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Possibility of a Portable Power Generator Using Dielectric Elastomers and a Charging System for Secondary Batteries

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Abstract: Energy generation using dielectric elastomers (DE) has received a great deal of attention due to their light weight, low cost, and high efficiency. This method is an environmentally friendly system that generates electricity without emitting carbon dioxide and without using rare earths, and can contribute to the reduction of global warming. However, this DE system is expected to be used for wearables, such as shoe power generation, because it is not yet possible to make an energy generation element of a very large size. The problem is that this small DE generator can only generate a small amount of energy at one time. Therefore, in order to increase energy generation efficiency, it is necessary to use a material with higher conductivity for the DE electrode. Moreover, since DE energy generation is output at a high voltage, a circuit capable of stepping down with high efficiency is required in order to use this power for ordinary electric appliances. In addition to this, a circuit that can charge the secondary battery with high efficiency from the surplus power obtained by energy generation is also required. However, these are still technically difficult and have hardly been studied so far. We identified a highly efficient step-down circuit using two diaphragm-type DEs with a diameter of 8 cm, dropped 3000 V to 3.3 V, and succeeded in charging the secondary battery. The possibility of wearable or portable energy generation was shown in a commercial manner.

Keywords: dielectric elastomers; generators; high efficiency conversion; portable; wearable; secondary battery charging; step-down circuit; commercial manner

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1. Introduction

An electroactive polymer (EAP) is called a "soft actuator" or "artificial muscle" because of its flexible movement [1–5]. Among EAPs, the most promising one is the dielectric elastomer (DE) [5]. In 1990, SRI's S. Chiba, R. Perline, and other researchers at Stanford Research Institute started DE research [6]. This research and development is currently progressing rapidly all over the world towards the practical application of this technology.

The DE structure is simple. Flexible electrodes [5–7] are placed above and below the elastomer film, which is the main component. The driving principle is that when a voltage difference is applied between the electrodes, the Coulomb force causes the polymer to shrink in thickness, causing planar expansion.

So far, many studies have been conducted on different materials and their physical properties, DE systems, and electric circuits [5–27]. The main materials of DEs are viscoelastic elastomers (polymers) such as silicon, acrylic, hydrogenated nitrile rubber (HNBR), polyurethane, natural rubber, fluorosilicone, PVC, fluoroelastomer, and styrene. [7–9]. By having viscoelasticity, muscle-like movement is reproduced. In addition, the typical thickness of an elastomer is about 200 μm to 1 mm [10].

Ultra-thin gold and silver, carbon grease, carbon black, graphene, single-wall nanotubes (SWCNTs) and multi-wall nanotubes (MWCNTs), etc., are used as the electrode materials [10,11]. The elongation and output of DEs using a material with high conductivity as an electrode, such as SWCNT, are large [11]. Metallic materials have excellent conductivity, but the material itself is not very flexible, so the elongation of the DEs is quite small [10]. E. Hajiesmailie et al. examined carbon nanotubes (CNTs) as electrodes [12]. However, the electrodes using CNTs shown in the paper were very thick, several hundred μm, inflexible, and unfortunately not sufficiently elastic. It was presumed that the carbon nanotubes were not sufficiently dispersed. ZEON Corp. first added SWCNTs and 2% sodium cholic acid by weight to the dispersion medium. The mixture was then well dispersed over time using an ultrasonic homogenizer. As a result of using the dispersed SWCNTs, it was possible to develop an electrode that was ultra-flexible and sufficiently stretchable [11].

The electrode made by ZEON corporation uses a relatively high voltage to drive the DE and produces large elongations and outputs. However, attempts have been made to drive it at a relatively low voltage even if the elongation or output is small. P. Hu et al. tried to use a soft silicon material with a low degree of chemical cross-linking and drive an electrode at a relatively low voltage [13,14]. Alternatively, if the film thickness of the elastomer is set to about 20–40 μ, it can be driven with a few volts or less [10]. Furthermore, since the electric permittivity is thought to improve the performance of the DE, M. Carmel added a metal filler as one way to improve the permittivity [15]. For the same reason, attempts have been made to add barium titanate [16]. L. Romasanta et al. [17], E. Hajiesmailiet et al. [12], and Li et al. [8,9] have reviewed the SS curve, permittivity, dielectric loss, viscoelastic damping, etc., so far.

Larger elongation or output can be obtained by first pre-stretching the elastomer, called the pre-stretching method, and then attaching electrodes to it [7]. However, H. Kumamoto developed a small mobile robot that can be driven and deformed without pre-stretching of the elastomers [18]. S. Hayat et al. [19] considered an electric supply driver for the DE actuator (DEA). It seems that their design concept could lack safety and their efficiency was a bit questionable. ZEON Corporation and others have developed a driver for the DEA [20]. Their drivers are capable of supplying high voltage accurately and quickly.

F. Albuquerque studied the effects of humidity, temperature, and elastomeric materials on the life of a silicone elastomer-based DEA [21]. It is also known that in order to extend the life of the elastomer, it is better to create one with the best performance and operate it at a lower performance level [22]. In a recent study to maximize the performance of acrylic elastomer DE, we succeeded in lifting 8 kgf by more than 1 mm at a rate of 88 msec using 0.15 g of the elastomer [20,23,24]. The edges of the DE were reinforced with acrylic so they would not be destroyed by repeated loads. As a result, the total weight was 0.97 g. This result shows that the DE lifespan will be dramatically extended if it is driven with lower performance.

In the currently reported papers on robots using the DE actuator (DEA), as mentioned above, there are only research cases of small robots. As further examples, L. Romasanta et al. [17], L. Xu et al. [25], and J. Youn et al. [26] challenged the development of small DEA grippers, but their grip output was very small. W. Thongking et al. achieved improved grip by stacking DEs. [27] J. Ashby et al. created a small serpentine DE robot with electro-adhesive pads [28]. To make a large robot, it is better to use a large amount of highly conductive material such as CNTs, but the following two points seem to be the bottleneck: (1) the price of CNTs is quite high, and as mentioned above, (2) it is very difficult to disperse CNTs.

