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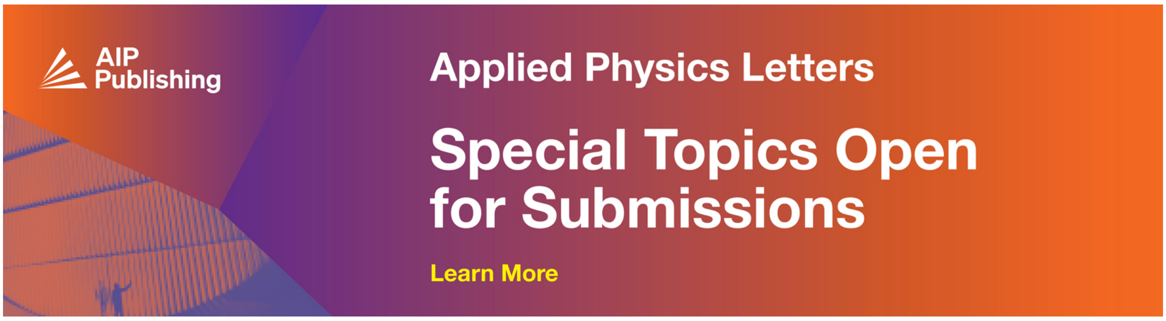

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Vibration-based energy harvesting with stacked piezoelectrets

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Vibration-based energy harvesters with multi-layer piezoelectrets (ferroelectrets) are presented. Using a simple setup with nine layers and a seismic mass of 8 g, it is possible to generate a power up to 1.3 μW at 140 Hz with an input acceleration of 1*g*. With better coupling between seismic mass and piezoelectret, and thus reduced damping, the power output of a single-layer system is increased to 5 μW at 700 Hz. Simulations indicate that for such improved setups with 10-layer stacks, utilizing seismic masses of 80 g, power levels of 0.1 to 1 mW can be expected below 100 Hz. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4874305]

Piezoelectric energy harvesting has long been considered a prime method to generate electrical energy from mechanical motion.[1] Several different piezoelectric transduction mechanisms, such as bending devices, membranes, or thickness elements, have been suggested to accomplish this task. Also, a variety of piezoelectric materials has been used for the transduction process. Foremost among these are the ceramic material lead zirconate titanate (PZT) and the polymer material polyvinylidenefluoride (PVDF).[2–4]

The appearance of another group of piezoelectric materials, namely, charged, cellular polymers, referred to as ferroelectrets or piezoelectrets, has opened up an alternate avenue to energy harvesting. Such ferroelectrets have relatively high dynamic piezoelectric charge coefficients d_{33} (up to about 500 pC/N), they are lightweight and flexible, and they can be made in a wide variety of shapes and sizes.[5] Early ferroelectrets have been primarily made of foamed polypropylene internally charged by a corona process,[6,7] and their resonance behavior has been explained by dielectric measurements.[8] Later on, the d_{33} coefficient of ferroelectrets was improved by pressure expansion[9,10] and DC-biasing,[11] resulting in a high figure of merit[12] $d_{33}\ g_{33}$, where g_{33} is the piezoelectric voltage coefficient. Recently, also some other materials with better thermal stability of the piezoelectric activity, primarily based on fluoropolymers, have been suggested.[13–15] The use of ferroelectrets in energy harvesting has only been described in a few papers.[16–19]

In the present paper, vibration-based energy harvesting with ferroelectrets utilizing the piezoelectric thickness effect is discussed. As compared to the previous work, pressure expanded piezoelectrets in arrangements consisting of stacked film layers are used. This increases, for the same weight and size of the setup, the electric power generation by a considerable amount. In the following, after a short analysis of the power generation, measurements of produced charge and power are presented, and the limits of this kind of energy harvesting with respect to output power are evaluated.

