Design and Simulation of a Micro Piezoelectric Energy Harvester Based on a Mass Proof Cantilever

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1. Abstract

A micro piezoelectric vibrational energy harvester based on a mass proof cantilever with a thin aluminium nitride film was designed and simulated. The fabrication strategy, design parameters and simulation results were presented and an evaluation of its applicability is discussed.

2. Introduction and Motivation

The continuous improvement of electronic devices has enabled the development of sophisticated ultra-low power systems with integrated sensors, low range wireless transmitters and controlling processing units. The research for alternative methods for powering these systems led to the development of micro vibrational energy harvesters. The use of piezoelectric materials has a significant advantage for this application, due to the direct conversion of mechanical stress in electrical charge, and the use of aluminium nitride (AlN) enables an easy integration with microfabrication processes.

The proposed energy harvester design was made for the MEMSCAP PiezoMUMPs process [1], offered in a multi wafer project manner to enable low-cost prototyping of piezoelectric micro-electro-mechanical-systems (MEMS) devices. The process is based on a silicon on insulator (SOI) wafer and consists of five lithographic steps. Structures in the top silicon layer can be released with a through-wafer etch of the bottom silicon layer. An AlN thin film is deposited on top of the top silicon, and a conductive metal film can be deposited over it, acting as a top electrode and electrical path. The top silicon is used for the patterning of the mechanical structures and also acts as bottom electrode. A thermal oxide film is used for interlayer isolation.

3. Device Operation and Design

The mass proof cantilever has been proved as an effective design for vibrational energy harvesting by numerous authors [2, 3, 4, 5, 6] and the AlN has been compared with PZT (a material with a much higher piezoelectric coefficient) showing theoretical better results for this application [7].

The oscillation of the mass in the free tip of the cantilever, due to the ambient mechanical vibrations, promotes a high stress in the anchored end of the structure where the piezoelectric film is deposited, generating charge that flows as an electric current to the circuit to be powered. In this way, the energy generated depends, among many other factors, on the size of the tip mass, the geometrical parameters of the cantilever, the frequency and intensity of the environmental vibrations and the input load of the powered circuit.

In order to effectively harvest the environment vibrational energy the device must be designed with a low resonant frequency, matching the higher energy harmonics frequencies in typical sources of mechanical vibrations [8]. For that reason, the aimed resonant frequency for the designed structure was below 200Hz.

The weight of the tip mass, the increased length and the reduced width of the cantilever contributes to a lower resonant frequency [6]. The PiezoMUMPs process imposes a maximum released mass of 1x1mm and due to sub-die dimensional constraints, the length of the cantilever was limited to 3200µm. A conservative width of 400µm was chosen in order to avoid premature mechanical failure of the silicon beam. The PiezoMUMPs process sets the thicknesses of the layers as follows: 400µm bottom silicon; 1µm buried oxide; 10µm top silicon; 0.5µm AlN; 1.015µm metal layer (0.015µm of chrome with 1µm aluminium on top).

A tri-dimensional model of the designed structure is shown in Fig.1. The calculated fundamental resonant frequency of 147.41Hz was obtained disregarding the effects of the thin films on top of silicon. This value was validated by a finite-elements method (FEM) simulation using COMSOL Multiphysics software.

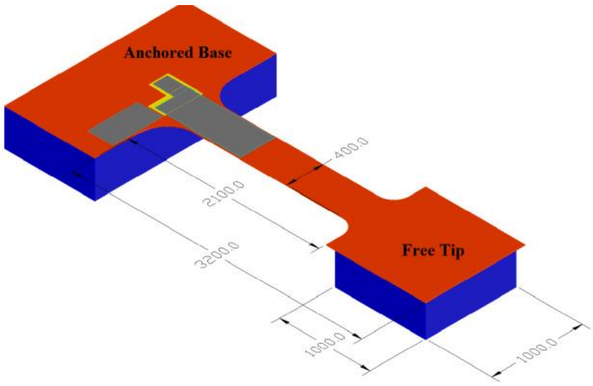

Fig.1. *Device structure with dimensions in µm.*

4. Simulation

The proposed design performance was simulated using a simple one dimensional model based on a piezoelectric accelerometer [9]. The specific AlN parameters were extracted from measurements published in relevant articles using similar AlN deposition processes. The actual parameters are highly dependent on the process recipe and can only be accurately determined once the fabricated device is tested, but for estimation purposes the parameters values used will suffice. The Table I below lists those.

Table I. *Material parameters values and references.*

Parameters	Value	Reference
Monocrystalline silicon density and elasticity coefficient	2320kg/m³ 160GPa	[10]
AlN transversal piezoelectric coefficient, resistivity and relative dielectric coefficient	-2.8pC/N 252MΩm 10	[11] [12] [13]
Dry air viscosity and density	17.66μNs/m² 1.134kg/m³	[14]

The generated power has a complex relation with many parameters, but it is directly proportional to the square of the acceleration of the ambient vibrations; to the tip mass; to the match between the device resonant frequency and the ambient vibrations frequency; and to the inverse of the damping coefficient. The damping coefficient was modeled using Navier-Stokes equations, having multiple parcels related to the different sources of damping in the structure [15].

Considering a moderate intensity source of environmental vibration, with an acceleration of $4m/s^2$ in the resonant frequency of the device, the generated power and output voltage relates to the resistive electrical load of the powered circuit as shown in Fig. 2.

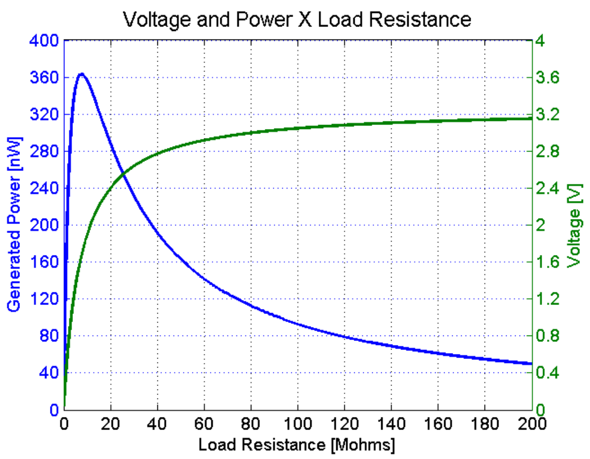

Fig.2. *Plot of generated power and voltage vs load resistance for ambient vibrations of 4m/s² of intensity in 147.41Hz.*

A maximum of 363nW power generation occurs for the optimal load of 7.61MΩ, with a voltage of 1.66V. The relationship of the generated power and the optimal load resistance with the ambient vibration frequency was also simulated and it will be presented in another work.

5. Discussion and Conclusion

The ambient vibration acceleration used is of moderate intensity and can be found in industrial environments. The total generated power achieved by fitting the maximum of 6 devices in a PiezoMUMPs regular-size die, considering optimal conditions, would be of 2.18μW. This is enough to feed a low-power wireless sensor system. Auxiliary circuitry such as rectifiers and impedance matching circuits should be used in a real application and that shall be discussed in future work.

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