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Nanotube Boiler: Attogram Copper Evaporation Driven by Electric Current, Joule Heating, Charge, and Ionization

Lixin Dong, *Member, IEEE,* Xinyong Tao, Mustapha Hamdi, *Member, IEEE,* Li Zhang, Xiaobin Zhang,
Antoine Ferreira, *Member, IEEE,* Bradley J. Nelson, *Senior Member, IEEE*

Abstract— **Controlled copper evaporation at attogram level from individual carbon nanotube (CNT) vessels, which we call nanotube boilers, is investigated experimentally and theoretically. We compared the evaporation modes induced by electric current, Joule heating, charge, and ionization in these CNT boilers, which can serve as sources for mass transport and deposition in nanofluidic systems. Experiments and molecular dynamics simulations show that the most effective method for evaporation is by positively ionizing the encapsulated copper, therefore, an electrostatic field can be used to guide the flow.**

***Index Terms*— Carbon nanotube, transmission electron microscope, nanofluidics, nanoboiler, nanorobotic manipulation**

I. INTRODUCTION

CONTROLLED melting and flowing of mass within and between nanochannels is of great interest both fundamentally and from an application perspective[1-8]. We report an experimental and theoretical investigation into attogram copper evaporation from individual carbon nanotubes (CNTs), which is motivated by the need to understand the mechanism of this phenomenon. Copper has played a significant role in the history of civilization. In modern semiconductor industry, copper is increasingly replacing aluminum because of its superior electrical conductivity. Growing interest in using it as electrodes and functional elements for the next generation of integrated circuits has been stimulated by the discovery of CNTs, nanowires, and other building blocks, and enabled by bottom-up nanotechnologies such as self-assembly [9], robotic assembly [10], and welding [6, 11]. With the possibility of delivering attogram copper from conduits [6, 7], copper-filled CNTs [12] are an ideal combination for self-welding of self-assembled nanotubes [9] onto electrodes, among other potential nanofluidic applications [13-15].

Previous experimental investigations of controlled melting and flowing of single crystalline copper from individual CNTs [6, 7] have shown that very low current induces melting and drives the flow, which is much more efficient than irradiation-based techniques involving high energy electron beams[16-19], focused-ion beams (FIB) [20], or lasers[14]. Furthermore, conservation of the material is facilitated by its encapsulation as opposed to conveying mass on the external surface of nanotubes [21]. Because both the rate and direction of mass transport depend on the external electrical drive, precise control and delivery of minute amounts of material is possible. However, due to the coupling of the electronic and thermal effects, the mechanisms have not been well understood.

II. SYSTEM SETUP

To understand the mechanisms induced by various physical effects, experimental investigations have been done using the setup shown in Fig. 1, where two Cu-filled CNTs supported on a common sample holder and a probe provide four different experimental modes: (1) The upper section of the left nanotube, $CNT_{1,A}$, has electric current passing through and accordingly Joule heating will occur. (2) The lower section of the left nanotube, $CNT_{1,B}$, has no current and will experience only thermal transport. In (3) and (4), the right tube, CNT_2, has no electric current but can be either negatively charged or

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L. X. Dong, L. Zhang, and B. J. Nelson are with the Institute of Robotics and Intelligent Systems, ETH Zurich, 8092 Zurich, Switzerland (phone: +41-44-632-2539; fax: +41-44-632-1078; e-mail: ldong@ethz.ch). L.X. Dong is currently with the Department of Electrical & Computer Engineering, Michigan State University, East Lansing, MI 48824-1226, U.S.A.

X.Y. Tao is with the College of Chemical Engineering and Materials Science, Zhejiang University of Technology, Hangzhou 310032, China, and was with the Department of Materials Science and Engineering, Zhejiang University, Hangzhou 310027, China.

X.B. Zhang is with Department of Materials Science and Engineering, Zhejiang University, Hangzhou 310027, China.

