Theoretical model and design of electroadhesive pad with interdigitated electrodes

Changyong Cao^{1,2,3*}, Xiaoyu Sun^{3,4}, Yuhui Fang^{1,2}, Qinghua Qin¹, Aibing Yu⁵ and Xi-Qiao Feng³

¹ *Research School of Engineering, Australian National University, Canberra, ACT 0200, Australia*

² *Department of Mechanical Engineering and Materials Science, Duke University, Durham, NC 27708, USA*

³ *Institute of Biomechanics and Medical Engineering, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China*

⁴ *Department of Engineering Mechanics, School of Civil Engineering, Wuhan University, Wuhan 430072, China*

⁵ *Department of Chemical Engineering, Monash University, Clayton, VIC 3800, Australia.*

* Corresponding author. Email: changyong.cao@duke.edu, Tel: +1-919-681-9593, Fax: +1-919-660-5293.

Abstract: Electric fields alter adhesive forces between materials. Electrodehesive forces have been utilized in diverse applications ranging from climbing robots, electrostatic levitation to electro-sticky boards. However, the design of electrodehesive devices still largely relies on empirical or “trial-and-error” approaches. In this work, a theoretical model is presented to analyze the electrostatic field between the supporting wall and the electrodehesive device with periodic coplanar electrodes. The air-gap between the surface of electrodehesive device and the dielectric wall is explicitly taken into account in the model to consider its significant impact on electrodehesive forces. On the basis of this model, the electrodehesive force is calculated by using the Maxwell stress tensor. The effects of key design parameters and working environments on the electrodehesion behavior are further investigated. This study not only provides a tool to reveal the underlying mechanisms of electrodehesion but also suggests potential strategies to optimize novel electrodehesive devices for engineering applications.

Key words: theoretical model, electrodehesive pad, interdigitated electrodes, electrodehesion, dry adhesion, soft robotics.

1. Introduction

Electric fields can alter adhesive forces between materials, which allow surfaces to reversibly attach to each other without the use of mechanical grippers, suckers, fasteners, or chemical adhesives [1-6]. Electrodehesive devices have been developed by patterning electrodes in air or matrices of insulating dielectrics. Once an electric

voltage is applied, the devices can invoke the adhesive forces to a wide variety of substrate materials (e.g., silicon, silicon dioxide, wood, drywall, glass, concrete, steel, and plastics) with various shapes, sizes, and roughness [2, 5-7]. Compared to mechanical and chemical adhesions, the electroadhesion has distinct advantages, e.g., fast response (response time <10 ms), quiet operation, low cost, easy control, low energy consumption, and **dust tolerance** [2]. Due to these many benefits, electroadhesive devices have been widely used in various applications. Examples include **electrostatic levitation** used in liquid-crystal-display manufacturing [4, 8-12], electroadhesive grippers for handling microcomponents of semiconductors [13, 14], and electroadhesive pads for wall climbing robots [2, 5, 6, 15, 16] and sticky boards [17].

An electroadhesive device uses the electrostatic force between the supporting material (e.g., wall surface) and the electroadhesive pad. For Coulomb-type electrostatic pads (ESP), the electrostatic force is generated by the dielectric polarization due to the electric potential difference. Based on the charge (or electrode) configuration, ESPs can be classified into two types: mono-polar (plate-plate-capacitors) and bipolar (interdigitated electrodes) [1]. Mono-polar type ESPs generate adhesive forces in accordance with the principle that the two plates in a parallel capacitor attract each other if there is a voltage difference between them. Therefore, the target structure (e.g., a concrete wall) is required to be conductive such that a capacitor is formed between the electrode and the supporting wall [18]. A bipolar type electroadhesive device is typically constituted by interlacing the fingers of two conducting combs, as shown in Figure 1. The space between the electrode fingers is usually filled with an electrical insulator. The fingers and the filler are insulated from the substrate by a dielectric layer (i.e. the cover in Figure 1). When alternating positive and negative charges are induced on the adjacent electrodes and the device is placed in contact with a wall, the electric fields set up opposite charges on the wall and thus cause electrostatic adhesion between the electrodes and the induced charges on the supporting wall. This force may be explained by two mechanisms, namely, the gradient force and the Johnson-Rahbeck force [19].

