

DESIGN, FABRICATION AND SIMULATIONS OF MICROELECTROMAGNETIC VIBRATION-POWERED GENERATOR FOR LOW POWER MEMS

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ABSTRACT

In this paper we report on the design, simulation and fabrication of a microgenerator, which converts external vibrations into electrical energy. Power is generated by means of electromagnetic transduction with static magnets positioned either side of a moving coil located on a silicon structure designed to resonate laterally in the plane of the chip. Previous millimetre scale electromagnetic generators have been fabricated using discrete components and traditional fabrication techniques. In this paper the development and fabrication of a micromachined microgenerator that uses standard silicon-based fabrication techniques and low-cost, batch process is presented. Finite element simulations have been carried out using ANSYS to determine an optimum geometry for the microgenerator. Electromagnetic FEA simulations using Ansoft's Maxwell 2D software have shown voltage levels of 4 to 9V can be generated from the single beam generator designs.

1. INTRODUCTION

Over the last few years, low-power design has become one of the most important requirements for many electronic and instrumentation systems since these are developing towards portable units, which can operate autonomously. Low-power Microelectromechanical Systems (MEMS) has allowed the development of highly accurate, portable sensors and instruments for numerous applications in health care, industrial (embedded sensors in building and bridges), consumer products, and defence [1]. In many cases, the microsystems have to be completely embedded in the structure, with no physical connection to the outside. Typically, the energy necessary

to power such systems is stored in batteries. These have many drawbacks: they tend to be bulky, contain a finite amount of energy and have a limited shelf life. Alternative power sources for MEMS can potentially overcome these drawbacks.

A good alternative to batteries is miniature, self-contained, renewable power supplies. These convert energy from an existing source in the environment into electrical energy. An example of this is the generation of electrical energy from kinetic energy using electromagnetic induction. Kinetic energy can be in the form of environmental vibrations and several devices that exploit this source have been developed to date [2-4].

The motivation of this work is the development and fabrication of a MEMS version of a microgenerator that uses standard silicon-based fabrication techniques and low-cost, batch process.

2. MEMS ELECTROMAGNETIC GENERATOR

The envisaged arrangement for the MEMS version of a device based on four magnets is shown in figure 1. The coil is located on a silicon cantilevered paddle, designed to vibrate laterally in the plane of the wafer. Magnets are positioned within etched recesses in Pyrex wafers, which are then bonded to each face of the silicon layer. The bonding process is aligned to ensure correct placement of the coil relative to the magnets. The paddle is realised by deep reactive ion etched (DRIE) through the thickness of the wafer. Figure 2 shows the top view of the silicon paddle layer.

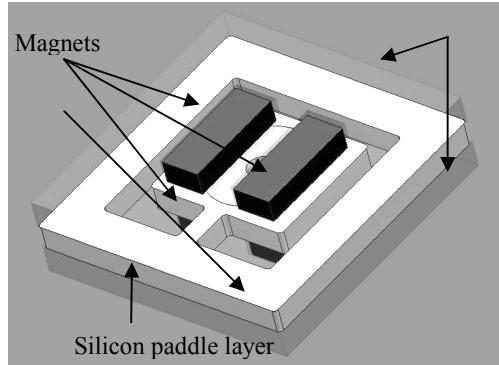


Figure 1. Micromachined silicon generator

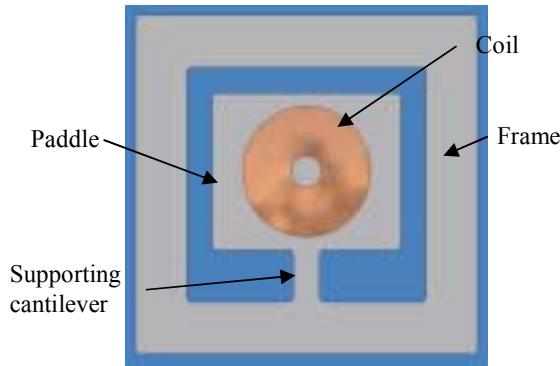


Figure 2. Top view silicon paddle

3. MECHANICAL MODELLING

The mechanical characteristics of the dynamic component of the generator (the cantilevered silicon paddle) have been simulated using ANSYS finite element analysis (FEA). The natural frequencies of different cantilever configurations have been determined using modal analysis. Mechanical stresses induced by the deformation have also been simulated in order to ensure the structure can withstand repeated cyclical stressing at maximum amplitude.

Three sets of supporting paddle beam dimensions have been simulated, each 1mm long and 0.5mm thick. In model A the beam is 500 μ m wide, B 400 μ m wide and C 300 μ m wide. Table 1 lists the resonant frequencies of the fundamental lateral mode of the generator, which is the operating mode of interest. This mode is shown viewed from above in figure 3. The amplitude of vibration is limited by the surrounding silicon frame, which limits the displacement of the centre



Figure 3. Generator mode of operation

point of the coil to 240 μ m. The device frame forms a physical over-range protection by limiting the motion of the paddle.

