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Huidong Li, Chuan Tian, and Z. Daniel Deng

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APPLIED PHYSICS REVIEWS

Energy harvesting from low frequency applications using piezoelectric materials

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In an effort to eliminate the replacement of the batteries of electronic devices that are difficult or impractical to service once deployed, harvesting energy from mechanical vibrations or impacts using piezoelectric materials has been researched over the last several decades. However, a majority of these applications have very low input frequencies. This presents a challenge for the researchers to optimize the energy output of piezoelectric energy harvesters, due to the relatively high elastic moduli of piezoelectric materials used to date. This paper reviews the current state of research on piezoelectric energy harvesting devices for low frequency (0–100 Hz) applications and the methods that have been developed to improve the power outputs of the piezoelectric energy harvesters. Various key aspects that contribute to the overall performance of a piezoelectric energy harvester are discussed, including geometries of the piezoelectric element, types of piezoelectric material used, techniques employed to match the resonance frequency of the piezoelectric element to input frequency of the host structure, and electronic circuits specifically designed for energy harvesters. © *2014 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License*. [http://dx.doi.org/10.1063/1.4900845]

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I. INTRODUCTION OF ENERGY HARVESTING AND LOW FREQUENCY APPLICATIONS

The continuous improvement of semiconductor manufacturing technologies has led to tremendous technological advancements in small electronic devices, such as portable electronics, sensors, and transmitters in the last three decades. Functionality has been largely broadened and energy efficiency has been greatly enhanced, all while reducing size by orders of magnitude. In addition, as the energy density of batteries continues to improve, many of these devices are able to operate for long periods of time solely on battery power. In some applications, such as sensors deployed in remote locations or inside the human body, however, replacement of the battery at the end of its service life can be challenging or even unpractical. Therefore, the need of harvesting ambient energy to power the electronic devices in these situations arises. Examples of ambient energy sources

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include wind, solar, mechanical vibration, and movement of the human body. For small electronic devices, the level of power consumption usually lies in mW or μW range and the size of the powering unit needs to be small in order to accompany the host device. In addition, most of these applications require the device to be able to operate both indoors and outdoors, without heavy dependence on weather conditions. In this regard, mechanical vibration and human body motion become attractive energy source options for small electronic devices.

There are various methods to convert mechanical energy from vibrating or moving objects into electrical energy needed by electronic devices, including electromagnetic induction, electrostatic induction, and the piezoelectric effect. Compared with electromagnetic and electrostatic methods, energy harvesting with piezoelectric materials provides higher energy density and higher flexibility of being integrated into a system, and thus has been the most widely studied.[1,2]

Piezoelectric materials possess crystalline structures in which the centers of positive and negative charges do not overlap, yielding dipole moments. When subjected to mechanical vibrations or motion, mechanical strain is applied to these materials and leads to distortion of the dipoles, creating electrical charge. The electrical energy can be harvested by storing it in rechargeable batteries or capacitors.

Piezoelectric materials are divided into four categories based on their structure characteristics: ceramics, single crystals, polymers, and composites (the composite material is a combination of piezoelectric ceramics or single crystals with polymers). Most piezoelectric ceramics and single crystals used to date for energy harvesting are a subgroup of piezoelectrics called "ferroelectrics." The typical examples are PZT (lead zirconate titanate) and PMN-PT (the solid solution of lead magnesium niobate and lead titanate). Below a critical temperature called the Curie temperature, these materials possess spontaneous dipoles, which bestows excellent piezoelectric properties. Thus, ferroelectric single crystals, ceramics, and composites have much better piezoelectric properties than polymers. Piezoelectric polymers, however, have the ability to sustain much higher strain due to their intrinsic flexibility, making them better suited for applications where the device will be subjected to large amount of bending or conforming to a curved mounting surface (e.g., wearable devices).

Efficiency and power density of a piezoelectric vibrational energy harvesting device are strongly frequency dependent because the piezoelectric generates maximum power at its resonance frequency. Therefore, the fundamental frequency of the host determines the size of the piezoelectric element of a piezoelectric energy harvesting unit. Roundy[3] identified that the low frequency fundamental mode should be targeted in the design of the energy harvesting device, as opposed to the higher frequency because the potential output power is proportional to $1/\omega$, where ω is the frequency of the fundamental vibration mode. The frequencies of some of the typical vibration sources are listed in Table I. Most machinery equipment has a frequency of 100 Hz or higher, whereas human or animal motion exhibits a much lower frequency, typically within the 1–30 Hz range. Piezoelectric ceramics are metal oxides, resulting in much higher fundamental frequencies when compared to composites and polymers of the same size and geometry, with the same vibration mode. Within the reasonable size range allowed by small electronic devices, if monolithic piezoelectric ceramics are used as the energy harvesting element, the lowest resonance frequency mode is in the kilohertz range or higher, significantly beyond the frequency range of vibration sources as shown in Table I. Therefore, to achieve a lower resonance frequency in a relatively small package size, various techniques have been employed, including the choice of piezoelectric material used, configuration and design of the energy harvesting element, and conditioning of the energy harvesting circuitry. For applications with higher vibration frequencies (100 Hz or higher), the choice of the piezoelectric material is relatively simple. Piezoelectric ceramics are usually selected for these applications because the elements fabricated possess higher resonance frequencies to match the application, and their piezoelectric properties are superior to composites and polymers. However, the lower the frequency of the vibration host, the more complex it becomes to design the energy harvesting unit, as the dimension and weight constraints limit the use of the ceramics to achieve the desired fundamental frequency. Thus, for these situations, piezoelectric composites and polymers can often be the material candidates. Frequency tuning techniques are also utilized, unless the application involves large direct mechanical impact on the piezoelectric elements, generating sufficient power.

TABLE I. Frequency and acceleration of various vibration sources.[3,4]

Vibration source	Frequency (Hz)	Acceleration amplitude (m/s^2)
Car instrument panel	13	3
Casing of kitchen blender	121	6.4
Clothe dryer	121	3.5
HVAC vents in office building	60	0.2–1.5
Car engine compartment	200	12
Refrigerator	240	0.1
Human walking	2–3	2–3

This review focuses on the recent development in piezoelectric energy harvesting for applications where the vibration source has a frequency lower than 100 Hz. The selection of the appropriate piezoelectric material for a specific application and methods to optimize the design of the piezoelectric energy harvester will be discussed.

II. TYPICAL CONFIGURATIONS OF PIEZOELECTRIC ENERGY HARVESTERS

In most cases of piezoelectric energy harvesting, the vibration or mechanical energy sources either have low motion frequencies or low acceleration. A thin and flat form factor allows a piezoelectric element to readily react to the motion for the host structure. In addition, such a form factor is also beneficial in reducing the overall dimensions and weight of the energy harvesting device. Thus, the piezoelectric materials used in most of the piezoelectric energy

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harvester designs and configurations explored to date possess a thin-layer geometric shape.

A. Cantilever beams

Cantilever geometry is one of the most used structures in piezoelectric energy harvesters, especially for mechanical energy harvesting from vibrations, as large mechanical strain can be produced within the piezoelectric during vibration, and construction of piezoelectric cantilevers is relatively simple. More importantly, the resonance frequency of the fundamental flexural modes of a cantilever is much lower than the other vibration modes of the piezoelectric element. Therefore, a majority of the piezoelectric energy harvesting devices reported today involve a unimorph or bimorph cantilever design.

A thin layer of piezoelectric ceramics can be built into a cantilever, bonding it with a non-piezoelectric layer (usually a metal serving as a conductor of the generated charge), and having its one end fixed in order to utilize the flexural mode of the structure (Figure 1(a)). Such a configuration is called a "unimorph" as only one active layer (the piezoelectric layer) is used in this structure. A cantilever can also be made by bonding the two thin layers of piezoelectric ceramic onto the same metal layer to increase the power output of the unit (Figure 1(b)). This is called a "bimorph" structure as two active layers are used. Bimorph piezoelectric cantilevers are more commonly used in piezoelectric energy harvesting studies because the bimorph structure doubles the energy output of the energy harvester without a significant increase in the device volume.

In a piezoelectric cantilever, the poled directions of the piezoelectric layers are usually perpendicular to the planar direction of the piezoelectric layers because it is the most convenient way to polarize piezoelectric sheets when they are fabricated. Piezoelectric cantilevers operating in the above manner are said to be operating in the "31 mode," where "3" denotes the polarization direction of the piezoelectric layer and "1" denotes the direction of the stress, which is primarily in the planar direction of the cantilever. The 31 mode utilizes the d_{31} piezoelectric charge constant, the induced polarization in the poled direction (direction "3") of the piezoelectric per unit stress applied in direction "1." For a given piezoelectric material, d_{31} is always smaller than d_{33} because in the 31 mode the stress is not applied along the polar axis of the piezoelectric material. Therefore, in order to utilize a piezoelectric sheet in the "d_{33}" mode for higher energy output, an interdigitated electrode design can be used (Figure 1(c)). In this electrode design, an array of narrow positive and negative electrodes is placed alternately on the surface of a piezoelectric sheet when it is fabricated. During poling treatment of the sheet, the interdigitated electrodes direct the electric field to apply laterally within the sheet so that the sheet is polarized in the lateral direction instead of the conventional vertical direction. This way, when the sheet is subjected to bending, the stress direction is parallel to the poled direction of the piezoelectric, enabling the utilization of the primary piezoelectric charge constant, d_{33}.

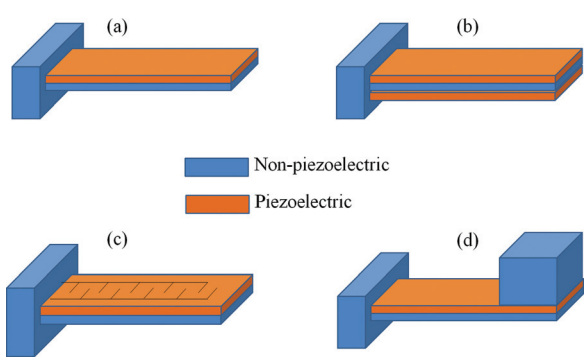

FIG. 1. Various configurations of piezoelectric cantilevers: (a) unimorph; (b) bimorph; (c) a piezoelectric cantilever with interdigitated electrodes; (d) a piezoelectric cantilever with proof mass at its free end.

The resonance frequency of a simply supported cantilever beam can be calculated using the following equation:[4–6]

$$f_r = \frac{\nu_n^2}{2\pi}\frac{1}{L^2}\sqrt{\frac{EI}{mw}}, \tag{1}$$

where E is the Young's modulus, I is the moment of inertia, L is the length, w is the width of the cantilever, m is the mass per unit length of the cantilever beam, and $\nu_n = 1.875$ is the eigenvalue for the fundamental vibration mode.

To further lower the resonance frequency of the cantilever, a proof mass can be attached to the free end of the cantilever (Figure 1(d)). Equation (1) can be approximated into Eq. (2) to include the proof mass[6]

$$f_r = \frac{\nu_n'^2}{2\pi}\frac{1}{L^2}\sqrt{\frac{K}{m_e + \Delta m}}, \tag{2}$$

where $\nu_n'^2 = \nu_n^2\sqrt{0.236/3}$, $m_e = 0.236mwL$ is the effective mass of the cantilever, Δm is the proof mass, and K is the effective spring constant of the cantilever.

