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Most of the countercharge in the conventional electret-based electromechanical transducer, where the electret is formed on a conducting or semiconducting substrate, is induced in the substrate. Here we introduce a type of electret transducer that contains a freestanding electret without a conducting substrate, thereby enhancing the electric field between the electret and the electrodes where the output current is generated. A measurement of the power output from an electromechanical transducer yielded approximately five times larger power when a freestanding electret film was used than when the same electret material was deposited on a conducting substrate. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2985899]

Since the discovery,[1,2] the electret (EL) has been used widely for devices such as polymer electret microphones.[3] In the burgeoning field of microenergy harvesting,[4,5] the EL has attracted renewed interest as an element for electromechanical energy conversion.[6–11] An EL is a dielectric that produces a permanent electric field in its surrounding space, owing to an implanted charge or, in some cases, an internal charge polarization. The charge implantation is usually performed using a corona discharge process with a corona triode.[12] The principle behind the EL-based electromechanical transducer is straightforward: Because the EL has a permanent charge, it induces an opposite-sign countercharge on the surface of a nearby electric circuit. When the EL moves, the countercharge moves with it, producing an electric current in the circuit. The reverse process of converting electrical energy to mechanical energy works also in this fashion.

An EL material that can hold a large amount of charge would certainly enable improving the efficiency of an EL transducer. However, it is the countercharge density on the surfaces of the associated electric circuit that ultimately matters for an electromechanical conversion. Most of the countercharge is induced on the substrate of the EL film in the standard EL transducers. A straightforward solution for reducing the gap between the EL and what shall be referred to as the "work electrode," (WE) a part of the output circuit facing the electret, is problematic because this small gap must have sufficient mechanical stability. In fact, the gap distance remains about three times larger than the EL film thickness even in the recent devices based on microelectromechanical system technology. In this letter, we report on a method that effectively utilizes the implanted charge by removing the substrate from the EL, rather than attempting to implant a higher amount of charge in an EL material or to reduce the gap distance.

Figure 1 shows our concept, in the context of an EL-based vibration energy harvester[13] that is designed to produce electric power out of ambient vibration energy. While vibration energy harvesters based on piezomaterials[14] have a better performance, their EL-based counterpart has potential advantages such as simpler fabrication processes. The conventional energy harvester design is shown in the left side of

Fig. 1. The surface charge on the EL with density σ induces countercharge density $\tilde{\sigma}$ on the surface of metallic WEs. Because the EL moves relative to the WEs as a result of external vibration, the countercharge follows the motion, resulting in a current going through the load (LD). In this design, an EL film with relative permittivity ε is formed on a metallic backing plate (BP). The gap distance to the WE, g (at a potential V), is usually much larger than the EL film thickness, d. While the gap may be filled with air, the permittivity of air is approximately the same as the vacuum permittivity, ε_0. When the horizontal dimensions (in Fig. 1) of the EL film and the WE are much larger than d and g, neglecting the fringing field at the edge of the EL makes a good approximation.[6] In this case, the induced charge density is given by

$$\tilde{\sigma} = -(d\sigma - \varepsilon_0 \varepsilon V)/(d + \varepsilon g). \tag{1}$$

Typically, V is much smaller than the surface potential of the EL. As a result, most of the countercharges of the opposite sign, which could be as much as 90% of them, is induced on the BP. To increase the induced charge density on the WEs, we *removed* the metallic BP from the EL film so that most of the electric field lines originating from the implanted charge go toward the WEs instead of the BP, as shown in the right side of Fig. 1. However, the BP should be removed while maintaining the same level of implanted surface charge density in the EL. In the corona-charging process, the attainable
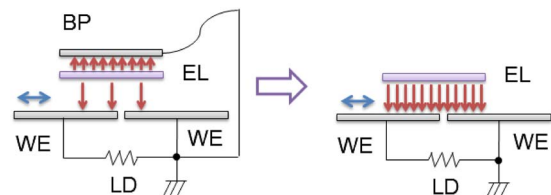

FIG. 1. (Color online) The improvement in an EL transducer. An ordinary device (left) consists of two WEs moving together horizontally, as shown by the horizontal left-right arrow, an EL film on a fixed and grounded metallic BP, and a LD. In the ordinary device, most of the electric field lines expressed as vertical arrows originating from the EL surface go to the BP. (In the figure, the BP is slightly removed to show the field lines.) The principal idea was to move the end points of the electric field lines from the BP to the WEs by removing the BP. In the improved device shown in the right, all the field lines terminate at the WEs, thereby inducing a larger amount of countercharge on them.

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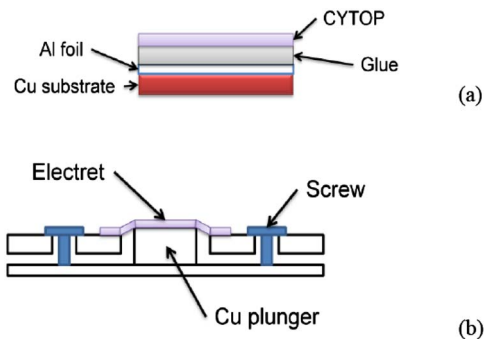[b]Electronic mail: kuwano@nanosys.mech.tohoku.ac.jp.

