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Review Article

Piezoelectric Energy Harvesting Devices: An Alternative Energy Source for Wireless Sensors

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The recent advances in ultralow power device integration, communication electronics, and microelectromechanical systems (MEMS) technology have fuelled the emerging technology of wireless sensor networks (WSNs). The spatial distributed nature of WSNs often requires that batteries power the individual sensor nodes. One of the major limitations on performance and lifetime of WSNs is the limited capacity of these finite power sources, which must be manually replaced when they are depleted. Moreover, the embedded nature of some of the sensors and hazardous sensing environment make battery replacement very difficult and costly. The process of harnessing and converting ambient energy sources into usable electrical energy is called energy harvesting. Energy harvesting raises the possibility of self-powered systems which are ubiquitous and truly autonomous, and without human intervention for energy replenishment. Among the ambient energy sources such as solar energy, heat, and wind, mechanical vibrations are an attractive ambient source mainly because they are widely available and are ideal for the use of piezoelectric materials, which have the ability to convert mechanical strain energy into electrical energy. This paper presents a concise review of piezoelectric microgenerators and nanogenerators as a renewable energy resource to power wireless sensors.

1. Introduction

The advances in low power electronics, and wireless sensor networks (WSNs) in particular, have driven numerous researches in the field of energy harvesting in the past decade [1–3]. A wireless sensor node consists of low power microcontroller unit, radio frequency transceiver and microelectromechanical- (MEMS-) based sensor. The task of each node is to collect and transmit data to the outside world via a radio link. Thousands of spatially distributed wireless sensors can be developed which can be embedded virtually anywhere in civil structures, bridges, or in the human body. WSN technology has gained increasing importance in industrial automation [4, 5], structural health monitoring [6], healthcare [7], agriculture [8], and civil and military applications [9–11]. Traditionally, batteries are used as the electrical energy power sources to power wireless sensors and embedded electronics. However, batteries have a limited life span and they are expensive to maintain and hence they are not a long-term viable source of energy for WSNs and embedded systems. In fact, the limited capacity of batteries is one of the main factors constraining the performance and limiting the lifespan of a typical WSN [2, 3]. Energy harvesting is the most promising way of overcoming the challenges currently presented by finite life power sources like batteries. The process of energy harvesting involves the harnessing of ambient energy from within the vicinity of the sensor device and converting this energy into usable electrical energy. Compared to batteries, energy harvesting presents a potentially infinite source of energy for powering wireless sensor devices and embedded electronics in general. Energy harvesting is not a new concept; in essence it has been practiced for decades in the context of windmills to harness energy from wind, in hydroelectric generators to harvest energy from moving water, and in solar panels that power satellites using energy from the sun. However, what is new with energy harvesting technology is how to design and implement efficient energy harvesting capabilities into modern embedded systems while satisfying all their constraints. For any energy harvesting system to be attractive, it should allow miniaturization and integration using the present MEMS technology, otherwise it is not useful for embedded system applications. While solar energy harvesting is a fairly established technology, it is not the best choice for mobile, implantable, and embedded electronics where solar energy is not accessible. Mechanical energy in form of ambient vibrations, fluid flow, machine rotations, and biomotion presents a source of energy that is available widely and at all times. Piezoelectric materials can be used to harvest this energy since they have the unique ability of converting mechanical strain energy into useful electrical energy. Piezoelectric energy harvesting devices—in the form of MEMS generators or nanogenerators—are a novel technology that is a reliable alternative energy source for powering wireless sensor devices. Unlike conventional MEMS generators, nanogenerators have an added advantage of being flexible and foldable power sources which is ideal for applications such as implantable biomedical sensors [12, 13].

This paper discusses the recent advances in micro- and nanoscale energy generation using piezoelectric materials for ultra low power sensor applications.

The paper is organised as follows: Section 2 gives a brief overview of the energy sources for wireless sensor devices. Section 3 gives a brief discussion of energy harvesting from vibrations using piezoelectric smart materials. Section 4 presents the application context of energy harvesting devices, power management issues, and challenges and suggestions for future research efforts necessary for improvement of piezoelectric energy generators. Section 5 concludes the paper.

2. Energy Sources for WSNs

2.1. Overview of Power Requirements of a Typical Wireless Sensor Node. A wireless sensor node is designed to perform sensing, data acquisition, localized processing, and wireless communication and is usually powered by battery. A power generator which scavenges energy from the immediate environment of the sensor can potentially be used to recharge the battery or independently power the senor node. A typical wireless sensor node is shown in Figure 1, with each block showing a subsystem with its own power requirements.

The subsystems in Figure 1 essentially show the power consuming elements of the sensor node based on functionality, and Figure 2 shows the typical distribution of power consumption amongst these subsystems [14].

2.1.1. Sensing Subsystem. The sensing subsystem consists mainly of the sensors and an analog to digital conversion (ADC) unit and is responsible for converting the physical phenomena of interest into digital signal form. The power consumed in the sensing subsystem is used in sensor sampling, which includes the wake-up and stabilization time associated with the sensor and the data acquisition time. At all other times, the sensors are completely off and consume no power. The power consumption of the ADC is typically proportional to the amount of the samples acquired and the sampling rate (SR) used [15]. With a low rate ADC and

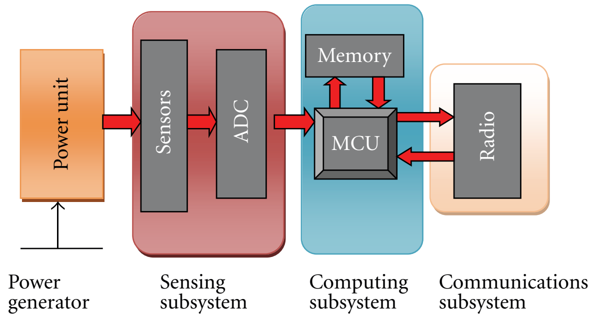


FIGURE 1: Wireless sensor node showing the main subsystems.

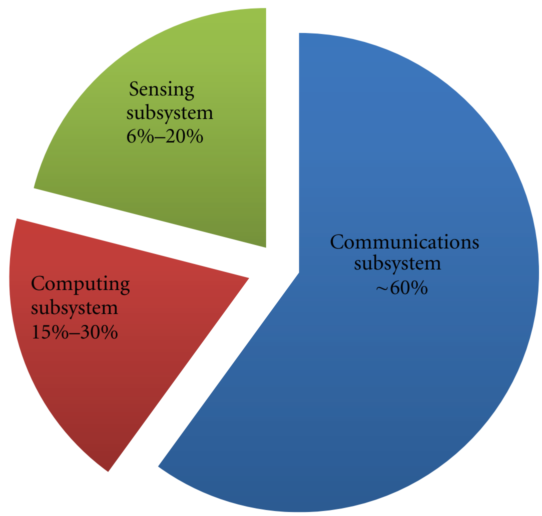


FIGURE 2: Power consumption distribution for a wireless sensor node.

TABLE 1: Sensor specifications for wireless module in building management system [17].

Sensor	Voltage (V)	Current (mA)	Power (mW)	Sampling time (s)	Energy/sample (μJ)
Temperature	3.3	0.008	0.026	0.0002	0.00528
Light	3.3	0.03	0.099	0.0002	0.0198
Humidity	3.3	0.3	0.99	0.8	792
Vibration	3.3	0.6	1.98	0.02	39.6
Barometric pressure	5.0	7.0	35.0	0.02	0.7

passive sensors, the sensing subsystem will be one of the least energy consumers. However, if higher rate ADC's and/or energy hungry sensors are used for a particular application, the power consumption of the sensing subsystem can quickly rival that of the communications subsystem [16]. Some power consumption specifications for various senor devices used in a building management system [17] are shown in Table 1 to give a general idea of the order of the energy requirements.

2.1.2. Computing Subsystem. The computing subsystem is comprised of a processing unit which is usually a microcontroller unit (MCU) and the supporting electronics. This subsystem controls all sensor node activities and performs some local processing. When not processing data and not controlling the system operation, the processor is in a low power sleep mode. Table 2 shows an overview of the power requirements of some of the self-microprocessor systems employed in wireless sensor technologies.

The energy required by the computing subsystem to complete a task, (E_{comp}), is approximated by [18],

$$E_{\text{comp}} = O(p) \cdot \gamma\left(\frac{f}{k} + \varepsilon\right), \quad (1)$$

where $O(p)$ is the computational complexity, f is the processor frequency, γ is the switching capacitance, and ε and k are hardware specific constants.

