ABSTRACT
This paper reviews the state of the art in miniature microsystems for harvesting energy from external environmental vibration, and describes two specific microsystems developed at the University of Michigan. One of these microsystems allows broadband harvesting of mechanical energy from extremely low frequency (1-5 Hz) random vibrations abundant in civil infrastructure, such as bridges. These parametric frequency increased generators have a combined operating range covering two orders of magnitude in acceleration (0.54-19.6 m/s²) and a frequency range spanning up to 60 Hz, making them some of the most versatile harvesters in existence. The second of these systems is an integrated microsystem for harvesting energy from periodic vibrations at moderate frequencies (50-400 Hz) typically present in devices such as motors or transportation systems. This harvester utilizes a thinned-PZT structure to produce 2.74 μW at 0.1 g (167 Hz) and 205 μW at 1.5 g (154 Hz) at resonance. Challenges in the design of electronic circuitry (integrated or hybrid) for regulating the scavenged energy are briefly discussed.

KEYWORDS

1. INTRODUCTION
“Power” – some work hard to gain it, and some struggle to keep it. This is certainly true in integrated circuits, and increasingly important in emerging applications that utilize a range of electronic computation and communication circuits and a variety of sensors and actuators. The IC industry is facing a significant challenge to its incredible 50-year run motivated by Moore’s law – how to dissipate the heat generated as billions of transistors gobble up an enormous amount of power. Here, the goal is clearly not to lose power as computation speed increases. However, the signs are clear that future ICs have to give up some power since the generated heat cannot be easily dissipated. On the other side, many emerging applications require autonomous operation in a variety of areas ranging from portable consumer electronics and information technology devices, to distributed wireless sensor networks that will soon populate our planet and be embedded in everything from household items to infrastructure and environmental monitors. These emerging applications require power, and this power has to be “gained” from the environment. Stored power in the form of batteries is not sufficient for many of these applications. The reasons are clear. Distributed networks and sensing systems are meant to be permanent, providing the needed information around the clock, ideally for a very long time. Often these networks are not easily accessible, so battery replacement is not practical. Even if access was possible, the mere number of nodes needed in these networks makes the cost of replacement too high. Furthermore, battery and power storage technologies still utilize materials that are not eco-friendly; these materials cannot be scattered, left unchecked, or allowed to disintegrate. Clearly, there are many applications whose power needs will be satisfied with batteries. But many others, some not yet imagined, cannot use batteries readily for the reasons mentioned above.

Despite these challenges, we are at an interesting point in the development of microelectronics and microsystems. On one end, the IC revolution has reached a point where the power needed per function has drastically decreased, and it is now possible to perform many functions (computation, communication and sensing) with very limited power (in the range of a few microwatts). On the other end, the surge in microsystems technologies (sensors and actuators) has facilitated the development of high-performance microinstruments that are enabling many emerging applications in distributed sensing and monitoring. So, one does not need much power to achieve one’s objectives, nor does one have to significantly compromise on the quality or the quantity of information needed. Integrated microsystems combine electronics (for computation and communication) with micromachined sensors and actuators (for sensing and control). They invariably need power. Figure 1 shows the architecture of what we refer to as a “hybrid” power source, that we believe is needed in many emerging microsystems. This source has to address three basic needs: 1) how to gain power from external sources present in the environment of the microsystem; 2) how and where to store this power; and 3) how to regulate the power to make it useful for the microsystems, and how to manage this valuable stored power so it is used efficiently and only for those functions that are critical.

This paper explains how to “gain” power from environmental vibrations through devices that are broadly referred to as power/energy scavengers or

MICROSYSTEMS FOR ENERGY HARVESTING

Invited Paper

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harvesters. First a quick review of past work on energy harvesters or scavengers will be provided, followed by a discussion on the different types of approaches that are being pursued. Next, a short discussion on how reported inertial power harvesters can be evaluated in a normalized fashion to allow a user to compare their usefulness is presented. Two vibration power harvesters developed at the University of Michigan will next be briefly described for two broad applications of emerging microsystems. A short discussion on power management and regulation circuitry will be presented. Finally, the paper provides concluding remarks.

