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Fabrication and adhesion of a bio-inspired microarray: capillarity-induced casting using porous silicon mold†

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Abstract

Inspired by the setal microstructure found on the gecko's toe-pads, a highly dense array of high-aspect-ratio (HAR) artificial setae has been developed with a novel mold-casting technique using a porous silicon (PSi) template. To overcome the high fluid resistance in the HAR capillary pores, the PSi template surface is modified with a monolayer coating of dimethylsilane. The coating exhibits similar chemical composition and surface energy to the precursor of the poly(dimethylsiloxane) (PDMS) replica. The compatibility between the template and the replica addresses the major challenge of molding HAR microstructures, resulting in high-resolution replicas of artificial PDMS microsetae with complicated geometry resembling a real gecko's setae. The artificial setae are characterized by a mean radius of 1.3 μm , an aspect ratio of 35.1, and a density of $\sim 4.7 \times 10^5$ per mm^2 . Results from adhesion characterizations reveal that with increasing preload, the shear adhesion of micro-setae continually increases while the normal adhesion decreases. The unique adhesion performance is caused by both van der Waals forces and the elastic resistance of PDMS setae. With further structural optimizations and the addition of an actuation mechanism, artificial setal arrays might eventually demonstrate the fascinating adhesion performances of the gecko for mimetic devices such as wall-climbing devices.

1 Introduction

The micro-seta arrays found in geckos,^{1,2} spiders,³ flies,³ beetles,³ water striders,⁴ and other insects^{5,6} exhibit extraordinary performances, such as controllable adhesion, tunable friction, antifouling and self-cleaning properties.⁷⁻⁹ Owing to the special surface roughness or micro/nano structure,¹⁰ toe-pads of these insects exhibit super hydrophobicity with an extremely high water contact angle ($>150^\circ$) and/or low roll-off angle.⁴ Similar micro/nano textures have also been found in the leaves of some plants such as the lotus leaf and the rice leaf.^{6,11,12} These fascinating structures and properties have stimulated studies of fabrication

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techniques of bio-inspired micro/nano arrays. Producing mimetic setal structures has become an interdisciplinary research area that combines materials, bionics, mechanics, nanotechnology, and many other fields.¹³

Recent developments in micro/nano-fabrication technology have greatly prompted the progress of artificial adhesive setal arrays.¹⁴ Current fabrication techniques include photolithography,¹⁵ soft-lithography,¹⁶ electron beam lithography,¹⁷ nano-printing,¹⁸ and hot embossing.¹⁹ Most of these techniques utilize a mold-casting process which involves demolding the setal array from patterned templates made of photo resist SU-8,^{15,20} poly(dimethylsiloxane) (PDMS),¹⁶ poly(urethane acrylate),²¹ polymethyl methacrylate,²² or other materials.^{23,24} The fabricated structures are often smooth and straight with a cylindrical or trapezoidal shape,²⁵ largely different from the hierarchical, tilted, large-end structure shown by the gecko's micro-setae for tuning microsetal adhesion and mechanical compliance.^{1,2} To further mimic the gecko's setae, this study, for the first time, employed electrochemical porous silicon (PSi) as the negative template to cast artificial micro-setae. The PSi template possesses great potential due to following characteristics: (a) through specific etching conditions and Si crystalline structures, branched, tilted, and large-end structures can be obtained from the PSi template;²⁶⁻²⁸ (b) it is possible to fabricate PSi pore structures with fixed pore size and tunable pore depth using a fixed electrolysis procedure with varied time, which is critical to the production of a HAR template;^{29,30} (c) large-scale fabrication of PSi based on an electrochemical etching method is possible.