2.1.3. Communications Subsystem. The communications subsystem comprises mainly the radio transceiver (RF transceiver) with the amplifiers and associated electronics. The RF transceiver enables the wireless module to communicate and transmit the processed sensor data. When the RF transceiver is not transmitting or receiving, the transceiver is in a low power sleep mode. As shown in Figure 2, communication subsystem—transmitting, receiving, and listening—dominates the scarce power budget with 60% consumption of the total available energy and determines the lifetime of sensor network. Its power consumption is evaluated by such parameters as voltage supply, transmitting current, receiving current, and current at power-down mode. Typical power parameters for some communication modules are shown in Table 3. The energy consumed by the communications subsystem, (E_{comm}) can be estimated by [19]:

$$E_{\text{comm}} = \frac{p_i \cdot B}{b}\left(F \cdot r^2\left(2^b - 1\right) + G\right), \quad (2)$$

where r is the transmission distance, p_i is the number of bits to be transmitted during transmission event i, B is the sample resolution in bits per sample, b is the modulation setting for the transmitter, F, and G are hardware specific constants.

Table 3 shows the power consumption specifications of some RF modules based on Zigbee/IEEE802.15.4 protocol specification.

From Table 3, CC2420 RF module has the lowest power parameters in terms of current in different operation modes and the supply voltage. Equivalently, the power consumption of the CC2420 RF module can be quoted as 36.5 mW in transmit mode, 41.4 mW in receive mode, 41.4 mW in idle mode, and 42 μW in sleep mode [20]. The idle mode consumes nearly the same power as the transmit mode, and hence turning the radio to sleep mode is a critical technique in saving power.

The Texas instruments MSP430 family of microcontrollers (see MSP430CG4618 power parameters in Table 2) represents a competitive choice of ultralow power core to run a typical computing subsystem of a wireless sensor node. It consumes 2 mA at 8 MHz and 3.0 V and consumes a few microamps of current in low power sleep mode. This corresponds to an energy consumption of roughly 750 pJ per instruction. Therefore, a current larger than 30 mA and a supply voltage of at least 3 V is enough to support the routine work of a typical wireless sensor node. Power consumption can be minimised by optimising the relative amount of time spent in low-power sleep mode and reducing the active mode time. That is, wireless sensor nodes spend most of their time in sleep mode. The only part of the system that stays awake is the real time clock (RTC) and is responsible for keeping the time and waking up the wireless sensor node to measure a sensor input. A fast processing core enables the microprocessing unit to execute the control algorithm very quickly, enabling a rapid return to low-power sleep mode and thereby minimizing the power-hungry area under the current consumption curve. The power consumption of commercial wireless sensor nodes is shown in Table 4. With a well managed power control management, an ideal wireless sensor node has a power consumption of about 100 μW for a life time operation [3, 5, 21, 22].

Table 2: Power parameters of part microprocessors [58].

Microprocessor	Supply current, I (mA)	Supply voltage (V)	Run frequency (MHz)	Current at power down mode, I_{PD} (μA)
C8051F930	4.25	0.9	25	0.05
PIC18F4620	16	4.2	40	0.1
MC9s08GT	6.5	3	16	2.5
AMTEGA 128L	5.5	3	4	<5
MSP430CG4618	0.4	2.2	1	0.35
ML610Q431	0.65	1.1	4	0.25

Table 3: Power parameters of part microprocessors [58].

RF module	V (V)	Reception mode current, I_{RX} (mA)	Transmission mode current, I_{TX} (mA)	Current at power down mode, I_{PD} (μA)
CC2420	2.1~3.6	18.8	17.4	0.9
MC13192	2.0~3.4	42	35	1
UZ2400	2.7~3.6	18	22	2
xBee	2.8~3.4	50	45	<10
xBee-PRO	2.8~3.4	55	270	<10
NanoPAN5360	2.8~3.6	35	78	1.5
NanoPAN5361	2.8~3.6	35	78	1.5

2.2. Energy Sources for WSNs

2.2.1. Batteries. At present, batteries still dominate energy source for low power electronics in general. Typical characteristics of Li-ion and thinfilm batteries are shown in Table 5. The values for supercapacitor are given for comparison.

Batteries, particularly Li-ion and thin films variants, are considerably a cheap and convenient and the best solution available in terms of energy density. Over the past two

Table 4: Power consumption of some commercial wireless sensor nodes.

	Crossbow MICAz [21, 59]	Intel Mote 2 [21, 59]	Jennie JN5139 [21, 60]
Radio standard	IEEE802.15.4/ZigBee	IEEE802.15.4	IEEE802.15.4/ZigBee
Typical range	100 m (outdoor), 30 m (indoor)	30 m	1 km
Data rate (kbps)	250 kbps	250 kbps	250 kbps
Sleep mode (deep sleep)	15 μA	390 μA	2.8 μA (1.6 μA)
Processor only	8 mA active mode	31–53 mA	2.7 + 0.325 mA/MHz
RX	19.7 mA	44 mA	34 mA
TX	17.4 mA (+0 dbm)	44 mA	34 mA (+3 dBm)
Supply voltage (minimum)	2.7 V	3.2 V	2.7 V
Average	2.8 mW	12 mW	3 mW

Table 5: Characteristics of Li-ion, thin film batteries [57].

Characteristic	Battery		Supercapacitor
	Li-ion	Thin film	
Operating voltage (V)	3–3.70	3.70	1.25
Energy density (W h/l)	435	<50	6
Specific energy (W h/kg)	211	<1	1.5
Self-discharge rate (%/month) at 20°C	0.1–1	0.1–1	100
Cycle life (cycles)	2000	>1000	>10,000
Temperature range (°C)	−20/50	−20/+70	−40/+65

decades, research and development in battery technology has resulted in an increased battery energy density by a factor of three. Still, battery technology has evolved very slowly compared to electronic technology. For example, while computer disk storage density has increased over 1,200 times since 1990, battery's energy density has increased only about 3 times [23]. On average, the computational or processing power doubles every 2 years while battery capacity doubles every 10 years. Thus, it is battery life that can forestall the deployment and lifespan of WSNs and embedded systems. Replacement, recharging, and disposal of batteries present costly challenges [23, 24]. Furthermore, the size of the batteries is often larger compared to the devices they are meant to power while at the same time reducing the battery dimensions compromises the power density. For these reasons, alternative solutions to batteries need to be sought, and ambient energy harvesting devices are the potential alternatives.

2.2.2. Ambient Energy Sources. To provide a reliable source of energy for a wireless sensor system, one can consider extracting energy from the environment in order to complement the battery energy storage or even replace it. The process by which energy from the physical environment is captured and converted into usable electrical energy is called energy harvesting. Table 6 shows some of the potential ambient sources, their corresponding energy densities, and some of the current challenges associated with each source [25]. The most common, for which promising results have already been achieved, is the extraction of power from the following sources:

(i) light energy: captured from sunlight or room light via photo sensors, or solar panels,

(ii) mechanical vibrations: from sources such as car engine compartment, trains, ships, helicopters, bridges, floors (offices, train stations, nightclubs), speakers, window panes, walls, household appliances (fridges, washing machines, microwave ovens), pumps, motors, compressors, chillers, conveyors). Table 7 shows the characteristics of some of the vibration sources,

(iii) thermal energy from furnaces, domestic radiators, human skin, vehicle exhausts, and friction sources,

(iv) radio frequency: microwaves, infrared, cell phones, and high power line emissions.

From Table 6, mechanical vibrations have a sufficiently high energy density and may potentially outperform solar harvesting systems in applications where embedded wireless sensor nodes are deployed indoors or overcast areas such as buildings, and forestry terrains, where access to direct sunlight is often not available, solar energy source may not be a suitable choice. In addition, vibrations are an attractive choice because they are one of the most prevalent sources of energy as they represent much of the "mechanical" category of energy source found in the environment. Mechanical vibrations are an energy source that is easily accessible through MEMS technology and is ubiquitous in applications at microscale level [2, 6, 26]. There are three main mechanisms by which vibrations can be converted into electrical energy: electromagnetic, electrostatic, and piezoelectric. Among them, piezoelectric vibration-to-electricity converters have received much attention, as they have high electromechanical coupling and no external voltage source requirement, and they are particularly attractive for use in MEMS [26–28]. Energy harvesting using piezoelectric materials allows for a device that is self-contained, that is, does not require any external supporting accruements. Furthermore, piezoelectric energy harvesting devices have a minimum of moving parts and are capable of generating power with voltage levels that can be easily conditioned (e.g., converted to DC or boosted) [2, 26, 29].

Table 6: Power densities of typical ambient energy sources.

