use of water as casting and/or developing solvent, or on eliminating environmentally harmful components from existing resists[7,8]. However, the idea of exploiting the solubility switching of silk is unique in the field of resists, and provides an approach that combines naturally inspired bottom-up self-assembly fabrication with the precision of a traditional top-down technique[9].

In addition to standard lithographic performance, Omenetto and colleagues also demonstrate the potential of silk fibroin as a functional resist material: that is, a resist that has specific properties useful for practical purposes other than surface patterning. For example, by doping the resist with quantum dots or with green fluorescent protein, the researchers prepare photonic crystal structures and observe clear fluorescence enhancement. Moreover, they show that the silk protein structures can protect encapsulated biological dopants, such as enzymes, from electron-beam irradiation and vacuum exposure. This property allows them to make a horseradish-based peroxidize sensor array in a single fabrication step (Fig. 1c).

A silk fibroin resist has the potential to benefit a wide range of bio-nano device applications. For such purposes, however, it is essential to reduce the required electron-beam dose, at least to levels commensurate with those used with typical electron-beam resists such as poly(methyl methacrylate). Nevertheless, by taking advantage of the polymorphic transformations of silk proteins to drive changes in solubility, Omenetto and colleagues have provided a stimulating new approach to the field of electron-beam lithography. ❐

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References

1. Omenetto, F. G. & Kaplan, D. L. *Science* **329,** 528–531 (2010).
2. Kim, S. *et al. Nature Photon.* **6,** 818–823 (2012).
3. Mukherjee, C., Hota, M. K., Naskar, D., Kundu, S. C. & Maiti, C. K. *Phys. Status Solidi A* **210,** 1797–1805 (2013).
4. Bhumiratana, S. *et al. Biomaterials* **32,** 2812–2820 (2011).
5. Kim, S. *et al. Nature Nanotech.* **9,** 306–310 (2014).
6. Levinson, H. J. *Jpn. J. Appl. Phys.* **50,** 06GA01 (2011).
7. Satoshi Takei, S., Oshima, A., Wakabayashi, T., Kozawa, T. & Tagawa, S. *Appl. Phys. Lett.* **101,** 03106 (2012).
8. Sun, W. *et al. Arch. Environ. Contam. Toxicol.* **64,** 187–197 (2013).
9. Onses, S. M. *et al. Nature Nanotech.* **8,** 667–675 (2013).

OPTICAL TWEEZERS

Dressed for success

Controlled optical manipulation of a single dielectric nanoparticle is achieved with a bowtie nanoantenna placed at the end of the probe of a near-field scanning microscope.

Patrick C. Chaumet and Adel Rahmani

Since Arthur Ashkin demonstrated in 1970 that light can be used to trap particles[1], optical trapping has become a staple of atomic physics, optics and even biology. Optical tweezers, in particular, use focused laser beams to trap and manipulate small objects such as biological cells[2], bacteria and viruses[3]. Despite the success of optical trapping at the atomic (~0.1 nm) and microscopic (~1–10 µm) scales, trapping and manipulation of a single, dielectric nanoparticle (~50 nm) has been an elusive goal. Now writing in *Nature Nanotechnology*, Romain Quidant and co-workers from the Institut de Ciencies Fotoniques and Institució Catalana de Recerca i Estudis Avancats in Barcelona, and Macquarie University in Sydney report on the demonstration of optical trapping and three-dimensional manipulation of a single, 50-nm dielectric particle[4]. The researchers use optical forces to trap single particles, manipulate them over several micrometres, and release them without damaging them.

