International Journal of Enhanced Research in Science, Technology & Engineering
ISSN: 2319-7463, Vol. 5 Issue 7, July-2016

Key Challenges & Issues in Piezoelectric Energy Harvesting At Micro, MEMS, and Nano Scales

Ashwani Kumar

Department of Mechanical Engineering, University Institute of Engineering &Technology Maharshi Dayanand University, Rohtak, Haryana, INDIA

ABSTRACT

The area of piezoelectric energy harvesting has emerged as the best alternate of non-green energy because of the simplicity of its implementation, high power density, structural simplicity and ease of available driving energy. As a consequence, the number of studies on piezoelectric energy harvesting published in the last 5 years is more than twice the amount of publications on its electromagnetic and electrostatic counterparts. This report gives a comprehensive critique of the history and current state-of-the art of piezoelectric energy harvesting. A brief theory section presents the basic principles of piezoelectric energy conversion and presents the most commonly used mechanical architectures. The theory part is succeeded by a literature survey on piezoelectric energy harvesters, which are separated into three groups: (i) macro- and mesoscale, (ii) MEMS scale, and (iii) nano scale. The size of a piezoelectric energy harvester affects a variety of parameters such as its weight, manufacturing method, achievable power output level, and possible application fields. Consequently, size-based classification provides a dependable and effective basis to study various piezoelectric energy harvesters. The literature study on each scale group is resolved with a summary, potential application areas, and future directions. In a separate section, the most prominent challenges in piezoelectric energy harvesting and the studies focusing on these challenges are discussed. The conclusion section summarizes the current standing of piezoelectric energy harvesters as possible nominees for several applications and discusses the topics that need to be addressed for realization of practical piezoelectric energy harvesting devices.

I. INTRODUCTION

In its most elementary configuration, energy harvesting can be defined as changing the unused energy available in the environment into electrical energy, which can be applied right away or stored for later usage. This broad definition also implies a diversity of applications, which strongly depend on the shell of the harvestable energy. Large scale sources such as vehicle suspension systems, tall buildings, or ocean waves can control power levels up to tens of kilowatts, which might be utilized as a form of renewable energy source. Along the other end of the scale, relatively small energy sources such as ambient vibrations or temperature gradients are not capable of supplying power output levels that are high enough to be conceived for power grids. Alternatively, they can be used to provide sustainable, clean power for standalone electronic sensor or transducer elements. In current technology examples, this important task is managed only by batteries. In conjunction with shrinking transistor sizes, improvements in CMOS and MEMS technologies enabled the mass manufacture of very low sensor and transducers with remarkably low power demands. The size, weight, and cost of these arrangements are currently determined by the available battery technologies.

More importantly, replacement of depleted batteries is mostly infeasible, which sets the lifetime and sustainability of these organizations. As a consequence, energy harvesting applications are required to increase the lifetime, or even lead to self-sustaining systems by completely doing away with the demand for batteries while creating a substantial impetus for developing research in industry and academe.

Thither are a number of available ambient energy sources suitable for energy harvesting applications including solar, vibration, radio frequency (RF), acoustic waves, and temperature gradients. Achievable power densities from various energy sources as easily as their advantages and disadvantages are previously reported in the literature. Ambient vibrations can provide a high energy density per unit device volume; and unlike solar cells, they can operate in implanted or embedded systems. In that respect are several vibration sources in the environment, generating vibrations with different amplitudes and frequencies. Vibration energy can be harvested using an inertial mechanism, in which the vibration is coupled to a proof mass and then extracted by damping the mechanical movement of the wad. There are three primary types of oscillation- based energy harvesters: piezoelectric, electromagnetic, and static. Piezoelectric vibration energy harvesters are reported to cause a higher energy density for practical applications. Piezoelectric materials convert the mechanical energy directly to electrical energy without any further external input. This built-in capability allows simpler architectures for piezoelectric energy harvesters (PEHs) compared to their electromagnetic and electrostatic counterparts. Simple architectures are especially preferable in MEMS scale devices, where the social systems have to be created by micromachining techniques. Scaling of the power with volume also favors the piezoelectric devices in smaller scales: output power scales with $V^{4/3}$and V^2 in piezoelectric and electromagnetic con- version mechanisms, respectively. The critical volume that piezoelectric converters provide a more serious power output is fixed as 0.5 cm3 in the same field. Due to these most salient advantages, PEHs have been examined extensively in the final ten. Figure 1 shows the number of publications.

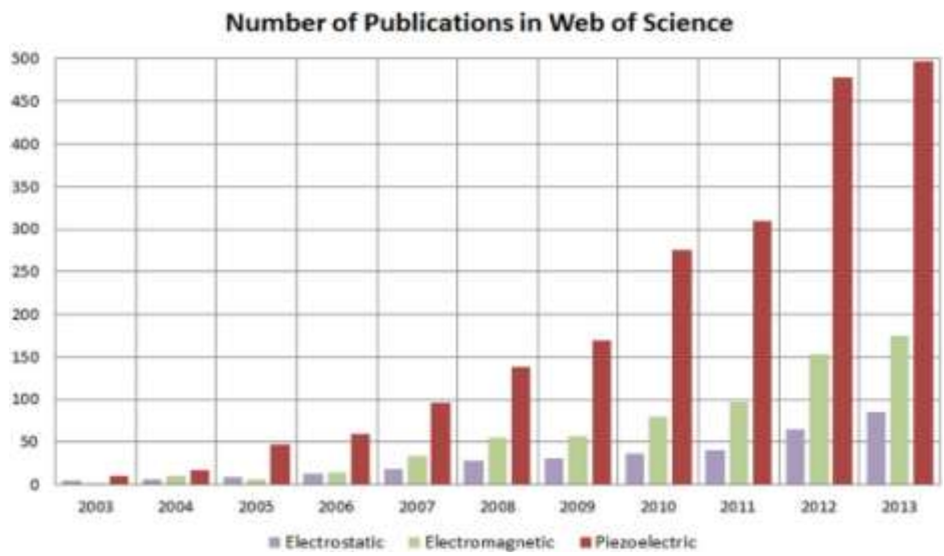

Fig. 1. Number of publications on piezoelectric, electromagnetic, and electrostatic energy harvesters in Web of Science between years 2003 and 2013.

On piezoelectric, electrostatic, and electromagnetic energy harvesters indexed in Web of Science between years 2003 and 2013. The graph clearly shows the steadily rising interest on PEHs especially in the final 5 years. This review paper presents a critique of the current status of PEHs. Part II brief presents the theory of piezoelectric energy harvesting. Part III introduces the current status of PEHs in three categories depending on their size: macro- and mesoscale, MEMS scale, and nano scale. The primary challenges of PEHs and proposed resolutions to surmount these challenges are discussed in Sec. IV, and Sec. V concludes the report.