Energy source	Characteristics	Efficiency	Power density	Comments/challenges
Light	Outdoor Indoor	10–25%	100 mW/cm^2 100 μW/cm^2	While solar energy is harvesting is an established technology, aiming for small-scale harvesters is difficult because power output directly linked to surface area. For design of embedded wireless sensor nodes to be deployed indoors or overcast areas such as buildings, and forestry terrains, where access to direct sunlight is often not available, solar energy source may not be a suitable choice.
Thermal	Human Industrial	0.1% 3%	60 μW/cm^2 10 mW/cm^2	Electric current is generated when there is a temperature difference between two junctions of a conducting material (called the Seebeck effect). Thermal energy harvesting uses temperature differences or gradients to generate electricity. Efficiency of conversion is limited by the Carnot efficiency. The efficiency of thermoelectric generators is typically less than 1% for temperature gradient less than 40°C and it is hard to find such temperature gradient in the normal ambient environment.
Vibration	Hz-human kHz-machines	25–50%	4 μW/cm^2 800 μW/cm^2	Energy from vibrations can be extracted using a suitable mechanical-to-electrical energy converter or generator. Generators proposed to date use electromagnetic, electrostatic, or piezoelectric principles. Vibration energy harvesting is highly dependent on excitation (power tends to be proportional to the driving frequency and the input displacement).
Radio frequency	GSM 900 MHz WiFi 2.4 GHz	50%	0.1 μW/cm^2 0.001 μW/cm^2	Without a dedicated radiating source, ambient levels are very low and are spread over a wide spectrum. There is a limit to the amount of power available for harvesting since the IEEE 802.11 standard prescribes the maximum allowable transmission power allowable (1000 mW in the USA, 100 mW in Europe, and 10 mW/MHz in Japan).

Table 7: Some vibration sources and acceleration magnitude and frequency of fundamental vibration from [61].

Vibration sources	Peak acceleration (m/s^2)	Frequency of peak (Hz)
Car engine compartment	12	200
Small microwave oven	2.5	121
HVAC vents in office building	0.2–1.5	60
Windows next to a busy road	0.7	100
Notebook computer while CD is being read	0.6	75
Second story floor of busy office	0.2	100

3. Piezoelectric Energy Harvesting from Vibrations

3.1. Piezoelectric Materials. Piezoelectricity stems from the Greek word "piezo" for pressure and the word "electric" for electricity. When a force or stress is applied to a piezoelectric material, it leads to an electric charge being induced across the material. This is known as the direct piezoelectric effect. Conversely, the application of a charge or electric field to the same material will result in a change in strain or mechanical deformation. This is known as the indirect piezoelectric effect. It is the direct piezoelectric effect that is employed in energy harvesting. Examples of ceramics which exhibit the piezoelectric effect are lead-zirconate-titanate (PZT), lead-titanate ($PbTiO_2$), lead-zirconate ($PbZrO_3$), and barium-titanate ($BaTiO_3$). To date, the most commonly used piezoelectric ceramic is PZT mainly because it has very high electromechanical coupling ability. However, PZT is an extremely brittle material and hence this presents limitations to the strain that it can safely withstand without being damaged [26, 27]. Polyvinylidenefluoride (PVDF) is another common piezoelectric polymer which is more flexible and can be employed in energy harvesting applications [27].

Research in nanoscience has outputted novel piezoelectric material systems used to fabricate next generation nanogenerators employed in energy harvesting technology. The notable work of Wang and Song introduced piezoelectric nanogeneration using a single zinc oxide (ZnO) nanowire by atomic microscopy [30]. Since then, piezoelectric semiconductor materials such as ZnO [31–33], indium nitride (InN) [34, 35] gallium nitride (GaN) [36], and zinc sulphide (ZnS) [37], and piezoelectric insulator materials, such as PVDF [38], BaTiO3 [39] and PZT [40], have been studied for potential electrical power generation.

3.2. Piezoelectric MEMS Generator System. In piezoelectric energy harvesting from vibration, a mass is suspended by a beam, with a piezoelectric layer on top of the beam. When the mass vibrates, the piezoelectric lever is mechanically deformed and a voltage is generated. The most common energy harvesting systems are cantilever structures that are mainly designed to operate at their resonance frequencies. Such structures (unimorph or bimorph cantilevers) are popular because they enable relatively high stress levels on the piezoelectric material while minimizing the dimensions of the devices [1, 2, 26, 28]. Figure 3 shows such a system composed of a piezoelectric patch which is bonded to the host cantilever beam surface, which is under alternating

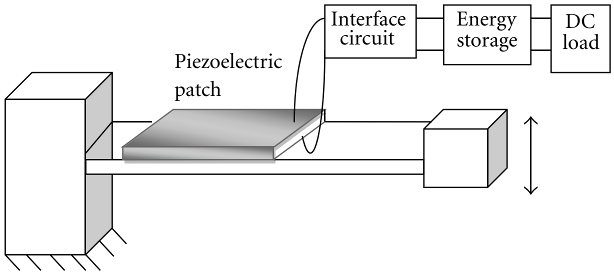


FIGURE 3: Typical piezoelectric energy harvesting system [28].

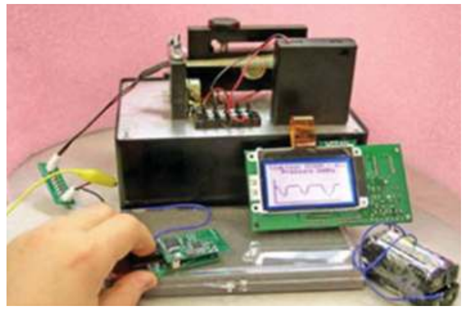


FIGURE 4: Prototype piezoelectric energy harvesting system powering a pressure sensor-developed at Clarkson University.

deformation. When the beam is excited by mechanical vibration in the host structure, a large strain is induced in the piezoelectric material and an alternating voltage (AC) is generated between the electrodes. The AC voltage is then conditioned by interface circuits for proper delivery of the harvested energy to a storage element or compatibility with load specifications. Nonlinear interface circuits are the latest state of the art conditioning circuits employed to enhance the output power [29]. Figure 4 shows a prototype device made at Clarkson University [41]. A summary of MEMS energy harvesters is given in Table 8.

3.3. Piezoelectric Nanogenerator System. The ground breaking work by Zhong L. Wang and his Nano Research Group at the Georgia Institute of Technology, USA, has greatly influenced the current research efforts in the conversion of nanoscale mechanical energy into usable electrical energy using nanogenerators. In their original paper Wang and Song first introduced piezoelectric nanogeneration by examining the piezoelectric properties of a single ZnO nanowire (NW) by atomic force microscopy in 2006 [30].

The insulating properties of piezoelectric insulator materials do not permit carrier transport from metal electrodes into the insulating active materials. As a result, the nanogenerators fabricated from these materials produce alternating (AC) power. On the other hand, the power generation mechanisms of nanogenerators fabricated from piezoelectric semiconductor materials produce both AC and direct power (DC). The coupled semiconducting and piezoelectric properties are in essence responsible for the DC and AC power, respectively. When piezoelectric semiconducting nanowires are subjected to an external force perpendicular to the nanowires, a piezoelectric potential is generated along the nanowires owing to the relative displacement of cations with respect to anion under uniaxial strain [42]. DC power from the nanogenerators is attributed to the force exerted perpendicular to the axis of superconducting nanowires; as a result, the nanowires bend laterally [43]. The generation of direct current (DC) from piezoelectric semiconductor nanomaterials is attributed to the force exerted perpendicular to the axis of the semiconducting nanowire—typically by subjecting a vertically grown nanowire to the laterally moving tip. When a nanowire is subjected to an external force by the moving tip, deformation occurs throughout the nanowire and an electric field is created inside the nanostructure due to the piezoelectric effect. A piezoelectric potential is generated along the width of NW owing to the relative displacement of the cations with respect to anions. The stretched part with the positive strain will exhibit a positive electrical potential, whereas the compressed part with the negative strain will show a negative electrical potential. As a result, the tip of the NW will have an electrical potential distribution on its surface, whereas the bottom of the NW is neutralized because it is grounded. The maximum voltage generated in the NW can be calculated using the following equation [44, 45]:

$$V_{\max} = \pm \frac{3}{4(k_o + k)} \left[e_{33} - 2(1+\nu)e_{15} - 2\nu e_{31}\right] \frac{a^3}{l^3} v_{\max}, \quad (3)$$

where k_0 is the permittivity in a vacuum, k is the dielectric constant, e_{33}, e_{15}, and e_{31} are the piezoelectric coefficients, ν is the Poisson ratio, a is the radius of the NW, l is the length of the NW and $v_{\max}$ is the maximum deflection of the NW's tip.

The electrical contact plays a crucial in role pumping out charges on the surface of the tips. The effective Schottky contact must be formed between the counter electrode and the tip of the NW because the Ohmic contact will neutralize the electrical field generated at the tips. Owing to formation of the Schottky contact, the electrons will pass to the counter electrode from the surface of the tip when the counter electrode is in contact with the region of the negative potential and the current will be measured, whereas no current will be generated when it is in contact with the regions of a positive potential, resulting in the generation of the DC output [62]. This mechanism suggests that the rectifying characteristic of the Schottky barrier formed between the metal tip and the NW leads to generation of a DC voltage, the principle is shown in Figure 5. Wang et al. [62] introduced the first ZnO NW-based DC power nanogenerator that was driven by an ultrasonic wave with a frequency of 41 kHz. They used zigzag trenches as the top electrode to replace the atomic force microscopy (AFM) tip. This work formed the basic platform for optimizing and improving the performance of the nanogenerators by integrating them into layered structures. Since then, several vertical NWs integrated nanogenerators and lateral NWs-integrated nanogenerators were fabricated by integrating them into layered structures to improve their performance [46, 63–67].

