Towards Pick-and-Place Assembly of Nanostructures

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We examine an approach to three-dimensional pick-and-place assembly of wire-like nanoscale components, such as carbon nanotubes and silicon nanowires, on microstructures inside a scanning electron microscope. In this article we demonstrate that microfabricated electrostatically actuated tweezers can pick up silicon nanowires and show how electron beam deposition of carbon residues can be used to assemble carbon nanotubes on microelectrodes.

Keywords: Nanomanipulation; Nanowire; Nanotube; Tweezers; Electron Beam Deposition or Electron Beam Induced Deposition.

1. INTRODUCTION

Since the discovery of carbon nanotubes a decade ago, the fascinating properties of these and other wire-like nanostructures have been the subjects of intense study. To realize the potential of nanotubes and nanowires as active components in electronic devices, methods for reliable integration with microstructures are required.

Scanning probe microscopes have been widely used for manipulation of nanotubes on planar surfaces to measure rolling, sliding, and bending properties of single-walled nanotubes (SWNTs),[1, 2] construction of field-effect transistors,[3] and detailed studies of nanotube junctions.[4] In these experiments, tube-surface adhesion often plays a dominating role. It has also been shown that the electrical properties of SWNTs can be considerably affected by direct contact to a surface.[5]

Common strategies for three-dimensional integration include directed growth of nanostructures on microelectrodes,[6, 7] assembly in liquid solution using flow alignment,[8] and direct mechanical assembly using sharp tips.[9, 10] Opening and closing of nanotweezers designed for nanomanipulation have been demonstrated in a scanning electron microscope (SEM),[11–13] and nanotweezers have also been used to pick up nanoscale objects in ambient conditions.[11, 13]

So far, approaches to reliable pick-and-place assembly of nanowires and nanotubes have not been reported. The key issue is to control the balance between the sum of forces acting between the object and the surface, $F_{surface}$, and the forces acting between the object and the tool, F_{tool}. Although picking up an object requires F_{tool} to overcome $F_{surface}$, the balance must be reversed to place and release the object. On the nanoscale, controlling this balance is particularly difficult due to the presence of forces such as van der Waals and electrostatic forces. The snap-in and sticking effects arising from these forces are among the main challenges of micro- and nanoscale pick-and-place manipulation.

In this work we examine an approach to pick-and-place integration of nanowires and nanotubes on microstructures inside a SEM. We use microfabricated, electrostatically actuated tweezers capable of applying an adjustable force to an object. When the tweezers are opened to release an object, electrostatic forces may still prevent well-controlled placement. To secure precise placing of the object, electron beam deposition (EBD) may be used *in situ* to "solder" the nanotube/nanowire onto the desired location and thereby increase the surface adhesion. Electron beam deposits are formed through a decomposition of gas molecules by localized electron irradiation inside a SEM. The gas source can be the carbonaceous background gas present in the SEM, which has been used to attach carbon nanotubes to other objects[14, 15] or a selected organometallic precursor gas, which can result in deposits with high metal contents[16] and can form highly conductive connections to carbon nanotubes.[17]

In this article we first describe the design of tweezers and manipulation of silicon nanowires using these tweezers. Then we demonstrate that EBD provides a convenient tool for accurately placing nanocomponents, by soldering with deposits smaller than 50 nm.

2. EXPERIMENTAL DETAILS

The microtweezers consist of three to five cantilevers. Figure 1 shows a SEM image of a five-electrode tweezers chip, fabricated in a silicon microfabrication process.[12, 18] The process allows any planar miltielectrode geometry with a linewidth down to 750 nm and cantilever lengths up

