Electrostatic chuck consisting of polymeric electrostatic inductive fibers for handling of objects with rough surfaces

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Abstract
An electrostatic chuck (ESC) is a type of reversible dry adhesive which clamps objects by means of electrostatic force. Currently an ESC is used only for objects having flat surfaces because the attractive force is reduced for rough surfaces. An ESC that can handle objects with rough surfaces will expand its applications to MEMS (micro electro mechanical system) or optical parts handling. An ESC consisting of compliant electrostatic inductive fibers which conform to the profile of the surface has been proposed for such use. This paper aims at furthering previous research by observing the attractive force/pressure generated, both theoretically and experimentally, through step-by-step fabrication and analysis. Additionally, how the proposed fiber ESC behaves toward rough surfaces is also observed. The attractive force/pressure of the fiber ESC is theoretically investigated using a robust mechano-electrostatic model. Subsequently, a prototype of the fiber ESC consisting of ten fibers arranged at an angle is employed to experimentally observe its attractive force/pressure for objects with rough surfaces. The attractive force of the surface which is modeled as a sinusoidal wave with various amplitudes is observed, through which the feasibility of a fiber ESC is justified.

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(Some figures may appear in colour only in the online journal)

1. Introduction
An electrostatic chuck (ESC) [1, 2] is a tool used to clamp objects by means of electrostatic force. Since they can be used in a vacuum, ESCs are widely used in the semiconductor industries to hold silicon wafers during lithography processes in a clean room. Various studies have focused their attention on increasing the attractive force generated by the ESC, either by increasing the breakdown voltage of the insulator or dielectric or by manipulating the electrode design and spacing [3–6]. It is worth noting, however, that the use of a conventional ESC, which comprises a metal base-plate with a thin dielectric part, has always been focused on handling flat-surfaced objects. When handling rough-surfaced objects, the attractive force resulting from the electrostatic force, which is inversely proportional to the square of the distance, reduces significantly due to the irregularity in the surface profile.

In a broader sense, by analyzing the mechanism, an ESC can also be categorized into a type of reversible dry adhesive [7] with an electrostatic force as the technique used...
to realize the adhesion. As one area of research focuses on the broad field of reversible dry adhesives, scientists have tried to achieve the important target of conforming their product to rough surfaces. Various technologies and approaches have been reported to this aim, including the fabrication of a gecko-like hierarchical structure with a strong van der Waals force [8–14], the use of surface patterns [15], the use of a thermally-controlled polymer [16, 17], a combination of electrostatic force and van der Waals force [18], and so on. Despite all the advances, however, research which involves the use of electrostatic force to handle rough-surfaced objects is notably lacking. Some of the most significant results can be observed in the field of wall-climbing robots. Several researchers have put their interests in techniques to improve a robot’s holding force against a rough wall. Yamamoto et al [19] presented the idea of a wall-climbing robot using a flexible electrode which reportedly worked for both conductive and non-conductive walls. In a comparable account, Prahlad et al [20] offered another idea utilizing a compliant polymeric pad for damp surfaces. It is arguable, however, that these approaches, although they have provided important insights into the ESC field, are still insufficient for handling objects with rough surfaces and a high aspect ratio.

If an ESC with the capability of handling rough-surfaced objects could be realized, the benefits could be extended to various applications, such as MEMS parts or microlens array handling.

Our group [21] have proposed the use of compliant electrostatic inductive fibers made of a polymer, focusing on ESC applications for handling mm-order rough-surfaced objects. We developed a prototype for an ESC with the fibers bundled by heat-shrink tubing, utilizing the mechanical compliance characteristics possessed by the fibers so that they can conform to the surface roughness. A conceptual image of this idea is shown in figure 1. Through the experimental results, we have shown [21] that polymeric fibers possess compliance characteristics and that a large attractive force could be produced with respect to an object.

In this study, we conduct research to understand a fiber’s behavior for ESC applications, with a special emphasis on handling rough surfaces. Theoretical attractive forces exerted toward rough surfaces are studied and compared with the experimental results obtained. The rough surfaces of interest are modeled after a sinusoidal curve with certain wave amplitudes. The study as well as the experiment are conducted via two steps of analysis: the single fiber model and the arranged fibers model consisting of ten fibers aligned in a row. Subsequently, the findings in the two steps are taken so as to confirm the feasibility of realizing a third step which is termed arrayed fibers. The arrayed fibers with the most complex structure are the closest in concept to the desired fiber ESC. An illustration of the concept in each of the steps is depicted in figure 2. In addition to that, figure 3 presents an animated illustration of the ESC with a possible application of transporting a rough-surfaced microlens array in the imaging industry.

