Trapping and Rotation of Nanowires Assisted by Surface Plasmons

Xiaoyu Miao, *Student Member, IEEE*, Benjamin K. Wilson, Guozhong Cao, Suzie H. Pun, and Lih Y. Lin, *Senior Member, IEEE*

Abstract—We report long-range trapping of vanadium dioxide (VO$_2$) and vanadium oxyhydroxide (H$_2$V$_3$O$_8$) nanowires at a distance as large as 50 μm outside the laser spot using plasmonic tweezers and controlled rotation of the nanowires by combining trapping with microfluidic drag force. The plasmonic tweezers are built upon a self-assembled gold nanoparticle array platform. In addition to the long-range trapping and rotation capability, the required optical intensity for the plasmonic tweezers to initiate trapping is much lower ($<8\ \mu$W/μm^2) than that required by conventional optical tweezers for similar nanowires. We also investigate possible mechanisms for the unique long-range trapping of nanowires through performing control experiments.

Index Terms—Nanostructures, optical manipulation, surface plasmons.

I. INTRODUCTION

THE INCEPTION of optical tweezers [1]–[3] marked a new era for trapping and manipulating micrometer and submicromete-sized particles using focused laser beams. While direct conversion from optical energy to mechanical energy is often an inefficient process and optical tweezers require a tightly focused intense laser beam to achieve significant amount of optical force, the enhancement of an electric field close to a metal nanostructure through localized surface plasmon resonance (LSPR) induced by light has been investigated to increase the optical-to-mechanical energy conversion efficiency [4], [5]. Recently, it has been theoretically predicted and experimentally demonstrated that optical trapping and manipulation technology with surface plasmons is able to relax the requirement on incident laser focusing and intensity, with subdiffraction-limited trapping volume defined by the metal nanostructure [6]–[8]. Parallel and selective trapping of micrometer-sized dielectric beads have been realized using engineering plasmonic patterns [9], [10]. More recently, nanometric optical tweezers that are able to trap a 200-nm dielectric bead have been demonstrated by utilizing optical near-fields between gold nanodots fabricated by electron beam lithography [11]. Furthermore, the plasmonic approach has been used to trap biological entities [12] and has been proposed to manipulate (trap or repulse) metal nanoparticles [13]. Here, we report our recent study using the plasmonic approach to trap and manipulate 1-D nanostructures.

Manipulation and assembly of 1-D nanostructures such as nanowires and nanotubes have been investigated in great detail over the last decade for their potential use as building blocks of nanoscale electronic and optical devices. Current available technologies including dielectrophoresis [14], microfluidic transport [15], and Langmuir–Blodgett compression [16] are used to manipulate and assemble 1-D nanostructures in bulk but lack the capability to selectively manipulate individual nanostructures with high spatial and angular resolution. Recently, single-beam optical tweezers were utilized to trap and assemble individual semiconducting nanowires in water and physiological environments through the control of a tightly focused laser beam [17]. Furthermore, holographic optical tweezers [18] and optical line tweezers [19] were employed to enable translation and in-plane rotation control of individual nanowires by creating many independently controlled optical traps. However, the applications of optical tweezer-related techniques are limited by the required high optical intensity and small working area. Although the intensity requirement can be greatly reduced by combining optical tweezers with dielectrophoresis [20], [21], an electrical bias configuration is required that adds to system complexity. On the contrary, plasmonic manipulation technology is an all-optical approach that can be applied without requiring tight focus and high laser power.

In this paper, we demonstrate for the first time trapping of nanowires instigated at a distance from the low-intensity laser source assisted by surface plasmons. We also report the controlled rotation of nanowires. In Section II, we describe the details of the experiment including fabrication and characterization of plasmonic nanoparticle array, synthesis of 1-D nanostructures, as well as trapping and rotation experiment. In Section III, we discuss the underlying mechanism for the long-range trapping behavior through presenting further experimental results. The summary and future study are presented in the last section.

II. EXPERIMENTS AND RESULTS

The system under study is shown in Fig. 1. It consists of a gold nanoparticle array lying upon a glass coverslip. A low optical intensity laser light is used to excite the localized surface

X. Miao and B. K. Wilson are with the Department of Electrical Engineering, University of Washington, Seattle, WA 98195 USA (e-mail: xiaoyu.miao@gmail.com; bewilson@u.washington.edu).