However, strong fluid resistance in the capillary greatly prevents the viscous precursor of the replica polymer from entering the pores, leading to failure of high-resolution replication for creating microsetal patterns. In general, the strong fluid resistance is derived from several chemical and topological characteristics of PSi: (a) unlike the common templates such as anodic aluminum oxide^{22,31} or track-etched poly-carbonate¹⁹ which have two open ends, the PSi only has one open end, easily trapping air and strongly resisting the precursor's spreading; (b) strong friction exists on the rough and hierarchical surface of PSi, preventing the precursor from spreading; (c) the inorganic crystal Si surface is incompatible with organic precursors such as PDMS and poly-(methylmethacrylate) colloids, which leads to a weak intermolecular adhesion between the capillary and the replica. To tackle these challenges, our strategies here include: (a) to remove trapped air in the PSi pores, a high vacuum pressure (~3 Pa) was applied; (b) to reduce the template-precursor adhesion energy, the PSi surface was modified with an organic monolayer coating which changes surface polarity, energy and adhesive work.^{32,33} But the high vacuum pressure used during casting requires the interaction between PSi and its organic coating to be extremely strong; a physically absorbed monolayer could be removed under high vacuum. The present study has developed a coating made of an organic monolayer with chemistry, polarity, and surface energy similar to those of PDMS, and coupled it with the PSi surface through covalent bonds (Fig. 1). We functionalize the PSi surface with Si-OH³⁴ (Fig. 1c), and use dichlorodimethylsilane (DDMS) to assemble an organic dimethylsiloxane (DMS) monolayer of Si-O-Si(Me)₂ onto the PSi surface (Fig. 1d). Because DMS is the monomer of the PDMS precursor, it improves the intermolecular adhesion between the PSi template and PDMS precursor, facilitating the precursor to spread in PSi capillary pores (Fig. 1e).^{35,36}

2 Experimental

2.1 Fabrication of a bio-inspired setal array

The single side polished crystal Si (100) oriented p-type Si wafers (B doped, 7.5–8.0 Ω cm resistivity) (55th Research Institute of Ministry of the Electronics Industry, China) was pre-cleaned in a boiled piranha solution (3 : 1 (v/v) concentrated H_2SO_4 –30% H_2O_2 mixture) for 30 min and rinsed repeatedly with deionized water. The clean Si wafer was then immersed in 0.5% aqueous HF solution for 30 s at room temperature to remove the native oxide.

As shown in Fig. 1, the crystal Si was first etched in a solution of 4 : 1 (v/v) DMF(pure)–HF(40%) with a weak current (5 mA cm^{-2}) for 40 min, which produced a porous brown-dark substrate (Sample a). A second etch was then performed in a solution of 1 : 1 (v/v) EtOH(pure)–HF(40%) with a current of 10 mA cm^{-2} for 3 min, which produced a porous dark red substrate (Sample b). Sample b was oxidized in a boiling piranha solution for half an hour to yield the active Si–OH functionalized surface. Subsequently, Sample c was placed in a closed vessel for chemical vapor deposition of DDMS. After one-hour of deposition, a DMS monolayer was assembled on the PSi surface (Sample d). Sample d was then used for casting in a vacuum container (Edwards RV5), using Sylgard 184 (Dow Corning) with a 5 : 1 ratio (polymer : crosslinker). After vulcanization of PDMS prepolymer at a temperature of 80 °C for half an hour, the Si crystal was removed by using an etching solution of 1 : 1 (v/v) HNO_3 (pure)–HF(40%) for 5 min. Finally, the micro-seta (Sample f) was obtained.

2.2 Characterization of the topological structure and chemical composition

The PSi templates and the PDMS setal arrays were observed by scanning electron microscope (SEM) (S4800, Hitachi, Japan) by using a Schottky field emission source. PDMS-based setal samples were sputtered with gold particles (~10 nm) prior to SEM observations. The abdominal profile and toe-pad image of a gecko (Guangxi, China) were captured by a common CCD camera (Nikon D90), and its setae and lamellae structure were observed with a 3D optical microscope (Keyence, VHX-600). The compositions of PSi surfaces were detected by transmittance infrared spectroscopy (Tr-IR), using a clear crystal Si as background. The PDMS precursor was detected by attenuated total reflectance infrared spectroscopy (ATR-IR), using air as background. Both IR spectra were collected by a Bruker IFS66/S spectrometer with a DTGS detector.