93, 122901-1

FIG. 2. (Color online) (a) A layered structure that was first produced to create a freestanding CYTOP EL film. (b) The resultant freestanding film was exposed to a corona discharge, while a gold-coated copper plunger tightly contacted the back surface of the EL film. Springs (not shown) were inserted between the two plates to press the upper plate upward against the screw heads. The EL film was glued to the upper plate with a minimum amount of adhesive.
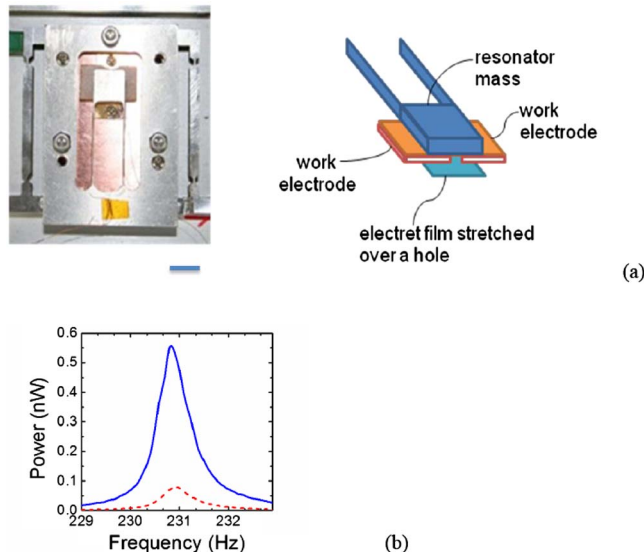

FIG. 3. (Color online) (a) The evaluation of the scheme by using a vibration energy harvester consisting of a mass element at the end of a pair of beams, comprising a resonator, that in turn was mounted on a vibration generator (partially shown in the photograph). The WE were located on the mass element, facing a fixed EL, as shown in the drawing on the right side. Scale bar: 10 mm. (b) Power output from the vibration energy harvester when a freestanding EL was used (blue, continuous) compared against a case where the same type of EL was formed on a metallic substrate (red, dotted) around the resonant peak of the energy harvester. The plot clearly demonstrates the superiority of our scheme.

surface potential is limited to about $V_s \sim 1$ KV. From $\sigma = \varepsilon_0 \varepsilon V_s / h$, where h is the distance to the electrical ground from the EL surface during the corona-charging process, we see that h must be small to obtain a large σ. Therefore, even though an EL film formed on an insulating substrate *per se* has already been reported,[8] removing the EL from the substrate *after* the corona-charging process improves the performance.

To validate this concept experimentally, we first produced EL films that can be peeled off from the substrate by using a four-layer structure shown in Fig. 2(a). We chose a polymer named CYTOP as an EL material (a fluorocarbon polymer manufactured by Asahi Glass Co., type CTL-809M), which can be spin coated on a substrate. CYTOP has been reported[7] to exhibit a better EL property than Polytetrafluoroethylene. The structure was produced as follows. The substrate was a $20 \times 20 \times 0.3$ mm^3 copper plate, a choice of material that presumably was not crucial. A piece of 12-μm-thick aluminum foil was then glued on the substrate. The next layer was liquid glue ("Arabic Yamato" manufactured by Yamato Co., Ltd., of which the main component was polyvinyl alcohol). The glue is a standard office item, and we believe that any similar glue would work as well, although the detailed processing conditions may change. The glue was spin coated (500 rpm for 10 s, followed by 1500 rpm for 20 s) and then baked at 150 °C for 20 min to solidify it. However, the glue needed to be baked to prevent air bubbles from forming during the CYTOP curing process. If the air bubbles appeared, the CYTOP film was ruined. Finally, the CYTOP layer was spin coated (500 rpm for 30 s), followed by baking at 150 °C for 1 h. We found that the liquid glue and CYTOP did not mix at all even in a liquid state because the former is hydrophilic whereas the latter is highly hydrophobic. The solidified glue layer under the CYTOP layer was the key to enabling the separation because of its weak attachment to the CYTOP, whereas in standard use, the solidified CYTOP film tightly stuck to a substrate after a standard heat treatment (150–180 °C, 1 h). The separation process was made even easier by first removing the flexible aluminum layer from the solid Cu substrate, allowing for an initial peeling at the edge by bending the foil there. The glue layer occasionally remained attached to the CYTOP layer after the peeling-off process. However, a clean CYTOP film was obtained in this case by immersing it in hot (not boiling)

de-ionized water to dissolve the glue. The film was found to be negatively charged to a considerable degree after the glue was peeled off.