2. Theoretical basis

2.1. The mechanical model of a single fiber

A polymeric electrostatic inductive fiber is considered in this study. As shown in figure 1, the fiber is fabricated so as to contain a conductive core, and it is hence able to produce an electrostatic force when a voltage is applied.

A mechanical model of a single fiber ESC device is constructed as depicted in figure 4 to explain the fiber’s behavior. In the model, the fiber is associated with a model of a spring unit with a contacting tip. The spring constant contributes to the elastic force whereas the tip’s and the object’s surfaces, which resemble the concept of a parallel-plate capacitor, contribute to the electrostatic force. The displacement of the device base, \( Z \), is 0 when the fiber makes contact with the object without any voltage applied.

In this model, the fiber’s stiffness is \( k \). This property introduces compliance to the proposed ESC. Additionally, the fiber’s tip surface area is \( S_{\text{tip}} \); the dielectric thickness is \( d_{\text{ins}} \); the permittivity of the free space is \( \varepsilon_0 \); the dielectric
permittivity is $\varepsilon_{\text{ins}}$; and the distance from the dielectric layer to the object’s surface is $d$. Subsequently, we may express the electrostatic force, $f_e$, and the elastic force, $f_k$, of the fiber as follows

$$f_k = k(d - Z),$$  
(1)

and

$$f_e = \frac{\varepsilon_0 \varepsilon_{\text{ins}} S_{\text{tip}} V^2}{2(\varepsilon_0 d_{\text{ins}} + \varepsilon_{\text{ins}} d)^2}. $$  
(2)

The expression for the electrostatic force is obtained by deriving the equation for a model of a capacitor with two different dielectric substrates in series.

The force is positive in the upward direction from the object’s surface. Given the mechanical model of the fiber, we are able to construct a force curve mathematically as shown in figure 5. The force curve signifies the relationship between $f_{\text{att}}$ with respect to the displacement of the device base, $Z$, for a single fiber ESC device when approaching a flat-surfaced object upon applying a voltage. Since the electrostatic force becomes constant once the fiber makes contact with the object, the characteristics of the attractive force are significantly dependent on the elastic force. Therefore, figure 5 shows only the portion with elastic force, from which the behavior of the fiber during the approach and release phases can be analyzed.

If a voltage is applied when the fiber tip is far enough away from the object, it will approach the surface because of the electrostatic force. In this phase, there is a point where $f_k + f_e = 0$, which keeps the fiber at a stable position. If the fiber is brought closer to the object, the fiber will lose its stable energy point [21], and spontaneously make contact with the object’s surface. The contact occurs when $f_e > -f_k$. This jump-to-contact phenomenon from an energy perspective is discussed thoroughly in Saito et al [21]. The displacement in which contact occurs, $Z_{\text{cont}}$, is indicated in the horizontal axis of figure 5.

After the fiber is already in contact with the object ($d = 0$), the base can still be displaced further, i.e. $Z$ can be increased. This means that at this phase the electrostatic
force will remain constant at its maximum value, while the elastic force will keep changing until it becomes repulsive when $f_k > 0$.

Detachment occurs when $f_k$ during the release phase is larger than the maximum attractive force, or $f_k > f_{k_{\text{max}}}$ in the horizontal axis of figure 5 indicates the displacement when detachment occurs. When utilizing a fiber with compliance, it can be understood that the maximum attractive force is obtained in the release phase, rather than in the approach phase.

### 2.2. Theoretical attractive force of an arranged fibers ESC device toward a rough surface

The next step in this study is the analysis of an arranged fibers ESC device and its behavior with respect to a rough surface modeled after a sinusoidal curve. Considering an arranged fibers ESC device consisting of eight fibers, we may observe that the attractive force generation becomes more complicated. As opposed to the single fiber model with a flat-surfaced object in which full contact of the spring unit occurs, in the arranged fibers model with an aggregation of spring units, each fiber generates a different attractive force because each has a different $d$ due to the rough surface. In other words, some fibers make full contact while others do not. We could, however, mathematically estimate the total attractive force of the whole ESC device by summing up the attractive force in the individual spring unit. The following equation expresses $f_{\text{device}}$, the force of an arranged fibers ESC device,

$$f_{\text{device}} = \sum_{i} f_i$$

where $N$ is the number of fibers and $f_i$ is the force of the $i$th fiber.