G. Cao is with the Department of Material Science and Engineering, University of Washington, Seattle, WA 98195 USA (e-mail: gzcao@u.washington.edu).

S. H. Pun is with the Department of Bioengineering, University of Washington, Seattle, WA 98195 USA (e-mail: spun@u.washington.edu).

L. Y. Lin is with the Departments of Electrical Engineering and Physics, University of Washington, Seattle, WA 98195 USA (e-mail: lylin@washington.edu).
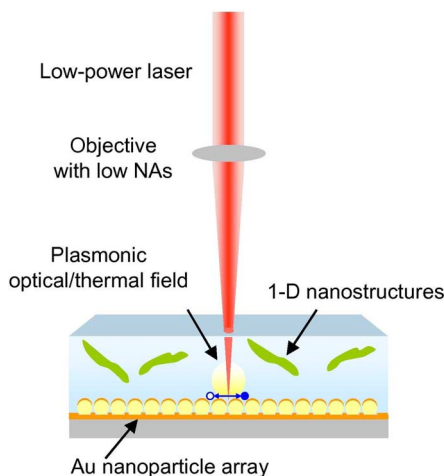
Fig. 1.   Schematic diagram of the experimental configuration for trapping and manipulation of 1-D nanostructures using the plasmonic approach.
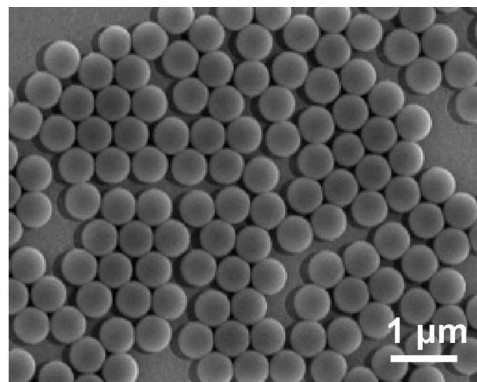

Fig. 2.   Scanning electron micrograph of the random gold nanoparticle array.

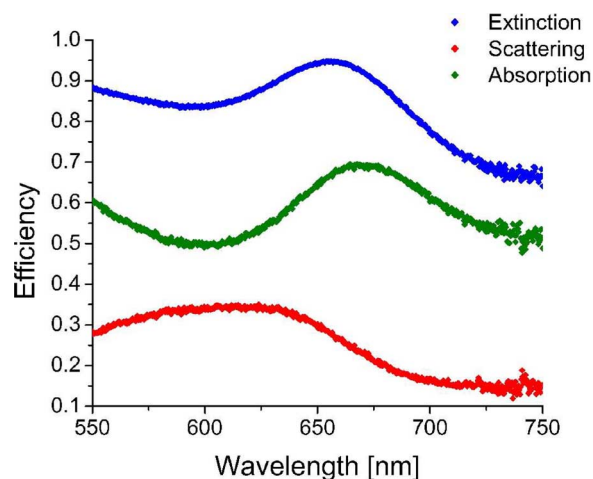Fig. 3.   Normalized extinction, scattering, and absorption efficiency spectrum of the random close-packed gold nanoparticle array.

plasmons on the gold nanoparticle array, which forms the enhanced plasmonic optical and thermal field that is induced by the radiative and nonradiative damping of localized surface plasmons, respectively. At the appropriate wavelength, the localized surface plasmons consist of oscillating electrons moving resonantly with the incident electromagnetic field. The 1-D nanostructures used for trapping experiment are suspended in the thin liquid layer that is placed above the gold nanoparticle array. The location and movement of 1-D nanostructures can be monitored by an optical microscope and recorded by a charge-coupled device (CCD) camera.

A. Fabrication of the Gold Nanoparticle Array

The gold nanoparticle array on the glass coverslip is fabricated by a chemical self-assembly approach using surface-adsorbed latex spheres (Polysciences, Inc.) with a mean diameter of 454 nm as a template. Gold is first evaporated on the glass coverslip to a thickness of 20 nm using chromium as the adhesion layer. The latex sphere monolayer is self-assembled by exposing the gold-coated substrate to a mixture of 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride (EDC), latex sphere suspension, and deionized water. The adsorption process is allowed to last for about one hour and the nonabsorbed spheres are washed away with a copious amount of water. Subsequently, the formed monolayer is dried in the air. Finally, another 20 nm of gold is evaporated on the latex sphere monolayer to form the core/shell-structured gold nanoparticle array. Fig. 2 shows the scanning electron micrograph of the gold nanoparticle array, which is random and has a close-packed configuration.

