Microfabricated adhesive mimicking gecko foot-hair

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The amazing climbing ability of geckos has attracted the interest of philosophers and scientists alike for centuries[1–3]. However, only in the past few years[2,3] has progress been made in understanding the mechanism behind this ability, which relies on submicrometre keratin hairs covering the soles of geckos. Each hair produces a miniscule force ≈10^{-7} N (due to van der Waals and/or capillary interactions) but millions of hairs acting together create a formidable adhesion of ≈10 N cm^{-2}: sufficient to keep geckos firmly on their feet, even when upside down on a glass ceiling. It is very tempting[3] to create a new type of adhesive by mimicking the gecko mechanism. Here we report on a prototype of such 'gecko tape' made by microfabrication of dense arrays of flexible plastic pillars, the geometry of which is optimized to ensure their collective adhesion. Our approach shows a way to manufacture self-cleaning, re-attachable dry adhesives, although problems related to their durability and mass production are yet to be resolved.

In principle, any submicrometre object—whether it is the tip of an atomic force microscope (AFM), a small piece of dust or a single gecko hair—sticks to a solid surface with an adhesive force in the range 10 to 1,000 nN, depending on the exact geometry and materials involved[2–6]. In the case of hydrophilic materials, it is often an atomic layer of absorbed water (capillary force) that is responsible for the adhesion[4,5]. The capillary force decreases with decreasing a characteristic size R of an object, and can be estimated as $F_c \approx \sigma R$ where σ is the surface tension of water. On a submicrometre scale, van der Waals interaction is also no longer negligible and can compete with the capillary force. A typical value of van der Waals forces for a submicrometre object is ≈100 nN, and this force becomes dominant in the case of hydrophobic surfaces[2–5]. It is interesting to note that diameters of gecko foot-hair (0.2 to 0.5 µm) fall exactly in the range where the two forces become comparable[3]. This probably indicates that, in the course of evolution, geckos have developed their foot hairs to be of the most appropriate diameter to exploit both the van der Waals and capillary forces, and to climb surfaces of various hydrophilicities.

Based on the understanding of the gecko's climbing mechanism, an AFM tip has been used to produce a set of dimples on a wax surface, which was then used as a mould for making a number of mesoscopic polymer pyramids[3]. With the help of another AFM cantilever with a flat tip, the adhesive force to an individual pyramid was measured. The force

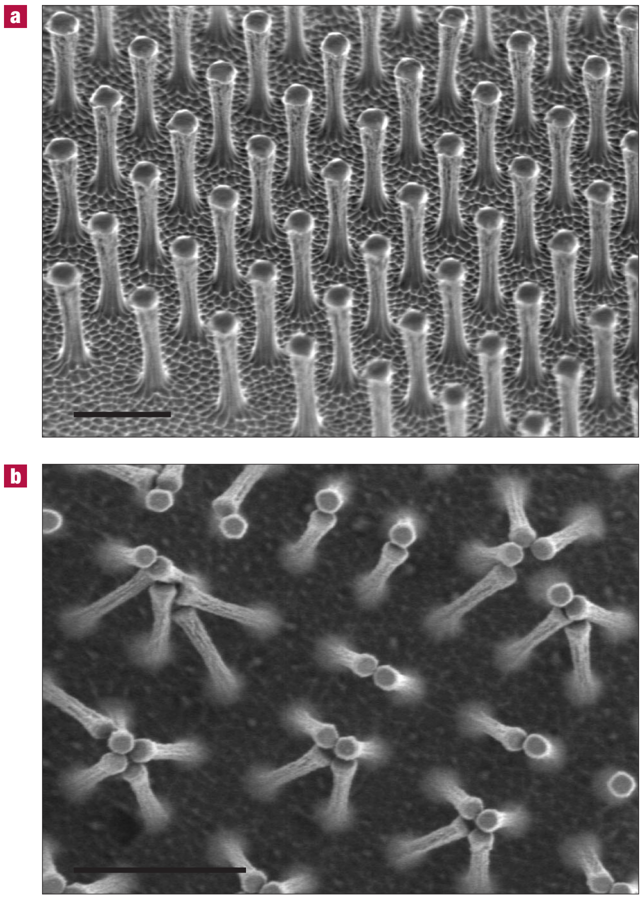

Figure 1 Scanning electron micrographs of microfabricated polyimide hairs. **a**, A small area near the edge of a 1 cm^2 array of polyimide hairs. This array was later used to evaluate macroscopic adhesive properties of the mimetic material. **b**, Bunching is found to be one of the mechanisms responsible for the reduction of adhesive strength of the artificial hair. This micrograph also demonstrates the high flexibility of polyimide pillars. Both scale bars are 2 µm.

