MEMS STRUCTURE FOR ENERGY HARVESTING

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CONTENTS

Motivation

The great majority of present day microelectronic devices use battery for getting energy. A battery suffers from several limitations :

- requires recharging or sometimes even replacement from time to time.
- large size
- large weight

} compared to high technology electronics

These constraints become very significant in some applications such as sensors for structural health monitoring in remote locations, etc.

Remedy: Energy can be extracted from the environment to either recharge a battery, or even directly power the electronic device.

Advantage: (1) Reduction in size and weight of the device.
(2) Such energy harvesting devices can be made using standard CMOS fabrication techniques. Hence the complete system including the power source can be fabricated on a chip (SOC).

ENERGY SOURCES IN NATURE

Source of energy	Energy type
Human	Kinetic, Thermal
Environment	Kinetic, Thermal, Radiation

AIM

- To develop a cantilever based "vibrational energy harvesting MEMS structure" which can be fabricated using MOSIS standard CMOS fabrication techniques.
- Validating the concept by simulating the device using COMSOL.
- To develop a process flow for the fabrication of the cantilever using standard CMOS processes.

MEMS structure for energy harvesting

Design Specifications:

(All dimensions in μm)

- Si Cantilever:

Length = 2000/3000/4000
Width = 800
Thickness = 4/8/12/16/20

- Proof mass (Si):

Density of Si = 2330 kg/m^3
Length = 1000
Width = 800
Thickness = 300
Mass = Volume x density
= 0.5592 μg

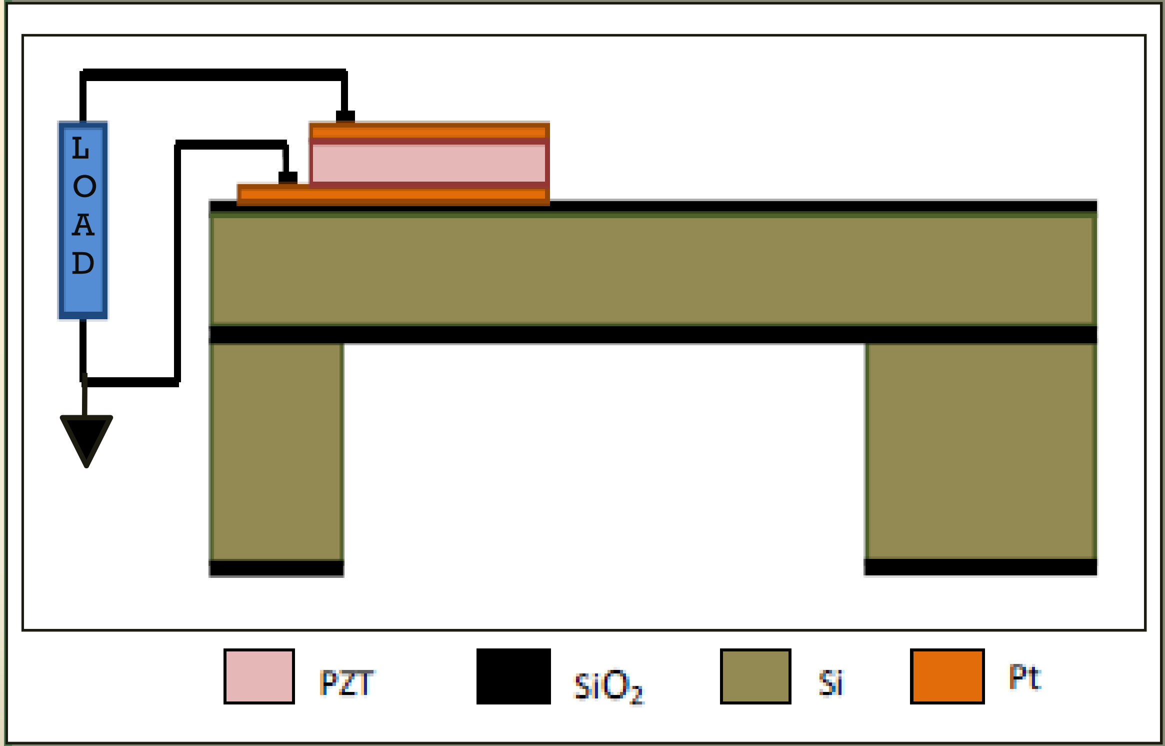


Fig. Lateral view of the MEMS structure

Basic principle of operation

- ✓ A cantilever oscillates when placed in a vibrational environment.
- ✓ The oscillation attains a peak value if the vibration frequency of the environment matches the resonance frequency of the cantilever, and dies out dramatically for other frequencies.
- ✓ These oscillations produce strain, which in turn produce stress. Both stress and strain vary along the length of the cantilever.
- ✓ The amplitude of oscillation is maximum at the free end and the stress is maximum at the fixed end.
- ✓ This stress results in the generation of charges, and hence electric potential when it is applied across a piezoelectric material.
- ✓ The electrical power output is maximum when the stress produced is maximum, i.e. at the resonance frequency.
- ✓ The proof mass lowers the resonance frequency of the beam to a value of the order of few hundreds of Hz which is generally the order of the frequency of vibrations present in the nature.
- ✓ It also increases the amount of deflection, which increases the amount of stress produced at the fixed end which consequently increases the output voltage and power.

