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W-217 PIEZOELECTRIC MICRO ENERGY HARVESTERS EMPLOYING ADVANCED (MG,ZR)-CODOPED ALN THIN FILM

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We report the new doped-AlN thin film, (Mg,Zr)AlN, based micro energy harvester. By co-doping Mg and Zr into AlN crystal, (Mg,Zr)AlN shows giant piezoelectricity and preserves low permittivity. (Mg,Zr)AlN has higher figure of merit (FOM=$e_{31}^2(\varepsilon_0\varepsilon)$)) than conventional PZT. The 13 at%-(Mg,Zr)AlN had the experimental FOM of up to 16.7 GPa. The micromachining harvester provided the high normalized power density of 3.72 $mW.g^{-2}.cm^{-3}$. This achievement was 1.5-fold increase compared to state of the art.

M-218 PULSE POLING WITHIN 1 SECOND ENHANCE THE PIEZOELECTRIC PROPERTY OF PZT THIN FILMS

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We present simple but fast poling technique to enhance the piezoelectric property of PZT thin films. Application of pulse voltage to the PZT thin films on MEMS microcantilevers has resulted in large piezoelectric constant (d31) as high as 105 pm/V. It took only 1 second for poling the PZT thin films.

Nanoscale Actuators and PowerMEMS

T-219 A BETAVOLTAIC MICROCELL BASED ON SEMICONDUCTING SINGLE-WALLED CARBON NANOTUBE ARRAYS/SI HETEROJUNCTIONS

M.G. Li and J. Zhang
Peking University, CHINA

This paper reports a novel betavoltaic microcell based on semiconducting single-walled carbon nanotubes (s-SWCNTs). The aligned arrays of p-type s-SWCNTs were prepared onto n-type silicon forming the p-n heterojunction as the energy conversion. This heterojunction displays good rectification characteristics with I_0=1.5pA and n=1.83. Under 7.8mCi/cm^2 ^{63}Ni irradiation, the microcell achieves higher performance of V_{OC}=62mV, J_{SC}=3.8μA/cm^2, FF=33.4% and η=9.8% compared with our previous devices.

Other Actuators and PowerMEMS

W-220 A MICROGRIPPER WITH A RATCHET SELF-LOCKING MECHANISM

Y.C. Hao, W.Z. Yuan, H.M. Zhang, and H.L. Chang
Northwestern Polytechnical University, CHINA

This paper reports a novel electrostatic actuated microgripper with a ratchet self-locking mechanism which enables the longtime gripping without continuously applying the external driving signal such as electrical, thermal or magnetic fields. This greatly reduces the influence and damage on the gripped micro objects induced by the external driving signals.

PowerMEMS Components and Systems

M-221 A HIGH-EFFICIENT BROADBAND ENERGY HARVESTER BASED ON NON-CONTACT COUPLING TECHNIQUE FOR AMBIENT VIBRATIONS

X. Wu and D.W. Lee
Chonnam National University, SOUTH KOREA

In this work, a high-efficient piezoelectric energy harvester based on non-contact coupling technique is proposed and characterized, which allows it, for the first time, to take advantage of multi-cantilevers and frequency-up conversion technique to enhance the power generation efficiency for ambient excitation. The unique energy harvester can effectively scavenge environmental vibration energy with a wide bandwidth. Aiming for high space efficiency, folded cantilevers are designed.

T-222 BIDIRECTIONAL THERMOELECTRIC ENERGY GENERATOR BASED ON A PHASE-CHANGE LENS FOR CONCENTRATING SOLAR POWER

M.S. Kim, M.K. Kim, H.R. Ahn, and Y.J. Kim
Yonsei University, SOUTH KOREA

This paper reports a bidirectional thermoelectric energy generator (TEG) with double type lenses for concentrating solar power. When solar power was applied to the TEG, solar energy is concentrated by PMMA lens firstly. The concentrated energy is absorbed as heat energy through phase-change of PCM. And then, the liquid PCM lens focuses energy on the TEG. After removing energy source, the latent heat in PCM is released. Therefore, the proposed TEG generates energy steadily.