Despite these technologically important applications of electroadhesion, the design of electroadhesive devices has largely relied on trial-and-error approaches and the electroadhesive stresses and energy are usually estimated by empirical equations [2, 7, 10, 13, 15]. Prahlad and coworkers experimentally investigated the compliant electroadhesion technique and developed a variety of wall climbing robots such as tracked and legged robots [2]. They tested the attractive force of the robots climbing on distinct surfaces of materials and demonstrated the validity and superior performance of electroadhesion in climbing robots. Yamamoto et al. [15] designed a wall climbing robot with flexible electrodes that were fabricated by a plastic film and a conductive foil. They tested the attaching

performance of the flexible electrode panel against both conductive and non-conductive walls, in which the adhesive forces is proportional to the square of voltage. Other innovative designs, e.g. gecko inspired electrostatic-chuck (ESC) [1], were also proposed to improve the poor performance of conventional ESCs on relatively rough surfaces. However, most of the studies were mainly experimental and there is still a lack of theoretical models to reveal the relationship between the adhesive force and the key design parameters. Optimal design principles are still unavailable for a majority of electroadhesive devices, in which the electrodes are actually embedded in insulating dielectrics. Only recently, Woo and Higuchi [9] developed a numerical model of electrostatic-levitation to calculate the forces generated by electrodes and discussed the optimization of the electric charging rate with respect to the geometrical parameters of electrodes.

In this paper, we attempt to theoretically address the basic design principles of electroadhesion. A semi-analytical method is presented to calculate the electric field in a four-layer or five-layer model. The Maxwell stress tensor is used to calculate the desired electroadhesive force. We demonstrate that various key factors, including the dielectric constants of constituent materials, the thicknesses of cover layer, the air-gap, and the supporting walls, as well as the applied voltage and the dielectric constant of walls, have significant effect on the performance of electroadhesive devices. This work not only helps in the comprehension of the adhesion mechanisms in electrostatic devices but also supplies guidance for their optimal design.

2. Model of Electroadhesive Forces

Consider an electroadhesive pad consisting of periodic coplanar electrodes sandwiched between a dielectric cover and a substrate, as shown in Figure 1. Such electroadhesive pads can be made in a variety of methods. To enhance the compliance of the pad, the interdigitated electrodes can be deposited by flexible materials such as carbon mixed with a polymer binder [2] or crumpled metal film [20]. The cover and substrate can be made of elastomers, polymers or plastics with different dielectric constants while the supporting wall can be any common material, e.g. concrete cement or wood.

A four-layer model is here established, including the dielectric wall, the air gap, the cover, and the dielectric substrate. To investigate the electroadhesion, we first need to calculate the electric field distribution generated by the electrodes embedded in the electroadhesive device. It is well known that the electric field $\mathbf{E}$ in the solution space can be readily calculated from the electric potential ϕ by

$$\mathbf{E} = -\nabla\phi, \quad (1)$$

And that the potential in a dielectric medium satisfies the Laplace equation

$$\nabla^2 \phi = 0. \quad (2)$$

When the solution domain of the problem is filled with a homogenous material, the electrostatic field can be analytically solved by the conformal mapping technique [21, 22]. However, for a structure made of several different materials as shown in Figure 2(a), the conformal mapping technique fails to solve the problem. Therefore, a point matching method is used here to calculate the electric fields [9, 23]. In this method, the potential function in each layer is defined by a series expansion in terms of the solutions of the Laplace equation, which are periodic in the direction parallel to the electrodes. For different layers, the coefficients in the series are related to each other and to the electric potentials applied on the electrodes. The boundary conditions in the electrode plane are satisfied at N discrete points, with N being the number of terms in the series expansion [23]. The details of the calculation method are given in the supplemental information (SI) [24].