MEMS micro generator used for charging a battery

- ✓ Electrodes are used to conduct the electric charge produced to an electrical circuit.
- ✓ The entire MEMS structure can be modeled by an equivalent current source with capacitive source impedance.
- ✓ This source can be used to store energy or drive a load directly.
- ✓ The output voltage of the piezoelectric source is transient in nature, and is converted to a more useful DC voltage by using some form of rectification.

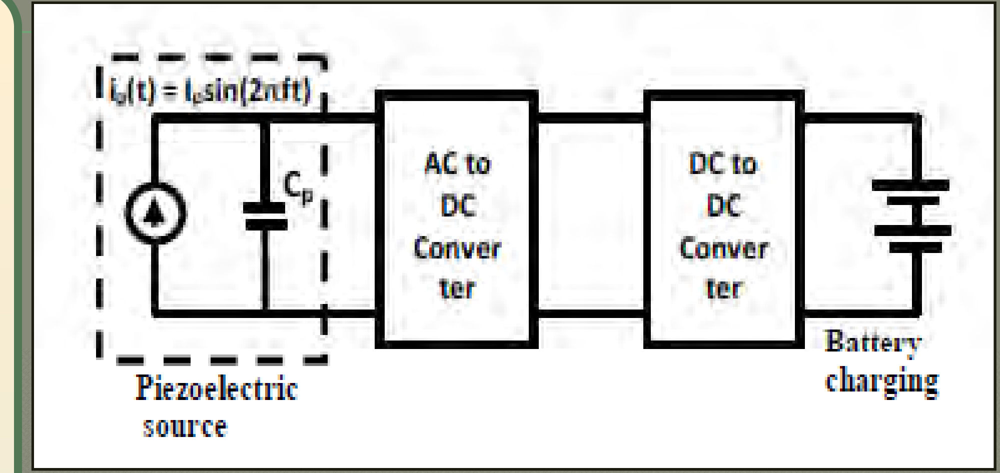


Fig. EH system charging a battery

- ✓ DC to DC conversion schemes are used for enhancing the charging efficiency of the battery by allowing the device to draw more power over a short period than the harvester is able to provide.

Theoretical background

Piezoelectric effect

Piezoelectricity means electricity resulting from pressure. The piezoelectric effect can be understood as the electromechanical interactions in crystalline materials with no inversion symmetry. The IEEE standard on piezoelectricity gives different forms of piezoelectric constitutive equations. The form used here is strain-charge form, and the equations are as follows:

$$\epsilon = s^E \sigma + d^T E$$
$$D = d\sigma + \epsilon_0 \epsilon_{rs} E$$

where, σ = Stress
ϵ = Strain
ϵ_{rs} = Relative permittivity
s^E = Compliance matrix
d = Coupling matrix
D = Electric displacement vector
E = Electric field

Theoretical background

Mathematical analysis of cantilever

The resonance frequency of the cantilever can be theoretically estimated by assuming the cantilever to be an Euler's Bernoulli beam and the proof mass as a point load at the free end.

- Governing equation of Euler's Bernoulli beam

$$\frac{\partial^4 \delta}{\partial x^4} + \frac{\rho A}{EI}\frac{\partial^2 \delta}{\partial t^2} = 0$$

- General solution for sinusoidal oscillation

$$\delta(x,t)=\{A(x)+B(x)+C(x)+D(x)\}.\sin(\omega t)$$

where, $A(x) = c1\sin\beta x$, $B(x) = c2\cos\beta x$,
$C(x) = c3\sinh\beta x$, $D(x) = c4\cosh\beta x$

and

$$\beta^4 = \frac{\rho A \omega^2}{EI}$$

- With proof mass assumed to be acting as a point load at free end, boundary conditions for a beam of length L are:

$\delta(0,t) = 0$; $\delta_x(0,t) = 0$; $\delta_{xx}(L,t) = 0$
and $\delta_{xxx}(L,t) = -(m\omega^2/EI)\delta(L,t)$

Theoretical background

Mathematical analysis of cantilever

- If we model the beam deflection as a 1st order spring-mass system, then the resonant frequency can be estimated as:

