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Design and low cost fabrication of green vibration energy harvester

Suresh S. Balpande[a,*], Rajesh S. Pande[a], Rajendra M. Patrikar[b]

[a] Shri Ramdeobaba College of Engineering and Management (RCOEM), Nagpur, India
[b] Visveswaraya National Institute of Technology (VNIT), Nagpur, India

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ABSTRACT

The Energy harvesting (EH) technologies are receiving significant interest due to realization of 'zero-power' wireless sensors and Internet-of-Things (IoT). Power consumption of current milli-scale commercial node has an average consumption of 0.1–1000 μW which has made self powered sensor nodes a reality. Zinc oxide (ZnO) a green piezoelectric material has been spun in x-y plane and injected along z direction using syringe on flexible tapered beam of varying cross section. A energy harvester fabricated in this study consists of layers of PDMS/Ag/ZnO/Ag/PDMS where Ag(silver) fabric used as parallel plate electrodes and also extended for external interfaces. Wearable energy harvester is feasible due to use of biocompatible materials. The XRD results show that ZnO deposited has crystalline structure. The performance of the energy harvester is validated by numerical simulations and detail electrical characterization. The electrical characterization results show that measured power density of the device is 10 $\mu W/mm^3$. A comparison with prior published results of flexible EH shows that the device performance is very good with added advantage of biocompatibility. In addition, novel structure of vibration exciter using woofer diaphragm has been fabricated and deployed as vibration source during characterization.

1. Introduction

Energy scavenging devices have become important part of Wireless sensors nodes (WSN) or body area network (BAN). New standards of IOT i.e. Zigbee 3.0 [1] requires support for zero power devices, which can come only through energy scavenging devices. WSN are an integral part of biomedical implants, military monitoring devices, structure-embedded instrumentation, remote weather station, calculators, watches, Bluetooth headsets. IOT deploys millions of battery operated sensor nodes, but batteries are not reliable because of many issues including frequent maintenance, disposal of battery, short lifetime, bulky nature and need for regular replacement that does not gel with electronics used in IoT [2,3]. These limitations force us to think about long lasting, maintenance free green alternatives.

Energy harvesting is a viable solution which makes system perpetually powered. It is becoming omnipresent and finding their way into a variety of commercial field at a fast pace. Typically, the piezoelectric EH structure is a free beam clamped to anchor, with a piezoelectric thin layer deposited and optional tip mass to reduce the resonance frequency. Many energy harvesters are based on the principle of piezoelectricity in which vibration energy is converted into electrical energy, whenever surface stresses are generated by change in the equilibrium positions of the atoms near the surface. Parasitic energy available locally in industrial machines, human activity, vehicles, structures, and environment sources listed in Table 1, could be an excellent sources for capturing small amounts of power without affecting the source itself [4].

In addition to vibration energy, many researcher developed harvester to scavenge energy from one or more energy sources concurrently like solar, thermoelectric, wind energy or combinations like thermo-acoustic-piezoelectric, piezoelectric-electromagnetic, piezoelectric-thermoelectric. Energy harvester developed to scavenge energy from industrial waste heat generated by burning fossil fuel, which is usually released to the atmosphere. It is based on the principle of transduction from thermal to acoustic and acoustic to piezoelectricity [5,6]. A novel hybrid energy harvester integrated with piezoelectric-electromagnetic, piezoelectric-thermoelectric were designed to enhance the performance [7,8]. A wind flow has an advantage of being a continuous source of kinetic energy. Rectangular wings with a piezoelectric generator were fabricated to harvest the wind energy [9,10].

EH using silicon substrate, rectangular cantilever structure, lead zirconium Titanate (PZT) piezoelectric material have been reported by many researchers, which are not flexible,environment friendly

* Corresponding author.
E-mail addresses: ssbalpande@gmail.com (S.S. Balpande), panders@rknec.edu (R.S. Pande), rajendra@computer.org (R.M. Patrikar).

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Table 1
Vibration sources with peak acceleration and frequency.

Vibration sources	Peak acceleration (m/s$^{2)}$	Frequency of peak (Hz)
Car engine	12	200
Small microwave oven	2.5	121
HVAC vents	0.2–1.5	60
Blender	0.6	200
Washing Machine	0.5	90–110
Vacuum cleaner	0.158	80–100
Transformers	21.57	50–400

and biocompatible. Such devices cannot be stretched\twisted or placed on arbitrary surfaces because of rigid substrate and traditional metal electrodes.

In this work, ZnO has been employed due to biocompatibility, better piezoelectric coupling coefficient, low deposition temperature, excellent bonding, non ferroelectric material, good optical properties and environment friendly production of material [11–13]. It is also proved to be the most flexible material among all piezoelectric materials, which is appropriate for polymer substrates.

Conventional electrodes include metal plate, conductive ink, sputter deposited metal, thermal evaporated or spin coated metal composed of nickel, copper, gold or silver are prone to cracks upon bending or stretching of substrate [14]. In this work, fabric electrodes made up of textile materials as base material with conductive material coating was used. Mesh structure of conductive fibers is fabricated using regular textile processes including weaving, knitting, and embroidering. A silver fabric is breathable, foldable, washable, comfortable and also compatible with wearable medical devices [15]. The silver fabric electrodes are used as parallel plate electrodes and extended for external interfaces.