2.3 Adhesion detection of bio-inspired setal arrays

One 2-dimensional force sensor (UMT-2, USA) with a maximal force of 100 mN and a sensitivity of 0.001 mN was employed to collect the adhesion force data. A commercially available sapphire ball ($\Phi = 1.87$ mm) was fixed at the end of the force sensor to act as the upper mating ball. Setal samples were mounted on the substrate table to act as the lower working surface. During the pre-loading step, the sapphire ball approached the sample with a constant speed of 0.1 mm s^{-1} under a preload varying from 0.5–25 mN, which was kept stable for 10 s. During the following normal adhesion measurements, the sapphire ball was lifted at a constant rate of 25 $\mu\text{m s}^{-1}$ for 10 s, and then the normal preload was reduced to 0.01 mN. During the shear adhesion measurements, the sapphire ball was mounted to slide

at a constant rate of $15 \mu\text{m s}^{-1}$ for 10 s along the x axis; the stable friction was equivalent to the shear adhesion force. All the experimental error was derived from the mean deviation of 9 measurements.

2.4 Measurement of precursor contact angle on the PSi templates and water contact angle on the PDMS setal arrays

To determine the surface tension difference among different PSi templates, a drop ($5 \mu\text{L}$) of PDMS precursor (5 : 1) was delivered onto Samples a, d, and f using a micro-injector. To measure the hydrophobicity changes caused by topography of setal arrays on PDMS, a drop ($5 \mu\text{L}$) of deionized water was delivered onto the surface of flat PDMS elastomer membrane and PDMS setal array, respectively. After 5 s spreading, the static contact angle images were captured by an optical microscope, and the angles were determined with AutoCAD software. The average value of measurements in three locations was utilized for the results.

3 Results and discussions

3.1 Compositional comparison between PSi templates and PDMS precursor

Fourier transform IR spectroscopy was used to monitor the entire modification process (Fig. 2). The IR spectrum of Sample a exhibits a Si–O–Si functionalized surface,³⁷ where double peaks of Si–O–Si at 1160 and 1066 cm^{-1} are found. After second etching, the Si–O–Si band disappears while the stretching vibrations of Si–H_x at 2089 , 2116 , and 2139 cm^{-1} and the bending vibrations of Si–H_x at 921 , 664 , and 642 cm^{-1} appear in the IR spectrum of Sample b. This demonstrates successful Si–H functionalization.³⁰ After oxidization with the piranha solution, the Si–H_x peaks disappear, and a wide stretching band of Si–OH appears at 3448 cm^{-1} in the IR spectrum of Sample c. Because Si–OH is active,³⁴ it crosslinks with DDMS to assemble the organic DMS monolayer on the surface through Si–O–Si. Thus, in the IR spectrum of Sample d, the Si–OH peak disappears and the C–H_x stretching vibrations of 2965 and 2912 cm^{-1} appear. Meanwhile, a new double absorbance peak of the backbone Si–O–Si group appears at 1102 and 1025 cm^{-1} , and a C–H₃ deformation shows at 1266 cm^{-1} . These results demonstrate that an organic DMS monolayer is successfully assembled on the PSi surface (Surface d) which has a similar IR spectrum to the PDMS precursor except for a small Si–H vibration at 2160 cm^{-1} .³⁸ Additionally, each double methyl group on Sample d is assembled at the end of a Si–O–Si group, similar to the structural distribution of PDMS, where methyl groups are exposed on the most outside surface to reduce the surface energy.³⁹ Therefore, the surface energy of Sample d matches that of the PDMS precursor. This chemical and structural similarity is important to the casting process, in which the micro-seta pattern on the PSi template is inversely replicated on the surface of PDMS membrane.