Paddle beam C is the most promising geometry since the smaller width reduces the resonant frequency of the structure compared to beams A and B. The reduced stiffness of this beam means that the structure is more flexible and the level of stress experienced at the maximum deflection is 2.6GPa, well below the yield strength of silicon. The ultimate robustness of the generator will in practice be limited by surface and/or material imperfections and any impact stress arising from the paddle contacting the frame.

4. MAGNETIC MODELLING

Electromagnetic FEA simulations using Ansoft's Maxwell 2D software have also been performed to determine the voltages which can be generated from the single beam generator designs. The coil used in the generator is to consist of a circular wire wound enamelled copper coil with 600 turns of 25 μ m wire. The coil outer diameter is 2.4mm and the inner diameter is 0.6mm. The dc resistance of the coil is 112 Ω and the inductance is 367 μ H measured at 10kHz. This coil is to be recessed in a hole etched into the silicon paddle. The resulting mass of the silicon paddle plus coil is estimated to be 0.028 g. As described above the coil is to be sandwiched between magnets. Four magnets are placed so as to form a two pole arrangement, two magnets, with opposite polarity, are placed above and below the coil (four magnets in total), to form the two poles of opposite polarity, see figure 4. The magnets used are sintered NdFeB.

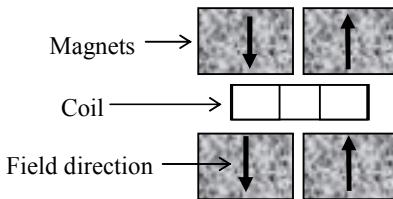


Figure 4: Magnet configuration used in the simulation.

3D FEA simulation has been used to verify the flux density distribution between the magnets. The flux density distribution for the two pole configuration is shown in figure 5. As can be seen from the plot the flux density varies from approximately $+0.5\text{T}$ under one pole to approximately -0.5T under the other pole.

In order to determine the voltage which would be induced in the coil, given a certain vibration frequency, f , coil displacement, X_{\max} , and velocity, v , a 2D transient finite element simulation is used. A sinusoidal velocity given by $v = X_{\max}2\pi f \sin(2\pi ft)$, is used as input to the transient simulation to specify the coil movement.

Table 1 gives the predicted results for the voltages and powers generated according to the FE simulation for all three beam geometries, and both magnet configurations for a $240\text{ }\mu\text{m}$ coil displacement.

Model	f_{res} (kHz)	R_{load} ($\text{k}\Omega$)	V_{load} (V)	P_{load} (mW)
A	9.812	20.4	9.0	2.0
B	7.149	14.8	6.5	1.45
C	4.743	9.8	4.3	0.96

Table 1. Simulation results for the natural frequency, f_{res} , voltages, V_{load} , (peak) and power, P_{load} , delivered to the load resistance, R_{load} for three generator structures.

In contrast to many micro-fabricated magnetic generator structures, the simulation results indicate that reasonable voltages can be generated. The estimated power is based on the power delivered to the load resistance indicated in the table. This value of load resistance has been chosen so as to maximise displacement for 1g vibration acceleration as described in the following section.

For the purposes of the 2D finite element simulation the maximum displacement is fixed at $240\text{ }\mu\text{m}$ and it is assumed that sufficient mechanical force, given by the product of mass and acceleration, exists to give the required displacement. In order to illustrate how this is affected by the choice of load resistance, we assume that the motion of the device can be described as a single degree of freedom, damped mass-spring system, as

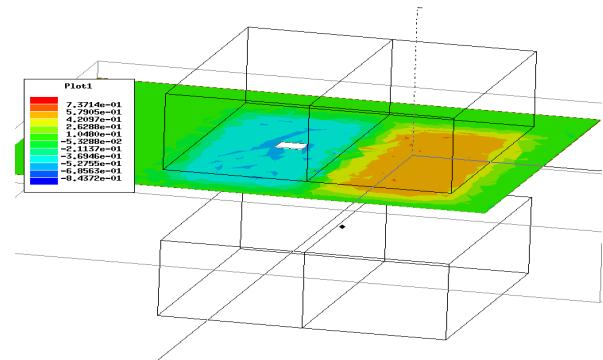


Figure 5. 3D FEA simulation of flux density for the two pole configuration.