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m_{eff}}}$$

Where, total effective mass

$$m_{eff} = 0.236\rho AL + m_{proof}$$

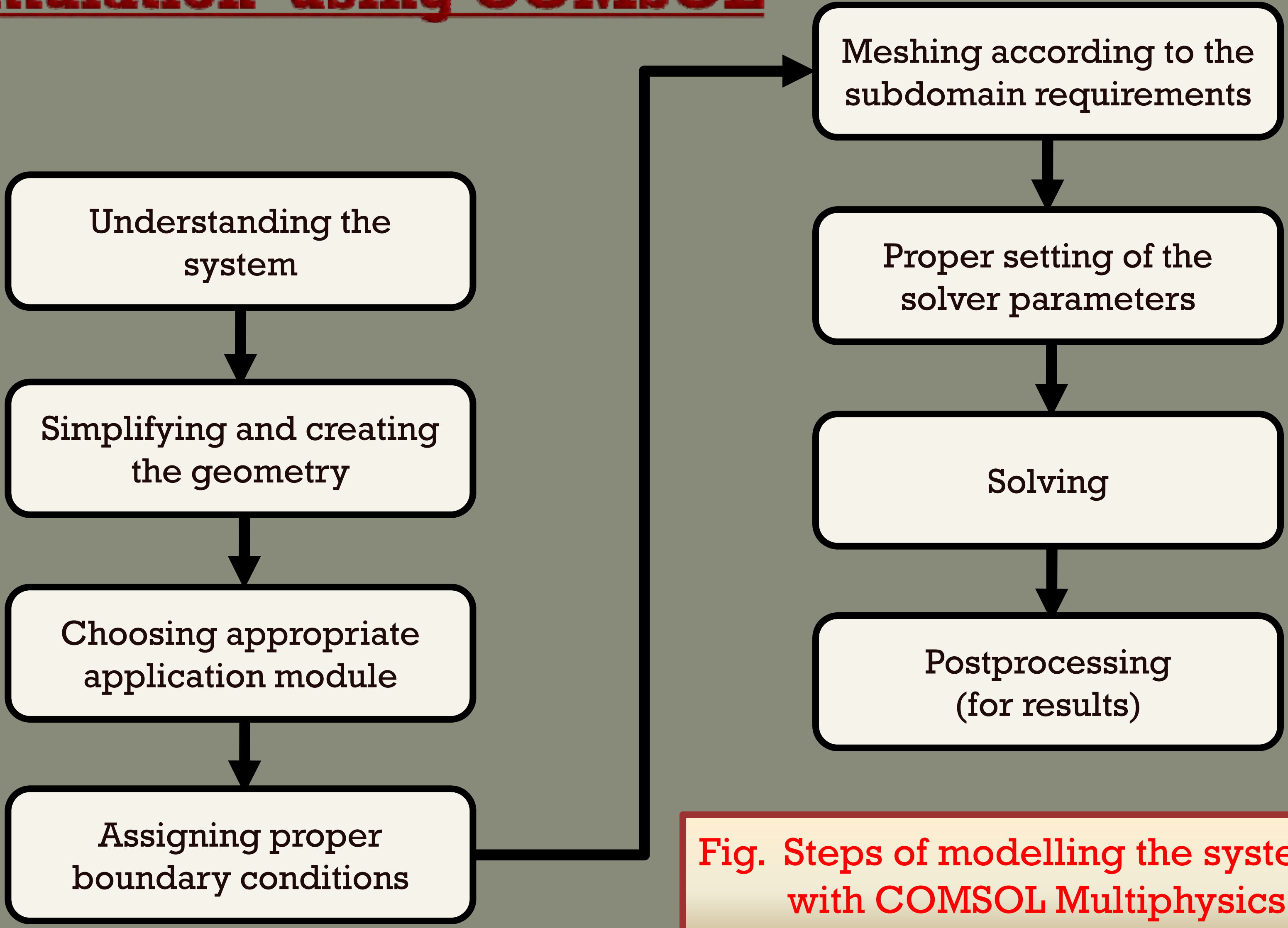
and, effective stiffness coefficient

$$k_{eff} = \frac{3EI}{L^3}$$

To model the effects of the distributed mass loading of the proof mass, the effective length of the cantilever can be substituted for the length of cantilever:

$$L_{eff} = L_{beam} - 0.5L_{proof}$$

Simulation using COMSOL



Understanding the system

Simplifying and creating the geometry

Choosing appropriate application module

Assigning proper boundary conditions

Meshing according to the subdomain requirements

Proper setting of the solver parameters

Solving

Postprocessing (for results)

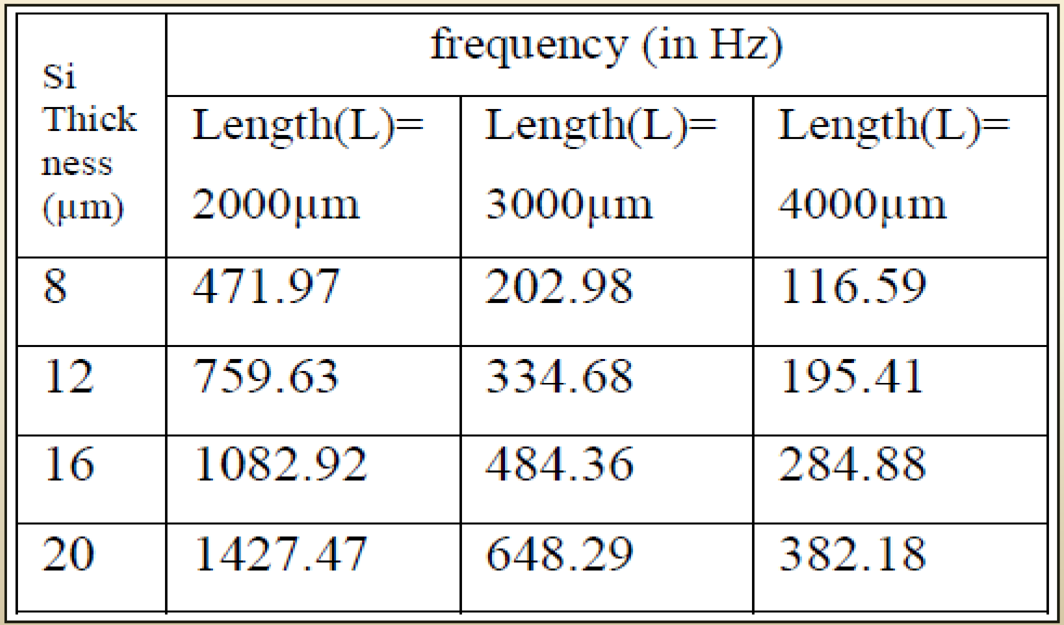
Fig. Steps of modelling the system with COMSOL Multiphysics

Simulation results

- ☐ The structure was simulated using MEMS module of COMSOL Multiphysics.
- ☐ The electrical circuit (a resistive load) was introduced through PSPICE netlist.