3.2. SEM images of PSi templates and PDMS setae

SEM images were taken to show the top and cross-sectional views of Samples a–d. Images of all the samples show similar structures with small differences in the radius and depth of the pores. For Sample c (Fig. 3c), the radii and wall thicknesses of the pores are in the range of 1.3 – $1.5 \mu\text{m}$ and 0.2 – $0.3 \mu\text{m}$, respectively, and the mean depth of the porous layer is around $54 \mu\text{m}$. Compared to Sample a (s-Fig. 1 in the ESI†), the pore radius and depth

increase and the thickness of the pore wall decreases due to the second etching. Because second etching utilizes an electrolyte of EtOH–diluted HF which can result in a network of structural PSi,³⁰ it must be strictly controlled within a short period of time to limit the formation of a porous network structure to the outmost layer while producing a cylindrical pore structure with sufficient active Si–H groups.

Using the PSi template with a coating of DMS monolayer (Sample d), we produced PDMS-based micro-setae arrays which demonstrated a high density of around 4.7×10^5 setae per mm^2 (Fig. 3f and s-Fig. 2[†]). Each micro-seta exhibits a spherical tip and a concave–convex topography. The setal morphology matches the pore structure of the PSi template (Fig. 3c), which demonstrates successful replication. The mean radius and length of the setae are around 1.3 μm and 45.6 μm , respectively. The mean aspect ratio (AR) is around 35.1, much higher than the collapse limit of 3.5 for PDMS-based setae.⁴⁰ Therefore, the produced setae underwent severe lateral collapse, which is due to capillary tension generated during dehydration pushing the adjacent setae to stick together. The strong capillary tension is mainly caused by the tiny space among the high-density setae, particularly when polar aqueous reagent is used. Compared to the height ($\sim 54 \mu\text{m}$) and AR (~ 41.5) of the PSi template, the height and AR of setal arrays are slightly lower. The possible causes could be the lateral collapse of the setal array and the elastic contraction of PDMS elastomer during demolding. To reduce the cohesive forces among setae and thus the collapse, we varied the polymer-to-crosslinker composition of PDMS from 10 : 1 (the suggested standard ratio) to 5 : 1. Compared to PDMS with a 10 : 1 composition, PDMS with a 5 : 1 composition has lower viscosity and adhesiveness, which allows PDMS to enter the small structures on the PSi surface and reduces lateral collapse of the micro-setae. Furthermore, PDMS with a 5 : 1 composition is stiffer,³⁶ producing more straight upright setal arrays to prevent ground collapse. We also found that DMS coating is absolutely necessary for casting the setal array from the template. Casting PDMS precursors using templates from Samples a–c did not result in any seta features (s-Fig. 3[†]).

3.3 Contact angles

To evaluate the DMS coating on the template, the contact angle of PDMS precursor was determined for Samples a and d. As shown in Fig. 4(I) and (II), results showed that the average precursor contact angles on Samples a and d are 61.78 and 13.36°, respectively. This indicates that the PDMS precursor can wet both template surfaces, but compared to Sample a, Sample d exhibits a significantly lower precursor contact angle (~ 5 times), showing the efficiency of DMS coating in enhancing the precursor wetting on the surface and reducing the template–precursor adhesion energy. According to the Young–Dupré equation: the solid–liquid adhesion energy (W_{SLV}) is directly related to the contact angle (θ_{C}). Although the contact angle of the PDMS precursor on the unmodified template (Sample a) is also low, showing a low surface energy and good wettability, the high viscosity of the precursor, the high aspect ratio and the concave–convex surface morphology of PSi impose high fluid resistance, which prevents the colloid from spreading. According to Poiseuille’s Law, the fluid resistance of a single capillary tube is: $R = p/F = 8\mu L/\pi r^4$, where

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μ is the fluid viscosity, L is the length, and r is the radius (diameter/2). After DMS coating, the intermolecular adhesion force between PSi and PDMS colloid molecules increases,⁴¹ which enhances the colloid spreading on the overall surface of the template. Therefore, Sample d exhibits a high compatibility with PDMS precursor.

