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Development of a Vibration-Based Electromagnetic Energy Harvester by a Conductive Direct-Write Process

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Abstract: A conductive direct-write process of multilayered coils for micro electromagnetic generators is proposed. This novel approach of using silver ink to form the conductive structures largely reduces the fabrication complexity, and it provides a faster alternative to the conventional semiconductor methods. Multi-layered coils with insulation were accurately layered on a micro-machined cantilevered diaphragm by a dispenser. Coils several layers thick could be used to increase the power output and double coils were separated by a layer of insulation. Six prototypes, all capable of efficient conversion of vibrational energy into electrical energy, were fabricated. The experimental results, which include measurements of the electromotive force and power output, are presented. Prototypes with two coils and thicker conducting layers had less resistance and the power output was much more than that of a single-coil unit. This generator can produce 82 nW of power at a resonance frequency of 275 Hz under 5 g excitation.

Keywords: electromagnetic generator; vibrational energy; direct-write

1. Introduction

The miniaturization of consumer electronics and mechanical structures has been receiving a great deal of attention for a considerable time. Extensive fabrication techniques have been developed for complex structures, including gray-scale lithography, reactive ion etching, LIGA (lithography, electroplating, and molding), and electron beam lithography [1–3]. Several three-dimensional (3D) fabrication techniques have been developed recently for the fabrication of conductive structures with electrical functionality, which include micro-stereolithography [4], micro-laser-sintering [5], inkjet printing [6,7], and continuous writing [8–10]. These offer dramatic advantages over typical methods in terms of low cost, large area, and a quick processing time, but still suffer from some limitations with respect to the structure and material.

Laser writing creates patterned structures through ablation or selective sintering. Lee proposed a micro-stereolithography process for the fabrication of metal microstructures that used a low-viscosity metal powder suspension sintered by a focused laser beam [4]. Regenfuss realized structural features and performed laser micro-sintering with sub-micrometer grained metal powders, where the challenge was the high temperature and porosity [5]. These techniques often require expensive equipment or costly photopolymers.

Lower-cost inkjet printing for the creation of functional 3D structures of material with specific electrical properties, layer by layer, have also been extensively studied. Fuller additively built electrical circuitry by inkjet printing using nanoparticle metal colloids which were then sintered at 300 °C [6]. Kullmann used piezoelectric inkjet printing to grow micro-wires and micro-walls, selectively combined with simultaneous in situ laser annealing [7]. However, the printing performance was limited by the rough edges and the low viscosity of the material.

To achieve a good flat surface in a short time at a low cost, several direct-write processes using micro-nozzles or syringe needles have been developed in one-step processes to make continuous conducting structures. Lebel used direct-write micro-extrusion to fabricate carbon nanotube/polymer nanocomposite coils through a micro-nozzle which were then cured using UV irradiation which followed the extrusion point [8]. Lu presented a hybrid technology combined with direct-write and projection micro-stereolithography with carbon nanotubes dispersed in a photopolymer solution for 3D conductive structures [9]. Ladd demonstrated free-standing 3D microstructures patterning by extruding a low-viscosity liquid metal through a capillary [10].

In this study we used a three-axis dispenser to demonstrate conductive-structure fabrication on micro electromagnetic generators [11,12]. To increase the output voltage and power, continuous volumes of metallic or insulating material were stacked on a cantilever microstructure at computer-defined positions, which enabled the all-additive fabrication of layers of coils without using vacuum deposition or any high-temperature process. Movement of the coils in the magnetic field from external permanent magnets causes the induction of an electromotive force according to Faraday's law. The output power would increase as the numbers of coil turns increase. A schematic of the micro-generator with two coils is shown in Figure 1.

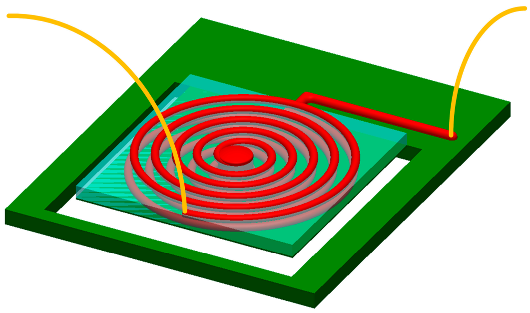

Figure 1. Schematic of coils on a cantilever microstructure.

