Proceedings of 9th IEEE International Conference
on CYBER Technology in Automation, Control, and Intelligent Systems
July 29- August 2, 2019, Suzhou, China

Low-voltage Electroadhesive Pad with Thin Insulation Layer Fabricated by Parylene Deposition

Guoyong Xie[1,2], Wenguang Wang[2], Xianqiong Zhao[1], Hongqiang Wang[2, *]

***Abstract*— Electroadhesion has a large potential to be extensively used due to its advantages such as lightweight, strong force, and flexibility, but the high excitation voltage (usually more than 1.5 kV) bottle-necks its broad applications. Although increasing the dielectric constant is promising, the dielectric strength and tensile strength become lower simultaneously. Reducing the insulation layer thickness is another possible approach to lower the voltage, but previous fabrication methods and materials do not support this way. This work implants the parylene coating method, which is well-developed in semiconductor industry, into the fabrication of thin insulation layer of the electroadhesive pads. A pad with 7 µm thin insulation layer is demonstrated, and it can generate comparably strong force under 340 V while previous polymer-based insulation requires more than 1.5 kV voltage. For the thin insulation layer, air gap becomes noticeable, and its effects are experimentally studied and analyzed.**

I. INTRODUCTION

Electrostatic adhesion has attracted increasing interest from researchers in recent years due to its potentially extensive applications in industrial product manipulation, surgical operation, and field exploration [1-4]. This novel adhesion technique shows various merits compared with traditional methods such as vacuum attraction and magnetic attraction. Vacuum attraction fails on a porous substrate, and magnetic attraction only works on ferromagnetic materials, while electroadhesion is available on the substrate that is either porous or made from one of the various materials such as metals, semiconductors, glass, eggs, papers [1]. Moreover, electroadhesive pad has the good nature of low-profile, light-weight, great flexibility and low energy consumption [5]. Therefore, the devices based on electrostatic adhesion has been widely used in wearable devices [6, 7], robotics [8, 9], and grippers [1, 3].

However, one of the primary challenges in current electroadhesive devices is the high voltage applied, normally more than 2 kV [1, 10-13], as shown in Fig. 1, which poses a potential risk, requires more specific power supplier and limits the broader applications in, e.g., wearable and medical devices. To lower the supplied voltage but keep the strength of the attractive force, there are two possible approaches: 1) increasing the dielectric constant of the insulator, or 2) decreasing the thickness of the insulation cover layer. Following the former approach, polymer-ceramic composite material (insulation material mixed with ceramic materials, such as $BaTiO_3$) is employed to achieve a high dielectric constant (can be around 34 [14]) to lower the excitation voltage to approximately 200 V, as shown in Fig. 1. Nevertheless, the breakdown dielectric strength and tensile strength becomes lower simultaneously.

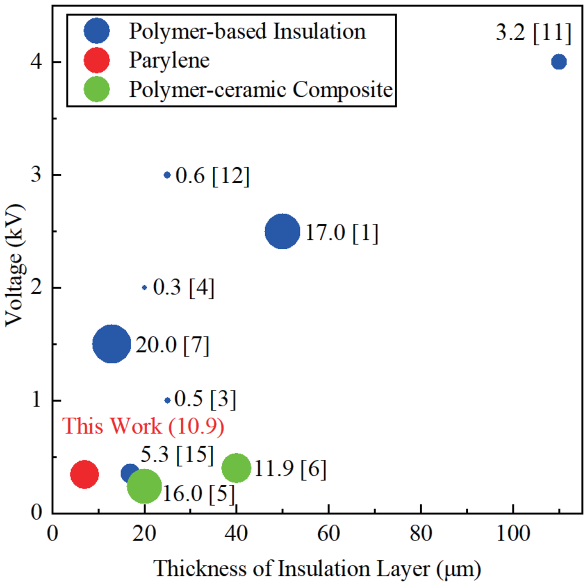

Figure 1. The excitation voltage and the minimum thickness of insulation layer in previous literature and this work. Polymer-based insulation includes PDMS, PI, and PET here. The shear force resulted by electroadhesion is indicated by the size of the circles and the unit of number is kPa.