B. Scattering and Absorption Characterization

The localized surface plasmon resonance of the gold nanoparticle array is presented by the enhanced scattering and absorption cross sections macroscopically, which are attributed to the radiative and nonradiative damping of localized surface plasmons, respectively. The characterization setup for the scattering and extinction spectra of the gold nanoparticle array is built

upon the same microscope for the trapping experiment. The gold nanoparticle array is placed on the specimen plane of the microscope and focused under a $50\times$ objective lens by adjusting the stage height. A broadband white light source is used for excitation purpose. The scattered light from gold nanoparticle array is collected in dark-field configuration by the objective lens and sent to a UV/VIS spectrometer (OSM100, Newport) through a multimode fiber. The extinction spectrum is measured in a similar way but in the bright-field configuration by subtracting the spectrum of reflection light from the spectrum of incident light. Furthermore, the absorption information of the gold nanoparticle array can be obtained by subtracting the scattering from the total extinction. These spectra are shown in Fig. 3, where the efficiency on Y-axis represents the percentage of incident light scattered or absorbed by the gold nanoparticle array.

C. Synthesis of 1-D Nanostructures

The 1-D nanostructures used in our experiment include vanadium dioxide (VO_2) nanowires, vanadium oxyhydroxide ($H_2V_3O_8$) nanowires, and titanium dioxide (TiO_2) nanotubes. These metal oxide nanostructures are at the center of many emerging applications such as nanophotonics (ultrafast optical shutter [22]) and nanoelectronics (nanoscale FET [23]). These
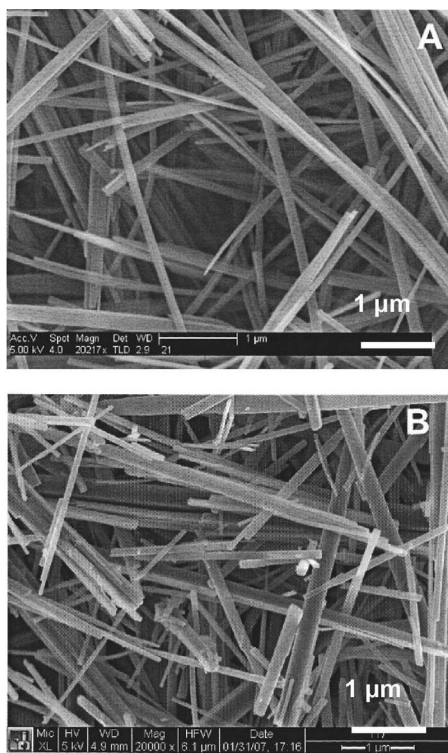
Fig. 4. Scanning electron micrograph of $H_2V_3O_8$ nanowires (a) and VO_2 nanowires (b) in the ensemble.

Fig. 5. Long-range trapping of an individual $H_2V_3O_8$ nanowire. The two ends of the nanowire are marked by the crosses (+). The background is due to scattering from the gold nanoparticle array under the optical microscope. A short-pass filter is mounted in front of the charrge-coupled CCD camera to partially block the HeNe laser light, which results in an overall green color of the images. The time interval between the snapshots is 3 seconds.

metal oxide nanostructures usually have high polarizabilities and extinction cross sections.

In our experiment, the VO_2 nanowires are synthesized using a hydrothermal method at $220\,°C$ for 48 hours from an aqueous colloidal dispersion consisting of amorphous precipitate of VO_2^+ from hydrazine-containing aqueous solution [24]. When the vanadium concentration is kept below 0.1 M with a pH below 4, $H_2V_3O_8$ nanowires form [25]. TiO_2 crystals are grown hydrothermally from a mixture of TiO_2 powder dispersed in an aqueous NaOH solution at $110\,°C$ for 24 hours [26]. The scanning electron micrograph of the VO_2 and $H_2V_3O_8$ nanowires are shown in Fig. 4(a) and (b), where the $H_2V_3O_8$ nanowire has a length $\sim50\ \mu m$ and a diameter ~200 nm; the VO_2 nanowire has a length $\sim20\ \mu m$ and a diameter ~200 nm.

