

# Bio-Inspired Adhesive Systems for Next-Generation Green Manufacturing

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*Inspired by the remarkable adhesion properties of gecko lizards, bio-inspired dry adhesives with smart adhesion properties have been developed in the last decade. Compared to earlier dry adhesives, the recently developed ones exhibit excellent adhesion strength, smart directional adhesion, and structural robustness. With these unique adhesion properties, bio-inspired dry adhesive pads have strong potential for use in precision industries such as semiconductor or display manufacturing. In this communication, we present a new manufacturing technology based on advanced dry adhesive systems that enable precise manipulation of large-area substrates over repeating cycles without any requirement for external force application. This new manufacturing technique is also highly accurate and environment-friendly, and thus has strong potential as a next-generation clean manufacturing technology.*

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## NOMENCLATURE

SOI wafer = silicon-on-insulator wafer

PDMS = polydimethylsiloxane

DRIE = deep reactive ion etching

PECVD = plasma enhanced chemical vapor deposition

Si = silicon

SR = spacing ratio

## 1. Introduction

The attachment pads of gecko lizards represent one of the most versatile and effective adhesive structures in nature, reflected in their exceptional ability to walk freely on various surfaces including vertical walls and even ceilings without any surface contamination.<sup>1,2</sup> This unusual adhesion capability is attributed to arrays of millions of microscopic foot hairs that split into hundreds of smaller nanoscale ends called spatulas.<sup>3-8</sup> Inspired by the fascinating adhesion properties of gecko lizards, artificial dry adhesives with superior and smart

adhesion properties have been developed over the last decade with the aid of micro- and nanoscale manufacturing techniques.<sup>5-7,9-12</sup> Compared to earlier dry adhesives, the recently developed ones show remarkable adhesion strength, repeatable and reversible adhesion, rough surface adaptation, and directional adhesion.<sup>5-7,9,10,13</sup>

Therefore, now it is time to drive fundamental research on bio-inspired dry adhesives into a new epoch by developing unique and practical applications for these materials. Among their many possible applications in various aspects of the daily life as well as in industries, dry adhesives have strong potential for use in precision industries such as semiconductor or display manufacturing, where clean and residue-free transportation of fragile silicon or glass substrates is required during the product-assembly process.<sup>5,6</sup> During the assembly process of semiconductors or display devices, silicon wafers or glass substrates, which are usually very thin, large, and fragile, should be carefully handled with high accuracy. Moreover, there should be no surface contamination on the substrates.<sup>5,6</sup> Thus, dry adhesive technology has strong potential to replace existing techniques such as vacuum suction or electrostatic chucks since dry adhesives enable precise manipulation of various substrates without any surface contamination in a reversible, repeatable, and durable manner. Furthermore, dry adhesive technology does not require external forces (e.g., vacuum or electrostatic forces)

for the attachment of substrates, which will enable cost-effective and environment-friendly manufacturing in precision industries.

Here, we introduce a new manufacturing technology based on advanced dry adhesive systems that enable precise manipulation of various substrates over tens of thousands of repeating cycles without any requirement for external force application. This new manufacturing technique is also highly accurate and environment-friendly, and thus has strong potential as a next-generation clean manufacturing technology.

## 2. Fabrication of Gecko-Inspired Dry Adhesives

To develop a new manufacturing system that enables precise manipulation and transportation of large-area substrates, we utilized bio-inspired, mushroom-like micropillar arrays. These arrays present an efficient form for a dry adhesive, since both the normal and shear adhesion strength can be significantly enhanced owing to the presence of a thin spatulate structure,<sup>14,15</sup> which maximizes the adhesive area in contact with the target surface.<sup>10,16-19</sup> Furthermore, they are relatively easy to produce in a scalable manner and also mechanically more durable as compared with hierarchical nanostructures.<sup>6</sup>

