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All 3D printed energy harvester for autonomous and sustainable resource utilization

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ABSTRACT

Despite rapid advances in 3D printing, fabrication of energy harvesters has not benefited much due to incompatible materials and fabrication processes for conventional energy conversion mechanisms and associated devices. In this work, an all 3D printed energy harvester is introduced based on the triboelectric mechanism. Grating disk type triboelectric nanogenerator (TENG) is fabricated by assembling the electrode layer, triboelectric layer and case package, all of which are made by 3D printing. Effects of various structural and material designs are evaluated. In particular, the order of electrification of representative printable materials is characterized to provide material selection guidelines. The all 3D printed TENG provides a root-mean-square (RMS) open-circuit voltage of 231 V, RMS short-circuit current of 18.9 μA, and maximum RMS power of 2.13 mW, which are sufficient to power general wireless electronic systems. The combination of 3D printing and energy harvesting realizes the ideal resource utilization strategy by implementing a sustainable energy device through a sustainable process.

1. Introduction

Three-dimensional (3D) printing technology (i.e. additive manufacturing) enables new manufacturing capabilities in diverse fields. As the technology matures, the scope is expanding from simple mechanical structures to functional devices. Meanwhile, the growing demand of internet-of-things and wireless electronics accelerates the development of the 3D printed devices in consideration with mass customization, light weight and low material waste. The issue governing the success of the new technology is the performance level provided by the available material and fabrication capability, preferably based on off-the-shelf material and generic 3D printing equipment. It is important at this stage to experimentally demonstrate prototype devices, analyze present and potential performance level and provide design guidelines for the future [1–9].

In particular, 3D printing is essential for space exploration. Conventional resource supply has heavily relied on deliveries from earth, which accompanies costly launching and intermittent flight schedule. The In-Space Manufacturing (ISM) mission aims at autonomous on-demand manufacturing in space toward sustainable exploration and habitats [10–13]. For this purpose, a 3D printer for the initial demonstration was installed in the International Space Station (ISS) in 2014, and various component printing demonstrations have been successfully made since then [14,15].

Energy is among the most critical but limited resource both in our planet and outer space. Generating and managing energy is our urgent duty for sustainability. In this regard, energy harvesting – the energy conversion process from various ambient sources into electricity – is attracting much interest [16–21]. Despite the importance, producing an energy harvester solely by printing methods has been challenging because of material and fabrication incompatibility of conventional energy harvesting methods. For example, the electromagnetic approach requires permanent magnets and coil spools as core components, thus requiring non-generic materials to be implemented by the current printing technology, which is not yet possible. Other methods involving piezoelectric, electrostatic and electrochemical mechanisms require

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high power, vacuum or aqueous process, which cause fabrication difficulties.

In this work, an all 3D printed energy harvester is presented based on the triboelectric mechanism. The triboelectric nanogenerator (TENG) utilizes static charges generated from repeated contact as the energy source [22–29]. The combination of 3D printing and TENG offers three practical advantages. First, the essential materials are completely compatible with 3D printing and affordable in the current market. Second, such materials do not demand high power, vacuum or post-treatment processes, resulting in high fabrication compatibility as well as low manufacturing energy consumption. The simplified process is particularly important for increasing throughput, reducing human intervention, reducing waste, and thereby protecting our environment. In addition, the absence of high power and vacuum process is attractive in small area and high safety facilities such as the ISS. Third, the precise patterning capability of 3D printing is beneficial for structural customization of TENG. The TENG requires different structures and sizes depending on the mechanical environment and power consumption, and hence, rapid prototyping by 3D printing meets this customization demand. Thus, the focus of this study is to demonstrate 3D printing of TENG devices and for this purpose, we have chosen a well known existing device structure (grating disk type). In addition, we also provide a material analysis comparison of several printable materials suitable for TENG construction for future material selection guidelines.