M. Hamdi and A. Ferreira are with the Institut PRISME, ENSI Bourges, 88 Boulevard Lahitolle, 18000 Bourges, France.

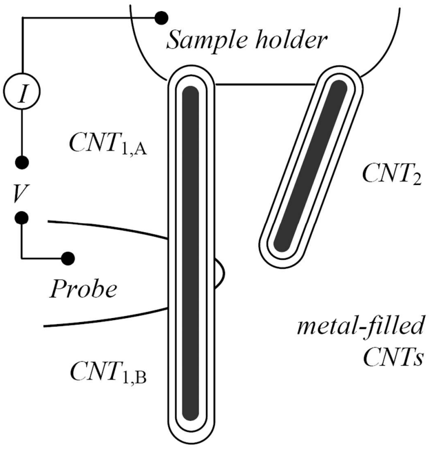

Fig. 1. Schematic setup of a nanotube boiler. Two Cu-filled CNTs supported on a sample holder and a probe provide three different cases to investigate, $CNT_{1,A}$, $CNT_{1,B}$, and CNT_2, subjected to electric current, thermal transport, and charges, respectively.

positively ionized. Thermal transport also occurs from the common sample holder, but not as directly as $CNT_{1,B}$ due to CNTs superior heat conduction ability (Thermal conductivity: 3320 W/m·K; c.f. Ag: 429 W/m·K, Cu: 386 W/m·K, Au: 318 W/m·K) [22].

The samples we use are Cu-filled CNTs. As described elsewhere, the Cu-tipped CNT samples are synthesized using an alkali doped Cu catalyst by a thermal chemical vapor deposition (CVD) method [12]. The CNTs are up to 5 μm long with outer diameters in a range of 40–80 nm. The single crystalline Cu nanoneedles are encapsulated in graphite walls approximately 4 to 6 nm thick at the tips of CNTs. The graphite layers are not parallel to the tube axis.

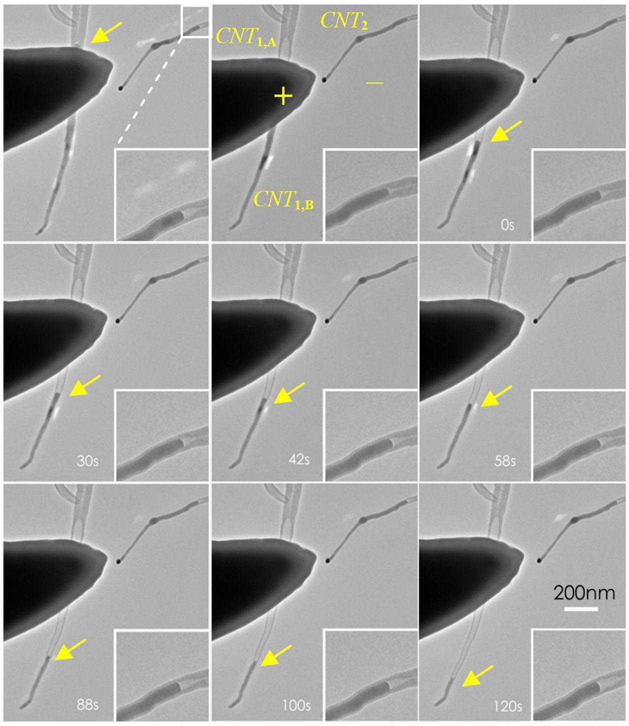

Fig. 2. Electric current and Joule heating driven Cu evaporation. A series of TEM images recorded the transport of Cu inside two single CNTs when the probe is positively biased (7V). It can be seen that the length of the copper core inside the CNT on the left side continuously decreases.

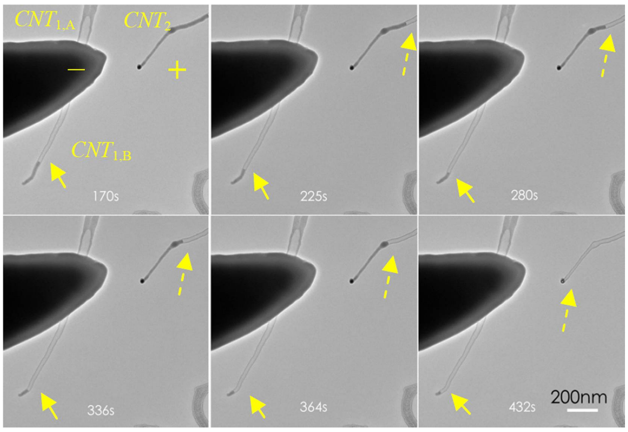

Fig. 3. Thermal transport and positive charges induced Cu evaporation. A series of TEM images recorded the transport of Cu inside two single CNTs when the probe is negatively biased (-3.5V). It can be seen that the length of the copper core inside the CNT on the left side also continuously decreases.