Roundy discovered that the power output of a cantilever energy harvester is proportional to the proof mass. In other words, the proof mass should be maximized within the design constraints imposed by the beam strength and the resonance frequency.[1]

Aside from the resonance matching between the energy harvester and the primary input frequency of the host, strain distribution within the piezoelectric material is also an important aspect to reduce the size and weight of the piezoelectric cantilever. The energy output is largely dependent upon the volume of the piezoelectric material subjected to mechanical stress. The stress induced in a cantilever during bending is concentrated near the clamped end of the cantilever.[7] In other words, the strain is at its maximum in the clamped end and decreases in magnitude at locations further away from the clamp.[8] As a result, the non-stressed portion of the piezoelectric layer does not actually contribute to power generation. Both theoretical analysis and experimental studies have shown that a "tapered" or triangular cantilever shape may achieve constant strain level throughout the entire length of the cantilever.[9–11] Therefore, piezoelectric cantilevers with a tapered shape have often been used to minimize the size and weight of the cantilever.

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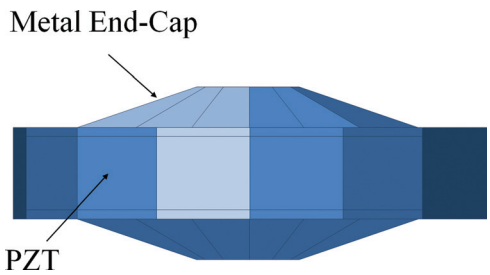

FIG. 2. Schematic of a piezoelectric "cymbal" transducer. Reprinted with permission from Kim *et al*., Jpn. J. Appl. Phys., Part 1 **43**(15), 6178 (2004). Copyright 2004 The Japan Society of Applied Physics.

B. Discs (discs, cymbals, diaphragms)

In addition to cantilevers, energy harvesters with circular shapes, such as cymbal transducers and piezoelectric diaphragms, have also been explored.

1. Cymbal transducers

Cymbal transducers were developed for applications that have high impact forces. It typically consists of a piezoelectric ceramic disc and a metal (steel) end cap on each side (Figure 2). Steel is typically used because it provides higher yield strength than brass and aluminum, thus leading to higher force loading capability of the transducer.[12]

When an axial stress is applied to the cymbal transducer, the steel end caps convert and amplify the axial stress to radial stress in the PZT disc. Therefore, both d_{33} and d_{31} piezoelectric charge coefficients are combined to contribute to the charge generation of the transducer. The effective piezoelectric charge constant d_{33} of a cymbal transducer is expressed as[13]

$$d^{eff} = d_{33} + A|d_{31}|, \tag{3}$$

where A is amplification factor.

Cymbal transducers can provide a higher energy output than cantilever energy harvesters because the cymbal structure withstands a higher impact than the cantilever beam. For example, a cymbal transducer with a piezoelectric ceramic disc of a diameter of 29 mm and a thickness of 1 mm showed an output power of 39 mW and 52 mW under AC force of 7.8 N and 70 N, respectively, at 100 Hz.[13] On the other hand, however, the robust nature of the cymbal structure also limits its potential use to applications that provide high magnitude vibration sources. They are not suitable for energy harvesting from natural ambient vibration sources, which have a low magnitude of vibrations.

2. Circular diaphragms

A piezoelectric circular diaphragm transducer operates in a similar fashion to that of piezoelectric cantilevers. To construct a piezoelectric circular diaphragm transducer, a thin circular piezoelectric ceramic disc is first bonded to a metal shim and then the whole structure is clamped on the edge, while piezoelectric cantilevers are only clamped at one end of the cantilever beam. In some cases, a proof mass is attached at the center of the diaphragm to provide prestress to the piezoelectric ceramic, as it has been found that prestress within the piezoelectric element can improve the low-frequency performance of the energy harvester and increase the power output.[13–16] Another method to introduce prestress within the piezoelectric ceramic occurs during the fabrication stage of the piezoelectric-metal composite, as in the case of THUNDER® (Thin Layer Unimorph Driver) transducer.[17–19] A piezoelectric ceramic layer is first sandwiched between two dissimilar metal layers, and then the composite is heated and cooled to room temperature. The difference in the thermal expansion coefficients of the two dissimilar metals causes the whole structure to warp, thus introducing prestress in the piezoelectric.

Similar to piezoelectric cantilevers, a conventional piezoelectric diaphragm operates in the 31 mode. To utilize the 33 mode of the ceramic, NASA developed a spiral electrode pattern for piezoelectric ceramic diaphragms that functions in a similar fashion to interdigitated electrodes. In this pattern, the positive and negative electrodes spiral alternately inward to the center of the piezoelectric disc (Figure 3). Such piezoelectric diaphragm transducers are called Radial Field Diaphragms (RFD).[20–22] At a low frequency of 10 Hz, it has been shown that RFD's exhibit 3–4 times larger out-of-plane displacement than a conventional piezoelectric diaphragm.[20] 33-mode piezoelectric diaphragms were only recently studied for energy harvesting applications. Shen *et al*. reported results of using a PZT disc with the spiral interdigitated-style electrodes as an energy harvester.[16] Due to the small size of the device, the lowest resonance frequency of the device in that study was 1.56 kHz and the power output was in the nano-watt range under 1 g

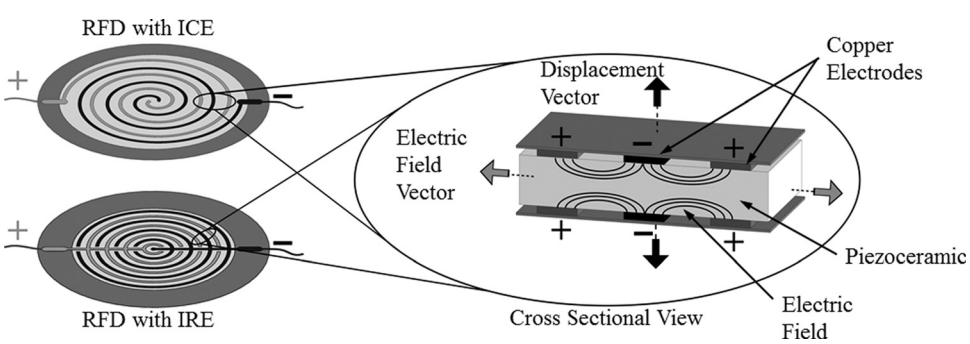

FIG. 3. A schematic of Radial Field Diaphragms (RFD). Reprinted with permission from Bryant *et al*., J. Intell. Mater. Syst. Struct. **15**(7), 527–538 (2004). Copyright 2004 SAGE Publications.

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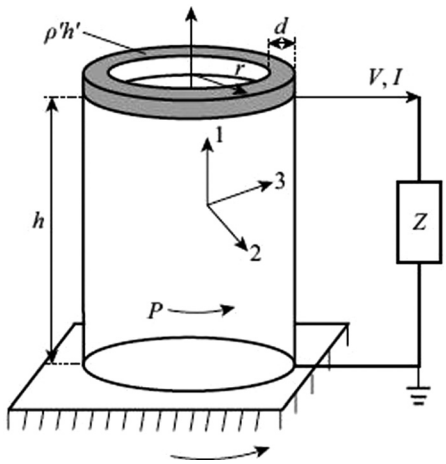

FIG. 4. Illustration of the concept of a cylindrical piezoelectric shell energy harvester. Reprinted with permission from Chen *et al.*, Appl. Math. Mech. **28**(6), 779–784 (2007). Copyright 2007 Springer Science and Business Media.

acceleration. However, a power density comparable to cymbal transducers and 33-mode cantilevers was shown.

C. Other configurations

In addition to cantilevers, cymbals and diaphragms, there are other piezoelectric element configurations which have been explored in mechanical energy harvesting.

For rotational or angular vibration sources, a concept of a piezoelectric shell generator was proposed by Chen *et al.* in 2007. In this design, a cylindrical piezoelectric ceramic shell poled tangentially was fixed to a base moving in an angular motion. A thin mass was attached on the upper end of the shell, acting as a proof mass in a similar manner as with the cantilever. The resonance frequency of the shell structure is lowered, forcing the shell to be strained more severely for higher power output (Figure 4).[23]

When harvesting mechanical energy from vibrations for Micro-Electro-Mechanical systems (MEMS) applications, the small dimensions of the devices inevitably impose challenges to achieve low resonance frequencies due to the large elastic moduli of piezoelectric ceramics and single crystals. In the past several years, some innovative harvester designs have been proposed including an interesting ring design reported by Massaro *et al.* in 2011 (Figure 5).[24] The so-called ring-MEMS (RMEMS) structure was fabricated by etching away a substrate layer underneath a strip of aluminum nitride (AlN) thin film. The large residual stress within the layered structure caused the AlN strip to roll up, forming the RMEMS structure. The experimental results showed that the RMEMS prototype not only could achieve a strong resonance at a low frequency of 64 Hz but also possess other resonance peaks at even lower frequencies (40 and 48 Hz) due to the torsional motion of the ring structure.

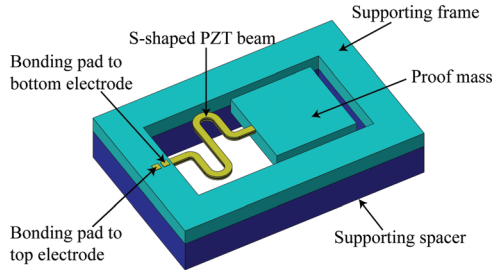

FIG. 6. A MEMS S-shaped PZT cantilever proposed by Liu *et al.* Reprinted with permission from Liu *et al.*, Microsyst. Technol. **18**(4), 497–506 (2012). Copyright 2012 Springer-Verlag.

Another innovative cantilever design was developed by Liu *et al.* in 2012, which pushed the resonance frequencies of a MEMS PZT cantilever to below 30 Hz.[25,26] Instead of a conventional straight beam, this new cantilever design featured an S-shaped meandering beam (Figure 6), reducing the stiffness of the cantilever in order to achieve a low resonance frequency.

In addition to using MEMS devices to harvest energy from vibrations, another important energy harvesting application using piezoelectric MEMS devices are wearable and implantable biomedical devices, such as heart rate monitors and artificial pacemakers. In these cases, the source of the mechanical energy is usually the movements of human muscles or internal organs. To be compatible with the soft and dynamic nature of the human body, these piezoelectric energy harvesting devices are usually thin and flexible. A typical way to fabricate such devices is to print piezoelectric ceramic thin films, such as PZT[27,28] and ZnO,[29,30] in ribbon geometry onto flexible substrates. A recent study reported by Dagdeviren *et al.* demonstrated encouraging results from a PZT ribbon energy harvester that successfully harvested mechanical energy *in vivo* from the natural contractile and relaxation motion of the heart and lung.[28] The device incorporated a PZT element, a rectifier, and a chip-scale rechargeable battery on a flexible polyimide substrate. The PZT element consisted of 12 groups of 10 PZT ribbons that were

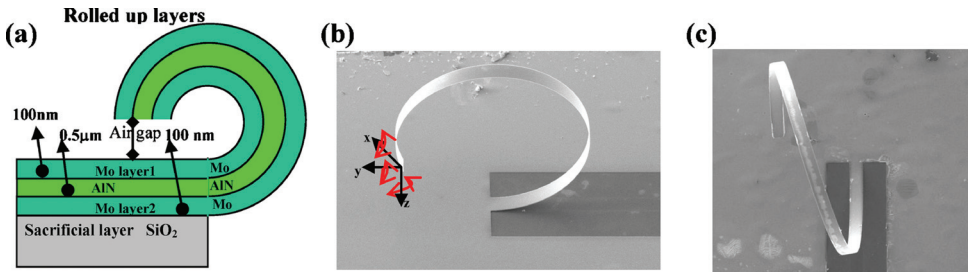

FIG. 5. A low-frequency piezoelectric ring MEMS (RMEMS) harvester: (a) schematic of the ring's layered structure; (b) SEM image of the RMEMS showing the torsional moments of the tip; (c) SEM image showing the top view of the RMEMS. Reprinted with permission from Massaro *et al.*, Appl. Phys. Lett. **98**(5), 053202 (2011). Copyright 2011 AIP Publishing LLC.