W-223 BIOTEMPLATED HIERARCHICAL NICKEL OXIDE SUPERCAPACITOR ELECTRODES

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University of Maryland, College Park, USA

We present hierarchical Ni/NiO supercapacitor electrodes utilizing Tobacco mosaic virus (TMV) as bio-nanotemplates. The hierarchical electrodes were fabricated by integrating high aspect ratio silicon micropillars with thermally oxidized nickel-coated TMVs. An ultra-high areal capacitance of 585.9mF/cm2 was achieved with hierarchical Ni/NiO electrodes, exceeding the capacitance of nanostructured only and planar Ni/NiO by a factor of 3.4 and 29.7, respectively.

A HIGH-EFFICIENT BROADBAND ENERGY HARVESTER BASED ON NON-CONTACT COUPLING TECHNIQUE FOR AMBIENT VIBRATIONS

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ABSTRACT

In this paper, a high-efficient piezoelectric energy harvester based on non-contact coupling technique is proposed and characterized, which allows it, for the first time, to take advantage of multi-cantilevers and frequency up-conversion technique to enhance the power generation efficiency for ambient excitation. The unique energy harvester can effectively scavenge environmental vibration energy with a wide bandwidth. Aiming for high space efficiency and less installation constrains, folded cantilevers are designed for this energy harvester. With a load resistance of 50 kΩ, a maximum output power of 18.45 μW is achieved with the fabricated energy harvester, which is a suitable power supply for the sensor nodes in WSN applications.

INTRODUCTION

With the increasing demand of real-time information communication in the modern world, wireless sensor networks (WSNs) technology plays a key role in the information era [1]. To avoid the extremely large maintenance cost and inconvenience caused by the limited life of batteries employed in commercial WSNs, various energy harvesters have been developed as substitutes, which can scavenge unlimited ambient energy for powering the sensor nodes in WSNs [2, 3].

Among many options, considering its sufficiency as a power source and its potential for miniaturization, piezoelectric energy harvesting has been regarded as an alternative way to replace the battery used for WSN applications [4]. However, since the ambient vibration often lies around a broad low frequency range, i.e., in the range of 0-40 Hz, the high resonant frequency (~hundreds or thousands of Hertz) of many vibration energy harvesters leads to inefficient power generation owing to the frequency mismatching [5]. To overcome the frequency gap between the environment and energy harvesters, frequency up-conversion technique is proposed and applied on the energy harvesters [6, 7]. Unfortunately, the performance of this type of energy harvester relies too heavily on the driving element, which is designed for harvesting ambient low frequency vibration. Being subjected to the narrow bandwidth of the driving part, the power generation efficiency will be confined under the broad vibration range in our environment. On the other hand, the physical impact during operation in this technique reduces the reliability and service life of the device. Aiming for a wide bandwidth to match the environmental vibration, energy harvesters combining numbers of piezoelectric cantilevers with various resonant frequencies are developed [8, 9]. However, for such a multi-cantilever (or cantilever array) based energy harvester, not only will the narrow response bandwidth of each cantilever restrict the total frequency range of the device, but the increasing number of cantilevers also make a drawback in the space efficiency. Moreover, the frequency selecting mechanism (only one cantilever can achieve the resonance for each excitation frequency) leads to low power generation efficiency when under a wide frequency range of excitation.

In this work, a high-efficient energy harvester based on non-contact coupling technique is proposed, which can realize a broadband under real environmental vibrations. The energy harvester takes advantage of the frequency up-conversion technique and multi-cantilevers to enhance the power generation efficiency for ambient low frequency excitation. In addition, a folded cantilever structure is utilized to improve the space and the power efficiency.

DESIGN AND MODELING

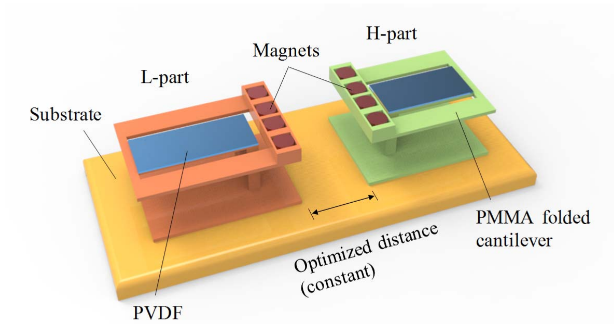

Figure 1: The designed high-efficient broadband energy harvester based on non-contact coupling technique.