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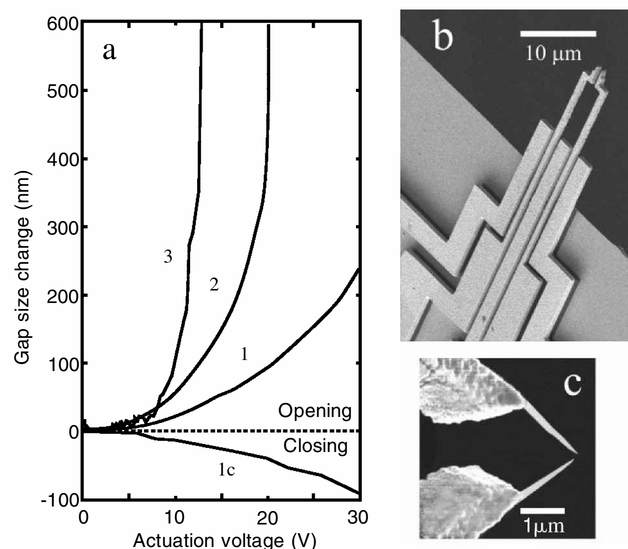

Fig. 1. (a) Actuation curves for three different microtweezer arms, showing the change in gap size relative to the neutral position as a function of applied voltage. Curves 1 and 1c are opening (1) and closing (1c) actuation curves from the same device. In both cases, the actuation curves exhibit a nearly parabolic behavior at low voltages. Curve 2 shows two consecutive actuation curves for a 50-μm-long microtweezer arm, where the arms snapped in between the first and the second measurement. The negligible difference demonstrates the reproducibility of the actuation. Curve 3 shows an actuation range of 400 nm at 14 V obtained using a 60-μm-long pair of tweezers. (b) SEM image of a pair of microtweezers with three wide driver electrodes and two long flexible tweezers electrodes. (c) SEM image showing the apex of a pair of microtweezers with EBD tips deposited using the SEM background gas. The deposited tips reduce the size of the gap to 100 nm.

to 80 μm. The cantilevers are made of a 1-μm-thick silicon oxide layer covered with a thin layer of metal (100 Å Ti/1000 Å Au). By applying a voltage between the narrow flexible tweezers electrodes and the wide "driver" electrodes (Fig. 1b), the electrostatic attraction causes the tweezers gap to open or close, depending on whether the inner or the outer driver electrodes are biased. Because no voltage difference has to be applied between the tweezers arms, the electrostatic fields near the grabbed object can be made insignificant, reducing the risk of unwanted electrostatic forces on the object. EBD can be used to add tips with diameters in the 100 nm range at the apex of the microcantilevers (Fig. 1c), which should make it possible to manipulate objects much smaller than the micron-sized cantilevers. With this technique we achieve a considerable reduction of the contact area, thereby reducing the tip–object adhesion forces. The minimum stable gap obtained with this technique is 25 nm.[12]

The change in gap size as a function of applied voltage is shown in Figure 1a for three devices with varying lengths of tweezers arms. The bottom curves demonstrate opening (1) and closing (1c) of one 40-μm-long tweezer arm. The longer devices (50- and 60-μm arms) exhibit steeper actuation curves (2 and 3). The maximal gripping forces are in the sub-μN range. In the experiments described below, these nanotweezers devices were used as tools for manipulation of nanowires and for support for suspended nanotube bridges attached using EBD.

The manipulation setup consists of two platforms that can be positioned in three dimensions with nanometer precision using joystick-controlled PC interfaces. One platform is placed on the 5 dF stage of a LEO 1550 SEM and is capable of supporting several substrates and tools, such as microtweezers and four-point probes. The other platform is mounted on a xyz-manipulator from Klocke Nanotechnik and holds a single pair of microtweezers.

3. RESULTS

The image sequence in Figure 2a–c shows a pair of microtweezers grabbing a silicon nanowire. The tweezers have an actuation range of 300 nm at a voltage of 30 V. The silicon nanowire has a diameter less than 100 nm and is initially lying on a gold-coated Si substrate. To confirm that the applied force and *not* the adhesion of the wire to the tweezers is dominating the pick-up process, the microtweezers were first closed around the wire (Fig. 2a) and subsequently reopened (Fig. 2b). Although the nanowire adhered to the tweezers, the adhesion forces were not sufficient to pull the wire off. Closing the tweezers again (Fig. 2c) allowed the wire to be picked up.