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500 nm thick. Although the system's energy harvesting efficiency was merely 1.7%, a power density of 0.18 μW/cm^2 was achieved with a single harvester, and 1.2 μW/cm^2 was achieved when 5 of these harvesters were stacked together, sufficient to power a cardiac pacemaker.

III. PIEZOELECTRIC MATERIALS AND THEIR PERFORMANCES IN ENERGY HARVESTING

Piezoelectric materials are a group of materials that can generate charge when mechanical stress is applied. Piezoelectricity results from the dipoles naturally occurred, or artificially induced in the crystalline or molecular structures of these materials. Based on their structural characteristics, piezoelectric materials can be divided into four different categories: ceramics, single crystals, polymers, and composites. In single crystal materials, positive and negative ions are organized in a periodic fashion throughout the entire material except for the occasional crystalline defects. One of the most widely used piezoelectric single crystals is the solid solution of PMN-PT. In contrast, ceramics are polycrystalline materials. Namely, they are comprised of many single crystal "grains" that possess the same chemical composition. However, ions in the individual grains of a ceramic can orient differently from one another and the spacing between the ions can be slightly different as well. Polymers are carbon-based materials composed of long polymer chains which have many repeated structural units called "monomers." These materials are much more flexible than ceramics and single crystals. In some applications, in order to achieve certain properties that none of these three groups of materials can provide on their own, these materials can be combined together to form composites.

Because of the strong polarizations in their crystalline structures, piezoelectric single crystals and ceramics exhibit much better piezoelectric properties than piezoelectric polymers. On the other hand, compared with piezoelectric polymers, they also have the disadvantages of being rigid and brittle. Therefore, the selection of a certain piezoelectric material for a specific energy harvesting application is determined not only by the piezoelectric properties but also the specific design requirements of the energy harvesting unit, such as the application frequency, the available volume, and the form in which mechanical energy is fed into the system. However, strictly from the materials perspective, the important properties of piezoelectric materials for energy harvesting applications include piezoelectric strain constant d (induced polarization per unit stress applied, or induced strain per unit electric field applied), piezoelectric voltage constant g (induced electric field per unit stress applied), electromechanical coupling factor k (square root of the mechanical-electrical energy conversion efficiency), mechanical quality factor Q (degree of damping; lower value indicates higher damping), and dielectric constant ε (the ability of the material storing charge). Table II shows some typical values of these parameters for piezoelectric single crystals, ceramics, composites, and polymers. The values of d, k, and ε for piezoelectric single crystals and ceramics are much higher than those of piezoelectric polymers. The g constants of the polymers are higher because of their much lower dielectric constants compared to those of the single crystals and ceramics as $g = d/\varepsilon$. Since the goal of energy harvesting is to convert as much input mechanical energy into electric energy, when selecting a piezoelectric material for an energy harvesting application, one would want to choose a material with high electromechanical coupling factor k, as the square of k is the efficiency of this material converting the input mechanical energy to the output electric energy. A piezoelectric ceramic with high k's usually also has high d's because under static or quasi-static conditions (i.e., at frequencies much lower than the resonance frequency), k is directly related to d through elastic compliance and permittivity of the material. For example, for a piezoelectric ceramic plate poled along its thickness direction, the planar-mode electromechanical coupling factor

$$k_{31}^2 = \frac{d_{31}^2}{s_{11}^E \varepsilon_{33}^T}, \tag{4}$$

where d_{31} is the piezoelectric strain constant (induced polarization in the "3" direction per unit stress applied in "1" direction), s_{11}^E is the elastic compliance, and ε_{33}^T is the permittivity under constant stress.

As stated earlier, to extract maximum amount of power, the piezoelectric energy harvester is preferable to operate it at its resonance. However, in many cases, it is impractical to match the resonance frequency of the piezoelectric with the input frequency of the host structure due to the volume constraint of the device. This is especially common for low-frequency applications, as a lower resonance frequency usually demands a larger piezoelectric element. In this situation, the piezoelectric element has to operate in off-resonance

TABLE II. Properties for selected piezoelectric ceramics, single crystals, PZT-polymer composites, and polymers.

	PZT-5H (ceramic)	PMN-32PT with ⟨001⟩ orientation (single crystal)	PZT rod-Polymer composite with 30 vol. % PZT	PVDF (polymer)
Density (g/cm^3)	7.65	8.10	3.08	1.78
Dielectric constant ε_r	3250	7000	380	6.0
Young's modulus Y_{33} (GPa)	71.4	20.3		2
Mechanical quality factor Q_m	32			10
Piezoelectric charge constant d_{33} (pC/N)	590	1620	375	25
Piezoelectric charge constant d_{31} (pC/N)	−270	−760		12–23
Electro-mechanical coupling factor k_{33}	0.75	0.93		0.22
Reference	31	32	33	34, 35

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conditions. Therefore, at low-frequency conditions, a piezoelectric element can be approximated as a parallel plate capacitor so the electric energy of the piezoelectric element is given by

$$U = \frac{1}{2}CV^2$$

or energy per unit volume[36]

$$u = \frac{1}{2}(d \cdot g)\left(\frac{F}{A}\right)^2, \tag{5}$$

where C is capacitance, V is the voltage, d is the piezoelectric strain constant, g is the piezoelectric constant, F is the force, and A is the area. In Eq. (5), one can see that for a piezoelectric element of given area and thickness under the same applied force, a material with a higher value of $(d \cdot g)$ will provide more power. It is not difficult for one to recognize the similarity between $(d \cdot g)$ and the expression of k^2 in Eq. (4) since $g_{31=\frac{d_{31}}{\varepsilon_{33}^T}}$. This relation between the power density and $(d \cdot g)$ has been experimentally verified by the study of Choi *et al.* in $Pb(Zr_{0.47}Ti_{0.53})O_3$–$Pb((Zn_{0.4}Ni_{0.6})_{1/3}Nb_{2/3})O_3$ (or PZT-PZNN) ceramics that had various compositions.[37]

For near resonance applications, however, theoretical studies have shown that the optimum output power of a piezoelectric energy harvester at resonance is actually independent of the piezoelectric properties of the piezoelectric material. Miso used a piezoelectric cantilever beam model to deduce that when the electrical resistance of the system is tuned to optimum, the optimum output power at resonance, and the corresponding output voltage are given by the following equations:[38]

$$|P_{out}|_{opt,r} \approx \frac{B_f^2}{\sqrt{KM}}\frac{\ddot{\omega}_B^2}{8\zeta_m}, \tag{6}$$

$$|v_{out}|_{opt,r} \approx \frac{1}{2|\theta|}B_f\ddot{\omega}_B, \tag{7}$$

where B_f is the forcing vector that accounts for the inertial loading on the cantilever beam due to the base excitation, K is the stiffness, M is the mass, ζ_m is the mechanical damping ratio, θ is a coupling term that is a direct function of the piezoelectric strain constant, and $\ddot{\omega}_B$ is the acceleration of the base. As Eq. (6) does not contain any term related to the piezoelectric parameters of the piezoelectric element, it is clear that the optimum power output of the harvester at resonance is *not* dependent upon the piezoelectric properties of the material. However, the output voltage of the harvester at resonance *is* related to the piezoelectric coupling of the material since the coupling term θ is a function of the piezoelectric strain constant (Eq. (7)).

The selection of the piezoelectric material is more complex. An important material parameter to consider at resonance is the mechanical quality factor Q as it represents how sharp the resonance peak is. Although a sharp resonance peak (high Q) is beneficial from the output power point of view, it also leads to a narrower bandwidth, which means that the output power will fall off quickly if the input frequency of the vibration host is only slightly off the resonance frequency of the harvester.

A. Piezoelectric ceramics

Piezoelectric ceramics are the materials commonly selected for piezoelectric elements used in energy harvesting devices because of their low cost, good piezoelectric properties, and ease to be incorporated into energy harvesting devices. Amongst all the piezoelectric ceramics, PZT is important because of its excellent piezoelectric properties and high Curie temperatures (the critical temperature above which piezoelectric materials lose their piezoelectricity). Based on a wide range of material property requirements for piezoelectric materials, over the last few decades, PZT has been expanded into a large family of ceramics that cover a broad range of properties by modifying its chemical composition or fabrication processes. PZT-5H and PZT-5A are some of the more frequently used ones.

Based on the characteristics of the mechanical energy source, piezoelectric ceramics can be used in different configurations. For energy harvesting from vibrations, piezoelectric ceramic thin films, thick films, and plates are usually preferred because they can be readily integrated in a cantilever structure. To harvest energy from mechanical impacts, layers of piezoelectric ceramic materials can be stacked to stand the impact.

Roundy's study used a PZT bimorph cantilever as an energy harvesting device to energy from harvesting low level vibrations to power wireless sensor nodes.[3] In the study, Roundy first confined the harvester volume within 1 cm^3. A PZT cantilever was made using PZT-5A ceramic and a steel center shim. The length of the cantilever was 1.75 cm. A proof mass was attached to the tip of the cantilever to lower the cantilever's resonance frequency. The device was driven at 100 Hz, matching the natural frequency of the energy harvester, and the driving acceleration was 2.25 m/s^2. When the load resistance was set to the optimum value ($\sim$220 kΩ), 60 μW of power was achieved. Following this first experiment, Roundy fabricated and investigated two cantilevers using PZT-5H ceramic by imposing two additional length constraints at 1.5 cm and 3 cm, respectively. At their optimal operating conditions, these cantilevers achieved power outputs of about 200 μW and 380 μW, respectively.

In 2003, Sodano *et al.* reported that when a wide PZT-5H cantilever with dimensions of $63.5 \times 60.3 \times 0.27\,mm^3$ was driven on an electromagnetic shaker at 50 Hz (the resonance frequency of the cantilever), the cantilever was able to charge a 1000 mAh NiMH rechargeable battery to 90% of the battery's capacity within 22 h.[39]

Yuan *et al.* investigated the energy harvesting performance of a trapezoidal PZT cantilever compared to a conventional rectangular PZT cantilever that had the exact same dimensions.[40] The size of the PZT used in this study was a few times larger than that used by Roundy. The length and width of the cantilevers were 45 mm and 20 mm, respectively, and the thickness of the PZT layer on each side of the metal layer was 0.3 mm. Without a proof mass, although these cantilevers were longer than Roundy's, the trapezoidal

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PZT cantilever showed higher resonance frequencies at 140–180 Hz. When driven at the resonance frequency, under an optimal resistive load, 8.6 mW of power was obtained with the rectangular PZT cantilever; whereas 24.2 mW was obtained with the trapezoidal one.