Instead of removing the CYTOP layer after the corona-charging process, we first produced a freestanding CYTOP film. The freestanding CYTOP films were then positively corona charged to the surface potential of approximately 230–300 V while their back side was tightly attached to a grounded, gold-coated copper plunger [Fig. 2(b)]. All the surface potentials described in this paper were measured using an electrostatic voltmeter (TREK, model 344), where the probe-specimen distance was 1 mm. The corona-discharging process was performed using a corona triode, where the high-voltage electrode was a set of parallel stainless steel wires of 100 μm diameter placed above a grid mesh electrode. Meanwhile, the specimen at the bottom was grounded. The potentials in the high-voltage electrode and that in the grid electrode were approximately 3.9 kV and 300 V. The surface of the plunger was highly polished and made slightly convex to ensure good mechanical contact. When the plunger was retracted from the EL films, the surface potential of the EL drastically increased as expected. In most cases, it exceeded 2 kV, which was the measurement limit of our electrostatic voltmeter.

The charged EL films were then set in a vibration energy harvester for evaluation [Fig. 3(a)]. However, the experiment was not intended to maximize the power output, but rather to perform a comparative study between EL that are either freestanding or not. The effective area of the EL was 10 mm^2, while the gap between the EL and the WE was 1 mm. The state of the experiment was that the gap length could not be decreased without increasing the associated error because small wrinkles were in the freestanding EL film. A piezo-driven vibration generator provided an input vibration

(231 Hz, 1.8 $\mu m_{p.-p.}$) to the energy harvester. When we used a freestanding CYTOP film, which was charged up to a 230 V surface potential before retracting the plunger, the output power generated in a 10 MΩ LD was 0.55 nW. (However, the output impedance of the energy harvester was larger than 10 MΩ.) The corresponding voltage was 74 mV. While this voltage was too small for efficient rectification, it could in principle be made much larger by making a set of patterned EL and counterelectrodes connected in parallel to force a larger current flowing through a higher impedance LD.[7] This result was compared to a case with a conventional EL setup, where a CYTOP film was formed on a gold-coated copper substrate and was charged up to 250 V surface potential. The coating and curing conditions of the CYTOP were identical for the two experiments. We found that the power output was improved by a factor of approximately 7 using the freestanding EL, compared to the conventional setup, as shown in Fig. 3(b). However, it should be noted that some errors could have occurred in the figure obtained in the previous comparative study because of difficulties with precisely controlling the corona-charging conditions and the characterization of the resultant EL. The several experiments we conducted lead us to estimate the improvement factor conservatively to be 5. The factor associated with the performance improvement was sufficiently large that it clearly establishes our method to be superior to the conventional method. However, the simple theory of Eq. (1) predicted a much larger improvement. The reason for the improvement factor being only 5 remains unclear.

Despite the conceptual simplicity, we believe that our scheme will have a significant impact not only on micropower generators but quite possibly also on microactuators and microphones.

[1] M. Eguchi, Philos. Mag. **49**, 178 (1925).
[2] For review, see M. Goel, Curr. Sci. **85**, 443 (2003).
[3] G. M. Sessler and J. E. West, U.S. Patent No.3,118,022 (22 May 1962).
[4] Z. L. Wang, Sci. Am. 82 (January, 2008).
[5] A. Kansal and M. B. Srivastava, in *Proceedings of the 2003 International Symposium on Low Power Electronics and Design (ISLPED03)* (ACM, New York, 2003), p. 481.
[6] J. Boland, Y. H. Chao, Y. Suzuki, and Y. C. Tai, in *Proceedings of MEMS 2003 Technical Digest*, 2003 (unpublished), p. 538.
[7] T. Tsutsumino, Y. Suzuki, N. Kasagi, K. Kashiwagi, and Y. Morizawa, Proceedings of the 23rd Sensor Symposium, Takamatsu, Japan, 2006 (unpublished), p. 52; Y. Sakane, Y. Suzuki, and N. Kasagi, Proceedings of the PowerMEMS, 2007 (unpublished), p. 53.
[8] H. W. Lo and Y. C. Tai, Proceedings of MEMS, 2008 (unpublished), p. 984.
[9] T. Sterken, P. Fiorini, G. Altena, C. Van Hoof, and R. Puers, Proceedings of the Transducers and Eurosensors, 2007 (unpublished), p. 129.
[10] J. Zhang, Z. Chen, Y. Hao, Z. Wen, Y. Jin, and Z. Wen, Technical Digest, PowerMEMS, 2007 (unpublished), p. 105.
[11] M. Loehndorf, T. Kvisteroy, E. Westby, and E. Halvorsen, Technical Digest, PowerMEMS, 2007 (unpublished), p. 331.
[12] For review and developments, see J. A. Giacometti, S. Fedosov, and M. M. Costa, Braz. J. Phys. **29**, 269 (1999).
[13] C. B. Williams and R. B. Yates, Sens. Actuators, A **A52**, 8 (1996).
[14] Y. B. Jeon, R. Sood, J.-H. Jeong, and S.-G. Kim, Sens. Actuators, A **A122**, 16 (2005).