A similar approach to force curve generation with a different surface profile treatment was also carried out by Takahashi et al [22]. In that paper, a gecko’s foot hair structure is considered and convolution is performed between the height distribution function and the force curve of a single spring unit.

Since for multiple fiber experiments, the values for pressure are of more interest, particularly for practicality purposes when scaling up the ESC in real applications, some discussions in this paper are focused on pressure, instead of force. The area used in the pressure calculation is the total area of the conductive cores of the fibers. Additionally, in this study of an arranged fibers ESC device, since the maximum attractive pressure is of the utmost interest, the pressure curve considered is the only one during the release phase in which the maximum attractive pressure occurs.

Figure 6 shows the theoretical attractive pressure for the arranged fibers ESC device when handling an object with a sinusoidal surface. This pressure curve is plotted by considering eight fibers of 1 mm spacing and $0.1 \text{ N m}^{-1}$ spring constant acting on a sinusoidal surface with a 100 $\mu\text{m}$ wave amplitude. The surface profile is defined as $h = A \sin x$, where $A$ is the surface wave amplitude, and with fiber tips positioned at $x = 0$ to $7\pi/8$ with a $\pi/8$ increment (see figure 6). Several ripples appearing on the pressure curve correspond to the detachment of one or several fibers. For instance, the first ripple to occur in the release process, marked by the rightmost red circle in figure 6, corresponds to the detachment of fiber number 7. In the fiber arrangement of eight fibers in a row, fiber number 7 happens to be the one with the longest stretch which results in the first detachment during the release process for the device. The detachment of one or several fibers, such as number 7 in this case, contributes to the change in the attractive pressure for the whole device. This phenomenon explains the origin of the ripples in the theoretical pressure curve for the arranged fibers. Consequently, the occurrence of subsequent ripples can also be explained in a similar fashion, for example, the second ripple corresponds to the detachment of the pair of fibers numbered 6 and 8, and so on.

### 3. Experimental section

Fabrication of polymeric electrostatic inductive fibers. A polymeric electrostatic inductive fiber is considered in this study. The fiber used in this research is made of polymer with a conductive part at the core, fabricated using a bicomponent melt spinning apparatus [21]. The material for the sheath is polystyrene (PS), whereas that of the core is polypropylene (PP) blended with vapor grown carbon fiber (VGCF). In this research, fibers with properties as specified in table 1
Figure 7. Materials and experimental setup. (a) Image of the surface sample made of duralumin with 200 $\mu$m wave amplitude and 4 mm wavelength, (b) the arranged fibers ESC device prototype, (c) experimental system setup and (d) photos of arranged fibers’ tips when making contact with a duralumin surface sample covered by a layer of propylene tape.

Table 1. Properties of a single electrostatic inductive fiber.

| Parameter                                      | Value          |
|------------------------------------------------|----------------|
| Diameter of the fiber                         | 250 $\mu$m     |
| Diameter of the conductive core               | 120 $\mu$m     |
| Area of the conductive core at fiber’s tip    | $1.60 \times 10^{-8}$ $m^2$ |
| Young’s modulus                               | 4 GPa          |
| Resistivity                                   | 2.21 $\Omega$ $m$ |
| Fiber’s stiffness                             | 0.4 N m$^{-1}$  |

were used. The fiber’s stiffness was measured by plotting experimentally the linear relation between applied force and the displacement. The fiber was cut after being arranged at an angle of 45$^\circ$ and thus the fiber’s tip is approximated to have an elliptical shape. The area of the conductive core at the fiber’s tip, obtained as $1.60 \times 10^{-8}$ $m^2$, is achieved by utilizing an ellipse formula for the area calculation (see figure 8(e) for a schematic illustration).

Fabrication of rough-object samples. In order to confirm the feasibility of the concept of a fiber ESC in handling rough surfaces, we fabricated object samples made of duralumin with sinusoidal-shaped surfaces for surface profiles. Several object samples were made with various wave amplitudes (depth): 0 (flat), 50, 100, and 200 $\mu$m (see figure 7(a)) while the wavelength for each was kept the same at 4 mm. Since there is no insulating layer on the fiber tip, as an alternative a polypropylene tape with a thickness of 50 $\mu$m and a dielectric constant of 2.8 was affixed to each of the sample’s surfaces.