D. Trapping and Rotation of Individual Nanowires

An HeNe laser beam ($\lambda = 633$ nm) is directed into the optical path of an upright microscope (Zeiss Axio Imager) and focused onto the sample plane right above the gold nanoparticle array on a motorized stage by a $20\times$ objective lens (numerical aperture $= 0.22$). The HeNe laser has a full power of 25 mW at the output, much lower than the typical full power ($1\sim10$ W) of the laser used in conventional single-beam optical traps. With the low-NA lens, the focused laser spot size is about $20\ \mu m$, which is much larger than the diffraction limit ($\sim1\ \mu m$) required for conventional single-beam optical traps. Overall, the optical intensity measured at the sample plane for the plasmonic tweezers is several orders of magnitude lower than the minimum requirement for conventional single-beam optical traps.
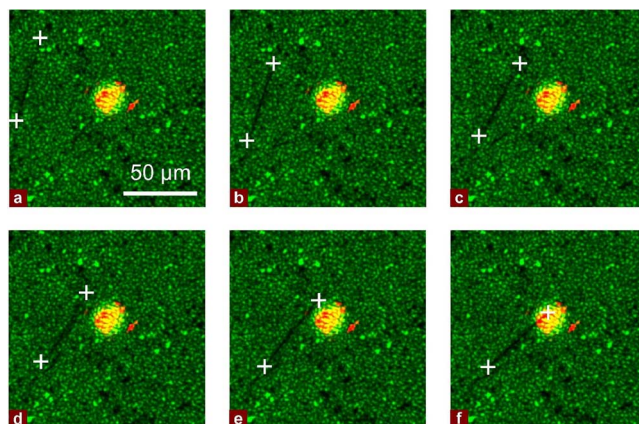
Before performing the demonstration experiment, the synthesized VO_2 and $H_2V_3O_8$ nanowires were suspended in deionized water through sonication. Several microliters of the nanowire suspension were transferred by a pipette onto the gold nanoparticle array and sandwiched into a thin liquid layer with a glass coverslip on top. The thickness of the liquid layer is estimated to be ~1 mm. The chamber is sealed by putting a thin spacer surrounding the liquid drop between the gold nanoparticle array and the glass coverslip. The liquid evaporation can be prevented effectively and the experiment can be performed for several hours without noticeable decrease in the liquid volume.

The snapshots in Fig. 5 show the trapping process of an individual $H_2V_3O_8$ nanowire. Under the optical microscope, randomly oriented nanowires were observed close to the surface of the gold nanoparticle array. A single nanowire was identified, and the laser was turned ON to activate the localized surface plasmons. Contrary to most of the optical trapping experiments where the particles need to be right around the laser spot for trapping to be initiated, the nanowire located at a distance of $\sim40\ \mu m$ outside the laser spot experiences the attractive force and moves toward the illuminated area when the incident laser power exceeds a certain threshold. The nanowire undergoes both translation and rotation simultaneously as it approaches the illuminated area. The nanowire is trapped stably when one end of the nanowire is pulled into the center of the illuminated area.

Starting from this stable state, the trapped end of the nanowire can be repulled into the illuminated area when the laser spot moves away slowly. Therefore, the orientation of the nanowire can be finely tuned when the laser spot gradually moves perpendicular to the long axis of the nanowire, shown in Fig. 6. The view fields of the snapshots in Fig. 6 were adjusted to move with the laser spot.

The trapping and rotation process of the nanowire observed in our experiment are always maintained in the horizontal plane close to the gold nanoparticle array surface. This is
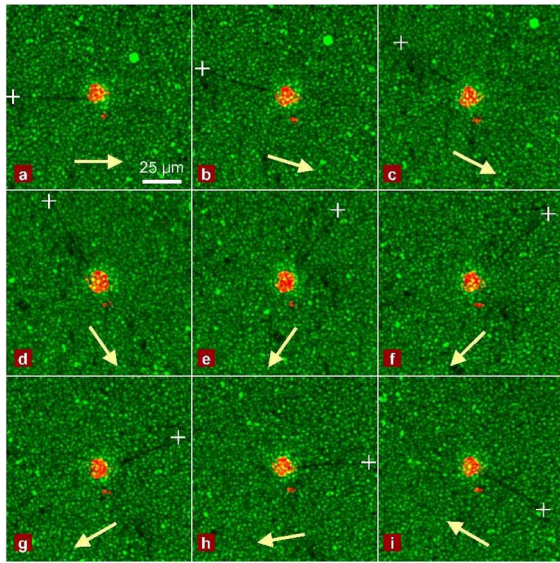
Fig. 6.   Orientation control of an individual $H_2V_3O_8$ nanowire (a)–(i). The orientation of the nanowire is parallel to that of the arrow in each snapshot. Notice that the view fields of the snapshots were adjusted to move with the laser spot.

different from the behavior of nanowires in a single-beam optical trap [17] or in the optoelectronic tweezers [21], where the long axes of nanowires are oriented parallel to the propagation axis of the laser light, and usually, in the vertical direction.