In 2004, Kim *et al.* reported a study that investigated the energy harvesting capability of a cymbal transducer.[12] The cavity depth d_c and cavity diameter ϕ_c are important design parameters that affect the energy output because the strain amplification factor A is approximately proportional to the ratio of ϕ_c/d_c. The fabricated cymbal transducer was 29 mm in diameter and had a PZT disc with a thickness of 1 mm. Three different PZT ceramics were evaluated for comparison: a hard PZT, a soft PZT, and a PZT that had a high g. Under a cyclic force of 7.8 N at 100 Hz, the PZT with a high g constant showed the highest output voltage (~100 V). When an optimal resistive load was used, the high-g PZT cymbal transducer was able to output 39 mW of power. It is worth mentioning that the high-g PZT in this study also possessed the highest $(d \cdot g)$ product amongst the three PZT materials. Later, Kim and his colleagues fabricated a cymbal transducer using thicker steel end caps and the same high-g PZT ceramic with the same thickness as the previous experiment to further explore the transducer's power generating capability under higher force conditions. They found that under an AC force of 70 N at 100 Hz, a maximum power of 52 mW was obtained when the steel cap thickness was 0.4 mm.

While piezoelectric ceramics in the form of thin layers have been favorable in piezoelectric energy harvesting studies based on vibrations, piezoelectric ceramic stacks can be used in energy harvesting from mechanical impacts. Platt *et al.* studied the possibility of embedding three PZT stacks within a total knee replacement (TKR) implant to power the encapsulated sensors, capable of monitoring the health and working status of the implant.[41] Three rectangular PZT stacks were constructed as the energy harvesting elements. Each stack had the dimensions of $1.0 \times 1.0 \times 2.0\,\text{cm}^3$ and consisted of ~145 PZT layers that were electrically connected in parallel. Placed inside a TKR implant, these PZT stacks were designed to be subjected to axial force applied by the human body. It was observed that under a 900 -N load at a frequency of 1 Hz, the maximum power output per PZT stack was approximately 1.6 mW with a matched resistive load, implying 4.8 mW for the entire energy harvesting device, which was then proven to be able to continuously power a low-power microprocessor.

From the reports described above, one can see that for a piezoelectric ceramic energy harvester to have a reasonably small size, the resonance frequency of the piezoelectric element is usually the range of tens of hertz or higher. However, in many energy harvesting applications that are based on vibrations, both the amplitude and frequency of the host structure can be very low, making it challenging for the ceramic element to adapt to the motion of the host. In an attempt to solve this problem, Renaud *et al.* proposed a new piezoelectric generator design that converts small motions of the host structure into the movement of a moving mass. The mass then delivers impact to the piezoelectric ceramic element.[42] In this design, two piezoelectric cantilevers positioned on the two ends of the device housing were connected with a guiding channel that guides a moving steel "missile" (mass = 4 g) that has an oblong shape. Mechanical energy of small vibrations or rotatory motion of the host structure converts into electrical energy as the steel "missile" bounces between the two piezoelectric beams, providing impact. The prototype harvester has a volume of $25\,\text{cm}^3$ and a weight of 60 g. With repeated rotatory motion at 1 Hz, the average power output of the device was 47 μW. While held in hand and shook at an amplitude of 10 cm and a frequency of 10 Hz, a maximum of 600 μW was measured.

B. Piezoelectric polymers

PVDF (polyvinylidene difluoride) is the most frequently used piezoelectric polymer. It is a semi-crystalline polymer with a repeating unit of (CH_2-CF_2) and it contains about 50% crystals that are embedded in an amorphous matrix. Piezoelectric polymers are flexible and easy to deform, which makes them resilient to mechanical shock and also allows them to be easily mounted to curved surfaces. In addition, the densities of piezoelectric polymers are less than $^1/_4$ of that of PZT ceramics, desirable for lightweight piezoelectric elements. Compared with piezoelectric ceramics, PVDF has much lower piezoelectric constants. For instance, the d_{31} value of PVDF ranges merely 12–23 pC/N depending upon the fabrication and poling processes.[35,43]

Because of the flexible nature of PVDF, it has been investigated for piezoelectric energy harvesting from wearable items, such as shoes and backpacks.

Kendall first studied using PVDF as an energy harvesting material in shoes to harvest the mechanical energy produced during human walking.[44] The energy harvesting element had a bimorph structure fabricated by laminating two PVDF stacks with a 1-mm thick plastic substrate in between. Each PVDF stack consisted of eight 28-μm sheets that had a hexagonal shape with dimensions of $10 \times 8\,\text{cm}^2$. Designed to be a sole-bending system that operated during a walking person's up-step, the bimorph was placed under the ball of the foot with a small gap underneath. For comparison, a heel strike system that used a THUNDER PZT transducer was also developed and investigated. The THUNDER transducer was a pre-stressed PZT unimorph beam with dimensions of $7 \times 7\,\text{cm}^2$. Kendall's results showed that when matched with appropriate resistive load, under a 2-Hz excitation (the frequency of normal human walking motion); the PVDF sole-bending system provided a power output of 0.6 mW, whereas the PZT-based heel-strike system showed an output of 5 mW.

Theoretical studies for an insole shoe energy harvester have also been conducted. Mateu and Moll compared different cantilever beam structures (homogeneous bimorph, symmetric heterogeneous bimorph, and asymmetric heterogeneous bimorph) that used PVDF film as the piezoelectric layers, in an attempt to identify the optimal piezoelectric bender structure used in the insole of a shoe.[11] They found the asymmetric heterogeneous bimorph structure (one or more piezoelectric film on top of a non-piezoelectric material) with large Young's modulus ratio ($Y_{nonpiezo}/Y_{piezo}$) to be the most efficient structure for an insole piezoelectric bender.

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Piezoelectric energy harvesting from backpacks has been investigated. Sodano *et al.* studied using PVDF to replace the traditional straps of a backpack.[45] The working mechanism was that as the person wearing the backpack walks, the differential forces between the person and the backpack will act on the PVDF straps, thus converting the mechanical energy to electrical energy. A theoretical model was developed with two experimental thicknesses (28 μm and 52 μm) of PVDF film and three different strap configurations (single strap, four straps in series, and four straps in parallel). Using the model, it was predicted that a 50-lb load with two PVDF straps could generate $\sim$10 mW of power.

In 2003, Elvin *et al.* conducted theoretical and experimental studies using a 28-μm thick PVDF film with a size of $26 \times 15\,\mathrm{mm}^2$ as a self-powered strain energy sensor to detect cracks on a beam structure.[46] In this study, the PVDF film was attached to a Plexiglas beam using double-sided tape. Two wires were then attached to the PVDF film to connect the film to a radio transmitter circuit. When the beam was subjected to a 1-Hz dynamic force that caused a 2.2-mm beam displacement, the electrical energy generated by the film was sufficient to power the transmitter to complete a RF transmission. However, no power values were reported.

Due to the flexible nature of piezoelectric polymers, use as an energy harvesting device in fluids or air has also been studied.

Pobering and Schwesinger proposed a PVDF flag design that can be used in a river for flow energy harvesting.[47] The flag had a bimorph cantilever structure and the fixed end of the cantilever had a bar structure which was designed to create flow disturbance (Figure 7). When the flag was oriented in the downstream position, the flow disturbance structure developed a type of flow called a Von Karman's vortex street. The alternating forces of the flow on the two sides of the flag resulted in the fluttering motion of the flag, thus generating electrical energy. Accounting for the turbulent flow, striped electrodes were used on the flag. It was concluded that with a flow velocity of 2 m/s, the power output of the flag could be 11–32 W/m^2.

Wind energy harvesters using PVDF have also been studied. PVDF films were used as a cantilever[48,49] or attached to a leaf-shaped structure.[50] The findings showed that the output power density of the PVDF energy harvesters generally does not exceed 2 mW/cm^3.

In summary, one can see that within a reasonably small volume, energy harvesters using piezoelectric polymers typically provide lower power output in the micro Watt range, smaller than what a piezoelectric ceramics-based energy harvester can deliver.

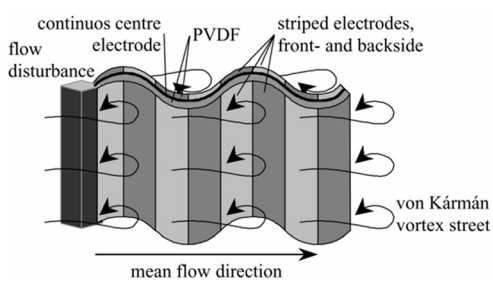

FIG. 7. The PVDF flag design proposed by Pobering *et al* for energy harvesting from river flows. Reprinted with permission from S. Pobering and N. Schwesinger, in *Proceedings of the International Conference on Mems, Nano and Smart Systems* (2004), p. 480. Copyright 2004 IEEE.

C. Piezoelectric ceramic-polymer composites

The energy harvesting capabilities of PZT-polymer composites have been studied extensively in order to combine the excellent piezoelectric properties of PZT ceramics with the flexibility of polymer. These composites are fabricated by structurally combining PZT ceramics with polymers in a certain pattern. The ceramic is either in the form of particles, fibers, or rods while the polymer fills up the rest of the space. The composites based on PZT fibers are most explored for mechanical energy harvesting due to the ease of use when fabricating thin layer structures. The flexibility of PZT-polymer composites comes at the expense of their piezoelectric performance (Table II); this is because a significant volume of the material is replaced with inactive polymers, in comparison to active piezoelectric grains throughout the entire material in the case of the ceramics.

In 2003, Churchill *et al.* investigated the possibility of using a piezoelectric fiber-based film to power a wireless sensor.[51] The composite film was a PZT-polymer composite film called "Piezoelectric fiber composites" (PFC), which was manufactured by Advanced Cerametrics, Inc. (ACI). The PFC consisted of unidirectionally aligned PZT fibers embedded in a resin matrix and used interdigitated electrodes so that the fibers operated in 33 mode. The PFC film used in this particular study had the fibers with a round cross-section whose diameter was 250 μm. The film was 0.38 mm thick, 130 mm long, 13 mm wide, and was bonded to a beam test structure that was subjected to 3-point bending. Under a cyclic strain load of 300 $\mu\varepsilon$ at 180 Hz, the film was able to output 0.75 mW of power. A much more moderate condition of 150 $\mu\varepsilon$ at 60 Hz resulted in a much lower output of 50 μW, which, however, was still sufficient to provide enough energy to power a radio wireless transmitter for one transmission every 165 s.

Sodano *et al.* used another commercial composite transducer called "Micro Fiber Composite" (MFC), manufactured by Smart Material Corporation, for a comparison study of the energy harvesting performance of the MFC and two other monolithic PZT transducers, a unpackaged PZT-5H sheet, and a packaged PZT sheet called "QuickPack" that was made by MIDE.[39,52] An electromagnetic shaker was used as the driving host structure. Similar to the PFC transducer used in Churchill's study, the MFC was a composite consisting of PZT fibers embedded in a polymer matrix with interdigitated electrodes for 33-mode operation. The major difference, however, was that the PZT fibers in the MFC were diced from a monolithic PZT block, thus having a rectangular cross section. The results revealed that the MFC film was the least efficient of the three and unable to charge a 40 mAh nickel-metal hybrid battery unless the driving vibration had very large amplitude, whereas the two monolithic PZT transducers were able to charge the battery within a few hours at a driving frequency of 50 Hz, or a random frequency ranging from 0 to 500 Hz.

Composites of polymers and other piezoelectric ceramics such as ZnO were also investigated. A recent article published

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by Hu *et al.* reported the successful use of a ZnO nanowire composite film ($1 \times 1\,cm^2$) as a nanogenerator to power a digital watch for more than one minute, after the nanogenerator ran for 1000 strain cycles in 20 min.[53] However, the overall time-average power capability of these energy harvesters still lies in the realm of nano watts or less, well below the power requirement of most electronic devices to date.[54]

In the last several years, a number of studies have focused on placing MEMS-scaled piezoelectric ceramic fibers or ribbons onto a biocompatible polymer substrate to obtain a flexible composite device for *in vivo* mechanical energy harvesting. The device that harvested energy from the motion of the heart and lung discussed in Sec. II C is one example of a recent development. Other interesting work was done by Jeong *et al.*, in which $BaTiO_3$ nanocrystals were synthesized using a viral template.[55] The bio-synthesized $BaTiO_3$ was mixed with polydimethylsiloxane (PDMS) to form a flexible piezoelectric layer for energy harvesting. An output of ~300 nA and ~6 V was obtained under a bending/releasing motion of 3.5 Hz, sufficient to power a commercial low-power LCD.