2. Theory

A micro electromagnetic generator can be modeled as a second-order system, $m\ddot{z}(t) + c\dot{z}(t) + kz(t) = -m\ddot{y}(t)$, where $z(t)$ is the relative displacement of the mass to the vibrating housing (see Figure 2).

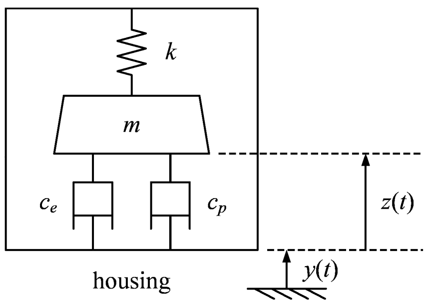

Figure 2. Linear model of the vibrational energy harvester, which includes a mass, a damper, and a spring.

For a given sinusoidal displacement input of the housing, $y(t) = Y\cos(\omega t)$, the time response of the system can be expressed by [13–15]

$$z(t) = \frac{(\omega/\omega_n)^2 Y}{\sqrt{[1-(\omega/\omega_n)^2]^2 + [2\xi(\omega/\omega_n)]^2}} \cos(\omega t + \phi), \tag{1}$$

$$\phi = \tan^{-1}\left(\frac{c\omega}{k - m\omega^2}\right), \quad (2)$$

where ω_n is the natural frequency given by $\omega_n = \sqrt{k/m}$, ξ is the overall damping ratio given by $\xi = c/2m\omega_n$, and c is the overall damping coefficient. When the system is operated at the natural frequency, $\omega = \omega_n$, the phase (ϕ) equals $-90°$, and the relative displacement, $z_m(t)$, is given by

$$z_m(t) = \frac{Y}{2\xi}\cos\left(\omega t - 90^\circ\right), \quad (3)$$

$$\xi = \xi_e + \xi_p = \frac{c_e + c_p}{2m\omega_n}, \quad (4)$$

where c_e, c_p, ξ_e and ξ_p are defined as the transducer damping coefficient, the parasitic damping coefficient, the transducer damping ratio and the parasitic damping ratio, respectively.

The output power is generated by the relative motion between an external magnet and the coils fabricated on the cantilevers. The instantaneous kinetic power dissipation of the mass due to the damping is defined by $p(t) = c\dot{z}(t)^2$. Part of the power is converted to electricity by electromagnetic transduction, and the rest is lost through the parasitic damping of the system. For maximum electrical power generation, the energy harvester is typically designed to operate at a resonance which results in large coil displacement. The average power generation can be further expressed by [14–16]

$$P_e = \frac{1}{2}c_e\left|\dot{z_m}(t)\right|^2 = \frac{m\xi_e{\omega_n}^3Y^2}{4\xi^2}, \quad (5)$$

The power generation is therefore a function of the mass, damping ratio, natural frequency, and input displacement.

3. Fabrication

The fabrication processes of the proposed energy harvester are schematically shown in Figure 3. First, a silicon-based cantilever diaphragm was fabricated using a standard microelectromechanical systems (MEMS) process. To make the coils on the 7 mm × 7 mm cantilevers, conductive ink was extruded from a nozzle over a helical path to form the first coil (one to three layers) which was then cured at 150 °C for 30 min. Insulating material was then extruded evenly over the top of the first coil and cured, and then more conductive ink (one to three layers) was deposited to form the second coil and a final 30 min curing at 150 °C was done. This technique gives better control over the thick metal laid down, by means of pressure, speed, and temperature, than a typical micromachining process does. Table 1 shows the detailed sizes of the fabricated generator.

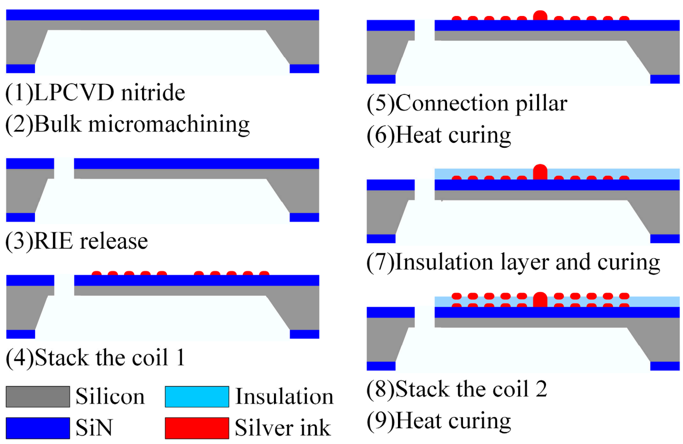

Figure 3. Fabrication process steps.