As shown in Figure 2(a), the electroadhesive device consists of a coplanar array of electrodes whose uniform pitch and width are assumed to be $L = 2b$ and $2a$, respectively. The electrodes are assumed to have a negligible thickness and to be charged alternately by the electric potentials Φ and $-\Phi$. Due to the periodic feature of the electrodes, only one period of the structure is analyzed. More details of the model and the solution method are given in SI[24]. As shown in Figs. 2(b)-(d), using this four-layer model, we calculate the distributions of electric potential ϕ and electric field components E_x and E_y for one period of the structure with the assumed dielectric and geometric parameters $\epsilon_w = 10\epsilon_0$, $\epsilon_c = 2\epsilon_0$, $a/b = 0.5$, and $t/b = 0.02$, where ϵ_0 denotes the dielectric constant of air, ϵ_w is the dielectric constant of the wall (supporting substrate), ϵ_c the dielectric constant of the cover, t is the air gap thickness between the electroadhesion pad and the wall. It can be seen that E_y is the dominating component and its intensity in the air gap is much larger than those in the dielectric wall and the cover, yielding a relative larger attractive force between the pad and the wall.

The electrostatic attractive force exerted on the dielectric plate arises from the interaction between the applied non-uniform electric field and the induced conduction and polarization charge [9]. Once we have obtained the electric field, the attractive force can be calculated from the Maxwell stress tensor T_{ij} , which is defined as

$$T_{ij} = \epsilon \left(E_i E_j - \frac{1}{2} \delta_{ij} |\mathbf{E}|^2 \right), \quad (3)$$

where ε denotes the electric permittivity and δ_{ij} the Kronecker delta. The attraction force F_N along the normal direction of the dielectric surface is obtained by integrating the Maxwell stress tensor T_{ij} over the enclosing surfaces of the dielectric medium. Assuming the pad surface is parallel to the wall (Figure 2(a)), the electroadhesive force acting on the wall of unit length and width L can be calculated by

$$F_N = \iiint_V f_y dv = \iint_S T_{yy} ds = \frac{1}{2} \varepsilon_0 \int_0^L (E_y^2 - E_x^2) dl, \quad (4)$$

where E_x and E_y are the electric field components in the air-gap between the electroadhesive device and the dielectric wall.

Because the wall is regarded to be infinite in length along the y -direction, the attraction force acting on the upper surface of the wall is negligible. The electric field is uniform in the z -direction when the marginal part of the pad is neglected. Then the electroadhesive force acting on the whole dielectric wall of a period length L is calculated by

$$F_N = \frac{1}{2} \varepsilon_0 \int_0^L \left[\left(\varepsilon_w / \varepsilon_0 \right)^2 E_{1y}^2 - E_{1x}^2 \right] dl \Big|_{y=h_2^+}, \quad (5)$$

where E_{1x} and E_{1y} are the components of the electric field on the surface of the dielectric wall. Thus, the average adhesion stress can be given by

$$\sigma_{ad} = \frac{1}{4b} \varepsilon_0 \int_0^{2b} \left[\left(\frac{\varepsilon_w}{\varepsilon_0} \right)^2 E_{1y}^2 - E_{1x}^2 \right] dx. \quad (6)$$

With the assumption of the electric potential ϕ for the infinite wall, as shown in the SI[24], one can prove