Another important aspect for the future of the DE is that when the DEA is reverse-driven, it generates electricity with high efficiency [24,29]. In this paper, we researched and developed a small portable DE generator (DEG) to consider the factors that improve the performance of the above DEG.

2. Background of the DEG System

Since the output of DE energy generation is intermittent, it is indicated using (J) in this paper. In the energy generation mode, a DE is considered a variable capacity device [10]. Electric charges are generated on the elastomer film in a stretched state (high capacitance). When the film shrinks (low capacitance), the elastic stress of the film acts against the electric field pressure, increasing the energy. At the microscopic level, the polymer pushes away the opposite charge on the opposite electrode (thickness increases in the contracted state) and brings similar charges closer in the electrode (decreased in-plane area in the contracted state). Both of these changes to the charge increase the voltage difference, thereby increasing the stored electrical energy. The principle of the DEG is shown in Figure 1.

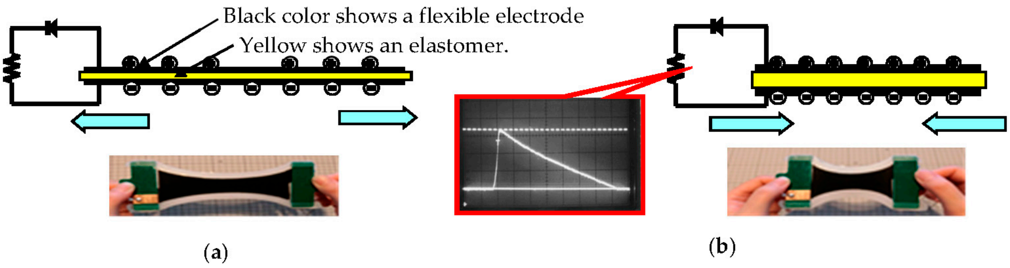


Figure 1. DEG Principle: The middle photo shows a typical oscilloscope trace from a DE contraction. Voltage spikes occur during contraction and gradually return to the voltage of the stretched stage due to load resistance. (**a**) DE extended by external force, (**b**) DE returns to its original shape.

The capacitance C of a DE film can be written as

$$C = \varepsilon_0 \varepsilon A/t = \varepsilon_0 \varepsilon b/t^2 \quad (1)$$

where ε_0 is the dielectric permittivity of free space, ε is the dielectric constant of the polymer, A is the active polymer area, t is the thickness, and b is the polymer volume. The last equality in Equation (1) can be written because, for elastomers, the volume is essentially constant; that is, A*t = b = constant. The energy output of a DEG for a single cycle of stretching and contraction is related to the change in capacitance of the DE layers as

$$E = 0.5C_1 V_b^2[(C_1/C_2) - 1] \quad (2)$$

where C_1 and C_2 are the total capacitances of the DE layers in the stretched and contracted states, respectively, and V_b is the bias voltage. Thus, some energy is needed first to put a charge on the DE, but this charge actually recirculates. Net power is generated just by expanding and contracting the DE.

Considering the changes with respect to voltages, the electric charge Q on a DE film can be considered to be constant over a short period of time and in the basic circuit. Since V = Q/C, the voltages in the stretched state and the contracted state can be expressed as V_b (i.e., the bias voltage) and V_2, respectively, and the following equation is obtained:

$$V_2 = Q/C_2 = (C_1/C_2)\,(Q/C_1) = (C_1/C_2)\,V_b \quad (3)$$

Since $C_2 < C_1$, the contraction voltage is higher than the extension voltage, which corresponds to the energy discussion above. Higher voltages can be measured and compared with theoretical predictions developed in our previous work [30,31]. This theory was proved in 2013 by a generation experiment using a two-dimensional wave tank [30]. In general, experimental data based on high impedance measurements are in excellent agreement with predictions. Considering the change in voltage, the charge Q of the DE can be regarded as constant in a basic short circuit.

Like the DEA, the DEG has been researched and developed with various DE materials, mechanical systems, and circuits. Some examples of DE materials and mechanical systems under consideration are silicon and acrylic, which were used to create DEGs of the same size. In the results, acrylic obtained larger power generation [10]. This is considered to be due to the difference in viscoelasticity. Similarly, Zhu et al. showed that the viscoelasticity of an elastic material has a significant effect on electromechanical coupling and dynamic performance [8,9]. Moreover, like DEAs, the effectiveness of carbon nanotubes as electrodes for DEGs has been shown [11]. Koh et al. showed that various failure models such as electromechanical instability, dielectric breakdown, loss of tension, and elongation failure define the cycle of maximum conversion energy [32]. Huang et al. claimed to have achieved some improvement in energy density as well as power density using equibiaxial stretching [33]. Vertechy et al. show a reduced, dynamic model for inflated circular diaphragm DE generators (ICD-DEGs), featuring one kinematic degree of freedom, and account for DE viscoelasticity [34]. The performance of a DEG composed of an annular membrane deformed out-of-plane by an external oscillating loading was investigated by using a hyper-electro-elastic model with parameters adjusted to simulate the behavior of material such as an acrylic elastomer and a type of natural rubber [35]. Moretti et al. also studied parallelogram-shaped DEs (PS-DEGs) and argued that they were effectively used as both rotary and linear transducers [36]. Brochu et al. made a wind power generator using DEGs and made a single DE layer device with an active elastomer volume of 0.57 cm^3. It was observed that a maximum energy conversion efficiency of more than 55% can generate about 40 mJ per cycle [37].

