. In contrast, if electrical energy is applied then it will induce mechanical deformation [14]. The electrical and mechanical behavior can be modeled by the following two equations:

$$S = S^E T + dE \tag{1}$$

$$D = dT + \epsilon^T E \tag{2}$$

Where S = mechanical strain, D= electric displacement, T = applied stress, E = electric field, d = piezoelectric strain constant, S^E = elasticity matrix under constant electric field, ϵ^T = permittivity matrix under constant mechanical strain. The cantilever model can be used in two different modes, d_{33} (compressive mode) and d_{31} (transverse mode). The suffix denotes the direction of induced polarization and the stress direction. In d_{33} mode the induced polarization is in direction 3 per unit stress applied in direction 3, where as in d_{31} mode the induced polarization is in direction 3 per unit stress applied in direction 1, which is depicted in Figure 2.

3 Design of P(VDF-TrFE) cantilevers and beams

Unimorph d_{33} mode P (VDF-TrFE) single cantilevers and beams were designed using Comsol Multiphysics simulation software. Single cantilever is one which is anchored at only end whereas beams are anchored at two ends. These single cantilevers and beams consists of an active P(VDF-TrFE) layer and Cr/Au electrode of interdigitated(IDE) pattern for power/signal output which as shown in the Figure 3. The properties of P (VDF-TrFE) and Cr/Au have been shown in Table 1. In this study four different dimensions of devices were analyzed, Table 2 shows the different dimensions used for simulations.

4 Simulation set up

Comsol Multiphysics a finite element method (FEM) based partial differential equation (PDE) solver is used to simulate our devices. We used the solid mechanics module to simulate the mechanical domains and the piezoelectric devices module to simulate the piezoelectric properties of the P(VDF-TrFE) layer. In solid mechanics physics, the boundary conditions for the devices such as free end, fixed end, applied vibration and damping of the beam materials have been set up. The base parts of the devices were kept constant. The rest of the beam was under free conditions. After applying vibration, the free part can be displaced. A constant force of 0.5 μN is applied on all the devices.

Table 1: Material properties

Material properties	Material used		
	P(VDF-TrFE)	Chrome	Gold
Young's Modulus (GPa)	0.7	279	70
Density (Kg/m^3)	1890	7150	19300
Poisson's ratio (GPa)	0.43	0.21	0.44

Table 2: Device dimensions.

Si. No.	Length (L) um	Width (W) um	Thickness (t) um
1	200	100	2.5
2	600	200	
3	1000	300	
4	2000	400	

During the boundary condition of electrostatic physics, the top and bottom fingers of the IDE were used as terminals and all other faces of the piezoelectric layer were kept at zero charge constraint. The electrostatics physics was coupled with electrical circuit physics so that electrical response of the beam can be obtained. After that, tetrahedral mesh with fine element size was used for the discretization of the beam. Eigen frequency analysis and stationary analysis were performed to determine resonant frequency and output voltage of the devices, respectively.

5 Results and discussion

P(VDF-TrFE) single cantilevers and beams of d_{33} mode unimorph structure have been studied to obtain mechanical and electrical properties. In this study, resonant frequencies and the output voltage of the devices were analyzed by applying a load of 0.5μ N.

Table 3: Resonant frequencies obtained for single cantilever and beams.

Dimensions μm^3	Frequency in Hz	
	Single cantilever	Beams
100 (W) x 200 (L) x 2.5 (t)	6.483 k	41.98 k
200(W) x 600 (L) x 2.5 (t)	709.57	4.781 k
300(W) x 1000 (L) x 2.5 (t)	264.47	1.659 k
400 (W) x 2000 (L) x 2.5 (t)	63.58	410.76

5.1 Eigen frequency analysis

Eigen frequency analysis was conducted to obtain the resonant frequency of the piezoelectric P(VDF-TrFE) cantilevers. The value of resonant frequency is essential, since the energy conversion from the mechanical to electrical energy will be maximum when the piezoelectric cantilever is driven at its resonant frequency. These cantilevers can have many different modes of vibrations, each with different resonance frequency. The first mode of vibration has lowest resonance frequency, provides maximum displacement, and hence, maximum output voltage. Figure 3 (a) and 3(b) depict the results related to the first mode of vibration resonance frequencies of single cantilever and beams of dimension 300(W) x 1000(L) μm^2, respectively.