$\int_0^L E_{1y}^2 dx \Big|_{y=h_2^+} = \int_0^L E_{1x}^2 dx \Big|_{y=h_2^+}$. Thus, Eq. (6) becomes

$$\sigma_{ad} = \frac{1}{2} \varepsilon_0 \left[\left(\frac{\varepsilon_w}{\varepsilon_0} \right)^2 - 1 \right] C \left(\frac{a}{b}, \frac{h_1}{b}, \frac{t}{b}, \frac{\varepsilon_c}{\varepsilon_w} \right) \left(\frac{\Phi}{2b} \right)^2, \quad (7)$$

where $C \left(\frac{a}{b}, \frac{h_1}{b}, \frac{t}{b}, \frac{\varepsilon_c}{\varepsilon_w} \right)$ is defined as a dimensionless function of geometric parameters $\frac{a}{b}$, $\frac{h_1}{b}$ and $\frac{t}{b}$, and material

parameter $\frac{\varepsilon_c}{\varepsilon_w} \cdot \left(\frac{\Phi}{2b} \right)^2$ is the normalized electric field generated by the applied voltage. The factor $\frac{1}{2} \varepsilon_0 \left[\left(\frac{\varepsilon_w}{\varepsilon_0} \right)^2 - 1 \right]$

is a constant depending only on the dielectric constants of the air and the wall. It is seen from Eq. (7) that the

electroadhesive force is proportional to the square of the applied voltage [15] when the function $C\left(\frac{a}{b}, \frac{h_1}{b}, \frac{t}{b}, \frac{\varepsilon_w}{\varepsilon_c}\right)$

and the dielectric constant of the wall ε_w are fixed. In the following section, we will use Eq. (7) to examine the effect of geometric and material parameters on the electroadhesive force generated by the electroadhesive pad.

3. Results and Discussions

3.1. Electroadhesion without air-gap at the interface

We first examine the special case, in which the electroadhesion pad contacts the supporting wall without the air-gap, *i.e.*, there exists a zero-thickness air-gap between the contact surface of electroadhesion pad and the wall. The dielectric wall and the cover of the pad usually have different dielectric constants, *i.e.*, $\varepsilon_c \neq \varepsilon_w$. Since no analytical solution can be obtained for such an inhomogeneous medium, the point matching method is employed to calculate the electric field with the four-layer model presented in Section II. With the zero-thickness air-gap and $\varepsilon_c \neq \varepsilon_w$, Eq. (7) can be re-expressed as

$$\sigma_{\text{ad}} = \frac{1}{2} \varepsilon_0 \left[\left(\frac{\varepsilon_w}{\varepsilon_0} \right)^2 - 1 \right] C' \left(\frac{a}{b}, \frac{h_1}{b}, \frac{\varepsilon_c}{\varepsilon_w} \right) \left(\frac{\Phi}{2b} \right)^2, \quad (8)$$

where $C'(a/b, h_1/b, \varepsilon_c/\varepsilon_w)$ is a newly defined function of geometric parameter a/b , h_1/b and material parameter $\varepsilon_c/\varepsilon_w$.

Figs. 3(a) and (b) plot the variation of $C'(a/b, h_1/b, \varepsilon_c/\varepsilon_w)$ with respect to the ratio of dielectric constants $\varepsilon_c/\varepsilon_w$ for various h_1/b and a/b , respectively. It can be seen from Figure 3 that $C'(a/b, h_1/b, \varepsilon_c/\varepsilon_w)$ increases with the increase in $\varepsilon_c/\varepsilon_w$ for a fixed value of h_1/b . However, the influence of $\varepsilon_c/\varepsilon_w$ becomes less significant when $\varepsilon_c/\varepsilon_w > 5$, and thus each curve has a plateau. As a result, from the viewpoint of fabrication, it is desired to select materials with higher dielectric constants as the cover. This inspires us to select proper devices in various working environments [2]. It is also found that the dielectric constant of the substrate material has no influence on the electroadhesive performance of the device. In addition, Figure 3 shows that both the normalized electrode width a/b and the cover thickness h_1/b have significant effects on electroadhesion, and that a smaller h_1/b or a larger a/b results in a larger electrostatic attractive force on the supporting wall. These results indicate that it is better to reduce the cover thickness and to increase the electrode width in order to enhance the adhesion force of the