To evaluate the hydrophobicity changes caused by the setal topographic features on the PDMS membrane, the water contact angle on Sample f and a PDMS planar membrane was determined. Results (Fig. 4(III) and (IV)) showed that both surfaces exhibited high hydrophobicity; the water contact angles on flat and structured PDMS membranes are 102.65 and 127.92°, respectively. This result demonstrates that the resultant setal array is characterized by higher hydrophobicity due to microstructured features on the surface. The high hydrophobicity even matches that of actual microseta arrays of insects and geckos.¹

3.4 Capillarity-induced casting using a porous silicon mold

Due to the compatibility in the surface chemical composition and molecular structure, Sample d (but not Samples a–c) was able to successfully produce a PDMS setal array by replicating the microstructure under the assistance of atmospheric pressure (Fig. 1). Major determinants here are the intermolecular adhesion force⁴¹ between the PDMS precursor and the PSi template (F_1) and the attractive cohesion force among colloidal PDMS molecules (F_2) (Fig. 5(I)). In Samples a–c, F_1 is low because of the large difference in the surface energies between the PSi template (1.1–1.9 J m⁻²)⁴² and the PDMS (~0.022 J m⁻²).⁴³ The net force (F) nearly points towards the inner PDMS colloid. The precursor contracts, which prevents the precursor from entering the pores. With an organic DMS monolayer coating, the surface energy of Sample d matches PDMS colloid, increasing F_1 . Theoretically, F_1 is equal to F_2 , because the coating shows the same chemical composition and molecular structure as the PDMS colloid. Therefore, F directs outwards; it thus overcomes the fluid resistance. High flow pulls the PDMS colloid along the surface of capillary pores during casting (Fig. 5(II)), and then spreads it evenly inside the PSi (Fig. 5(III)). The resolution of the structural replication from the PSi template to the PDMS elastomer is mainly determined by the capillary molecular interactions between the PDMS and the PSi surface.

3.5 Structural comparisons of the artificial setae with the gecko's setae

The gecko's extraordinary motion capability comes from the reversible, strong adhesion produced by van der Waals forces¹ and/or capillary interaction in humid conditions.² According to the Johnson–Kendall–Robert (JKR) model⁴⁴ and the “contact splitting” model,³ van der Waals forces contribute to the strength of setal adhesion. These models show that the setal radius, length, angle, and contact with the surface all determine setal adhesion.^{13,14} Thus, Fig. 6 compares the detailed microstructures of the artificial PDMS setae with those of the real gecko's setae to evaluate the artificial setae. As shown in Fig. 6, the gecko's toe-pad is made up of rows of lamellae which consist of highly dense micro-scale setal arrays with a mean length of around 140 μ m. The 3D optical images and SEM images of artificial setae exhibit a similar lamella-like setal array structure (Fig. 6(V) and (VI), s-Fig. 2[†]). More specifically, two main geometric similarities between them are revealed: (a) the top-view images (Fig. 6(V) and (VI)) show that both setal arrays are composed of millions of highly dense micro-scale setae, a critical feature for generating a

large contact area and strong adhesion.⁴⁴ (b) The cross-sectional images (Fig. 6(III) and (VI)) show that both setae have high AR, a critical feature for generating high flexibility to make various motions on special surfaces.²¹ Therefore, the artificial setae demonstrate the fundamental geometric features of the gecko's setae.