For the latter approach, although a lot of research have been conducted to reduce the thickness of insulation layer until now, the results are still not satisfactory due to the limitation from current used fabrication process and materials used for the electroadhesion. In the previous work, there are three common ways to fabricate electroadhesive pads: lamination [15], film coating [16] and spinning coating [17]. Lamination bonds insulating layers and conductive foils by heating and pressing. All the materials are in the form of films and purchased in the market, and the commercially available thickness options of the film are limited (usually larger than 7.5 µm). In film coating, a film applicator spreads viscous insulating material evenly on a flat electrode, and then the materials are solidified at high temperature. Because the evaporation of the solvent of the insulating material during solidifying, the thickness and homogeneousness of the insulation layer is difficult to control. The same problem occurs in spin coating, which also makes the insulation layer from viscous fluid materials, although it deploys centrifuge force to spread the materials on the surface.

With the concerns on these problems in the current manufacturing method, this work proposes to introduce other manufacturing method for thinner insulation layers of

---

[1] College of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China.
[2] The Department of Mechanical and Energy Engineering, Southern University of Science and Technology, Shenzhen 518055, Guangdong, China.
*Corresponding author: phone: +86-(0)755-88015367; e-mail: wanghq6@sustc.edu.cn.

978-1-7281-0770-7/19/$31.00 © 2019 IEEE

electroadhesive pad. The well-developed film generation methods in semiconductor industry, such as the method in the category of chemical vaper deposition (CVD) [18], can be a good option. To explore this approach, we choose the parylene coating method, in which process thin insulation material called parylene is coated on the surface of a conductive foil, due to the following advantages and performances (Tab. I):

(1) the coated parylene layer is thin, several micrometers, and precisely controllable (0.1 μm resolution) with the online thickness monitoring sensor inside of the coating machine;

(2) the parylene material has a high theoretical breakdown voltage;

(3) in the coating process, the generated parylene layer is homogeneous even though the conductive foil has wrinkles, and the parylene layer is coated on all the bare surfaces of the conductive plate, even including the lateral side, which is good for short-circuit proof and water proof of the electroadhesive pad.

(4) the coated samples are placed at ambient temperature, and hence this process is also available for conductive material of low melt point, such as conductive polymers;

(5) the parylene layer is chemically stable, and insolvable to all the common solvent, and hence the electroadhesive pad can be used in a harsh environment.

TABLE I. PERFORMANCE COMPARISON OF PARYLENE WITH OTHER INSULATION MATERIALS

Properties	***PDMS***	***Polyimide***	***Polymer -ceramic composite***	***Parylene (this work)***
Dielectric constant	3.2-4.5[19]	3.4	>40[14]	3.15
Dielectric strength (V/μm)	20	118	30	220
CO_2 Permeability (cm^3·20μ/m^2·24hr·atm)	2440[20]	950	-	140
96% Sulfuric resistance	Dissolve	Dissolve	-	0.4%
Tensile strength (MPa)	3	231	34.8	68.9

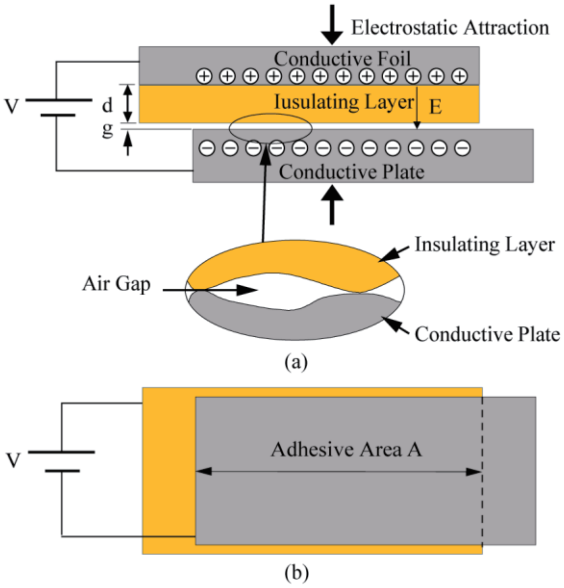

Figure 2. Schematic of the electroadhesive pad adhering on a substrate: (a) side view and (b) top view.