Fabrication of fiber ESC device prototypes and attractive force measurement. Additionally, in order to confirm the theoretical force/pressure curves which were previously obtained, two kinds of fiber ESC device prototypes were developed: one was a prototype with only one fiber and the other one was with ten fibers arranged at an angle of 45$^\circ$, with a 1 mm gap in between each fiber (see figure 7(b)). Figure 8 shows a schematic of the fabrication process for the ESC device prototype. The applied voltage was 600 V. The attractive force was measured by an analytical balance on which the object sample was placed and the prototype was moved to approach the object sample. Figure 7(c) shows a schematic of the experimental setup whereas figure 7(d) depicts an image of the fibers’ tips before and after making contact with a neutrally-charged sample object of 200 $\mu$m amplitude. The force exerted by the prototype with respect to the object was then observed. The experiments were conducted in atmospheric pressure and at room temperature with a relative humidity of 23%.

4. Results and discussions

The experimental pressure curve for the single fiber ESC device prototype is given in figure 9(a). Through the experiments, with the aid of a video camera, it was observed that upon applying a voltage, when the fiber was within a certain distance, it spontaneously jumped into contact with the object. Additionally, it was also observed that during the release phase, the fiber maintained contact with the object before detachment, which resulted in the largest attractive pressure in the cycle. These two physically-observed phenomena are consistent with the behavior of the theoretical force curve as shown in figure 5 and as was discussed by Saito et al [21]. The maximum attractive pressure obtained
Figure 8. Steps involved in the arranged fibers ESC device fabrication (not to scale): (a) ten fibers of arbitrary lengths are arranged with the aid of a jig at an angle of 45°, (b) conductive tape is attached, (c) conductive paste is applied to the root of the fibers, (d) the fibers are cut at a necessary length, (e) the ready-to-use arranged fibers ESC device with an inset showing an elliptical shape of the fiber’s tip.

was −852 Pa during the approach phase and −968 Pa during the release phase.

Similarly, the experimental pressure curve during the release phase for the arranged fibers ESC device prototype was also obtained as shown in figure 9(b). The applied voltage was 600 V and the sinusoidal surface with 100 μm wave amplitude was employed as the surface sample. In this experiment, a maximum attractive pressure of −813 Pa was obtained. Comparing to figure 6, a similar phenomenon of ripples which correspond to the detachment of fiber(s) during the release phase could be observed.

Furthermore, in order to understand the effect of a fiber’s spring constant in handling rough surfaces, a graph of maximum attractive pressure with respect to surface wave amplitude for different spring constants is presented in figure 9(c). In the graph, the experimental maximum attractive pressures for surface samples of various amplitudes are plotted as circles along with the theoretical curves for the different fiber’s spring constants of $k = 0.1 \text{ N m}^{-1}$, $k = 0.4 \text{ N m}^{-1}$, and larger values of $k$ (no compliance). The value for $k$ of 0.4 N m$^{-1}$ is of specific interest because it is the same value as the spring constant for the fibers used in this experiment.

An important point from figure 9(c) is that the more compliant the fibers, i.e. the smaller the stiffness value, $k$, the more they are able to adapt to rougher surfaces. The smaller the stiffness value, the more linear the curve becomes without a significant drop in maximum attractive pressure when handling large wave amplitudes. In contrast, a significant drop in maximum attractive pressure is visible for fibers with no compliance, i.e. the pressure drops by about 70% when handling a surface of 100 μm wave amplitude as compared to the handling of a flat surface.

The four measured pressure values correspond to the four different amplitudes of the surface sample fabricated for this study, i.e. 200, 100, 50, and 0 μm (flat surface). The variations in experimental data were observed to be relatively small and they can be deemed insignificant as far as the maximum attractive pressure is concerned. The range is between 2–4% for surface samples with 0 and 50 μm amplitude and 6–7% for those with 100 and 200 μm amplitude.

Along with the increase in the sample’s surface amplitude, the attractive pressure decreases, but for those with an amplitude of 50, 100, and 200 μm, attractive pressures larger than the ones theoretically predicted with non-compliant fibers were observed experimentally. It can be argued that the fiber’s compliance contributes to the performance improvement of the attractive pressure toward a rough surface. Measured attractive pressures for $k = 0.4$ are found to match the theoretical values and are thought to be generally consistent with theory. To assess the capacitor’s fringe effect, a simple finite element simulation for capacitance calculations has been conducted. The simulated value shows a significantly small variation to the theoretical
value. The simulation result, in addition to the experimental results which are generally well-matched with the theory, strongly infer that the capacitor’s fringe effect, though important to consider, is of no significant influence in this ESC device prototype. The fringe effect, however, shall be considered more thoroughly in our future work which involves more fibers for a fully-fledged operation.