D. Piezoelectric single crystals

Piezoelectric single crystals, as their name indicates, are the single crystalline counterparts of piezoelectric ceramics, which are polycrystalline. Among piezoelectric single crystals, ferroelectric single crystals such as the solid solution of PMN-PT, and that of lead nickel niobate and lead titanate (PZN-PT) are most widely used because of their superior piezoelectric performance. For ferroelectric materials, the single crystals have higher piezoelectric strain constants than the ceramics (Table II). This is because the arrangement of the positive and negative ions in single crystals is highly ordered, leading to greater alignment of the dipoles across the entire material. Moreover, ferroelectric single crystals also possess much lower Young's moduli than the ceramics, which are beneficial to achieving lower resonance frequencies with smaller device sizes.

Badel *et al.* compared the energy harvesting performance of a PMN-25%PT single crystal with a ceramic of the same composition using a unimorph cantilever beam structure.[56] The dimensions of the piezoelectric elements were $10 \times 7 \times 1\,mm^3$. Due to the small size of the piezoelectric elements, the resonance frequencies of the cantilevers were near 900 Hz. At this frequency, with the same beam tip displacement of 150 μm, the single crystal cantilever was able to output 4.0 mW of power, whereas the ceramic cantilever achieved only about 0.2 mW, showing a 20-time difference in power production.

Mo *et al.* also conducted a modeling study to evaluate the energy harvesting potential of using PMN-33%PT single crystals as compared to PZT-5H ceramic in a circular unimorph diaphragm for implantable medical devices.[57] The dimensions of the piezoelectric were fixed at 1.5 in. in diameter and 350 μm in thickness. A 5330-Pa uniform pressure excitation at a frequency of 1 Hz was assumed. By varying the diameter ratio and thickness ratio of the piezoelectric layer to the non-piezoelectric layer, the maximum power outputs of the two types of transducers were theoretically determined. The effect of using different metals (aluminum, brass, and steel) as the shim material was also studied. The results revealed that the PMN-PT diaphragm consistently produced about 4 mW of maximum power compared to 0.3 mW by the PZT-5H diaphragm. Moreover, these absolute power values and the power ratios between the two materials remained fairly consistent regardless of the type of the metal used.

Most recently, Hwang *et al.* reported a flexible PMN-PT single crystal energy harvester for a self-powered cardiac pacemaker.[58] The piezoelectric element in the device was a piece of PMN-PT single crystal thin film that had an area of $1.7 \times 1.7\,cm^2$ and was merely 8.4 μm thick. The PMN-PT thin film was first grown as a bulk material and then thinned down to the 8.4-μm thickness by chemical mechanical polishing (CMP), followed by an innovative layer transfer process[59] to transfer onto a polyethylene terephthalate (PET) plastic layer to achieve the flexible device. When subjected to a simple bending motion at 0.3 Hz and a strain rate of 0.36%, which simulated the movement of human muscles, the harvester was able to generate 2.7 μJ of energy from each bending motion. This device was demonstrated to be capable of charging a coin cell battery from 0.05 V to 1.7 V in 3 h.

Due to the complexity of fabricating piezoelectric single crystals, the cost of manufacturing is significantly higher than that of ceramics. Accordingly, use of piezoelectric single crystals has been relatively limited compared to ceramics. As a result, the utilization of single crystals for mechanical energy harvesting applications has just started to be explored in recent years.[60–67] In addition to the cost, single crystal materials also have the disadvantage of being more brittle than polycrystalline ones, due to the lack of ceramic grain boundaries.[68] Compared to their polycrystalline counterparts, single crystal materials also more easily lose piezoelectric properties when exposed to high electric fields that are opposite to their poling directions.

E. Summary of piezoelectric materials used in mechanical energy harvesting

Table III summarizes the power outputs reported by a number of references that used the different types of piezoelectric materials discussed above for mechanical energy harvesting. The level of power output of piezoelectric energy harvesters to date varies greatly from nanowatts to milliwatts. This is due to the fact that the power output of a piezoelectric energy harvester depends upon both intrinsic (such as the resonance frequency of the piezoelectric element, piezoelectric and mechanical properties of the material, design of the piezoelectric element, and design of the circuitry) and extrinsic factors (such as the input frequency and acceleration of the host structure and the amplitude of the excitation).

From the materials perspective (Table III), one can make the following observations:

(1) Though having the disadvantage of being brittle and less capable of sustaining large strain, overall, piezoelectric ceramics provide a higher power output than the other materials. Their power output usually lies in the magnitude of milliwatts.

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TABLE III. Some piezoelectric energy harvesters reported in the literature and their performances.

Material type	Peak power (μW)	Volume	Frequency (Hz)	Excitation (acceleration or force or pressure)	Reference
PVDF	2	28 modules of $16.5 \times 9.5 \times 0.15\,cm^3$ film	2	0.1 or 0.2 G	69
PVDF	0.0005	$30 \times 12 \times 0.005\,mm^3$	2	3-point bending at 3 N	70
PVDF	610	$72 \times 16 \times 0.41\,mm^3$	3	Wind speed of 4 m/s	49
PVDF	2.75	$10.94 \times 22 \times 0.354\,mm^3$	104	1 G	4
PVDF	2	$20 \times 16.1 \times 0.2\,mm^3$	146	Acoustic pressure: 9 Pa	71
PZT ceramic	47	$25 \times 10 \times 0.8\,mm^3$ bimorph	1	Shook by hand. Ball hits piezo beams	42
PZT ceramic	265	$1 \times 1 \times 2\,cm^3$	1	900 N	41
PZT ceramic	2000	$45 \times 20 \times 0.3\,mm^3$	20	1 N	40
PZT ceramic	40	$31.8 \times 6.4 \times 0.51\,mm^3$	36	0.2 G	72
PZT ceramic	30 000	$63.5 \times 60.3 \times 0.27\,mm^3$	50		39
PZT ceramic	39 000	$1\,cm^3$	100	7.8 N	12
PZT ceramic	52 000	$1.5\,cm^3$	100	70 N	13
PZT ceramic	60	$1\,cm^3$	100	0.23 G	3
PZT ceramic		$1\,cm^3$	120	0.25 G	1
PZT ceramic	1800		2580	2 G	73
PZT ceramics	144	$90.4 \times 14.5 \times 0.79\,mm^3$	2.5		74
PZT fiber	750		180		51
PZT fiber	120 000	$2.2\,cm^3$		Dropping a 33.5 g steel ball from 10 cm	75
PMN-PZT single crystal	14.7	$20 \times 5 \times 0.5\,mm^3$	1744		67
PMN-PT single crystal	3700	$25 \times 5 \times 1\,mm^3$	102	3.2 G	66
PMN-PT single crystal	6.7	$1.7 \times 1.7 \times 0.00084\,cm^3$	0.3	Bending motion at a strain of 0.36%	58

(2) With the greatest flexibility and smallest coupling coefficients, piezoelectric polymers generally provide the smallest power output, at a magnitude of microwatts or nanowatts.
(3) The application frequencies of PZT ceramic-based harvesters are usually 50 Hz or higher. To use them at lower frequencies, either a long or large PZT element is required, or large excitation (acceleration or force) is needed to achieve a milliwatt-level power output.
(4) Piezoelectric polymer-based energy harvesters are suitable for applications with very low input frequencies (<10 Hz) or large amplitude of excitations. This is because their flexible nature allows them to respond faster than the other piezoelectric materials.
(5) The incorporation of polymers into the structure allows PZT-polymer composites to achieve larger mechanical strain without breaking. However, their power output is similar to that of the PZT ceramics and the applications frequencies which they are suited for are just slightly lower than or similar to those for PZT ceramics.
(6) Use of piezoelectric single crystals-based energy harvesters is rare due to the high cost of the single crystals. Although they have shown better power density than the other piezoelectric materials, the prototype piezoelectric energy harvesters reported to date still only provides power outputs up to a few milliwatts.

IV. OPTIMIZATION OF THE PIEZOELECTRIC ELEMENTS IN PIEZOELECTRIC ENERGY HARVESTERS

From the structure configuration standpoint, there are many ways to improve or optimize the piezoelectric elements in piezoelectric energy harvesters. The simplest approach is to stack two or more piezoelectric material layers together and connect them in parallel, as in the case of piezoelectric bimorphs.[76,77] Although a parallel connection scheme does not add up the output voltage from the individual layers, a multilayer design can provide not only a higher output current but also lower impedance to better match the impedance of electrical devices.[77]

Aside from using multiple piezoelectric layers, matching the resonance frequency (f_r) of the piezoelectric energy harvester with the input frequency (f_i) of the host structure has been considered the paramount aspect of improving the efficiency of the piezoelectric element. Many studies have shown that even a 5% mismatch may result in 100-time smaller power generation than the maximum value obtained around resonance.[37,78] For ambient vibration energy harvesting, the energy sources typically have fairly low resonance frequencies (Table I). Therefore, in the last decade, a great number of studies have been conducted to improve the design of piezoelectric harvesters for higher efficiency, developing various techniques. Based on the mechanism in which each technique functions, they can be categorized into the following groups: (1) lowering f_r towards f_i, (2) Up-converting f_i to f_r, and (3) broadening the bandwidth of the harvester.

A. Lowering f_r towards f_i

The resonance frequency of a mechanical energy harvester is determined by K, the stiffness of the system, and m, the effective mass of the system (Eq. (1)). In essence, all of the frequency-tuning techniques which have been explored for piezoelectric energy harvesting are various ways to modify these two parameters of the energy harvesting systems. A

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majority of the frequency-tuning techniques have been focusing on lowering the resonance frequencies of the devices. One of the more frequently used techniques is the use of a proof mass, which can be attached to the free end of a piezoelectric cantilever, the center of a piezoelectric diaphragm, or two-point-supported beam. The proof mass is obviously preferred to be maximized within the space and weight constraints allowed by a given device design. Unfortunately, due to the high elastic moduli of piezoelectric materials (except for the polymers), maximizing the proof mass alone in many cases is insufficient to reduce f_r to the vicinity of f_i. Accordingly, additional measures to reduce the stiffness of the piezoelectric element are necessary. This can be realized either by extending the bending length of the structure or lowering the elastic modulus of the piezoelectric material.

Cornwell *et al.* conducted an analytical study using an auxiliary beam to help the piezoelectric material excite at the resonance frequency of the host structure.[79] The frequency response of the host structure was first measured, and then the auxiliary beam was attached to the host structure and tuned to the resonance frequency of the dominant vibration mode of the host structure. A PZT patch was glued at the clamped end of the auxiliary beam so it would vibrate with the beam. In addition, to further enhance the power output, the beam was also placed at a location where the displacement of that particular mode was the greatest. The findings showed that a tuned auxiliary beam resulted in an output voltage increase by a factor of 5, which corresponded to a 25-time increase in power.