The length and thickness of the cantilever were changed to obtain different resonant frequencies.

The resonant frequency increases with an increase in the cantilever thickness and decreases with an increase in the cantilever length.



Si Thickness (μm)	frequency (in Hz)		
	Length(L)= 2000μm	Length(L)= 3000μm	Length(L)= 4000μm
8	471.97	202.98	116.59
12	759.63	334.68	195.41
16	1082.92	484.36	284.88
20	1427.47	648.29	382.18

Simulation results

❑ Maximum displacement occurs at the free end of the cantilever.

❑ There is zero displacement at the fixed end; which means stress developed here is maximum.

❑ Higher is the displacement amplitude at the free end, more will be the stress developed at the fixed end.

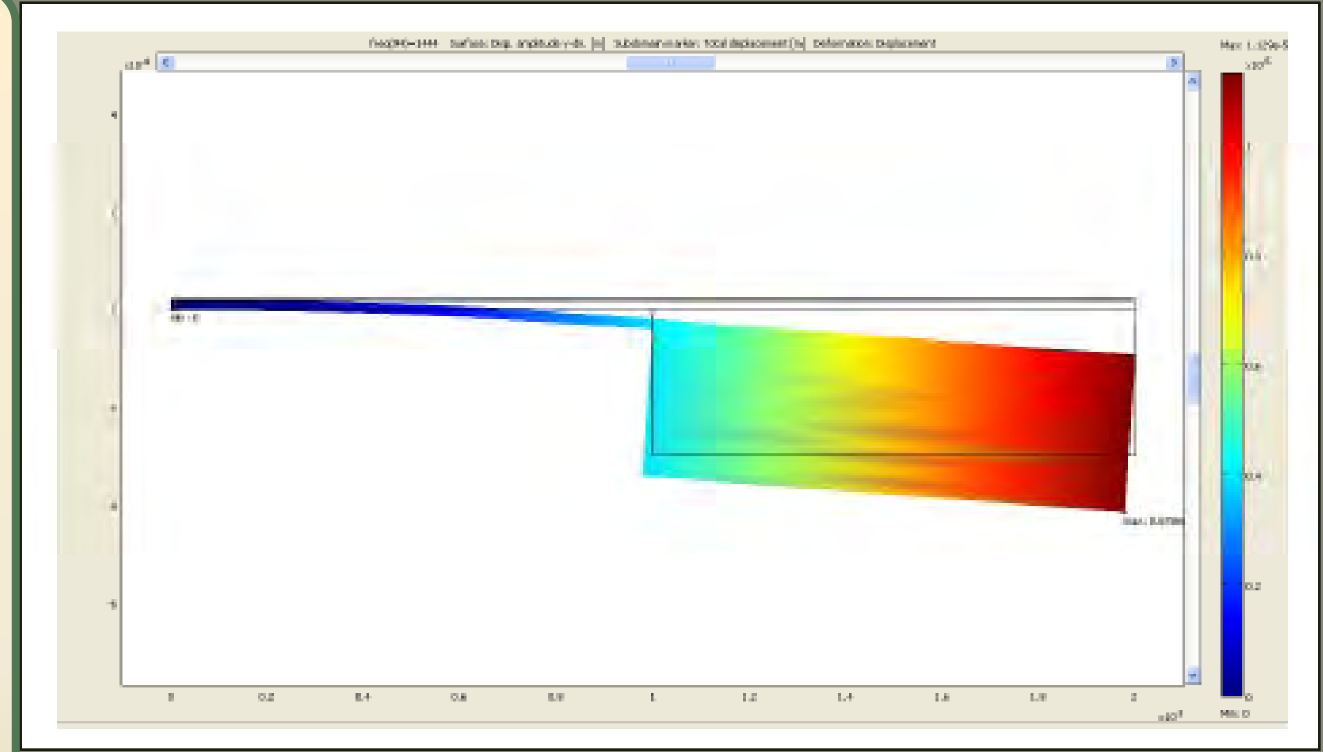


Fig. Displacement of different points along the length of cantilever

Simulation results

- ❑The amplitude rises only for the resonant frequencies and dies out to negligible values for others.

- ❑ First resonant frequency is observed at 1427 Hz.

- ❑ Second resonance occurs at 15287 Hz.

- ❑ The amplitude of vibration decreases for higher resonance mode.

