Silicon MEMS bistable electromagnetic vibration energy harvester using double-layer micro-coils

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Abstract. This work reports the development of a MEMS bistable electromagnetic vibrational energy harvester (EMVEH) consisting of a silicon-on-insulator (SOI) spiral spring, double layer micro-coils and miniaturized NdFeB magnets. Furthermore, with respect to the spiral silicon spring based VEH, four different square micro-coil topologies with different copper track width and number of turns have been investigated to determine the optimal coil dimensions. The micro-generator with the optimal micro-coil generated 0.68 micro-watt load power over an optimum resistive load at 0.1g acceleration, leading to normalized power density of 3.5 kg.s/m³. At higher accelerations the load power increased, and the vibrating magnet collides with the planar micro-coil producing wider bandwidth. Simulation results show that a substantially wider bandwidth could be achieved in the same device by introducing bistable nonlinearity through a repulsive configuration between the moving and fixed permanent magnets.

1. Introduction
With the progress in CMOS integrated circuit technology, the power consumption of individual electronic devices has been lowered to the level of few micro-watts. These advancements in low power electronics have facilitated the drive towards the development of the ‘internet of things (IoT)’ in the forthcoming decades, comprising billions of low power autonomous sensor modules connected to the internet via wireless networks. However, one of the major roadblocks towards the deployment of the IoT is the lack of appropriate energy sources to power the individual sensor modules for long period. Ambient mechanical vibrations, which are abundant in the modern urbanized landscape, provide an untapped energy source which can be harvested to power wireless sensor nodes for autonomous operation [1-3]. Nonetheless, most of the ambient vibrations are either random in nature, or have frequencies spread across a considerably wide range, which are difficult to harvest using linear oscillator based vibration energy harvesters. Additionally the power output of the micro-fabricated VEH devices utilizing piezoelectric transduction is often too low to power sensor modules. An alternative solution to this problem would be the adoption of electromagnetic transduction [4, 5] and nonlinear bi-stable oscillator based VEH device [6, 7], which typically has a wider operational bandwidth. In this paper we present the design, fabrication and experimental validation of a MEMS electromagnetic VEH device utilizing double-layer planar micro-coils. Four different types of planar micro-coils, each with different number of turns and copper track width within the same area, have been investigated to experimentally determine the optimum coil layout. The micro-VEH generated 0.68 μW power at 0.1g acceleration for the optimum coil and resistive load configuration.

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2. Design and simulation of micro-EMVEH

The proposed micro electromagnetic vibrational energy harvester comprise of silicon spring, tiny NdFeB magnets and double-layer planar copper micro-coil. The silicon spring and micro coils are fabricated separately using standard MEMS fabrication process and all components are assembled to form the micro-EMVEH. As illustrated in figure 1(a), bistable nonlinearity is incorporated in the simulation by means of repulsive interaction between a pair of additional magnets placed on the frame. Figure 1(b) exhibits the simulated stress profile in the silicon spring structure when the central pad is deflected by 1mm. The maximum stress (750 MPa) is shown to be well below the yield stress of silicon (7000 MPa). The numerically simulated frequency responses for two different micro-coils, type 2 and 3 (see Table 1) are illustrated in figure 1(c). It is shown that while the linear configuration of the device produces resonant peak in the frequency response, the nonlinear bistable configuration achieves a hysteretic response with wider bandwidth.

![Figure 1. (a) Schematic diagram of the proposed micro-EMVEH, (b) mechanical simulation showing the von Mises stress distribution and (b) frequency responses for coil types 2 and 3. Solid lines represent the forward sweep and dashed lines represent the reverse sweep plots respectively.](image)

3. Fabrication of micro-EMVEH

The micro-fabricated EMVEH consists of three principal components, the silicon spring, the planar micro-coil and the miniaturized NdFeB magnets. The silicon springs and micro-coils are fabricated separately using silicon MEMS process and post-fabrication, these two components together with the miniaturized magnets are assembled to form the complete micro-EMVEH system.

3.1. Fabrication of silicon spring

The silicon springs (Figure 2(a, b)) are fabricated on double-side polished 0.5mm thick SOI (silicon-on-insulator) wafer with SOI, buried oxide and handle wafer thicknesses of 50μm, 3μm and 450μm respectively. The fabrication process begins with transferring the spring patterns onto the SOI layer using photolithography and etching the spring patterns using DRIE process. In the next step, the back side (handle wafer) is etched using DRIE to release the springs. Following release of the springs, the delicate spring structures are protected by sputtered aluminium (0.2 μm) and sprayed photoresist. The wafers are then diced with individual die size of 7mm × 7mm and a movable central paddle (1.1mm × 1.1mm) supported by four spiral springs (50μm thick, 0.2mm wide). Finally, the protective aluminium and sprayed photoresist layers are etched to obtain the individual springs.
3.2. Fabrication of double-layer planar copper micro-coil
The double layer planar micro-coils (Figure 2(c, d)) are fabricated using photolithography and electro-deposition of copper on sputtered seed layers. The two coil layers are separated by an insulating SU8 layer and connected at the centre through a via which traverses through the insulation layer. The thicknesses of the bottom and top electroplated copper coil layers are 15μm and 12.5μm respectively. The overall area of the coils is 2.8mm × 2.8mm where the total number of turns, for both layers and the corresponding measured resistances are listed in Table 1. A passivation layer of SU-8 was used to protect the coil from shorting or damaging due to contaminants. The two ends of the copper coils are terminated in two copper pads to provide contact with PCB through wire bonding or soldering.