II. PIEZOELECTRIC ENERGY HARVESTING THEORY

Piezoelectric materials have the ability to create an electric charge in response to a mechanical tension, which is called direct piezoelectric effect. The reciprocal process, mechanical strain in response to an electrical potential, is named inverse piezoelectric effect. The piezoelectric energy harvesting process uses the direct piezoelectric effect, which is identified by the constitutive equation

Direct piezoelectric effect:

$$D_i = e_{ij}^{\sigma} E_j + d_{im}^{d} \sigma_m$$

Converse piezoelectric effect:

$$\varepsilon_k = d_{jk}^{c} E_j + S_{km}^{E} \sigma_m$$

Where D is the electric displacement, d is the piezoelectric stress coefficient, T is the stress, is the dielectric constant, and E is the electric sphere. The subscript indices in this equation refer to different directions inside the material, coordinate system, and the superscript "T" means that the dielectric constants are measured under constant tension. Subscripts i and k denote the coordinate axes, numbered from 1 to 3, similar to Cartesian coordinate axes x, y, and z. By convention, direction 3 is specified as the polarization direction of the piezoelectric material. Subscript j, in addition to the same three axes, defines the rotational motions around them; thus, it is denoted with numbers from 1 to 6. The operation modes, i.e., expected directions of mechanical strain and electric field, of a piezoelectric device is also shown using the specified indices. To afford an instance, a piezoelectric sensor is

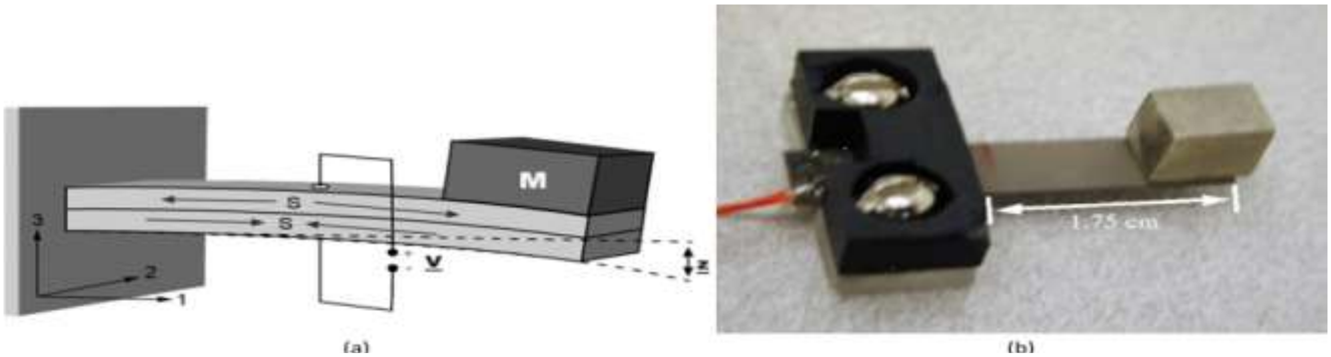

FIG. 2. (a) Schematic view, describing the working principle of a cantilever type PEH, and (b) a prototype PEH that consists of two PZT-5A layers bonded on two sides of a steel shim and a proof mass at the top.

Ambient vibrations are matched to the cantilever-mass system through the stem of the cantilever, and the tune due to bending is converted to voltage by the piezoelectric material. The proof mass is applied to increase the coupled mechanical energy and reduce the resonant frequency of the social system. Reproduced by permission from S. Roundy and P. K. Wright, Smart Mater. Struct. 13(5), 1131–1142 (2004). Copyright 2004 IOP Publishing.

Determined to be operating in d31mode if it is subject to a stress on axis 1 and the output is sensed via the electrodes placed across the device on axis 3. In this instance, the electrical output is relative to the coefficient d31, hence the epithet of the operation mode. The first term of Eq. (1) Implies that the charge brought forth in a piezoelectric material is proportional to the applied strain. Therefore, PEHs are designed to maximize the stress under a certain mechanical load. The most commonly used shapes in piezoelectric energy harvesting are the cantilever beam, since this complex body part produces the highest average strain for a given input power. Form 2 (a) depicts the schematic view depicting the working principle of a cantilever type PEH, and Fig. Shows a proto- type PEH that consists of two lead zircon ate titan ate (PZT) layers bonded on two sides of a steel shim and a proof mass at the top. Ambient vibrations are matched to the cantilever- mass system through the stem of the cantilever, causing the social system to oscillate. The alternating bending strains during the oscillations are converted to an AC voltage by the piezo- electric material.

One of the most significant design considerations in this architecture is the frequency matching, which calls for the exact coupling of ambient vibration frequencies to the natural oscillation frequency of the shaft. Cantilever beams, usually have a high mechanical quality factor, or equivalently, a narrow bandwidth. The oscillation amplitude rapidly drops as the excitation frequency shifts from the resonance frequency. Since most ambient vibrations are at low frequencies, additional proof masses are applied to cut down the resonance frequency of the energy harvester. Furthermore, the proof mass increases the overall mechanical energy stored in the cantilever-mass system, increasing the amount of harvestable energy. Another mechanical structure used for PEH is the circular diaphragm. In one of the earliest studies on PEHs, Umeda et al. Popped the question using a thin disk of piezoelectric material to convert impact energy to electrical energy. They verified the energy conversion by dropping a steel ball on top of a 0.25 mm thick piezoelectric disk mounted on a bronze disk with the same heaviness. In such an impact-type PEH, the structure starts oscillating at its resonance frequency, which is typically a good deal more eminent than the frequency of shocks. The bountifulness of the oscillations, then gradually decreases because of the mechanical and electrical damping. An important advantage of diaphragm structure over the cantilever shaft is its compatibility with pressure mode operation.

In pressure mode operation, a varying pressure field such as sound can be converted to an AC electrical signal by a piezo-electric converter. In parliamentary law to be capable to create a stress in response to a pressure change in the surrounding medium, two sides of the mechanical structure must be isolated as in the event of a diaphragm structure. Form 3 (a) depicts the deflection of a diaphragm structure in pressure mode operation, which has different stress types, i.e., compressive or tensile, to build up on the top layer depending on the position. The switching stress sign necessitates the poling direction be switched as well for optimal power production.