Fig. 2 shows a schematic procedure for fabricating bio-inspired dry adhesives with mushroom-like micropillars by a series of surface micromachining steps and replica molding of PDMS. First, a SOI wafer with microholes was prepared by photolithography and subsequent DRIE. The SOI wafer (p-type, 100) possessed a 1- $\mu\text{m}$ -thick oxide layer on a 500- $\mu\text{m}$ -thick silicon layer. A 20- $\mu\text{m}$ -thick top silicon layer was then formed over the oxide layer. Additionally, an 800-nm-thick  $\text{SiO}_2$  layer was deposited on top of the silicon layer for realizing enhanced etching resistivity during DRIE by PECVD. Here, the 1- $\mu\text{m}$ -thick oxide layer imbedded between the top and bottom Si substrates acted as an etch-stop layer. DRIE in the vertical direction was carried out to pattern microhole arrays until the complete exposure of the etch-stop layer was achieved. Subsequent over-etching in the lateral direction resulted in negative patterns of mushroom-shaped micropillars on the SOI wafer (Fig. 3(a)). For replica molding, the patterned wafer was treated with trichloro(1H,1H,2H,2H-perfluorooctyl) silane. After the SOI master was prepared, PDMS replicas were prepared by molding the fabricated SOI master with a PDMS prepolymer. A 10:1 mixture of the PDMS prepolymer (Sylgard 184A) and curing agent (Sylgard 184B) was poured onto the SOI master. Then, it was put into a convection oven and cured for 2 h at 70°C. After curing, the PDMS replicas were carefully removed from the master to avoid possible fracture of the spatulate tips.

Fig. 3(b) shows a photograph of the replicated dry adhesives in which four different kinds of mushroom-shaped microstructures are embedded: micropillars with (i) 17  $\mu\text{m}$  tip diameter, 15  $\mu\text{m}$  post diameter, and 30  $\mu\text{m}$  space (spacing between neighboring pillars); (ii) 22  $\mu\text{m}$  tip diameter, 20  $\mu\text{m}$  post diameter, and 40  $\mu\text{m}$  space; (iii) 17  $\mu\text{m}$  tip diameter, 15  $\mu\text{m}$  post diameter, and 15  $\mu\text{m}$  space; and (iv) 22  $\mu\text{m}$  tip diameter, 20  $\mu\text{m}$  post diameter, and 20  $\mu\text{m}$  space. The height of the micropillars was about 20  $\mu\text{m}$ , and each micropillar had a patterned area of 3 $\times$ 3  $\text{cm}^2$ . Fig. 3(c) shows the representative SEM image of the resulting microstructures. As shown, a mushroom-shaped micropillar

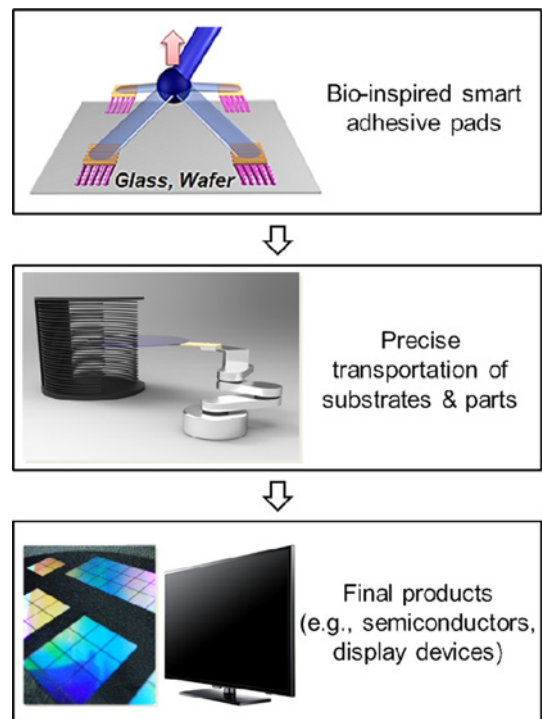


Fig. 1 Examples of applications of bio-inspired dry adhesives in precision manufacturing

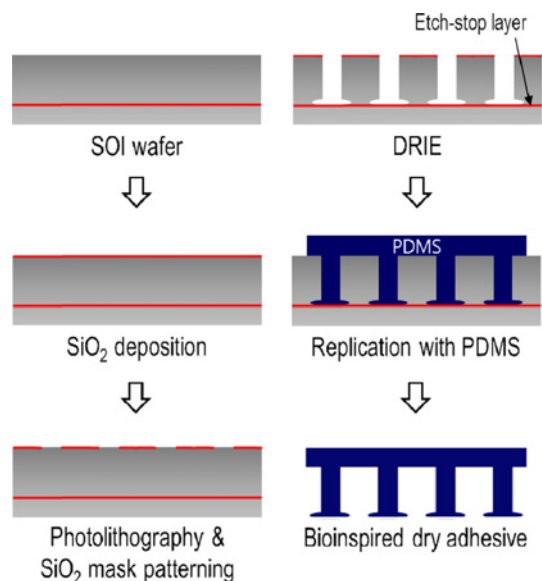


Fig. 2 Schematic illustration of fabricating bio-inspired dry adhesives with mushroom-like microstructures