An important observation is also made when the surface amplitude is 0; the measured attractive pressure was only around 65% of the theoretical value. This finding may be the result of irregularities of the fibers’ tips as depicted in figure 10(a). Fiber tips which are longer than the rest exert a repelling pressure during contact with the surface, by which the attractive pressure decreases. In our prototype, a difference of about 50–100 µm in fiber tip lengths for the device prototype were measured. These length irregularities came about from the fabrication process, which shall be improved in future work. This occurrence brings up a practical implication: 50–100 µm irregularities in fiber tip lengths for handling a flat surface are generally comparable to an ideal arranged fibers ESC device prototype handling an object with a sinusoidal surface roughness of 50–100 µm in amplitude. Of course, the latter results in significantly lower attractive pressure than handling of a flat surface. This is believed to be a possible reason to explain the unmatched theoretical and experimental results. Figure 10(b) illustrates this argument by comparing both models.

5. Feasibility of an arrayed fibers ESC for rough surfaces

Though it has been shown in the previous sections that the proposed ESC concept successfully produced an attractive force/pressure compared to what has been theoretically predicted, it is still important to show whether with the force it is able to perform the function of an ESC, i.e. to pick up an object. Therefore, to ascertain the feasibility of a desired arrayed fibers ESC as shown earlier in figure 3, a demonstration to pick up an object was conducted. The prototype of 10 arranged fibers was used, the object a neutrally-charged flat-surfaced aluminum pipe with a weight of 185.05 µN. In this experiment, 600 V was applied. While the approach and pick up phase were carried out with voltage applied, the release was made possible by simply cutting off the voltage supply. The demonstration was recorded by a video camera (supplemental video available at stacks.iop.org/SMS/22/095010/mmedia) and its screen captures are given in figure 11. Through the demonstration, it can be shown that the ESC prototype was successful in picking up and releasing the object.

From equation (3), it can be understood that the number of fibers determines the total attractive force that can be produced by the ESC. Therefore, the success of this pick-up experiment would suggest that upon scalability of the
Figure 10. Irregularities in the fiber ESC device prototype. (a) Irregular tip lengths for the fiber ESC device prototype and (b) an illustration showing the consequences of irregular tip lengths.

Figure 11. The pick-up experiment utilizing an arranged fibers ESC device prototype. (a) The device prototype is making an approach to an aluminum pipe and subsequently: (b) making contact; (c) picking up; and (d) releasing (by cutting off the voltage supply). Two fibers, the left-most and the fourth from the left, are not making contact with the object. (Supplemental video available at stacks.iop.org/SMS/22/095010/mmedia.)

It is important to note, however, that this demonstration corresponds to the previous experiment when the wave amplitude of the object sample is 0, i.e. a flat surface (see figure 9(c)). Though the attractive force obtained previously was only 184.36 µN, which is slightly less than 185.05 µN, the weight of the aluminum pipe used for the demonstration, the success in picking up the pipe shows that the attractive force produced this time must have been improved and is closer to that of the theoretical value presented in figure 9(c). This also demonstrates that the uncertainty level for the attractive force produced is still high, which might have resulted from unwanted defects in the device prototype as can be seen from figure 11(c). From this screen capture, it is apparent that the left-most fiber and the fourth fiber from the left are not in contact with the object. A similar phenomenon of incomplete individual fiber contact was also visible in the previous experiments involving various different rough surfaces. This kind of defect, which might have resulted from imperfections during the device prototype fabrication process, is also arguably the source of the unmatched theoretical and experimental values for attractive pressure as discussed in the previous section. It is therefore important to improve the defects in the ESC or fibers in the future, especially for applications concerning the handling of rough-surfaced objects, as such applications will require a high and stable attractive force.

6. Conclusions

A device prototype for a fiber ESC was developed, from which its characteristics were discussed. In addition, theoretical force/pressure produced by the prototype was compared with the measured force in experiments with rough-surfaced objects modeled after a sinusoidal wave with various
amplitudes. Subsequently, to show that the concept works for picking up and releasing an object, an experiment to pick up a flat-surfaced aluminum pipe with the device prototype was conducted (supplemental video available at stacks.iop.org/SMS/22/095010/mmedia). The object was successfully picked up and released with switching off of the voltage applied, though several defects in the device prototype were observed. Further improvements, especially in fabrication are needed so as to produce a fully-fledged ESC for handling rough-surfaced objects. Future work will include improvements in the design of the shape of the tips as well as in the device fabrication process, which will help to improve the way the fibers make contact with the surface, upon which an increase in attractive pressure is expected.

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