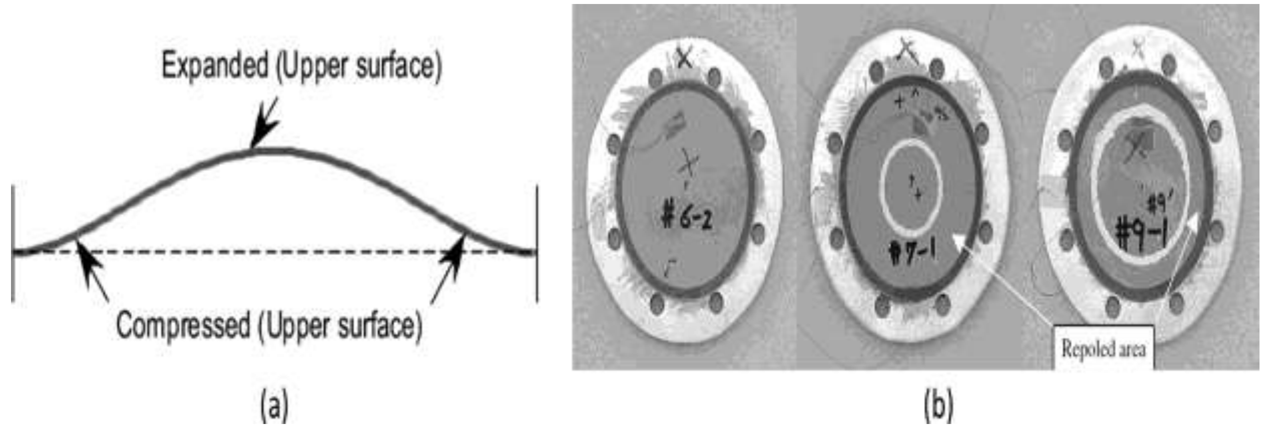

FIG. 3. (a) Deflection of a diaphragm structure in pressure mode operation, which has different stress types, i.e., compressive or tensile, on the top layer depending on the position. The switching stress sign necessitates the poling direction be switched as well for optimal power production. Part (b) shows diaphragm type PEH prototypes with different poling switch locations as designated by the cols in the top electrodes. Reprinted with permission from Kim et al., J. Intell. Mater. Syst. Struct. 16(10) 847–854 (2005) and from Kim et al., J. Intell. Mater. Syst. Struct. 16(10), 855–863 (2005). Copyright 2005 SAGE Publications.

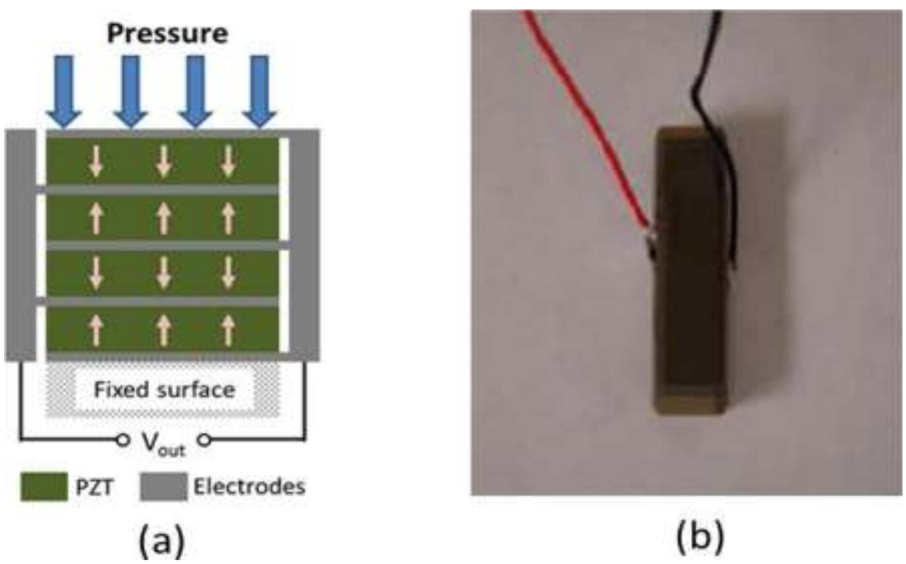

FIG. 4. (a) Simplified view of a 4-layer PZT stack architecture, and (b) actual photograph of a 300-layer PZT stack actuator. Small arrows inside the PZT show the poling direction. Poling direction is on the same axis as the applied pressure, which implies d33 mode operation. Reproduced by per- mission from Xu et al., Smart Mater. Struct. 22(6), 065015 (2013). Copyright 2013 IOP Publishing.

Form 3 (b) shows diaphragm type PEH prototypes with different poling switch locations as designated by the cols in the top electrodes. The theoretical and experimental analyses of piezoelectric circular diaphragms operating under varying pressure were shown by Kim et al. The midriff is a versatile structure that can be utilized to harvest energy from slowly varying, a periodic pressure fields or periodic acoustic waves, as well as mechanical vibrations. Nevertheless, it should be mentioned that it is considerably stronger than a cantilever of the same size, contributing to higher resonance frequencies in vibration mode operation. Pressure mode operation can be achieved also using stack architectures. Form 4 (a) indicates the simplified view of a 4-layer PZT stack, and Fig. 4(b) actual photograph of a 300-layer PZT stack actuator. In the stack architecture, piezoelectric layers are set such that the poling axes of the layers align with the applied pressure in society to utilize the d33 mode, which causes a higher coefficient than d31. Alternating poling directions of subsequent layers provides that the centering of the electric field is always towards the same electrode. Although piezoelectric stacks utilize the d33 mode, the mechanical energy coupled from the applied pres- sure is usually low due to the high stiffness of the structure. So, they are either utilized in applications where high

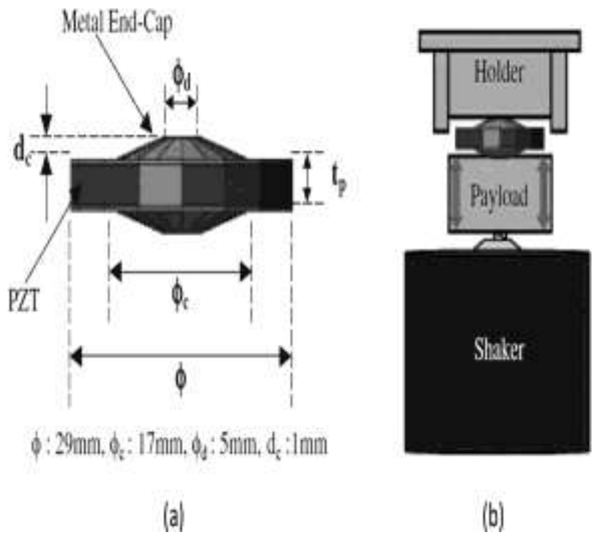

FIG. 5. (a) A cymbal transducer consisting of a metal cap attached to a PZT disc, and (b) schematic view of the test setup used to investigate the energy harvesting performance of a prototype. The axial stress applied by the shaker is amplified and converted to radial stress in the PZT material. Stress amplification provides a higher effective piezoelectric constant for the structure. Reprinted with permission from Kim et al., Jpn. J. Appl. Phys., Part 1 43(9A), 6178–6183 (2004). Copyright 2004 Japan Society of Applied Physics.