Commercial vibration setups, often called shakers are used for testing EH devices, which are designed to produce random or single frequency vibrations. In this work, the novel design of low cost woofer-based vibration exciter has been designed and fabricated.

Rest of the paper is organized as follows. Section 2 cover device designs and simulation, Section 3 encompasses material preparation and device fabrication, Section 4 present structural and electrical characterization, followed by conclusion in Section 5.

2. Device design

The energy harvesters (EH), which converts mechanical energy into electrical generally use the principle of piezoelectricity exhibited by natural and engineered piezoelectric materials like Rochelle salt,Quartz, PVDF, AlN, PZT, BaTiO3, ZnO, etc. It consists of a thin slab of piezoelectric material sandwiched between top and bottom electrodes. When piezoelectric material is placed under mechanical stress, a shifting of the positive and negative charge centers in the material takes place. This stress-dependent change in polarization manifests significant electric potential difference across the material referred as the direct piezoelectric effect. This phenomenon is described by the piezo- electric constitutive equations

$$\begin{aligned} S_i &= s_{ij}^E T_j + d_{li} E_l \\ D_m &= \varepsilon_{mn}^T E_n + d_{mk} T_k \end{aligned} \tag{1}$$

For i, j, k = 1,2...6 and l, m, n = 1,2,3. Where T is the applied mechanical stress,E is the applied electric field, d corresponds to piezoelectric strain, ε_{mn}^T is the permittivity under conditions of constant stress, D is the electric displacement, S is the mechanical strain and s_{ij}^E is the compliance tensor under conditions of constant electric field.

Typically, cantilever type piezoelectric harvester is rectangular in shape with or without a proof mass attached at the free end, which causes non-uniform stress distribution along the length and more stress concentration near the anchored end. Tapered beam used in this work results in a uniform stress distribution along the surface of the beam due to the constantly changing moment of inertia. This phenomena lowers maximums stresses, which results in improvement in coupling coefficient of the device. Numerical simulation study shows that tapered beam with varying cross section causes more deflection compared to rectangular structure, hence beam of trapezoidal profile has been chosen in this work to confirm the results experimentally.

In order to estimate deflection and safe spacing between cantilever and substrate, Stoney's equation for trapezoidal profile is referred

$$\Delta Z = \frac{8(1-\nu)\Delta\sigma l^2}{E(t_0 - t_1)^2}\left[\ln\left[\frac{t_o}{t_1}\right] + \frac{t_1}{t_0} - 1\right] \tag{2}$$

Where $\Delta\sigma$ surface stress, ν is Poisson's ratio, E is Young's Modulus, l is the cantilever's length and t_0, tl are the thicknesses of the cantilever at the clamped and free ends.

Energy harvesters are highly frequency dependant and thus computation of resonant frequency is very important. Upon finalizing applications and dimensions of cantilever, fundamental resonant frequency for a tapered beam was computed using Eq. (3). This is an iterative process in which length and thickness are varied in order to tune to desire fundamental resonant frequency.

$$f_0 = C\sqrt{\frac{k}{m}} \quad \text{Where} \quad C = c_1\sqrt{\frac{1}{c_2 c_3}} \tag{3}$$

Where m is cantilever mass, and c1, c2, c3 are tapering-ratio dependent mass distribution parameters for the cantilever, k is the spring constant which is a function of thickness of tapered profile at fixed and free end, length, young's modulus and angle of cross-sectional of shape of cantilever [16].

The deflection and frequency are computed with following procedure

Initial parameters for calculations are as follows.

a (width at free end) = 3 mm, b (width at fixed end) = 9 mm, length = 13 mm, Tapered beam thickness: t0(thickness at fixed end) = 500 μm, t1 (thickness at free end) = 300 μm, Average thickness = 400 μm, θ(angle between lower base and oblique side of tapered beam) = 76^0, Poisson's ratio(PDMS) = 0.5, Density(PDMS) = 965 Kg/m^3, E(PDMS) = 500 Kpa.

In order to simplify analytical calculations, piezoelectric layer of micrometer thickness is ignored and only PDMS substrate is considered while calculating deflection and resonant frequency. Volume of tapered beam can be computed by considering average thickness of PDMS followed by force calculations. Surface stress can be quantified by taking ratio of force F and width a = 3 mm. All the other parameters in Eq. (2) are known and hence deflection can be analytically calculated. Resonant frequency was calculated using Eq. (3) in which C and K are unknown. The parameter C can be computed directly using polynomial. Tapering-ratio dependent mass distribution parameters i.e. c1, c2, c3 can also be computed individually and then aggregated to C [17]. A method for calculation of spring constant K value included in flow chart as shown in Fig. 1 [18]. These studies were carried out to finalize device dimensions and geometry. The estimated analytical values of deflections and resonant frequency were 1.1 mm and 108 Hz respectively for geometrical parameters considered here.

A model of cantilever based EH has been built using above relations. EH is designed to harvest power from one of the source such as washing machines, vacuum cleaners, transformers, vehicle-machine vibrations and human motions which has fundamental resonant frequency closed to 100 Hz.