Figure 1. Architecture of a “Hybrid Power” source for integrated microsystems.

2. BACKGROUND

Review of Past Harvesters:

The idea of using harvested energy for powering microsystems dates back as far as 1969 [1], when Ko patented the idea of using a vibrating piezoelectric beam as a means of powering biomedical implants. The idea was rejuvenated by Shearwood et al. [2] who developed the first bulk fabricated electromagnetic prototype, in addition to laying the theoretical foundation used by authors in the field since that time. It was not until 2003, with the publishing of the widely cited work of Roundy et al [3], that the piezoelectric bimorph beam harvester was demonstrated. Since around this time, the field of harvesting energy from various energy sources, most notable of which is vibration, has grown exponentially.

Power can be gained from the environment from a number of different sources. The most popular is solar or photo optical power scavengers. In this paper we will not address this category of scavengers. Other sources include: vibration, heat, electromagnetic radiation (RF sources), air flow or wind, fluid flow (hydraulics and transpiration), strain or pressure, biological sources, and a variety of chemical and radioactive reactions. An extensive review of these sources is provided by Roundy and others and will not be repeated here. Conversion of energy from each of these sources can be achieved using a variety of approaches using different transduction techniques. Solar cells utilize electronic devices in the form of photovoltaic cells. Mechanical vibration is converted to electric energy using electromagnetic, piezoelectric, electrostatic, magnetostrictive or electrostrictive transducers. Air and liquid flow often utilizes similar transduction techniques. Pressure and strain energy typically utilize piezoelectric transducers.

This is not to say that other techniques have not been utilized or possible. However, electromagnetic, piezoelectric, and electrostatic are the first choice because of established and mature technologies, easier implementation in small form factors, better efficiency, or easier integration with electronics. Whatever the transduction technique, the most important requirement is that they produce reasonable power in a device with wide bandwidth, small volume, low weight, and low-cost.

Figure 2 shows a summary of power vs. volume of some of the most recent power scavengers (primarily inertial and thermal), highlighting the different transduction technologies, including piezoelectric (PE), electromagnetic (EM), electrostatic (ES), and thermolectric (TE). As evident, the size and power level of these scavengers is spread over a large range, partly dictated by the application area and partly by the available technologies. The most important conclusion is that most scavengers produce on the order of $10-100\mu\text{W/cm}^3$. This is not much power, but as mentioned before, it is useful for many of the emerging applications.

Figure 2. Power v. volume for a number of power harvesters reported in the literature.

It is also evident that harvesters reported in the literature do not always provide the needed information to allow reasonable and meaningful comparison. However, it is instructive to develop “figures of merit” that provide some insight into how the performance of these harvesters compare, and how they can be improved. We focus primarily on vibration harvesters in the rest of this paper.

Figures of Merit

Energy harvesters need relevant metrics of performance that will allow an even-handed comparison. A good metric will normalize with respect to the incoming energy so that a fair comparison can be made. For vibration harvesters conversion efficiency is a strong function of frequency and amplitude. One metric that is commonly used is the Normalized Power Density (NPD) [4], where power density is divided by acceleration$^2$. NPD has one drawback in that it does not completely
eliminate the frequency dependence. A very useful metric is proposed in [5] called the Volume Figure of Merit \(F_vM\), which compares device performance as a function of overall size and fully eliminates the source vibration:

\[
F_vM = \frac{1}{2} \frac{\text{Useful Power Output}}{Y_v \rho A U \text{Vol}^{3/5}}
\]

In order to account for the bandwidth of harvesters, an important characteristic that speaks to their versatility, additional metrics are needed. Our group has used a metric called Figure of Merit \(F_vM\), which is appropriate for comparing harvesters operating at similar frequencies:

\[
F_vM = NPD \times BW
\]

A more general metric is the Bandwidth Figure of Merit \(F_vM_{BW}\) [5], which is simply the volume figure of merit \(F_vM\) multiplied by the fractional bandwidth (1dB bandwidth divided by the center frequency). Bandwidth comparisons are notoriously complicated because few authors publish bandwidth data.