electroadhesive device. However, it should be noticed that the electrodes must not reach the value $a/b=1$, at which the positive and negative electrodes would touch each other to form a short circuit. In the above discussions, we have ignored the restrictions of dielectric materials and allow the maximum voltage to be increased as required. However, the applied voltage cannot be increased infinitely due to the breakdown voltage of dielectric materials. For electroadhesion, this limit is determined by the breakdown electric strength of air E_{BD}^{air} , which is about 3×10^6 V/m. Therefore, when the applied voltage reaches the threshold of breakdown, there is an optimal value for a/b to maximize the electroadhesive force (See supplemental material SI.3 [24]). To validate the above theoretical model, we calculate the electroadhesion force generated by an electroadhesive pad described in the literature [25], which has the same structural configuration as shown in Figure 1(b). In this design, the cover layer of the pad is 123 μm in thickness, made of epoxy resin (dielectric constant $\epsilon_c = 7.8$), and the substrate is made of glass-epoxy resin. The copper electrodes are 35 μm thick and 1 mm wide. To measure the electroadhesion generated by the pad, a 4-inch silicon wafer was used as the supporting wall. As shown in Figure 3(c), the theoretical results agree with the experimental data. The little discrepancy may result from the fact that in the ideal model the electrodes are considered to have zero thickness and that there existed fringe effect in the testing device.

3.2. Electroadhesion with an air gap at the interface

In the former section, we discussed the ideal case with perfect contact between the electroadhesive device and the supporting wall. In practice, however, a small air-gap with a thickness of just a few hundred nanometers exists between the electroadhesive pad and the wall [18]. Thus, it is necessary to investigate the effect of the air-gap thickness on the electroadhesive force. Figure 4(a) shows the variation of $C\left(\frac{a}{b}, \frac{h_1}{b}, \frac{t}{b}, \frac{\epsilon_c}{\epsilon_w}\right)$ as a function of normalized air-gap t/b when $h_1/b=0.02$, $\epsilon_c=7\epsilon_0$ and $\epsilon_w=5\epsilon_0$ for different values of the electrode width a/b . It can be seen that the air-gap indeed has a significant effect on electroadhesion, and a very small air-gap (e.g., $0.05b$) can drastically reduce about by 70% of its original force when $a/b=0.8$. It is also noted that the degeneration of the attractive force is relatively faster for a smaller thickness of the cover. For some representative values of the air-gap t/b in the range from 0 to 0.2, Figure 4(b) shows the variation of $C\left(\frac{a}{b}, \frac{h_1}{b}, \frac{t}{b}, \frac{\epsilon_c}{\epsilon_w}\right)$ as a function of the electrode width a/b when $h_1/b=0.02$, $\epsilon_c=7\epsilon_0$ and $\epsilon_w=5\epsilon_0$. It is found that the attractive force

increases with the increase in the electrode width a/b , but the influence of a/b sharply reduces when the air-gap t/b is large. Thus it is concluded that the reducing air-gap thickness is important to increase the electroadhesive force.

3.3. Electroadhesion on a wall with finite thickness

In the above analyses, for the sake of simplicity, we assumed that the supporting wall is of infinite thickness compared with the electroadhesive pad. However, in such practical applications as electrostatic-levitation, we often encounter objects with finite thickness, e.g., thin LCD panels. Therefore, it is essential to understand the influence of the thickness of targeting substrates (i.e., attachments, walls or panels). In what follows, we employ a five-layer model (For details of the model, see supplemental materials SI.2[24]) to study the effect of the thickness of supporting structure or attachment (e.g., wall). The electroadhesive force acting on the whole dielectric wall of a period length L is calculated by

$$F_N = \frac{1}{2} \varepsilon_0 \int_0^L \left[(E_{3y}^2 - E_{3x}^2) - (E_{1y}^2 - E_{1x}^2) \right] dl, \quad (9)$$

where E_{1x} and E_{1y} are the electric field components above the dielectric wall, and E_{3x} and E_{3y} are the electric field components below the wall (See Figure S1 in supplemental material[24]). The average adhesion stress is written as