A vibration-based piezoelectric energy harvester basically consists of a seismic mass applying a stress on a piezoelectric element. When this system is subjected to acceleration, electric voltage and current are generated, which depend mostly on the seismic mass and on the piezoelectric coefficients of the used material. After rectification, the transduced energy can be used to supply power to electronic components.

An efficient way of optimizing the mechanical to electrical conversion with piezoelectrets without increasing the seismic mass is to fold and stack the films and thus to increase the number of layers subjected to the mechanical force. A similar procedure was used to improve the sensitivity of piezoelectret transducers.[20–23] Assuming that a film strip is folded (p − 1) times (see Fig. 1) to form a folded element of p film layers connected in parallel, one obtains an increase of the charge output and of the capacitance. In a second step, s such folded elements are combined to form a piezoelectret stack. For such a stack, the elements are connected electrically in series; thus the output voltage will be increased and the capacitance will be reduced. The total

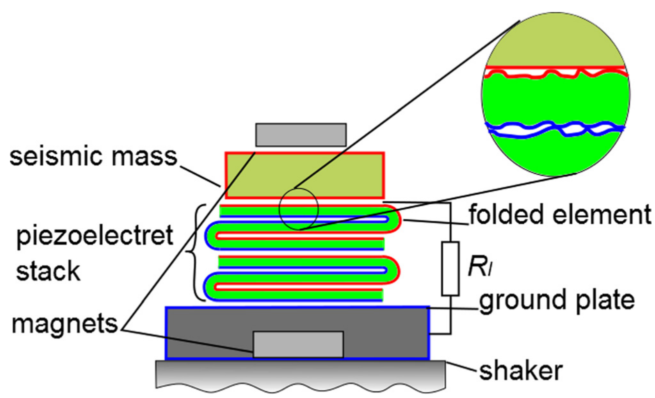

FIG. 1. Schematic of experimental setup consisting of energy harvester and shaker. In the illustrated example, a piezoelectret stack of s = 2 folded elements, each with p = 3 layers, is shown. The stack is placed between the seismic mass and the ground plate and these are held together by two magnets. For the measurements, this harvester is positioned on an electrodynamic shaker. The resistor R_l allows one to measure the electrical power generated by the mechanical vibrations.

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number of layers in the stack is then n = sp, as seen in Fig. 1, for the case p = 3 and s = 2.

The experimental setup for characterizing a piezoelectret energy harvester is also schematically presented in Fig. 1. The harvester consists of a seismic mass placed on top of one or several layers of piezoelectret films on a ground plate, held in place with two magnets. This device is subjected to an acceleration by an electrodynamic shaker (B&K 4809), which is fed by an audio analyzer (UPD R&S) through a power amplifier (B&K 2706). The acceleration thus applied to the energy harvester is measured with an accelerometer (B&K 4332) placed directly on the shaker, using the substitution method. A resistor R_l is connected to the outer electrodes of the piezoelectret stack. The charge flows into a charge amplifier (B&K 2635) in series with R_l and is measured with the audio analyzer. A parasitic capacitance of the arrangement of about 3 to 5 pF was determined.

The power generated by a device consisting of a piezoelectret stack with n = sp layers may be derived from its equivalent circuit[24] and is given by

$$P_{\mathrm{s,p}} = \frac{m_s^2 R_l (\mathrm{p}\, d_{33})^2 \omega^2 a^2}{[((\omega/\omega_{0,\mathrm{n}})^2 - 1)^2 + 4\,\zeta_m^2\,(\omega/\omega_{0,\mathrm{n}})^2][1 + (R_l(\frac{\mathrm{p}}{\mathrm{s}} C_0 + C_{par})\omega)^2]}. \quad (1)$$