As shown in Fig. 1, one piezoelectric energy harvester with low resonant frequency (L-part) is coupled with another piezoelectric energy harvester with high resonant frequency (H-part) through a non-contact magnetic force. The non-contact magnetic force is provided by 8 identical permanent NdFeB magnets, which are mounted on the end of cantilevers with the same magnetic pole arrangements. Polyvinylidene fluoride (PVDF) film is attached uniformly on the cantilevers for generating power during vibrations. D_{31}-mode is utilized in order to obtain higher power output [10]. By adjusting the dimension parameters (i.e., thickness and length of the cantilever), resonant frequencies of both the L-part and H-part are designed within a range of 0-40 Hz (L-part: 18 Hz, H-part: 32 Hz), which satisfy the ordinary range of ambient vibration.

In this case, both parts have their own high-efficient range for environmental vibration in normal conditions. Moreover, due to the non-contact magnetic force coupling, the two parts can enhance each others' output performance. This is described in detail as the following two conditions. a) Under an environmental excitation with low vibration frequency, the L-part can generate power with high efficiency due to the matching between ambient excitation and its own resonant frequency, meanwhile driving the H-part to generate power with high efficiency because of the frequency up-conversion mechanism. b) On the other hand, when the ambient vibration frequency is close to the high-efficient zone of the H-part (near its natural frequency), the H-part can also promote the deformation/stress of the L-part owing to the magnetic force, which contributes to the output of the L-part. An expanded high-efficient bandwidth can thus be achieved for ambient vibration. Apart from the aforementioned advantages, due to the non-contact driving method, the lifespan of this device can be largely enhanced. In this design, the separation between the L-part and H-part is maintained with an optimized distance to achieve a maximum output. The two parts can be mounted on a substrate with this optimized separation during operating. In addition, a folded cantilever structure is designed and employed to enhance the space efficiency of this energy harvester.

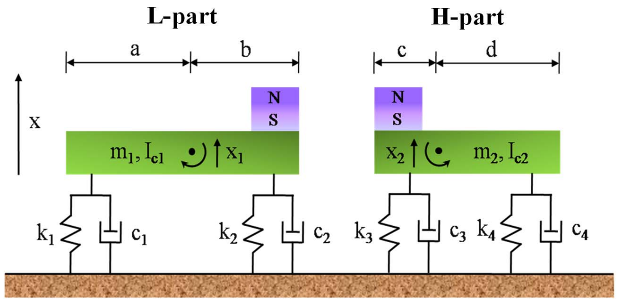

Figure 2: The simplified dynamic model of the designed energy harvester.

In order to investigate the characteristics of the designed energy harvester, a simplified dynamic model is established. As shown in Fig. 2, each part of the designed energy harvester can be modeled as a damped two degree-of-freedom (DOF) mass-spring system. Supported by damped springs with spring constant k_i and damping coefficient c_i (where i=1, 2, 3, 4), the equation of motion for the complete model can be expressed as:

$$\begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & I_{c1} & 0 & 0 \\ 0 & 0 & m_2 & 0 \\ 0 & 0 & 0 & I_{c2} \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{\theta}_1 \\ \ddot{x}_2 \\ \ddot{\theta}_2 \end{bmatrix} + \begin{bmatrix} c_1 & 0 & 0 & 0 \\ 0 & c_2 & 0 & 0 \\ 0 & 0 & c_3 & 0 \\ 0 & 0 & 0 & c_4 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{\theta}_1 \\ \dot{x}_2 \\ \dot{\theta}_2 \end{bmatrix} +$$
$$\begin{bmatrix} k_1+k_2 & -(k_1a-k_2b) & 0 & 0 \\ -(k_1a-k_2b) & k_1a^2+k_2b^2 & 0 & 0 \\ 0 & 0 & k_3+k_4 & -(k_3d-k_4c) \\ 0 & 0 & -(k_3d-k_4c) & k_3c^2+k_4d^2 \end{bmatrix} \begin{bmatrix} x_1 \\ \theta_1 \\ x_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} F_{G1}+F_{mag} \\ -F_{mag}b \\ F_{G2}-F_{mag} \\ F_{mag}c \end{bmatrix} \quad (1)$$

