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Investigation of biocompatible Parylene as triboelectric layer for wearable energy harvesting

Abstract: Triboelectric nanogenerators (TENGs) are energy converters or energy harvesters that convert mechanical motion into electrical energy on the basis of their material properties. A particular advantage of the TENG is its ability to convert small, low-frequency and random mechanical movements that are relevant for body movements and wearable applications. Within the presented study, different Parylene types were analysed as the dielectric material in TENG and found to be promising with respect to providing high output voltages and powers, respectively. Besides the verification of the usability of Parylene for TENG and its superior triboelectric properties, also significant differences were found between the Parylene types.

Keywords: triboelectric nanogenerators, Parylene, wearables, energy harvesting, energy converters

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1 Introduction

The recent trends of the Internet of Things and Smart Everything include also an increasing use of wearables. Particularly, wearables for medical purposes are of high interest, e. g. for monitoring vital parameters. The global wearable market is expected to grow to USD 100 billion by 2025, which is a compound annual growth rate (CAGR) of more than 11 % considering the market volume of USD 51.9 billions in 2019. Doing so, also the number of wearable devices is forecasted to more than double itself from

347 million units in 2019 to 754 million units in 2025. [1] Besides components for sensing, signal processing and data transmission, a key issue for the realization of wearables is the energy supply. The most elegant solution for this challenge is the conversion of energy (energy harvesting) directly on the wearable, avoiding energy storages such as batteries that have to be replaced or charged continuously. A variety of effects for energy harvesting have been reported in the literature including the piezoelectric effect [2,3,4], thermoelectric and pyroelectric effects [5,6] or the energy harvesting by surface charges in microfluidic channels [7].

Beside these, another possibility is energy harvesting by using the triboelectric effect. This effect describes electrical charging by contact electrification, i. e. some materials become electrically charged after being in contact and separated again from the surface of another material. The intensity of this effect depends on various parameters such as the used materials, their surface properties, temperature and the setup. [8-11] For the realization of triboelectric nanogenerators (TENGs), different setups are reported in literature, which include the vertical contact separation mode, the lateral sliding mode, the freestanding triboelectric layer mode and the single electrode mode. [12-16]

Within this study, Parylene is investigated for its usability in TENG. Parylene is a family of thermoplastic polymers, which combines a variety of unique properties including dielectricity, biocompatibility, chemical inertness against all common acids, bases and solvents, optical transparency and a low permeability for gases and moisture. [17] Due to this combination as well as its high flexibility and good mechanical strength even thicknesses in the low micrometer range, Parylene provides an excellent platform for the realization of fully biocompatible wearables whereas Parylene can act as an ultra-thin flexible printed circuit board (PCB), dielectric and encapsulation layer. [18] Hence, a Parylene based TENG would complete the different functionalities of Parylene and enable the realization of smart wearables based on Parylene as a flexible substrate, energy conversion layer, dielectric and encapsulation.

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2 Experimental

Due to its advantage of a freely movable triboelectric layer, within this study a single electrode mode TENG is chosen. The general setup of this mode as well as the adapted setup used in this study is given in figure 1 and can be summarized by a varying distance and contact between a dielectric and the electrodes. Doing so, the bottom electrode can be electrically grounded. For the realization of the TENG based on Parylene dielectric, slides of Polymethylmethacrylate (PMMA) with a size of $100 \times 100 \times 0.5 \text{ mm}^3$ were coated with the different Parylene types N, C, D, F and AF using chemical vapour deposition (CVD). During the Parylene deposition, the

Figure 1: Scheme of a single electrode mode TENG (a) and the adapted setup used within this study (b).

Figure 2: Photographs of the characterization setup (a) and the fabricated TENGs (b).

backside of the PMMA slide was masked with protective foil in order to achieve a single side coating. For reference, an uncoated Polycarbonate (PC) slide with a thickness of 0.5 mm and an uncoated slide of Polytetrafluoroethylene (PTFE) with a thickness of 1 mm were used. The electrode was realized by an 0.5 mm PMMA slide on which a copper foil of 50 μm thickness was laminated. For the characterization, the TENG was mounted on a stage and connected to an oscilloscope, that measured the generated voltage over time. For the further discussion, the root mean square of the peak voltages was calculated (mean peak voltage). During the measurements of the mean peak voltages, different resistances in the range of 1 M Ω to 100 M Ω were used to simulate different loads. Based on this load resistance R and the measured voltage V , the generated power P was calculated by $P = U^2 / R$. For the deflection, an electromagnetically actuated solenoid was realized over the TENG, that pressed the dielectric of the TENG with a frequency of $\sim 2 \text{ Hz}$. To improve the signal to noise ratio, a copper foil was placed between the TENG and the solenoid. For the realization of a more homogeneous force distribution as well as a larger contact area, a rigid disc of 6 cm diameter was placed on top of the TENG. Figure 2 provides photos of the characterization setup as well as of a TENG.

