FULLY BATCH-FABRICATED MEMS MAGNETIC VIBRATIONAL ENERGY HARVESTERS

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Abstract: This paper reports the fabrication and characterization of fully-integrated, fully-batch-microfabricated electromagnetic vibrational energy harvesters. The 4 – 15 mm³ structures utilize embedded NdFeB powder micromagnet technology, and represent some of the smallest magnetic energy harvesters demonstrated to date. Of three different designs, the best performing demonstrated 13.2 μVrms at the device resonance of 530 Hz and 1 g (9.8 m/s²) excitation. This corresponds to a predicted maximum output power of 23 pW and a normalized power density of 1.6 ×10⁻⁹ W/cm³·g². While the power from these prototype devices is limited, ongoing design and fabrication improvements aim to increase their performance.

Keywords: Vibrational Energy Harvester, Magnetic Harvester, Micromagnet Technology, Microfabrication

INTRODUCTION

In recent years, miniature vibrational energy harvesters have received great attention as potential power sources for wireless sensor nodes, portable electronics, and micro/nano transducers [1]. Advances in MEMS fabrication techniques offer opportunities for integrating microscale power generators into microelectronic devices to achieve complex self-powered systems.

Three transduction mechanisms—electrostatic, piezoelectric and electromagnetic—have been widely studied to convert the mechanical vibrational energy to electrical energy [2]. For certain applications, chip-scale micro-watt power generators may be suitable. At these size scales, it is highly desirable to employ MEMS batch-fabrication techniques to potentially enable large-scale manufacturing of numerous devices at low cost. Additionally, microfabricated energy harvesters offer the potential for cofabrication with CMOS or other semiconductor devices for system-on-chip solutions.

While micromachined electrostatic [3-5] and piezoelectric [6, 7] energy harvesters have been explored intensively, micromachined electromagnetic harvesters are less popular because of the challenges for integration of permanent magnetic materials into MEMS processing. Most reported microscale electromagnetic energy harvesters use MEMS fabrication technology for only a portion of the device. For example, micromachining may be used to create beams [8], diaphragms [9], or coils [9, 10], but then other discrete components, such as coil windings [8], membranes [10] or magnets [8-10], are manually assembled to form a complete device. In particular, almost all the magnets are bulk manufactured and manually bonded on to the device [8-10]. This manual assembly raises problems such as misalignment and low manufacturability.

Most methods for fabrication of micromagnets with good magnetic performance are not fully compatible with conventional MEMS processing [11]. For example, the best magnetic materials, rare-earth magnets, cannot be electroplated via aqueous solutions, and physically deposited (sputtered, pulsed laser deposited) rare-earth films require high-temperature processing (400–800°C) to realize good magnetic performance. This temperature range is too high for other conventional MEMS materials, such as polymers and some metals, to survive the processing.

Previously, we have developed a wax-bonded micromagnet fabrication process [12] that shows the potential for full integrability into MEMS process flows. The purpose of this paper is to demonstrate that these micromagnets can be used to fabricate fully-integrated, fully-batch-microfabricated electromagnetic vibrational energy harvesters. Three energy harvester prototypes are fabricated, and their performances are characterized in this work.

OPERATING PRINCIPLE

Figure 1 shows the schematic of the vibrational harvester, using a conventional diaphragm-based mass-spring-damper mechanical resonator. A wax-bonded NdFeB micromagnet acts as a central proof mass supported by a polydimethylsiloxane (PDMS) membrane. Around the resonator, a 3-turn, planar spiral Cu coil is electroplated on the top wafer surface. The coil also helps anchor the PDMS diaphragm to the silicon wafer, since PDMS generally doesn’t adhere very well to silicon.
Out-of-plane vibration of the silicon frame will excite the magnet into oscillation, resulting in a change of magnetic flux within the area closed by the Cu coil. Therefore, an induced voltage will be created in the coil based on Faraday’s law.

PDMS is an attractive material for MEMS energy harvester applications. PDMS has very low Young’s modulus of 750 kPa [13], much lower than silicon (162 GPa) or other polymers such as polyimide (2.5 GPa) [10] or parylene (2.8 GPa) [14]. Since a lower modulus enables more compliant mechanical flexures, the resonant frequency of the final miniaturized device can be pushed down to lower frequencies (<500 Hz), where most natural vibrations occur [15]. In addition, PDMS has good thermal and chemical stability, permitting other MEMS processing steps.