$$\sigma_{ad} = \varepsilon_0 \bar{C} \left(\frac{a}{b}, \frac{h_1}{b}, \frac{t}{b}, \frac{\varepsilon_c}{\varepsilon_w} \right) \left(\frac{\Phi}{2b} \right)^2, \quad (10)$$

where $\bar{C} \left(\frac{a}{b}, \frac{h_1}{b}, \frac{t}{b}, \frac{\varepsilon_c}{\varepsilon_w} \right)$ is a defined dimensionless factor. Figure 5(a) describes the variation of $\bar{C} \left(\frac{a}{b}, \frac{h_1}{b}, \frac{t}{b}, \frac{\varepsilon_c}{\varepsilon_w} \right)$

with the normalized wall thickness H/b . For each distinct $\varepsilon_w/\varepsilon_c$, we fix the electrode width as $a/b=0.8$ and $h_1/b=0.02$, and assume there is no air-gap at the contact interface. It can be found from Figure 5 that finite wall thickness has a significant effect on electroadhesion. For a given value of $\varepsilon_w/\varepsilon_c$, the electroadhesion stress increases with wall thickness, and the stress approaches a limit value when the wall thickness exceeds $2b$. For

different air-gaps, Figure 5(b) shows the variation of $\bar{C} \left(\frac{a}{b}, \frac{h_1}{b}, \frac{t}{b}, \frac{\varepsilon_c}{\varepsilon_w} \right)$ with respect to the normalized wall thickness

H/b , where we take the parameters $a/b=0.8$, $h_1/b=0.02$, $\varepsilon_c=5$, and $\varepsilon_w=7.5$. It can be seen that the wall thickness has more significant impact when the air-gap is smaller.

3.4. Effect of surface roughness

In Section III.B, we have shown that the electro-attractive force is significantly affected by the air-gap between pad and wall. Thus, the electroadhesive force of a rigid pad will be sensitive to its surface roughness. Therefore, one possible approach to alleviate the negative influence of roughness is to develop a compliant pad, *e.g.*, depositing compliant electrodes into elastomeric insulators, which is able to adaptively adhere to a wide range of roughness [15]. Another promising method is to design a compliant electrostatic pad by mimicking the structure of gecko feet [26-28]. Such a biomimetic structure enables the electroadhesive pad to maintain a much larger electroadhesive force on rough surfaces. To design an adaptive electroadhesion pad like gecko feet, one can add a layer consisting of short hairs on top of the cover layer of the pad to enhance its adaptability on rough surfaces, as shown in Figure 6(a). To analyze the performance of the biomimetic compliant pad using the present model, the added layer can be treated as a composite with an effective dielectric constant ε_m , which can be evaluated by a parallel mixing rule[29] as $\varepsilon_m = V_a \varepsilon_c + V_w \varepsilon_0$, where V_a and V_w are the volume fractions of the dielectric phase and air-gap phase ($V_a + V_w = 1$), respectively. For different values of the hair length, Figure 6(b) shows the variation of $\bar{C} \left(\frac{a}{b}, \frac{h_1}{b}, \frac{t}{b}, \frac{\varepsilon_c}{\varepsilon_w}, \frac{\varepsilon_m}{\varepsilon_w}, \frac{h_m}{b} \right)$ as a function of dielectric constants ratio $\varepsilon_m/\varepsilon_w$ where we take $a/b=0.9$, $h_1/b=0.01$, $t/b=0$, $\varepsilon_w=5\varepsilon_0$, and $\varepsilon_c=7\varepsilon_0$. It is obvious that the electroadhesion reduces as the length of hair layer increases and will reach a peak value for each h_m/b when the mixed dielectric constant ε_m is larger than ε_w . It is expected that such a design has another attractive merit, *i.e.*, combining the electroadhesive force together with the van der Waals force to generate stronger adhesion. It is known that when the dimension of gecko-feet-like structures goes down to the micro or even nano scale, the van der Waals force generated by the hair layer becomes much stronger[26-28, 30, 31]. Therefore, the hair layer not only improves the adaptability of a pad on rough surfaces but also enhances the attraction force. It will be promising to fabricate a novel electroadhesive device or to develop a new micro-transfer technique by superimposing both electroadhesive and van der Waals forces.

