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A fully soft generator with embedded conditioning circuitry

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This letter presents a fully soft dielectric elastomer generator (DEG) based on a capacitive kinetic-energy-harvesting mechanism. First, using the principle of a passive charge pump, a self-cycling conditioning circuit topology is proposed. Through the electrical reciprocity of a cyclically deforming DEG and another capacitor in series with it, the generated charge can be continuously supplied to the load, via a bilateral conditioning bridge. The antagonistic dual-DEG scheme not only produces a larger potential to drive more charge in the flow but also provides a basic solution to soften the whole device. A further measure is to replace the bridge diodes with special dielectric elastic switches (DESSs), which can be embedded into the DEG and synchronously deformed with the latter to control the on/off state of the circuit branches. The intrinsic physical mechanism and characteristics of the change in the resistance of the DES as a function of stretch and electric fields are investigated. We tested and compared the diode-bridge and DES-bridge schemes under different electrical loads and tensile strokes. The results indicate that under certain conditions, the DES-bridge circuit can achieve comparable performance with that of a conventional scheme, which suggests that a fully soft DEG system is possible. We experimentally evaluated and discussed its reliability in practice. *Published by AIP Publishing.* <https://doi.org/10.1063/1.5036777>

Dielectric elastomers (DEs), a class of so-called electro-active polymers (EAPs), have been proposed and validated in recent years in principle for their capability to harvest energy from nature or human motion.^{1–3} Since this emerging technology potentially enables soft, lightweight, and green energy harvesters with excellent mechanical impedance matching to human muscle,⁴ it is expected to provide a good solution for powering portable and wearable electronics.

The essence of DE-based energy harvesting is to convert the input mechanical energy into electrical energy through cyclic elastic deformations of a soft device made of functional materials, called a DE generator (DEG). In DE energy harvesting, there is a synergistic and interactive behavior among the soft generator, the circuitry, and the external environment. As the core functional component in the system, electrically, the soft DEG is a variable capacitor, while mechanically, it is a strain energy store. In principle, as it recovers from its maximum energy state (the pre-charged maximum tensile state) to the initial undeformed state, the pre-stored strain energy will be converted into electrical energy, increasing the latter. Many valuable fundamental investigations have focused on this process,^{5–9} trying to create the ideal conditions (such as an open-circuit boundary) to maximize the conversion to electricity. Amongst them, according to Huang *et al.*,¹⁰ an equi-biaxially stretched DEG can achieve an electrical energy density of up to 560 mJ/g at the electrical and mechanical strength limitations, which seems to be unattainable for other functional materials used for the same purpose (e.g., piezoelectricity).

However, energy harvesting requires more than just this conversion. The captured electrical energy must be subsequently removed from the DEG, i.e., be harvested by supplying

the load in an appropriate form. Then, after losing energy, the DEG needs to be recharged or polarized again, to start the next cycle. Only in this way, we can realize a complete continuous cycle with practical value. Its realization relies more on the collaborative interactions between the DEG and the conditioning circuit, rather than on a single device. Specifically, the basic role of the circuit is to comply with and allow the above two functions, i.e., supply charge to the generator and extract it after each voltage boost. Lo *et al.*¹¹ reviewed circuit designs and proposed a self-priming circuit,¹² in which an initial low DC bias voltage can be automatically boosted to a higher level through DEG deformation cycles, so that the device no longer relies on high-voltage bias supplies. To harvest the electrical energy, they put forward designs for two conditioning circuits, based on a buck converter and a passive charge pump, respectively. Eitzen *et al.*¹³ also proposed a circuit topology that matches the bilateral DC–DC switching of a high-voltage power supply.

In this letter, based on the charge pump effect, we propose a self-cycling conditioning circuit for harvesting electrical energy automatically and discuss how to integrate it with DEG structures to construct a fully soft energy-harvesting system for wearable applications.

The proposed harvesting prototype circuit is illustrated in Fig. 1. After an initial pre-charging (the external power supply is not shown), the generating process will run continuously through cyclic deformations of the DEG. There is no need for manual control or an additional supply of electricity. Moreover, the load is directly supplied with an adjustable alternating current, which not only avoids using buck converters, but also overcomes the shortcoming of the scheme presented by Lo *et al.*,¹¹ where the output is restricted to the forward turn-on voltage of the Zener diode.

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FIG. 1. Designed energy-harvesting circuit.