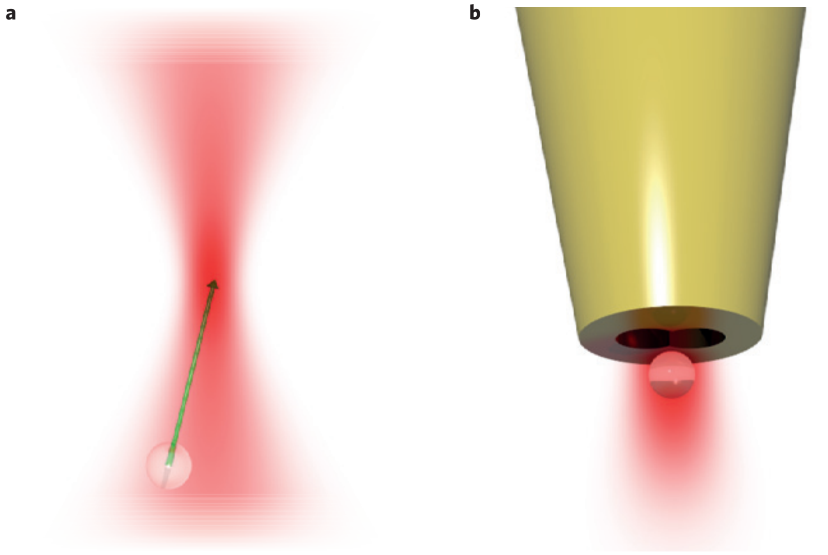

Figure 1 | Reducing the size of an optical trap. **a**, Schematic of a standard optical tweezer. When a particle is illuminated by a focused laser beam, the gradient force attracts the particle towards the higher-intensity area (green arrow). **b**, Near-field scanning optical microscope probe with a particle trapped at its apex.

To appreciate the ingenuity of the technique developed by Quidant and co-workers we can consider the case of a laser beam focused on a small, spherical, lossless, dielectric particle in a fluid (for example, water). We can separate the optical force into two contributions. The scattering force (radiation pressure), results from the light bouncing off the particle and scales as $(a/\lambda)^6$, where a is the particle radius and λ the wavelength of the laser beam. The gradient force is associated with spatial variations of the intensity of light, and scales as $(a/\lambda)^3$. For a nanoparticle $a < \lambda$, and thus, in general, the gradient force is the dominant contribution, attracting the particle towards high-intensity regions (Fig. 1a). However, due to the small size of the nanoparticle the gradient force remains weak and Brownian motion within the fluid is constantly nudging it in random directions, thus hindering its trapping. As the optical force is proportional to the irradiance of light (intensity per unit of surface area), it could be possible to increase the power of the laser to overcome Brownian motion. However, a high irradiance could damage or even destroy the nanoparticle. Hence, the first challenge is to generate an optical trap for a moderate irradiance. A second, more subtle issue is that to trap a single nanoparticle the size of the trap should be of the order of the nanoparticle size. Such a small optical trap would be so sensitive to its environment that the interaction with the single nanoparticle that should be trapped may perturb it enough to destroy its trapping ability.

The technique presented by Quidant and co-workers overcomes these problems by using a modified near-field scanning optical microscope (NSOM) probe to create a subwavelength optical trap (Fig. 1b) and exploit, rather than fight, the trap's high sensitivity to its environment. The idea of using a NSOM probe for optical manipulation is not new[5,6]. The implementation of this idea, however, was hindered by the challenge of obtaining a strong enough trapping potential at a reasonable irradiance. The solution was to introduce a bowtie aperture at the end of the near-field probe (Fig. 2). Whereas, a NSOM probe usually consists of a chemically etched, metal-coated optical fibre with a round opening at the end, the authors' probe has a bowtie opening at its apex. The bowtie acts as a plasmonic nanoantenna, confining light on a subwavelength scale. The associated large gradient of the electric field ensures that, when light is funnelled down the probe, an efficient optical trap is created at the apex. To make sure that the sensitivity of such a trap could be used as an advantage, Quidant and co-workers modified the bowtie nanoantenna such that its resonance is slightly blue-shifted compared with the trapping wavelength. This way only when a nanoparticle is present near the bowtie opening is the optical trap activated. The result is an efficient optical trap for a relatively weak irradiance. Because the trap is formed at the tip of a NSOM probe, the trapped nanoparticle can be moved at will, and released by turning the illumination off.