Monitoring systems, for which 32 railway pads were put back with their piezoelectric generator pads. This applied science is not mature enough to be fully commercialized yet. A recent consultant report prepared for California Energy Commission evaluated the feasibility of the plan of attack and concluded that more comprehensive examinations are necessary to realize the energy output, the cost, and the lifetime of such organizations. Mesoscale PEHs usually aim to supply power for wire- less sensor networks or implantable medical devices (IMDs). The earliest examples of mesoscale PEHs were proposed in 1960s to supply power for pacemakers. Both devices used the expansion of the aorta during systole/diastole cycle as the energy source, which was converted to electrical energy using PZT beams.

In 1984, Hasler et al. designed an implant- able energy harvester to get electrical power from the relative motion of the ribs during breathing. Later on these initial studies for implantable energy harvesters, Antaki et al. pro- posed a shoe-embedded piezoelectric generator to harvest energy for medical implants from human walking in 1995. They carried on experiments using a single cylindrical PZT stack with 0.5 cm3 volume, which ensued in an average power of 5.7 MW/kg during walking. In another study on harvesting energy from human gait, the performances of one electromagnetic and two PEHs were compared. The harvesters were designed to harvest energy mainly from the heel strike and the sole bending during walking. Utilization of the energy harvesters were also demonstrated by intermittently operating a radio frequency identification (RFID) tag using the harvested power. The writers reasoned that although the electromagnetic harvester has two orders of magnitude higher power output, piezoelectric ones are a lot easier to integrate into shoes without interfering with the pace. In 2001, the same group published a follow up study on shoe embedded piezoelectric generators as depicted in Figure 6.

Form 6 (a) illustrates the proposed energy harvesting devices and their positions in the shoe, and Fig. 6 (b) shows the potential and power outputs of fabricated devices with optimized resistive loads under a normal walking pace, which is around 0.9 Hz as evident from the spikes on the turnouts. In this field, a dump was used instead of a unimorph at the heel, and a more efficient power conditioning circuitry was used to be able to rectify the output and store it on a condenser. The whole scheme, including the power conditioning circuitry and memory elements, was shown to provide 1.3 MW continuous power from a walking speed of 0.8 Hz. Using PEHs with the purpose of charging the batteries of portable electronic devices was first proposed by Umeda et al. in 1996. In this work, the authors pointed out that portable devices are subjected to mechanical shock during transportation, which can be converted to electrical energy and utilized to recharge their batteries. They produced an

International Journal of Enhanced Research in Science, Technology & Engineering
ISSN: 2319-7463, Vol. 5 Issue 7, July-2016

equivalent circuit model for the piezoelectric generator and did experiments by dropping a steel ball on a circular piezoelectric disk clamped at the borders. The piezoelectric disk converted the vibrations caused by the impingement of the steel ball into electrical energy, which was spread out on a resistive load. The outcomes of the experiments showed that the harvested electrical power depends on a number of

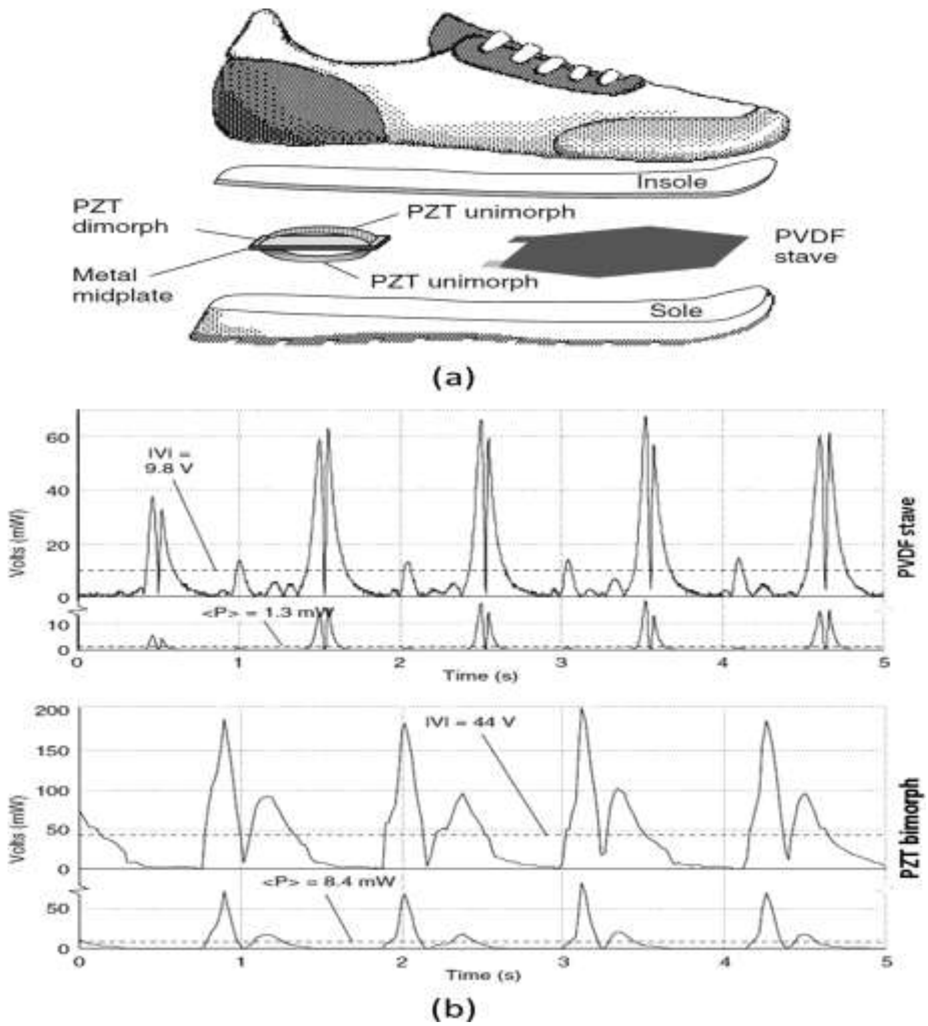

FIG. 6. (a) Energy harvesting scheme from two different regions in a shoe: (i) polyvinylidene fluoride (PVDF) stave placed under the ball of the foot to harvest the energy from bending, and (ii) PZT dimorph placed under the heel to harvest the heel strike energy. Part (b) shows the potential and power outputs of fabricated devices with optimized resistive loads under a normal walking pace, which is around 0.9 Hz as evident from the spikes on the turnouts. Reprinted with permission from N. S. Shenck and J. A. Paradiso, IEEE Micro 21(3), 30–42 (2001). Copyright 2001 IEEE Micro.