In this circuit, the DEG and the fixed capacitor C_f alternately switch between discharging and charging, providing the necessary conditions for energy delivery and circulation. When the pre-charged DEG becomes relaxed from its maximum stretch, the intrinsic capacitance of the device, C_{int} , decreases and the charge will flow into C_f . The reciprocal electrical behaviors of the two serial capacitors pump the electrons successively forward and backward. As marked by the red solid line, the main discharging current, therefore, loops through the capacitor C_f , the diode D2, the load R_L , and the diode D3, and then, it returns to the DEG. Conversely, when the device is stretched again, C_{int} increases and the charging process restarts with the current flowing within a reverse loop (C_f -DEG-D4- R_L -D1- C_f), as marked by the blue dashed line. This time, C_f is the power supply. The voltage difference between DEG and C_f is actually the voltage drop across the load, which can be adjusted by choosing the capacitance and resistance parameters.

If we consider the resistance of electrode R_s and that of the elastomer itself, R_p , the DEG is integrally equivalent to a circuit where C_{int} and R_p are connected in parallel and then in series with R_s .¹⁴ The current flowing through the main loop can be expressed as

$$I_R = \frac{d}{dt}(C_{int}V_{int}) \pm I_{leak} = C_{int} \frac{dV_{int}}{dt} + V_{int} \frac{dC_{int}}{dt} \pm I_{leak}, \quad (1)$$

where V_{int} denotes the voltage across the intrinsic capacitor and $I_{leak} = V_{int}/R_p$ is the leakage current through the dielectric film. $C_{int} = C_{int}(t) \in [C_{int}^{min}, C_{int}^{max}]$, and the interval limits represent the capacitance of the DEG in its maximum and minimum (initial) stretch states, respectively. The positive sign is chosen for DEG charging, while the negative sign is for discharging.

According to Kirchhoff's voltage law (e.g., the discharging process)

$$V_{int} = V_f + V_s + V_L, \quad (2)$$

where V_f , V_s , and V_R denote the voltage across the elements C_f , R_s , and R_L , respectively. This can be rewritten as

$$\left[\frac{1}{C_{int}(t)} (V_0 C_{int}^{max} - \int (I_R + I_{leak}) dt) \right] - \left[V_0 + \frac{1}{C_f} \int I_R dt \right] = I_R (R_s + R_L). \quad (3)$$

In fact, during this dynamic process of energy circulation, the DEG and C_f alternately serve as the power supply.

The integral terms in Eq. (3) represent the voltage increments across the two capacitors based on the initial voltage V_0 , due to the charge fluctuations throughout the loop.

In general, the bulk resistivity of a DE film is of the order of $10^{15} \Omega \text{ cm}$.¹⁵ The electrode is usually not more than a few hundred ohms (e.g., for conductive carbon paste, it is about $114 \Omega \text{ cm}$). Compared to the load resistance under normal operating conditions, which typically falls in the range of hundreds of mega-ohms, the two resistors are often negligible in a theoretical analysis, and the following discussion treats them in this way.

Adopting the design concept of antagonism, the fixed capacitor in the basic circuit topology can be replaced by an identical DEG (denoted as DEG2), with its deformation kept at a 180° difference with the primary DEG (denoted as DEG1). This is the critical first step in constructing a fully embedded soft system.

It can be easily inferred that for this dual-DEG scheme, the voltage and current characteristics will be superior to those for a fixed capacitor, due to the reverse-phase changes of the twinned DEGs. Figure 2 shows the voltage and current for a fixed capacitor and a dual DEG where the primary DEG behaves sinusoidally and R_s is ignored, $V_{DEG} = V_{int}$. Here, V_{DEG} , V_{DEG1} , and V_{DEG2} denote the voltages across the devices. Actually, for the fixed capacitor, $C_f \gg C_{int}$ for good performance. However, a larger capacitance would increase the time constant of the circuit, aggravating the current asymmetry in the two half-cycles.

Figure 3 presents an electromechanical cycle in the charge-voltage plane to illustrate the proposed design more clearly and to compare the two schemes. For a periodic variation of the DEG capacitance [in the direction of the arrow from C_{int}^{max} (A and A') to C_{int}^{min} (B and B')], the Q-V diagram is a closed loop in the electrical plane. The area is numerically equal to the energy harvested during a stable cycle. Intuitively, this further demonstrates the superior performance of the dual-DEG solution.

The second step in constructing a soft system is to replace the diodes constituting the rectifier bridge with some kinds of soft switches that have reverse piezoresistivity. O'Brien *et al.*¹⁶ prepared a special dielectric elastomer switch (DES) by mixing non-conductive grease and conductive particles in proportion and applying them onto a DE film. Its working principle is complicated, involving different physical mechanisms as the operating condition changes.^{17,18} When the concentration of conductive particles is high, most of them will come into contact with each other and form a real conducting network. Ohmic conduction, which describes the behavior of current passing through a resistor, is, thus, dominant. However, if the film is stretched, the particles suspended inside the mixture will move far away from each other, that is, the filler concentration decreases. This consequently makes conduction become difficult, and it depends on other mechanisms. Generally, when the filler concentration (characterized as the volume fraction of conductive particles) is below a threshold (ϕ_c), the resistance will undergo a rapid increase in magnitude due to the percolation effect, as shown in Fig. 4(a).

In the fabrication of such a DES, the non-conductive grease (Molykote 44 medium) and carbon black (Cabot Vulcan XC72) are mixed in a weight ratio of 5:1. After

FIG. 2. Time-varying curves of simulated voltage and current. (a) Single DEG. (b) Dual DEG.

applying the DE film, the mixture is dried at 55 °C for 2 h. Performance tests on the samples show that their resistance can increase from the level of mega-ohms to giga-ohms, and only a 1.17 times stretch is required. Moreover, the conductivity depends on the applied electrical field,^{19,20} especially when the film is significantly stretched. There are two conditional mechanisms that contribute to this non-contact particle conduction. When the field strength is low, the channel effect is dominant, in which the current is due to electron hopping. However, as the field increases, the so-called field emission mechanism becomes significant. The electrons have a greater probability of climbing over the potential barrier formed by the polymer layer to adjacent conductive particles, producing a field emission current. This can explain why a higher voltage leads to better conductivity and lower resistance, as indicated in Fig. 4(b).

We designed and fabricated an annular DEG with integrated DESs. Such an out-of-plane deforming structure can achieve a type of membrane deformation very close to the ideal equi-axially stretch mode, as has been proven by previous investigations.^{21,22} The fabrication procedure is illustrated in Fig. 5(a). The DEG is made from the VHB 4910

acrylic elastomer (3M, USA) and consists of two basic units. One has compliant electrodes (MG 846-type carbon paste) on both surfaces to form a sandwich variable capacitor, while two M-shaped DESs are fixed onto the outside surface of the other unit. Figure 5(b) shows a photograph of a completed DEG. To obtain good performance, as suggested by Bortot and Gei,²² the membrane is subjected to a relatively optimal biaxial pre-stretch of 3×3 during fabrication.

The electrical topology of the DES-based fully soft system is illustrated in Fig. 5(c). When working, the two DEGs are mounted on a support to maintain a 180° phase difference, with their inner rings linked together and actuated by a servo-controlled pushrod [Fig. 5(d)]. In the initial equilibrium, DEG1 is stretched maximally and DEG2 is undeformed; therefore, the soft switches S2 and S3 are not conductive, while S1 and S4 are. As DEG1 relaxes from its maximum stretch, S2 and S3 gradually switch from the off to on state. Naturally, due to the stretching of DEG2, S1 and S4 switch to the off state accordingly. Thus, we constructed a soft rectifier bridge with the same functionality as a diode combination.

We then tested and compared the performance of the two circuits with different rectifier bridges, for tensile strokes of 25 mm (with a stretch ratio of 1.41) and 35 mm (with a stretch ratio of 1.72), respectively. The tests were performed with a bias voltage of 1000 V and an operating frequency of 1 Hz. The harvested electrical energy density was calculated by measuring the current I_R as $E_h = \frac{1}{m} \int_0^T I_R^2 R_L dt$, where m denotes the mass of the effective area of the film.

Figure 6(a) compares the measured current (Galvanometer TH1961, TongHui, China) using the two types of rectifier bridges during nine operating cycles at a load resistance of 150 MΩ. Each experimental data point is the average of seven testing runs. With the DES bridge, the current

FIG. 3. Charge-voltage diagram for single- and dual-DEG schemes.

FIG. 4. Mechanism for the change in resistance and factors affecting the DES. (a) The distribution of conductive particles near the percolation threshold. (b) The measured resistance of DES varies with the amount of stretch at different voltages.

amplitude fluctuates more and the waveform is steeper. Actually, the energy (density) depends on the effective value of the current. From Fig. 6(b), we can see that for each circuit, the harvested energy rises at first and then decreases as the resistance increases, with an optimal resistance that matches the maximum energy density.

According to the maximum power transfer theorem, such an optimal value occurs when the load impedance equals that of the source as viewed from its output terminals. As mentioned previously, in the proposed circuit, the DEG and the capacitor in series with it can be collectively regarded as power supplies. For the dual-DEG scheme, the equivalent source impedance can then be derived as

$$Z_{source} = \frac{1}{j\omega C_{eq}} \approx \frac{1}{\pi f C_{int}}, \quad (4)$$

where $C_{eq} = \frac{C_{int}^2}{2C_{int}} = \frac{C_{int}}{2}$.

Since the capacitance of the DEG used in this study is at the level of nanofarads, the equivalent impedance at the low frequency of 1 Hz is, thus, at the mega-ohm level. This is basically consistent with the experimental results in Fig. 6(b).

Comparing the two circuit schemes, it is obvious that when the load resistance is relatively small (around 50 MΩ), the DES-bridge circuit harvests more energy than the diode-bridge circuit. However, as the load resistance increases, this changes. With the shorter tensile stroke (25 mm), there is no

longer a significant difference between the two schemes. As the tensile stroke gets longer (35 mm), the performance of the DES-bridge circuit, in contrast, becomes inferior to that of the diode bridge.

Possible reasons for this are as follows. First, a DES is not an ideal switch. Whether it is stretched or relaxed, the change in resistance is continuous, and the desired instantaneous switch between the two representative states cannot be achieved in practice. The generated current, thereby, will not completely flow along the main unilateral-bridge path as designed but will be partially shunted along the other branches. Take the discharging stage as an example. During the recovery of DEG1 in which switches S_2 and S_3 are relaxed while S_1 and S_4 are stretched, the whole current will theoretically flow back along the main path $DEG2-S_2-R_L-S_3$ after the on/off states of the two sets of opposite switches are interchanged. However, since the resistance of the two stretched switches cannot reach (at least not in an instant) a sufficiently large level relative to that of switches that

FIG. 5. Fabrication of a soft DEG and its working conditions. (a) Fabrication procedures of a DEG. (b) Photograph of a completed DEG. (c) Electrical topology of the soft system. (d) Installation diagram of the soft system.

FIG. 6. Comparison of measured current and the energy density of two circuits. (a) Measured current. (b) Energy density harvested in different loads under different tensile strokes.

FIG. 7. Leakage characteristics of the generated current for 500 cycles.

gradually turn on, having a current shunting through them is actually unavoidable. That is, at this point, the discharging current will pass concurrently through the four branches of the DES bilateral bridge.

A larger change in DEG capacitance (corresponding to a larger tensile stroke) leads to a larger generated current and will put the DESs in a stronger electric field. According to previous investigations on DESs, internal field emission may account for the conductive behaviors of a DES, giving the switches conductivity for a larger current. In the present experiments, both tensile strokes can reduce the conductive filler concentration below the threshold. Even so, for the larger stroke of 35 mm, a higher proportion of the current is shunted due to the lower resistance of the open switches. The effective current through the load, which dominates the harvested electrical energy, consequently declines more. In addition, with a greater load resistance, such shunt attenuation appears more pronounced.

A series of test experiments were then performed on the dual-DEG prototype with embedded DESs to analyze the combined effects of bias voltage, operating frequency, and the load on the performance of this soft system. Some results in good agreement with theoretical expectations were obtained, but they are not given here in detail.

In general, the antagonistic energy-harvesting circuit proposed not only has a simple configuration and is easy to realize but also is more efficient at converting electrical energy. By replacing the diodes in the rectifier bridge with soft switches attached to the DEGs, we constructed a fully soft DEG system, which can easily be interfaced with external electrical loads as well as with a bias supply for one-off pre-charging. Thanks to the contributions of McKay *et al.*²³ to dual-DEG self-priming circuits, the two compatible parts can be further integrated into a more functional system, which would completely get rid of the dependence on a high-voltage bias supply.

The reliability of the system is useful for practical applications. Fatigue cracks may nucleate under cyclic loading although previous studies show that DE materials can generally undergo millions of mechanical tensile cycles without failure.¹ The primary failure actually comes from charge leakage, which will strongly degrade the performance of a

DEG. From a theoretical analysis, we found that whilst the current leaking through the material in a single cycle is almost negligible, the cumulative effect after multiple cycles cannot be ignored. Moreover, the charge transfer loss at the connections (e.g., clamps) is also difficult to avoid completely in practice. As shown in Fig. 7, in our tests, the performance of the DEG does not change significantly after the first 20 cycles. However, after about 270 cycles, the generated current decays to less than 1 μ A and the DEG needs to be recharged. Nevertheless, the performance could be improved with better material properties and fabrication approaches.

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