In this equation, a is the acceleration, m_s is the seismic mass including the upper magnet, ω is the angular frequency, ζ_m is the damping ratio of the stack, C_0 is the capacitance of a single layer, and C_{par} is the parasitic capacitance of the electrical circuit. Furthermore, $\omega_{0,\mathrm{n}}$ is the resonance frequency of the harvester, which is given by

$$\omega_{0,\mathrm{n}} = \sqrt{\frac{YA}{\mathrm{n}\, t\, m_s}}, \quad (2)$$

where t is the thickness of a single layer, Y is the Young's modulus of the entire piezoelectret stack, and A is the support area of the seismic mass. For n = 1, Eq. (1) follows from the literature if the coupling coefficient $k_e^2 \ll 1$ (see, e.g., Ref. 25). It is reasonable[2] to use the energy harvester at the resonance frequency $\omega_{0,\mathrm{n}}$. The maximum power harvested at this frequency is directly obtained from Eq. (1) for

$$R_{l,opt} = \frac{1}{\omega_{0,\mathrm{n}} C'}, \quad (3)$$

where

$$C' = \frac{\mathrm{p}}{\mathrm{s}} C_0 + C_{par}. \quad (4)$$

Thus, when operating the energy harvester at $\omega_{0,\mathrm{n}}$, maximum power is harvested if $\omega_{0,\mathrm{n}}$ is also the upper cut-off frequency ω_c of the electrical circuit.

The power at the resonance frequency $\omega_{0,\mathrm{n}}$ is then

$$P_{opt,\mathrm{n}} = \frac{\mathrm{p}^2 m_s^2 d_{33}^2 a^2 \omega_{0,\mathrm{n}}}{8\,\zeta_m^2 C'}. \quad (5)$$

If $C_{par} \ll \mathrm{p}C_0/\mathrm{s}$, then C_{par} can be neglected in Eq. (5). Thus, with n = sp (see above), this equation yields for the power dissipated at $\omega_{0,\mathrm{n}}$ in the optimal load resistance

$$P_{opt,\mathrm{n}} = \mathrm{n}\,\frac{m_s^2 d_{33}^2 a^2 \omega_{0,\mathrm{n}}}{8\,\zeta_m^2 C_0} = \sqrt{\mathrm{n}}\,\frac{m_s^2 d_{33}^2 a^2 \omega_{0,1}}{8\,\zeta_m^2 C_0}. \quad (6)$$

Since the load resistance $R_{opt,\mathrm{n}}$ depends on the kind of connection of the film layers (series or parallel), it is remarkable that, according to Eq. (6), the maximum power that can be harvested from mechanical vibrations only depends on the number of layers and not on the kind of connection of the layers, as long as $C_{par} \ll \mathrm{p}\, C_0/\mathrm{s}$ is again assumed.

The parameters Y, ζ_m, and d_{33}, required for the calculation of $P_{\mathrm{s,p}}$ from Eq. (1), were obtained from the measured charge sensitivity of piezoelectret energy harvesters in short circuit, such as shown in Fig. 2, below. The parameters for the theoretical curves in Figs. 3–5 are shown in Table I. Some disagreement of the various values of d_{33}, ζ_m, and Y will be noticed. The variations of d_{33} are typical for piezoelectret materials and are due to the irregular cellular structure.[26] Fluctuations of ζ_m and Y can be partially explained by the roughness of the piezoelectret films (cf. inset of Fig. 1). Due to their uneven surfaces, irregular areas of contact exist between film surfaces, ground plate, and seismic mass. The resulting air gaps are therefore of irregular shape. Vibrational excitation causes air streaming in these gaps, which gives rise to a damping ratio ζ_m that varies from sample to sample. The effective Young's modulus Y of the film