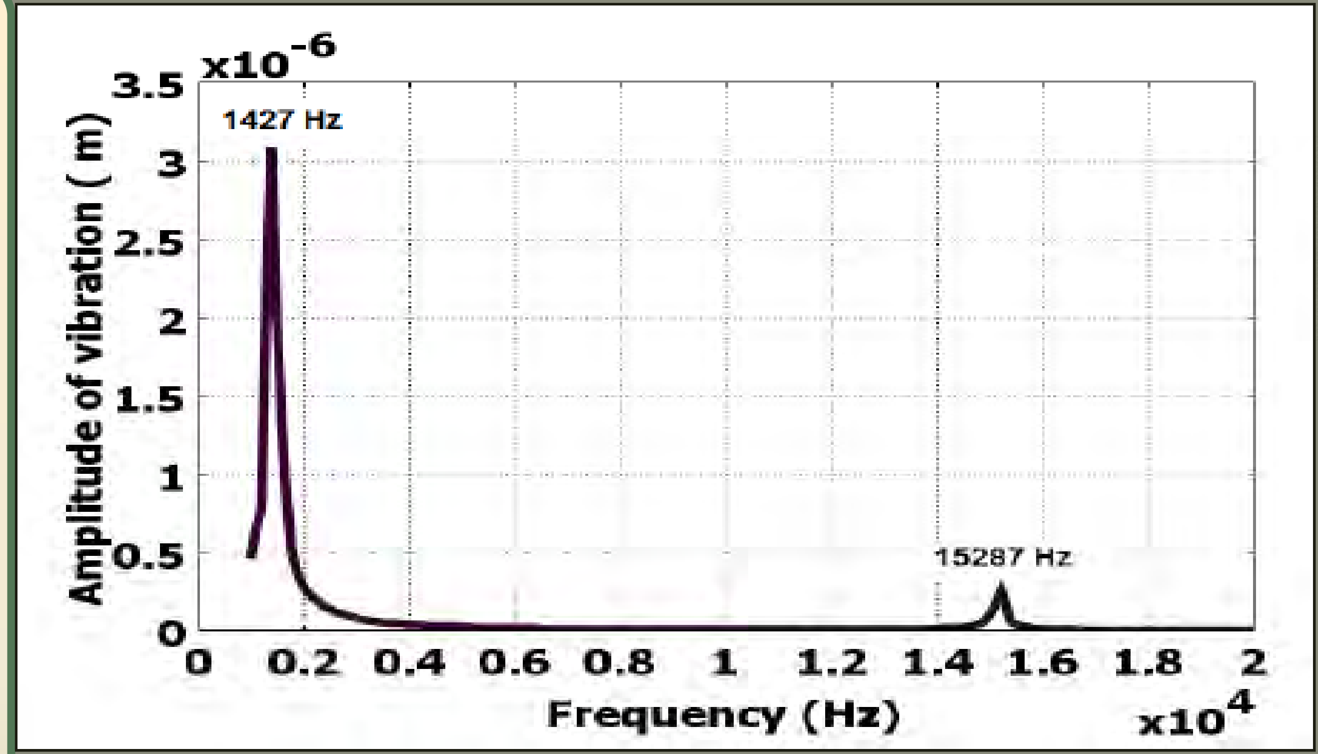


Fig. Variation of amplitude of vibration with frequency

Simulation results

- ❑The current amplitude attains a maximum value for the resonant frequency.
- ❑ It increases with an increase in the mechanical vibration.
- ❑ Current amplitude is approximately 11μA at resonant frequency for a mechanical pressure of 20 N/m^2 .