array (22  $\mu\text{m}$  tip diameter, 20  $\mu\text{m}$  post diameter, and 20  $\mu\text{m}$  space) was successfully fabricated with good structural integrity and uniformity. Specifically, the spatulate tip of the microstructures, which plays a significant role in enhancing adhesion strength, was successfully fabricated.

## 3. Results and Discussions

### 3.1. Evaluation of Adhesion Strength

The pull-off forces of PDMS micropillars were evaluated by

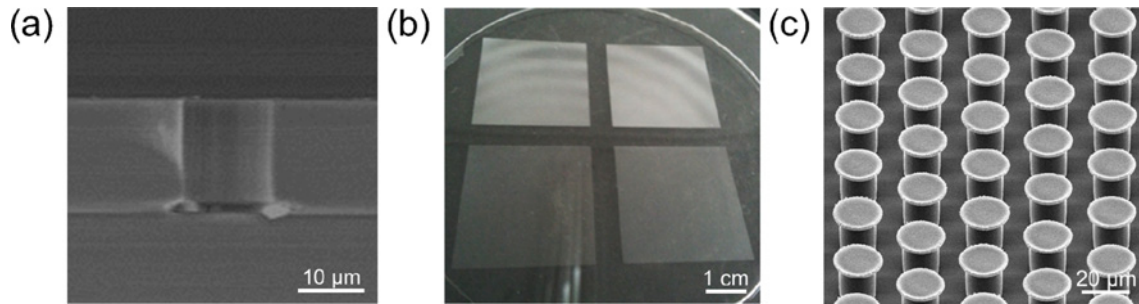


Fig. 3 (a) A cross-sectional SEM image of etched negative patterns of mushroom-shaped micropillars on the SOI wafer. (b) A photograph showing the fabricated dry adhesive film having four different mushroom-like micropillars. (c) An SEM image of fabricated mushroom-shaped micropillar array (22  $\mu\text{m}$  tip diameter, 20  $\mu\text{m}$  post diameter, and 20  $\mu\text{m}$  space)

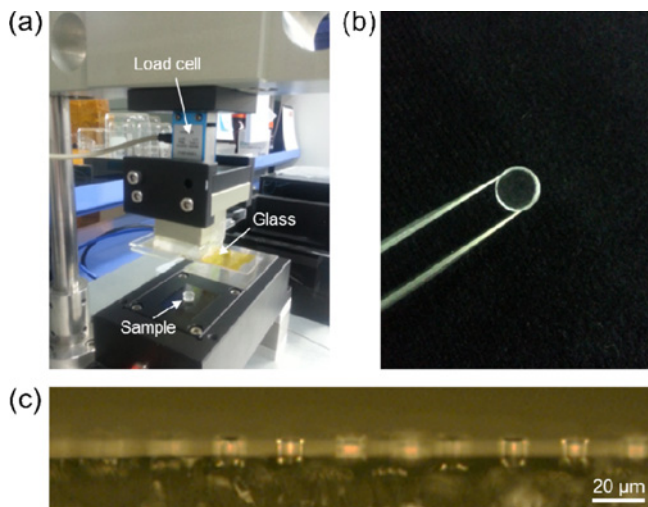


Fig. 4 (a) A custom-built adhesion measurement system. The system is composed of a motorized driving part with a load cell moving in vertical direction and a flat stage. (b) A photograph showing the circular dry adhesive pad (diameter = 7 mm). (c) An optical microscopy image showing the cross-section of dry adhesive pad with mushroom-like microstructures

custom-built equipment at a relative humidity of 40% and an ambient temperature of 25°C (Fig. 4(a)). The equipment consisted of motorized load cells and a flat stage. The load cell (333AL, KTOYO, Korea) was used for measuring the adhesion force in the  $z$  (vertical) direction. A circular dry adhesive patch (Fig. 4(b), diameter = 7 mm, thickness = 2 mm) was attached to a flat glass surface bonded to the load cell under a controlled preload ranging from 2 to 70 N (2 N, 5 N, 10 N, 20 N, 30 N, 40 N, 50 N, 60 N, and 70 N), and an in-plane strain was applied by the motorized stage until separation occurred. The adhesion measurement was carried out 30 times for each sample under identical conditions.