The silicon nanowires require much less force for released from the substrate than the carbon nanotube samples available for the study. While modifications of the nanotweezer shape to facilitate picking up of carbon nanotubes are in progress, we have explored the possibilities of controlled placing of nanotubes using EBD.

We first investigated the mechanical strength of the EBD-grown tweezers tips and a multiwalled carbon nanotube (MWNT) extending from a disordered bundle. They were brought in contact and soldered together using a 30-s exposure to a 5 kV beam, illustrated by the triangle in Figure 3a. When the microtweezers were retracted, the

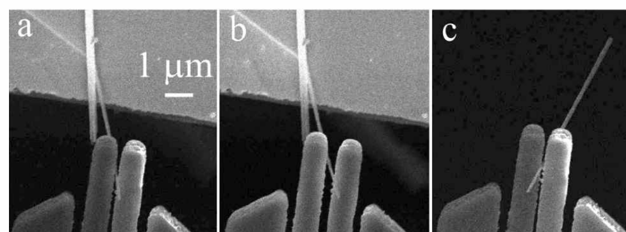

Fig. 2. SEM images of microtweezers gripping a silicon nanowire, which is less than 100 nm wide. (a) The nanowire is gripped at an actuation voltage of 30 V applied between the inner electrodes. (b) The wire is released to verify that adhesion forces alone are not sufficient to pull the wire off the substrate. (c) Finally, the tweezers are closed again using a 30 V bias voltage, enabling the nanowire to be gripped and pulled off the substrate.

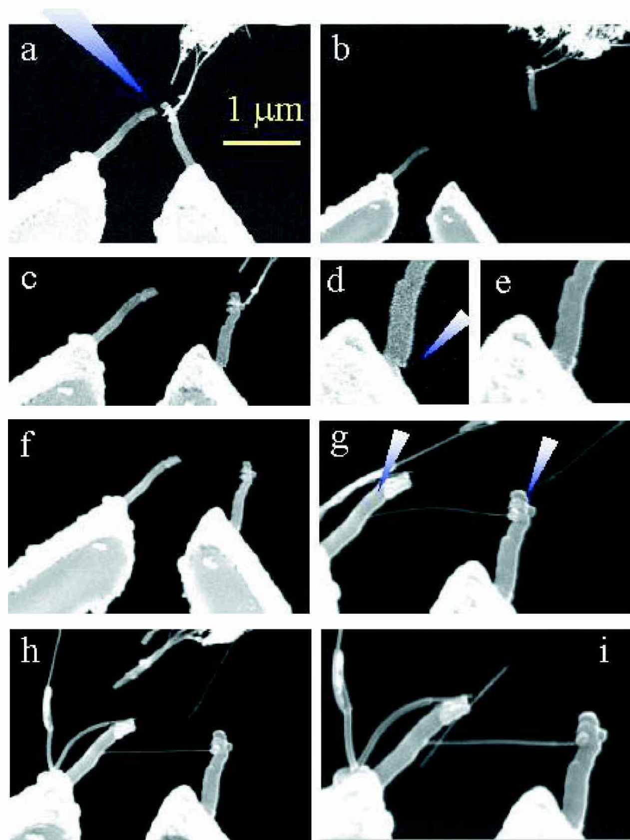

Fig. 3. Electron beam soldering of nanostructures. (a) A multiwalled carbon nanotube extending from an entangled bundle of nanotubes was bonded to the electrode using an electron beam. (b) The tweezers were retracted, whereby the nanotip broke off. (c) The nanotip was then placed in a new position near the electrode. (d) The electron beam spot was directed toward the gap between the tip and the electrode. (e) The sub-50 nm gap was filled with carbonaceous material by a 30-s exposure. (f) Retracting the nanotube broke it off and left the tip in the new position. (g) A multiwalled carbon nanotube was dragged across the two tips and bonded. The bonding fixed the nanotube so that it could be broken off the electrode. (h and i) A second, shorter nanotube was positioned and bonded to the bridging nanotube. Charging of the carbon tips by the electron beam deflected the nanotube and prevented it from being positioned in the middle of the gap.