Dhakar *et al.* proposed a similar design in 2013.[72] In their design, a 21-mm-long polymer extension beam was firmly clamped to the free end of a 32-mm-long PZT-5A bimorph cantilever and a proof mass of 0.72 g was attached at the tip of the polymer beam (Figure 8). This design lowered the stiffness of the entire cantilever, not only by extending the length of the cantilever structure but also by replacing part of the cantilever with the polymer, which had a much smaller elastic modulus than the PZT. As a result, the resonance frequency of the cantilever was reduced from 125 Hz to 36 Hz with the help of the polymer extension beam and the power output was increased by 32% at an excitation of 0.1 g.

Reducing the resonance frequency of a MEMS-scaled piezoelectric harvester is even more challenging because of the small sizes of MEMS devices. The RMEMS and the S-shaped PZT cantilever discussed in Sec. II C were innovative ways to overcome this issue. Due to their small sizes, at the resonance frequency and under a small acceleration of 0.06 g, the cantilever only displayed a maximum power of 1.1 nW. Nevertheless, these designs provided effective methods to lower the resonant frequencies and improve the power densities of piezoelectric energy harvesters, while enabling MEMS energy harvesters to finally reach low-level resonant frequencies.

Alternatively, frequency tuning of a piezoelectric element can be achieved by actively modifying the apparent stiffness of the piezoelectric element. Roundy and Zhang investigated active frequency tuning methods for piezoelectric energy harvesters.[80] This method uses actuators that are constantly on to alter the apparent stiffness of the piezoelectric harvester. Roundy and Zhang's prototype device was a

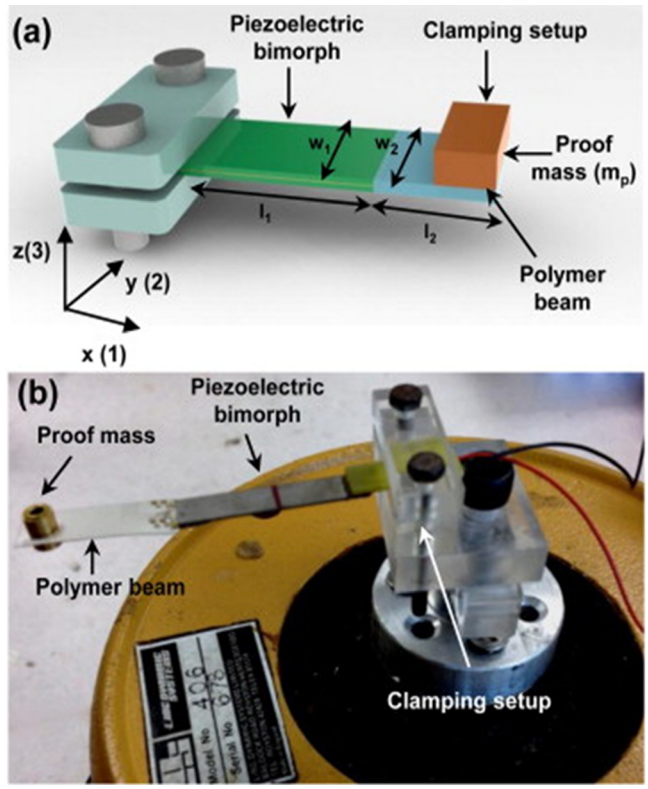

FIG. 8. A piezoelectric cantilever with a polymer extension to lower the resonance frequency: (a) A CAD drawing of the concept; (b) An actual device prototype mounted on an electromagnetic shaker. Reprinted with permission from Dhakar *et al.*, Sens. Actuators, A **199**, 344–352 (2013). Copyright 2013 Elsevier.

PZT cantilever with its electrode divided into two sections, one for energy harvesting and the other for frequency tuning. The frequency tuning electrode was positioned towards the free end of the cantilever, where the PZT is less strained (Figure 9). The voltage signal generated by the energy harvesting electrode is inverted and then applied onto the frequency tuning electrode. The opposing voltage signal "softens" the piezoelectric material and thus reduces its apparent stiffness. By its working principles, active frequency tuning evidently tunes the resonance frequency by consuming certain amount of power, subtracting from the energy harvested by the harvester. Roundy and Zhang's results revealed that although the tuning method successfully lowered the resonance frequency of the cantilever toward the input frequency, the net power output of the harvester did not improve.

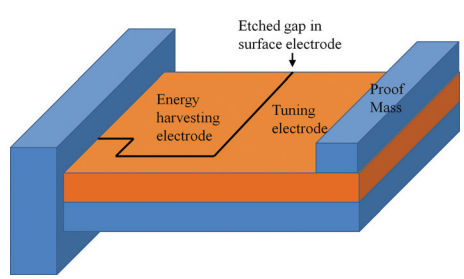

FIG. 9. A schematic of a unimorph cantilever which uses a tuning electrode to tune its resonance frequency. Reprinted with permission from S. Roundy and Y. Zhang, Proc. SPIE **5649**, 373 (2005). Copyright 2005 SPIE.

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The apparent stiffness of a cantilever beam can be altered by straining it with in axial prestress. A tensile axial load "stiffens" the beam, whereas a compressive one "softens" it. Leland and Wright proposed this method in 2006.[81] Leland demonstrated the concept using a PZT-5A bimorph beam which was clamped on both ends with a proof mass placed in the midpoint of the beam. It was shown that under an axial compressive preload of ~60 N, the resonance frequency of the beam decreased from ~250 Hz to ~200 Hz, showing a 24% reduction. Though this is an effective method to lower the resonance frequency, it must be noted that too high of an axial prestress will lead to failure of the ceramic. Leland's prototype beam failed under a 65 N loading.

B. Up-converting f_i to f_r

Another way to improve the performance of a vibrational energy harvester at an application frequency different from its own resonance frequency is through a frequency up-conversion technique. A concept two-stage design was proposed by Rastegar in 2006.[82] In their design, the spring-mass system is the primary vibrating system, responding at the input frequency of the host structure (Figure 10). The secondary system is an array of piezoelectric cantilevers that harvests the mechanical energy. As the mass vibrates, the mechanical energy transferring teeth hit and leave the piezoelectric cantilevers periodically, causing them to vibrate at their natural resonance frequency. Anderson and Wickenheiser conducted a theoretical study of a similar two-stage piezoelectric energy harvester for human walking, which used ferromagnetic structures to tune the natural frequency of a piezoelectric cantilever with a magnetic proof mass.[83] However, neither of these studies provided experimental results of prototypes fabricated based on these designs.

Significant improvement in power output was provided in experimental data from an electromagnetic vibration energy harvester, with a two-stage design, as proposed by Kulah and Najafi.[84] This design involved a cantilever and two magnets. The cantilever carries a coil for electromagnetic power generation and has a magnetic tip. One of the magnets is at the top of the housing of the device as the upper resonator, which vibrates with the host structure, and the other is positioned near the magnetic tip of the cantilever to interact with the coil for energy conversion (Figure 11). The spacing between the top magnet and the cantilever's magnetic tip was set such that the upper magnet would catch the cantilever at a certain point of its vibration and then releases it at another point. After release, the cantilever would start resonating at its own resonance frequency, which was higher than the vibration frequency of the host structure, thus "up-converting" the frequency. This design allows a vibration energy harvester to operate at its own resonance frequency regardless of the input frequency of the host, thus significantly improving the power output of the harvester. Compared with a much larger electromagnetic vibration energy harvester, which did not use the frequency up-conversion technique and had a resonance frequency same as the input frequency of the host structure, the cantilever using the frequency up-conversion technique produced 70 times more power. Due to the similarities existent between electromagnetic and piezoelectric energy harvesting, it is conceivable that piezoelectric energy harvesters utilizing this frequency up-converting technique may exhibit similar degree of improvement in power generation. Moreover, this technique could be readily adapted to magnetoelectric energy harvesters, another group of energy harvesters that combine a magnetic layer and a piezoelectric layer to convert vibration energy to electrical energy through magnetoelectric coupling.[85–87]

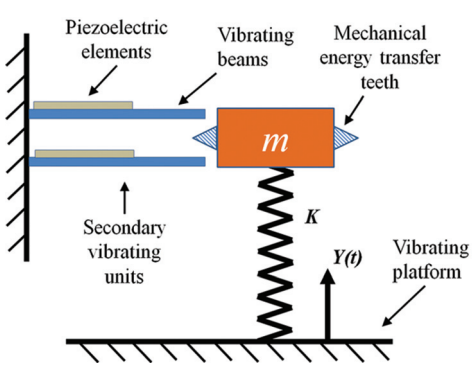

FIG. 10. Schematic of the two-stage frequency up-converting concept proposed by Rastegar *et al*. Reprinted with permission from Rastegar *et al*., Proc. SPIE **6171**, 617101 (2006). Copyright 2006 SPIE.

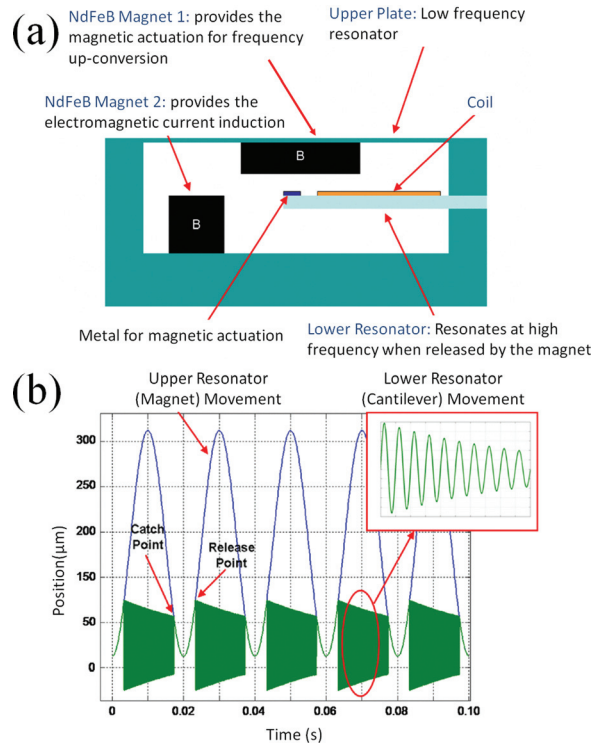

FIG. 11. The frequency up-converting design using magnets for frequency tuning: (a) a schematic of the concept; (b) the movements of the upper magnet and cantilever. Reprinted with permission from H. Kulah and K. Najafi, IEEE Sens. J. **8**(3), 261–268 (2008). Copyright 2004 IEEE.

C. Bandwidth broadening of piezoelectric energy harvesters

In reality, many ambient vibration sources possess a spectrum of random frequencies. In these situations, tuning a piezoelectric energy harvester to a specific resonance frequency may

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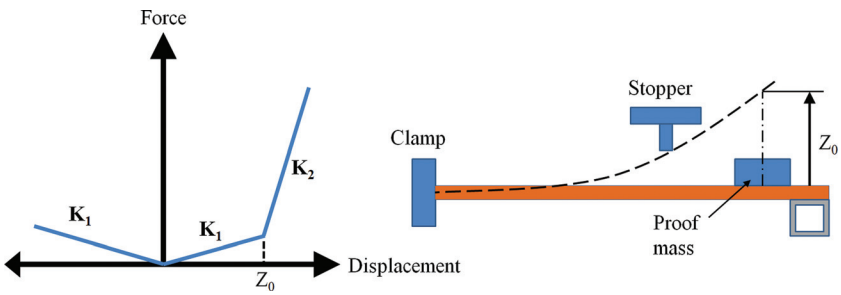

FIG. 12. Illustration of the stopper approach proposed by Soliman *et al.* that used a mechanical stopper to broaden the bandwidth of a cantilever's frequency response. Reproduced by permission from Soliman *et al.*, J. Micromech. Microeng. **18**(11), 115021 (2008). Copyright 2008 by IOP Publishing.

not be an effective approach to improve efficiency because even a small amount of fluctuation in the input frequency will result in a large drop in the power output. Therefore, the piezoelectric energy harvester is preferred to have broadband response with respect to the excitation from the host structure.