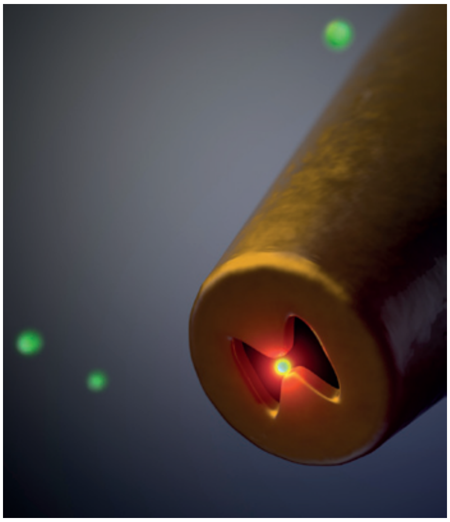

Figure 2 | Schematic of the optical nanotweezers. A nanoparticle is trapped near a bowtie plasmonic aperture at the end of a near-field optical probe. Image courtesy of Johann Berthelot.

The next challenge is to selectively trap a single nanoparticle. In the current scheme a particle has to wander near the bowtie to activate the optical trap, many applications would require an ability to locate a specific particle and capture it. If the nanoparticles are on a substrate, a bowtie nanoantenna probe can be a very effective, polarization-sensitive imaging device[7]. Local spectroscopy via the probe could provide a way to discriminate between different types of nanoparticle. This would be particularly interesting with metallic nanoparticles. The nanoantenna at the end of the NSOM probe could be tailored to a particular plasmon resonance for material-selective, or even size-selective trapping. We can also envisage an array of near-field probes[8] to capture and manipulate particles attached to different antigen–antibody complexes or DNA strands. As a result of the nanoantennas being at the apices of the probes, a nanoscale immunoassay or DNA biochip based on the selective capture and the parallel detection of biomolecules could be possible. ❐

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References

1. Ashkin, A. *Phys. Rev. Lett.* **24,** 156–159 (1970).
2. Ashkin, A., Dziedzic, J. M. & Yamane, T. *Nature* **330,** 769–771 (1987).
3. Ashkin, A. & Dziedzic, J. M. *Science* **235,** 1517–1520 (1987).
4. Berthelot, J. *et al. Nature Nanotech.* **9,** 295–299 (2014).
5. Novotny, L., Bian, R. X. & Xie, X. S. *Phys. Rev. Lett.* **79,** 645–648 (1997).
6. Chaumet, P. C., Rahmani, A. & Nieto-Vesperinas, M. *Phys. Rev. Lett.* **88,** 123601 (2002).
7. Vo, T.-P. *et al. Opt. Express* **20,** 4124–4135 (2012).
8. Chovin, A., Garrigue, P., Manek-Honninger, I. & Sojic, N. *Nano Lett.* **4,** 1965–1968 (2004).

NANOSCALE MRI

Dark spins in the spotlight

A single nitrogen–vacancy centre can be used to probe the location of electron spins with subnanometre precision.

Lloyd Hollenberg

The material and quantum properties of the negatively charged nitrogen–vacancy (NV) centre in diamond provide a range of quantum technology possibilities, including nanoscale sensing and imaging[1,2]. Remarkably, the electronic spin states of NV centres have relatively long quantum coherence at room temperature, making them a sensitive probe for a variety of external perturbations. The NV centre can be tracked and read-out optically; its position, local magnetic and electric fields, and temperature can all be monitored through quantum control via the application of microwaves. Furthermore, these properties lend themselves to biosensing applications as diamond is relatively bio-friendly[3–7]. A number of papers have reported the use of NVs as sensors of electronic and nuclear spins in nanoscale volumes[8–13], including in biological contexts[14–16]. Writing in *Nature Nanotechnology*, Mike Grinolds and co-workers from Harvard University,