Figure 2. Fabricated (a, b) silicon-on-insulator spring structure and (c, d) planar micro-coil

3.3. Assembly of the silicon micro-EMVEH
The silicon spring and double-layer planar micro-coils together with the miniaturized NdFeB magnets are assembled to form the complete micro-EMVEH system. The planar micro-coil is bonded using epoxy adhesive on an FR4 PCB board (10mm × 15mm) with copper pads onto which the copper coil pads are wire-bonded. An NdFeB magnet (2mm × 2mm × 2mm) is bonded on one side of the movable central paddle of the silicon spring structure. The silicon spring with the NdFeB magnet is aligned above the centre of the copper coil such that the magnetic flux lines pass through the coil. Two Perspex spacers are positioned in between the coil and frame of the spring such that the vertical gap between the micro-coil plane and the magnet is 0.5mm. The magnet can move vertically (out-of-plane) and induce current in the micro-coil due to change of flux-linkage.

Table 1. Micro-coil parameters

| Coil  | Copper Track width (μm) | Inter Track gap (μm) | No. of turns | Resistance (Ohm) |
|-------|-------------------------|----------------------|--------------|------------------|
| Type 1| 15                      | 10                   | 104          | 57.7             |
| Type 2| 12.5                    | 12.5                 | 104          | 95.6             |
| Type 3| 10                      | 10                   | 130          | 127.7            |
| Type 4| 10                      | 8                    | 144          | 156              |
4. Experimental results and discussions

Four different devices, each with the same magnet and silicon spring configurations but different micro-coils are fabricated and tested. The parameters of the different coils are given in Table 1. In the first set of experiments the optimum load resistances of the individual devices were obtained for a linear configuration of the device. It is observed that the optimum resistive load is very close to the resistances of the individual coils (Figure 4). This is due to the fact that the weak magnetic flux linkage between the magnet and coils result in weak electromagnetic coupling coefficient, leading to low electromagnetic damping in comparison to the mechanical damping which has negligible effect on the optimum load.

![Figure 3](image)

**Figure 3.** Fully assembled micro-EMVEH (a) perspective view showing the silicon spring (b) side view showing the NdFeB magnet suspended above the planar micro-coil.

![Figure 4](image)

**Figure 4.** Variations of (a) RMS load voltage and (b) Load power with load resistance for different types of micro-coil at 0.1g acceleration.

The RMS load voltage and the load powers of the different devices at 0.1g acceleration are shown in figure 4. At 0.1g acceleration, the device with Type 3 micro-coil generates the highest power (0.32 μW) while the device with Type 1 micro-coil produces the smallest power (0.24 μW). Experimentally, the Type 3 micro-coil is the optimum for this device as this configuration generates the highest voltage and power across the optimum load among all the configurations, which could be due to higher packing factor and optimum coil geometry. The experimental test set up, comprising of electromagnetic shaker, power amplifier, accelerometer and computer controlled vibration controller is schematically illustrated in figure 5(a). The output voltage responses of the micro-EMVEH are recorded using a digital storage oscilloscope and stored in a computer.
The experimental frequency response plots for the device with coil type 3 for different accelerations are shown in figure 5(b), which exhibits nonlinear behaviour due to stretching of the spiral beams, producing 0.68 μW power at 0.1g acceleration. As the acceleration is increased, the magnet starts to collide with the coil and the peaks of the frequency responses for accelerations 0.2g-0.5g are flattened, leading to wider bandwidth of 8-12 Hz. This type of impact induced bandwidth widening has been explored at macro scale [8, 9] for electromagnetic systems and at micro scale [10, 11] for electrostatic transduction systems previously. It is evident from figure 5(b) that the mechanical impact phenomenon can also be exploited for bandwidth widening at micro-scale using electromagnetic transduction.

5. Conclusions
This work describes the design, fabrication and experimental validation of a nonlinear electromagnetic micro-power generator. Four different types of double-layer planar micro-coils are tested at the same vibrational acceleration (0.1g) and the power generated in the optimum coil is 0.68 μW. Furthermore, it is observed that at higher vibrational accelerations, the movable magnet collides with the planar coil, resulting in wider bandwidth in comparison to a non-impact linear configuration. This work forms the background for further development in the device topology by incorporation of magnetically induced bistable nonlinearity and investigation of its effect on the device performance.

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