4. CONCLUSIONS

In summary, we have theoretically analyzed the electroadhesive forces of an interdigitated type electroadhesive device by employing a semi-analytical model and discussed the optimal design principles of electroadhesive devices for a wide variety of applications. It is found that, to enhance the electroadhesive force, the cover layer should employ dielectric materials with larger dielectric constants, and the electrodes should be wider while the cover should be thinner. However, for the extreme case where the electric potential is equal to the breakdown voltage, the maximum electroadhesive force will occur with a very small ratio of a/b . We have also proposed a novel route to improve the performance of electroadhesive pads by mimicking the structure of gecko feet, which enables the electrodes to maintain a good proximity with rough surfaces and **to combine both electroadhesion and van der Waals forces together to increase the overall adhesive force**. The present theoretical model is helpful to design new electroadhesive devices and to develop electroadhesion-based micro-transfer techniques.

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Figure Captions

Figure 1. Schematic of an electroadhesive pad with embedded interdigitated electrodes: (a) 3D view and (b) side view.

Figure 2. (a) A four-layer model for an electroadhesive pad with periodic coplanar electrodes sandwiched between a dielectric cover and a substrate. Contour plots of the calculated (b) electric potential ϕ , (c) electric field component E_x , and (d) electric field component E_y for a period of the model in (a).

Figure 3. Variation of $C'(a/b, h_1/b, \epsilon_c/\epsilon_w)$ as a function of dielectric constant ratio ϵ_c/ϵ_w (a) for various normalized cover thickness h_1/b when $a/b=0.8$ and $\epsilon_w=5\epsilon_0$; and (b) for various normalized electrode width a/b when $h_1/b=0.02$ and $\epsilon_w=5\epsilon_0$. (c) Comparison of the predicted electroadhesion with the experimental data from literature.

Figure 4. (a) Variation of $C(a/b, h_1/b, t/b, \epsilon_c/\epsilon_w)$ as a function of dielectric constants ratio t/b for various normalized electrode width a/b when $h_1/b=0.02$, $\epsilon_c=7\epsilon_0$, and $\epsilon_w=5\epsilon_0$. (b) Variation of $C(a/b, h_1/b, t/b, \epsilon_c/\epsilon_w)$ as a function of dielectric constants ratio a/b for various normalized thickness of air-gap t/b when $h_1/b=0.02$, $\epsilon_c=7\epsilon_0$, and $\epsilon_w=5\epsilon_0$.

Figure 5. (a) Variation of $\bar{C}(a/b, h_1/b, t/b, \epsilon_c/\epsilon_w)$ as a function of normalized wall thickness H/b for different dielectric constants ratio ϵ_c/ϵ_w when $a/b=0.8$, $h_1/b=0.02$, $t=0$. (b) Variation of $\bar{C}(a/b, h_1/b, t/b, \epsilon_c/\epsilon_w)$ as a function of normalized wall thickness H/b for different air-gap t/b when $a/b=0.8$, $h_1/b=0.02$, $\epsilon_c=5\epsilon_0$ and $\epsilon_w=7.5\epsilon_0$.

Figure 6. (a) Schematic design of a compliant electroadhesive pad with added hair layer by mimicking Gecko feet. (b) Variation of $\bar{\bar{C}}(a/b, h_1/b, t/b, \epsilon_c/\epsilon_w, \epsilon_m/\epsilon_w, h_m/b)$ as a function of dielectric constants ratio ϵ_m/ϵ_w for different hair length h_m/b when $a/b=0.9$, $h_1/b=0.01$, $t=0$, where $\epsilon_c=7\epsilon_0$ and $\epsilon_w=5\epsilon_0$.

Figures

(a)

(b)

(a)

(b)

Graphical Abstract: