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Citation: Appl. Phys. Lett. **98**, 142903 (2011); doi: 10.1063/1.3572338

View online: http://dx.doi.org/10.1063/1.3572338

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APPLIED PHYSICS LETTERS **98**, 142903 (2011)

Soft generators using dielectric elastomers

Thomas G. McKay,[1,a)] Benjamin M. O'Brien,[1] Emilio P. Calius,[2] and Iain A. Anderson[1,3]
[1]*The Biomimetics Laboratory, The Bioengineering Institute, The University of Auckland, 70 Symonds Street, Auckland 1001, New Zealand*
[2]*Industrial Research Limited, Brooke House, 24 Balfour Road, P.O. Box 2225, Auckland 1140, New Zealand*
[3]*Department of Engineering Science, The University of Auckland, Private Bag 92019, Auckland Mail Centre, New Zealand*

(Received 20 January 2011; accepted 11 March 2011; published online 5 April 2011)

The potential to produce light-weight, low-cost, wearable dielectric elastomer generators has been limited by the requirement for bulky rigid, and expensive external circuitry. In this letter, we present a soft dielectric elastomer generator whose stretchable circuit elements are integrated within the membrane. The soft generator achieved an energy density of 10 mJ/g at an efficiency of 12% and simply consisted of low-cost acrylic membranes and carbon grease mounted in a frame. © *2011 American Institute of Physics*. [doi:10.1063/1.3572338]

The uptake of portable electronics has grown rapidly but the advancement of battery technologies has lagged behind.[1] Also, the replacement and disposal of batteries is inconvenient and damaging to the environment. To overcome these problems there is an interest in powering mobile devices with wearable energy harvesters that for example could harvest over 10 W from human gait.[1]

Dielectric elastomer generators (DEG) are a class of variable capacitor generators with great potential for wearable energy harvesting.[2,3] DEG potentially enable light, soft, form-fitting, and silent energy harvesters with excellent mechanical impedance matching to human muscle.[4] An energy density of 400 mJ/g was reported for DEG excluding the external electronics mass,[3] a value which Prahlad *et al.*[5] report could be the highest ever recorded for any technology. Despite these advantages, they are being held back by the need for bulky, rigid, and heavy external electronics.

Electrical energy is produced when the deformation of a stretched, charged DEG is relaxed; like charges are compressed together and opposite charges are pushed apart, generally resulting in an increase in voltage. The purpose of the aforementioned external circuitry is to supply charge to the generator and extract it after each voltage boost. In previous work, the inherent capacitance of DEG was used to store this charge and the external circuitry was reduced to six diodes for controlling its supply and extraction.[6]

In this study, we present a soft generator based on self-priming DEG (Refs. 6–8) that does not require diodes or external energy storage devices because both functions are fully integrated onto the membrane.[9] The soft generator uses dielectric elastomer switches (DES) to control the distribution of charge.[10] DES consist of piezoresistive electrodes, fabricated directly onto a highly stretchable dielectric elastomer membrane, that exhibit large changes in resistance with stretch. The M-shaped DES (Fig. 1) had a resistance of several MΩ in their rest state, which increased to several GΩ when stretched to approximately 1.4 times their original length.[11] Consequently, the soft generator consists only of an acrylic membrane and carbon grease mounted in a frame.

Two membranes (Fig. 1) were fabricated by prestretching VHB4905 (3M) film equibiaxially to nine times its initial area and adhering it to inner and outer Perspex annuli. The free membrane consisted of ~0.35 g of material. Two Nyogel 756G carbon grease electrodes (1A, 1B, and 2) were applied to both sides of each membrane. The DES electrodes Q1, Q2, and Q3 painted onto the membrane were composed of five parts (by weight) Molykote 43G nonconductive grease and 1 part Cabot Vulcan XC72 carbon black.[11] The hubs of the two membranes were adhered together and their outer frames were separated by 19 mm spacers. The two membranes then formed an antagonistic pair [Fig. 1(b)], so when the hub was displaced to stretch one membrane, the other was relaxed.

The self-priming circuit consisted of a pair of DEG elements (G1A and G1B), shown in the Fig. 2 schematic, that converted energy to a higher charge form by receiving charge in a series configuration and toggling to a parallel configuration when it was extracted. The G1 pair was inter-

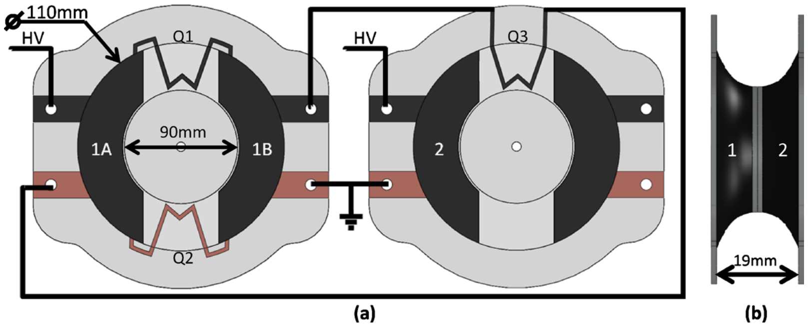

FIG. 1. (Color online) The physical layout of the soft generator.

[a)] Electronic mail: thomas.mckay@auckland.ac.nz.