Table 8: Summary of piezoelectric MEMS energy harvesting devices.

MEMS device description	Design/dimensions	Resonant frequency	Power output/voltage (reported)	Ref
AIN and PZT MEMS devices.	Piezoelectric generator located on top of a beam, piezoelectric layer sandwiched between top and bottom electrodes	300; 700 and 1000 Hz	1–100 μW	[68]
Energy harvesting MEMS device based on thin film PZT cantilevers,	Cantilever size: length = 13.5 mm, width = 9 mm, thickness = 192 μm	3 modes: 13.9; 21.9 and 48.5 kHz	2.4 V with 5.2 MΩ load, 1.01 μW	[69]
PZT-based MEMS with interdigital electrodes	Cantilever size: length = 3.000 μm, width = 1.500 μm, thickness = 22 μm	570–575 Hz	1.127 $V_{\text{p-p}}$, 0.123 μW	[70]
PZT harvesters and MEMS technology	Device packaged using two wafers	1.8 kHz	40 μW	[71]
Thin film PZT-based MEMS power generator array for vibration energy harvesting, operating in d_{31} mode	Cantilever size: 2.000–3.500 μm, width = 750–1.000 μm	226–234 Hz	3.98 μW; 3.93 V	[72]
Thick film PZT free standing energy harvester operating in d_{31} mode	Cantilever size: length = 13.5 mm, width = 9 mm, thickness = 192 μm	229 Hz	270 nW at 9.81 m/s^2; 130 V	[73]
Two layered PMNZT bender devices for micropower generation	Cantilever size: length = 10 mm, width = 10 mm	120 Hz	2.0 $V_{\text{p-p}}$ 0.5 mW	[74]
Laser machined piezoelectric cantilever devices for energy harvesting	10 cantilevers on both sides of ridge, 5 of them are placed with tip mass alternately:length = 5.74 mm, width = 4 mm	870 Hz	1.13 μW at 870 Hz through 288.5 kΩ, power density of 301.3 μW/cm^3	[75]
Multilayer unimorph PZT cantilever with micromachined Si proof mass based on SOI	Device volume (mass and beam)~0.7690 mm^3	183.8 Hz	0.32 μW with 16.0 kΩ load; power density of 416 μW/cm^3	[76]
High performance MEMS PZT thin film energy harvester based on d_{33} mode	800 × 100 μm^2 cantilever with 10 μm thickness, proof mass of 1000 × 1000 × 500 μm^3	528 Hz	1.1 μW with 2.2 MΩ load; 4.4 $V_{\text{p-p}}$ operating at vibration of 0.39 g. Power density 2.8 mWcm^{-3} g^{-1}	[77]
Piezoelectric energy harvesters based on Aluminum nitride (AIN)	Cantilever devices: length = 1.31 mm–2.10 mm, width = 3.0 mm–7.0 mm	200–1200 Hz	60 μW at 572 Hz, 2 g vibration level.	[78]

A summary of piezoelectric nanogenerators and their demonstrated capabilities as power sources is presented in Tables 9 and 10, respectively.

3.4. Comparison of Conventional Microgenerators and Nanogenerators. A simple nanogenerator is principally a nanowire which is a one-dimensional nanomaterial that has a typical diameter less than 100 nm and a length of 1 μm (see Figures 5, 6 and 7.) The majority of ceramic nanowires are in fact single crystal materials. Compared to the conventional ceramic/thin film-based piezoelectric cantilever energy harvesting devices, nanogenerators offer three distinct advantages as reported by Wang [46] as follows.

(1) *Enhanced Piezoelectric Effect*. When a strain gradient is experienced by a ferroelectric nanowire, 400–500% enhancement of the piezoelectric effect can be achieved.

(2) *Superior Mechanical Properties*. The lattice perfection of nanowires enables much larger critical strain, higher flexibility, and longer operational lifetime [42, 47]-compared to conventional ceramic microgenerators [44, 48].

(3) *High Sensitivity to Small Forces*. Large aspect ratio and small thickness allow the creation of significant strain in the nanowires under a force at the nanonewton or piconewton level.

4. Energy Harvesting and WSN Operation: Challenges and Opportunities

4.1. Energy Harvesting and Wireless Sensor Nodes Operation. Ambient mechanical vibrations are harvested and converted to useful electrical energy which is either stored in a storage element or is supplied directly to the load. Energy storage is a key element of the energy harvesting system because it is a bridge of stability between the energy source and the load that provides a constant energy flow from an otherwise variable environmental source. The power interface circuits condition the harvested energy to enable the charging of low capacitor batteries or supercapacitors and also provide compatibility with the load requirements. For a sensor node

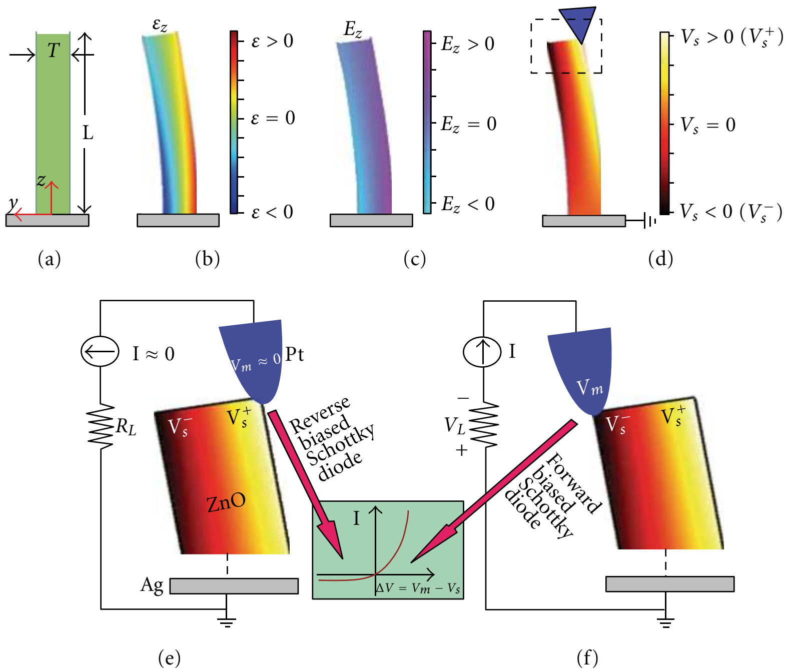


Figure 5: (a) Schematic definition of an NW and the coordination system. (b) Longitudinal strain ε_z distribution in the NW after being deflected by an atomic force microscopy (AFM) tip from the side. (c) The corresponding longitudinal piezoelectric-induced electric field Ez distribution in the NW. (d) Potential distribution in the NW as a result of the piezoelectric effect. (e and f) contacts between the AFM tip and the semiconductor ZnO NW (boxed area in (d)) at two reversed local contact potentials, showing reverse- and forward-biased Schottky rectifying behavior, respectively. This oppositely biased Schottky barrier across the NW preserves the PZ charges and later produces the discharge output. The inset shows a typical current-voltage (I-V) relation characteristic of a metal-semiconductor (n-type) Schottky barrier. The process in (e) is to separate and maintain the charges as well as build up the potential. The process in (f) is to discharge the potential and generate electric current [62].

Table 9: Summary of piezoelectric nanogenerators*.

	Output Performance					
Key material attributes	Generator type and dimensions (length × diameter)	Voltage	Current	Current density	Power or power density	Reference
n-ZnO synthesized by PVD. Eg: 3.37 eV; EA: 2.15 eV	AC type 50 μm × 200 μm	2.03 V	107 nA	—	11 mW/cm^3	[31]
n-ZnO synthesised by solution growth. Eg 3.37 eV; EA: 4.35 eV	DC type 2 μm × 100 nm	—	—	2 μA/cm^2	—	[32]
n-ZnO synthesised by CVD. Eg: 3.37 eV; EA: 4.35 eV	DC type 3 μm × 90 nm	20 mV		0.5 μA/cm^2	—	[33]
InN by use of VLS. Eg: 0.7–0.9 eV; EA: 5.8 eV	DC type 5 μm × 25–100 nm	1.0 V	—	—	—	[35]
GaN synthesised by CVD. Eg: 3.4 eV; EA: 4.1 eV	DC type 10–20 μm × 25–70 nm	20 mV	—	—	—	[36]
PVDF synthesised by E-SP. Eg: 9.23 eV: EA: −0.53 eV	Ac type 6.5 μm × 500 nm	5–30 mV	0.5–3 nA			[38]
PZT synthesised HT process. Eg: 2.4 eV; EA: 2.15 eV	AC type 5 μm × 500 nm	0.7 V	—	4 μA/cm^2	2.8 mW/cm^3	[40]
$BaTiO_3$ synthesised by HTCR growth. Eg: 3.3 eV; EA: 2.90 eV	AC type 15 μm × 280 nm	25 mV	—	—	—	[79]

*PVC: physical vapour deposition, CVD: chemical vapour deposition, E-SP: electro-spinning process, HT: hydrothermal, HTCR: high temperature chemical reaction, Eg: energy gap, EA: electron affinity, and "—" = not stated.