E. Measurement of Light Intensity Threshold

Similar experiments were performed on VO_2 nanowires using the same setup and procedure, and the same long-range trapping phenomena were observed. To quantify the trapping efficiency, the minimum optical intensities to initiate trapping of the nanowires were measured at different trapping radii, defined as the center-to-center distance from the laser spot to the nanowire, shown in Fig. 7(a) and (b). This measurement represents the threshold optical intensity for the induced attractive force to overcome the randomized Brownian motion of the particles and viscous drag force from the liquid medium. The threshold intensity increases with the distance, and a long-range trapping effect is evident. For example, trapping of individual $H_2V_3O_8$ nanowires can still be realized when the trapping radius is increased up to 50 μm with the input optical intensity as low as 7.2 μW/μm^2.

III. DISCUSSION

To investigate the underlying mechanism of the observed long-range trapping effect, we performed control experiments with modified configurations. First, we replaced the gold nanoparticle array substrate with a plain glass slide or with a flat gold film while keeping the other experimental conditions unchanged. In either situation, the long-range trapping phenomenon was not observed for the same nanowires. This suggests the existence of localized surface plasmons on the gold
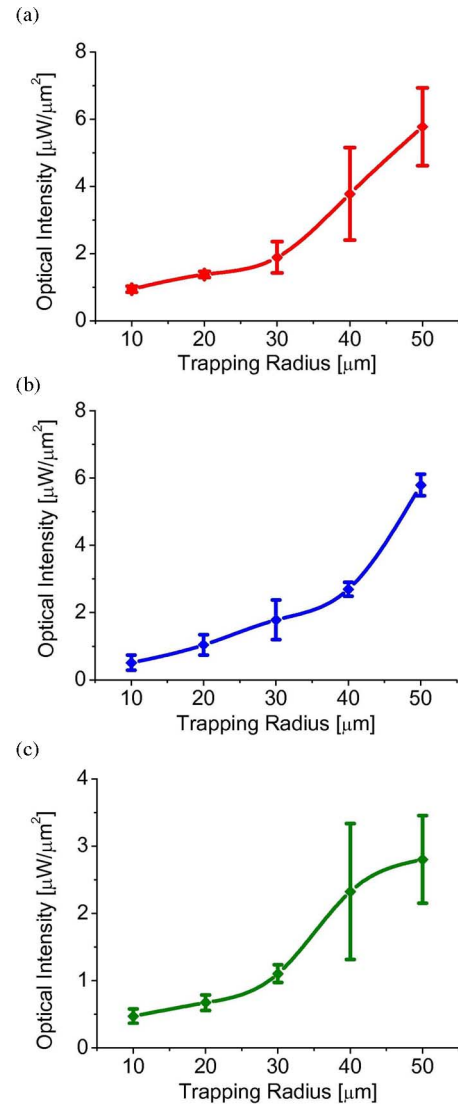

Fig. 7.   Minimum optical intensity to initiate trapping of (a) $H_2V_3O_8$ nanowires, (b) VO_2 nanowires, and (c) TiO_2 crystals versus the trapping radius. The solid lines are fitted polynomial curves to the experimental data. For each trapping radius, the minimum optical intensity is measured at five different locations. The data point and the error bar represent the average value and standard deviation of the minimum optical intensity, respectively.

nanoparticle array that is necessary for the long-range trapping to occur. Although surface plasmon polaritons can be excited on a thin gold film, it requires the excitation laser source incident at a specific angle, which our experimental configuration does not provide.