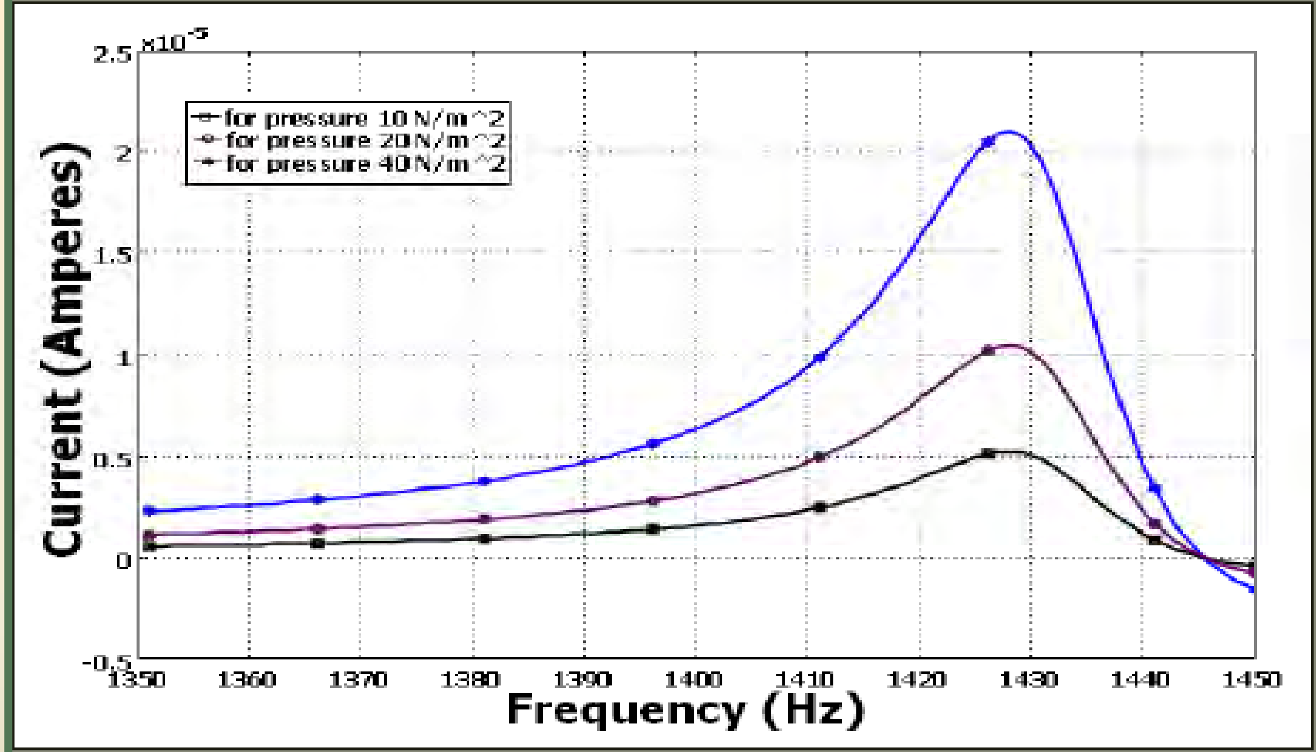


Fig. Variation of electric current with frequency for different mechanical pressures

Simulation results

- The voltage amplitude attains a maximum value for the resonant frequency.

- It increases with an increase in the mechanical vibration.

- Peak voltage is approximately 200mV at resonant frequency for a mechanical pressure of 20 N/m^2 .

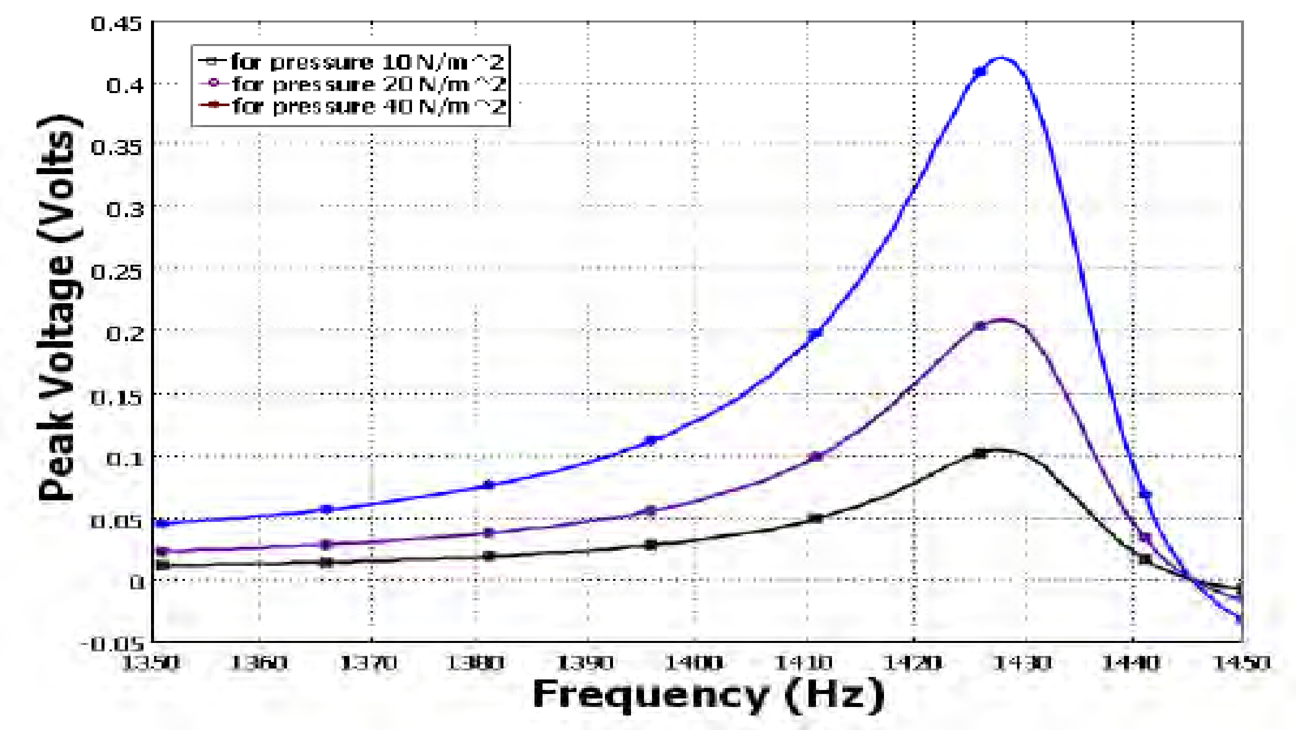


Fig. Variation of electric voltage with frequency for different mechanical pressures

Simulation results

☐The output power attains a maximum value for the resonant frequency.

☐ It increases with an increase in the mechanical vibration.

☐ Peak output power is approximately 2.1µW at resonant frequency for a mechanical pressure of 20 N/m^2 .