The structure of artificial setae could be further improved to better mimic the complicated hierarchical structure of real gecko's setae (Fig. 6(III) and (IV)), including the tilted setal stalk¹³ which contributes to high mechanical compliance and large surface contact,²¹ and the spatula-shaped setal tip which helps control over attachment and detachment, and maintains sufficient mechanical stability.^{8,20} Tilted pores may be produced for fabrication of tilted seta through the use of PSi templates with different crystal orientation changing from (1 0 0) to (1 1 3) or (3 2 2).²⁶⁻²⁸ To produce a complicated setal end, a secondary porous layer at the bottom of newly prepared PSi may be achieved by tuning second etching for finer pores.^{27-29,37} Additionally, PDMS-based artificial setae show severe lateral collapse and setal buckling (Fig. 6(VI) and (V)), different from those upright gecko's setae with high anti-buckling performance (Fig. 6(III) and (IV)). Development of a closer setal structure will require a novel material with surface energy as low as that of β -keratin, the protein component of gecko's setae.^{45,46}

3.6 Adhesion tests

To evaluate adhesion performance of the artificial micro-setae, an indenter with a rigid and smooth sapphire ball at the tip was built (s-Fig. 4[†]). As the setal surface is rough, a non-structured PDMS planar membrane was used as a control. As shown in Fig. 7(I), the normal detected forces demonstrate stage-wise changes of forces over the time. For both non-structured and seta-patterned surfaces, there are two regions in the B–C stage, illustrating two deformation behaviors: linear (or elastic) deformation and complex deformation showing elastic and plastic strains. The linear slope for the seta-patterned surface is around 66% that for the non-structured surface, which demonstrates high mechanical compliance of the micro-setae. In the C–D stage, the sapphire ball is lifted at a constant rate of $25 \mu\text{m s}^{-1}$ until the preload approaches zero. Because the micro-seta array is more flexible, the preload of 10 mN produces a higher loading depth, which results in higher bounce during the off-loading period. In the D–E stage, when the sapphire ball is continually lifted, the adhesion force continues increasing while the sapphire ball still attaches to the sample. When the sapphire ball detaches from the sample surfaces, the adhesion reaches the maximum. The detected adhesion is equal to the data difference between E and F points.

Shear adhesion results are shown in Fig. 7(II). The shear adhesion is generated by dragging the ball along the surface. When the ball slides on the non-structured surface, the shear adhesion shows no change because the contact area is fixed. Thus, the maximal shear adhesion is equal to the difference between C and B (or between D and E). But for the seta-patterned surface, the contact area changes during sliding. As the artificial setae are highly flexible, they bend towards the sliding direction under preload. The shear adhesion thus first decreases and then becomes stable. Herein, the stable shear force during the D–E stage is taken as the shear adhesion.

Fig. 7(III) shows the normal adhesion and shear adhesion as a function of preload. The normal adhesion first shows a rapid increase followed by a small decrease with increasing preload (Curve b), while the shear adhesion continually increases with increasing preload (Curve a). In theory, it is difficult to detect pure adhesion;¹³ the detected adhesion is inevitably affected by many factors.⁴⁷⁻⁵⁰ The adhesion measurement here is mainly influenced by two factors: the adhesion force based on van der Waals interactions due to contact and the elastic force due to elastic recovery of the PDMS elastomer. In the normal direction, the elastic force is opposite to the adhesion, and thus the detected adhesion is weakened by the elastic force; while in the shear direction, the detected adhesion is strongly coupled with the elastic resistance⁵¹ and is thus significantly higher. Therefore, most of the measured shear adhesions are around 10 times the corresponding normal adhesions under the same preload. Herein, we acknowledge the limitations of using the separate and standing pillar model to analyze the adhesion behavior. In reality, due to high aspect ratio of the sample, pillars stick together and form clusters. Therefore, the model overestimates the actual adhesion behavior.

Although we reported fabrication of highly mimetic gecko-inspired seta, a fully functional gecko-inspired adhesion is yet to be developed. Through a series of optimizations as discussed above, it is possible for the future artificial setae to mimic the complicated structures and reach the adhesive performances of geckos.⁵² This is critical to the design of gecko-inspired mimetic devices such as a wall-climbing robot with 3-dimensional obstacle-free motion. In addition, to fulfill other gecko-inspired functions such as tunable adhesion which geckos achieve by actively controlling setae with muscles,⁵³ artificial setae should be actively driven by an external influence such as temperature⁵⁴ or a magnetic field.⁵⁵ Electro-active polymer (EAP, also called artificial muscle),⁵⁶ as we have previously developed,⁵⁷ may be used in combination with the resultant artificial setae. The driving force generated by artificial muscle can be similar to that from gecko muscle and used to tune the adhesion of the artificial setal array.