described in [2, 4, 5]. If we assume that the device is operated at resonance, i.e. the frequency of the driving vibration is equal to the natural frequency of the device, then it can be shown that the amplitude of the movement of the mass is given by [4];

$$X_{\max} = \frac{ma}{D2\pi f_{\text{res}}} \quad (1)$$

where, D is the electromagnetic damping factor for the device, and m is the moving mass, and a is the acceleration of the input vibration. In this case only electromagnetic damping is considered, and the electromagnetic damping factor, D can be estimated by [4]

$$D = \frac{(NLB)^2}{R_{\text{load}} + R_{\text{coil}} + j\omega L_{\text{coil}}} \quad (2)$$

where N is the number of turns in the generator coil, l is the side length of the coil (assumed square), and B is the flux density to which it is subjected and R_{load} , R_{coil} , and L_{coil} are the load resistance, coil resistance and coil inductance respectively. The expression in (2) is really only valid for the case where the coil moves from a high field region B, to a zero field region. Therefore it is not an exact expression for the structure used here, and a more exact value for the electromagnetic damping should be determined from the finite element analysis. However, equation (2) does show that the damping factor depends of the load resistance, given that all the other parameters are fixed by the geometry of the device. The expression in (1) shows that the maximum displacement is inversely proportional to the damping factor, and proportional to the input acceleration. The other parameters in (1) are fixed by the device geometry. If the input acceleration is fixed at a value of 1g (9.81 m/s^2), then the maximum displacement can be controlled by choosing the value of load resistance, R_{load} . The value of load resistance shown

in table 1 corresponds to the value required to achieve a 240 μm displacement of the paddle for a 1g acceleration input.

5. GENERATOR FABRICATION

The prototype design uses discrete components for the permanent magnets and coil, and employs seven masks in the process. Six different mechanical designs for the generator are being evaluated with varying beam widths (200 to 500 μm), beam arrangement (i.e. single beam cantilevered paddle and double beam encastre paddle), and contact pad configuration. The magnets used were sintered NdFeB with dimensions of 1x1x0.75mm.

The full device consists of three wafers bonded together. The central silicon wafer was etched by DRIE to fabricate the silicon paddle, frame and beam. A KOH etched V groove is also included along the centre line of the beam to provide a channel for the copper wire from the coil to run along. In this way the wires can be kept below the surface of the wafer and not interfere with subsequent bonding. The full fabrication process flow is shown in figures 5.

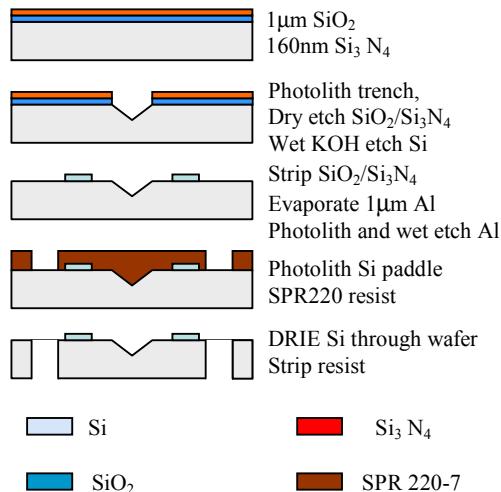


Figure 5. First prototype, discrete coil generator fabrication

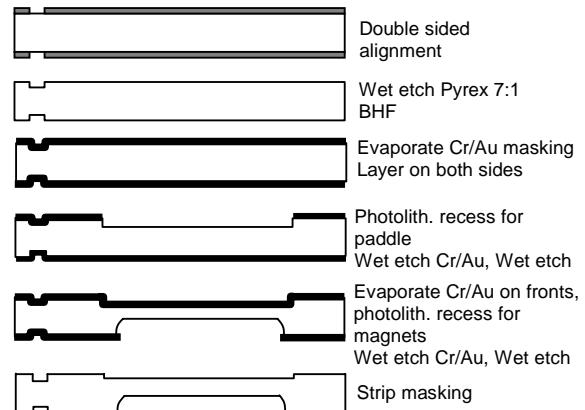


Figure 6. First prototype, Pyrex chip fabrication

The Pyrex wafers are etched to make recesses for location of the permanent magnets and to provide clearance for the paddle to vibrate. The full process is shown in figure 6.

The Pyrex wafer is designed to be anodically bonded to each face of the silicon wafer. In addition to the Pyrex chips for holding the magnets, to speed up the development Perspex chips of similar dimensions were also fabricated using traditional milling techniques. The Perspex chips are not suitable for anodic bonding but can be individually glued to the silicon chip. Single and double beam arrangements of the silicon paddle and frame for the prototype microgenerator are shown in photograph 8 and 9 respectively.