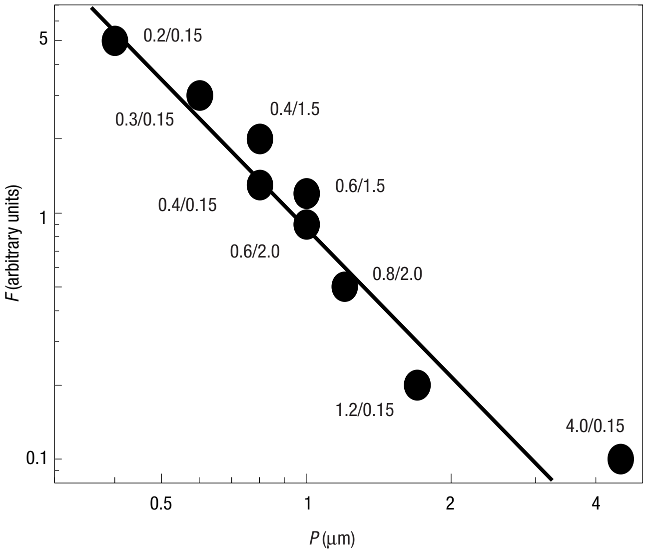

Figure 2 The perpendicular force *F* required for detaching various samples of polyimide hairs from a silicon surface. The experimental points are marked by *D*/*H*, indicating the hairs' diameters *D* and heights *H*, respectively. The solid curve is the best fit to $F \propto P^{-2}$.

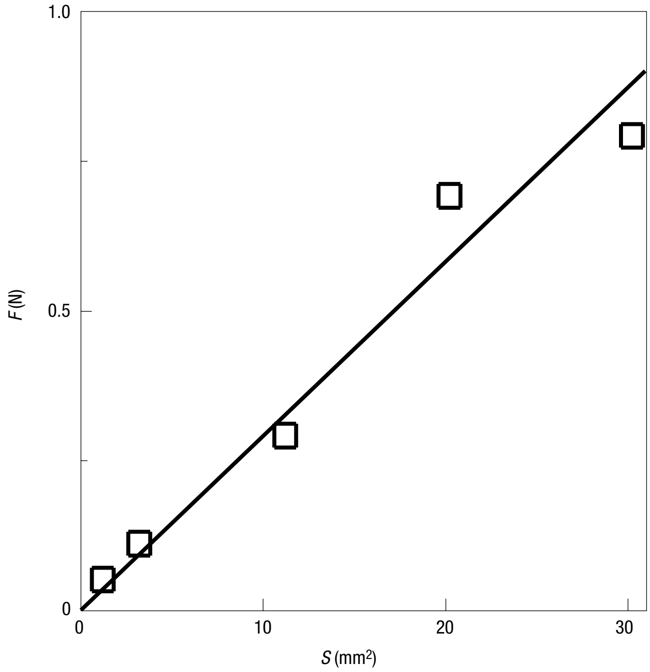

Figure 3 The adhesive force *F* exhibited by 'gecko tape' as a function of contact area *S*. Squares are experimental data; the solid line is the best linear fit.

was found to be ≈200 nN, which is comparable to the average adhesive force estimated per individual gecko hair[2,3].