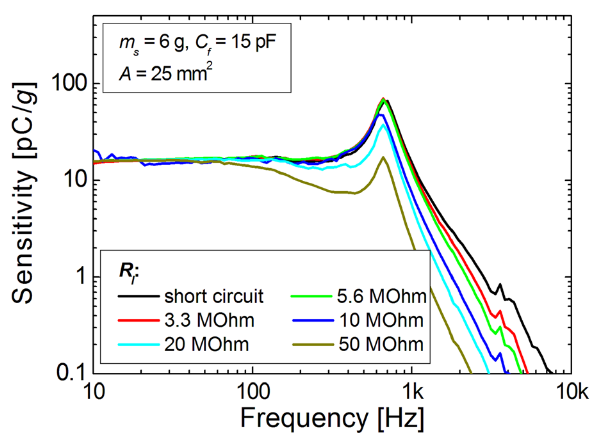

FIG. 2. Charge flowing from the energy harvester with a single ferroelectret layer for an acceleration of $1g \equiv 9.81\ \mathrm{m/s^2}$ through various load resistances from 0 Ω to 50 MΩ.

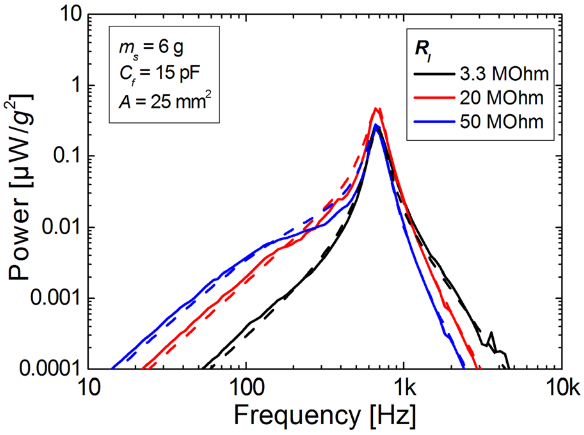

FIG. 3. Power generated by a single piezoelectret layer across several load resistances connected to the electrodes of the piezoelectret energy harvester. The full lines represent measured data, obtained from the charge measurements in Fig. 2, the dashed ones show the results calculated with Eq. (1).

arrangement, as measured between ground plate and seismic mass, is similarly affected by the contact areas and air gaps and is therefore also expected to be different for different samples. Note that the single-layer harvesting device described in the third to last column, in which the film is glued to the ground plate and seismic mass (see below), has considerably lower damping.

Measurements of the AC-charge flowing from the energy harvester through various resistors for an input acceleration of 1g (with "g" in italics equal to the gravity of earth) are presented in Fig. 2. A seismic mass of 6 g was placed on a single layer of piezoelectret film and various resistors were connected to the film electrodes. Below the resonance frequency, the measured charge sensitivity in short circuit of 17 pC/g corresponds to a piezoelectric d_{33} coefficient of about 280 pC/N. The resonance occurs at 700 Hz.

The frequency responses with non-zero values of the resistances show the properties of first order low-pass filters with the cut-off frequency ω_c. For example, for a resistance of 50 MΩ, the cutoff frequency amounts to 200 Hz. At considerably lower frequencies, the absolute value of the film impedance is much larger than the resistance R_l, which can be neglected, whereas at far higher frequencies the circuit can be approximated as an open circuit.

Measurements and calculations of the power converted in several load resistances by the ferroelectret film of Fig. 2, subjected to a base acceleration of 1g, are presented in Fig. 3. The experimental data were obtained from the relation

$$P = R_l I^2 = R_l \omega^2 Q^2, \tag{7}$$

where the charge Q is taken from Fig. 2. The calculations were carried out with Eq. (1), using the parameter values from Table I.

At the resonance frequency, a maximum power of 0.5 μW is generated in a resistance of 20 MΩ. Further increasing the value of the resistance shifts the cut-off frequency ω_c of the electric circuit below the resonance $\omega_{0,1}$ and thus lowers the maximum harvested power (see statement after Eq. (4)). The agreement between the calculated curves and the measured data in Fig. 3 is generally very good.