The contributions of this work are that we suggest implanting well-developed film generation methods into the manufacturing of electroadhesive pad. This work demonstrates an adhesive pad with 7 μm thin insulation layer that is fabricated by parylene coating. This adhesive pad can generate comparably strong lateral electroadhesive force (10.9 kPa) by only 340 V, while previous adhesive pads made from polymer-based insulation (except the polymer-ceramic composites) need voltage higher than 1 kV. The homogeneousness and the smoothness of the parylene layer, as well as the adhesive force, are characterized. The influence of the air gap, which is non-negligible when insulation layer is thin, is also experimentally analyzed and discussed.

The structure of this paper is as follows: the next section introduces the principle of electroadhesion, Section III explains the details of the fabrication method, Section IV describes experimental the set-up and process, Section V presents the

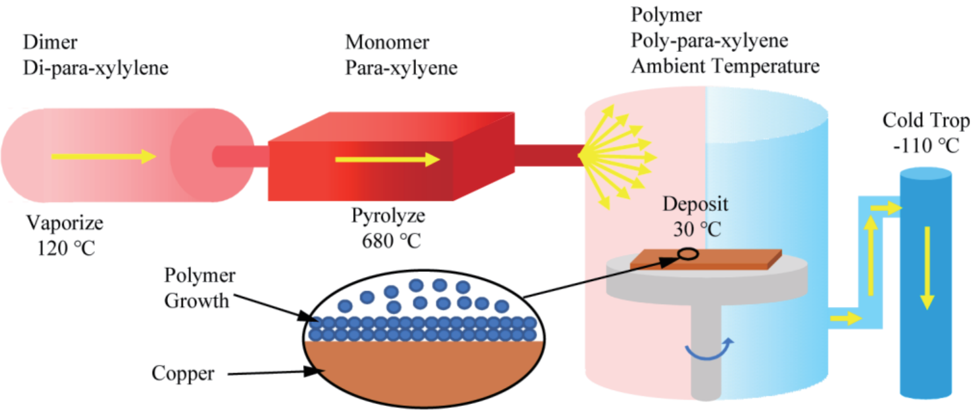

Figure 3. The principle of parylene coating.

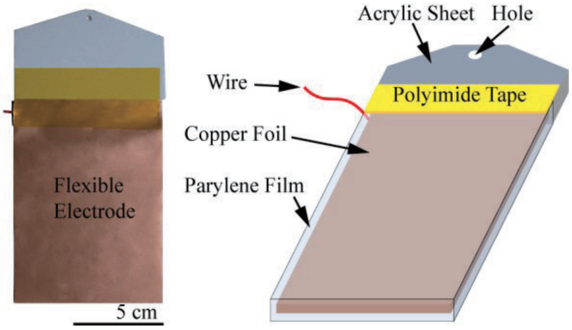

Figure 4. The structure of electroadhesive pad.

results of experiments, and in the end, Section VI discusses and summarizes the content.

II. PRINCIPLE OF ELECTROADHESION

As shown in Fig. 2, an electroadhesive pad consists of a conductive plane electrode and an insulation layer, which are bonded together. When the electrode is connected to an electrical source, an electric field is created between the adhesive pad and the conductive substrate, which turns the whole system into a capacitor, and consequently the electrode will be attracted to the substrate. Based on the parallel-plate capacitor model, the normal attractive electrostatic force can be calculated by

$$F_{\perp} = 0.5\varepsilon_0 \varepsilon_r A (V/d)^2, \tag{1}$$

where V is the voltage, d is the thickness of the insulation layer, ε_0 is the permittivity of vacuum, ε_r is the relative permittivity of the insulation layer, and A is the adhesive area. The normal attractive force produces a lateral resist force simultaneously. The maximum lateral force can be represented by

$$F_{\tau} = \mu F_{\perp}, \tag{2}$$

where μ is static friction coefficient between the insulation layer and copper plate.

In spite the electrodes attract together tightly, air gaps occur between the surfaces of the adhesive pad and substrate as a result of the surface roughness and waviness. Then the electrostatic attraction force is:

$$F_g = 0.5\varepsilon_0 A V^2 / (\varepsilon_g (g/\varepsilon_g + d/\varepsilon_r)^2),$$

where g is the effective thickness of the air gap, ε_g is the relative permittivity of the air, which is idealized as vacuum and so ε_g=1. When the insulation layer is thick (more than tens of micrometers), air gap is negligible, while under a comparably thin insulation layer, the air gap thickness becomes noticeable, which happens in this work and is analyzed and discussed in Section V.

