Nanotube Nanotweezers

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Nanoscale electromechanical systems—nanotweezers—based on carbon nanotubes have been developed for manipulation and interrogation of nanostructures. Electrically conducting and mechanically robust carbon nanotubes were attached to independent electrodes fabricated on pulled glass micropipettes. Voltages applied to the electrodes closed and opened the free ends of the nanotubes, and this electromechanical response was simulated quantitatively using known nanotweezer structure and nanotube properties. The mechanical capabilities of the nanotweezers were demonstrated by grabbing and manipulating submicron clusters and nanowires. The conducting nanotube arms of the tweezers were also used for measuring the electrical properties of silicon carbide nanoclusters and gallium arsenide nanowires.

The development of new tools for manipulating and probing matter at nanometer length scales is critical to advances in nanoscale science and technology. Scanning probe microscopes (SPMs) such as the scanning tunneling microscope (STM) and atomic force microscope (AFM) are now widely used for these purposes and have the capability of working at length scales as small as a single atom (*1–4*). However, the single probe tips used in SPMs limit these tools' ability to manipulate objects and measure physical properties; for example, one tip cannot grab an object, and electrical measurements cannot be made without a second contact to structures. Two probes in the form of tweezers could overcome these limitations of SPMs and thus might enable new types of fabrication and easy electrical measurements on nanostructures.

Micrometer-scale electromechanical tweezers, which represent basic microelectromechanical systems, have been fabricated previously on silicon (*5–7*). Tungsten deposition and subsequent processing were used to produce tungsten arms 200 μm long by 2.5 μm wide that could be closed by applying a potential (V) of ~150 V and then opened again by reducing V to zero (*5*). The potential difference between the tungsten tweezer arms produces an attractive electrostatic force that can overcome the elastic restoring force of the beams in closing the tweezers. Smaller tweezers with single-crystal silicon arms 30 μm long by 0.25 μm long, which respond at a potential of 45 V, have also been made with conventional lithography and processing steps (*6*). Such microtweezers, if removed from the substrate support, could be useful tools for manipulation but are limited by their relatively large size and large actuating voltages for nanoscale work.

We used nanometer-diameter carbon nanotubes to create robust nanotweezers that can be utilized for nanoscale manipulation and measurement. Carbon nanotubes are ideal materials for nanoscale electromechanical devices because they exhibit remarkable mechanical toughness (*3, 8*) and electrical conductivity (*4, 9*) down to diameters as small as 1 nm. For fabrication of our nanotube nanotweezers (Fig. 1), free-standing electrically independent electrodes were deposited onto tapered glass micropipettes, which can be routinely made with end diameters of 100 nm (*10*) (Fig. 1B and inset). Second, carbon nanotubes were attached to the independent Au electrodes using an approach similar to that used for the fabrication of single-nanotube SPM tips (*11*). This approach is routinely used to attach multiwalled nanotube (MWNT) or single-walled nanotube (SWNT) bundles 20 to 50 nm in diameter to the two Au electrodes under the direct view of an optical microscope (*12*). A representative scanning electron microscope (SEM) image of one of the 30 nanotube tweezers fabricated in this way (Fig. 1C) shows that the MWNT arms of the tweezer are about 4 μm long but only 50 nm in diameter. Because the diameter or cross section of the arms constrains the size of objects that can be reliably grabbed, we call these new structures nanotweezers. The present size of the nanotweezers is limited only by the optical microscope resolution used to monitor the nanotube attachment process. If required, it will be possible to make substantially smaller tweezers by carrying out nanotube attachment within a SEM or by directly growing the tweezer arms by chemical vapor deposition (*13*).

The electromechanical response of nanotube nanotweezers was investigated by applying bias voltages to the electrodes while simultaneously imaging the nanotube displacements. As the bias voltage increased from 0 to 8.3 V (Fig. 2), the ends of the tweezer arms bent closer to each other from their relaxed position (at 0 V). The tweezer arms relaxed to the original position when the applied voltage was removed, and this process could be repeated more than 10 times, producing the same displacement each time within the optical microscope resolution limit. These results demonstrate that the mechanical response is elastic and thus that neither the nanotubes nor the nanotube-electrode junctions deform plastically. At 8.3 V, the distance between the tweezer ends had decreased by about 50% of the initial value, and as the voltage was increased further to 8.5 V, the tweezer arms suddenly closed (Fig. 2E). The nanotweezer arms typically remain closed after removal of the actuating voltage, because the van der Waals interaction between tubes produces a second potential minimum at contact (*14*). The nanotweezers can, how-

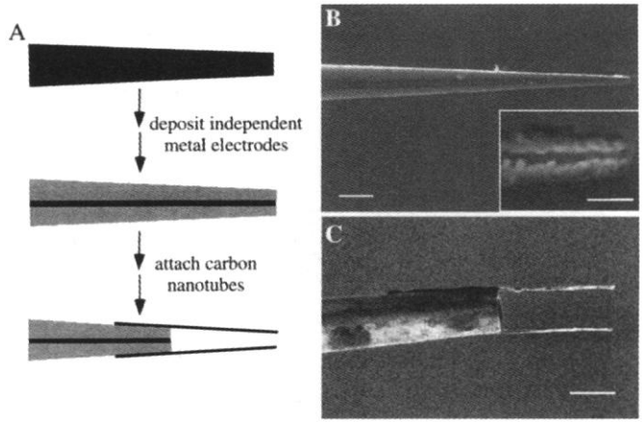

Fig. 1. Overview of the fabrication of carbon nanotube nanotweezers. (**A**) Schematic illustrating the deposition of two independent metal electrodes and the subsequent attachment of carbon nanotubes to these electrodes. (**B**) SEM image of the end of a tapered glass structure after the two deposition steps (*10*). Two electrodes (top and bottom) are separated by a gap (dark belt in the middle) that extends from the beginning of the template (diameter = 1 mm) to the end (diameter = 100 nm). Scale bar, 1 μm. The higher resolution inset shows clearly that the electrodes are separated. Scale bar, 200 nm. (**C**) SEM image of nanotweezers after mounting two MWNT bundles on each electrode. Scale bar, 2 μm.

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ever, be readily opened by applying voltage of the same polarity to both tweezer arms relative to a nearby ground electrode.

We carried out simulations to understand the response and sudden closure of the nanotweezers. The operating principle of the nanotweezer is to balance the elastic energy cost with the electrostatic energy gain. The deformation of the beams at a given bias voltage, V, is determined by equating the elastic force of the beams with the electrostatic force along the beams. Let $y(x)$ designate deflected distance of the tweezer arm from the equilibrium position at x, where x is the distance along a relaxed tweezer arm from the electrode. The static equilibrium shape of tweezer $y(x)$ at bias voltage V is obtained by minimizing the free energy

$$G_{tot}\{y\} = -\frac{1}{2} C\{y\}V^2 + \frac{\pi E R^4}{4}\int_0^L \left(\frac{d^2y}{dx^2}\right)^2 dx \quad (1)$$

with respect to $y(x)$, where $C\{y\}$ is the capacitance between the tweezer arms; and E, L, and R are the Young's modulus, length, and diameter of the tweezer arm, respectively. Figure 2F shows a discontinuous step in the nanotube end separation above threshold voltage V_{th} = 9.4 V, which is close to the observed experimental value of 8.3 V. These simulations show that static equilibrium is maintained for $V < V_{th}$; that is, the electrostatic force exactly balances the elastic restoring force as observed experimentally. However, the nonlinear nature of the electrostatic force precludes equilibrium (until contact) for $V > V_{th}$ and thus explains the origin of the discontinuous step at closure (*7*).

We explored the power of these new nanotube nanotweezers by manipulating and probing nanostructures. First, we demonstrated our ability to grab and pick up nanoscale objects in studies of fluorescently labeled polystyrene spheres (*15*). The emission from the dye molecules within the beads enables these submicrometer structures to be readily observed in an optical microscope. Under dark-field illumination, the nanotweezers were moved to a group of supported clusters, and after electrostatically deflecting the nanotube arms to grab a small cluster, the nanotweezers were used to move the nanocluster from the sample surface (Fig. 3). SEM analysis of this nanostructure showed that it was 500 nm in diameter and contained several nanoclusters unresolved in the optical micrograph. These results demonstrate that we can readily grab and manipulate nanostructures that are on the scale of cellular substructures. The adhesive force between a nanotube arm and the nanoclusters is not generally strong enough to move the nanoclusters; the applied voltage that closes the tweezer arms on the nanoclusters is required to remove them reproducibly from the substrate (*16*).

Once a nanoscale object has been grasped in our nanotube nanotweezers, it is also possible to probe its electrical properties, because the nanotube arms serve as conducting wires to the nanoworld. Optical images of nanotweezers closed without a sample or grasping doped β-SiC nanoclusters (*17*) or a GaAs nanowire (*18*) are shown in Fig. 4, A, B, and C, respectively (*19*). The β-SiC nanocluster and GaAs nanowire samples were grabbed and removed from supports using the approach described above. In the case of GaAs nanowires, the extension and removal of single wires from the entangled sample clearly shows the power of a tweezers device. Figure 4D depicts the current (I) versus voltage (V) characteristics of these structures. The closed nanotweezers and SiC exhibit ohmic behavior with room temperature resistances of 600 (10) kilohm and 39 (0.1) megohm, respectively, where the numbers in parenthesis represent the standard deviation. The measured resistances agree well with independent measurements of nanotube junc-

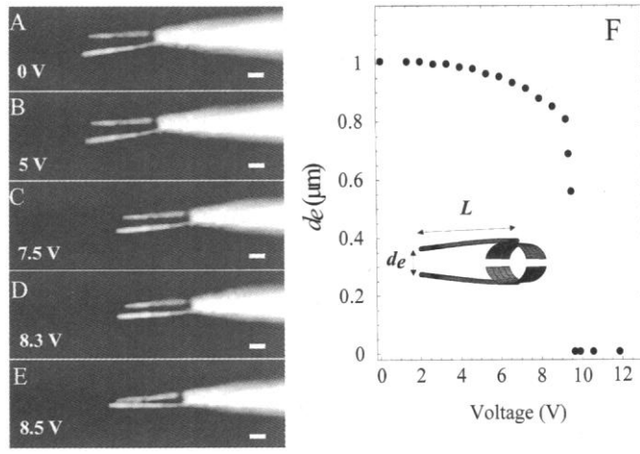

Fig. 2. Electromechanical response of the nanotube nanotweezers. (**A** through **E**) Dark-field optical micrographs of the nanotube arms at potentials of 0, 5, 7.5, 8.3, and 8.5 V, respectively. Scale bars, 1 μm. The mechanical deflection of the nanotweezers in response to the bias voltage applied to the electrodes is shown. Although the nanotweezer arms are substantially smaller (50 nm in diameter) than optical wavelengths, they scatter sufficient light to be readily observed in the dark-field images. (**F**) Voltage response of carbon nanotweezers calculated using Eq. 1. The separation of the ends of the nanotube arms, d_e, is plotted as a function of applied voltage. The dimensions of the tweezers used in the calculation (L = 5 μm, nanotube diameter = 45 nm) are similar to those of the experimental structure; and the Young's modulus, 1 TPa, is from previous experiments (*3*). A more thorough comparison to experimental results will require that the present simplified model (two identical parallel elastic rods) be elaborated to reflect the detailed geometry of the device.

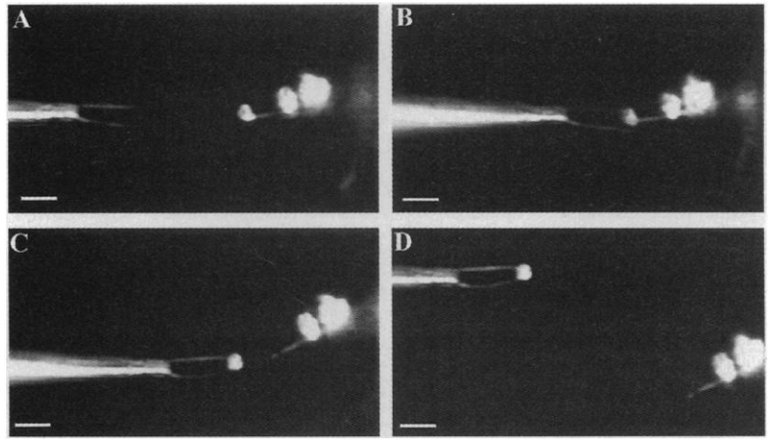

Fig. 3. Dark-field optical micrographs showing the sequential process of nanotweezer manipulation of polystyrene nanoclusters containing fluorescent dye molecules (*14*). (**A**) Approach of the nanotweezers to nanoclusters. (**B**) Alignment of the tweezer arms on a small cluster. A voltage was applied to nanotweezer arms on the nanocluster, and then the nanotweezers and cluster were moved away from the sample support (**C** and **D**). The fluorescent polystyrene nanoclusters and nanotube arms are both readily observed in the dark-field image. The SiC sample, which was deposited from a water-based suspension, consisted primarily of clusters of individual 310-nm polystyrene beads. We focused on grabbing the smallest clusters, ~500 nm in diameter, in our experiments. SEM analysis of these clusters showed that they consisted of several 310-nm nanoclusters. Scale bars, 2 μm.

