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Microfabrication of High-aspect-ratio Microstructured Polydimethylsiloxane Elastomer for Sustainable Mechanical Energy Harvesting Application

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Abstract

The polydimethylsiloxane (PDMS) elastomer with merits of non-toxic, transparent, flexible, biocompatible and negative triboelectric properties attracts great attentions for wide applications in various fields of micro-electro-mechanical system (MEMS), wearable devices and the emerging sustainable green energy. This review focuses on the affordable microfabrication of high-aspect-ratio (HAR) Microstructured PDMS for the high-performance Al/PDMS triboelectric nanogenerator (TENG) as the clean sustainable mechanical energy harvester. The output performance of TENG related to the increased effective contact area is highly depending on the morphology and feature density of the triboelectric layers. Traditional TENG morphologies namely lines, cubes, pyramids, pillars, and domes were generally fabricated using an expensive and time-consuming lithography and etching process. These features are usually low aspect ratio with limited contact surface area during triboelectrification. In contrast, the laser ablation and polymer casting are well-known low-cost MEMS processes for rapid prototyping development. Combining the CO2 laser ablation and PDMS casting, the HAR microneedle (MN) PDMS can be fabricated for increasing the total contact surface area of HAR-MN Al/PDMS TENG as well as the outperformance. This integration process for TENG manufacturing is a candidate for the affordable and clean energy of the sustainable development goal.

Keywords: Microfabrication; Polydimethylsiloxane; Elastomer; Triboelectricity; TENG; Sustainable Energy

Introduction

The transparent and flexible polydimethylsiloxane (PDMS) elastomer polymer is a popular material in the micro-electro-mechanical system (MEMS) for microfluidics [1,2] and bio-MEMS application [3,4]. The PDMS microstructure is usually formed by the polymer casting on the mother mold that may be fabricated by the photolithography SU8 on a Si substrate or by the laser ablation of polymethyl methacrylate (PMMA) bulk material. The PDMS property is dependent on the mixing ratio of elastomer to curing agent for the adjustable Young's modulus and thermosetting characteristic. The additive into PDMS may further modify the optical and electric properties. With the development of emerging triboelectric nanogenerators (TENG) that is an energy harvesting device to convert mechanical energy into electrical energy through the cycling contact-separation operation [5-6], the study of triboelectric tendency series for common materials in TENG is essential and listed in Table 1 [5]. Compared to the high-cost electrode (Ag, Au or ITO) and the rigid tribo-layer negative-triboelectricity fluoropolymers, the combination of low-cost Al and flexible PDMS is a good candidate for the affordable and clean sustainable energy development as well as for wearable devices [8-10]. The output performance of TENG is linked to the effective surface contact area that is concerned with the surface morphology of PDMS. The fabrication of traditional TENG morphologies employs the expensive and time-consuming lithography and etching process to form lines, cubes and pyramids microstructure. The low-cost CO_2 laser is able to ablate the high-aspect-ratio (HAR) hollow microstructure of PMMA as a mother mold and followed by the PDMS casting to form the micro-needle (MN) structured PDMS for the increased effective contact surface area. The assembled Al-PDMS MN-TENG with high output performance can light on hundreds of LEDs connected in series, store energy in capacitors for the self-powered devices and behave a self-powered force sensor [9,10].

Positive	Polyamide 11	Polyester	
	Polyamide 6-6	Polyuretane flexible sponge	
	Melanimel formol	Polychlorobutadiene	
	Wool	Nature rubber	
	Silk	Polybisphenol carbonate	
	Aluminum	Polychloroether	
	Paper	Polystyrene	
	Cotton	Polyethylene	
	Steel	Polypropylene	
	Wood	Polyimide (Kapton)	
	Hard rubber	Polyvinyl chloride (PVC)	
	Nickel, Copper	Polydimethylsiloxane (PDMS)	
	Brass, Silver	Polytetrafluoroethylene (Teflon)	Negative

Table 1: The comparison of triboelectric tendency of common materials used in TENG development.

Discussion

Microfabrication of MN-structured PDMS and assembly of TENG test jig

The schematic process flow of microneedle (MN) array of a PDMS film is shown in Figure 1 [8]. The CO_2 laser processing is used to ablate the hollow-structured PMMA micromold (Figure 1(a) & 1(b)). A commercial CO_2 laser system (VL-200, Universal Laser system Inc., U.S.A.) is used for micro-mold fabrication with the specifications of maximum laser power of 30 W, the central wavelength of 10.6 mm, and the maximum scanning speed of 1140 mm s^{-1}. A computer-aided design tool of CorelDraw software is used to create and control laser processing parameters following X and Y directions on the PMMA substrate for the following PDMS casting to form MN-PDMS. The height, aspect ratio, and density of MNs are adjustable by the laser parameters of scanning speed, laser power, and inter-hole distance. The PDMS solution is prepared by the well-mixed elastomer (Sylgard 184, Dow corning) and curing agent (10:1 in weight). The degassed solution was poured into the micro-mold with the desired thickness by a doctor-blade and tapes (Figure 1(c)). Then cure the PDMS in the oven about 85°C during 1h and cool down for peeling off the micro structured PDMS (Figure 1(d)). The test jig is used to examine the performance of the Al/PDMS MN-TEG and assembled from the easy-finding materials including two PMMA substrate plates, one MN-PDMS film, one Al foil, four couple nut-bolt-springs, and one piece of sponge. The top electrode is the MN-PDMS film attached on the Al film and the Al foil fixed on the PMMA plate is as the bottom electrode.

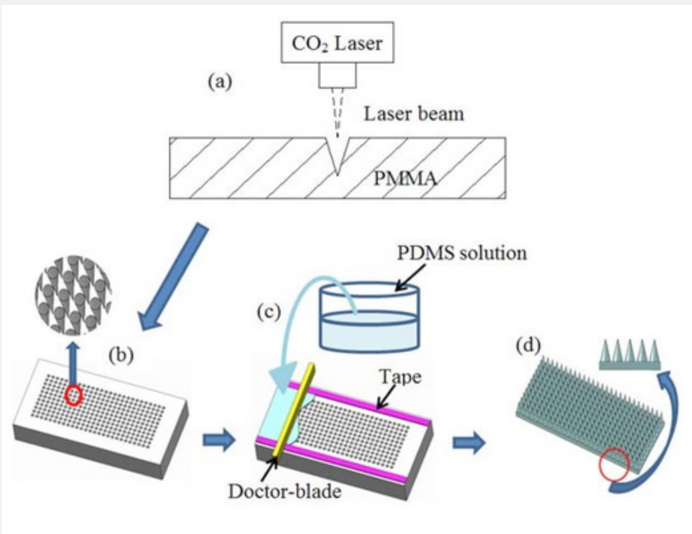

Figure 1: Schematic MN-structured PDMS fabrication using the combined CO2 laser ablation of PMMA as a mother mold and followed by PDMS casting to form HAR MN-array

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Enhancement of output performance of Al/PDMS HAR MN-TENG

The output performance of TENG is related to two issues of the materials' triboelectric polarity and morphology for contact surface area [8-10]. Based on the Al/PDMS TENG, increasing the contact surface area is able to produce more charge transfer during friction for enhancing the output performance. The sensitivity of a force or pressure sensor strongly depends on the output performance of TENG. It is noted that the output performance of TENG under the low-aspect-ratio morphology is in the order: flat film <line <cube <pyramid, and the pyramid exhibits the highest sensitivity of pressure sensor [6]. Integrating both technologies of the CO_2 laser ablation of PMMA and the PDMS molding may fabricate the HAR MN-morphology. The MN-PDMS with HAR morphology merits high-degree bending and recovery for high effective contact area. Increasing both aspect ratio and MN density can enhance total contact surface area for the high output performance of open-circuit voltage (V_{oc}) and short circuit current (I_{sc}) [8-10] as well for promoting the sensitivity of force sensor. Five types of MN arrays namely the low-density microneedle (LD-MN), high-density microneedle (HD-MN), overlapped microneedle (OL-MN), overlapped two-height microneedle (OL-TH-MN), and overlapped deep two-height microneedle (OL-DTH-MN) [9,10] are reported for the performance comparison: LD-MN-TENG < HD-MN-TENG < OL-MN-TENG < OL-TH-MN-TENG < OL-DTH-MN-TENG. The best performance of OL-DTH-MN-TENG exhibits the Voc and Isc are 167 V and 129.3 μA. In addition, it can lighten the colorful 226 LED connected in series and charge a 0.1 μF capacitor to a maximum voltage of 3.22 V and rapid to 2.75 V at 1.19 s. The charging capacity is potential for the activateing the various self-powered devices. Also, the OL-DTH-MN-TENG is used for the high-sensitivity force and pressure sensor with a high sensitivity about 1.03 V N^{-1} and 3.11 V kPa^{-1}, respectively [10].

Conclusion

Laser processing is one of the important microfabrication technologies for various materials especially the CO2 laser ablation of PMMA widely applied to MEMS components. The flexible PDMS elastomer polymer with the merits of transparent, biocompatibility, fast casting and negative triboelectric properties are widely used in the microfluidics, wearable devices and TENG mechanical energy emerging harvester. The integrated low-cost CO2 laser ablation and PDMS molding processes simply make the HAR MN-PDMS layer that is assembled with Al into an affordable and clean TENG to efficiently harvesting mechanical energy converted into electrical energy through the cycling contact-separation operation. The high-performance Al/PDMS MN-TENG can efficiently charge the capacitors for the self-powered devices, light on hundreds of LEDs connected in series for decoration and advertising board for flickering communication application, and exhibits as a high-sensitivity self-powered force sensor. Instead of the traditional complicated, time-consuming, and high-cost lithography and etching process, the combined process for efficient TENG fabrication has high potential for one of the UN sustainable development goals for the affordable and clean energy in the future.

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