**FABRICATION**

As shown in Figure 2, the fabrication process starts from a standard silicon wafer. First, a thin layer (500 nm) of oxide is deposited on the front side of the wafer by PECVD. Then, a seed layer of 10 nm titanium and 100 nm copper is deposited by dc sputtering and followed by patterning 25 μm thick photoresist (AZ 9260) to form an electroplating mold for the copper coil. Thick Cu coils (~35 μm) are then electroplated. The thickness of the Cu coils is intended to be larger than the thickness of the photoresist mold in order to form a mushroom head on top of the coils, as shown in Figure 3. This mushroom head is used to mechanically lock the PDMS membrane and enhance the adhesion of the PDMS with the silicon substrate. After stripping the photoresist mold and seed layers, 10 μm thick PDMS is then spin-coated overtop the coil and cured at 90 ºC for 2 hours. The topside processing is now complete.

The remainder of the process flow focuses on the backside to create embedded magnets and to release the structure. First, DRIE is used from the backside to define cavities for the magnets ~450 μm deep. The rare earth NbFeB magnetic powder used in fabrication of micromagnets is supplied by Magnequench, Inc. (MQP-11-9). The particles have ball shapes, distributed size and an average diameter of about 50 μm. The binder wax, supplied by Logitech Ltd. (0CON-196), has a melting temperature of 180 ºC. The wax powder has an average diameter about 10 μm. The magnetic powder is homogeneously mixed with wax powder loading fraction of 8 wt%. The mixture is dry-packed at room temperature into the pre-etched cavities with compression by wiping a flat edge across the wafer, leaving only powder in the trenches. After packing, the whole silicon wafer is heated on a hotplate at 180 ºC for 30 s and then cooled down in air, allowing the wax to melt and bond the magnetic particles.

The wafer is then pulse magnetized using a pulsed magnetic field of ~3 T to magnetize the magnets out-of-plane. Lastly, the backside the wafer is patterned again and deep-etched to release the diaphragm. Individual devices are then diced from the processed wafer for characterization. Contact windows for the coil bond pads are opened by laser ablation of the
PDMS using a 1047-nm Nd:YLF laser (Resonetics, Inc.). Figure 4 shows the top-side views of various prototype devices. Figure 5 shows the back-side views of the micromagnets with different patterns used in the energy harvesters.

Figure 6 shows a sample hysteresis loop of a micromagnet test sample, as measured by a vibrating sample magnetometer (ADE Technologies, EV9 VSM). The magnet has a coercivity of 736.7 kA/m, a remanence of 0.25 T, and a maximum energy product of 13 kJ/m³.

Figure 6. A typical magnetic hysteresis loop (disk with 1.8mm diameter and 0.36 mm thickness)

RESULTS

Three microfabricated energy harvesters are characterized in this paper, as listed in Table 1. The resistivity of the coils are 1.89, 1.56, and 1.51 Ω, respectively. The devices are glued and wire-bonded onto a PCB for characterization using a shaker with sinusoidal excitation at 1 g (9.8 m/s²). The frequency response of the open-circuit voltage is recorded together with the acceleration signal using a spectrum analyzer (Stanford Research System model SR780).

Figure 7 shows the results for the three different designs. The devices show resonance at 530, 503 and 763 Hz, respectively. At resonance, normalized rms voltages of 13.2, 10.8 and 5.6 μV/g are obtained. The corresponding power is calculated by assuming matched resistive load (i.e. \( P_{match} = \frac{V_{rms}^2}{4 \cdot R_{coil}} \)).

The power and normalized power density of the devices are listed in Table 2.

<table>
<thead>
<tr>
<th>Device</th>
<th>Thickness of diaphragm (µm)</th>
<th>Diameter of diaphragm (mm)</th>
<th>Diameter of magnet (mm)</th>
<th>Shape of magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>5.4</td>
<td>4.6</td>
<td>Ring fig 5 (b)</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>5.4</td>
<td>4.6</td>
<td>Star fig 5 (a)</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>2.6</td>
<td>1.8</td>
<td>Circular fig 5 (d)</td>
</tr>
</tbody>
</table>

Table 1. Microfabricated energy harvesters designs
CONCLUSION

These prototype devices verify the feasibility of magnetic energy harvesters using MEMS batch-fabrication technologies. Although the performances of the devices here are limited, many design improvements can be made to enhance the performance. These include increasing the coil turns, positioning the magnet and coil closer, using thinner PDMS diaphragms for more compliance, increasing the center proof mass, using strong magnets, and/or creating altogether different structures.

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REFERENCES