Parameters, including the load impedance and the mechanical quality factor of the piezoelectric generator. The same group also considered the efficiency in event of an output load consisting of a rectifier and a capacitor, which can be utilized to store the harvested energy and achieved a maximum electro- mechanical conversion efficiency of 35%. Using resonant mode piezoelectric devices to harvest energy from periodic vibrations has also been widely examined by researchers. The most common architecture for harvesting energy from vibrations is the cantilever shaft. Cantilever type energy harvesters typically consist of a thin cantilever beam with a proof mass at its loose end and a fixed base at the other terminal. The total construction is mechanically bonded to a vibrating body via the specified foot, in order to match the vibrations to the cantilever and the proof mass. Resultant OS- cillation is converted to an AC electrical signal by the piezo- electric material of the cantilever shaft. The bountifulness of the oscillation, and therefore, the electrical output, strongly depend on the frequency matching between the input vibrations and the natural frequency of the shaft. Glynne-Jones et al. Designed, constructed, and tested a cantilever type vibrational mode PEH as a proof-of-concept in 2001. The proposed device consisted of a tapered PZT layer with electrodes on both sides, bonded to a 23 mm wide trapezoidal steel beam; it caused a resonance frequency of 80 Hz and generated 3 Low power on an optimal resistance of 333 KX at a tip displacement of 0.8 millimeter. Another demonstration for the exercise of the vibration energy harvested by piezoelectric cantilevers was presented by Roundy and Wright in 2004. In this study, a 1.9 GHz radio transmitter was operated intermittently using the harvested energy stored in a 47 if capacitor. The energy was supplied from a 1 cm^3 rectangular cantilever type PEH subjected to an input acceleration of 2.5 m/s^2 at its resonance frequency of 120 Hz. The power output was evaluated at 375 kW, and corresponding maximum duty cycle at which the radio transmitter can be operated was calculated as 1.6% by the generators. A similar experiment was performed by Reilly et al. in 2011 using a trapezoidal cantilever beam structure, which was reported to operate a radio transmitter at 0.2% duty cycle. Although the aforementioned devices use PZT as the piezoelectric material, at that place are other studies reporting the use of other fabrics. In 2012, Cao et al. Fabricated an AlN based energy harvester on a stainless steel substrate to improve the fracture toughness of the construction. They brought together a relatively large copper proof mass to reduce the resonance frequency, which was then measured as 69.8 Hz for a 6.1 mm long cantilever.

Most recently reported cantilever type devices usually aim to amend the force output by using optimally curved cantilevers or other mechanical structures that can provide a more uniform stress distribution. Cantilever beams provide an easy method to create high tension from a comparatively little power; nevertheless, they are non compatible with pressure mode operation. In 2003, Kim et al. looked into the feasibility of harvesting energy from pressure using a diaphragm structure. They examined the stress distribution in a clamped circular diaphragm and pro- posed a re-pooling scheme to maximize the electrical output energy. The same group published detailed analytical models and observational results for clamped and simply sup- ported circular diaphragms operated on a quasi-static mode, where the varying pressure frequency is a good deal more downcast than the resonance frequency of the diaphragms. In both examples, experimental results showed good correspondence with the analytical models. Diaphragm structure can be utilized to harvest vibrational energy as well, which has been shown in a routine of fields.

All the same, the awkwardness of this construction is considerably higher than a same size cantilever, which contributes to high resonance frequencies such as 1.71 kHz for a 25-mm diameter diaphragm. Making for the resonance frequency below 200 Hz for similar sized diaphragm harvesters necessitate using proof masses on the order of 0.1 kilogram. Pressure mode energy harvesting using stack architecture usually requires mechanical force amplifier structures. Kim et al. Coupled a PZT disk, which can be viewed as a single layer stack, with a cymbal mechanical transducer. The cymbal energy harvester with 29 mm diameter and 1 mm thickness generated 39 mW output when excited with a sinusoidal force of 7.8 N at 100 Hz. Renetal. used a rectangular cymbal coupled with a single crystal lead magnesium niobate/lead titanate (PMN-PT) for vibrational energy harvesting. The reported output power was 14.0 mW under a cyclic force of 0.55 N at 500 Hz with a 17 g proof mass. Feenstra et al. used a 130-layer, 400 mm^3 PZT stack coupled to a mechanical force amplifier to harvest energy from the tension created at the straps of a backpack during walking.

They did experiments using a backpack with a 220 N load. Grounded on the terminations, the authors predicted a power out-put of 0.4 MW from each piezoelectric stack under typical walking conditions. 22 Nevertheless, a piezoelectric stack can be employed right away as well if the input power is big enough: Xu et al. Used a 300-layer PZT stack with a mass of 1.75 cm3 for vibration energy harvesting, which generated 15 MW at 1767 Hz in resonance mode and 15 kW at 800 Hz in off-resonance mode in reaction to a 1 Nrms force. In summary, large scale PEHs are currently being investigated for feasibility and reliability. Deployment of such schemes would involve high investment costs; therefore, commercialization can be expected but if their feasibility is proven via thorough experimental studies. On the other hand, in that respect are various examples of mesoscale PEHs that can be manufactured at low costs reported in the literature. Power outputs of these devices cover a range from hundreds of lW to a few mW, depending on the device size and input acceleration levels. The reported power levels can be sufficient to operate a kind of electronic sensors or transducers. All the same, these power outputs are obtained in controlled lab- oratory environments using frequency controlled test equipment. Pragmatic application of PEHs to real systems has certain challenges such as operation bandwidth, as it will be discussed in Sec. However, new methods are being proposed continuously to come up to these problems, and small systems utilizing PEHs might be possible in the near future.

B. MEMS scale

High level integration capability of modern CMOS and MEMS fabrication technologies enabled monolithic fabrication of complete sensor systems in sub-cm sized chips. The modest proportions and low unit costs of these devices increase the impact of the batteries on the overall system size and monetary value. With this driving force, there accept been a noteworthy number of studies on MEMS scale energy harvesters in the final decade, most of which are piezoelectric type due to their aforementioned advantages. Yet, unlike the electronic circuits, functionality of vibration energy harvesters depends primarily or strongly on their proportions. These devices harvest the mechanical energy of a moving mass; thus, the harvestable energy is diluted as the pile starts out smaller. Therefore, maximizing the output power obtained per unit mass at a certain input acceleration is crucial in MEMS scale. This turns even more challenging in thin films due their lower electromechanical conversion efficiencies. Furthermore, MEMS scale PEHs are mostly in unimorph configuration, which has lower electromechanical conversion factor compared to bimorphs, since the micro fabrication techniques are not desirable to fabricate bitmap structures. Some other problem caused by the small device dimensions is higher resonance frequencies. Small masses and relatively high spring constants of sub-mm length cantilevers make it difficult to melt off the resonance frequencies below 250 Hz, which encompasses the spectrum of commonly available ambient vibration sources.