Table 1. Parameters of the fabricated generator.

Parameter	Size
cantilever size	7 mm × 7 mm × 0.02 mm
coil thickness	0.05 mm
insulation layer thickness	0.3 mm

Figure 4 shows the arrangement of several layers of metal used to form the coils and the insulation. Figure 5 shows the cross-sectional photos for a single coil. Figure 6 shows photos of six electromagnetic energy harvesters of one or two coils with one to three layers: (1a, 2a) one layer, (1b, 2b) two layers, and (1c, 2c) three layers.

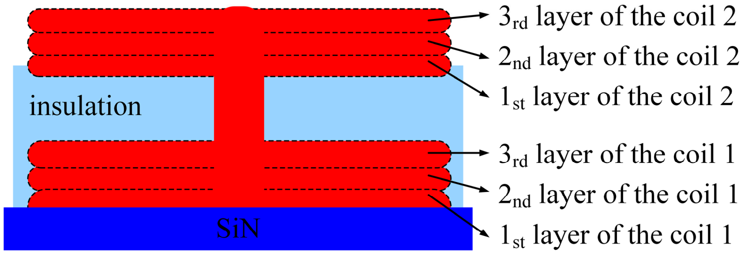

Figure 4. Arrangement of the stacking of two coils.

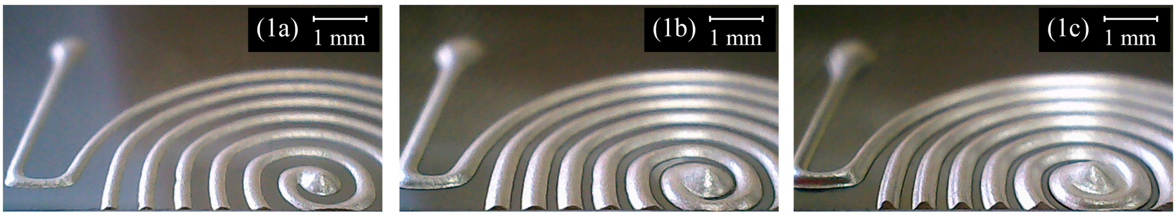

Figure 5. Cross-sectional views of a coil with one to three layers: (**1a**) one; (**1b**) two; and (**1c**) three.

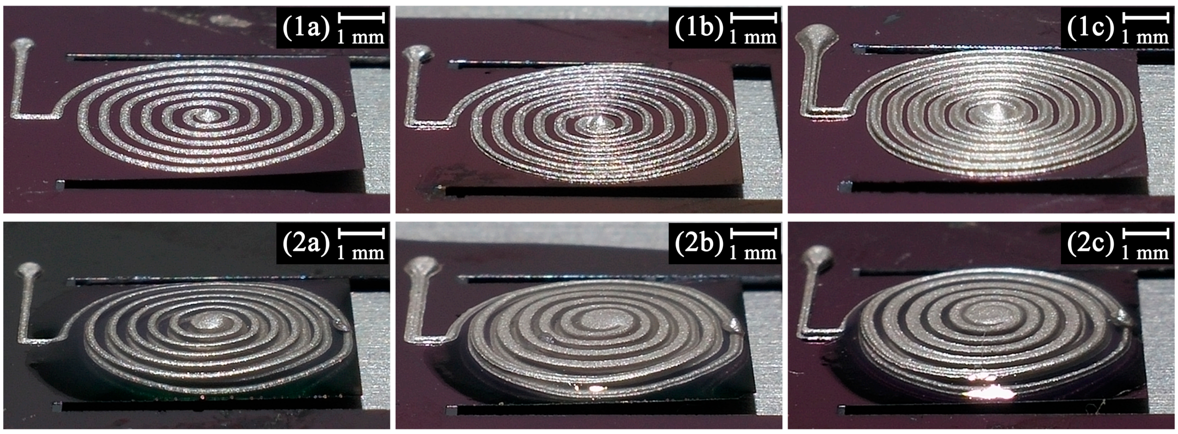

Figure 6. The fabricated devices. A single coil with one to three layers: (**1a**) one; (**1b**) two; and (**1c**) three. A double coil with one to three layers: (**2a**) one; (**2b**) two; and (**2c**) three.