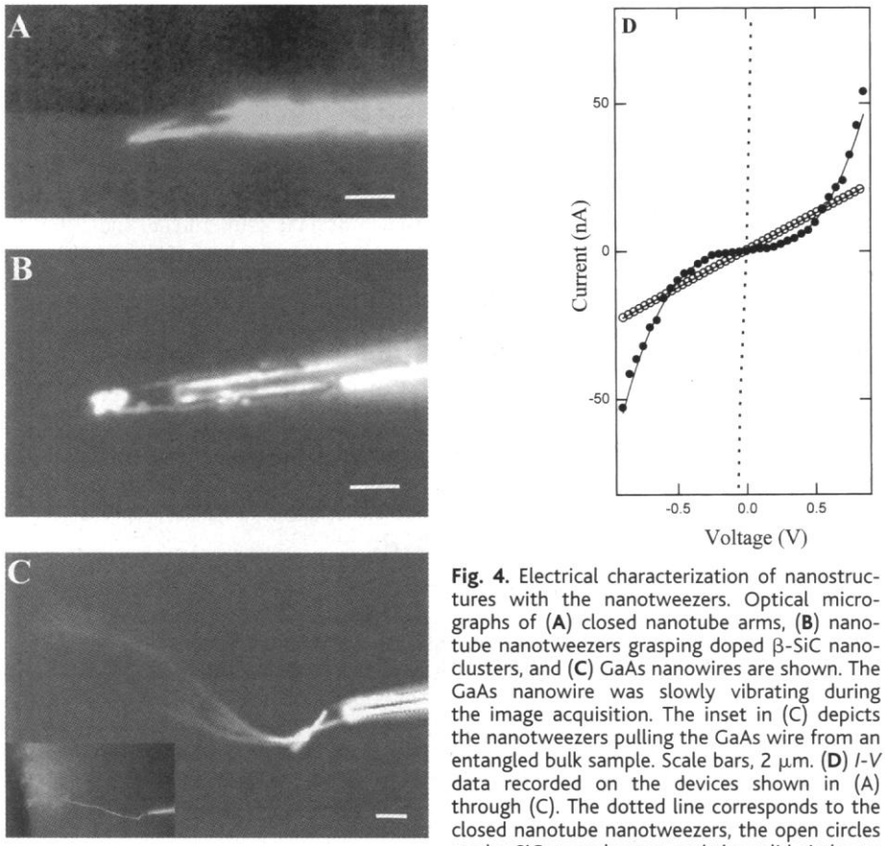

Fig. 4. Electrical characterization of nanostructures with the nanotweezers. Optical micrographs of (**A**) closed nanotube arms, (**B**) nanotube nanotweezers grasping doped β-SiC nanoclusters, and (**C**) GaAs nanowires are shown. The GaAs nanowire was slowly vibrating during the image acquisition. The inset in (C) depicts the nanotweezers pulling the GaAs wire from an entangled bulk sample. Scale bars, 2 μm. (**D**) *I-V* data recorded on the devices shown in (A) through (C). The dotted line corresponds to the closed nanotube nanotweezers, the open circles to the SiC nanoclusters, and the solid circles to the GaAs nanowire. Ohmic (linear *I-V*) behavior was observed for the closed nanotube and for SiC nanoclusters with resistances of 600 kilohm and 39 megohm, respectively. The solid line through the solid circles corresponds to a cubic fit consistent with tunneling transport through the insulating oxide layer on the nanowires.

tions (*20*) and doped β-SiC crystals (*21*). The GaAs nanowires exhibit highly nonlinear (cubic) *I-V* behavior that is characteristic of tunneling through a barrier (*22*). This behavior is consistent with our observation (*18*) that the crystalline n-doped GaAs core is covered with an insulating oxide layer.

The results described here demonstrate that nanotube nanotweezers can be used to manipulate individual nanostructures and directly probe their electrical properties. We believe that these capabilities can be exploited in a number of ways. The nanotweezers can be used to create new types of quantum dot and quantum wire structures that are not possible, for example, with colloidal crystallization (*23*). Another possible application of the nanotweezers is a novel electromechanical sensor that can detect pressure or viscosity of media by measuring the change in resonance frequency and Q-factor of the device. The nanotube nanotweezers could also be used as a two-tip STM or conducting AFM probe. Such a probe can measure the single-electron Green's function between the two local tunneling junctions and thus provide detailed information about electronic properties of materials (*24*). At their current size, the nanotube nanotweezers also open up exciting opportunities for manipulation and modification of biological systems such as structures within a cell (*25*).

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14. Calculations show that the potential energy versus separation typically has two minima corresponding to the open/relaxed and contact structures; that is, the system is bistable (P. Kim, K. Kim, T. Rueckes, E. Joselevich, C. M. Lieber, unpublished results).
15. The spheres used were uniformly dyed polystyrene microspheres 0.31 μm in diameter (XC Estapor, Bangs Laboratories, Fishers, IN).
16. The grabbing force exerted on the spheres by the nanotweezers is ≥10 nN. Without the applied voltage to close the nanotweezers' arms, <10% (20 trials) of the experiments resulted in the removal of a polystyrene sphere. This shows that the adhesion force is generally not sufficient to enable sphere manipulation. However, when the applied voltage was used to close the nanotweezers on a polystyrene sphere, >80% of the experiments resulted in the removal of the spheres.
17. The nanoclusters were composed of β-SiC powder (99.8%, Johnson Matthey, Ward Hill, MA) and had an average diameter of 500 nm. The SiC contained 0.2% N and was thus heavily doped.
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20. The resistance R of SiC clusters can be estimated using the simple relation $R = \rho L/A$, where ρ, A, and L are the resistivity, cross-sectional area, and length of the measured sample, respectively. Using $\rho \sim 10^{-4}$ ohm · cm determined in a previous study of heavily N-doped β-SiC [W. Hellmich, G. Muller, G. Krotz, G. Derst, S. Kalbitzer, *Appl. Phys. A* **61**, 193 (1995)] yields a resistance, 100 megohm, that is comparable to our measured value.
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