One of the most commonly used piezoelectric materials in MEMS scale energy harvesting is PZT. The first study reporting utilization of thin film PZT for MEMS scale energy harvesting purposes was published by Jeon et al. in 2003. The proposed energy harvester architecture was a rectangular cantilever consisting of a structural oxide layer, a colloidal suspension-gel coated PZT thin film layer, an inter digitated electrode layer, and an SU-8 proof mass layer. Inter digitated electrodes enable the utilization of d33 mode operation in a cantilever beam, allow the output voltage to be settled by the finger spacing, rather than the piezoelectric material thickness, and reduce the number of layers to be modeled. Image 7 illustrates the electrode shapes and corresponding poling directions in d31 and d33 mode cantilevers, which are constructed using plate electrodes and inter digitated electrodes, respectively. It should be noted that interdigitated electrode configuration necessitates the piezoelectric material be polled using the same electrodes; and thus, this contour is not applicable to non-ferroelectric piezoelectric materials. The same group reported some follow-up studies, where they reduced the strain-induced bending of fabricated cantilevers. Fabricated devices generated 1 Low power under a top acceleration of approximately 10.9 g at the resonance frequency of 13.9 kilohertz. The high resonance frequency is primarily done by the small cantilever dimensions, which yield high cantilever stiffness and low volume.

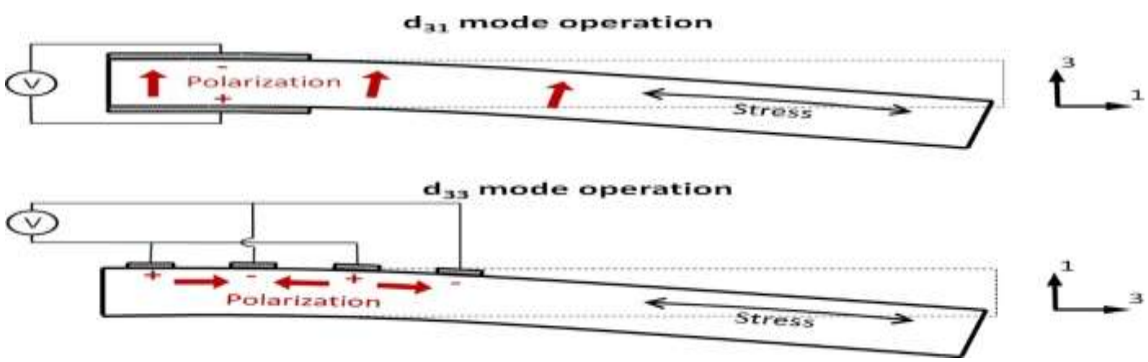

FIG. 7. Representative of the electrode shapes and corresponding poling directions in d31 and d33 mode cantilevers, which are constructed using plate electrodes and interdigitated electrodes, respectively. It should be noted that interdigitated electrode configuration necessitates the piezoelectric material be poled using the same electrodes. Thus, this form is not applicable to non-ferroelectric piezoelectric materials.

C. Nanoscale

Piezoelectric energy harvesting at the nanometer scale is typically taken out by nanowires that are synthesized from piezoelectric materials. Piezoelectric nanowire generators were first demonstrated by Dr. Wang's group at Georgia Institute of Technology in 2006. In these surveys, single ZnO nanowires were bent by a conductive atomic force microscope (AFM) probe used in touch mode. Form 9 (a) establishes the interaction between the AFM probe and a single ZnO nanowire during a contact mode scan and Fig. 9 (b) corresponding electrical potential along the nanowire. The semi-conducting characteristics of the ZnO creates a Schottky contact between the conductive tip of the AFM and the nano- wire itself, creating a rectifying structure that allows observable voltage output at an external resistive load. The same group demonstrated that the nanowires can also be produced on flexible plastic substrates, which might prove advantageous for implantable energy harvesters. These initial studies demonstrated the electrical energy generation capability of a single ZnO nanowire. Withal, a practice- Cal application requires thousands of nanowires to be mechanically excited without a limited gimmick. Typical ZnO nanowire fabrication processes yield very high spatial densities; however, the orientations of these nanowires are usually random.

In order to address this need, Wang et al. used a zigzag-shaped top electrode on a vertically aligned ZnO nanowire array. In this twist, each point of the zigzag- shaped top electrode emulates an AFM tip that bends the nanowire. The output power strongly depends on the density and height uniformity of the nanowires as well as the contact distance between the nanowire array and the top electrode. Nonetheless, the fabricated device generated a DC output power of 1 ps from a 2 mm2 active area when excited with an ultrasound wave. Another method to increase the number of nanowires contributing to the electrical output is using conical shaped nanowires. The conical shape provides that the c-axis of a nanowire have a downward pointing angle, which ensures a unipolar alignment in every stratum. A Flexible, multilayer generator fabricated using conical nanowires was used to provide power to a simple LCD screen. The same group showed a self-powered sensor with wire- less transmission and a device's harvesting energy from a rotating tire that can perhaps be employed as a self-powered press- sure or speed sensor. As evidenced by these nascent approaches, energy harvesting from nanostructures is a promising field with a broad application range. This growing interest helped founding a dedicated scientific journal on Nano Energy and its applications.

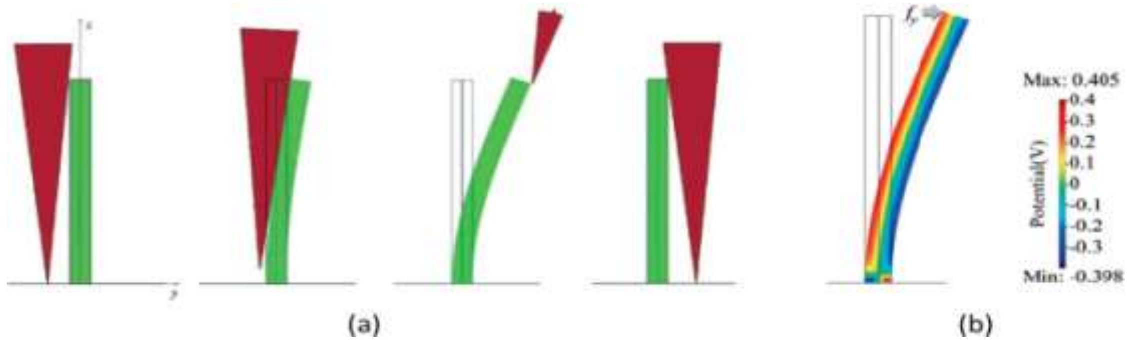

FIG. 8. (a) Interaction of an AFM probe with a ZnO nanowire during a contact mode scan and (b) corresponding electrical potential on the nanowire. (Image courtesy of Professor Z. L. Wang, Georgia Tech.) Reprinted with permission from Y. Gao and Z. L. Wang, Nano Lett. 7(8), 2499–2505 (2007). Copyright 2007 ACS Publications.