Next, as an example of circuit design, McKay et al. showed a DEG in which elastic circuit elements were integrated into a DE film [38]. Anderson et al. introduced soft DE electronics technology that could replace the diodes in the DEG priming circuit [39]. It has been shown that the diode can be replaced with an active switch between the DEF and the voltage source and load to improve control of the DEF charge state [38,39]. Kussel et al. developed a passive DEG system which uses only diodes at the generator level [40].

Various applications of DEGs have also been studied. Generator applications can be divided into two types [41]: (1) point generator application, a type that generates electricity using a single generator, and (2) distributed generator application, a type that installs many generators in a local place for the purpose of local production for local consumption. For example, one such system installs a large number of wind power generators over a wide area and obtains a large amount of power generation to some extent.

Home-sized wind turbines are being studied as a point application for DEGs [37,42,43]. A type using the Kalman style is possible with high efficiency. This power generation causes the Kalman flow by wind or water flow to generate electricity. There is also considerable research on power generation systems that incorporate DEGs into buoys. This generator has been proven to generate electricity fairly efficiently against various waves. The oscillating water column type wave generator was devised by Moretti et al. [44–47] and Vertechy [34].

Wearable power generation using the movement of people is also being researched. Jean-Mistral et al. showed a wearable DEG that could obtain very small amounts of energy using human movement [48]. However, it is quite tiring for humans to use it for longer because they must extend the elastomer themselves to generate electricity. Therefore, shoe power generation was devised by incorporating DEGs into the heel of shoes [20]. This type does not bother wearers much because it uses the wearer's weight to generate electricity. Moreover, a system was devised that incorporates a DEG into a ball and rolls it to generate electricity [49]. It is thought that in the future, it will be possible to generate electricity from vibrations of cars, structures, pipes, etc. [10]. Research on DEGs using solar heat is also being conducted. Furthermore, temperature difference power generation and waste heat power generation are also being studied [50].

One example of the distributed power generation of DEGs is a system for constructing a large-scale power generation system by assembling a large number of buoy generators mentioned above [24,49–52]. When buoys loaded with DEGs are arranged in three rows, the waves hit each buoy in turn and generate electricity. Interestingly, the height of the wave at the last buoy was lower than the height of the wave just before hitting the first buoy [50–52]. It is thought that some of the wave energy was converted into electrical energy. Moreover, as with wave power generation, it seems effective to build a system by collecting a large number of DEGs that generate power using the Kalman style from the viewpoint of local production for local consumption.

3. Experimental Procedure

We first made DEGs and measured their power generation performance. After that, using this DEG, we investigated and improved circuits that step down and a circuit that can charge a secondary battery.

3.1. Manufacture of DE Cartridges and DEGs

The DE cartridge used in the experiment was a circular type with an outer diameter of 100 mm and a DE diameter of 80 mm (see Figure 2). The elastomer used for the DE was processed from a 3M acrylic sheet (VHB4905, thickness 0.5 mm). At that time, prestrain of 100% was given. The point to note here is that the elastomer sheet often has micro-un-uniformities, so in this experiment, the sheet was placed on a horizontal workbench, and a weight was placed on it for a while to remove local distortion. [9]. The spacers on the outside and the center of the DEG cartridge were made by processing a hard acrylic sheet with a thickness of 5 mm.

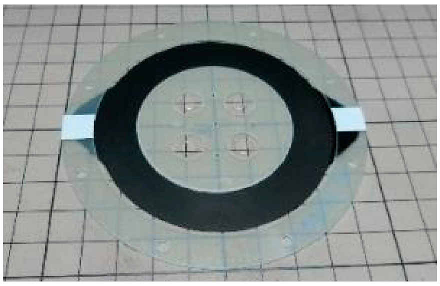


Figure 2. Circular DE cartridge.

As the materials for electrodes, SWCNTs (ZEONANO®-SG101, Zeon Corp., Tokyo, Japan) were used. As described above, first, SWCNT synthesized by the super growth CNT method [53] and 2 wt % sodium cholic acid were added to the dispersion medium. Next, an ultrasonic homogenizer was used to disperse enough over time. A small amount of binder was mixed with the sufficiently dispersed SWCNTs to prepare SWCNT ink. In order to make it easier to apply the ink to the elastomer, it was packed in a spray bottle to achieve uniform application (see Figure 3). Through these operations, we were able to make an electrode that was ultra-flexible and fully stretchable [11].

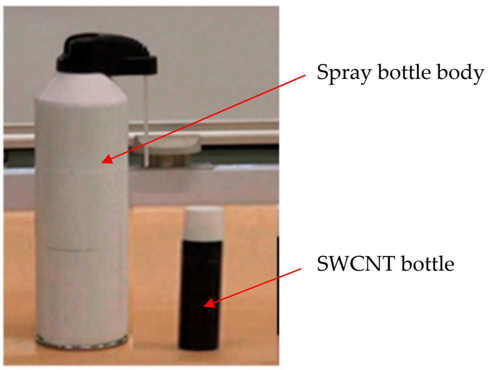


Figure 3. Spray bottle body and SWCNT bottle for spraying SWCNTs. To use the bottle containing SWCNTs on the right side, it is inserted it into the plastic tube (see arrow) of the spray body.

The thickness of the electrode of the SWCNT was 70 μ. Using the above two DE cartridges, a DEG was manufactured and used as a small power generation (DEG) device.

3.2. Measurement of the Amount of Power Generated by the Small DEG Device

The electric energy (E) actually obtained by the DEG can be calculated by the following procedure using each of the above equations:

(1) The voltage (V_2) between the upper and lower electrodes of the DEG in the contracted state can be measured for each wave frequency using a digital oscilloscope (see Figure 4).