One simple approach to achieve relatively broadband response is to incorporate an array of energy harvesters with different resonance frequencies into a single system, which has been demonstrated by researchers.[88–90] This method is easy to implement but has the obvious disadvantage of leading to significantly higher weight and volume of the system. Additionally, for a given input frequency, only one of the harvesters in the array can respond at its resonance.

In 2008, Soliman *et al.* proposed a design that utilized mechanical stoppers in a cantilever-based energy harvesting system to broaden the bandwidth of the system.[91] A stopper carried by a slider is positioned above the cantilever beam and close to the proof mass (Figure 12). As the cantilever beam oscillates at amplitude greater than Z_0, it engages the stopper and the contact point becomes a new fixed point of the beam, which gives the portion of the beam beyond this point a higher effective stiffness (K_1) than that of the rest of the beam (K_2), thus extending the resonance over a wider span of the frequency spectrum. Liu *et al.* later applied a similar technique to their meandering cantilever energy harvester, in which a fixed stopper was used.[25] It was experimentally shown that the bandwidth of the cantilever increased as the vertical spacing between the cantilever and the stopper decreased. However, this broadening of the bandwidth came at the expense of the output power, as smaller cantilever-stopper spacing limits the vibration amplitude of the cantilever. Additionally, the degree of the broadening increased with the acceleration of the host structure. Both Soliman and Liu's studies showed that the amount of bandwidth broadening using stoppers was very limited; giving merely about 10% of the f_r. Liu's results also showed that the sacrifice in the output power for the gain in the bandwidth was greater than desired.

A more effective bandwidth broadening technique was proposed by Marzencki and Basrour in 2009,[92] which exploits the nonlinear behavior strain stiffening effect of piezoelectric ceramics. It had been known that, for a piezoelectric beam with increasing strain levels, a shift of f_r towards the lower frequencies occur, and a sudden change (called the "jump") and/or a hysteresis can be observed in the f_r during a frequency sweep.[93] The hysteresis is what broadens the bandwidth of the resonance. The broadening increases with the input acceleration. Marzencki and Basrour used pre-stressed cantilever beams to demonstrate that at an input acceleration of 2 G, the broadening could be as large as 30%–40% of the f_r. However, the major drawback of this technique is that the bandwidth broadening is much more pronounced during the frequency up sweep. At a given input acceleration, the output power difference between up sweep and down sweep can be as large as 10 times.

D. Other methods to improve power output of piezoelectric energy harvesting systems

In addition to the aforementioned methods exploring efficiency improvement of piezoelectric energy harvesters from the frequency aspect, there have been also other approaches to achieve higher power output. For instance, cymbal transducers improve power output by utilizing metal end caps to amplify the effective piezoelectric strain constant of the piezoelectric ceramic, but they are not suited for ambient vibration energy harvesting applications where the vibration amplitude is small, because the cymbal structure does not respond to weak vibrations as well as cantilever structures do. However, in 2012, Xu *et al.* combined both cantilever and cymbal structures and proposed a cantilever-driving low frequency energy harvester, named "CANDLE," which uses a cantilever as the driving mechanism for two cymbal transducers.[66] The working mechanism is that, as the cantilever vibrates with the host structure, the bending motion of the cantilever compresses the cymbal transducers so the mechanical stress is transferred to the cymbals, generating electrical energy (Figure 13). One evident drawback of this design is the inevitable mechanical energy loss at the contact points between the cantilever and the cymbals. Nevertheless, this design paved a pathway for cymbal transducers to be utilized in low-frequency applications.

For applications with white noise excitations, a bi-stable cantilever structure was developed by Cottone *et al.* This

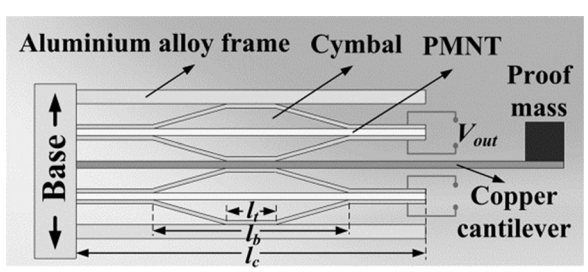

FIG. 13. The schematic of the CANDLE vibration harvester. Reprinted with permission from Xu *et al.*, Appl. Phys. Lett. **101**(3), 033502 (2012). Copyright 2012 AIP Publishing LLC.

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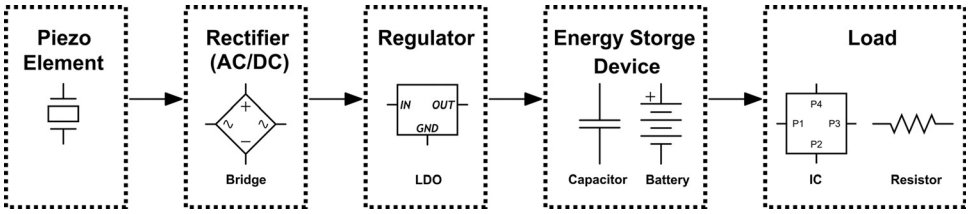

FIG. 14. Block diagram of a general electronic circuit for piezoelectric energy harvesting systems.

design uses a magnet placed at a small distance from the tip of the cantilever, where there is also a magnet with opposite polarity. When the distance between the two magnets is large, the device behaves as a conventional cantilever. When it is smaller than a critical distance, the magnetic force becomes significant and provides two equilibrium positions for the potential energy of the cantilever (hence the term "bi-stable"). At a distance slightly below the critical point, the energy wells of the two equilibriums start forming, giving a maximum in power output as the white noise excitation assists the cantilever jump between the two states.[94] This technique was shown to improve the power output of the cantilever by 4–6 times.

V. ELECTRONIC CIRCUITS FOR PIEZOELECTRIC ENERGY HARVESTING SYSTEMS

The electronic circuit in an energy harvesting device is an integral part of the system and also plays an important role in the energy harvesting efficiency of the entire system. In general, an energy harvesting system interface circuit consists of three main components—an AC-DC rectifier, a voltage regulator, and an energy storing device (Figure 14). They respectively perform the following functions: (a) rectifying the AC voltage output from the piezoelectric material to DC, (b) regulating the DC power supplied to the external load or the storage device, and (c) storing the harvested energy.

A. AC-DC rectifiers

The most commonly used AC-DC rectifiers in energy harvesting systems are full-wave[52,95–101] or half-wave bridge rectifiers,[102] which are an arrangement of 4 or 2 diodes in a bridge circuit to change the input AC power to DC power. Among the two, full-wave rectifiers are more frequently used for piezoelectric energy harvesting applications, as half-wave rectifiers will filter out half of the voltage output from the piezoelectric material.

Compared to full-wave or half-wave bridge rectifiers, synchronous rectifiers can more efficiently rectify the AC voltages generated by piezoelectric materials. Synchronous rectifiers use Metal-Oxide-Semiconductor Field Effect Transistors (MOSFET) instead of diodes, which can significantly improve the rectification efficiency. The forward voltage drop of a Schottky diode in full-wave or half-wave bridge rectifier is usually at least 0.3 V dependent upon the load. However, the ON resistance of MOSFETs is lower than that of diodes, which translates into a smaller voltage drop when a current crosses a MOSFET.

Han *et al.* did some studies based on synchronous rectifier in energy harvesting and compared the performance with other traditional rectifiers.[103] The circuit in their study functioned through two stages, a rectifier and a DC-DC converter. They analyzed three different rectifying circuits using simulation and determined that the synchronous rectification method was most efficient. The synchronous rectifier used in the circuit significantly improved the extracted power from the piezoelectric generator. When experimentally compared with a traditional diode-resistor pair rectifier, the synchronous rectifier's maximum extracted power was about 508% of that of the diode resistor pair rectifier. With the power consumption of the two comparators in the synchronous rectifier taken into account, the extracted power of the synchronous rectifier still shows over 3× improvement. For an 80 kΩ resistive load, the efficiency of the diode-resistor pair rectifier was about 34%, whereas the efficiency of the synchronous rectifier was 92%.

Due to the forward voltage drop of diodes, efficiency of DC output voltage is limited. Dallago *et al.* used an active voltage doubler to rectify in the energy harvesting system.[104,105] Although the voltage doubler rectifier could generate two times the output voltage compared to full-wave bridge rectifiers, it could only provide the output current during positive half-cycle of the input. For this reason, Ramadass and Chandrakasan presented two additional types of rectifiers, called "switch-only" and "Bias-flip" rectifiers, respectively (Figure 15).[106] For the switch-only rectifier, a switch was connected in parallel with the piezoelectric harvester. The capacitance of the piezoelectric material C_p was discharged when the switch was ON and was fully charged when the switch was OFF. Such design enabled the rectifier

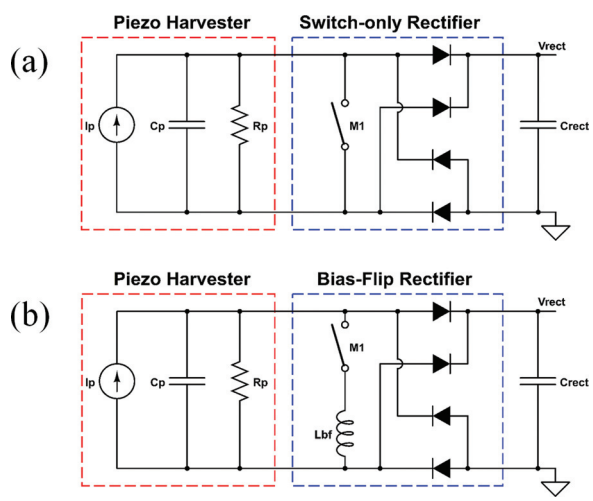

FIG. 15. The "switch-only" and "Bias-flip" rectifier circuits. Reprinted with permission from Y. K. Ramadass and A. P. Chandrakasan, IEEE J. Solid-State Circuits **45**(1), 189–204 (2010). Copyright 2010 IEEE.

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to utilize both half-cycles of the input current. The simulated results showed that the switch-only rectifier could provide 2× power compared to commonly used full-bridge rectifiers or voltage doublers. However, although the switch-only rectifier could improve the power extraction, almost a half of the charge was still lost during every half-cycle. To solve this problem, the author presented an improved design called the "Bias-flip" rectifier by adding an inductor in series with the switch. The inductor could store the energy with external magnetic field and flip the voltage across the piezoelectric element, making it unnecessary to fully discharge C_p before it could be charged again. The switch turned on when the direction of i_p changed and turned off when the current in the inductor was at zero. The simulation results closely matched the theoretical power and the rectifier was able to provide more power when the inductor value was increased. An energy harvesting chip with an area of 4.25 mm^2 based on the Bias-flip rectifier system was fabricated, which included a buck and boost DC-DC converter, an inductor arbiter and a voltage inverter. The experimental results showed that the rectifier with an 820 μH inductor was able to output more than 4 times power than a traditional full-bridge rectifier or voltage doubler.