III. EXPERIMENTS

Our experiments were performed in a Philips CM30 transmission electron microscope (TEM) equipped with a scanning tunneling microscope (STM) built in a TEM holder (Nanofactory Instruments AB, ST-1000) serving as a manipulator [2, 6, 23]. The material consisting of a CNT bundle is attached to a 0.35mm thick Au wire using silver paint, and the wire is held in the sample holder (Fig. 1). An etched 10 μm thick tungsten wire with a tip radius of approximately 100nm (Picoprobe, T-4-10-1mm) is used as the probe. The probe can be positioned in a millimeter-scale workspace with sub-nanometer resolution with the STM unit actuated by a three-degree-of-freedom piezo-tube, making it possible to select a specific CNT and pick it up. Physical contact can be made between the probe and the tip of a nanotube or between two nanotubes. Applying a voltage between the probe and the sample holder establishes an electrical circuit through a CNT and injects thermal energy into the system via Joule heating. By increasing the applied voltage, the local temperature can be increased past the melting point of the material encapsulated in a tube. The process is recorded by TEM images, a multimeter, and a nA meter. The acceleration voltage used in all experiments was 300kV, the spot size of the electron beam was 100 nm, and the beam current density is in the range of regular imaging, i.e., about 1-2 A/cm^2. This ensured that the beam does not have obvious influence on the evaporation.

Figure 2 includes a series of TEM images recording the evaporation of Cu driven by current and Joule heating inside two single CNTs when the probe is positively biased (7V). Both of the CNTs have caps on their two ends. It can be seen that the

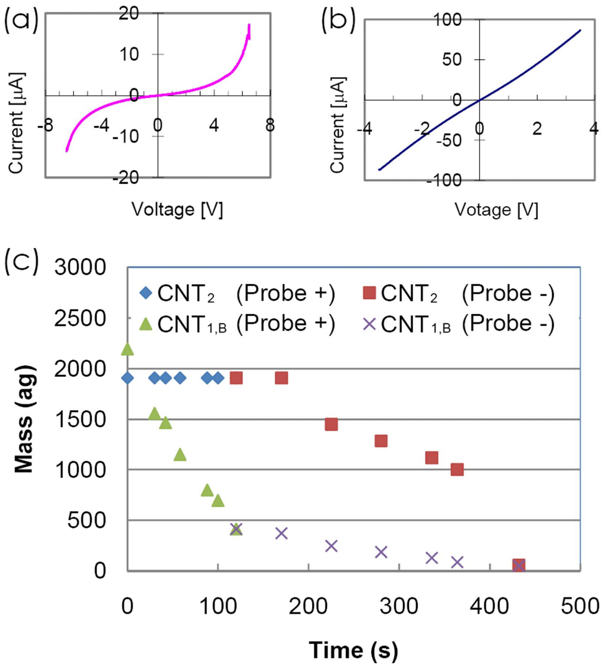

Fig. 4. (a) and (b) are I-V curves before the threshold on positive and negative biases is reached. It can be seen by comparing (a) and (b) that conductance improved after copper transport (the minimum resistance changed from (a) 377 kΩ to (b) 40 kΩ). (c) Mass evaporation rate.

length of the copper core inside the CNT on the left side (both $CNT_{1,A}$ and $CNT_{1,B}$) decreases continuously. Figure 3 is a series of TEM images recording the transport of Cu inside two single CNTs when the probe is negatively biased (-3.5V). It can be seen that the length of the copper core inside the CNT on the left side ($CNT_{1,B}$) also decreases continuously. Because the copper core is not between the electrodes, the polarity of the electrodes does not matter, copper will transport towards one of them.