III. FABRICATION METHOD

Parylene coating is a chemical vapor deposition process. The raw material is solid granular dimer. Under vacuum and high temperature, the dimer is evaporated (120 ºC) and pyrolyzed (680 ºC) into monomeric gas (Fig. 3). Then the gas deposits on all the surfaces of the electrode in the deposition chamber, and consequently creates a thin and transparent parylene insulation layer under an ambient temperature.

Parylene has high dielectric strength, comparable to the popular insulation material, PI, and much better than other materials such as PDMS and polymer-ceramic composite, which are deployed in previous electroadhesive devices [5, 11]. Moreover, parylene is insoluble in all common solvents, acids and alkalis, and hence it adapts to harsh conditions. In addition, parylene, as a crystalline polymer, has a higher mechanical strength compared with other polymer materials. These properties make parylene one of the most promising materials for electroadhesive devices.

In this work, the conductive layer of the adhesive pad is made from a thin copper foil (8 μm). After coating process in the deposition machine (PTP-3V, Penta Technology), an achieve an electroadhesive pad with a parylene insulation layer is made. We fabricate three different thicknesses of parylene layers, 7 μm, 15 μm, and 24 μm, from 5 g, 10 g, and 15 g dimer powder (Galxyl C, Galentis) respectively. To facilitate the force measurement, the electroadhesive pad is attached to an acrylic sheet (1 mm) by polyimide tape, and a hole is drilled in the acrylic sheet for fixture (see Fig. 4).

IV. EXPERIMENTAL SETUP AND PROCESS

In order to measure the lateral force, a simple force characterization setup (Fig. 5) was implemented. The setup mainly includes a digital force gauge (WD-100/10, Wei Degree), a digital ruler, and a handle. The electroadhesive pad is fixed to the hook of the force gauge, and the conductive substrate consisting of a copper foil and an acrylic board is anchored by a clamper. By slowly turning the handle, the

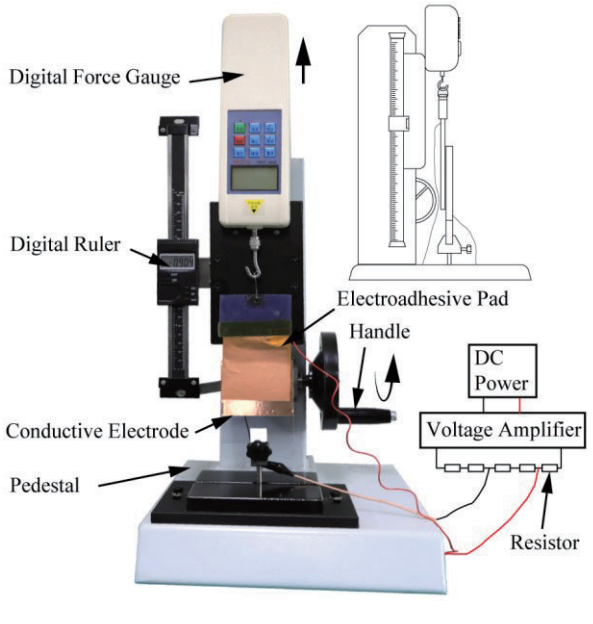

Figure 5. Force measurement setup.

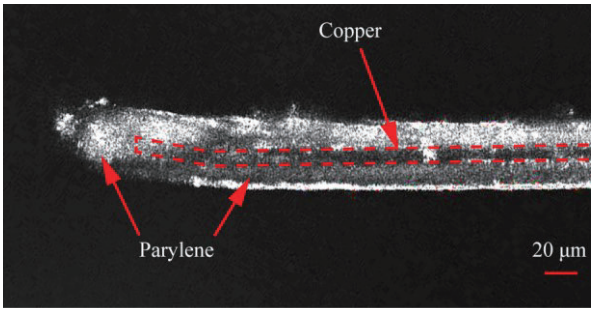

Figure 6. Cross section of the electroadhesive pad

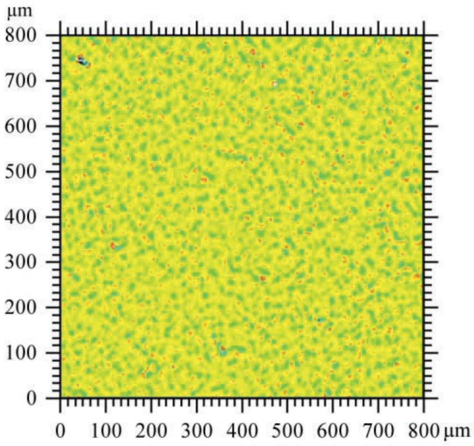

Figure 7. The local surface roughness of a parylene coated electroadhesive pad.