A review of the vibration harvesting work reported to date is shown in Figure 3. The plot shows the vibrations produced by various sources (acceleration vs. frequency) as shaded windows. Superimposed on this plot using the right hand axis and the various ‘dots’ are the \(F_vM\) values reported to date. These works are cited in [6]. The plot highlights the relative importance of the low end of the frequency spectrum, in terms of applications, versus the small amount of work that has gone into addressing these applications. The plot also shows the state-of-the-art that has been achieved in developing resonant harvesters using bulk micromachining for various microsystems applications. The most important conclusion derived from this plot is that the majority of reported harvesters operate above 50 Hz. There are two reasons for this: 1) many of the applications do reside around this frequency range, and more importantly 2) harvesting useful energy is much easier at higher frequencies. However, many of the emerging applications including those involving infrastructure monitoring or human motion need to scavenge power at below 10Hz. At these vibration frequencies, it is hard to scavenge reasonable energy, and it is even harder to regulate the harvested power.

### 3. EXAMPLE INERTIAL HARVESTERS:

Below we report two harvesters developed at the University of Michigan for scavenging energy from environmental vibrations. One of these harvesters utilizes frequency up-conversion to scavenge energy from extremely low-frequency and non-periodic vibrations, and utilizes a novel parametric technique to significantly extend the operational bandwidth. The second utilizes piezoelectric transducers in a novel microfabrication process to produce electrical power from high frequency periodic vibrations.

**Low-Frequency Broadband Mechanical Harvester:**

Low frequency motion is important in applications such as wearable and implantable devices, environmental monitoring, agricultural applications, and security uses, just to name a few. However, in addition to the typical challenges encountered by vibration harvesters such as achieving a high conversion efficiency in a small volume, materials integration, and eliminating parasitic losses, low-frequency harvesters have a lower expected power density because of three unique challenges: 1) the required spatial displacement is higher because of the larger amplitude of the vibrations, 2) at low frequencies the electromechanical coupling in the conversion mechanism will be weaker, and 3) low frequency vibrations are more likely to be produced by natural phenomena thereby increasing the probability that they are not periodic.

We have developed a novel harvester architecture to address these challenges. The Parametric Frequency Increased Generator (PFig) is shown in Figure 4a [7]. It uses a large central mass to couple mechanical energy inside the harvester and through a magnetic latching mechanism to pass a portion of this energy to one of two electromechanical transducers (Frequency Increased Generators or FIGs) located on either side. The FIGs convert the mechanical energy to electrical (Figure 4b). Much like the plucking of a guitar string, the FIGs up-convert the frequency of the ambient motion in order to achieve better conversion efficiency. More detailed analysis of this harvester can be found in [6]. It is important to note is that as the volume of the harvester shrinks, the frequency range over which it is more efficient to use a PFIG harvester increases.

Three generations of the PFIG generator have already been fabricated and tested [8-10]. The three PFIG devices have a combined operating range covering two orders of magnitude in acceleration \((0.54-19.6 \text{ m/s}^2)\) and a frequency range spanning up to 60Hz; making them some of the most versatile generators in existence. The first electromagnetic harvester (GEN 1) (Figure 5 left) can generate a peak power of 163 \(\mu\text{W}\) and an average power of 13.6 \(\mu\text{W}\) from an input acceleration of...
9.8 m/s² at 10 Hz, and it can operate up to 60 Hz. The internal volume of the generator is 2.12 cm³. A second piezoelectric implementation (GEN 2) (Figure 5 right) generates 3.25 µW of average power under the same excitation conditions, while the volume of the generator is halved (1.2 cm³). A third PFIG was developed for critical infrastructure monitoring applications (GEN 3). It is used to harvest the very low-amplitude, low-frequency, and non-periodic vibrations present on bridges. The device generates 2.3 µW of average power from an input acceleration of 0.54 m/s² at only 2 Hz. It can operate over an unprecedentedly large acceleration (0.54-9.8 m/s²) and frequency range (up to 30 Hz) without any modifications or tuning. The operation of this harvester is verified on multiple locations on a suspension bridge. The results of this study are published in the technical digest of this conference.