Surprisingly, it can be seen from Fig. 3 that the length of the copper core inside the CNT on the right side (CNT_2) also decreases continuously until almost all copper disappears. A closer inspection of the insets of Fig. 2 reveals the same phenomena occurred when the probe is positively biased. This implies the possibility that charge induced transport is more significant than current-induced Joule heating and thermal transport. The obvious difference of the evaporation rate for Cu inside CNT_2 suggests that as the Cu is positively ionized (Fig. 3), the repulsive forces between Cu ions are larger than negatively charged case (Fig. 2).

Figure 4(a) and (b) are I-V curves before the positive and negative threshold biases are reached. It can be seen by comparing Fig. 4(a) and (b) that the conductance improved after the copper was transported (the minimum resistance changed from Fig. 4(a) 377 kΩ to Fig. 4(b) 40 kΩ). This suggests copper deposited on the probe in the case of Fig. 4(a) changed the contact from a Schottky-type to Ohmic. The decrease of resistance from 477 kΩ (-6.5 V) to 377 kΩ (6.5 V) in the case of Fig. 4(a) indicates the transport/deposition on the probe occurred during the bias sweeps from -6.5 V to 6.5V.

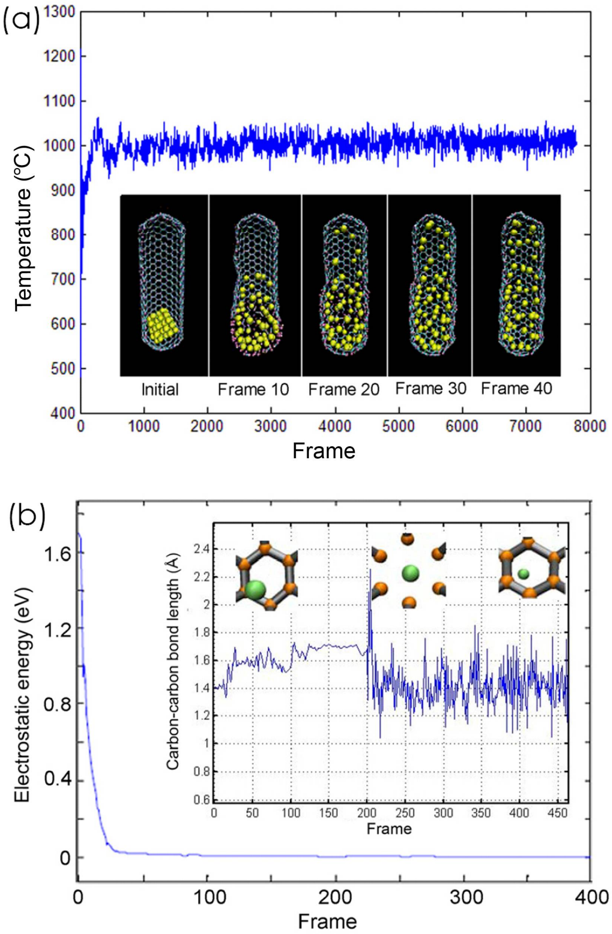

Fig. 5. Molecular dynamics simulation of Joule-heating and ionization-induced. (a) Evaporation induced by Joule-heating. The diffusion of copper atoms inside the carbon shells can obviously be seen from the inset including the initial configuration and frames 10, 20, 30, and 40. (b) The electrostatic repulsive energy between copper ions. The inset shows carbon-carbon bond length during copper diffusion. At frame 200 the copper ions pass through the hexagonal rings, which correspond to the maximum opening of the carbon rings.