digital force gauge moves vertically by a speed of about 4 mm/min. Once the adhesive pad slips, the digital force gauge records the maximum lateral force. The high excitation voltage originally comes from a DC power source (HUAYI HY3005B), which is amplified by a voltage amplifier (EMCO A Series). In case of electrical breakdown in the adhesive pad, the measurement is operated with voltage lower than 400 V.

To keep the results consistent, we (1) frequently wipe the surfaces lightly with clean tissues and isopropyl alcohol, (2) measure the lateral force at intervals of one hour to eliminate the effect of residual charge on the electrode surface, (3) keep the pair of electrodes as parallel as possible in the vertical direction to avoid peeling, which is likely to reduce the force a lot to separate the adhesive film from the substrate [21], and (4) keep the experiment in the same environment to avoid the effects of floating humidity and temperature.

V. RESULTS

A. Characterization of the parylene insulation layer

The cross section of one of the electroadhesive pad made in this work is measured by a laser scanning microscope (VK-X1000, Keyence). As shown in Fig. 6, all the surfaces including the narrow edge of the electrode is covered, and the parylene layer thickness is homogeneous on the copper electrode. Using a film measurement sensor (FS-1, Film Sense), the thickness of an electroadhesive film is measured, on five points, and the standard deviation is 0.476 µm, indicating the high precision of the parylene coating process. The thickness discrepancy might result from the temperature difference at different position during the deposition process. Measured by a white light interferometry (Taylor Hobon CCI MP-HS), the parylene layer seems very smooth (see Fig. 7), and the mean height (Ra) is 0.760 µm.

B. Electroadhesive force

The electroadhesive pad fabricated in this work, although, is thin and lightweight, it can generate a strong adhesive force. For example, one of the electroadhesive pad (9.6 g) can adhere to another electrode foil and lift up a 2.5 kg dumbbell at 300 V, as shown in Fig. 8. Since the thickness of the insulation layer can be as thin as 7 µm, a low voltage (340) is adequate to generate a comparably strong adhesive force (10.9 kPa), while other polymer-based insulation (except the polymer-ceramic composite) usually needs more than 1.5 kV to generate a force of such strength.

To verify the model in Eq. (3), we measured the lateral force caused by electrostatic adhesion, and the results are compared with the calculation results as shown in Fig. 9 and Fig. 10. The electroadhesive force is proportional to the squared value of voltage (see Fig. 9), and the adhesive area (see Fig. 10), as calculated, regardless of the insulation thickness difference. In the calculation, the thickness of the air gap is achieved by trial tests on 280 V. The discrepancy between the experiments and model might mainly result from the variant air gap thickness under different voltage and the corresponding normal adhesive force. The adhesive force for the adhesive pad with 7 µm (Fig. 9) has a larger discrepancy when the voltage is 340 V. This difference results from the corona discharge, and we observed shiny sparks several times.

C. The effect of air gap

To clarify the effects of the air gap, we measure the lateral adhesive force with a high data density on different voltage. As shown in Fig. 11, if the air gap is not considered the experimental force is around 30% lower than the estimation, and hence the air gap is noticeable for the adhesive pad with thin layer of parylene insulation. To find the thickness variance of the air gap, based on the data shown in Fig. 11 and Eq. (3), we calculate the air gap on different voltage. As shown in Fig.