It would be natural to assume that large arrays of tip-like submicrometre objects would mimic gecko's foot-hair and provide a similar adhesion. However, one has to take into account that real surfaces are never ideally flat. In fact, our earlier attempts (unpublished) to imitate gecko foot-hair by making large arrays of plastic tips (similar to the pyramids reported previously[3]) have failed. The reason was that only a small fraction of tips based on a solid substrate could make physical contact with the opposite surface (see below). Thus, to create a gecko adhesive, one also has to find a way to make hairs sufficiently flexible and to place them on a soft, flexible substrate, so that individual tips can act in unison and attach to uneven surfaces all at the same time. To meet these non-trivial objectives, we have chosen to micropattern thin polyimide films, which are both robust and flexible and allow a wide range of microfabrication procedures.

Figure 1 shows two examples of polyimide hairs microfabricated using electron-beam lithography and dry etching in oxygen plasma (see Methods). While searching for the most suitable design for such artificial hairs, we first tested how their adhesion depends on geometry. To this end, we prepared ten relatively small (≈50 × 50 μm^2) arrays of hairs having diameters *D* ranging between 0.2 and 4 μm, heights *H* from 0.15 to 2 μm, and periodicity *P* from 0.4 to 4.5 μm (parameters of all samples are given in Fig. 2). Then, we measured the perpendicular force *F* required to detach the samples from a SiO_2 surface. This was done by using an AFM (in force mode) with a home-made cantilever having a flat silicon tip of ≈50 μm in size. The adhesion between our samples and the flat tip was found to depend strongly on the initial preload and, for all the measurements in Fig. 2, we used the same preload ≈10 mg (the maximum allowed by our cantilever). We note that this preload was not sufficient to provide an optimum contact and, even for densest arrays, the adhesive force reached only ≈10 μN. Comparison of this value with a typical adhesion of ≈200 nN measured between a standard AFM tip and the top of an individual polyimide pillar shows that only a small number (<100) of hairs could actually make contact with the flat tip.

All data obtained in the above measurements (and repeated for another preload) fall on a single smooth curve if plotted against the separation between pillars *P*. Figure 2 clearly shows that *F* is proportional to the density of hairs (P^{-2}) and depends only weakly on *H* and *D*. Although intuitively plausible, this finding is rather unexpected, because both capillary and van der Waals forces depend[2–6] on *D*. We speculate that large polyimide pillars do not attach over the whole top surface, but that each pillar makes a point-like mechanical contact, which results in a fixed value of force per pillar, almost independent of its diameter.

These results suggest that, for maximum adhesion, one has to maximize the number of hairs capable of attaching to a surface, and their particular geometry is of less importance. One also has to consider limitations on the maximum density of hairs. For example, hairs should be flexible enough to attach to uneven surfaces but should not break, curl or tangle. Examination in a scanning electron microscope (SEM) revealed that very thin pillars ($D < 0.3$ μm) tend to fall down, whereas long, closely spaced hairs tend to bunch after being in contact with the opposite surface (Fig. 1b). For an optimal geometry, we have eventually chosen hairs to be as long as we could make them ($H \approx 2$ μm), reasonably dense ($P \approx 1.6$ μm) and not too thin ($D \approx 0.5$ μm) (Fig. 1a).

To test the adhesive properties of the optimized mimetic material on a macroscopic scale, we microfabricated a large (1 cm^2) sample of polyimide pillars with the above parameters. With the polyimide microstructure remaining on a silicon wafer, we pressed the sample against a microscope glass slide with a preload force of ≈20 kg. Rather discouragingly, this resulted in a very small adhesive force of ≈0.01 N or 1 g. This shows that less than 1% of hairs were in actual contact with the glass surface. To increase the number of 'active', attaching hairs, the microfabricated polyimide film was peeled off the wafer and transferred onto a soft bonding substrate (see Methods), so that the resulting material could be handled just as an adhesive tape. The use of a soft rather than solid base has dramatically (by nearly 1,000 times) improved

Figure 4 Re-attachable dry adhesives based on the gecko principle can find a variety of applications. The photo illustrates this point by showing a spider-man toy clinging with one of its hands to a horizontal glass plate. The toy (15 cm high; weighing 40 g) has its hand covered with the microfabricated gecko tape, which provides a $\approx$0.5 cm^2 contact with the glass and a carrying capacity of >100 g. Note that the toy was already re-attached several times to various surfaces before this photo was taken.

the adhesive capacity of the microstructure (Fig. 3). We believe that the added flexibility of the base allowed the mimetic tape to compensate for unevenness and dust particles on the surface, which could not be compensated for by the flexibility of polyimide pillars alone.