There are several elements affecting the power output from piezoelectric resonant harvesters as shown in the equation below. On the design side, it is necessary to maximize the effective proof mass, and optimize the structural dimensions in a limited volume. On the fabrication side, high piezoelectric coupling and low mechanical damping losses need to be achieved. Here, although a high mechanical quality factor may be desired for a larger power output, this comes with a trade-off of having decreased operational bandwidth.

\[
\text{Power}_{\text{RES}} \propto k_{31}^2 \cdot \text{mass}_{\text{EFF}} \cdot \frac{\text{Acceleration}^2}{\text{Res. Frequency}} \cdot Q^2
\]

Since the power output is directly proportional to the square of the electromechanical coupling coefficient \(k_{31}\), it is critical to utilize a high quality piezoelectric material in a harvester. For integration of piezoelectric materials on silicon, various thin and thick film deposition techniques have been developed to date, including sputtered AlN [11-12], screen-printed PZT [13], sol-gel PZT [14-16], aerosol PZT [17], and others. However, in addition to their individual fabrication challenges, these deposited films are generally limited in their maximum allowable film thicknesses (2-5 µm), and show poor piezoelectricity compared to commercially available bulk ceramics. Bulk piezoelectric ceramics can provide greater electro-mechanical force and charge capacity than deposited piezoelectric thin films [18], and thus are highly desirable in micro power scavengers.

Recently, a batch-mode wafer-level fabrication technology for integration of bulk ceramics in microsystems is introduced [18]. The process involves aligned solder bonding of commercially available bulk piezoelectric substrates on silicon, and mechanical thinning to obtain the desired PZT thickness (5-100 µm). Advantages of this new fabrication technology include conservation of bulk piezoelectric properties in the final thinned film, flexibility to use different piezoelectric materials, avoiding PZT chemical patterning for simple structures, and the use of traditional clean-room tools instead of sophisticated, hard-to-tune deposition systems.

A thinned-PZT energy harvester fabricated with this new process is demonstrated to produce a record power output and has state-of-the-art efficiency [19]. An unpackaged harvester with a tungsten proof mass produces 2.74 µW at 0.1 g (167 Hz), and 205 µW at 1.5 g (154 Hz) at resonance (where g = 9.8 m/s² acceleration input). The active device volume is 27 mm³, while a
hermetically packaged harvester occupies < 150 mm³. Vertical Si vias enable the integration of the harvester to its power management IC, which allows autonomous charging of an ultra-capacitor from 0 V to a regulated voltage level of 1.85 V [20] (Fig. 7). The overall system is completely self-supplied by vibration energy, and has no dependence on a previously charged battery.

State-of-art piezoelectric resonant harvesters realized through different micro-fabrication techniques are compared in Table 1. Here, Normalized Power Density (i.e., Power/volume/acceleration³) is used to compare the effectiveness of harvesters, where the power output is normalized with respect to the vibration input and the active device volume [21].