4. Measurement

The fabricated micro-generators were tested by using a vibrational system, as shown in the schematic in Figure 7. A function generator was used to control the vibration frequency between

100 and 600 Hz. An accelerometer was used to measure the acceleration of the generators. An external magnet was placed at a distance of 0.5 mm from the generator.

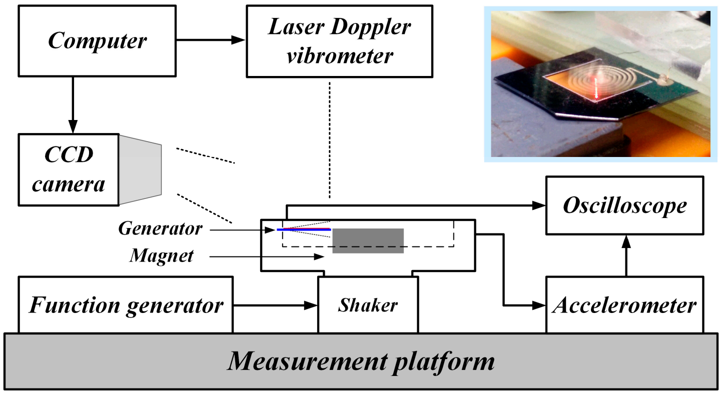

Figure 7. Measurement setup.

Measurements which included resistance, voltage, and power were performed on six different prototypes: 1a, 1b, 1c, 2a, 2b, 2c. We measured the resistance of the load, and calculated the power of the generator by using Equation (6) as

$$P = \frac{V^2}{2R} \tag{6}$$

where V is the measured voltage, and R is the load resistance. Figure 8 shows the measured resistance for micro-generators with different numbers of coil layers for a single or double coil. The resistance was inversely proportional to the number of layers. Figure 9 shows the measured open-circuit peak-to-peak voltages under an acceleration of 5 g with respect to the vibration frequencies as viewed on the oscilloscope. The output voltages had maximum values at frequencies of 417, 445, and 475 Hz for a single coil (1a, 1b, 1c) and 218, 246, and 275 Hz for a double coil (2a, 2b, 2c).

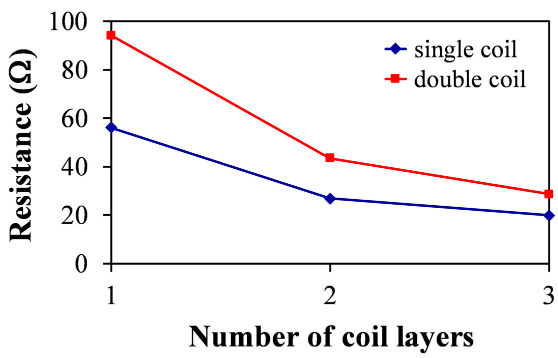

Figure 8. Measured resistance with respect to the number of coil layers for a single or double coil.

For power measurements, the generator was connected to a resistive load and operated at its fundamental frequency. Figure 10 shows the measured output power. For a single coil, the average power produced was 16, 36, and 51 nW. For two coils, the average power produced was 22, 51, and 82 nW. This power increase was due to the greater number of coil turns. When a three-layer coil is compared with a single-layer coil, the resistance decreases and the output power increases by 218% in the case of a single coil, or 272% in the case of a double coil.

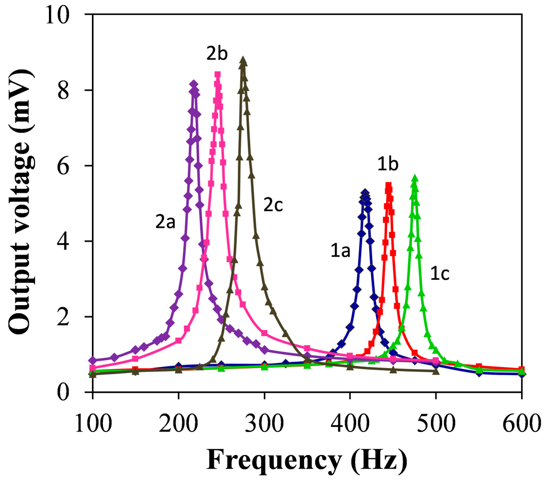

Figure 9. Measured output voltage with respect to the excitation frequency.