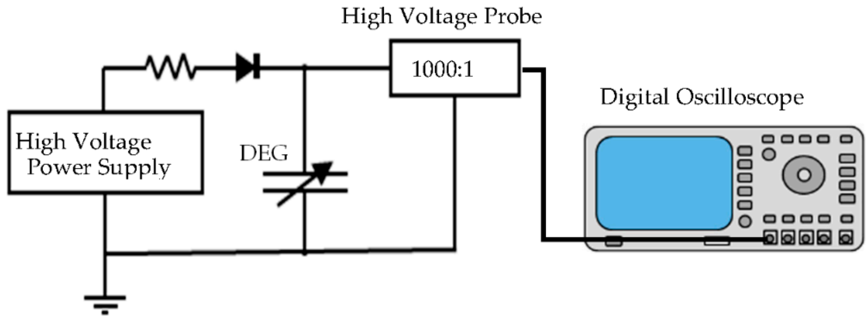


Figure 4. Voltage measurement circuit of the DEG in the contracted state.

(2) The capacitance (C_2) of the DEG in the contracted state is measured with a digital LCR meter (see Figure 5).

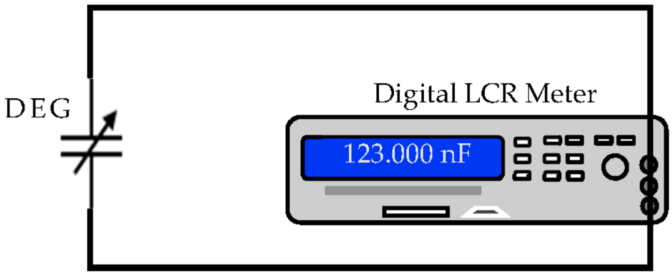


Figure 5. Measurement circuit of the capacity of the DEG in the contracted state.

(3) Using Equations (1) and (2) and the values of C_2 and V_2, the amount of energy generation can be calculated as follows:

I. The relationship $C_1 = V_2C_2/V_b$ is derived from Equation (1).

II. Next, by introducing C_1 into the Equation (2), the generated electric energy can be obtained.

$$E = 0.5V_bV_2C_2\ [(V_2/V_b) - 1] \tag{4}$$

III. Using Equation (4) and the values of C_2 and V_2, the energy generated at the frequency of each wave of the DEG can be calculated.

It should be noted here that if the amount of energy generation is not calculated according to the above procedure, the energy applied at the initial stage will be included in the calculation, yielding an erroneous result. Recently, in some papers, the amount of energy generation is calculated by the wrong procedure. It is not possible to determine the correct amount of energy generation unless the added energy and the generated energy are clearly separated.

3.3. Examination/Improvement of a Step-Down Circuit for Small Power Generation Devices

Commercially available step-down DC/DC converters (5 V, 12 V, and 24 V outputs) were examined. We first considered a method of directly supplying the output from the DEG to a DC/DC converter connected in series. Next, we examined/improved the method of constant voltage using a Zener diode, a direct conversion IC, or an energy harvesting-dedicated IC after stepping down to several V using a capacitor.

(1) MORNSUN 1DC/DC converter

The following two types of MORNSUN converters were examined.

1. 1000 V DC/DC converter (see Figure 6).
    - Input voltage: 100 to 1000 V.

- Output voltage: 12 V, 24 V.
- Three DC/DC converters were connected in series and the maximum input voltage was set to 3000 V.
- The circuit method of the DC/DC converter is unknown due to non-disclosure.

2. 1500 V DC/DC converter (see Figure 7)
    - Input voltage: 200 to 1500 V.
    - Output voltage: 12 V, 24 V.
    - Two DC/DC converters were connected in series and the maximum input voltage was set 3000 V.
    - The circuit method of the DC/DC converter is unknown due to non-disclosure.

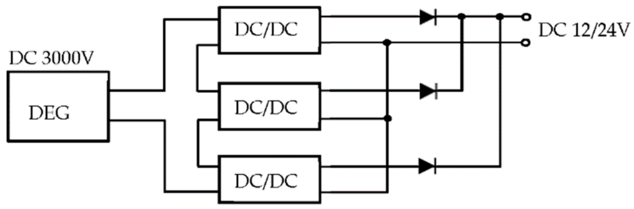


Figure 6. The 1000 V DC/DC converter.

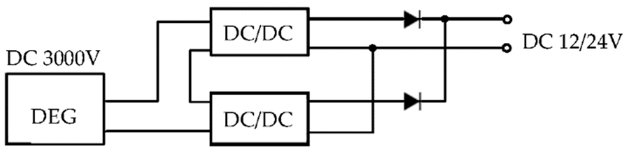


Figure 7. The 1500 V DC/DC converter.

(2) Fairchild DC/DC converter (12 V output) A step-down circuit was created using a direct conversion IC for this converter (see Figure 8).

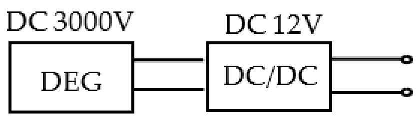


Figure 8. The 3000 V DC/DC converter.

(3) Circuit using HOLTEK DC/DC converter IC (5 V output) The output from the small DEG device was stepped down to the rated input voltage of the DC/DC converter by a circuit using a capacitor, and then the voltage was made constant by using the DC/DC converter (see Figure 9).
- The efficiency of the DC/DC converter used is 85% or less (catalog value).

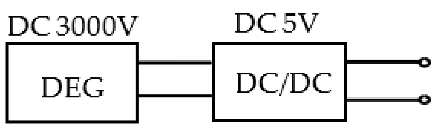


Figure 9. HOLTEK DC/DC converter IC.

(4) TOREX DC/DC converter The output from the small DEG device was stepped down to the rated input voltage of the DC/DC converter by a circuit using a capacitor, and then the voltage was made a constant by using a DC/DC converter (see Figure 10).
- The efficiency of the DC/DC converter used is 92% or less (catalog value).