Adhesive properties of the resulting 'gecko tape' were characterized by measuring the dependence of its adhesion on contact area S by using millimetre-sized glass wedges and a laboratory balance. The force was found to vary linearly with S (Fig. 3), and to be virtually independent of preload (for preloads $\geq$50 N cm^{-2}), which proves that practically all hairs on the gecko tape could attach to macroscopic surfaces simultaneously. The average force per hair was found to be $\approx$70 nN, and the whole 1 cm^2 patch was able to support 3 N. This number is comparable to the estimated adhesive force of 10 N cm^{-2} for gecko foot-hair[2,3]. Note that, in control experiments, similar but unstructured polyimide films (both freshly prepared and subjected to dry etching without patterning) exhibited negligibly small adhesion (<10^{-3} N cm^{-2}). Figure 3 also proves that our experiment can be scaled up, that is, that larger areas of gecko tape would support much heavier objects. For example, human palms have a total area of more than 200 cm^2 and, if covered by such a material, would be able to support the weight of an average human. To emphasise this point, we used the available (unfortunately, rather small) amount of gecko tape to support the weight of a suitably light familiar object (a toy in Fig. 4).

We found that the gecko tape could go through several detachment–attachment cycles before we noticed a degradation of its adhesive properties. A subsequent SEM analysis revealed that this was related to fallen and broken hairs. Many hairs were lying on the polyimide surface, presumably kept in this position by the capillary force. We have also tested the tape on different surfaces and found that the adhesion force varied only by a factor of three between hydrophobic GaAs and hydrophilic SiO_2. This indicates that our microfabricated adhesive makes use of both capillary and van der Waals forces.

Regarding possible applications, we believe that, instead of expensive and slow electron-beam lithography, other techniques (for example, based on the electrical instability of polymers[7]) can be applied to produce a similar material in large quantities. Our major concern is the durability of such microfabricated adhesives, which limits the number of successful re-attachments. Durability can probably be improved by trying other materials, which would be sufficiently flexible —similar to hydrophilic polyimide—but strongly hydrophobic (keratin, as in gecko hair, is a possible candidate). In this case, the hairs would not stick to each other or to the base surface, which should improve the resistance to attachment–detachment cycles. In addition, it would be possible to use denser arrays of pillars, thereby further increasing their adhesive strength.

METHODS

MICROFABRICATION

Arrays of submicrometre hairs were microfabricated by using the following set of procedures. First, we prepared a 5-µm-thick polyimide film (pyromellitic dianhydride-oxydianiline polyimide; baked at 250 °C) on top of a silicon wafer. Next, by using electron-beam lithography, thermal evaporation of an aluminium film ($\approx$150 nm thick) and lift-off, we prepared an array of submicrometre aluminium disks. The resulting aluminium pattern was then transferred in the polyimide film by dry etching in oxygen. The oxygen plasma etching was essential, because it provided a large difference between etching rates of aluminium oxide and polyimide, so that several micrometres of polyimide could be removed before the aluminium mask disappeared. In addition, we applied a negative d.c. bias to the substrate, which allowed us to achieve large aspect ratios (for example, see ref. 8), making the pillars sufficiently tall.

PEELING OFF AND TRANSFER OF POLYIMIDE FILMS ONTO ANOTHER SUBSTRATE

Polyimide films are very robust even when a few micrometres thick, and their peeling from the silicon wafer does not require any special skills or accuracy. Several support materials and bonding methods were tried (using unstructured films) before we finally opted for the use of scotch tape as the simplest and most reliable scheme for placing the peeled-off microstructures on a soft base. Note that transfer onto another substrate would not be required, if thicker (>50 µm) polyimide films were used. In our case of thin (5 µm) films, the use of a thicker flexible substrate was advantageous because it simplified handling of the microstructured material and made this more reliable.

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Competing financial interests

The authors declare that they have no competing financial interests.