Figure 4(c) indicates the estimated mass evaporation rate according to the apparent geometries shown in Figs. 1 and 2 and the density of copper (8.92 g/cm^3). Using linear fitting, the average mass evaporation rate has been found to be 14.3 ag/s and 1.2 ag/s for $CNT_{1,B}$ as the probe is positively (Fig. 2) and negatively (Fig. 3) biased, respectively. The difference (approximately 12 times) between the rates of $CNT_{1,B}$ is due to the competition between electrostatic forces and Joule heating induced evaporation. The latter is mainly caused by the different absolute values of the bias V (7V and -3.5V) and the resistance R (377 kΩ to 40 kΩ). Considering that thermal power scales with V^2/R, the bias differences translate into a factor of 2.4, but the evaporation rate as the probe is negatively biased should be larger. This is contrary to the experimental observation. Hence, it can be concluded that electrostatic forces dominate evaporation. The growing distance from the heated section also has contribution but less due to the excellent thermal conductivity of CNTs.

Similarly, using linear fitting, the average mass evaporation rate has been found to be 0.1 ag/s and 6.1 ag/s for CNT_2 as the probe is positively (Fig. 2) and negatively biased (Fig. 3), respectively. This suggests that when Cu is ionized, the repulsive interaction between Cu^+ is much larger than electron charges.

IV. SIMULATIONS

Using molecular dynamics simulation (MDS), we numerically investigated pure Joule-heating and ionization-induced Cu evaporation (Fig. 5). The potential energy of a CNT with a cluster of Cu inside was minimized at an internal pressure of 1 atm using the conjugate gradient method. To investigate copper diffusion, the system was simulated at temperatures between 700K and 1800K using molecular dynamics. Figure 5 (a) shows the system temperature during evaporation induced by Joule-heating when the carbon shells are electrically neutral. The diffusion of copper atoms inside the carbon shells can obviously be seen from the inset including the initial configuration and frames 10, 20, 30, and 40. An analysis of the repulsive electrostatic energy between copper ions is given in Fig. 5(b). It can be seen that a peak temperature was reached at frame 200. Accordingly, as shown in the inset, the carbon-carbon bond length obtained a maximum value at frame 200. The simulation indicates that electrostatic energy is responsible for heating, and that the repulsive charges increase the distances between copper ions and induce their diffusion with higher energy. It can be seen from the inset of Fig. 5(b) that with a large enough charge, copper ions can pass through the walls of CNTs without necessarily breaking the bonds. Images clearly show that the hexagon carbon rings stretch during diffusion.

V. SUMMARY

In summary, we have reported an experimental and theoretical investigation into attogram copper evaporation from individual CNTs for four modes induced by electric current, Joule heating, charges, and ionization. The experimental setup allowed the decoupling of the modes from each other. Experiments and molecular dynamics simulations have shown that the most effective way for evaporation is by positively ionizing the encapsulated copper, which indicate that the repulsive electrostatic energy between copper ions dominate thermal energy. The proposed CNT boilers can serve as sources for mass transport and deposition in nanofluidic systems using electrostatic fields to guide the flow.

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REFERENCES

[1] Y. H. Gao and Y. Bando, "Carbon nanothermometer containing gallium - Gallium's macroscopic properties are retained on a miniature scale in this nanodevice," *Nature,* vol. 415, pp. 599-599, Feb 2002.

[2] K. Svensson, H. Olin, and E. Olsson, "Nanopipettes for metal transport," *Physical Review Letters,* vol. 93, art. no. 145901, Oct 2004.

[3] A. K. Schaper, F. Phillipp, and H. Q. Hou, "Melting behavior of copper nanocrystals encapsulated in onion-like carbon cages," *Journal of Materials Research,* vol. 20, pp. 1844-1850, Jul 2005.

[4] L. Sun, F. Banhart, A. V. Krasheninnikov, J. A. Rodriguez-Manzo, M. Terrones, and P. M. Ajayan, "Carbon nanotubes as high-pressure cylinders and nanoextruders," *Science,* vol. 312, pp. 1199-1202, May 2006.

[5] M. Majumder, N. Chopra, R. Andrews, and B. J. Hinds, "Nanoscale hydrodynamics - Enhanced flow in carbon nanotubes," *Nature,* vol. 438, pp. 44-44, Nov 2005.

[6] L. X. Dong, X. Y. Tao, L. Zhang, X. B. Zhang, and B. J. Nelson, "Nanorobotic spot welding: Controlled metal deposition with attogram precision from copper-filled carbon nanotubes," *Nano Letters,* vol. 7, pp. 58-63, Jan 2007.