where m_j and I_{cj} (where j=1, 2), are the mass and moment of inertia around the centroid of each cantilever, respectively. F_{Gj} is the inertial forces acting on the mass m_j. Considering that the magnetic force contributes to the coupling effect and output performance, the magnetic force between the L-part and H-part could be derived as:

$$F_{mag} = -8\pi K_d R^2 \sum_{i=1}^{4} \sum_{j=5}^{8} \int_0^{+\infty} J_0\left(\frac{r_{ij}q}{R}\right) \frac{J_1^2(q)}{q} \sinh(q\tau_i)\sinh(q\tau_j) e^{-q\varsigma} dq \quad (2)$$

where K_d and R are the magnetostatic energy constant and radius of a single permanent magnet, respectively. r_{ij} is the lateral separation between magnet i and j. τ, ζ, and e represent the aspect ratio of each magnet, the reduced distance between the centers of the two magnet groups, and the total magnetic energy, respectively. J_0 and J_1 are the modified Bessel function of the first type for integer orders α=0, 1 [11].

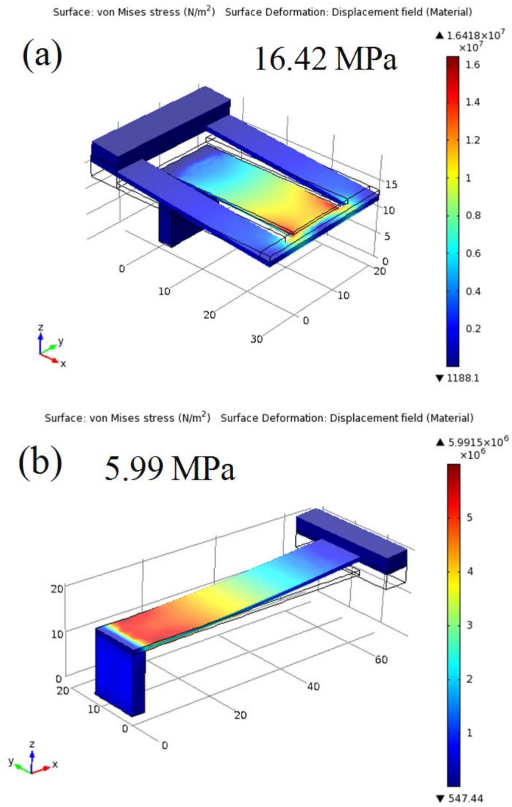

Figure 3: The comparison between folded cantilever and conventional straight cantilever (before folding) based on simulation results. Stress distribution: (a) and (b). Higher stress distribution can be achieved by the folded cantilever, which benefits the power generation.

For the piezoelectric energy harvester, a high stress distribution on the piezoelectric material can benefit the output. Therefore, high stress distribution is desired for the cantilever that attached with PVDF film in this device. For this reason, a folded cantilever is designed and adopted to this energy harvester. To verify the advantages of utilizing the designed folded structure as the cantilever in the designed energy harvester, Finite Element Method (FEM) simulations for both folded cantilever and conventional straight cantilever are carried out using COMSOL Multiphysics software with the same input conditions. For convenient comparison, the length of the conventional straight cantilever is equal to that of the folded cantilever before folding. Furthermore, the material and parameters of the folded cantilever model established in the simulation remain identical with those of the L-part. The magnets on L-part are simplified as a proof-mass but with the same physical properties. As can be seen from Fig. 3(a) and (b), a much higher stress distribution can be achieved by using this folded cantilever than by using a straight cantilever, which will effectively enhance the power generation capability and the efficiency for low frequency vibration energy harvesting.