IV. CHALLENGES AND PROPOSED SOLUTIONS IN PIEZOELECTRIC ENERGY HARVESTERS

Most of the vibration energy harvesters are designed to operate in resonance mode and the half-power bandwidth is normally minor. This is one of the most significant challenges of energy harvesting since the frequency of ambient vibrations varies within a wide range, from 1 Hz for heel tapping up to 240 Hz for an electric teapot. At that place are some vibration sources such as industrial machinery that can supply constant frequency vibrations over relatively long periods. To afford an instance, a synchronous AC electric motor operating in a mill during the work hours would provide vibrations at the AC line frequency for 8 h a day. Nevertheless, even the harvesters using this type sources might require tuning due to frequency shifts in the vibration source or drifts in the resonance frequency. This event gets more pronounced in case of random ambient vibration sources, which would span a wider frequency range. Apparently, it would not be feasible to continuously evaluate the vibration and manually tune the resonance frequency of the harvester in this instance. Two possible answers to this problem are dynamic resonance frequency tuning and wide bandwidth harvesters. Both methods have been investigated in the literature by several research groups. Roundy and Zhang investigated the feasibility of actively tuning the resonance frequency by using actuators and ? listed the requirements for a net power gain.

CMOS compatible MEMS processes allow fabrication of monolithic sensors and transducers, where the mechanical and electrical components are made along the same substrate. Monolithic fabrication reduces the overall device size and monetary value. Furthermore, the interconnections between the mechanical and electrical components are filled out by micro processing rather than wire bonding, which increases the reliability and reduces the parasitic effects. The key to a monolithic device is developing a CMOS compatible process, which does not harm the electronic circuits while fabricating the mechanical components. The most common fabric used in MEMS scale PEHs is thin-film PZT, which is normally deposited with the colloidal suspension - gel method. Crystallization temperature of PZT is around 600–700 C; therefore, the coated films must be annealed at these temperatures in order to obtain piezoelectric characteristics. Although in that respect are other methods to deposit thin film PZT such as aerosol deposition or epitaxial growth, all these methods require high temperature for proper crystallization. Therefore, these gimmicks are not CMOS compatible. Aktakka et al. proposed integrating bulk PZT on silicon using a low temperature bonding process as a solution to this problem. The thickness of bulk PZT is on the order of 200 lm, which is too deep for a MEMS scale device; thus, the bulk PZT crystal is mechanically thinned after the soldering. Thus, the proposed process brings CMOS compatibility at the monetary value of increased fabrication complexity.

One of the promising applications of PEHs is IMDs. On that point is considerable effort in making a self-sustained IMDs using PEHs as reported in the literature. One of the most significant considerations in IMDs is the biocompatibility of the utilized materials. The most commonly used piezo- electric material, PZT, is not favorable for implants due to its lead content, which is a toxic material. An alternative lead-free piezoelectric material is potassium sodium niobate (KNN), which has piezoelectric properties similar to those of PZT. Operation of KNN-based PEHs has been demonstrated in MEMS scale, and their performance has been found to be comparable to PZT based devices.

Biocompatibility of other widely used piezoelectric material, AlN, has been verified by in vivo and in vitro trials. Heidrich et al. Proposed a corrugated membrane type AlN- based energy harvester designed for a periodic vibrations at low acceleration levels, which is the expected input type for an embedded device. Jackson et al. demonstrated the deposition of AlN thin films on polyimide to create flexible devices, which can also be advantageous for implanted devices. Another alternative method to make a flexible, implantable energy harvester is used PVDF-based polymers. Biocompatibility of PVDF and PVDF-TrFE has also been verified. Biocompatibility and flexibility of these polymers make them a desirable candidate for implantable energy harvesters.

CONCLUSION

Piezoelectric devices have attracted more attention than other mechanical energy harvesting methods due to their certain advantages such as higher power output density, scalability, and the simplicity of the required external circuitry. The research on mechanical energy harvesting mostly focused on changing the energy in ambient vibrations; however, PEHs can convert the energy in varying pressure as well, which increases their potential applications. Piezoelectric energy harvesting has been presented in different plates from several m2 piezoelectric floors to sub-micron nanowire arrays. Large scale piezoelectric energy harvesting demonstrations so far aim to supply power for the nearby lighting or sensing systems in an attempt to cut the effective energy consumption of the overall organization. On the other hand, the ultimate goal of smaller scale energy harvesters is mostly creating self-powered systems. Improvements in piezoelectric energy harvesting and decreasing power requirements of CMOS circuits brought the supplied and required power levels close to each other, which brings us closer to such organizations. On that point are still certain challenges in PEHs such as increasing the operation band- width, developing CMOS compatible processes for integrated devices, or fabricating biocompatible devices for implants. Some other significant issue arises due to the availability level of harvestable energy, which is virtually impossible to anticipate in advance.

Thus, the organization should be able to harvest energy whenever it is available and store it for later usage. Memory of the harvested energy requires the AC outputs of PEHs be rectified using impedance-matched electrical circuits. The correction and storage processes have their own losses as well, which would shorten the already low amount of harvested energy. However, on that point is an ongoing research effort concentrated on these problems and new solutions is being proposed continuously. Presently, the most prominent candidates for self- powered systems are WSN and IMD. Ridding of the battery in a WSN will reduce the price, size, and weightiness of the node as well as increasing its life. Battery less IMDs have he extra advantage of eliminating invasive surgical procedures on the patient for battery replacement. Such self- powered systems have already been shown in special test environments, and we anticipate that they will be usable for real applications in the near future. Even if eliminating the batteries might not be potential for some applications depend- in on the power requirements and size restrictions, piezoelectric energy harvesting can be nonetheless useful by recharging the battery and therefore increasing the lifespan of the gimmick.

REFERENCES

[1]. Marin, S. Bressers, and S. Priya, J. Phys. D: Appl. Phys. 44(29), 295501 (2011).ANSI/IEEE Std 176–1987, 0_1, 1988.
[2]. Ren, S. W. Or, X. Zhao, and H. Luo, J. Appl. Phys. 107(3), 034501 (2010).
[3]. K. Mo, L. J. Radziemski, and W. W. Clark, Smart Mater. Struct. 19(7), 075010 (2010).
[4]. K. Mo, L. J. Radziemski, and W. W. Clark, Smart Mater. Struct. 19(2), 025016 (2010).
[5]. Hill and N. Tong, "Assessment of piezoelectric materials for roadway energy harvesting," California Energy Commission, CEC-500-2013-007, 2013.
[6]. D. N. Shen, J. H. Park, J. H. Noh, S. Y. Choe, S. H. Kim, H. C. Wikle, and D. J. Kim, Sens. Actuators, A 154(1), 103–108 (2009).
[7]. D. Shen, J.-H. Park, J. Ajitsaria, S.-Y. Choe, H. C. Wikle, and D.-J. Kim, J. Micromech. Microeng. 18(5), 055017 (2008).
[8]. Minazara, D. Vasic, F. Costa, and G. Poulin, Ultrasonics 44, e699–e703 (2006).
[9]. E. E. Aktakka, R. L. Peterson, and K. Najafi, paper presented at the International Electron Devices Meeting, 2010.