Table 10: Summary of some promising and demonstrated capabilities of nanogenerators (NGs).

Demonstrated capabilities of nanogenerators	Reference
(1) Flexible high output nanogenerator based on lateral ZnO array successfully lights a commercial LED	[31]
(2) A vertically integrated ZnO-based nanowire generator successfully powered pH and UV nanosensors, a self-powered nanowire system	[80]
(3) A high output nanogenerator managed to drive a small liquid crystal display (LCD), indicating a possibility of driving flexible displays	[81]
(4) Air/liquid-pressure and heartbeat-driven flexible fiber nanogenerators as a micro/nano-power source or diagnostic sensor have been successfully demonstrated	[82]
(5) Self-powered system with wireless data transmission—a system composed of integration of an NG, power conditioning electronics, sensor, and RF data transmitter. Wireless signals sent out by the system were detected by a commercial radio at a distance of 5–10 m. This opens potential application in wireless biosensing, environmental/infrastructure monitoring, sensor networks	[83]
(6) Self-powered environmental sensor system driven by nanogenerators, such a system is made of a ZnO nanowire-based nanogenerator, a rectification circuit, a capacitor for charge storage, a signal transmission LED light, and a carbon nanotube-based Hg^{2+} ion sensor. It is the first demonstration of a nanomaterial-based, self-powered sensor system for detecting a toxic pollutant	[84]
(7) Replacing a battery by a nanogenerator with 20 V output managed to drive a commercial buck convertor board, and a regulated voltage of 1.8 V with constant current load was achieved to drive an electrical watch for more than 1 minute after the board was charged by the NG with 1000 cycles of deformation. This is the first time that an NG works as a battery part for real commercial consumer electronics.	[85]

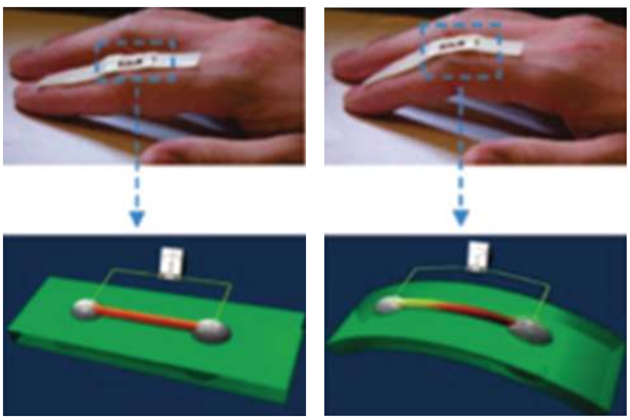


Figure 6: Energy harvesting from an oscillating human index finger using ZnO single wire generators [67].

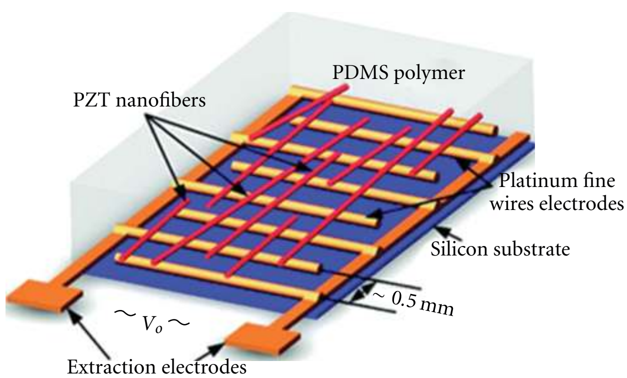


Figure 7: Concept and power generation of the PZT nanofiber generator [47].

fully powered by ambient energy, the generated mean power ($\overline{P}_g$) must be greater than or equal to the mean consumed power ($\overline{P}_c$) [49]:

$$\overline{P}_g \geq \overline{P}_c. \quad (4)$$

As noted earlier in Section 2.1, the power consumed by a wireless sensor node is typically a few tens to hundreds of milliwatts. Compared to the power output of MEMS piezoelectric energy harvesters such as shown in Table 8 and nanogenerators in Table 9 which have a range of a microwatt to tens of microwatts, it is quite evident that energy harvesting is not able to power the sensor node continuously.

The key question is how can the power consumption of the wireless sensor node be reduced so that energy harvesting can handle the supply requirements? The answer to the question is practically realized by what is called *duty cycling*, which allows the sensor to operate in an intermittent regime instead of a continuous form. In the duty cycling approach, wireless sensor nodes are designed to operate in a very low duty cycle (D), with moderate power consumption in active mode (P_{active}), and very low power consumption while in sleep (or idle) mode, (P_{sleep}). The intermittent operation of the sensor node is designed in such a way that the monitoring process of the WSN is not compromised [3]. The average power consumed by the sensor node is given by (2)

$$\overline{P_c} = P_{\text{sleep}} + DP_{\text{active}}. \quad (5)$$

From (4) and (5) it can be observed that if the duty-cycle (D) is made small, the sensor node is put to the sleep mode most of the time and it is activated to perform sensing and communication when needed. This results in a great reduction in the average power consumption of the wireless sensor node. Thus, for a given application requirement and characteristic of energy harvesting source, careful choice of the appropriate duty cycle is critical in designing power management algorithms. Ambient energy source like vibrations are variable in nature and there are times and situations when $\overline{P}_g < \overline{P}_c$. To address such a situation, a storage element such as a supercapacitor or a thin film battery is needed. For any arbitrary long period of time, T, a long-term storage (E_{storage}) element must be designed to fulfill the condition of [49]

$$E_{\text{storage}} \geq \max \int \left(P_c - P_g\right) dt. \tag{6}$$

Since WSNs operate on a strict power budget, ultralow power microcontroller units (MCUs) are required for processing and power management. A typical MCU like the Texas instruments MSP430 is ideal for energy harvesting since it has a low standby current of less than 1 μA and low active current 160 μA/MHz, and quick wakeup time of less than 1 μs, and operate on the range 1.8 V to 3.6 V [50]. The development of advanced power management techniques, together with ultra-low power MCU and novel storage elements, is likely to result in self-sustained embedded and wireless sensor networks.

4.2. Duty Cycling and Advanced Power Management Techniques. As discussed earlier in sections, most embedded sensor systems support sleeping modes, making a direct approach to duty cycling an attractive choice to power management. This direct implementation of the duty cycling technique, though popular in energy harvesting for wireless sensor networks, is not always the best choice [51–54]. Other than being a too simplistic approach, a fixed duty cycle implies that if the energy source is supplying more energy than is being consumed, the system will waste excess energy once the storage reservoir is fully charged. To get over some of these challenges, advanced power management techniques with strict hardware specifications have been proposed. These techniques are dynamic voltage scaling (DVS), dynamic frequency scaling (DFS), and a combination of DVS and DFS.

The operation principle of DVS technique is that increasing a circuit's voltage allows it to switch faster, but with an increase in energy consumption, and conversely the decrease in circuit voltage causes the circuit to have a low switching time with an accompanied decrease in energy consumption [55, 56]. A similar phenomenon is observed when the clock frequency is increased or decreased and is the basic premise of the DFS technique. Unlike duty cycling where all tasks stop during the sleeping mode, the advanced power management techniques allow the system to keep running at a low pace and with reduced energy consumption, without compromising the execution of important tasks [1, 56, 57]. Besides DBS, DFS, and duty cycling, the maximum power point tracking (MPPT) technique may be applied in the energy harvesting system. In the MPPT technique, the object is to transfer maximum power to the load. This technique is traditionally used in solar systems which have a dynamic voltage-current characteristic where the optimal load for maximum power depends on the operating point. The technique requires constant monitoring of incoming energy, to determine the optimal operating point, and an adaptive load.

4.3. Fundamental Material Issues. The performance of a piezoelectric energy harvesting systems primarily depends on the piezoelectric properties used to fabricate the generators. Generally, thin film piezoelectric materials show better piezoelectric properties compared to bulk piezoelectric materials. The use of single crystals and nanomaterials (nanowires) has, in principle, improved the power density and energy conversion efficiency hence the advance the miniaturization of device size while maintaining a reasonable power output. Despite great research efforts on these nanomaterials, there is lack of fundamental scientific understanding of and experimental research on piezoelectric and flexoelectric effects in single crystalline nanowires. This lag in research at this fundamental level compromises fidelity of the mathematical algorithms used in modeling and predicting the piezoelectric potential, mechanical to electrical energy conversion efficiency and device material optimization.