EXPERIMENT AND RESULTS

In order to verify the output performance of the design, a prototype of this energy harvester is manufactured using 3D printing technology, which can conveniently produce the integrated total structure. A ProJet HD 3500 Plus Professional 3D printer (3D Systems, Corp, Rock Hill, USA) is employed to manufacture the energy harvester as well as its folded cantilevers. The geometric dimensions and material details of the fabricated energy harvester are listed in Table 1. During the performance test, the energy harvester is mounted on a shaker TIRA Vib BAA 120 (TIRA Gmbh, Inc, Germany) and is vertically vibrated with sinusoidal excitation at various frequencies, which is provided by the Agilent 33120A function generator (Agilent Technologies, Inc, USA). The output voltage and power generation frequency of the energy harvester is measured using a Tektronix TDS 2014B oscilloscope (Tektronix, Inc, USA).

Table 1: Parameters of the fabricated energy harvester.

Parameters	**L-part**	**H-part**
Total size	39×28×15 mm^3	30×28×15 mm^3
Material	PMMA	PMMA
Natural frequency	Before coupling: 18 Hz After coupling: 17 Hz	Before coupling: 32 Hz After coupling: 30 Hz
End-magnets	Diam. 5 mm, thickness 2.5 mm	NdFeB, 0.14 T

Considering that the distance between the L-part and H-part significantly affects the strength of magnetic coupling, a suitable separation of the two parts should be selected for realizing effective coupling mechanism. Since the two magnet groups will be attracted to each other owing to the strong magnetic force when the distance is lower than 6 mm and thereby leading to invalid working performance, the range of this distance is selected as 6-15 mm. When the distance is small in this range, i.e. 6mm, due to the constraints of magnetic repulsive force, the output of the two parts is even lower than that for the condition without magnetic coupling. In this condition, the L-part and H-part cannot completely vibrate under excitation. On the contrary, when the distance is increased to 14 mm or larger, the magnetic force is too weak to maintain the coupling mechanism, thereby resulting in an output performance near that without coupling. With various gap distances between the two parts, a favorable output performance can be achieved by the energy harvester with 11 mm distance under different frequencies of vibration. Therefore, aiming for high output capability in the same conditions, 11 mm is utilized as the optimized separation between L-part and H-part when mounted on substrate in further experiments.

To verify the influence of a non-contact magnetic coupling for the energy harvester, a comparison experiment on output waveform characterization is carried out. The permanent magnets are replaced by 8 steel mass cylinders, which eliminate the influence of the magnetic coupling effect. The weight of mass cylinders used is exactly same as the total mass of the permanent magnets. In the experiment, for convenient observation, the excitation frequencies are set to the resonant frequencies of the two folded cantilever beams (before coupling: 18 Hz and 32 Hz, after coupling: 17 Hz and 30 Hz), respectively. As shown in Fig. 4(a) and (b), it can be found that the waveform phase (or frequency) of the two parts maintain exactly same when the energy harvester vibrate under the condition of the non-magnetic coupling. On the other hand, once the two parts are magnetically coupled with each other, not only the frequency up-conversion mechanism can be realized at a low frequency range, but the output voltage of the two parts can also be improved, which is shown in Fig. 4(c) and (d), respectively. It should be noted that the original resonant frequencies of the two parts are slightly lowered after coupling. This may be attributed to the influence of magnetic force.

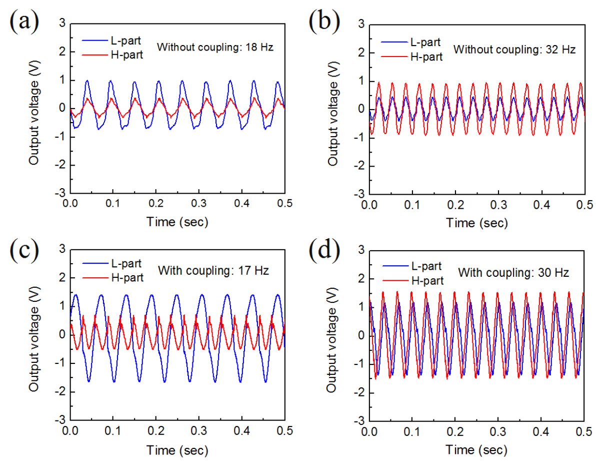

Figure 4: The output waveform comparison between the energy harvesters without and with non-contact magnetic coupling technique. (a) and (b) exhibit the waveform without coupling, (c) and (d) show the waveform with coupling.