In our previous experiments with spherical polystyrene beads using the same experimental setup, the long-range trapping behavior was not observed [7], [28]. To verify the likelihood of long-range trapping force associated with elongated geometry of the nanostructures, we performed the experiments on micrometer-sized TiO_2 crystals that have low aspect ratios and the shape of TiO_2 crystals is more similar to the spherical particles rather than the elongated nanowires. The same long-range trapping phenomena were observed for these TiO_2 crystals. The threshold optical intensity for the long-range trapping of TiO_2

crystals was also calibrated and shown in Fig. 7(c). The large uncertainty of threshold optical intensity at the trapping radius of 40 μm could possibly be attributed to the gold nanoparticle array defect. The control experiment with TiO_2 crystals excludes the possibility of shape dependence for long-range trapping and suggests that the high polarizability of the particle may be one of the factors for the long-range trapping.

Two types of attractive forces that can be used to possibly explain the long-range trapping of nanowires are optical forces and hydrodynamic force. The optical force is originated from the gradient of electromagnetic field and enhanced by the localized surface plasmons on the gold nanoparticle array. The hydrodynamic force exerted by the surrounding fluid is attributed to thermal convection, which is induced by the temperature gradient formed by heat absorption (nonradiative damping of localized surface plasmons). The optical force or the hydrodynamic force dominates under different experimental conditions such as the thickness of the liquid layer, the optical power, as well as the distance from the particle to the light spot. For instance, the enhanced optical force has been utilized to trap single polystyrene beads [7] and the hydrodynamic force has been utilized for mixing [27] and concentrating [28] polystyrene bead ensembles. Interested readers may refer to [29] for a detailed discussion of particle dynamics due to the interplay between optical and thermal forces. It is very likely that both the optical and thermal effects contribute to the long-range trapping process of nanowires. When the nanowires are far away from the light spot, the magnitude of the optical force is weak as the propagation through electromagnetic coupling of localized surface plasmons is unlikely to be achieved across the distance involved in our experiment considering the substantial absorption loss and array defects. Therefore, the thermal convection might be the dominant effect in this region to push the nanowire toward the light spot, where the local temperature is the highest. As the nanowire is gradually approaching the light spot, the optical force increases and eventually may take over when the end of the nanowire reaches the light spot.

IV. CONCLUSION

In summary, we report in this paper the first observation of long-range trapping of single nanowires based on plasmonic technology. We also demonstrated the orientation control of the trapped nanowires by changing the relative location of laser spot to the nanowire. The plasmonic technology, therefore, provides a potential tool for transporting and manipulating 1-D nanostructures. The powerful capability and low optical power requirement make this technology a potential candidate for a wide range of nanotechnology applications. Future study includes studying the applicability of this approach to other types of 1-D nanostructures as well as optimized design of plasmonic structure for better control of the manipulation.

ACKNOWLEDGMENT

REFERENCES

[1] A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, "Observation of a single-beam gradient force optical trap for dielectric particles," *Opt. Lett.*, vol. 11, pp. 288–290, 1986.

[2] A. Ashkin, J. M. Dziedzic, and T. Yamane, "Optical trapping and manipulation of single cells using infrared laser beams," *Nature*, vol. 330, pp. 769–771, 1987.

[3] A. Ashkin and J. M. Dziedzic, "Optical trapping and manipulation of viruses and bacteria," *Science*, vol. 235, pp. 1517–1520, 1987.

[4] L. Novotny, R. X. Bian, and S. Xie, "Theory of nanometric optical tweezers," *Phys. Rev. Lett.*, vol. 79, pp. 645–649, 1997.

[5] H. Xu and M. Käll, "Surface-plasmon-enhanced optical forces in silver nanoaggregates," *Phys. Rev. Lett.*, vol. 89, pp. 246802-1–246802-4, 2002.

[6] P. C. Chaumet, A. Rahmani, and M. Nieto-Vesperinas, "Optical trapping and manipulation of nano-objects with an apertureless probe," *Phys. Rev. Lett.*, vol. 88, pp. 123601-1–123601-4, 2002.

[7] X. Miao and L. Y. Lin, "Large dielectrophoresis force and torque induced by localized surface plasmon resonance of a cap-shaped Au nanoparticle array," *Opt. Lett.*, vol. 32, pp. 295–297, 2007.

[8] A. S. Zelenina, R. Quidant, and M. Nieto-Vesperinas, "Enhanced optical force between coupled resonant metal nanoparticles," *Opt. Lett.*, vol. 32, pp. 1156–1158, 2007.

[9] M. Righini, A. S. Zelenina, C. Girard, and R. Quidant, "Parallel and selective trapping in a patterned plasmonic landscape," *Nat. Phys.*, vol. 3, pp. 477–480, 2007.