nanotip eventually broke off at the microelectrode (Fig. 3b). By measuring the bending of the tweezers electrode, the tensile strength was estimated to be on the order of 0.1 μN. The nanotip was subsequently brought in contact with the electrode close to its original position (Fig. 3c). Another 30-s EBD exposure filled the gap between the dangling tip and the electrode, establishing a firm connection at the base of the tip (Fig. 3d–e). The deposit was less than 50 nm in size. By retracting the tweezers a second time, the nanotube broke off, leaving the tip in its new position.

In a subsequent experiment, we connected a MWNT with a diameter of 20–30 nm between the thin EBD tips by first soldering the tube to the left tip (Fig. 3g), dragging it across to the second tip, and finally soldering at the point of contact on the second tip (Fig. 3h). The second bond was strong enough to allow the excess tube to be broken off, while leaving the bridge intact. The EBD tips produced from the background gas in these experiments were not conducting and we measured no electrical conduction (<1 nA at 100 mV bias) in these devices, which sustained bias voltages of several volts.

4. DISCUSSION

We have demonstrated that silicon nanowires can be picked up by electrostatically actuated microtweezers provided that $F_{\mathrm{tool}} > F_{\mathrm{surface}}$ and that carbon nanostructures can be interconnected and integrated on microelectrodes using EBD. Although the two experiments show the feasibility of pick-and-place integration of nanoobjects using tweezers, the results also show the efficiency of EBD for performing nanomanipulation even for materials adhering so strongly to the substrate that they cannot be picked up by the tweezers ($F_{\mathrm{tool}} < F_{\mathrm{surface}}$).

Compared to manipulation using a sharp tip, grabbing of a nanowire with tweezers ideally prevents the nanowire from being misoriented by electrostatic forces in the SEM caused by charging, without the need for contamination of the wire by electron beam deposition. Compared with nanotube nanotweezers,[11, 13] the micrometer-wide arms seem efficient in limiting the freedom of movement of the gripped object. However, with the present setup and microtweezers designs, careful optimization of the accelerating voltage for the electron microscope is necessary to minimize charging of the gripped object and surroundings. Improved tweezers designs, capable of applying larger forces, are under development to widen the range of applications.

The source gas for EBD in the results presented was the background gas present in the electron microscope. The presence of the carbon nanotube sample appeared to contribute to the amount of carbonaceous gas near the electron beam, because the deposition rate was generally higher with carbon nanotube samples.

In the presence of the carbonaceous background gas, the electron beam also deposited material on the nanotubes by EBD when the nanotube was imaged over a long time and/or at high magnification. Using a clean sample reduced the contamination rate significantly. EBD soldering with negligible contamination should be possible by using an EBD gas source with a controllable flow rate. Such a system is under construction.

Compared with pick-and-place integration, methods such as dielectrophoretic integration and *in situ* growth are typically faster, simpler, and scaleable to large production quantities. However, control of the individual components is not easily accomplished with such processes, partly due to the randomness inherent to the assembly process.

We have shown how microfabricated tweezers are capable of picking up silicon nanowires and demonstrated that electron beam deposition is a versatile *in situ* method for making strong connections between nanostructures and microelectrodes. The proposed scheme is similar to automated pick-and-place of macroscopic electronic components onto printed circuit boards, only in this case the objects are 10000 times smaller. For large-scale production of nanotube/nanowire-based devices, self-assembly methods in principle offer a much higher throughput than the nanoscale pick-and-place. Provided that precise control of the positioning of the components can be obtained, such methods would be of great importance for nanocomponent production. We believe electron beam-assisted pick-and-place assembly could become a routine method available for a range of nanotechnology research and prototyping applications.