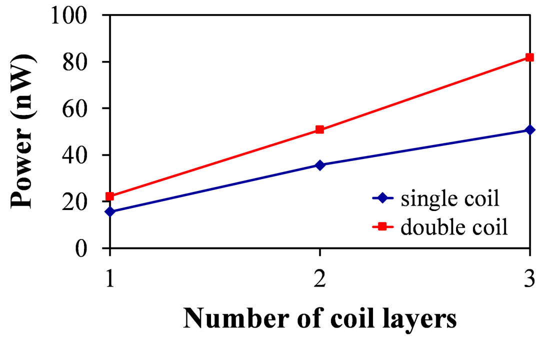

Figure 10. Measured power with respect to the number of coil layers for single or double coils.

5. Discussion

For energy harvesting, the typical vibrational frequencies are lower than 200 Hz, yet some have higher frequencies [17–19]. According to Table 2, the proposed structures with resonant frequencies from 218 to 475 Hz have the potential to be used in motorized equipment, such as transformers, refrigerators, car engines, etc. [17–19]. To further reduce the resonant frequency, possible methods are adding proof mass on the cantilever, modifying the coil structure, or making the cantilever thinner.

Table 2. Common vibration sources.

Source	Frequency (Hz)	Acceleration (g)	Reference
car engine compartment	200	1.2	[17]
acoustics	100–10,000	5–500	[18]
transformers	50–400	0.01–0.08	[18]
refrigerator	240	0.01	[19]
wooden deck with foot traffic	385	0.13	[19]

Conventional semiconductor processes use sputtering, electroplating, laser micromachining, or E-beam evaporating [20–27] to make conductive coils. In this work, we used a conductive direct-write method with silver ink to fabricate the conductive structures. This method provides a faster or cheaper alternative to the conventional methods. Table 3 shows the comparison of different fabrication methods for making the conductive coils of the energy harvesters, and the output power of the proposed method is acceptable.

Table 3. Comparison of the coil formation processes for vibrational energy harvesters.

Reference	Fabrication Method	Frequency (Hz)	Acceleration (g)	Power (W)
Zhang et al., 2016 [20]	Electroplated	250	1.5	1.43×10^{-5}
Tao et al., 2012 [21]	Electroplated	365	1	1.6×10^{-11}
Hoffmann et al., 2009 [22]	Electroplated	390	9	5×10^{-6}
Zhang et al., 2015 [23]	Electroplated	400	6.4	5.5×10^{-10}
Sari et al., 2010 [24]	Sputter deposited	95	40	2.5×10^{-10}
Wang et al., 2009 [25]	Sputter deposited	530	1	2.3×10^{-11}
Ching et al., 2002 [26]	Laser-micromachined	110	9.7	8.3×10^{-4}
Zhang et al., 2011 [27]	E-beam evaporated	350	4.9	2×10^{-12}
This work	Conductive direct-write	275	5	8.2×10^{-8}

According to Equation (6), reducing the resistance of the coils or enhancing the induced voltage would increase the generator's power. In other words, the profile of the coil (turns and width) would have influence on the energy harvester performance. Observed from the experimental results (Figures 8 and 9), it can be found that the resistance decreases as the thickness of the coils increases, and the output voltage increases as the number of coils increases. Therefore, by using the proposed direct-write method, the coil resistance and coil loops can be adjusted without too much trouble, thus improving the output performance of the generator.

6. Conclusions

Micro-generators fabricated by using direct-write conductive materials on cantilever diaphragms are proposed. Thick coil structures were fabricated as a whole and then heat-cured, largely suppressing the stress gradient. The generator vibrates around an external magnet and converts the vibrational power into electrical power. The resistance, open circuit voltage, and output power of six prototypes were measured. To increase the output power, the number of coils was increased and the resistance of the coils was reduced by increasing the number of layers of metal used. A single coil can produce 16, 36, and 51 nW at 417, 445, and 475 Hz, and a double coil can produce 22, 51, and 82 nW at 218, 246, and 275 Hz, both in response to 5 g vibration acceleration. This technique shows great promise for use in applications such as the powering of intelligent sensor networks.

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Conflicts of Interest: The authors declare no conflict of interest.

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