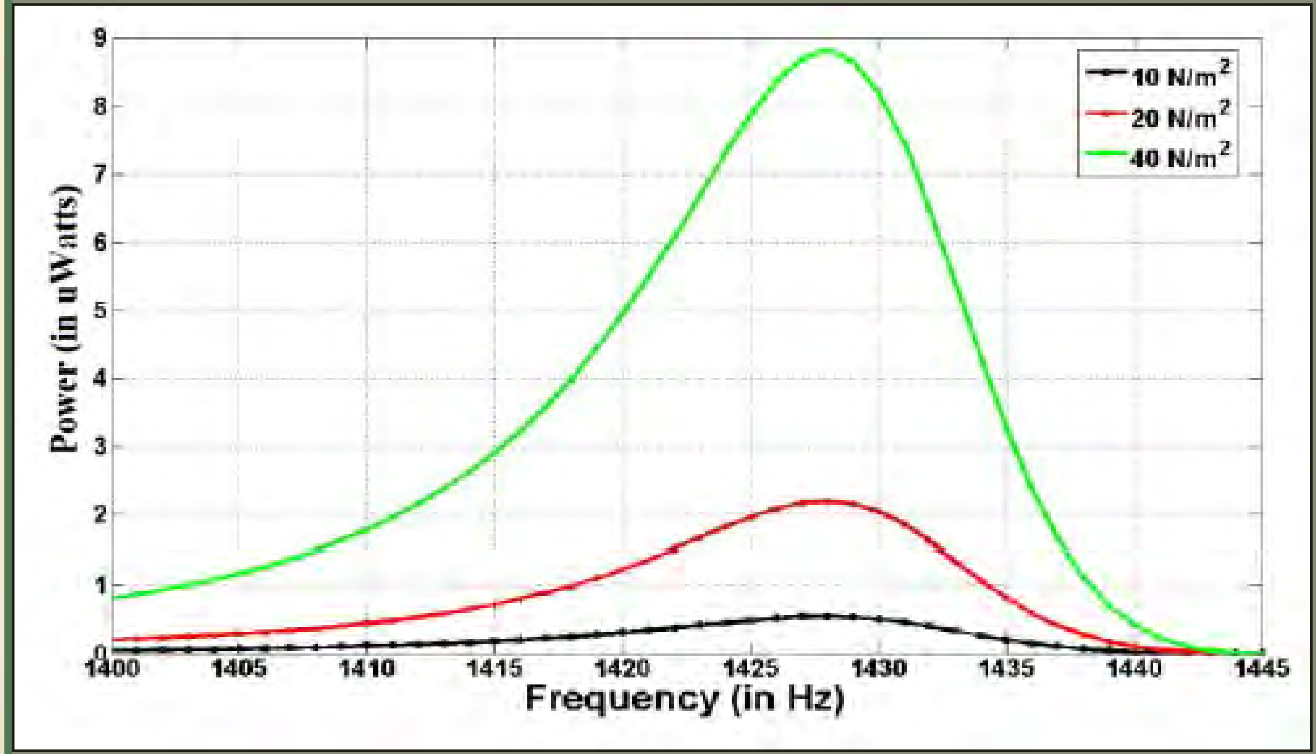


Fig. Variation of output electric power with frequency for different mechanical pressures

Simulation results

- ❑The voltage amplitude increases with an increase in resistive load.
- ❑The relationship between voltage and resistance is not linear. The slope of the curve decreases for higher values.
- ❑This corresponds to a decrease in the value of current for higher values of resistor.

