to determine the number of metallic and insulating domains in a given beam. When an insulating beam is heated above 68 °C, a single metallic domain will nucleate within the beam, and this domain will grow as the temperature is further increased until the entire beam is metallic above 105 °C. Optical images allow the authors to determine the fraction of the beam that is insulating at any temperature in this coexistence region between 68 and 105 °C.

The structural transition that occurs alongside the metal–insulator transition means that the low-temperature insulating phase and the high-temperature metallic phase have different lattice constants. And since the beams are pinned at their ends, the internal stress varies in the coexistence region, so the properties measured in this region trace the boundary between the insulating and metallic phases in the stress–temperature phase diagram (Fig. 1). This is analogous to the case of water and ice coexisting in a container of fixed volume.

The University of Washington researchers are able to leverage these circumstances to look at the underlying mechanism of the transition. By measuring the total electrical resistance of different beam segments in the fully insulating state, they can determine the resistivity of the insulating state as a function of temperature. They find that the fully insulating state acts just as expected for a semiconductor with a bandgap of 0.6 eV, which is the value inferred from previous optical measurements by other groups. They can then deduce the insulating state resistance in the coexistence region, and they find a remarkable result: the insulating state directly in equilibrium with the metallic state has constant resistivity throughout the coexistence region. This implies that the metal–insulator transition takes place at fixed carrier density in the insulator, strongly suggesting that electron–electron interactions have an important role in driving the transition.

Beyond this, Cobden and co-workers use the elastic properties of the nanobeams to determine the equilibrium transition temperature. At sufficiently low temperatures the nanobeams buckle for three reasons: built-in strain; the structure of the insulating phase; and the different thermal expansion coefficients of the beams and the silicon substrate. Elasticity theory for buckling beams is well established, and the equilibrium transition temperature is found by analysing this buckling temperature as a function of beam length.

Finally, just as pure water can be supercooled well below 0 °C before ice crystals form, vanadium dioxide can be cooled below 68 °C before the insulating phase nucleates. This effect has been seen in bulk vanadium dioxide films, but the supercooling by more than 50 °C below the transition temperature observed in vanadium dioxide nanobeams shows that they contain very few of the defects or impurities that would lead to heterogeneous nucleation of the insulating phase.

Strongly correlated materials are among the most intriguing condensed-matter systems, and this work is a clear illustration that nanoscale devices are outstanding tools for gaining new insights into the physics at work in such materials. Complementing scanning probe techniques, nanoscale devices incorporating strongly correlated materials can access local electronic properties in systems that would be inhomogeneous in bulk[1,4]. Furthermore, through their small sizes, such devices permit the application of significant electric fields at modest voltages[6], permitting new studies of non-equilibrium physics similar to that seen in macroscopic devices[7] with fewer concerns about large electron energies. With increasing access to state-of-the-art nanofabrication capabilities and high-quality crystal growth, nanobeams and other nanoscale devices will undoubtedly have more to contribute to our understanding of materials with properties that are dominated by electron–electron interactions. ❐

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NANOMATERIALS

Sticky but not messy

Inspired by the feet of the gecko lizard, researchers have tweaked a conventional plasma etching chamber so that it can make reusable adhesives that could have applications in the semiconductor industry.

Zhong Lin Wang

The creators of the fictional superhero Spider-Man gave him the ability to climb up walls and hang from ceilings (Fig. 1a), feats that are routinely performed by the gecko lizard in the real world. The gecko is interesting because its feet are able to stick strongly yet reversibly to surfaces of different roughness and orientation. Researchers have developed arrays of polymer pillars[1] and vertically aligned carbon nanotubes[2,3] that stick firmly to surfaces[4], but these structures cannot attach and detach repeatedly like the foot of a gecko. Now in *Proceedings of the National Academy of Sciences USA*, Sang Heup Moon, Kahp Suh and colleagues[5] at Seoul National University report a simple yet robust method for fabricating polymer nanohairs, and suggest that these nanostructures could be used as dry adhesives in the semiconductor industry.

The gecko foot is made up of well-aligned fine microscopic (3-130 μm in length) hairs called setae, which are split into hundreds of smaller nanoscale ends (0.2–0.5 μm in diameter) called spatulae (Fig. 1b)[6,7]. The van der Waals forces between the spatulae and a surface allow geckos to stick and walk on vertical walls without leaving any tracks behind. For manufactured adhesives to display similar properties, they need to have a strong shear adhesion for firm attachment and a relatively weak adhesion at right angles to the surface for easy detachment. This means that the surface structures need to be slanted so that they are only adhesive when force is applied in a particular direction. The surfaces also need to have structures on multiple scales, and the initial hairs need to have high aspect ratios and small radii.