As shown in Fig. 5, the pull-off forces of PDMS micropillars were maximized under a preload of 2 N and then decreased with increasing preload. The maximum adhesion force was as high as  $\sim 4.0$  N ( $\sim 10.4$  N  $\text{cm}^{-2}$ ) for a micropillar array with 15  $\mu\text{m}$  post diameter and 15  $\mu\text{m}$  space. The adhesion strength was reduced to  $\sim 0.6$  N ( $\sim 1.7$  N  $\text{cm}^{-2}$ ) when the preload increased to 70 N. The decrease in the pull-off strength with increasing preload may be caused by the displacement of the micropillars due to the lateral deformation of the back film by the Poisson effect under an excessive preload.<sup>20</sup> Interestingly, the adhesion strength of dry adhesives can be accurately controlled by changing the

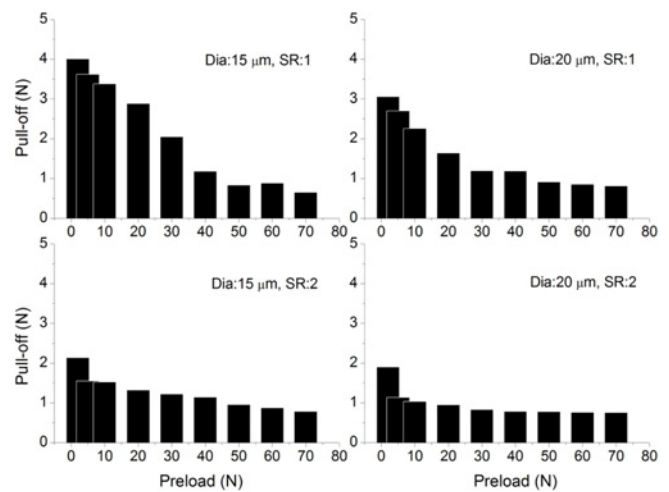


Fig. 5 Measurement of pull-off strength of fabricated mushroom-like micropillars as a function of applied preload

pillar geometries and preload, as shown in Fig. 5, which is highly useful for the development of precise substrate transportation systems. For example, we can tune and optimize the pull-off strength of substrate transportation systems depending on the types of target substrates and process requirements.

### 3.2 Application to Automated Transportation System with Dry Adhesive Pads

The fabricated bio-inspired adhesive pads have great potential to replace existing substrate transportation techniques including vacuum suction, mechanical clamping, electrostatic chucks, etc as dry adhesion mechanisms have several distinct advantages over other ones, which enable precise manipulation of various substrates with no surface contamination in a reversible and repeatable manner (see Table 1).<sup>5,6,20</sup> Furthermore, dry adhesive technology is cost-effective and environment-friendly as it does not require external forces (e.g., vacuum or electrostatic forces) for the attachment of substrates.

To demonstrate the practical applications of dry adhesives in precision manufacturing, we developed a wafer transport system by integrating the adhesive pads with an automated robotic system. Fig. 6 shows the automated transportation system based on dry adhesives. Three circular dry adhesive pads (diameter = 7 mm, thickness = 2 mm) were attached to a robotic arm that could move in the  $z$ ,  $R$ , and  $\theta$  directions. The robotic arm equipped with adhesive pads approached a

Table 1 Advantages and disadvantages of various transportation techniques

Techniques	Holding force	Prevention of contamination & damage	••••	•••	••	•
			Excellent	Good	Fare	Poor
			Prevention of substrate bending	Scalability	Energy saving	Cost saving
Dry adhesive	•••	••••	••••	••••	••••	••••
Vacuum chuck /Mechanical clamping	••••	•	•	••	•••	••
Electrostatic chuck	••••	••	••	••	•	•