The other challenge relates to the coupling of piezoelectric and semiconducting effect—resulting in the so-called piezotronic effect. The scientific understanding of the interaction of electron distribution and semiconductor band structures requires additional research efforts. The research will potentially present an opportunity to facilitate in situ rectification of the potential output by making use of the Schottky barrier formed between ZnO and metal electrodes. While single crystal materials offer better piezoelectric performance and give better power density compared to their bulk material counterparts, costs of these materials are still very high and at times very inhibitive. The current fabrication methods and the associated device integration techniques at nanoscale are not yet suited for large scale processing, and research efforts along this line will substantially reduce fabrication costs and help translate piezoelectric energy harvesting from mere experimental curiosity into real engineered device realisations to power wireless sensors.

4.4. Design and Power Management Issues. The design of piezoelectric micropower generators and nanogenerators is in itself a multidisciplinary area with challenges based in fundamental physics, material science, mechanical engineering, and electrical engineering. Different researchers from different discipline and background have reported several researches in the area of piezoelectric energy harvesting. The multidisciplinary approach and a holistic paradigm is perhaps the most promising way of designing piezoelectric energy harvesting device.

As can be observed from the review, there is still a need to improve the power output of piezoelectric generators to match the requirements of wireless sensor devices. This challenge can be addressed by using piezoelectric material with the best piezoelectric properties, the best device geometries, and the best power electronics to condition and manage the power output. This is arguably calls for a holistic design and optimization regime, together with an established international metrology standard of piezoelectric energy harvesting (which currently does not exist). Latest advances in synchronised switching techniques have been reported as the latest achievements in power conditioning interface circuits to date [29, 48]. Further research and intergation of efficient interface circuits, advances in power conditioning power management techniques and development in ultralow power wireless microcontroller units will greatly drive energy harvesting technology to heights never envisaged before.

5. Conclusion

Vibration energy harvesting using piezoelectric generators was discussed and its potential as an alternative energy source for wireless sensor devices overviewed. The maturity of piezoelectric energy harvesting as technology entails that WSNs are energy efficient and their dependence on batteries is limited. With advancement in ultralow microelectronics and ultra-low power wireless microcontroller units, power consumption of sensor nodes is getting lower and hence the harvested ambient energy may be sufficient to eliminate batteries completely. In addition, piezoelectric nanogenerators open new avenues for ambient power harvesting through foldable power options and miniaturization of power packages thus enabling implantable medical sensing capabilities. Energy harvesting using piezoelectric generators is an attractive alternative energy source that has the potential to provide energy autonomy to wireless sensor devices.

References

[1] G. K. Ottman, H. F. Hofmann, A. C. Bhatt, and G. A. Lesieutre, "Adaptive piezoelectric energy harvesting circuit for wireless remote power supply," *IEEE Transactions on Power Electronics*, vol. 17, no. 5, pp. 669–676, 2002.

[2] S. Roundy, P. K. Wright, and J. Rabaey, "A study of low level vibrations as a power source for wireless sensor nodes," *Computer Communications*, vol. 26, no. 11, pp. 1131–1144, 2003.

[3] X. Jiang, J. Polastre, and D. Culler, "Perpetual environmentally powered sensor networks," in *Proceedings of the 4th International Symposium on Information Processing in Sensor Networks (IPSN '05)*, pp. 463–468, April 2005.

[4] D. Christin, P. S. Mogre, and M. Hollick, "Survey on wireless sensor network technologies for industrial automation: the security and quality of service perspectives," *Future Internet*, vol. 2, no. 2, pp. 96–125, 2010.

[5] J. Chen, X. Cao, P. Cheng, Y. Xiao, and Y. Sun, "Distributed collaborative control for industrial automation with wireless sensor and actuator networks," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 12, pp. 4219–4230, 2010.

[6] G. Park, T. Rosing, M. D. Todd, C. R. Farrar, and W. Hodgkiss, "Energy harvesting for structural health monitoring sensor networks," *Journal of Infrastructure Systems*, vol. 14, no. 1, pp. 64–79, 2008.

[7] J. Ko, C. Lu, M. B. Srivastava, J. A. Stankovic, A. Terzis, and M. Welsh, "Wireless sensor networks for healthcare," *Proceedings of the IEEE*, vol. 98, no. 11, pp. 1947–1960, 2010.

[8] L. R. Garcia, L. Lunadei, P. Barreiro, and J. I. Robla, "A review of wireless sensor technologies and applications in agriculture and food industry: state of the art and current trends," *Sensors*, vol. 9, no. 6, pp. 4728–4750, 2009.

[9] W. H. Liao, D. H. Wang, and S. L. Huang, "Wireless monitoring of cable tension of cable-stayed bridges using PVDF piezoelectric films," *Journal of Intelligent Material Systems and Structures*, vol. 12, no. 5, pp. 331–339, 2001.

[10] L. Chalard, D. Helal, L Verbaere, A. Wellig, and J. Zory, "Wireless sensor networks devices: overview, issues, state-of-the-art and promising technologies," *ST Journal of Research*, vol. 4, no. 1, pp. 4–8, 2007.

[11] F. G. Carlos, H. I. Pablo, G. H. Joaquin., and A. P. Jesus, "Wireless sensor networks and applications: a survey," *International Journal of Computer Science and Network Security*, vol. 7, no. 3, 2007.

[12] P. X. Gao, J. Song, J. Liu, and Z. L. Wang, "Nanowire piezoelectric nanogenerators on plastic substrates as flexible power sources for nanodevices," *Advanced Materials*, vol. 19, no. 1, pp. 67–72, 2007.

[13] C. Sun, J. Shi, and X. Wang, "Fundamental study of mechanical energy harvesting using piezoelectric nanostructures," *Journal of Applied Physics*, vol. 108, no. 3, Article ID 034309, 2010.

[14] V. Raghunathan, C. Schurgers, S. Park, and M. B. Srivastava, "Energy-aware wireless microsensor networks," *IEEE Signal Processing Magazine*, vol. 19, no. 2, pp. 40–50, 2002.

[15] Application Note 43, Maxim Corporation, "12-Bit Sampling A/D converter conserves power, July," 1998, http://notes-application.abcelectronique.com/003/3-3801.pdf.

[16] C. Alippi, G. Anastasi, M. Di Francesco, and M. Roveri, "Energy management in wireless sensor networks with energy-hungry sensors," *IEEE Instrumentation and Measurement Magazine*, vol. 12, no. 2, pp. 16–23, 2009.

[17] C. O. Mathúna, T. O'Donnell, R. V. Martinez-Catala, J. Rohan, and B. O'Flynn, "Energy scavenging for long-term deployable wireless sensor networks," *Talanta*, vol. 75, no. 3, pp. 613–623, 2008.

[18] V. Gutnik and A. P. Chandrakasan, "Embedded power supply for low-power DSP," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, vol. 5, no. 4, pp. 425–435, 1997.

[19] C. Schurgers, V. Ragunathan, and M. Srivastava, "Power management for energy-aware communication systems," *ACM Transactions on Embedded Computing Systems*, vol. 2, no. 3, pp. 431–447, 2003.

[20] Chipcon Products from Texas Instruments, "CC2240/2.4 GHz IEEE 802.15.4/ZigBee-ready RF Transceiver data sheet," 2012, http://www.ti.com/lit/ds/symlink/cc2420.pdf.

[21] J. M. Gilbert and F. Balouchi, "Comparison of energy harvesting systems for wireless sensor networks," *International Journal of Automation and Computing*, vol. 5, no. 4, pp. 334–347, 2008.

[22] N. Correal and N. Patwari, "Wireless sensor networks: challenges and. opportunities," in *Proceedings of the MPRG/Virgina Tech Wireless Symposium on Wire-less Personal Communication*, pp. 1–9, Blacksburg, Va, USA, 2001.

[23] T. E. Starner, "Powerful change part 1: batteries and possible alternatives for the mobile market," *IEEE Pervasive Computing*, vol. 2, no. 4, pp. 86–88, 2003.

[24] R. Hahn and H. Reichl, "Batteries and power supplies for wearable and ubiquitous computing," in *Proceedings of the 3rd International Symposium on Wearable Computers*, pp. 168–169, San Francisco, Calif, USA, October 1999.

[25] A. Valenzuela, "Batteryless energy harvesting for embedded designs," 2009, http://www.embedded.com/218600144.

[26] S. R. Anton and H. A. Sodano, "A review of power harvesting using piezoelectric materials (2003-2006)," *Smart Materials and Structures*, vol. 16, no. 3, article R01, pp. R1–R21, 2007.

[27] H. A. Sodano, D. J. Inman, and G. Park, "Generation and storage of electricity from power harvesting devices," *Journal of Intelligent Material Systems and Structures*, vol. 16, no. 1, pp. 67–75, 2005.

[28] K. A. Cook-Chennault, N. Thambi, and A. M. Sastry, "Powering MEMS portable devices—a review of non-regenerative and regenerative power supply systems with special emphasis on piezoelectric energy harvesting systems," *Smart Materials and Structures*, vol. 17, no. 4, Article ID 043001, 2008.

[29] E. Lefeuvre, G. Sebald, D. Guyomar, M. Lallart, and C. Richard, "Materials, structures and power interfaces for efficient piezoelectric energy harvesting," *Journal of Electroceramics*, vol. 22, no. 1–3, pp. 171–179, 2009.