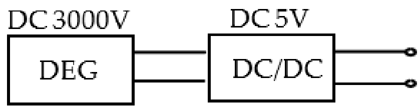


Figure 10. TOREX DC/DC converter.

(5) Circuit using Zener diode (5 V output) The output from the small DEG device was stepped down to a few volts by a circuit using a capacitor, and then converted to a constant voltage using a Zener diode (see Figure 11).

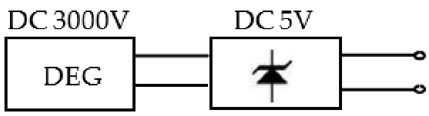


Figure 11. Circuit using Zener diode.

(6) Shunt regulator circuit with TI reference voltage IC (5 V output) The output from the small DEG device was stepped down to a few volts in a circuit using capacitors. After that, a constant voltage was set using a shunt regulator circuit using a reference voltage IC (see Figure 12).

- Uses TI reference voltage IC.
- Uses NEC reference voltage IC.

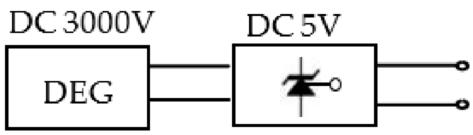


Figure 12. Shunt regulator circuit with TI reference voltage IC (5 V output).

(7) Shunt regulator circuit with TI reference voltage IC (2.5 V, 5 V output) The output from the small DEG device was stepped down by a few volts in a circuit using a capacitor, and then converted to a constant voltage using a reference voltage IC (see Figure 13).

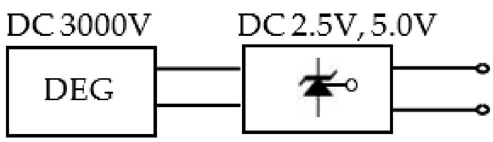


Figure 13. Shunt regulator circuit with TI reference voltage IC (2.5 V, 5 V output).

(8) Circuit using a dedicated energy harvesting IC manufactured by Analog Devices (DC3.3 V) After stepping down the rated input voltage of the energy harvesting-dedicated IC in a circuit using a capacitor, the output from the small DEG device was stored and converted to a constant voltage using the energy harvesting-dedicated IC (see Figure 14).

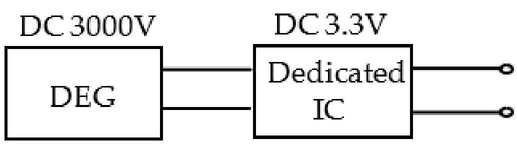


Figure 14. Circuit using a dedicated energy harvesting IC manufactured by Analog Devices (DC3.3 V).

3.4. Development of a Circuit That Can Charge a Secondary Battery

Since the power generated by a small DEG device is low and the generated energy is output intermittently, it is not possible to obtain stable power with a circuit using a general

DC/DC converter or regulator IC. In addition, in order to charge lead–acid batteries, nickel–metal hydride batteries, lithium-ion secondary batteries, etc., it is necessary to supply continuous electric energy for several hours using a dedicated charging circuit. It is difficult to use a power storage circuit using these secondary batteries because, as described above, the generated energy is intermittently output from the small DEG device. For these reasons, we decided to use a storage circuit that uses a capacitor that does not require a dedicated charging circuit and can efficiently store the energy that is intermittently generated with a short charging time for the power storage circuit used for small DEG devices (see Figure 15).

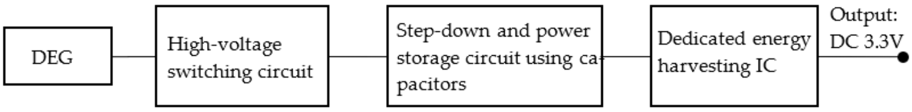


Figure 15. Block diagram of power storage circuit.

4. Results

The following results were obtained from the above experiments and circuit studies/improvements.

4.1. Power Generation Performance of DEG

In order to charge a secondary battery through a step-down circuit of a small DEG device, it is required to sufficiently improve its power generation performance. To this end, the strain of the 3M film was removed, and relatively larger pre-stretching was applied. In addition, SWCNTs with high conductivity were used. Moreover, the dispersibility of the SWCNTs was also further improved. That is, it is possible for SWCNTs to be properly and dispersed on the elastomer, so as to become more conductive [11]. The dispersed SWCNTs can be made into SWCNT ink, which makes it possible to pack the ink into the spray, which can simplify the manufacturing of the electrode. In addition, it has become possible to accurately control the thickness of the electrodes.

Figure 16 shows an overview of the small DEG device. The small DEG device consists of a device unit in which a DE cartridge (see Figure 2) is mounted in an acrylic insulating case, and a switch unit that connects to the load only during power generation. Since the small DEG device uses a high voltage of about DC3000 V, the device part was manufactured using acrylic as the main material in consideration of insulation.

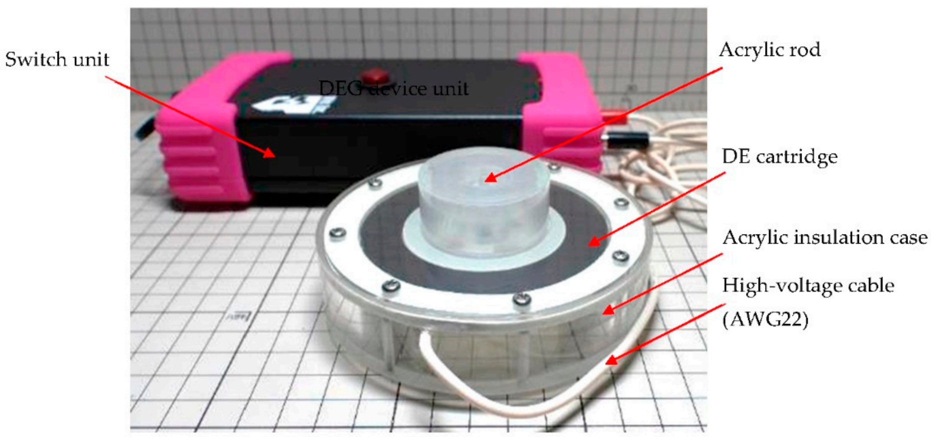


Figure 16. The small DEG device.