[7] D. Golberg, P. Costa, M. Mitome, S. Hampel, D. Haase, C. Mueller, A. Leonhardt, and Y. Bando, "Copper-filled carbon nanotubes: Rheostatlike Behavior and femtogram copper mass transport," *Advanced Materials,* vol. 19, pp. 1937-1942, Aug 2007.

[8] P. M. F. J. Costa, D. Golberg, M. Mitome, S. Hampel, A. Leonhardt, B. Buchner, and Y. Bando, "Stepwise current-driven release of attogram quantities of copper iodide encapsulated in carbon nanotubes," *Nano Letters,* vol. 8, pp. 3120-3125, Oct 2008.

[9] A. Subramanian, L. X. Dong, J. Tharian, U. Sennhauser, and B. J. Nelson, "Batch fabrication of carbon nanotube bearings," *Nanotechnology,* vol. 18, art. no. 075703, Feb 2007.

[10] L. X. Dong, A. Subramanian, and B. J. Nelson, "Carbon nanotubes for nanorobotics," *Nano Today,* vol. 2, pp. 12-21, Dec 2007.

[11] H. Hirayama, Y. Kawamoto, Y. Ohshima, and K. Takayanagi, "Nanospot welding of carbon nanotubes," *Applied Physics Letters,* vol. 79, pp. 1169-1171, Aug 2001.

[12] X. Y. Tao, X. B. Zhang, J. P. Cheng, Z. Q. Luo, S. M. Zhou, and F. Liu, "Thermal CVD synthesis of carbon nanotubes filled with single-crystalline Cu nanoneedles at tips," *Diamond and Related Materials,* vol. 15, pp. 1271-1275, Sep 2006.

[13] S. Supple and N. Quirke, "Rapid imbibition of fluids in carbon nanotubes," *Physical Review Letters,* vol. 90, art. no. 214501, May 2003.

[14] P. Kral and D. Tomanek, "Laser-driven atomic pump," *Physical Review Letters,* vol. 82, pp. 5373-5376, 1999.

[15] M. Whitby and N. Quirke, "Fluid flow in carbon nanotubes and nanopipes," *Nature Nanotechnology,* vol. 2, pp. 87-94, Feb 2007.

[16] L. X. Dong, F. Arai, and T. Fukuda, "Electron-beam-induced Deposition with Carbon Nanotube Emitters," *Applied Physics Letters,* vol. 81, pp. 1919-1921, Sep 2002.

[17] T. Yokota, M. Murayama, and J. M. Howe, "In situ transmission-electron-microscopy investigation of melting in submicron Al-Si alloy particles under electron-beam irradiation," *Physical Review Letters,* vol. 91, art. no. 265504, Dec 2003.

[18] S. Y. Xu, M. L. Tian, J. G. Wang, H. Xu, J. M. Redwing, and M. H. W. Chan, "Nanometer-scale modification and welding of silicon and metallic nanowires with a high-intensity electron beam," *Small,* vol. 1, pp. 1221-1229, Dec 2005.

[19] G. Q. Xie, M. H. Song, K. Furuya, D. V. Louzguine, and A. Inoue, "Compound nanostructures formed by metal nanoparticles dispersed on nanodendrites grown on insulator substrates," *Applied Physics Letters,* vol. 88, p. 263120, Jun 2006.

[20] R. Kometani, K. Kanda, Y. Haruyama, T. Kaito, and S. Matsui, "Evaluation of field electron emitter fabricated using focused-ion-beam chemical vapor deposition," *Japanese Journal of Applied Physics Part 2-Letters & Express Letters,* vol. 45, pp. L711-L713, Jul 2006.

[21] B. C. Regan, S. Aloni, R. O. Ritchie, U. Dahmen, and A. Zettl, "Carbon nanotubes as nanoscale mass conveyors," *Nature,* vol. 428, pp. 924-927, Apr 2004.

[22] P. G. Collins and P. Avouris, "Nanotubes for electronics," *Scientific American,* vol. 283, pp. 62-69, Dec 2000.