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References and Notes

1. M. R. Falvo, J. Steele, R. M. Taylor, and R. Superfine, *Phys. Rev. B* 62, R10665 (**2000**).
2. M. R. Falvo, G. T. Clary, R. M. Taylor, V. Chi, F. P. Brooks, S. Washburn, and R. Superfine, *Nature* 389, 582 (**1997**).
3. P. Avouris, T. Hertel, R. Martel, T. Schmidt, H. R. Shea, and R. E. Walkup, *Appl. Surf. Sci.* 141, 201 (**1999**).
4. C. Thelander, M. H. Magnusson, K. Deppert, L. Samuelson, P. R. Poulsen, J. Nygard, and J. Borggreen, *Appl. Phys. Lett.* 79, 2106 (**2001**).
5. J. Nygard and D. H., Cobden, *Appl. Phys. Lett.* 79, 4216 (**2001**).
6. Y. G. Zhang, A. L. Chang, J. Cao, Q. Wang, W. Kim, Y. M. Li, N. Morris, E. Yenilmez, J. Kong, and H. J., Dai, *Appl. Phys. Lett.* 79, 3155 (**2001**).
7. H. J. Dai, J. Kong, C. W. Zhou, N. Franklin, T. Tombler, A. Cassell, S. S. Fan, and M. Chapline, *J. Phys. Chem. B* 103, 11246 (**1999**).
8. Y. Huang, X. F. Duan, Q. Q. Wei, and C. M. Lieber, *Science* 291, 630 (**2001**).
9. M. F. Yu, M. J. Dyer, G. D. Skidmore, H. W. Rohrs, X. K. Lu, K. D. Ausman, J. R. Von Ehr, and R. S. Ruoff, *Nanotechnology* 10, 244 (**1999**).
10. W. S. Yun, J. Kim, K. H. Park, J. S. Ha, Y. J. Ko, K. Park, S. K. Kim, Y. J. Doh, H. J. Lee, J. P. Salvetat, and L. Forro, *J. Vac. Sci. Technol. A* 18, 1329 (**2000**).
11. P. Kim and C. M. Lieber, *Science* 286, 2148 (**1999**).
12. P. Boggild, T. M. Hansen, C. Tanasa, and F. Grey, *Nanotechnology* 12, 331 (**2001**).
13. S. Akita, Y. Nakayama, S. Mizooka, Y. Takano, T. Okawa, Y. Miyatake, S. Yamanaka, M. Tsuji, and T. Nosaka, *Appl. Phys. Lett.* 79, 1691 (**2001**).
14. P. A. Williams, S. J. Papadakis, M. R. Falvo, A. M. Patel, M. Sinclair, A. Seeger, A. Helser, R. M. Taylor, S. Washburn, and R. Superfine *Appl. Phys. Lett.* 80, 2574 (**2002**).
15. L. Dong, F. Arai, and T. Fukuda, in *IEEE-NANO 2001. Proceedings of the 1st IEEE Conference on Nanotechnology, 2001*, Maui, IEEE 93-98 (**2001**).
16. H. W. P. Koops, J. Kretz, M. Rudolph, and M. Weber, *J. Vac. Sci. Technol. B* 11, 2386 (**1993**).
17. D. N. Madsen, K. Mølhave, R. Mateiu, A. M. Rasmussen, M. Brorson, C. H. J. Jacobsen, and P. Boggild, *NanoLetters* 3, 47 (**2003**).
18. C. L. Petersen, T. M. Hansen, P. Boggild, A. Boisen, O. Hansen, T. Hassenkam, and F. Grey, *Sens. Actuator Phys.* 96, 53 (**2002**).

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