[10] M. Righini, G. Volpe, C. Girard, D. Petrov, and R. Quidant, "Surface plasmon optical tweezers: Tunable optical manipulation in the femtonewton range," *Phys. Rev. Lett.*, vol. 100, pp. 186804-1–186804-4, 2008.

[11] A. N. Grigorenko, N. W. Roberts, M. R. Dickinson, and Y. Zhang, "Nanometric optical tweezers based on nanostructured substrates," *Nat. Photonics*, vol. 2, pp. 365–370, 2008.

[12] X. Miao and L. Y. Lin, "Trapping and manipulation of biological particles through a plasmonic platform," *IEEE J. Sel. Topics Quantum Electron.*, vol. 13, no. 6, pp. 1–8, Nov./Dec. 2007.

[13] L. Huang and O. J. F. Martin, "Reversal of the optical force in a plasmonic trap," *Opt. Lett.*, vol. 33, pp. 3001–3003, 2008.

[14] P. A. Smith, C. D. Nordquist, T. N. Jackson, T. N. Mayer, B. R. Martin, J. Mbindyo, and T. T. Mallouk, "Electric-field assisted assembly and alignment of metallic nanowires," *Appl. Phys. Lett.*, vol. 77, pp. 1399–1401, 2000.

[15] B. Messer, J. S. Song, and P. Yang, "Microchannel networks for nanowire patterning," *J. Amer. Chem. Soc.*, vol. 122, pp. 10232–10233, 2000.

[16] P. Yang, "Nanotechnology: Wires on water," *Nature*, vol. 425, pp. 243–244, 2003.

[17] P. J. Pauzauskie, A. Radenovic, E. Trepagner, H. Shroff, P. Yang, and J. Liphardt, "Optical trapping and integration of semiconductor nanowire assemblies in water," *Nat. Mater.*, vol. 5, pp. 97–101, 2006.

[18] R. Agarwal, K. Ladavac, Y. Roichman, G. Yu, C. M. Lieber, and D. G. Grier, "Manipulation and assembly of nanowires with holographic optical traps," *Opt. Exp.*, vol. 13, pp. 8906–8912, 2005.

[19] A. Horst, A. I. Campbell, L. K. vanVugt, D. A. M. Vanmaekelbergh, M. Dogterom, and A. Blaaderen, "Manipulating metal–oxide nanowires using counter-propagating optical line tweezers," *Opt. Exp.*, vol. 15, pp. 11629–11639, 2007.

[20] P. Y. Chiou, A. T. Ohta, and M. C. Wu, "Massively parallel manipulation of single cells and microparticles using optical images," *Nature*, vol. 436, pp. 370–372, 2005.

[21] A. Jamshidi, P. J. Pauzauskie, P. J. Schuck, A. T. Ohta, P.-Y. Chiou, J. Chou, P. Yang, and M. C. Wu, "Dynamic manipulation and separation of individual semiconducting and metallic nanowires," *Nat. Photon.*, vol. 2, pp. 85–89, 2008.

[22] M. Rini, A. Cavalleri, R. W. Schoenlein, R. Lopez, L. C. Feldman, R. F. Haglund, L. A. Boatner, and T. E. Haynes, "Photoinduced phase transition in VO2 nanocrystals: Ultrafast control of surface-plasmon resonance," *Opt. Lett.*, vol. 30, pp. 558–560, 2005.

[23] P. Neugen, H. T. Ng, T. Yamada, M. K. Smith, J. Li, and M. Meyyappan, "Direct integration of metal oxide nanowire in vertical field-effect transistor," *Nano Lett.*, vol. 4, pp. 651–657, 2004.

[24] J. H. Son, G. Cao, and Y. N. Xia, "Hydrothermal synthesis of monoclinic VO$_2$ micro- and nanocrystals in one step and their use in fabricating inverse opals," *Chem. Mater.*, to be published.

[25] G. Li, K. Chao, H. Peng, K. Chen, and Z. Zhang, "Low-valent vanadium oxide nanostructures with controlled crystal structures and morphologies," *Inorg. Chem.*, vol. 46, pp. 5787–5790, 2007.

[26] J. W. Xu, C. H. Jia, B. Cao, and W. F. Zhang, "Electrochemical properties of anatase TiO$_2$ nanotubes as an anode material for Lithium-ion batteries," *Electrochim. Acta*, vol. 52, pp. 8044–8047, 2007.