[10]. E. K. Reilly, L. M. Miller, R. Fain, and P. Wright, in PowerMEMS, Washington, DC, USA (2009).
[11]. E. K. Reilly, F. Burghardt, R. Fain, and P. Wright, Smart Mater. Struct. 20(12), 125006 (2011).
[12]. East Japan Railway Company, "Demonstration experiment of the power generating floor at Tokyo station," see http://www.jreast.co.jp/e/develop-ment/press/20080111.pdf.
[13]. Liu, A. Phipps, S. Horowitz, K. Ngo, L. Cattafesta, T. Nishida, and M. Sheplak, J. Acoust. Soc. Am. 123, 1983 (2008).
[14]. Lewin, G. Myers, V. Parsonnet, and K. Raman, Trans. - Am. Soc. Artif. Inter. Organs 14, 215 (1968).
[15]. B. Fang, J. Q. Liu, Z. Y. Xu, L. Dong, L. Wang, D. Chen, B. C. Cai, and Y. Liu, Microelectron. J. 37(11), 1280–1284 (2006).
[16]. H. W. Kim, A. Batra, S. Priya, K. Uchino, D. Markley, R. E. Newnham, and H. F. Hofmann, Jpn. J. Appl. Phys., Part 1 43(9A), 6178–6183 (2004).
[17]. Innowattech Energy Harvesting Systems, Innowattech achieves a break- through in alternative energy by generating electricity from road traffic in a recent complete-system pilot project, see http://www.innowattech.co.il/events.aspx.
[18]. Innowattech Energy Harvesting Systems, Rail Project, see http://www.in- nowattech.co.il/events.aspx.
[19]. Baker, S. Roundy, and P. Wright, in 3rd International Energy Conversion Engineering Conference, San Francisco, CA, USA (2005).
[20]. Feenstra, J. Granstrom, and H. Sodano, Mech. Syst. Signal Process. 22(3), 721–734 (2008).
[21]. J. F. Antaki, G. E. Bertocci, E. C. Green, A. Nadeem, T. Rintoul, R. L.Kormos, and B. P. Griffith, ASAIO J. 41(3), M588–M595 (1995).
[22]. J. Kymissis, C. Kendall, J. Paradiso, and N. Gershenfeld, paper presented at the 2nd International Symposium on Wearable Computers, Digest ofPapers (1998).
[23]. Zuo and X. D. Tang, J. Intell. Mater. Syst. Struct. 24(11), 1405–1430 (2013). S. J. Roundy, Ph.D. dissertation, The University of California, Berkeley, 2003.
[24]. Deterre, E. Lefeuvre, and E. Dufour-Gergam, Smart Mater. Struct. 21(8), 085004 (2012).
[25]. Umeda, K. Nakamura, and S. Ueha, Jpn. J. Appl. Phys., Part 1 35, 3267–3273 (1996).
[26]. M. Umeda, K. Nakamura, and S. Ueha, Jpn. J. Appl. Phys., Part 1 36, 3146–3151 (1997).
[27]. S. Shenck and J. A. Paradiso, IEEE Micro 21(3), 30–42 (2001).
[28]. Becker, E. Hymon, B. Folkmer, and Y. Manoli, Sens. Actuators, A 202, 155–161 (2013).
[29]. Mandurino, G. Bertolotto Bianc, and R. Garbin, Proc. SPEI 4331, 408–419 (2001).
[30]. P. Glynne-Jones, S. Beeby, and N. White, IEE Proc.: Sci., Meas. Technol. 148(2), 68–72 (2001).
[31]. Sood, Y. B. Jeon, J. h. Jeong, and S. G. Kim, paper presented at the Proceedings of Solid-State Sensor and Actuator Workshop, South Carolina, 2004.
[32]. S. B. Horowitz, M. Sheplak, L. N. Cattafesta, and T. Nishida, J. Micromech. Microeng. 16(9), S174–S181 (2006).
[33]. Kim, W. W. Clark, and Q. M. Wang, J. Intell. Mater. Syst. Struct. 16(10), 847–854 (2005).
[34]. Kim, W. W. Clark, and Q. M. Wang, J. Intell. Mater. Syst. Struct. 16(10), 855–863 (2005).
[35]. S. Kim, W. W. Clark, and Q. M. Wang, Proc. SPIE 5055, 307–318 (2003).
[36]. S. Mehraeen, S. Jagannathan, and K. A. Corzine, IEEE Trans. Ind. Electron. 57(3), 820–830 (2010).
[37]. S. Roundy and P. K. Wright, Smart Mater. Struct. 13(5), 1131–1142 (2004).
[38]. S. Roundy, P. K. Wright, and J. Rabaey, Comput. Commun. 26(11), 1131–1144 (2003).
[39]. S. Roundy, E. S. Leland, J. Baker, E. Carleton, E. Reilly, E. Lai, B. Otis, J. M. Rabaey, P. K. Wright, and V. Sundararajan, IEEE Pervasive Comput. 4(1), 28–36 (2005).
[40]. S.-G. Kim, S. Priya, and I. Kanno, MRS Bull. 37(11), 1039–1050 (2012).
[41]. T.-B. Xu, E. J. Siochi, J. H. Kang, L. Zuo, W. Zhou, X. Tang, and X. Jiang, Smart Mater. Struct. 22(6), 065015 (2013).
[42]. V. Parsonnet, G. H. Myers, R. I. Zucker, H. Lotman, and M. M. Asa, ASAIO J. 9(1), 174– 177 (1963).
[43]. W. Wang, T. Yang, X. Chen, X. Yao, and Q. Zhou, paper presented at the Applications of Ferroelectrics (ISAF/PFM), 2011 International Symposium on and 2011 International Symposium on Piezoresponse Force Microscopy and Nanoscale Phenomena in Polar Materials (2011).
[44]. X.-r. Chen, T.-q. Yang, W. Wang, and X. Yao, Ceram. Int. 38, S271–S274 (2012).
[45]. Y. B. Jeon, R. Sood, J. H. Jeong, and S. G. Kim, Sens. Actuators, A 122(1), 16–22 (2005).
[46]. Y. Jeon, R. Sood, L. Steyn, and S. G. Kim, in CIRP Seminar on Micro and Nano Technology (2003).
[47]. Z. P. Cao, J. Y. Zhang, and H. Kuwano, Sens. Actuators, A 179, 178–184 (2012).