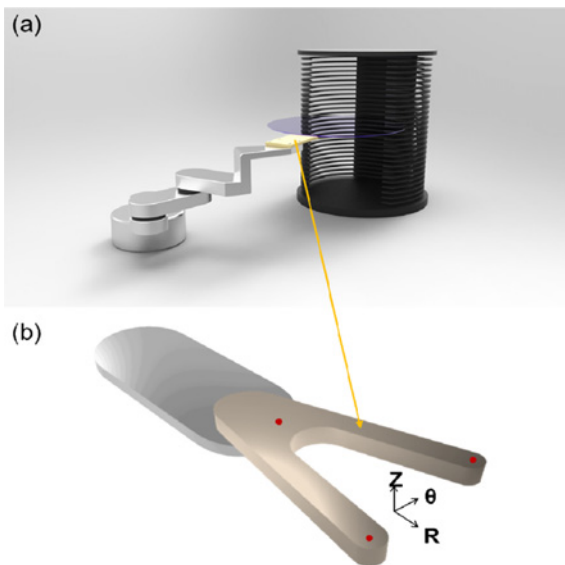


Fig. 6 (a) A schematic illustration of the automated wafer transportation system utilizing (b) a robotic arm equipped with bio-inspired dry adhesive pads

silicon wafer (diameter: 300 mm) and formed a conformal contact between the microstructures on the pad and the substrate. After forming a firm attachment between the dry adhesive and substrate, the automated system started to move and transport the silicon wafer without any sliding or detachment. After arriving at a target location (stackable wafer cassette), the arm started to move downward, releasing the wafer from the adhesive with the aid of a cassette guide.

Upon repeating the attachment and detachment test, the wafer transportation system based on dry adhesive pads exhibited superior transportation capabilities such as no surface contamination or damage, firm attachment, easy detachment, and a repeatability of >10,000 cycles (data not shown).

#### 4. Conclusions

In summary, we have presented a bio-inspired dry adhesive in the form of mushroom-shaped micropillar arrays and demonstrated an automated substrate transportation system based on the adhesive pads. The automated robotic system equipped with adhesive pads enabled precise and stable manipulation of a 300 mm Si wafer over 10,000 repeating cycles without any requirement for external force application. It is envisioned that the new approach presented here could prove to be a next-generation clean and environment-friendly transportation technique for precision manufacturing.

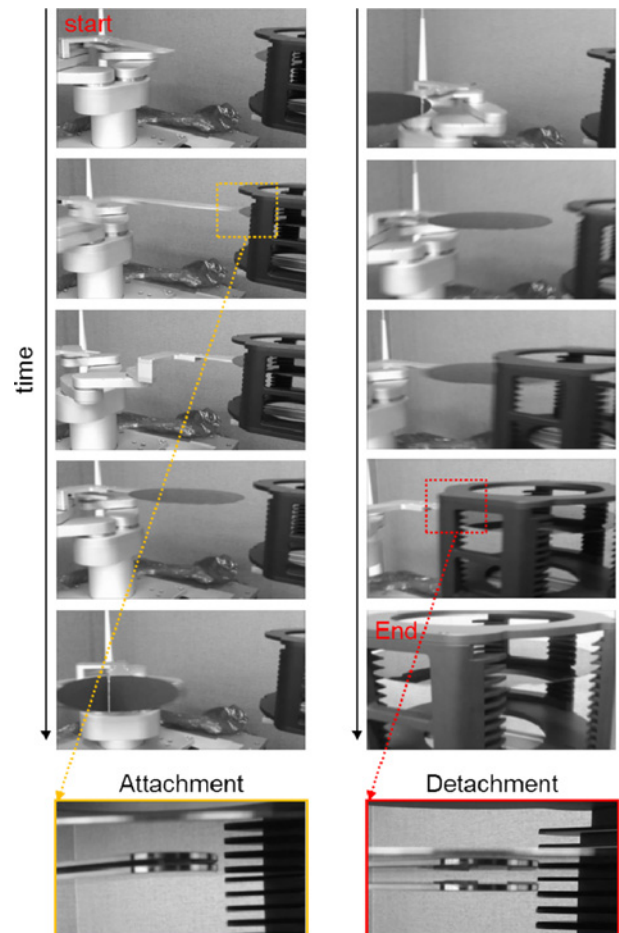


Fig. 7 Time-lapse images showing the demonstration of automated 300 mm wafer transportation based on smart dry adhesives

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