[23] L. X. Dong, K. Y. Shou, D. R. Frutiger, A. Subramanian, L. Zhang, B. J. Nelson, X. Y. Tao, and X. B. Zhang, "Engineering multiwalled carbon nanotubes inside a transmission electron microscope using nanorobotic manipulation," *IEEE Transactions on Nanotechnology,* vol. 7, pp. 508-517, Jul 2008.

Lixin Dong (S'01–M'03) received the B.S. and M.S. degrees in mechanical engineering from Xi'an University of Technology (XUT), Xi'an, China, in 1989 and 1992, respectively, and the Ph.D. degree in micro systems engineering from Nagoya University, Nagoya, Japan, in 2003.

He became a Research Associate in 1992, a Lecturer in 1995, and an Associate Professor in 1998 at XUT. In 2003, he became an Assistant Professor at Nagoya University. In 2004, he joined the Swiss Federal Institute of Technology (ETH) Zurich, Zurich, Switzerland, as a Research Scientist, and became a Senior Research Scientist in 2005, and led the NanoRobotics Group, Institute of Robotics and Intelligent Systems (IRIS), ETH Zurich. He joined Michigan State University as an Assistant Professor in December 2008. His current research interests include nanorobotics, nanoelectromechnical systems (NEMS), mechatronics, mechnochemistry, and nanobiomedical devices.

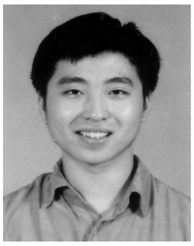
Dr. Dong is an Associate Editor of the IEEE TRANSACTIONS ON NANOTECHNOLOGY and the IEEE TRANSACTIONS ON AUTOMATION SCIENCE AND ENGINEERING. He received the IEEE Transactions On Automation Science And Engineering (T-ASE) Googol Best New Application Paper Award in 2007, the Best Conference Paper Award at the International Conference on Computer Science and Education (ICCSE) 2003, and has been a finalist for the Best Paper Awards at the IEEE International Conference on Robotics and Automation (ICRA) 2007, the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2005, and ICRA 2001. He has been awarded the Science and Technology Advancement Prize by the Ministry of Education of China in 1999, by the Shaanxi Province Government in 1995 and 1999, by Xi'an City Government in 1999, and by the Ministry of Machine-Building Industry of China in 1998 and 1992.

Xinyong Tao received the Ph.D. Degree in materials physics and chemistry from Zhejiang University, Hangzhou, China, in 2007. He was a postdoctoral fellow in Department of Mechanical Engineering, University of South Carolina, Columbia, USA.

He is currently an Assistant Professor of College of Chemical Engineering and Materials Science, Zhejiang University of Technology. His research interests include nanoindentation, nanocomposite, carbon nanomaterials, and boron nanomaterials.

Mustapha Hamdi (M'06) received the Ph.D. Degree in Bio-nanorobotics design and characterization from university of Orleans, France, in 2009. He is currently associate researcher in ENSI of Bourges, in 2009. His research activities include multiscale design and modeling of bio-nanodevices, finite element modeling of nano-conveyer for drug delivery.

He is an author of 20 journal and conference papers. He is IEEE member since 2006.



Li Zhang received the B.S. degree from the Department of Materials Science and Engineering, Zhejiang University, Hangzhou, China, in 2000, and the M.S. degree from the Department of Materials Science and Engineering, Christian Albrechts University, Kiel, Germany, in 2002, and the Ph.D. degree from the University of Basel, Basel, Switzerland, in 2007.

From 2002 to 2006, he was with the Laboratory for Micro- and Nanotechnology, Paul Scherrer Institute, and also with the Department of Physics, University of Basel. He is currently a Postdoctoral Researcher at the Institute of Robotics and Intelligent Systems, Swiss Federal Institute of Technology (ETH) Zurich, Zurich, Switzerland. His current research interests include thin-film technology, micro-/nanofabrication, nanorobotic manipulation, and microelectromechanical systems (MEMS)/nanoelectromechanical systems (NEMS).

Dr. Zhang received the Chinese Government Award for Outstanding Self-financed Students Abroad in 2005 and the Best Automation Paper Award—Finalist at the 2007 IEEE International Conference on Robotics and Automation (ICRA 2007).