With a structure that can push the acrylic rod installed in the center up to 15 mm, it is possible to give a displacement of up to 15 mm to the DE cartridge. The amount of power generated this time was 33.6 mJ in one operation. The amount of displacement can be increased up to about 20 mm. However, since the generated voltage approaches the breaking voltage of the DE cartridge (about 3200 V), the mechanism is designed so that it does not displace by 15 mm or more in consideration of durability for repeated experiments. In addition, since the voltage output from the DE cartridge is as high as about 3000 V, a high-voltage cable manufactured by Krabe Co., Ltd., Tokyo, Japan with a silicon coating was used for wiring. This high-voltage cable has a thickness of AWG22 (American Wire Gauge 22) and has a withstand voltage of 10,000 V DC. The switch unit has a function of being connected to a load only in the power generation state, and the switch is turned on when the generated voltage is higher than the initial applied voltage and turned off when the generated voltage is lower than the initial applied voltage. Circuit loss can be reduced by using a mechanical switch for this changeover switch, but the system configuration becomes more complicated because a mechanism for obtaining the timing for turning the switch on/off is required. In this experiment, we aimed to realize a power generation system with a simpler configuration, so we adopted a switch circuit using a diode that operates only with a voltage value.

Figure 17 shows the relationship between the amount of deformation (mm) when the acrylic rod installed in the center of the DE cartridge is pushed in the vertical direction, and the obtained energy (mJ). The weight of the acrylic elastomer used is 0.21 g.

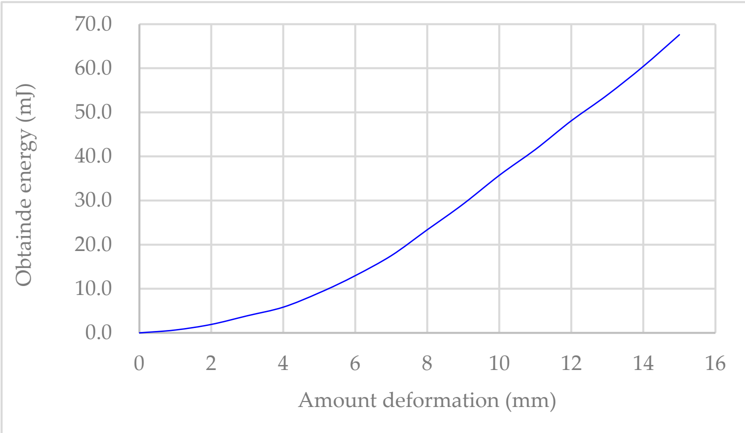


Figure 17. The relationship between the amount deformation (mm) when the acrylic rod installed in the center of the DE cartridge is pushed in the vertical direction, and the obtained energy (mJ).

4.2. *Examination of Step-Down Circuits for Small Power Generation Devices*

The results of the study and improvement of each DC/DC converter are detailed below.

4.2.1. MORNSUN DC/DC Converter

Two types of converters (1000 V and 1500 V) were examined. When a small DEG device was connected, no output was obtained for either type. The probable cause is that the conversion efficiency is low and output cannot be obtained with a small amount of power generation. The conversion efficiency (nominal value) of this unit is recorded to be 79% or less. This converter could probably be used in medium-sized DEG systems. However, in order to charge a 12 V battery, an additional charging circuit is required, so it seems that it is not suitable for charging a secondary battery.

4.2.2. Fairchild DC/DC Converter

This converter was connected to the small DEG device, but no output was obtained. The reason for this is thought to be that the IC cannot be driven with a single power generation energy source because it uses a self-excited switching regulator. This converter may also work with medium-sized debugs. Since this converter can change the output voltage and current by changing the circuit, it seems possible to use it as a charging circuit (except for batteries that require special control such as lithium-ion batteries).

4.2.3. Circuit Using HOLTEK DC/DC Converter IC (5 V Output)

The output from the small DEG device was divided and then directly connected to the DC/DC converter, but the output was small and the output voltage was reduced from 12 V to 5 V to increase the output energy. As a result, we were able to confirm some of the output, but not as much as we could confirm with a digital tester. It is necessary to consider a more efficient circuit, if using it for this purpose.

4.2.4. Circuit Using TOREX DC/DC Converter IC (5 V Output)

When the output from a small DEG device was divided and then directly connected to a DC/DC converter, an output of 1 V could be confirmed, but this circuit was originally designed with an output voltage of 5 V, so it did not work properly. This is thought to be due to the small amount of power generation.

4.2.5. Circuit Using Zener Diode (5 V Output)

When a circuit using a Zener diode was connected to a small DEG device, a 2.2 V output was confirmed, but a 5 V voltage was not obtained. It is considered that this is because the Zener current (I_Z) required to reach the Zener voltage (V_Z) cannot be supplied. An example of the Vz–Iz characteristic of the Zener diode is shown in Figure 18.