The main advantage of the proposed design is aiming for a wide working bandwidth under ambient vibrations. To determine the coupling influence on the bandwidth of the energy harvester, the bandwidth characterization before and after magnetic coupling should be carried out. Considering the stress distribution and output will be increased with the increase in displacement for a piezoelectric cantilever, the displacement characterization can be utilized to investigate the bandwidth of this energy harvester. As shown in Fig. 5, the displacement characterization for the two folded cantilevers is conducted in a frequency range of 0-40 Hz. Assuming 4 mm as the high-efficiency threshold, we can see that a wide high-efficient zone is achieved after non-contact magnetic force coupling, which is much broader than that before coupling. This wide band will allow the energy harvester to maintain a high-efficient output performance under random vibration conditions in real applications. In addition, because of the magnetic repulsive force, the maximum deformation of each piezoelectric cantilever become larger than that before coupling; thereby further enhancing the peak output voltage. A maximum voltage of 1.5 V can be achieved for L-part and H-part at their own resonant frequency, respectively. Therefore, owing to the non-contact magnetic coupling technique, not only enormous improvement on working bandwidth can be produced for the energy harvester, but the output performance can also be enhanced. Furthermore, a durable lifespan will be obtained. In this way, the high-efficient energy harvester proposed in this work can effectively convert ambient vibration energy into electricity in a broad bandwidth. Additionally, according to the displacement characterization, it can be seen that a minimum suspended height of 10 mm is desired for avoiding any collision between the cantilever end and the substrate, which has been carefully ensured during design process of this energy harvester.

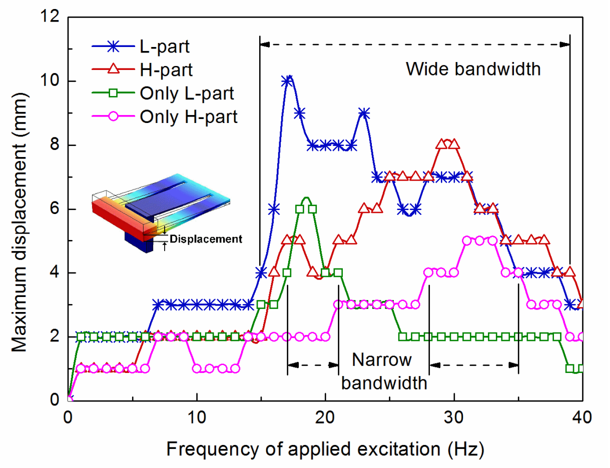

Figure 5: The maximum displacement of the cantilever end from its original position under various frequencies of excitations.

In order to investigate the power output of this energy harvester in practical applications, a load resistance of 50 kΩ is connected to the device. With a sinusoidal excitation of 30 Hz, a peak output power of 11.25 μW and 7.2 μW are achieved by the H-part and L-part (18.45 μW in total), which is suitable for the minimum power requirement of the WSN application (<10μW) [12].

CONCLUSIONS

In this study, a high-efficient piezoelectric energy harvester based on a non-contact magnetic coupling technique is designed and experimentally characterized. The two parts can effectively improve each others' output performance through the coupling mechanism in the ordinary vibration environment. Folded cantilevers are designed for this energy harvester to benefit space and power efficiency, which is verified in the FEM simulation results. An appropriate separation between the two parts is selected to ensure a favorable coupling mechanism and output performance. In the performance testing, a wide bandwidth for environmental low frequency vibration is achieved due to the non-contact coupling technique. With a load resistance of 50 kΩ, a peak output power of 18.45 μW is achieved by the energy harvester, which satisfies the power requirement of a sensor node in WSN applications.

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