### Table 1. Comparison of state-of-art piezoelectric harvesters

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Material</th>
<th>Mass</th>
<th>Input Vibe</th>
<th>Freq Hertz</th>
<th>Power µW</th>
<th>B.W. µW</th>
<th>N.P.D. mW/cm²/g²</th>
</tr>
</thead>
<tbody>
<tr>
<td>[19]</td>
<td>Thinned PZT</td>
<td>W</td>
<td>0.1g</td>
<td>167</td>
<td>2.74</td>
<td>6.1</td>
<td>10.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Si</td>
<td>0.1g</td>
<td>427</td>
<td>1.82</td>
<td>16.0</td>
<td>6.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.5g</td>
<td>415</td>
<td>160.8</td>
<td>33.3</td>
<td>2.65</td>
</tr>
<tr>
<td>[18]</td>
<td>Sputtered AIN</td>
<td>Si</td>
<td>0.1g</td>
<td>263</td>
<td>0.15</td>
<td>4.2</td>
<td>1.22</td>
</tr>
<tr>
<td>[11]</td>
<td>S.Printed PZT</td>
<td>Si</td>
<td>1.75g</td>
<td>325</td>
<td>85</td>
<td>3</td>
<td>0.97</td>
</tr>
<tr>
<td>[12]</td>
<td></td>
<td>Si</td>
<td>2.0g</td>
<td>572</td>
<td>60</td>
<td>2</td>
<td>1.00</td>
</tr>
<tr>
<td>[13]</td>
<td>S.Printed PZT</td>
<td>Si</td>
<td>1.0g</td>
<td>235</td>
<td>14</td>
<td>8</td>
<td>0.75</td>
</tr>
<tr>
<td>[14]</td>
<td>Sol-gel PZT</td>
<td>Si</td>
<td>2.0g</td>
<td>461</td>
<td>2.15</td>
<td>1.2</td>
<td>0.82</td>
</tr>
<tr>
<td>[15]</td>
<td></td>
<td>Si</td>
<td>2.0g</td>
<td>870</td>
<td>1.4</td>
<td>-</td>
<td>0.73</td>
</tr>
<tr>
<td>[16]</td>
<td></td>
<td>Si</td>
<td>2.35g</td>
<td>1800</td>
<td>40</td>
<td>1</td>
<td>0.39</td>
</tr>
<tr>
<td>[17]</td>
<td>Aerosol PZT</td>
<td>Si</td>
<td>2.5g</td>
<td>256</td>
<td>2.77</td>
<td>-</td>
<td>0.20</td>
</tr>
</tbody>
</table>

A microsystem for autonomous energy harvesting using the thinned-PZT harvester has been demonstrated in a small volume factor [20]. The circuitry utilizes 0.18 µm CMOS technology, and is formed of three main sub-circuits (Fig. 8). First, a bias-flip stage increases the available charge output of the piezoelectric device. Secondly, for low-voltage drop-out rectification, a negative voltage converter and an active diode is used. Finally, a trickle charger enables the initial and continuous charging of an ultra-capacitor up to the regulated voltage level. The comparators in this system are biased with a supply independent bias circuitry, which limits the overall power consumption to < 1 µW. The circuitry is self-powered by the harvested energy in the temporary reservoir.

### 4. POWER MANAGEMENT CIRCUITRY

An ideal power management circuitry should have high end-to-end conversion efficiency, be able to work with minimum available energy level from a harvester, have minimum or zero active power draw from the final energy reservoir, and be able to start-up with initially discharged energy reservoirs. Although proof-of-concept designs and fast prototyping can be met with off-the-shelf components, application-specific IC designs are mostly necessary for higher efficiency and more functional operation. Challenges in power management of harvested energy vary according to the utilized energy conversion technique, due to different output impedance, output voltage levels, and operating frequencies. Studies focused on increasing the extracted charge output from a piezoelectric device, include resonant bias-flipping on PZT capacitance, steering the energy through a rectifier-free LC-transfer network, and adaptive impedance matching. In addition to their hard-to-match high output impedances (> a few MOhms), electrostatic devices require initial charging of capacitor plates, and thus they are dependent on a pre-charged battery or external voltage source. On the thermoelectric and air flow harvesters side, the circuitry should account for discontinuous power outputs, and polarity changes in the output voltage. In thermoelectric harvesters, very low voltage outputs (10-50 mV) due to available small temperature differences (1-2 K) result in an additional challenges for the start-up circuitry and efficient rectification. Both electromagnetic and thermoelectric
devices require tracking the optimum voltage output at different available ambient energy levels, which can be achieved by use of a pulse-width modulated boost converter.

5. CONCLUSIONS:
Microsystems for harvesting energy from the environment will be needed in many emerging applications. Future distributed networks and sensing systems will certainly include harvesters. New fabrication technologies, novel device structures, and low-power integrated circuit techniques will continue to improve the power output, efficiency, size, and weight of many energy harvesters. Microsystems will gain more power from the environment, and they will give up some power as they utilize new circuit and sensing techniques.

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