

Organized assembly of carbon nanotubes

Cunning refinements help to customize the architecture of nanotube structures.

Nanoscale structures need to be arranged into well-defined configurations in order to build integrated systems. Here we use a chemical-vapour deposition method with gas-phase catalyst delivery to direct the assembly of carbon nanotubes in a variety of predetermined orientations onto silicon/silica substrates, building them into one-, two- and three-dimensional arrangements. The preference of nanotubes to grow selectively on and normal to silica surfaces forces them to inherit the lithographically machined template topography of their substrates, allowing the sites of nucleation and the direction of growth to be controlled.

Although carbon nanotubes promise to have a wide range of applications¹, better control is needed over the building and organization of nanotube-based architectures. Chemical-vapour deposition (CVD) has been used to align nanotubes vertically on catalyst-printed substrates^{2–8}, and we are now able to control the growth of aligned nanotubes in several directions at once in a single process.

We designed and built all of the nanotube structures on patterns created on silica (SiO₂) and silicon surfaces. The substrates consisted of Si(100) wafers capped

with 100-nm-thick thermal oxide, or thick chemical-vapour-deposited silica layers (up to about 8.5 μm thick). Patterning of Si/SiO₂ was generated by photolithography followed by a combination of wet and/or dry etching.

The catalyst material, which is generally required for CVD growth of nanotubes, was not patterned on the substrates; preparation of the template was therefore simplified. Instead, we stimulated CVD growth of nanotubes by exposing the substrate to a xylene/ferrocene (C₈H₁₀/Fe(C₂H₅)₂) vapour mixture at around 800 °C. This precursor combination gives rise to selective growth of multiwalled nanotubes of diameter 20–30 nm on silica surfaces⁹. There is no nanotube growth on silicon, but the aligned nanotubes grow readily on SiO₂ in a direction that is normal to the substrate surface. The template selectivity for growth is retained down to micrometre-sized SiO₂ templates, allowing ordered nanotube structures to be assembled on Si/SiO₂ substrates.

Figure 1 shows some striking examples of organized nanotube patterns grown on preselected substrate sites. In Fig. 1a, three blocks of micrometre-sized, cylindrical pillars of perfectly vertical, densely packed

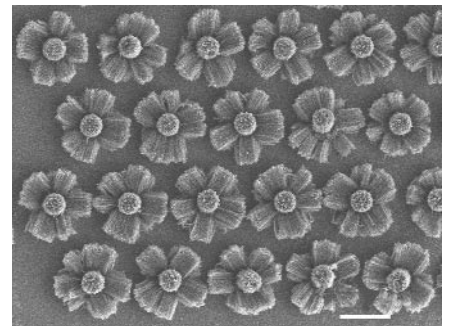


Figure 2 Repeating patterns containing mutually orthogonal nanotube arrays produced on deep (about 5 μm) silica features (circular cross-section) machined on silicon substrates. Growth in the vertical direction occurs from the top silica surface (seen as arrays emanating from the centre of each pattern); growth on the sides occurs as horizontal arrays (sideways growth seen on each pattern). Scale bar, 50 μm.

nanotubes are seen growing from the underlying SiO₂ pattern. The packing of the pillars in each block is determined by the separation between the SiO₂ patterns, and their height is controlled to within about 1–2 μm by tuning the CVD time (growth rates are typically around 10 μm min⁻¹). Nanotube structures with different architecture, such as blocks of rectangular platelets, can be constructed by varying the design of the SiO₂ substrate pattern.

This technique can be used to grow nanotubes in several different directions at once, which was not previously possible. We have realized simultaneous, multidirectional nanotube growth on templates with deeply etched trenches (drilled down to the silicon substrate) separating micrometre-tall SiO₂ features. Figure 1b shows periodic arrays of vertically and horizontally aligned nanotubes grown on repeating patterns of SiO₂ features machined on a planar silicon wafer; the nanotubes are evident in orthogonal directions in the plane of the substrate itself. Beautiful patterns of multiply orientated, organized nanotube structures can be created in this way (Fig. 2).

The simultaneous integration of ordered, geometrically varied nanotube structures in different orientations onto a single substrate could be useful in the manufacture of electromechanical devices. Our fabrication method can be scaled up to large areas and is compatible with standard silicon micro-fabrication technology.