[30] Z. L. Wang and J. Song, "Piezoelectric nanogenerators based on zinc oxide nanowire arrays," *Science*, vol. 312, no. 5771, pp. 243–246, 2006.

[31] G. Zhu, R. Yang, S. Wang, and Z. L. Wang, "Flexible high-output nanogenerator based on lateral ZnO nanowire array," *Nano Letters*, vol. 10, no. 8, pp. 3151–3155, 2010.

[32] D. Choi, M. Y. Choi, W. M. Choi et al., "Fully rollable transparent nanogenerators based on graphene electrodes," *Advanced Materials*, vol. 22, no. 19, pp. 2187–2192, 2010.

[33] B. Kumar, K. Y. Lee, H.-K. Park, S. J. Chae, Y. H. Lee, and S.-W. Kim, "Controlled growth of semiconducting nanowire, nanoball, and hybrid nanostructures on grapheme for piezoelectric nanogenerators," *ACS Nano*, vol. 5, no. 5, 2011.

[34] Z. L. Wang, "Nanogenerators for self-powering nanosystems and piezotronics for smart MEMS/NEMS," in *Proceedings of the 24th IEEE International Conference on Micro Electro Mechanical Systems (MEMS '11)*, pp. 115–120, Cancum, Mexico, January 2011.

[35] C. T. Huang, J. Song, C. M. Tsai et al., "Single-InN-nanowire nanogenerator with upto 1 v output voltage," *Advanced Materials*, vol. 22, no. 36, pp. 4008–4013, 2010.

[36] C. T. Huang, J. Song, W. F. Lee et al., "GaN nanowire arrays for high-output nanogenerators," *Journal of the American Chemical Society*, vol. 132, no. 13, pp. 4766–4771, 2010.

[37] M. Y. Lu, J. Song, M. P. Lu, C. Y. Lee, L. J. Chen, and Z. L. Wang, "ZnO#ZnS heterojunction and ZnS nanowire arrays for electricity generation," *ACS Nano*, vol. 3, no. 2, pp. 357–362, 2009.

[38] C. Chang, V. H. Tran, J. Wang, Y. K. Fuh, and L. Lin, "Direct-write piezoelectric polymeric nanogenerator with high energy conversion efficiency," *Nano Letters*, vol. 10, no. 2, pp. 726–731, 2010.

[39] Z. Wang, J. Hu, A. P. Suryavanshi, K. Yum, and M.-F. Yu, "Voltage generation from individual $BaTiO_3$ nanowires under periodic tensile mechanical load," *Nano Letters*, vol. 7, no. 10, pp. 2966–2969, 2007.

[40] S. Xu, B. J. Hansen, and Z. L. Wang, "Piezoelectric-nanowire-enabled power source for driving wireless microelectronics," *Nature Communications*, vol. 1, no. 7, pp. 1–5, 2010.

[41] R. Bogue, "Energy harvesting and wireless sensors: a review of recent developments," *Sensor Review*, vol. 29, no. 3, pp. 194–199, 2009.

[42] B. Kumar and S.-W. Kim, "Recent advances in power generation through piezoelectric nanogenerators," *Journal of Materials Chemistry*, vol. 21, pp. 18946–18958, 2011.

[43] S. Xu, *Oxide nanowire arrays for energy sciences*, Ph.D. thesis, School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Ga, USA, 2010.

[44] Z. L. Wang, "Towards self-powered nanosystems: from nanogenerators to nanopiezotronics," *Advanced Functional Materials*, vol. 18, no. 22, pp. 3553–3567, 2008.

[45] Y. Gao and Z. L. Wang, "Electrostatic potential in a bent piezoelectric nanowire. The fundamental theory of nanogenerator and nanopiezotronics," *Nano Letters*, vol. 7, no. 8, pp. 2499–2505, 2007.

[46] X. D. Wang, "Piezoelectric nanogenerators—harvesting ambient mechanical energy at the nanometer scale," *Nano Energy*, vol. 1, no. 1, pp. 13–24, 2012.

[47] X. Chen, S. Xu, N. Yao, and Y. Shi, "1.6 v nanogenerator for mechanical energy harvesting using PZT nanofibers," *Nano Letters*, vol. 10, no. 6, pp. 2133–2137, 2010.

[48] D. Guyomar and M. Lallart, "Recent progress in piezoelectric conversion and energy harvesting using nonlinear electronic interfaces and issues in small scale implementation," *Micromachines Journal*, vol. 2, no. 2, pp. 274–294, 2011.

[49] Y. K. Tan and S. K. Panda, "Review of energy harvesting technologies for sustainable wireless sensor network in sustainable wireless sensor networks," http://cdn.intechopen.com/pdfs/12418/InTech-Review_of_energy_harvesting_technologies_for_sustainable_wsn.pdf.

[50] L. Bierl, Texas Instruments, MSP430 Family Mixed Signal Microcontroller Application Reports, Literature Number SLAA024, January 2000, http://www.ti.com/lit/an/slaa024/slaa024.pdf.

[51] C. Moser, L. Thiele, D. Brunelli, and L. Benini, "Adaptive power management for environmentally powered systems," *IEEE Transactions on Computers*, vol. 59, no. 4, pp. 478–491, 2010.

[52] C. M. Vigorito, D. Ganesan, and A. G. Barto, "Adaptive control of duty cycling in energy harvesting wireless sensor networks," in *Proceedings of the 4th Annual IEEE Communications Society conference on Sensor, Mesh and Ad Hoc Communication and Networks (SECON '07)*, pp. 21–30, San Diego, Calif, USA, June 2007.

[53] J. Hsu, S. Zahedi, A. Kansal, M. Srivastava, and V. Raghunathan, "Adaptive duty cycling for energy harvesting systems," in *Proceedings of the 11th ACM/IEEE International Symposium on Low Power Electronics and Design (ISLPED '06)*, pp. 180–185, Tegernsee, Germany, October 2006.

[54] A. Kansal, J. Hsu, M. Srivastava, and V. Raghunathan, "Harvesting aware power management for sensor networks," in *Proceedings of the 43rd ACM/IEEE Design Automation Conference*, pp. 651–656, San Francisco, Calif, USA, September 2006.

[55] T. Pering, T. Burd, and R. Brodersen, "Dyanamic voltage scaling and the design of a low-microprocessor system," in *Proceedings of the Proceedings of Power Driven Micro Architecture Workshop, in Conjunction with International Symposium on Computer Architecture*, pp. 107–112, Barcelona, Spain, June 1998.

[56] A. Sinha and A. Chandrakasan, "Dynamic power management in wireless sensor networks," *IEEE Design and Test of Computers*, vol. 18, no. 2, pp. 62–74, 2001.

[57] R. J. M. Vullers, R. van Schaijk, I. Doms, C. van Hoof, and R. Mertens, "Micropower energy harvesting," *Solid-State Electronics*, vol. 53, no. 7, pp. 684–693, 2009.

[58] Z. Zhu, S. Mekid, and R. Pietruzkiewics, "Architecture investigation of energy harvester for wireless sensor nodes," in *Proceedings of the 5th Virtual International Conference on Intelligent Production Machines and Systems*, Elsevier, Oxford, UK, 2008.

[59] http://www.tecnologico.deusto.es/projects/smartmotes/files/D2.1_SmartMotes_WSN_ComparativeAnalysis_v1.8.pdf.

[60] Jennic Ltd, "JN5139 Wireless Microcontroller (IEEE 802.15.4 and ZigBee)," 2010, http://www.jennic.com/products.

[61] S. Roundy and P. K. Wright, "A piezoelectric vibration based generator for wireless electronics," *Smart Materials and Structures*, vol. 13, pp. 1131–1142, 2004.

[62] X. Wang, J. Song, J. Liu, and L. W. Zhong, "Direct-current nanogenerator driven by ultrasonic waves," *Science*, vol. 316, no. 5821, pp. 102–105, 2007.

[63] J. Song, J. Zhou, and Z. L. Wang, "Piezoelectric and semiconducting coupled power generating process of a single ZnO belt/wire: a technology for harvesting electricity from the environment," *Nano Letters*, vol. 6, no. 8, pp. 1656–1662, 2006.

[64] R. Yang, Y. Qin, L. Dai, and Z. L. Wang, "Power generation with laterally packaged piezoelectric fine wires," *Nature Nanotechnology*, vol. 4, no. 1, pp. 34–39, 2009.

[65] S. Xu, Y. Wei, J. Liu, R. Yang, and Z. L. Wang, "Integrated multilayer nanogenerator fabricated using paired nanotip-to-nanowire brushes," *Nano Letters*, vol. 8, no. 11, pp. 4027–4032, 2008.

[66] R. Yang, Y. Qin, C. Li, L. Dai, and Z. L. Wang, "Characteristics of output voltage and current of integrated nanogenerators," *Applied Physics Letters*, vol. 94, no. 2, Article ID 022905, 2009.