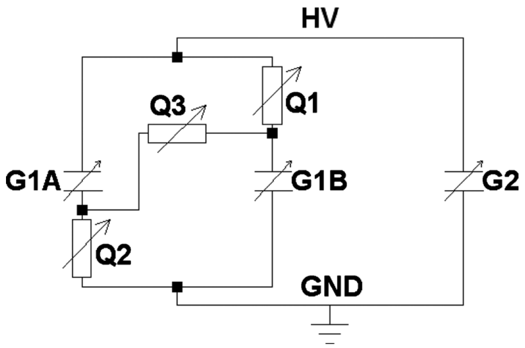

FIG. 2. The equivalent circuit of the soft generator.

connected with three DES (Q1, Q2, and Q3) and was deformed in phase with Q1 and Q2. G2 and Q3 were stretched 180° out of phase with the G1 pair because of the antagonistic configuration. Q1 and Q2 took on a high resistance and were not significantly conductive when stretched; meanwhile Q3 took on a low resistance, effectively placing the G1 pair in series. The pair toggled back to parallel when it relaxed because Q3 stopped conducting and the resistance of Q1 and Q2 dropped.

The soft generator was initially primed to 10 V [between the high voltage (HV) and ground (GND) nodes] through a high voltage diode and the inner hub was displaced sinusoidally at an amplitude of 19 mm. This mechanical cycling was stopped when the generator voltage reached 2 kV. Five of these experiments were repeated using the same generator at each of the frequencies of 1, 2, and 3 Hz. These experiments were also replicated using a second identical generator but with the DES substituted for diodes as described elsewhere by the authors.[12] The voltage between the HV and GND nodes was measured using a 1000:1 5 GΩ voltage divider. An interface SM-50N load cell was used to measure the force to deform the generator and the efficiency and energy generated in the final cycle were calculated as previously described.[7] The energy density was calculated by dividing the generated energy by the mass of the membrane and this mass included that of the diodes (additional 0.63 g) when they were used instead of DES. Two DES were weighed using Mettler PM4800 Delta Range scales but their mass was within the 0.01 g resolution, thus the DES mass was considered negligible. Although the mass of the Nyogel electrodes was significant (0.56 g), it was also neglected from the energy density calculations because very low mass electrodes such as carbon nanotubes could be substituted.[13]

A typical voltage output of the soft generator is shown in Fig. 3, which climbed from 10 V to a peak of 2000 V over a period of 11.5 s. The voltage boosted because the generator produced more charge in each cycle than was dissipated through the voltage divider and losses.

Figure 4 plots the energy density and efficiency of both generators at 1, 2, and 3 Hz. The soft generator produced a superior energy density at all three frequencies and both generators achieved efficiencies of 3% and 12% at 1 Hz and 3 Hz, respectively. The energy production and efficiency generally climbed with frequency. This is because the generated power increases with frequency whereas the losses remain relatively constant. In contrast to the diodes based generator the performance of the soft generator was worse at 2 Hz than 1 Hz, this requires further investigation focusing on DES aging, manufacturing, and materials.

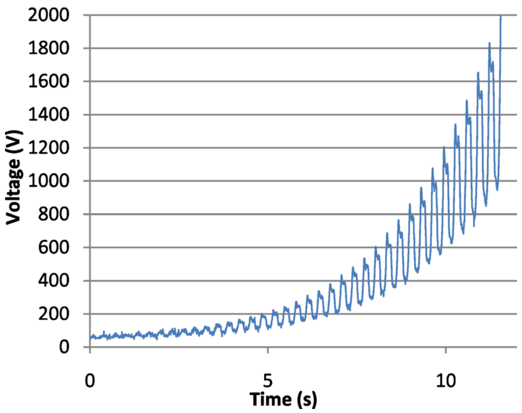

FIG. 3. (Color online) The output voltage of the soft generator when cycled at 3 Hz.

The soft generator exhibited an energy density of 10 mJ/g at 3 Hz whereas the diodes based generator produced 4.4 mJ/g. These energy densities compare favorably to that of the previously described integrated self-priming generator (2.7 mJ/g).[6] The soft DEG produced a superior energy density because the mass of the external diodes was significant compared to that of the membranes at the scale used in this work. Additional to their competitive efficiency when compared to the diode based generator, this demonstrates the potential for soft generators in small scale applications. These applications are not limited to wearable devices, they also include a light-weight power source for autonomous robots.[14]

Although the mechanism of DEG is scale invariant,[5] the cost of their electronics may be a significant disadvantage for small scale applications because of the unique combination of high voltages and low currents.[3] This work demonstrates the use of low-cost materials to produce DEG-based soft generators at a relatively small scale that lend themselves to cost effective manufacturing processes such as inkjet or three-dimensional printing.[15]

The soft generator was initially charged to 10 V from an external supply but lower voltages are feasible.[7] In an additional experiment the soft generator was able to climb to 2 kV after an initial priming of just 0.5 V. The development of DES with minimal losses could reduce the required initial

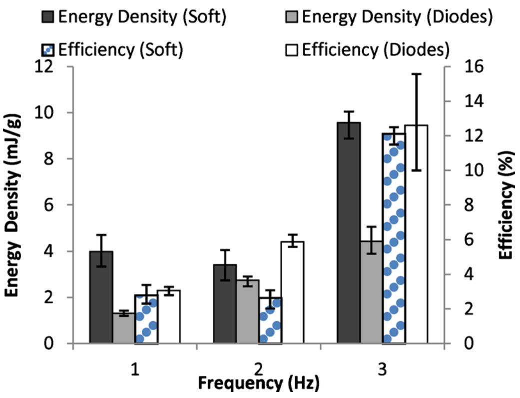

FIG. 4. (Color online) The average final cycle energy density and efficiency versus frequency for the soft DEG and the equivalent diodes based generator. The error bars indicate the maximum and minimum values obtained from five experiments.

voltage enough for ambient radiation to supply sufficient initial priming charges. Alternatively a piezoelectric polymer could be incorporated into the generator. These improvements will lead to truly autonomous wearable soft generators that utilize all the advantages of DEG.

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