B. Q. Wei*, **R. Vajtai***, **Y. Jung***, **J. Ward***, **R. Zhang†**, **G. Ramanath***, **P. M. Ajayan***

*Department of Materials Science and Engineering, Rensselaer Polytechnic Institute, Troy, New York 12180-3590, USA

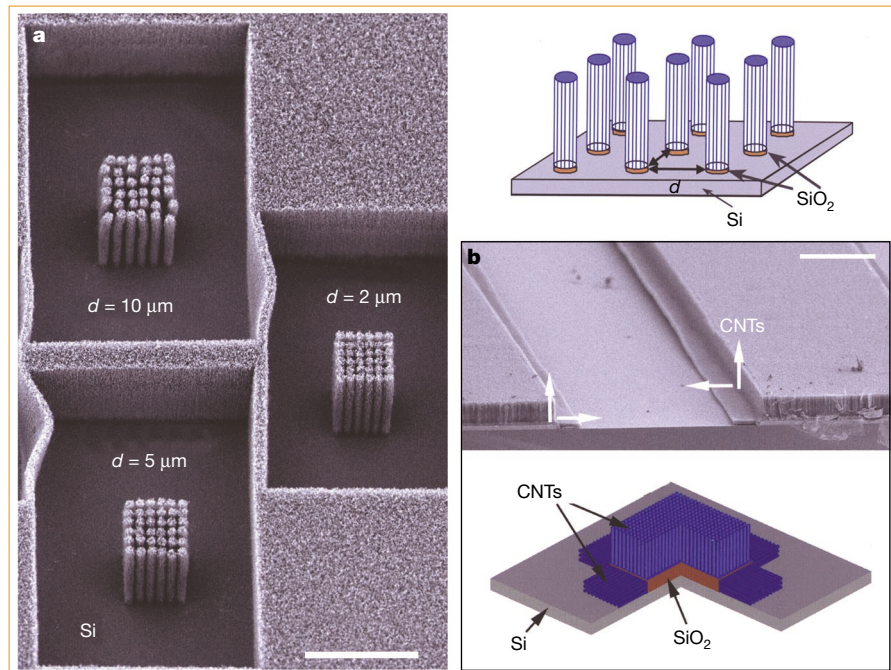


Figure 1 Directed assembly of organized, multiwalled carbon-nanotube structures grown by chemical-vapour deposition. **a**, Image obtained by scanning electron microscopy of three blocks of cylindrical pillars (about 10 μm in diameter) of aligned carbon-nanotube arrays. Each pillar consists of several tens of nanotubes grown in vertical alignment and in a normal direction to SiO₂ patterns on the Si/SiO₂ template. No growth occurs on the Si parts of the template. The separation (*d* in diagram, top right) between pillars in the three blocks is indicated. **b**, Vertical and horizontal growth of aligned nanotubes (CNTs), viewed in a cross-section of a patterned Si/SiO₂ wafer. Scale bars, 100 μm.

e-mail: ajayan@rpi.edu

†Motorola Physical Science Research Laboratories, Tempe, Arizona 85284, USA

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Sperm competition

Motility and the midpiece in primates

In animals with multiple-partner mating systems, the gametes of two or more males must compete to fertilize a given set of ova^{1–5}. Here we show that the volume of the midpiece in individual sperm is significantly greater in primate species in which the females mate with multiple partners, and in which males have larger testes in relation to their body weight, than in those species that mate with only one partner and have relatively small testes. Our results indicate that sexual selection by sperm competition has influenced the evolution of a specific component of male-gamete morphology, the volume of the sperm midpiece.

We classified different primate species as having either a single- or multiple-partner mating system on the basis of published descriptions of primary mating systems and behavioural information^{6,7}. We measured the lengths (in μm) and volumes (in μm^3) of sperm head, midpiece and flagellum in 31 species, representing 21 primate genera. We compared differences in sperm morphology between single- and multiple-

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partner mating systems at both the genus and species levels, using comparative analysis of independent contrasts (CAIC)⁸. Critical α -levels were adjusted for multiple comparisons of sperm traits using the sequential Bonferroni technique.

Sperm lengths did not differ statistically between single- and multiple-partner mating systems. By contrast, sperm midpiece volumes differed significantly at both the genus ($F=20.86$, $P<0.01$) and species ($F=3.46$, $P<0.05$) levels (Fig. 1a). When sperm-head volumes associated with single- and multiple-partner mating systems were compared, there was no significant difference between genera or species ($44.01 \pm 2.71 \mu\text{m}^3$ versus $41.82 \pm 2.40 \mu\text{m}^3$, and $46.20 \pm 3.2 \mu\text{m}^3$ versus $44.56 \pm 2.89 \mu\text{m}^3$, respectively). The same was true for flagellum volumes ($9.74 \pm 0.82 \mu\text{m}^3$ versus $9.73 \pm 1.21 \mu\text{m}^3$, and $8.01 \pm 0.81 \mu\text{m}^3$ versus $9.69 \pm 0.88 \mu\text{m}^3$, respectively).