[67] R. Yang, Y. Qin, C. Li, G. Zhu, and Z. L. Wang, "Converting biomechanical energy into electricity by a muscle-movement-driven nanogenerator," *Nano Letters*, vol. 9, no. 3, pp. 1201–1205, 2009.

[68] A. Schmitz, T. Sterken, M. Renaud, P. Fiorini, R. Puers, and C. van Hoof, "Piezoelectric scavengers in MEMS technology fabrication and simulation," in *Proceedings of the 5th International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS '05)*, pp. 61–64, Tokyo, Japan, November 2005.

[69] W. J. Choi, Y. Jeon, J. H. Jeong, R. Sood, and S. G. Kim, "Energy harvesting MEMS device based on thin film piezoelectric cantilevers," *Journal of Electroceramics*, vol. 17, no. 2–4, pp. 543–548, 2006.

[70] B. S. Lee, W. J. Wu, W. P. Shih, D. Vasic, and F. Costa, "Power harvesting using piezoelectric MEMS generator with interdigital electrodes," in *Proceedings of the IEEE Ultrasonics Symposium (IUS '07)*, pp. 1598–1601, New York, NY, USA, October 2007.

[71] M. Renaud, T. Sternen, A. Schmitz, p. Fiorini, C. van Hoof, and R. Puers, "Piezoelectric harvesters and MEMS technology: fabrication, modeling and measurements," in *Proceedings of the IEEE Transducers International Conference on Solid-State Sensors, Actuators and Microsystems*, pp. 891–894, September 2007, Lyon, France.

[72] J. Q. Liu, H. B. Fang, Z. Y. Xu et al., "A MEMS-based piezoelectric power generator array for vibration energy harvesting," *Microelectronics Journal*, vol. 39, no. 5, pp. 802–806, 2008.

[73] S. L. Kok, N. M. White, and N. R. Harris, "A free-standing, thick-film piezoelectric energy harvester," in *Proceedings of the IEEE Sensors Conference (SENSORS '08)*, pp. 589–592, Lecce, Italy, October 2009.

[74] S. J. Jeong, M. S. Kim, J. S. Song, and H. K. Lee, "Two-layered piezoelectric bender device for micro-power generator," *Sensors and Actuators A*, vol. 148, no. 1, pp. 158–167, 2008.

[75] H. Kim, V. Bedekar, R. A. Islam, W. H. Lee, D. Leo, and S. Priya, "Laser-machined piezoelectric cantilevers for mechanical energy harvesting," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 55, no. 9, pp. 1900–1905, 2008.

[76] D. Shen, J. H. Park, J. H. Noh et al., "Micromachined PZT cantilever based on SOI structure for low frequency vibration energy harvesting," *Sensors and Actuators A*, vol. 154, no. 1, pp. 103–108, 2009.

[77] J. C. Park, D. H. Lee, J. K. Park, Y. S. Chang, and Y. P. Lee, "High performance piezoelectric MEMS energy harvester based on d_{33} mode of PZT thin film on buffer with $PbTiO_3$ inter-layer," in *Proceedings of the IEEE Transducers 15th International Conference on Solid-State Sensors, Actuators and Microsystems*, pp. 517–520, Denver, Colo, USA, June 2009.

[78] R. Elfrink, T. M. Kamel, M. Goedbloed et al., "Vibration energy harvesting with aluminum nitride-based piezoelectric devices," *Journal of Micromechanics and Microengineering*, vol. 19, no. 9, Article ID 094005, 2009.

[79] K. I. Park, S. Xu, Y. Liu et al., "Piezoelectric $BaTiO_3$ thinfilm nanogenerator on plastic substrates," *Nano Letters*, vol. 10, no. 12, pp. 4939–4943, 2010.

[80] S. Xu, Y. Qin, C. Xu, Y. Wei, R. Yang, and Z. L. Wang, "Self-powerednanowire devices," *Nature Nanotechnology*, vol. 5, no. 5, pp. 366–373, 2010.

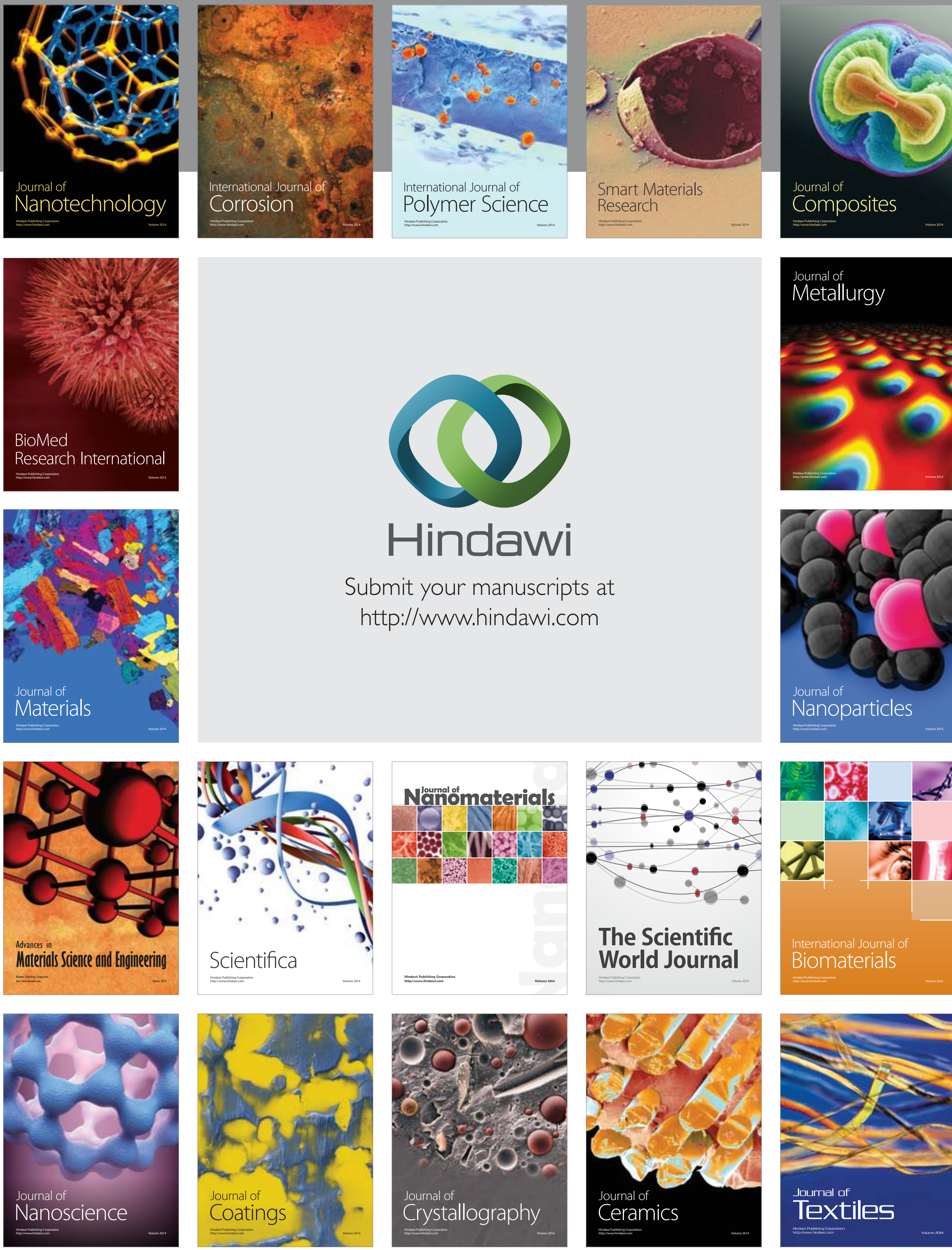
[81] Y. Hu, Y. Zhang, C. Xu, G. Zhu, and Z. L. Wang, "High-output nanogenerator by rational unipolar assembly of conical nanowires and its application for driving a small liquid crystal display," *Nano Letters*, vol. 10, no. 12, pp. 5025–5031, 2010.

[82] Z. Li and Z. L. Wang, "Air/liquid-pressure and heartbeat-driven flexible fiber nanogenerators as a micro/nano-power source or diagnostic sensor," *Advanced Materials*, vol. 23, no. 1, pp. 84–89, 2011.

[83] Y. Hu, Y. Zhang, C. Xu, L. Lin, R. L. Snyder, and Z. L. Wang, "Self-powered system with wireless data transmission," *Nano Letters*, vol. 11, no. 6, pp. 2572–2577, 2011.

[84] M. B. Lee, J. H. Bae, J. Y. Lee, C. S. Lee, S. H. Hong, and Z. L. Wang, "Self-powered environmental sensor system driven by nanogenerators," *Energy and Environmental Science*, vol. 4, pp. 3359–3363, 2011.

[85] Y. Hu, L. Lin, Y. Zhang, and Z. L. Wang, "Replacing battery by a nanogenerator with 20 V output," *Advanced Materials*, vol. 24, pp. 110–114, 2012.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