3 Results and Discussion

Figure 3 depicts the typical open circuit voltage characteristic over time, measured by the oscilloscope. Doing so, the peaks at negative voltages represent the piston getting in contact with the TENG, whereas the positive peaks represent the detachment of the piston. Furthermore, figure 4 depicts the dependency of the mean peak voltage and the power on the load resistance. As the figure indicates, the generated power features a maximum at lower load

Figure 3: Typical dependency of the open circuit voltage on the time, measured on a Parylene C TENG.

Figure 4: Mean peak voltage and generated power of a Parylene C TENG.

resistances. This power maximum was observed to be within 10 MΩ and 20 MΩ for all Parylene TENGs. Due to this dependency, figure 5 and table 1 summarize the values for the mean peak voltage and the generated power for a load resistance of 20 MΩ and 50 MΩ, respectively. The results reveal a strong dependency of the TENG output on the Parylene type. Doing so, for Parylene C, a significant higher output was measured than for the other types. For a Parylene AF based TENG a similar performance as for a PC based TENG was observed, whereas Parylene AF and Parylene N showed only minor differences. By far the lowest performance was measured for Parylene F. Considering the performance of the different Parylene types, it is hard to find any dependency of the generated power on the molecular structure. Neither the presence or position of the halogen substituents, nor the element (chlorine vs. fluorine) allow a clear conclusion on the

Figure 5: Comparison of the TENG output for different Parylene types and different load resistances.

performance. Based on the fact that Parylene C is the only Parylene type with an asymmetry in the molecule, and hence a polarity, it can be assumed that the asymmetric structure could be favourable. Particular it is interesting to note that Parylene AF in comparison with Parylene C does not generate a higher mean peak voltage and power, respectively, even though the molecular structure of Parylene AF is more related to the one of PTFE and hence, a better performance would be expected according to the triboelectric series [11]. Considering the fact that Parylene C is the Parylene type with the best cost to yield ratio and also the most common Parylene type being demonstrated for various applications such as the ultra-thin flexible Parylene PCB, the excellent triboelectric properties of this Parylene type can be used particularly advantageous.

For the comparison of the Parylene based TENGs with the references PC and PTFE, it can be concluded that the best

Table 1: Generated mean peak voltage and power for a resistance of 20 MΩ and 50 MΩ and different Parylene types.

Parylene type	Parylene thickness [μm]	20 MΩ Resistance		50 MΩ Resistance	
		Mean peak voltage [V]	Power [mW]	Mean peak voltage [V]	Power [mW]
Parylene N	6.42	130	0.85	135	0.37
Parylene C	6.72	270	3.63	315	1.98
Parylene D	4.30	66	0.26	87	0.16
Parylene F	4.56	24	0.03	27	0.01
Parylene AF	1.76	133	0.89	157	0.49
Polycarbonate	-	136	0.93	164	0.54
Polytetrafluoroethylene	-	83	0.35	113	0.26

results for Parylene indicate an improvement by a factor of almost 4 to PC. Comparing the results for PC and PTFE, a clear mismatch to the triboelectric series given in literature [11], which reports slightly better results for PTFE than for PC, is obvious. The most probable reason for this mismatch is the larger thickness of the used PTFE, which causes a different mechanical stiffness and hence, a potentially lower contact area. Hence, the results of PTFE should not be directly compared to any of the TENGs.

4 Conclusion

Within the presented study, the five most common Parylene types were investigated for their usability for TENG applications. Doing so, single electrode mode TENGs were fabricated and characterized. The measured results indicate that Parylene C with a mean peak voltage of 270 V and 315 V as well as a generated power of 3.63 mW and 1.98 mW, measured at 20 M Ω and 50 M Ω , respectively, showed the best performance of all Parylene types. Particularly, compared to the results of PC, the measured generated power was higher by a factor of ~ 4 . Even though, additional aspects such as dependency of the results on the layer thickness, additional treatments, contact area and force still as well as reproducibility need further investigations, the results pave the way for the usage of Parylene for TENG applications. Besides its usage as an ultra-thin flexible substrate, dielectric and encapsulation layer, this particularly adds the energy conversion as a fourth functionality of Parylene for the realization of an all Parylene smart wearable. Furthermore, for the realization of ultra-thin flexible Parylene PCB [18], the results indicate that the creation of an interference voltage can be suppressed by choosing a Parylene type, e. g. Parylene F, with a low mean peak voltage and generated power, respectively.

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