Xiaobin Zhang received the B.A. degree in electrical engineering from Zhejiang University, Hangzhou, China, in 1970, and the Ph.D. degree in physics from the University of Antwerp, Belgium, in 1994.

In 1980, he joined the Department of Materials Science and Engineering, Zhejiang University, where, from 1999 to 2006, he was the Deputy Director of the Institute of Materials Physics and Microstructure, and is currently a Professor. His current research interests include synthesis and applications of nanomaterials such as carbon nanotubes.

Dr. Zhang was Deputy Director of the Institute of Materials Physics and Microstructure at Zhejiang University from 1999 to 2006. Currently, he is President of the Electromicroscopy (EM) Society of Zhejiang Province, China.

Antoine Ferreira (M'00) received the MS and the PhD in Electrical and Electronics Engineering from the University of Franche-Comté (France) in 1993, 1996 respectively. In 1997 he was a Visiting Researcher at the ElectroTechnical Laboratory (ETL), in Tsukuba (Japan). In 2007, he became professor of Robotics Engineering at the Institut PRISME, Ecole Nationale Supérieure d'Ingénieurs de Bourges (France).

His main research interests are focused on the design, modeling and control of micro and nanorobotic systems using active materials, micro-nano-manipulation systems, biological nanosystems, bio-nanorobotics.

He served as Guest Editor for different focused sections of the International Journal of Robotics Research, IEEE/ASME TRANSACTIONS ON MECHATRONICS, and Nanotechnology Magazine. He has co-chaired several international IEEE workshops and conferences, and is serving as the head of the International Research Cooperation at ENSI Bourges. He is an author of more than 100 journal and conference papers and book contributions.

Bradley J. Nelson (M'90–SM'06) received the B.S. in mechanical engineering from the University of Illinois, Urbana-Champaign, in 1984, the M.S. degree in mechanical engineering from the University of Minnesota, Minneapolis, in 1987, and the Ph.D. degree in robotics from the School of Computer Science, Carnegie Mellon University, Pittsburgh, PA, in 1995. He worked as an engineer at Honeywell and Motorola, and served as a United States Peace Corps Volunteer in Botswana, Africa. In 1995, he became Assistant Professor at the University of Illinois at Chicago, Associate Professor at the University of Minnesota in 1998, and Professor at ETH Zurich in 2002.

His current research interest includes extending robotics research into emerging areas of science and engineering. His most recent scientific contributions have been in the area of microrobotics, biomicrorobotics, and nanorobotics, including efforts in robotic micromanipulation, microassembly, MEMS (sensors and actuators), mechanical manipulation of biological cells and tissue, and nanoelectromechanical systems (NEMS). He has also contributed to the fields of visual servoing, force control, sensor integration, and Web-based control and programming of robots.

Prof. Nelson has been awarded a McKnight Land-Grant Professorship and is a recipient of the Office of Naval Research Young Investigator Award, the National Science Foundation Faculty Early Career Development (CAREER) Award, the McKnight Presidential Fellows Award, and the Bronze Tablet. He was elected as a

Robotics and Automation Society Distinguished Lecturer in 2003 and won Best Paper Awards at major robotics conferences and journals in 2004, 2005, 2006, and 2007. He was named to the 2005 “Scientific American 50,” Scientific American magazine’s annual list recognizing fifty outstanding acts of leadership in science and technology from the past year for his efforts in nanotube manufacturing. His laboratory won the 2007 RoboCup Nanogram Competition, the first year the event was held. He serves on or has been a member of the editorial boards of the IEEE TRANSACTIONS ON ROBOTICS, the IEEE TRANSACTIONS ON NANOTECHNOLOGY, the Journal of Micromechatronics, the Journal of Optomechatronics, and the IEEE ROBOTICS AND AUTOMATION MAGAZINE. He has chaired several international workshops and conferences, has served as the head of the Department of Mechanical and Process Engineering from 2005–2007, and is currently the Chairman of the Board of Directors of the ETH Electron Microscopy Center (EMEZ).