Figure 4 shows the power produced by energy harvesters made either with a single film or with an arrangement of folded and/or stacked films, as explained in the caption of Fig. 4. Increasing the number of layers and optimizing the resistance value to make the cut-off frequency ω_c of the circuit equal to the resonance $\omega_{0,\mathrm{n}}$ (see above) results in an enhancement of the converted power. The maximum values are 0.5 μW at 540 Hz for one layer, 1.3 μW at 140 Hz (9 layers), and also 1.3 μW at 200 Hz (10 layers). Thus, while the generated power increases by a factor of 2.6, the frequency of operation of the harvester is lowered by a factor of 2.7 (10 layers) to 3.9 (9 layers). This reduction of the operating frequency is generally considered to be advantageous in actual applications, since the vibrations available in the environment are usually below 100 Hz.[27] The load resistances chosen agree approximately with the values obtained from Eq. (3) if the parasitic capacitances (between 3 and 5 pF, see above) are considered. The fact that the resonance frequency of the 9 layer harvester is lower than that of the 10 layer harvester is due to the scattering of Young's modulus discussed above.

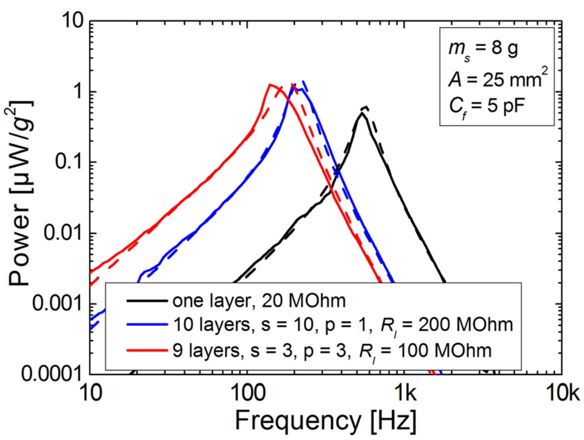

FIG. 4. Power generated by energy harvesters with various numbers of piezoelectret layers. The full lines represent data from the measurements, the dashed lines show the simulation results. The 10 layer stack consists of piezoelectret films connected in series (s = 10, p = 1), and the 9 layer stack of 3 films, each folded twice, and then connected in series (p = 3, s = 3).

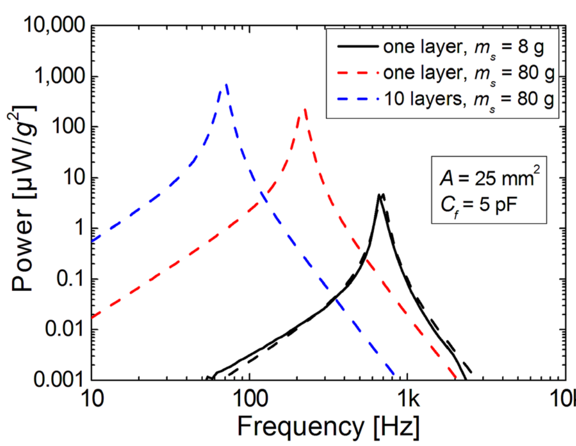

FIG. 5. Simulation of power generated by improved energy harvesting devices with various seismic masses and number of layers. The full line represents the measurement of the power generated with one layer and a mass of 8 g.

TABLE I. Parameters d_{33}, Y, ζ_m, and m_s used for the calculation (Eq. (1)) of the frequency dependence of the power generated by various piezoelectret energy harvesting devices. The optimal generated power P_{opt} at the resonance frequency f_n is also shown. The last two columns refer to systems not yet implemented.

Parameters and results	1 layer[a] (Figs. 2 and 3)	1 layer[a] (Fig. 4)	9 layers[a] (Fig. 4)	10 layers[a] (Fig. 4)	1 layer[b] (Fig. 5)	1 layer[c] (Fig. 5)	10 layers[c] (Fig. 5)
d_{33} [pC/N]	250	220	290	300	220	220	220
Y [MPa]	0.22	0.2	0.17	0.3	0.3	0.3	0.3
ζ_m	0.11	0.15	0.23	0.15	0.06	0.06	0.06
f_n [Hz]	700	540	140	200	700	220	70
m_s [g]	6	8	8	8	8	80	80
P_{opt} [μW/g]	0.5	0.5	1.2	1.2	5	240	720

[a]Layers not glued.
[b]Layer glued.
[c]Layers glued, calculated power.