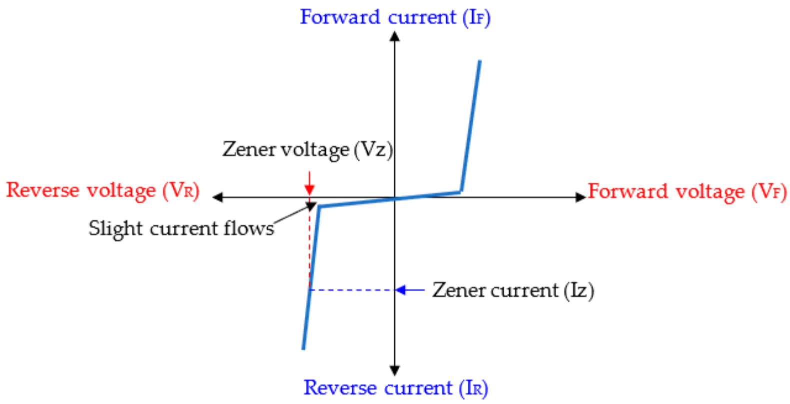


Figure 18. Example of Vz–Iz characteristics of Zener diode.

In order to improve the situation described, it is considered that stable voltage can be obtained even in this circuit by selecting a device whose Zener voltage changes rapidly even with a small amount of current or by increasing the number of DE cartridges used for small DEG devices.

4.2.6. Shunt Regulator Circuit with TI Reference Voltage IC (5 V Output)

When using a TI reference voltage IC and connecting it to a small DEG device, a 0.4 V output was confirmed. When using a reference voltage IC manufactured by NEC and connecting it to a small DEG device, an output of 0.6 V was confirmed. Since the shunt regulator circuit requires a reference voltage, current is constantly flowing, and it seems that it is not suitable for an intermittent power generation method.

4.2.7. Shunt Regulator Circuit with TI Reference Voltage IC (2.5 V, 5 V Output)

When a small DEG device was connected, 1.5 V output was confirmed in the DC2.5 V circuit, and 2.3 V was confirmed in the DC5 V circuit.

In this experiment, it was not much different from the Zener diode. In the case of a reference voltage IC, the voltage that can be output is limited compared to a Zener diode, so it is considered that it is not a very practical circuit.

4.2.8. Circuit Using an Energy Harvesting IC Manufactured by Analog Devices, Inc. (DC3.3 V)

It was confirmed that the generated energy was stored in the energy storage circuit in the IC, and after the energy was stored up to the specified value, a stable voltage of DC3.3 V was output. We also confirmed that a start-up signal (a signal that awakens an external microprocessor) was output.

4.3. A Circuit That Can Charge a Secondary Battery

The step-down circuit used here is a kind of switched capacitor circuit, which steps down the output voltage from a small DEG device to about 2 V. At the same time, by using it as a condenser for storage, the number of circuit parts was reduced and the efficiency of the circuit was improved. The impedance between each circuit of this power storage circuits was adjusted for the following purposes.

(1) To obtain an output of a stable voltage of 3.3 V by driving a small DEG about 20–30 times.
(2) To optimize the voltage and current applied to the DE module, step-down circuit, regulator circuit, and power storage circuit.

5. Discussion

SWCNT was used to increase the amount of energy generated by the DE cartridge. The following is the DEG energy generation data for wave energy generation that supports it. A Drape type with a height of 120 mm and a diameter of 260 mm (see Figure 19) could support a DE cartridge by changing the type of electrode material. A DEG was created and an energy generation experiment was conducted. Table 1 summarizes the amount of energy generated when the DE is pulled by about 60 mm [11]. The elastomer weight of the drape type DEG was 4.6 g, acrylic material was used, and carbon black, MWCNTs, SWCNT, and high crystal SWCNTs were used as the electrode materials. The amount of energy generated using carbon black was 284 mJ. Changing the electrodes to MWCNTs or SWCNTs will allow more energy to be obtained, as shown in Table 1. This is because the conductivity of MWCNT and SWCNT is higher than that of carbon black. As a result, as shown in Table 1, in the energy generation experiment using the SWCNT electrode, the amount of energy generation was about 2.3 times that of the carbon black electrode. High-crystal SWCNTs have produced about three times as much energy generation.

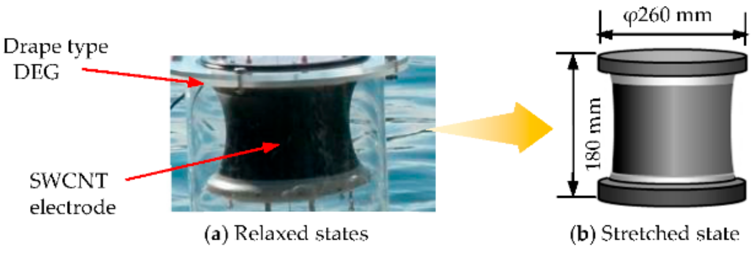


Figure 19. Drape type DEG: (**a**) buoy containing the drape type DEG having the size of 120 mm × 260 mm (no elongation state), (**b**) the time when it is extended by 60 mm from the original length by waves.

Table 1. Difference in energy obtained when changing electrode material.

Type of Electrode	Energy Obtained (mJ)
Carbon black	274
Multi-walled carbon nanotube (MWCNT)	445
Single-walled carbon nanotube (SWCNT)	630
High crystalline SWCNT	819

From this experiment, it appears best to use a high crystalline SWCNT as an electrode. However, it is extremely difficult to obtain this CNT. This is because the amount that can be synthesized at one time is extremely small. Furthermore, unlike so-called CNTs, this CNT morphology does not have many straight needle-shaped shapes and is considerably intertwined, so it is difficult to separate them. Therefore, it was not adopted in this experiment.

As for the elastomer strain correction, as shown in Figure 20, a comparison of the elongation of 3M acrylic (black) and the strain-removed film (red) clearly shows increased elongation of the removed film [9].