2. Experimental methods

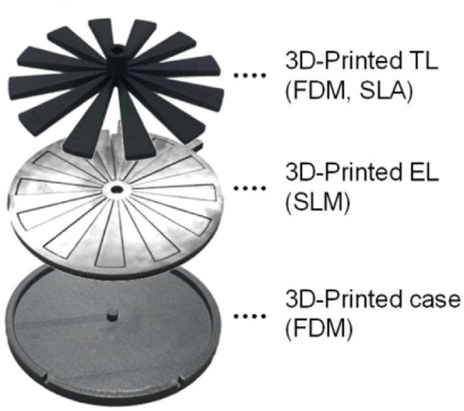
2.1. 3D printing of electrode parts

Titanium Grade 23 powder (Ti6Al4V ELI which contains 6% Al and 4% V with extra low interstitials from 3D Systems) was used as supply material to print metal blade structures. A 3D metal printer (ProX DMP 320 from 3D Systems) was used under an argon environment with a laser power of 245 W, a mark speed of 1250 mm/s, a layer thickness of 60 µm, and side step of 82 µm. Instead of using supporting structures, we printed each blade design directly from the metal base (horizontal direction). After printing, we thermally treated the sample for internal stress relief. A 1216 FL CM furnace with Furnace 3504 Temperature controller was used for the heat treatment under inert environment using an argon flow rate of 30 psi that prevents surface oxidation. The temperature was ramped to 315 °C, then to 537 °C and finally to 850 °C, with 15 min dwell times in between ramps and a final dwell time of 3 h. After heat treatment, we milled the part to have a smooth top surface using a Millport 2 vertical turret milling machine with a Walter F4033 Milling Cutter. Finally, the printed structures were separated from the base using a wire Electrical discharge machining (EDM). The maximum end-to-end resistances were of 0.4 Ω for Ti and 0.1 Ω for Al.

2.2. 3D printing of chassis and triboelectric parts

For the chassis part as a cover case, the Onyx filament (90% Nylon

a



b

Component	Material	Printing method
Case	Nylon	FDM
Electrode layer	Al	SLM
	Ti	SLM
Triboelectric layer	ABS	FDM
	PLA	FDM
	MMA	SLA
	Nylon	FDM
	PTFE (control)	Not printed

c

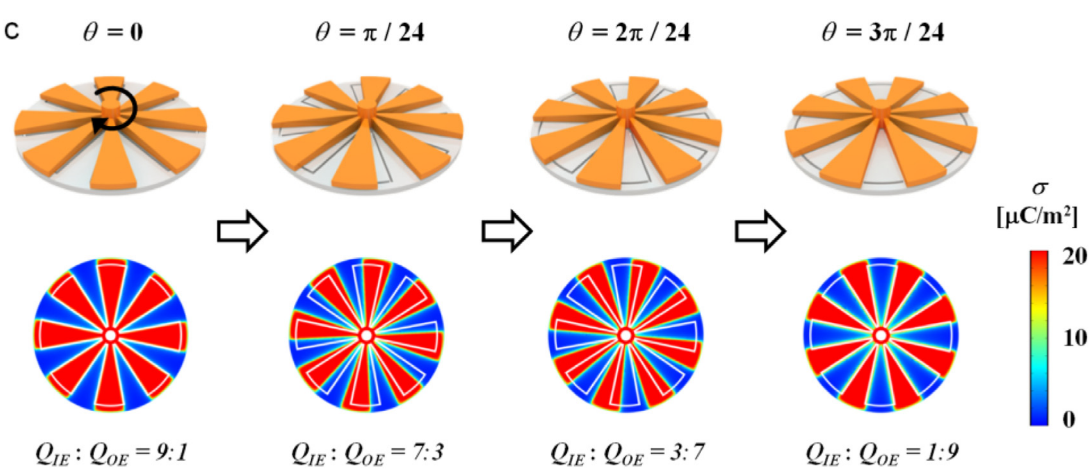


Fig. 1. Design and operation principle of the 3D-printed energy harvester (a) Structure of the grating disk type triboelectric nanogenerator that is composed of 3D-printed case, 3D-printed electrode layer (EL), and 3D-printed triboelectric layer (TL). (b) Materials and printing methods for each component. (c) Schematics of the device for various angular displacements, and the corresponding charge displacement profile of EL. Q_{IE} and Q_{OE} denote the mobile charge density of the inner electrode and the outer electrode, respectively.

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