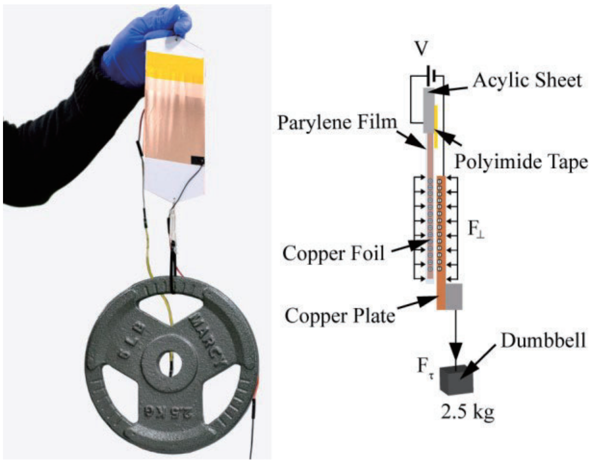

Figure 8. Demonstration of an electroadhesive clutch lifting a load of 2.5 kg.

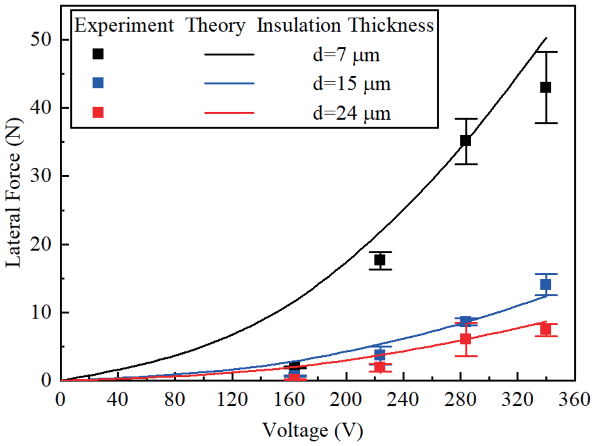

Figure 9. The lateral force at different insulating thickness. The adhesive area is 40 cm^2.

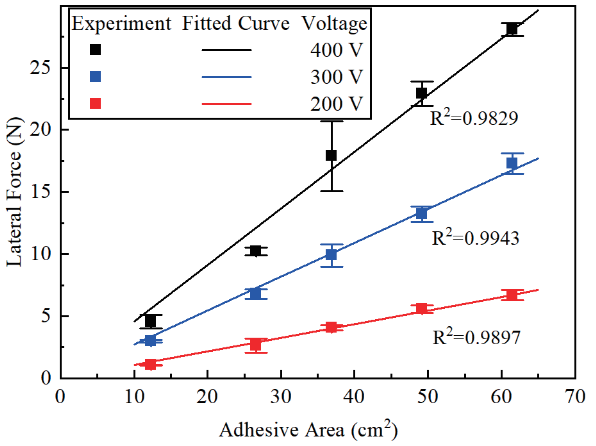

Figure 10. The lateral force at different adhesive area. The thickness of the parylene layer is 15μm.

12, the air gap is 6.37 μm when the voltage is 40 V. While the voltage increases, the air gap narrows, and then after the voltage is higher than 200 V, the thickness keeps almost constant, at around 2.12 μm. This tendency can be explained by the influence of changed normal adhesive force. Usually the adhesive pad is slightly wrinkled due to residue stress from fabrication, delivery, and stacking process. Hight voltage generates a stronger distributed normal force, compresses the wrinkled adhesive pad to the substrate, and consequently squeezes the air gap caused by the waviness of the adhesive pad. The film cannot, nevertheless, contact the surface of the substrate perfectly even though the normal adhesive force is strong, and a small air gap still exists finally due to the roughness of the adhesive pad and substrate.

VI. SUMMARY AND DISCUSSION

This work proposes to fabricate electroadhesive pad's insulation layer by parylene coating, and this method is not deployed in the manufacturing of electroadhesive devices in the past. An insulation layer as thin as 7 μm is generated in this work, and the excitation voltage decreases to 340 V, while other polymer-based materials need more than 1.5 kV to achieve the same force. Although the polymer-ceramic composite of high dielectric constant can reduce the excitation voltage to around 200 V, the tensile strength and breakdown dielectric strength is much lower than those of the parylene insulation layer. In the measurement, it shows that the parylene layer covers all the surfaces of the electrode, even including the edges, the thickness of the parylene layer is homogeneous on all the locations, and the surface is smooth. Since the insulation layer becomes thin (close to the thickness of the air gap) and the effects of air gap become noticeable. Based on experiments, we find that, when the voltage increases, the effective air gap narrows and then keeps almost the same, due to the pressable wrinkles and the impressable roughness of the electroadhesive pad respectively.