4 Conclusions

We reported a novel mold-casting technique to fabricate high-resolution bio-inspired microsetal arrays. Induced by capillary molecular interactions, poly(dimethylsiloxane) precursor spreads onto the dimethylsiloxane-grafted porous silicon surface with cylindrical pores, which produces artificial setae with high density (4.7×10^5 per mm^2), high aspect ratio (~ 35.1), high hydrophobicity (127.92°) and high mechanical compliance. Similar to the fine structures found in gecko's toe-pads, the artificial seta presents a lamella-like morphology, and demonstrates unique adhesion performance. Based on the comparisons of real gecko seta with artificial seta, this study suggests that further optimizations of micro-setal structures and potential use of EAP to fabricate micro-setae could lead to unprecedented devices such as a spiderman-like wall-climbing device.

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Fig. 1.

Schematic illustration of the casting process for preparing the bio-inspired seta. Sample a showing stable Si–O–Si bonds on the surface represents the PSi after first etching; Sample b showing active Si–H groups on the surface represents the sample after second etching; Sample c showing active Si–OH groups on the surface represents the sample after piranha oxidization; Sample d with an organic DMS monolayer assembled on the surface represents the sample after the DDMS coupling; Sample f represents the seta-patterned surface. The setal array could not be successfully obtained from any template of Samples a–c.

Fig. 2.

Absorbance mode IR spectra of Samples a–d and PDMS precursor (5 : 1).

Fig. 3. SEM images of porous silicon templates showing the top-view (c-1 and c-2) and cross-sectional (c-3 and c-4) images of Sample c, and the top-view images of Sample f (f-1 and f-2).

Fig. 4.

Comparisons of PDMS precursor (5 : 1) contact angles on Sample a (I) and d (II), and water contact angles on PDMS-based planar membrane (III) and seta-patterned surface (Sample f) (IV).

Fig. 5.

Schematic illustration of the casting processes for Samples a–c (I) and Sample d (II and III).

The dark-brown line inside the capillary pore represents the coating DMS monolayer. The inserted pictures show a strong intermolecular adhesion (II) between the PSi template and PDMS precursor. The blue dash (II) represents the adhesion.

Fig. 6.

Comparisons of the real gecko's setae with the artificial setae. Images show the Gecko's abdominal view (I), toe-pad (II), cross-section of the setae (III), and lamellae (IV). For comparison, an optical image shows the top-view of the artificial setae (V), and a SEM image shows the cross-sectional view of the artificial setae (VI).

Fig. 7.

Normal (I) and shear (II) force curves, and plot of adhesion curves as a function of preload (III). In (I), changes of force over time demonstrate 7 changing points alphabetically labeled as A–G and 4 measurement steps labeled with different colors: green shows pre-loading (A–B stage), blue shows off-loading including B–C and C–D stage, red shows adhering including D–E and E–F stage, and pink shows no-loading (F–G stage). The four inserted schematic diagrams illustrate the measurement steps. The arrows show the directions for preloading and adhesion. An inserted picture (left, top) illustrates the determination of the elasticity by magnifying the circled point, where θ_1 (non-structure surface) and θ_2 (seta-patterned surface) are 47.64 and 31.85°, respectively. In (II), as in (I), there exist 6 changing points labeled as A–F and 3 measurement steps labeled with different colors: green shows pre-loading (A–B stage), red shows sliding (C–D stage), and blue shows no-loading (E–F

stage). In (III), the sapphire ball fixed by one cantilever force sensor moves along the normal (inserted picture at the right-bottom) and shear (inserted image at the right-top) directions.