In a conventional plasma etching chamber, the incident ions bombard the

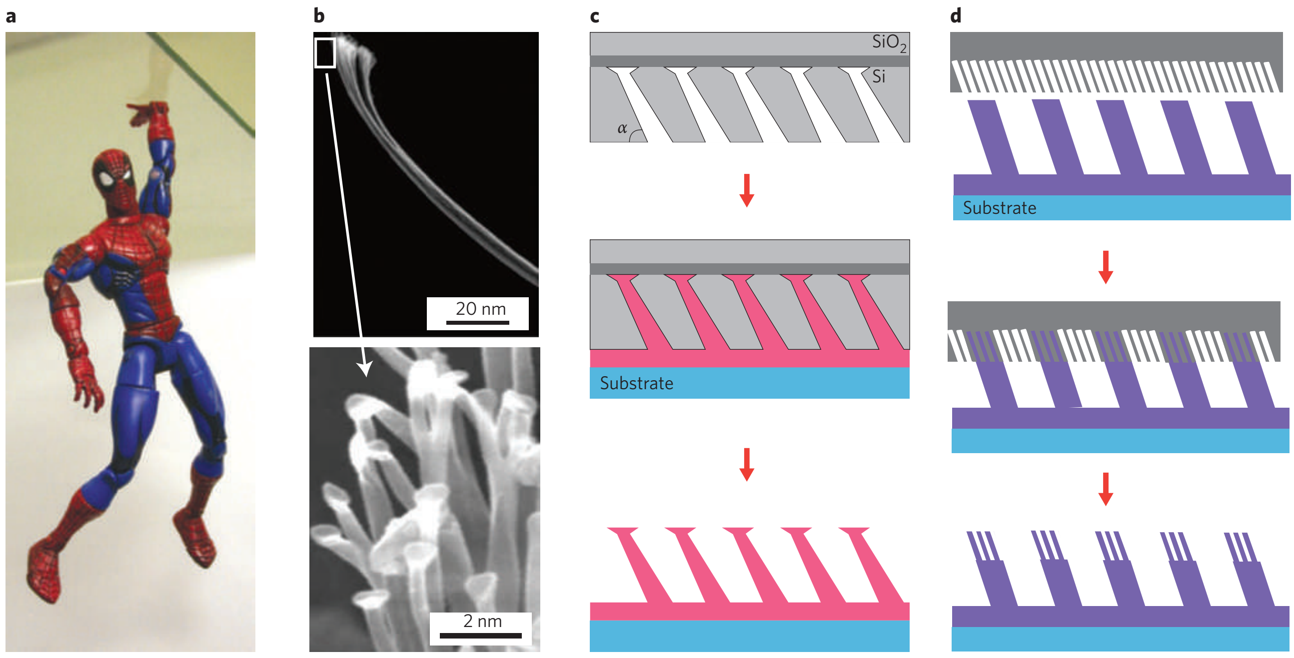

Figure 1 | Fabricating the structure of the gecko foot using a mould technique. **a**, Spider-Man is made to hang onto a glass ceiling by using dry adhesives. Reprinted from ref. 1 (© 2003 NPG). **b**, Scanning electron micrograph of a single setae (upper) and its finest terminal branches (lower), called spatulae, from the toe of a gecko. Reprinted from ref. 6 (© 2000 NPG). **c**, Slanted nanohairs with a controllable angle (α) are made by replicating the silicon mould (grey) with soft polymer (pink) that can be cured using ultraviolet light. The cured polymer is peeled off to obtain the angled polymer nanohair. **d**, Making nanohairs with a hierarchical structure. Placing the mould (dark grey) containing the slanted nanoholes on micrometre-size hairs (purple) forms slanted nanohairs on top of the hairs.

surface and etch holes normal to the surface; angled etching is not possible even when the surface is tilted. To overcome this, the Seoul team installed a Faraday cage in the etching system to control the angle of the incident ions bombarding the surface. This slight modification allowed them to etch slanted holes in a polysilicon substrate, which was subsequently used as a mould to make the slanted polymeric nanohairs using conventional curing techniques. There are other methods, such as lithography, that can make similar angled nanostructures, but these methods are complex and have problems such as low resolution and poor geometrical control.

The polyurethane acrylate nanohairs made with this method were slanted at a controllable angle with respect to the horizontal plane, and were uniformly packed over a large area at a density greater than 130 million hairs per square centimetre. The top of each nanohair is flat (like the gecko's spatula) to provide extra adhesive surface area, and the bottom is larger than the top by 40–80% to provide structural stability and strength (Fig. 1c). They showed strong shear attachment (a maximum of ~26 N cm^{-2}) in the angled direction and easy detachment (~2.2 N cm^{-2}) in the direction at right angles; the adhesion force was sustained even after over 50 cycles of attachment and detachment, suggesting they could be very robust adhesives.

Recent theoretical studies on the mechanics of the gecko foot have shown that hierarchical structures can improve adhesion strength on rough surfaces[8,9]. Moon, Suh and co-workers fabricated dual-scale hierarchical hairs using a two-step ultraviolet-light-assisted moulding technique (Fig. 1d). The first moulding step produced hairs of about 5 μm in diameter. Placing a mould containing the slanted nanoholes on the micrometre-size hairs and applying a small pressure and temperature formed slanted nanohairs on top of the microhairs. The hierarchical structure improved the adhesion on surfaces with roughness up to 20 μm, and because there is no interface between the differently sized structures, this material is structurally strong. Indeed, the dual-scale hierarchical nanohair adhesive could attach and transport a large piece of liquid-crystal display (about 0.9 mm thick and 48 cm × 38 cm in size) without leaving any contaminating traces.

Compared with carbon-nanotube-based adhesives, the polymer nanohairs may be limited to either low- or high-temperature applications because they are not as durable as nanotubes. Furthermore, it may be difficult to fabricate sufficiently long polymer nanohairs that can attach effectively on rough and irregular surfaces in practice.

Nevertheless, dry adhesives have numerous applications in nanoelectronics for micro- and nano-robotics, space and defence technology, and for attaching interconnects without soldering. The methodology presented by the Seoul team can be extrapolated to fabricate a wide range of aligned micro- and nanowire polymer arrays whose adhesion performance may be tuned by temperature, humidity or external electric field. Such aligned polymer nanowires can be used in field emission, flexible electronics, light-emitting devices and solar cells[10]. ❒

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