In addition, this work finds some problems in electroadhesive pad with thin insulation layer fabricated by parylene coating. Firstly, the breakdown voltage in practice is much lower than the theoretical value. For example, the actual breakdown voltage is 450 V while it is expected to be 1320 V for the electroadhesive pad. Most probably this discrepancy results from the poor-purity of the parylene powder used in this work, and higher quality materials perhaps can increase the maximum voltage and attractive force. If the insulation layer is very thin, the impurity in the layer is more likely to cause a

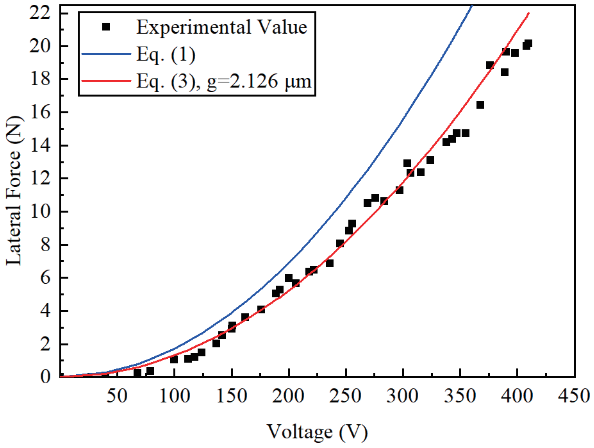

Figure 11. The lateral force caused by electrostatic adhesion at different voltage. The thickness of parylene layer is 15 μm, and the adhesive area is 46 cm^2.

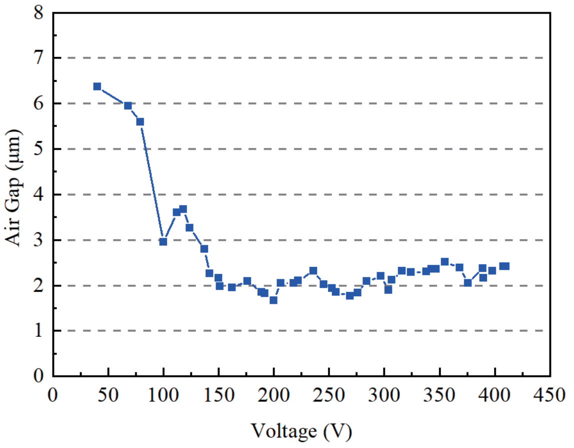

Figure 12. The air gap between adhesive pad and the substrate for different voltage. The thickness of parylene is15μm and the adhesive area is 46 cm^2.

dielectric breakdown, and hence in this work we just make the minimum thickness 7 μm. In the future, the thickness of the insulation layer and the excitation voltage have much space to be reduced further when the purity of parylene is improved. Secondly, after the power is turned off, the adhesive pad sometimes still adheres to the substrate due to the residual charges, and this phenomenon hinders the high-frequency operations of electroadhesion. We will solve this problem by adjusting the electrical signal and materials in the future.

REFERENCES

[1] J. Shintake, S. Rosset, B. Schubert, D. Floreano, and H. Shea, "Versatile soft grippers with intrinsic electroadhesion based on multifunctional polymer actuators," *Advanced Materials Technologies,* vol. 28, no. 2, pp. 231-238, 2016.

[2] D. S. Grimard, V. Parkhe, H. Levinstein, F. Chen, and M. G. Chafin, "Hybrid Johnsen-Rahbek electrostatic chuck having highly resistive mesas separating the chuck from a wafer supported thereupon and method of fabricating same," U.S.Patent.5 Patent 5,903,428, 1999.

[3] E. W. Schaler, D. Ruffatto, P. Glick, V. White, and A. Parness, "An electrostatic gripper for flexible objects," in *Intelligent Robots and Systems (IROS), 2017 IEEE/RSJ International Conference on*, 2017, pp. 1172-1179: IEEE.

[4] G. Gu, J. Zou, R. Zhao, X. Zhao, and X. Zhu, "Soft wall-climbing robots," *Science Robotics*, vol. 3, no. 25, p. eaat2874, 2018.