B. Voltage regulators in energy harvesting

After rectification, the voltage generated from the piezoelectric element still needs to be regulated for the energy storage device or external load. There are two types of voltage regulators commonly used in energy harvesting—step-down and step-up converters, among which the former is more commonly used because the output voltage of piezoelectric elements are generally too high for a battery or an electronic load.[2]

Step-down converters regulate high input voltages to low output voltages. Tayahi *et al.* designed and simulated a power management circuit that used a commercial step-down converter (LTC1474, Linear Technology) for powering remote sensing networks.[107] In this circuit, the output voltage of the piezoelectric element was rectified first and then charged a reservoir capacitor to store the harvested energy. When the capacitor reached a preset value, it discharged into the step-down converter. The circuit was designed to switch off the discharge circuit when the output voltage was lower than a preset value. This discharging circuit is easy to use and a Step-Down converter (LTC1474) can provide a stabilized output voltage for the load circuit.

Shenck and Paradiso researched on a power-conditioning electronic circuit for in-shoe RF tag system powered by human walking.[96] A linear regulator was initially used in the circuit design; however, the output voltage exhibited some ripples during transmission. The bucket capacitor had to wait to store enough energy to activate the transmitter for about half a second, resulting in a fairly inefficient system. In addition, the excitation characteristics of the application rendered the piezoelectric element a high impedance source with high voltage and low currents. Linear regulation thus was not suitable in this application. Therefore, an inexpensive offline forward-switching converter was developed. With a switching converter, the efficiency was much higher than the linear regulator when the difference between input and output voltage was large. After experiment evaluation and compared with linear regulator and switching converter, the efficiency of switching converter was found to be about 17.6% which is better than twice the linear regulator's efficiency and the forward converter was able to continuously provide at least 1.3 mW power at a walking frequency of 0.8 Hz.

To maximize the power input to an electrochemical battery, Ottman *et al.*[108] designed an adaptively controlled regulator circuit. Because the voltage of a storage battery changes very slowly during charging, the power being stored into the battery can thus be maximized by maximizing the current flowing into the battery. Ottman's control algorithm sensed current flow into the battery and adjusted the duty cycle of the switching DC-DC converter accordingly. The experimental results showed a 400% improvement compared to when a battery was charged directly by a harvesting circuit without the step-down converter. However, such control circuitry by itself requires more power than a small piezoelectric element can provide. Therefore, Ottman *et al.* later analyzed the interaction between the piezoelectric element and the DC-DC converter that operated in discontinuous conduction mode (DCM) and determined a fixed optimal converter duty cycle for maximum power flow. As a result, a simplified control scheme was presented.[97] The optimal duty cycle for the DC-DC converter was found to stay relatively constant under high excitation conditions. Following this discovery, Lesieutre *et al.* later designed a two-mode circuit.[109] Under low excitation conditions, the DC-DC converter was disabled and the rectifier directly charged the storage battery, whereas under high excitation conditions the DC-DC converter was powered by the battery. Ammar *et al.* improved Ottman's adaptive control scheme by using a more aggressive stepping algorithm, which led to a faster adaptation.[98] Compared to regulator circuits without adaptive control, adaptively controlled regulators require additional components to implement the control algorithm, which inevitably increases the complexity and cost of the circuit.

C. Different storage devices

Because of the generally low power output of piezoelectric energy harvesters, the energy converted by the piezoelectric element is usually not sufficient to directly power electronic devices. Therefore, in a piezoelectric energy harvesting system, the harvested energy is usually first accumulated in a storage medium before it is used by the load. The energy storage mediums studied for this purpose to date are mainly capacitors and rechargeable batteries.

Although both are electric energy storage mediums, capacitors and rechargeable batteries have very distinct characteristics that determine whether they are suitable for specific energy harvesting applications. Capacitors have been used as the energy storage medium by many researchers for energy harvesting applications.[46,110–112] Unlike rechargeable batteries, capacitors do not require a minimum voltage to start charging. They can be charged and discharged very

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quickly due to their high power density, enabling them to provide accumulated energy almost instantaneously. However, capacitors have much lower energy densities than batteries[113] and thus their voltages also decrease quickly as they discharge. Therefore, they are suitable for applications that only requires rapid energy transfer and not suitable for the applications where a stable output voltage or a steady energy output is required, unless continuous vibrations which can supply sufficient energy to sustain constant operation of the load are available. Batteries, on the other hand, are free of this shortcoming. They can store the accumulated energy from the piezoelectric material for later use and thus are able to supply constant voltage and power with intermittent vibrations. The main disadvantage of rechargeable batteries for piezoelectric energy harvesting applications, however, is the limited number of charging cycles. Both the traditional nickel metal hydride (NiMH) batteries and the relatively new lithium-based rechargeable batteries are subject to 300–1000 charging cycles,[114] after which the capacity of the battery becomes significantly reduced and eventually renders the battery unusable. This is not in accordance with the general purpose of energy harvesting, to enable the device to operate perpetually.

To create piezoelectric energy harvesting systems that are not subject to these shortcomings, use of supercapacitors as the energy storage medium have been explored in recent years.[100,115] Supercapacitors differ from the conventional capacitors in the fact that the electrostatic charge is stored by an electrolyte solution between two solid conductors rather than by a solid dielectric between two electrodes as in the case of the conventional capacitors. The electrodes in supercapacitors possess very large surface areas and the distance between two plates is usually less than 1 nm, thus achieving much higher capacitance and stored energy than conventional capacitors.[114] Compared to rechargeable batteries, the charging cycles of supercapacitors can be up to 10^6. Guan and Liao conducted studies to compare a supercapacitor with NiMH and lithium ion batteries for piezoelectric energy harvesting systems and concluded that in addition to the much higher lifetime, supercapacitors also had the highest charging/discharging efficiency at 95%, compared to 92% for the lithium ion battery and 65% for the NiMH battery.[100] The main disadvantage of supercapacitors is that their self-discharge rates are higher than those of rechargeable batteries.[113,116] More than half the stored energy can be lost in a matter of days,[2,114] therefore, the availability of the source vibration throughout a day is critical in determining whether supercapacitors are a viable solution for the energy storage of a piezoelectric energy harvesting system.

It is worth noting that a supercapacitor and an electrochemical battery can be employed in conjunction, with the battery as the primary storage device and supercapacitors as the secondary storage, providing relatively high power output that the battery cannot.[117]

In addition to the type of energy storage device, the voltage of the storage device could also influence the efficiency of the energy harvesting systems that use DC-DC converters. Guan and Liao conducted analytical and experimental studies to investigate the efficiency of the DC-DC converter in a piezoelectric energy harvesting system using energy storage devices of various voltages.[118] Their results showed that the efficiency of the converter could be improved by using storage devices with higher voltages.

To date, a number of commercial energy harvesting integrated circuits (ICs) have become available, such as the LTC3588–1 by Linear Technology[119] and Texas Instruments' BQ25505.[120] These commercial ICs typically have low energy consumption and are small in size. The LTC3588–1 is a complete energy harvesting power management package which contains a full-wave bridge rectifier as well as a high-efficiency buck converter, so it can be directly connected to a piezoelectric energy harvesting element and readily output the harvested energy. Therefore, this chip can be conveniently incorporated in systems such as wireless sensor networks and industrial equipment controls. In a recent study, the LTC3588–1 was used as the power management circuit in a power generator based on ZnO nanowires, demonstrated to power an electric watch.[53] TI's BQ25505 is a power management IC that essentially functions as a DC-DC converter. It includes a high-efficiency boost charger to output voltage which can be directly used to charge lithium ion batteries or supercapacitors. The conversion efficiency can be up to 90%. However, some external components are still needed as this IC does not include a rectifier.

VI. SUMMARY AND CONCLUDING REMARKS

This paper reviewed the state of research on piezoelectric energy harvesters. Various types of harvester configurations, piezoelectric materials, and techniques used to improve the mechanical-to-electrical energy conversion efficiency were discussed. Most of the piezoelectric energy harvesters studied today have focused on scavenging mechanical energy from vibration sources due to their abundance in both natural and industrial environments. Cantilever beams have been the most studied structure for piezoelectric energy harvester to date because of the high responsiveness to small vibrations.

The power output of a particular piezoelectric energy harvester depends upon many intrinsic and extrinsic factors, which leads to great variations in power output, ranging from nanowatts to milliwatts. Utilization of all four types of piezoelectric materials—piezoelectric ceramics, single crystals, ceramic-polymer composites, and polymers have been explored by researchers in various harvester configurations to adapt to the specific requirements of a great range of harvesting applications. Overall, piezoelectric polymers are flexible in terms of implementation due to their soft nature. However, due to their weak piezoelectric properties, the power outputs of the harvesting devices based on these materials in general are at the micro-watt level, whereas the devices based on the other three types of piezoelectric materials provide output power at the milliwatt level. PZT ceramics are the most commonly used piezoelectric materials due to their good piezoelectric properties and low cost. There have not been any major breakthroughs in boosting the intrinsic piezoelectric properties of piezoelectric materials since the discovery of PZN-PT and PMN-PT ferroelectric single

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crystals in the 1990s. These single crystals, such as PMN-PT, have much higher piezoelectric performance than other piezoelectric materials and only started to gain attention for energy harvesting applications in the last several years. The wide use of these materials for energy harvesting in the near future is still in question due to their high cost.

Most mechanical energy harvesting applications have characteristic frequencies at hundreds of hertz or lower, incompatible with the natural resonance frequency of small piezoelectric harvesters, which are desired for most applications. Moreover, the vibrations of host structures of many applications feature broad spectra of frequencies rather than a single one. For these reasons, a number of frequency tuning and bandwidth widening techniques have been developed in the last decade, in order to improve the efficiency of piezoelectric energy harvesters. Though some intriguing progress has been made in this field, these techniques also add to the intricacy, and thus the cost, of the harvesting systems.

Electronic circuits for piezoelectric energy harvesting system generally contain three main components: a rectifier, a regulator, and an energy storage device. Optimizing the circuit is as complex as optimizing the piezoelectric element for a given energy harvesting application. The overall efficiency of power conversion could vary greatly depending on the circuit design. Various methods and designs have been explored to improve the efficiencies of the rectifier and regulator circuits. With the advancement of microelectronic technology, small energy harvesting interface circuits have been successfully mounted into a single chip and have low quiescent currents. Some commercial integrated circuits are already available that can be directly connected to the piezoelectric material and output an adjustable voltage to the storage device or the load.

The biggest challenges for piezoelectric energy harvesting have been (1) the low input frequencies and accelerations of the mechanical energy sources and the difficulty to get piezoelectric harvesters to efficiently respond to them and (2) the performance ceiling of the current piezoelectric materials also adds to the difficulty of developing an energy harvester that can truly replace batteries as the sole power source. A piezoelectric material that can sustain larger strain than piezoelectric polymers can while possessing the exceptional piezoelectric properties of the PMN-PT single crystals currently does not exist. As a result, within a reasonable package size and under real-life operating conditions, even with the best piezoelectric materials available today, the maximum achievable power for an individual piezoelectric energy harvester is still limited in the neighborhood of tens of milliwatts. Though that is sufficient for some low-power devices in applications where the power requirements are not quite demanding, higher power outputs are still required for a majority of energy harvesting applications. On the other hand, as microelectronic and MEMS technologies advance, the power requirements of electronic devices continue to decrease. More and more reports have surfaced that demonstrate successful self-powering of electronic devices using piezoelectric energy harvesters. It is our opinion that the future of piezoelectric energy harvesting is more likely to be dependent upon the continuous lowering of the energy consumption of electronic devices, unless another breakthrough in the development of new piezoelectric materials can elevate the piezoelectric performance of these materials to another level.

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