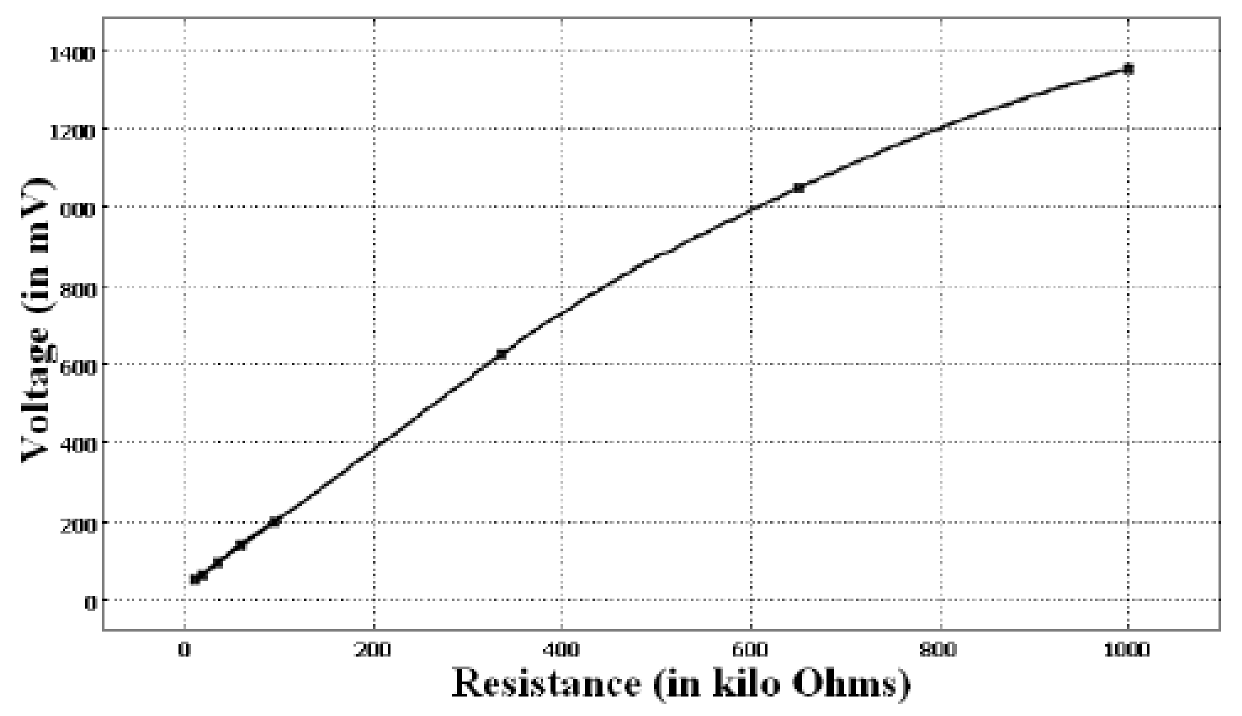


Fig. Variation of electric voltage with different load resistors

Simulation results

- The average power shows a maximum value at a certain resistance value, which is named as the optimal resistive load.

- The measured optimal load is 5kΩ.

- The output power at optimal load is approximately 2.1μW.

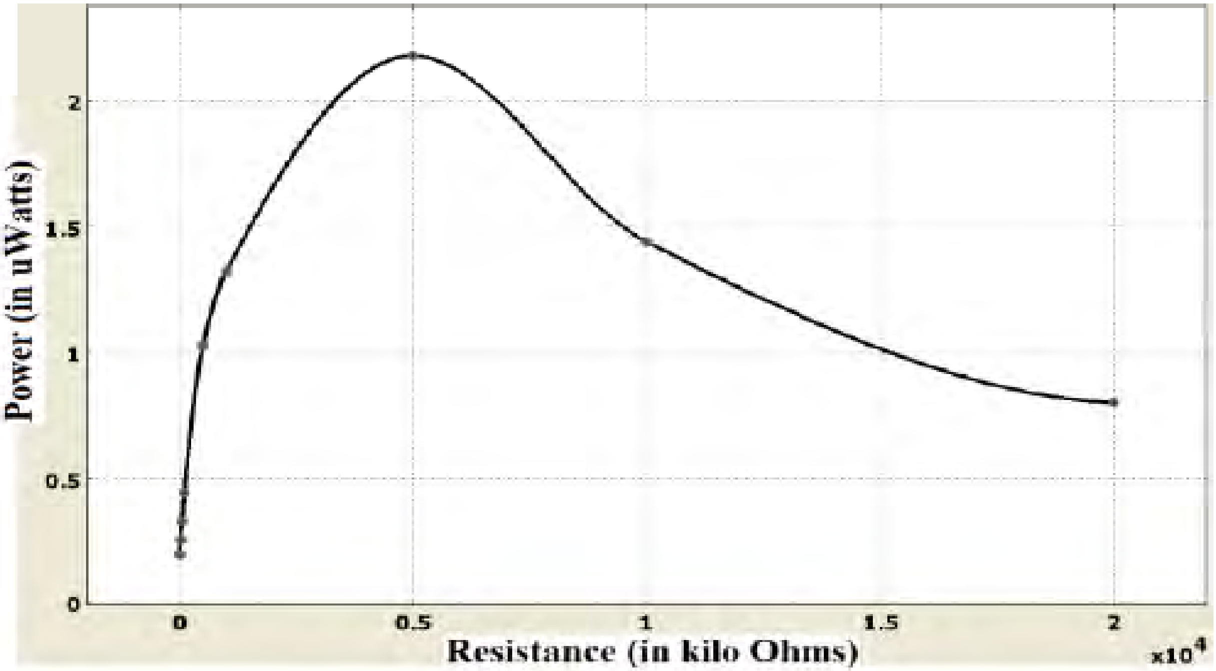


Fig. Variation of output average electric power with different load resistors

Fabrication process flow

Starting material: SOI wafer

Thermal oxidation to grow 0.5µm layer of SiO2 at both sides

Patterning of back side SiO_2 by wet etching (BHF) for opening window for back etching the bulk Si using KOH

Anisotropic back etching of bulk Si using KOH

Sequential Deposition of Ti & Pt by RF Magnetron sputtering and patterning

Deposition of PZT layer by sol-gel method and patterning

Deposition of upper electrode (Pt) using lift-off process

Release of cantilever

Fig. Flowchart for the fabrication of MEMS structure for energy harvesting

Conclusion and scope of the work

Conclusion

- A MEMS structure has been proposed for harvesting vibrational energy.
- The concept has been validated through simulations using COMSOL.
- The output current, voltage and power for optimal load at resonant frequency at a mechanical pressure of 20 N/m^2 are approximately 11μA, 200mV and 2.1μW respectively. **Such values show the potential for miniaturized devices.**
- The optimal load is 5 kΩ.
- A CMOS compatible fabrication process flow has also been suggested.

Scope of the work

- The simulation results suggest that such structures can be used for energy generation in wireless sensor networks.
- The efficiency of the energy harvesting system can be increased through different power conditioning circuits.

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THANKS