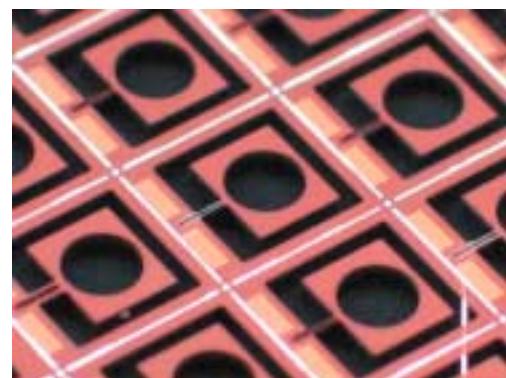


Figure 8. Photo of single beam device

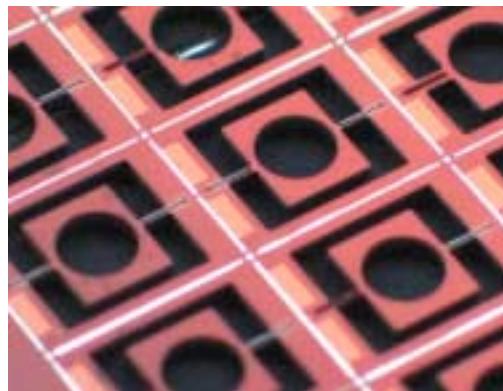


Figure 9. Photo of double beam device

6. ASSEMBLY

Assembly process consisted of several steps:

- Assemble the coil into the silicon paddle
- Attach two permanent magnets inside of the cavity of each Perspex chip
- Assemble the Perspex chips either side of the silicon die with the magnets aligned over the centre of the coil.

Figure 10 shows a Cu-coil integrated within the silicon paddle. Figure 11 shows the two permanent NdFeB magnets manually positioned and fixed inside the machined cavity using epoxy adhesive. Figure 12 shows an assembled microgenerator mounted into a standard package.

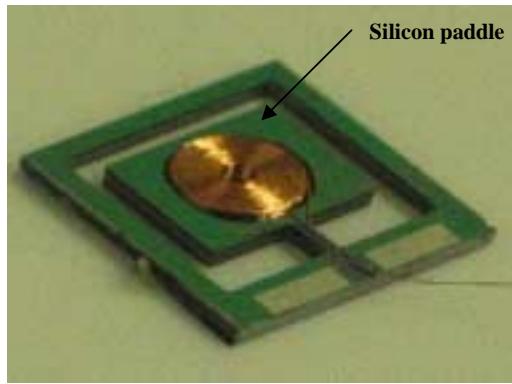


Figure 10. Cu-coil integrated in the silicon paddle

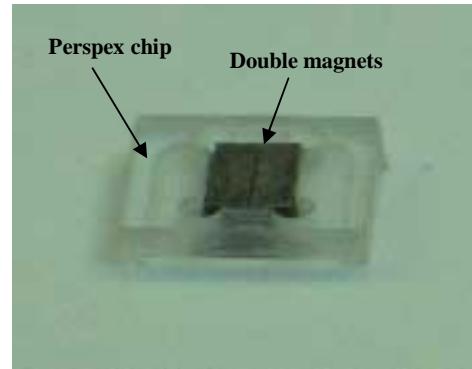


Figure 11. Two permanent magnets into a Perspex cavity.

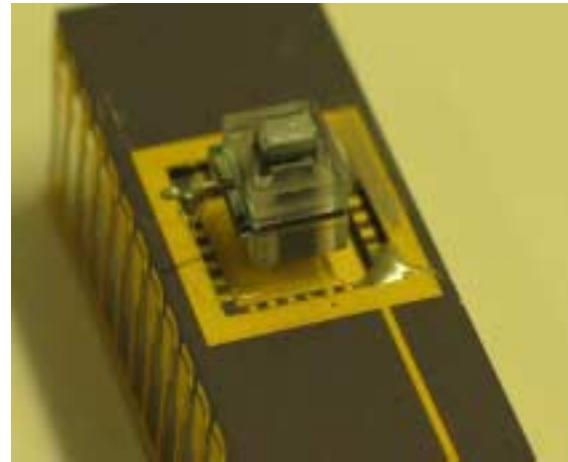


Figure 12. Assembled microgenerator

7. CONCLUSIONS

This work presents the results of the mechanical and electromagnetic behaviour of a silicon vibration-powered generator. Different beam dimensions have been investigated and model C (300 μ m wide and 1mm long) appears to be the most promising since it offers the lowest resonant frequency and least induced stress at maximum displacement.

Two dimensional transient finite element simulations have been performed in order to investigate the magnitude of voltages that can be generated. Finite element simulation predicts that voltage levels 4 to 9 V can be generated for a full displacement of the paddle. These voltages can be generated for a 1 g acceleration input, with an optimised choice of load resistance. The double pole arrangement can be further improved by the addition of a ferrous keeper guiding the flux between adjacent magnets.

8. REFERENCES

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