Because there is disagreement over the classification of primate mating systems, we also used relative testis weight as an indirect measure of likely sperm competition. We calculated residual values of testis weight from a regression plot of combined testes weight against body weight. We compared genera with relatively small testes (negative residuals) with those with relatively large

testes (positive residuals). Midpiece volumes were significantly greater in sperm from primate genera with relatively large testes (mean \pm s.e.m.: $9.758 \pm 0.558 \mu\text{m}^3$ for genera with large testes; $5.360 \pm 0.609 \mu\text{m}^3$ for genera with small testes; $t = -4.57$, $P < 0.001$). No significant difference was found when the analysis was repeated for sperm-head volume and flagellum volume.

We also tested for a possible correlation between relative testis weight and sperm midpiece volume, and found a strong effect ($r^2 = 0.49$, $P < 0.0001$; Fig. 1b), although none of the other variables examined was correlated with relative testis weight. We conclude that sexual selection has probably influenced midpiece volume as well as testicular size.

Certain features of midpiece anatomy are highly heritable⁹. The volume of the midpiece is a more informative measure than its length, as this section contains a densely packed, helical array of mitochondria which provides energy for motility in the absence of glycolytic support^{10,11}. The volume is therefore a likely indicator of the degree of mitochondrial loading.

Mitochondrial loading also has a bearing on flagellar hydrodynamics^{10,11}, and the ATP content of the sperm of domestic fowl is positively correlated with its motility¹². The greater midpiece volumes we have observed in primates with multiple-partner mating systems, in which sperm competition is most prevalent, may therefore result from selection for increased mitochondrial loading and greater motility. This would mirror the situation in domestic fowl, in which high sperm motility is correlated with successful sperm competition¹³.

Matthew J. Anderson, Alan F. Dixon

Center for the Reproduction of Endangered Species, Zoological Society of San Diego, PO Box 120551, San Diego, California 92112-0551, USA
e-mail: manderson@sandiegozoo.org

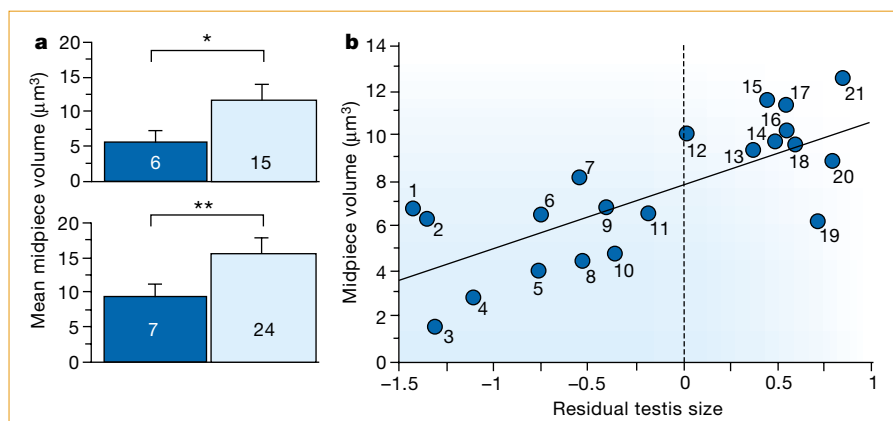


Figure 1 Sperm midpiece volume in relation to partner number and relative testis size. **a**, Comparison of sperm midpiece volume in primates with single-partner (black bars) or multiple-partner (white bars) mating systems at the genus level (top) and the species level (bottom; after comparative analysis of independent contrasts, CAIC). Numbers in bars show sample sizes (number of animals). Asterisk denotes $P < 0.01$; double asterisk denotes $P < 0.05$ (tablewide α -values maintained by sequential Bonferroni corrections). One hundred sperm from each of 106 specimens were measured at $\times 1,000$ magnification using a light-refractive microscope, a digital camera and Image NIH for Apple Macintosh. Midpiece volume was estimated using the formula for calculating the volume of a cylinder ($\pi \times$ midpiece width² \times midpiece length). **b**, Midpiece volume (in μm^3) in relation to relative testis size in 21 primate genera ($y = 2.55x + 7.52$; $P < 0.0001$). 1, *Gorilla*; 2, *Erythrocebus*; 3, *Callithrix*; 4, *Hylobates*; 5, *Pongo*; 6, *Theropithecus*; 7, *Saimiri*; 8, *Cebus*; 9, *Galago*; 10, *Homo*; 11, *Cercopithecus*; 12, *Lophocebus*; 13, *Mandrillus*; 14, *Pygathrix*; 15, *Lemur*; 16, *Eulemur*; 17, *Papio*; 18, *Nycticebus*; 19, *Microcebus*; 20, *Pan*; 21, *Macaca*.

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