[27] X. Miao, B. K. Wilson, and L. Y. Lin, "Localized surface plasmon assisted microfluidic mixing," *Appl. Phys. Lett.*, vol. 92, pp. 124108-1–124108-3, 2008.

[28] X. Miao, B. K. Wilson, S. H. Pun, and L. Y. Lin, "Optical manipulation of micro/submicron sized particles and biomolecules through plasmonics," *Opt. Exp.*, vol. 16, pp. 13517–13525, 2008.

[29] V. Garcés-Chávez, R. Quidant, P. J. Reece, G. Badenes, L. Torner, and K. Dholakia, "Extended organization of colloidal microparticles by surface plasmon polariton excitation," *Phys. Rev. B.*, vol. 73, pp. 085417-1–085417-5, 2006.

Xiaoyu Miao (S'04) received the B.S. degree (with honors) from the Department of Precision Instruments, Tsinghua University, Beijing, China, in 2003, and the Ph.D. degree from the Department of Electrical Engineering, University of Washington, Seattle, in 2008.

He then joined the Center for Integrated Nanotechnology, Sandia National Laboratory, Albuquerque. He is the author or coauthor of more than 20 publications in referred journals and conferences. His current research interests include biophotonics and nanophotonics.

Dr. Miao is a member of the IEEE Lasers and Electro-Optics Societ (LEOS) and the Optical Society of America.

Benjamin K. Wilson received the B.S. and M.S. degrees in electrical engineering from the University of Washington, Seattle, in 2005 and 2007, respectively, where he is currently working toward the Ph.D. degree.

He is currently a Research Assistant at the Photonics Laboratory, Department of Electrical Engineering, University of Washington, Seattle. His current research interests include nanophotonics, biophotonics, and optical microelectromechanical systems (MEMS) integration.

Guozhong Cao received the Ph.D. degree from Eindhoven University of Technology, Eindhoven, The Netherlands, in 1991.

He is the Boeing-Steiner Professor of materials science and engineering and Adjunct Professor of chemical and mechanical engineering at the University of Washington, Seattle.

He is the author or coauthor of more than 230 refereed papers. He has authored a book *Nanostructures and Nanomaterials*, and edited four monographs and three conference proceedings. Currently, he serves as an Associate Editor of the *Journal of Nanophotonics*. His current research interests include nanomaterials for energy-related applications including solar cells, lithium ion batteries, supercapacitors, and hydrogen storage materials.

Suzie H. Pun received the Ph.D. degree in chemical engineering from the California Institute of Technology, Pasadena, in 2000.

She was with Insert Therapeutics, Pasadena, as a Senior Scientist for three years. She is currently with the Department of Bioengineering, University of Washington, Seattle, as an Assistant Professor. Her research interests include gene and drug delivery systems.

Prof. Pun was recognized with a Presidential Early Career Award for Scientists and Engineers in 2006.

Lih Y. Lin (M'94–SM'02) received the Ph.D. degree (with highest honor) in electrical engineering in 1996 from the University of California, Los Angeles, where she was engaged in research on high-speed photodetectors and micromachined integrated optics.

She then joined AT&T Labs–Research as a Senior Technical Staff Member, where she conducted researches on micromachined technologies for optical switching and lightwave systems. In 2000, she joined Tellium, Inc. as Director of Optical Technologies. She joined the Electrical Engineering Department, University of Washington, Seattle, in 2003. She is the holder of 22 U.S. patents. She is the author or coauthor of more than 150 publications in refereed journals and conferences.

Dr. Lin is a member of the Optical Society of America (OSA) and the Amcircan Association for the Advancement of Science (AAAS). She has served on the technical program committee and co-Chairs of various technical conferences, including the International Conference on Optical MEMS and Nanophotonics, CLEO Pacific Rim, IEEE LEOS Annual Meeting, OSA Annual Meeting, and OSA Photonics in Switching Topical Meeting. She was the Guest Editor for the *Journal of Selected Topics in Quantum Electronics: Special Issue on Optical Micro- and Nanosystems* and for the *Journal of Lightwave Technology: Special Issue on Optical MEMS and its Future Trends*. Currently, she is on the steering committee of the International Conference on Optical MEMS and Nanophotonics. She received the MIT Technology Review 100 Award in 2003. She was also an invitee to the NAE 2005 Frontiers of Engineering Symposium.