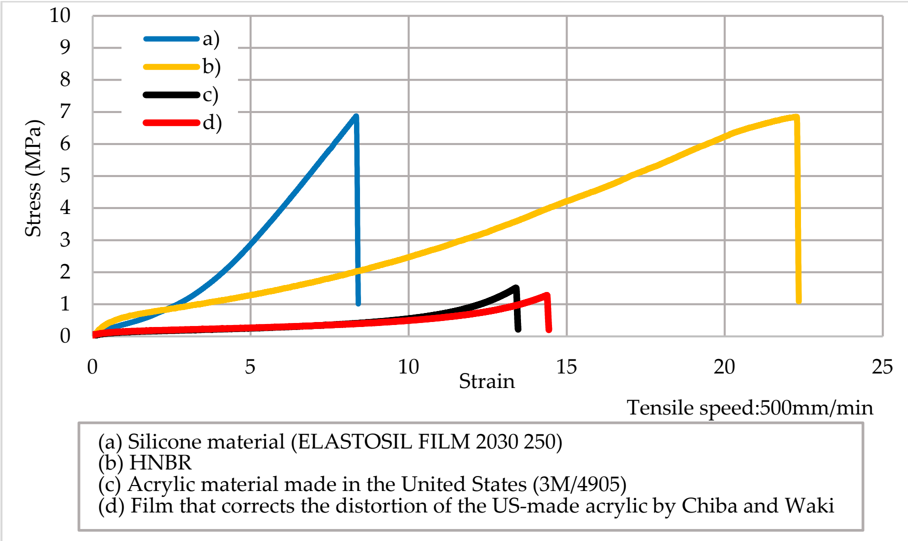
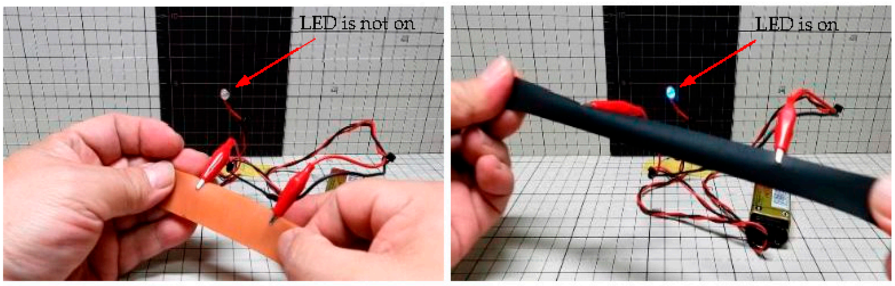


Figure 20. The results of SS curves of (a) the silicon (ELASTOSIL FILM 2030 250, shown in blue), (b) the HNBR ver.3 (orange line), (c) the acrylic material made in the United States (3M/4905, shown in black), and (d) the film that corrected the distortion of the U.S.-made acrylic (red line).

The meaning of a more stretchable film is that it deforms with less force and stretches more. That is, the power generation performance is improved. In addition, it is well known that the application of pre-stretching improves the performance of DEs and DEGs [10]. Therefore, the above distortion correction is considered to be important.

The difference in DE performance due to the difference in CNT dispersion is described in the Introduction Section, but if a well-dispersed CNT is used, a thinner electrode becomes possible. As shown in Figure 21, more flexible electrodes are possible, and even with a smaller force, the elongation of the DE with electrodes is increased, resulting in an excellent DEG [10,20].



(**a**) Before applying CNT spray (**b**) Even when stretched a lot the LED remains on

Figure 21. Ultra-flexible thin film electrode formation by SWCNT spray. (**a**) Elastomer (orange) before applying SWCNT spray. Naturally, the LED does not turn on. (**b**) After spraying the SWCNT, even if it is stretched considerably, the LED is still fully shining.

Next, regarding the step-down circuit, it seems that a commercially available DC/DC converter can be used for medium-sized DEG devices. When using a simple circuit such as a Zener diode, it is important to optimize the voltage and current between each circuit in order to match the relationship between the amount of power generated and the load. For example, if the voltage applied to a Zener diode or the like is made higher than necessary, the power consumed by the circuit increases and the efficiency decreases. Moreover, small DEG devices require a simple circuit, such as a Zener diode, because the power obtained is low and the generated energy is output intermittently. In other words, a general step-down circuit or regulator circuit cannot be used because the voltage fluctuates and the current that can be supplied is small. Moreover, since the power storage circuit is required to be charged in a shorter time by a simple method, it is desirable to use an electric double layer capacitor, a lithium-ion capacitor, or the like as a power storage device currently on the market.

The energy harvesting-dedicated IC has an ultra-low power consumption, a power storage circuit, a regulator circuit, and a start signal output. Furthermore, by increasing the capacity of the external storage capacitor, it can handle loads up to 100 mA, so it is considered to be optimal as a power source for IoT devices and the like.

6. Conclusions

The distortion of the acrylic film used for the DE was removed in advance, the dispersion of SWCNTs used for the electrodes was sufficiently improved, and the pre-stretch was set to 100% to create a DE cartridge. In this experiment, we created a small DEG device using two DE cartridges, connected a step-down circuit to this device, and developed a suitable charging circuit to enable charging of a secondary battery. The following conclusions were obtained:

- A small DEG device using two circular DE cartridges with a diameter of 8 cm was able to generate 33.6 mJ of energy.
- At present, SWCNTs are the best electrode to be used for DE cartridges. However, they need to be well dispersed.
- Using SWCNT spray, it is possible to make electrodes more easily.
- Since the amount of energy generation is small and the output is intermittent in a small DEG, it is necessary to keep the energy consumption of each component low, such as the regulator circuit or the energy storage circuit. Therefore, it is important to use a circuit that can be driven with as few parts as possible.

The circuit using the energy harvesting-dedicated IC is one IC, which includes a regulator circuit and an energy storage circuit, and since the number of additional parts used is small, it is most suitable for a small DEG.

- In this experiment, a film capacitor was used as the capacitor for a step-down circuit and a power storage circuit, but it seems that a more efficient power storage circuit could be realized by using a capacitor with lower internal resistance and less self-discharge.

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