Very recently, measurements of the generated power from an arrangement with enhanced coupling of the seismic mass were performed. The better coupling was achieved by gluing the piezoelectret layer on its two sides to the seismic mass and to the ground plate, respectively. This also diminishes the irregular air gaps on the two sides of the piezoelectret layer and thus reduces the damping due to air streaming in these gaps during the vibrational excitation. The damping ratio ζ_m is therefore lowered from about 0.14 (average for three arrangements) to 0.06, as seen in Table I. Fig. 5 shows (solid black curve online) that this improvement resulted in the generation of about 5 μW at 700 Hz from a single piezoelectret layer. According to Eq. (5), for a reduction of ζ_m by a factor of 2.3, an increase in the harvested power by a factor of about 5 is expected. This agrees reasonably well with the above experimental results. It should be mentioned, however, that the reduced damping also results in a reduction of the bandwidth of the resonance.

Based on this recent finding, an estimate of the power generated with enhanced coupling, a larger number of layers, and an increased seismic mass has been made. The results of this simulation, based on the experimental data from the improved single-film sample, are also shown in Fig. 5. Using such arrangements with glued layers and an increased seismic mass of 80 g, the generation of a power of 700 μW at 70 Hz with an input acceleration of 1g in the favorable frequency range below 100 Hz (Ref. 27) is estimated.

It has thus been shown that piezoelectret energy harvesting devices in a simple arrangement, where a seismic mass of 8 g is placed on one or several piezoelectret layers, can generate a power of 1.3 μW at 140 Hz with an input acceleration of 1g. This is a considerable improvement compared to previous energy harvesters with ferroelectrets of similar design utilizing the piezoelectric thickness effect, where the generated power has always been below 0.1 μW, even for considerably higher seismic masses. It is made possible because of the increased piezoelectric d_{33} coefficient of the present ferroelectrets and because of the use of multiple layers. With improved coupling between seismic mass, piezoelectret film, and ground plate, it was even possible to generate 5 μW at 700 Hz with a single film. Optimizing the harvester with a larger number of layers and/or increasing the seismic mass would allow one to generate electric power of the order of 0.1 to 1 mW at frequencies below 100 Hz. However, using reduced damping in the harvesters, due to the improved coupling, results in smaller resonance bandwidth (see below).

The optimized designs whose generated power is shown in Fig. 5 have a maximal volume figure of merit[2] of 0.06%. An important aspect is the resonance bandwidth of the transducers. The present harvesters, both with and without the improved coupling, have larger relative bandwidths than the conventional designs, which is of advantage for broadband applications. This is reflected in the definition of the bandwidth figure of merit.[2] This figure of merit is, for the optimized harvesters described above, considerably higher than for a majority of the electromagnetic or electrostatic energy harvesters and similar to those for piezoelectric cantilever or compression based devices.[2,16,28,29] Compared to most of these harvesters, the present transducers are of much simpler design.