[5] S. Diller, C. Majidi, and S. H. Collins, "A lightweight, low-power electroadhesive clutch and spring for exoskeleton actuation," in *Robotics and Automation (ICRA), 2016 IEEE International Conference on*, 2016, pp. 682-689: IEEE.

[6] V. Ramachandran, J. Shintake, and D. Floreano, "All-Fabric Wearable Electroadhesive Clutch," *Advanced Materials Technologies,* p. 1800313, 2018.

[7] R. Hinchet, V. Vechev, H. Shea, and O. Hilliges, "DextrES: Wearable Haptic Feedback for Grasping in VR via a Thin Form-Factor Electrostatic Brake," in *The 31st Annual ACM Symposium on User Interface Software and Technology*, 2018, pp. 901-912: ACM.

[8] H. Wang, A. Yamamoto, and T. Higuchi, "A crawler climbing robot integrating electroadhesion and electrostatic actuation," *International Journal of Advanced Robotic Systems,* vol. 11, no. 12, p. 191, 2014.

[9] M. Graule *et al.*, "Perching and takeoff of a robotic insect on overhangs using switchable electrostatic adhesion," *Science,* vol. 352, no. 6288, pp. 978-982, 2016.

[10] C. Cao *et al.*, "Theoretical model and design of electroadhesive pad with interdigitated electrodes," *Materials,* vol. 89, pp. 485-491, 2016.

[11] D. Ruffatto III, J. Shah, and M. Spenko, "Increasing the adhesion force of electrostatic adhesives using optimized electrode geometry and a novel manufacturing process," *Journal of Electrostatics,* vol. 72, no. 2, pp. 147-155, 2014.

[12] J. P. D. Téllez, J. Krahn, and C. Menon, "Characterization of electro-adhesives for robotic applications," in *Robotics and Biomimetics (ROBIO), 2011 IEEE International Conference on*, 2011, pp. 1867-1872: IEEE.

[13] R. Liu, R. Chen, H. Shen, and R. Zhang, "Wall climbing robot using electrostatic adhesion force generated by flexible interdigital electrodes," *International Journal of Advanced Robotic Systems,* vol. 10, no. 1, p. 36, 2013.

[14] X. You, N. Chen, G. Du, and Manufacturing, "Constructing three-dimensionally interwoven structures for ceramic/polymer composites to exhibit colossal dielectric constant and high mechanical strength: CaCu3Ti4O12/epoxy as an example," *Composites Part A: Applied Science,* vol. 105, pp. 214-222, 2018.

[15] M. Nakamura, C. Yang, K. Tajima, K. Hashimoto, and S. Cells, "High-performance polymer photovoltaic devices with inverted structure prepared by thermal lamination," *Solar Energy Materials,* vol. 93, no. 9, pp. 1681-1684, 2009.

[16] J. Fortin and T.-M. Lu, "A model for the chemical vapor deposition of poly (para-xylylene)(parylene) thin films," *Chemistry of materials,* vol. 14, no. 5, pp. 1945-1949, 2002.

[17] D. Ruffatto, A. Parness, and M. Spenko, "Improving controllable adhesion on both rough and smooth surfaces with a hybrid electrostatic/gecko-like adhesive," *Journal of The Royal Society Interface,* vol. 11, no. 93, p. 20131089, 2014.

[18] K. M. Vaeth and K. Jensen, "Transition metals for selective chemical vapor deposition of parylene-based polymers," *Chemistry of materials,* vol. 12, no. 5, pp. 1305-1313, 2000.

[19] K. Goswami, A. E. Daugaard, and A. L. Skov, "Dielectric properties of ultraviolet cured poly (dimethyl siloxane) sub-percolative composites containing percolative amounts of multi-walled carbon nanotubes," *RSC Advances,* vol. 5, no. 17, pp. 12792-12799, 2015.

[20] G. Firpo, E. Angeli, L. Repetto, and U. Valbusa, "Permeability thickness dependence of polydimethylsiloxane (PDMS) membranes," *Journal of Membrane Science,* vol. 481, pp. 1-8, 2015.

[21] H. WANG and A. YAMAMOTO, "Peel Force of Electrostatic Adhesion in Crawler-type Electrostatic Climbing Robots," *Journal of the Japan Society of Applied Electromagnetics Mechanics,* vol. 23, no. 3, pp. 498-503, 2015.