5.2 Voltage analysis

The voltage analysis was done by applying boundary conditions to the devices, in order to obtain the piezoelectric voltage generated in the P(VDF-TrFE) cantilevers and hence to calculate the power output. The obtained voltages and power output for single cantilever and beams of different dimensions are summarized in the Table 4.

Table 4: Simulated voltage and power output for single cantilever and beams of different dimensions at resonant frequencies.

Dimensions μm^3	Voltage (mV)		Power	
	Single cantilever	Beams	Single cantilever (mW)	Beams (μW)
100 (W) x 200 (L) x 2 (t)	70	2	4.08	3.33
200 (W) x 600 (L) x 2 (t)	100	6	8.3	30
300 (w) x 1000 (L) x 2 (t)	120	14	12	163.3
400 (W) x 1000 (L) x 2 (t)	180	20	27	333

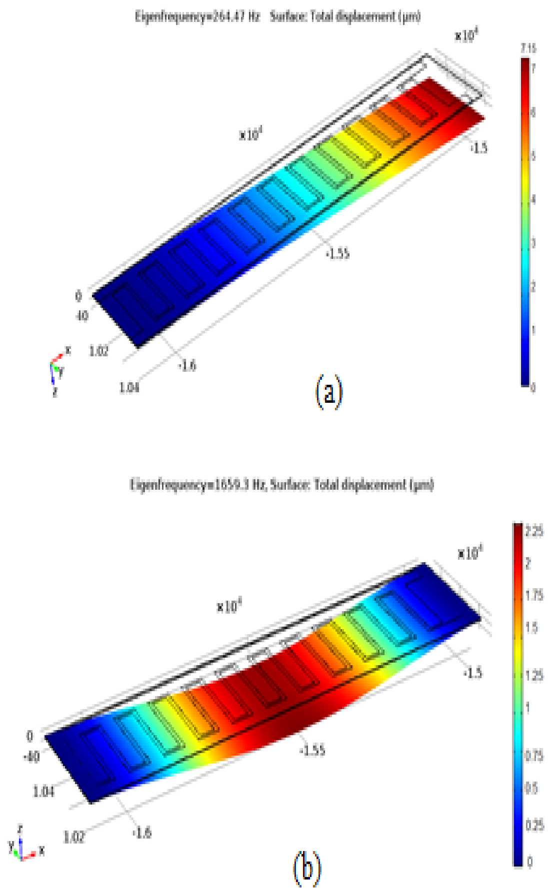

Figure 4: Simulated resonant frequency (a) Single cantilever (b) Beam.

It is clear from the above results that the single cantilever of dimension 400(W) x 2000(L) x 2(t) μm^3 gives the highest power output of 27 mW with lower resonance frequency of 63.58 Hz. Whereas other dimensions give less piezoelectric voltage and power output. Hence, we can say that all the designed devices with P(VDF-TrFE) shows ambient deflection but out of them single cantilever of dimension 400(W) x 2000(L) x 2(t) μm^3 gives the best results.

6 Summary

In this paper d_{33} mode unimorph P(VDF-TrFE) single cantilevers and beams were designed and simulated using COMSOL Multiphysics. The simulation results such as eigen frequency, voltage and power output were analyzed for different dimensions of the single cantilever and beam structure. It is analyzed that single cantilever of dimension 400(W) x 2000(L) x 2(t) μm^3 gives the maximum voltage of 180 mV and power output of 27 mW, with applied force of 0.5μ N at resonance frequency 63.58 Hz.

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