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[1]A. Erturk and D. J. Inman, *Piezoelectric Energy Harvesting* (John Wiley & Sons, New York, 2011).
[2]P. D. Mitcheson, E. M. Yeatman, G. K. Rao, A. S. Holmes, and T. C. Green, Proc. IEEE **96**, 1457 (2008).
[3]H. S. Kim, J.-H. Kim, and J. Kim, Int. J. Precis. Eng. Manuf. **12**, 1129 (2011).
[4]C. R. Bowen, H. A. Kim, P. M. Weaverb, and S. Dunn, Energy Environ. Sci. **7**, 25 (2014).
[5]S. Bauer, R. Gerhard-Multhaupt, and G. M. Sessler, Phys. Today **57**(2), 37 (2004).
[6]J. Lekkala, R. Poramo, K. Nyholm, and T. Kaikkonen, Med. Biol. Eng. Comput. **34**(Suppl. 1, Pt. 1), 67 (1996).
[7]G. M. Sessler and J. Hillenbrand, Appl. Phys. Lett. **75**, 3405 (1999).
[8]G. S. Neugschwandtner, R. Schwödiauer, M. Vieytes, S. Bauer-Gogonea, S. Bauer, J. Hillenbrand, R. Kressmann, G. M. Sessler, M. Paajanen, and J. Lekkala, Appl. Phys. Lett. **77**, 3827 (2000).
[9]M. Wegener, W. Wirges, R. Gerhard-Multhaupt, M. Dansachmüller, R. Schwödiauer, S. Bauer-Gogonea, S. Bauer, M. Paajanen, H. Minkkinen, and J. Raukola, Appl. Phys. Lett. **84**, 392 (2004).
[10]X. Zhang, G. M. Sessler, and J. Hillenbrand, J. Electrost. **65**, 94 (2007).
[11]J. Hillenbrand and G. M. Sessler, J. Appl. Phys. **103**, 074103 (2008).
[12]G. M. Sessler and J. Hillenbrand, Appl. Phys. Lett. **103**, 122904 (2013).
[13]R. A. P. Altafim, X. Qiu, W. Wirges, R. Gerhard, R. A. C. Altafim, H. C. Basso, W. Jenninger, and J. Wagner, J. Appl. Phys. **106**, 014106 (2009).
[14]X. Zhang, J. Hillenbrand, and G. M. Sessler, J. Appl. Phys. **101**, 054114 (2007).
[15]H. von Seggern, S. Zhukov, and S. Fedosov, IEEE Trans. Dielectr. Electr. Insul. **18**, 49 (2011).

[16]S. R. Anton and K. M. Farinholt, Proc. SPIE **8341**, 83410G (2012).
[17]S. R. Anton and K. M. Farinholt, in *Proceedings of the ASME* (2012), pp. 929–937.
[18]Y. Feng, K. Hagiwara, Y. Iguchi, and Y. Suzuki, Appl. Phys. Lett. **100**, 262901 (2012).
[19]Y. Feng and Y. Suzuki, in *Proceedings of the IEEE International Conference on MEMS* (2013), pp. 865–868.
[20]A. Streicher, R. Müller, H. Peremans, and R. Lerch, in *Proceedings of the IEEE Ultrasonic Symposium* (2005), pp. 1364–1367.
[21]S. J. Rupitsch, R. Lerch, J. Strobel, and A. Streicher, IEEE Trans. Dielectr. Electr. Insul. **18**, 69 (2011).
[22]J. Hillenbrand and G. M. Sessler, IEEE Trans. Dielectr. Electr. Insul. **13**, 973 (2006).
[23]J. Hillenbrand, M. Kodejska, Y. Garcin, H. von Seggern, and G. M. Sessler, IEEE Trans. Dielectr. Electr. Insul. **17**, 1021 (2010).
[24]P. Pondrom, J. Hillenbrand, G. M. Sessler, J. Bös, and T. Melz, "Stacked piezoelectret energy harvesting: modelling and experimental verification" (unpublished).
[25]A. Erturk and D. J. Inman, Smart Mater. Struct. **17**, 065016 (2008).
[26]See http://www.emfit.com/uploads/pdf/Emfit_film_specifications.pdf for Emfit film specifications, Rev C, 17.3. 2003, Emfit LTD, Sensor products division, Konttisentie 8, FI-40800 Vaajakoski, Finland.
[27]Y. Suzuki, IEEJ Trans. Electr. Electron. Eng. **6**, 101 (2011).
[28]M. Defosseux, M. Allain, E. Defay, and S. Basrour, Sens. Actuators, A **188**, 489 (2012).
[29]H. Wang and Q. Meng, Mech. Syst. Signal Process. **36**, 193 (2013).