Controllable High-Speed Rotation of Nanowires

D. L. Fan,[1,2] F. Q. Zhu,[2] R. C. Cammarata,[1] and C. L. Chien[2,*]

[1]*Department of Materials Science and Engineering, Johns Hopkins University, Baltimore, Maryland 21218, USA*
[2]*Department of Physics and Astronomy, Johns Hopkins University, Baltimore, Maryland 21218, USA*

(Received 3 March 2005; published 24 June 2005)

We report a versatile method for executing controllable high-speed rotation of nanowires by ac voltages applied to multiple electrodes. The rotation of the nanowires can be instantly switched on or off with precisely controlled rotation speed (to at least 1800 rpm), definite chirality, and total angle of rotation. We have determined the torque due to the fluidic drag force on nanowire of different lengths. We also demonstrate a micromotor using a rotating nanowire driving a dust particle into circular motion. This method has been used to rotate magnetic and nonmagnetic nanowires as well as carbon nanotubes.

DOI: 10.1103/PhysRevLett.94.247208 PACS numbers: 85.85.+j, 47.15.Gf, 61.46.+w

In the intense exploration of nanoscience and nanotechnology, it is often desirable, and indeed necessary, to manipulate nanoscale particles. The manipulation of small objects with sizes less than 10 μm encounters several formidable obstacles. Small entities are usually suspended in a suitable liquid to avoid the perils of adhering to the surface by the van der Waals forces. However, the motion of small particles in a liquid is in the realm of very low Reynolds numbers (defined as $\mathrm{Re} = D_p v \rho / \eta$, where D_p, v, ρ, and η are size of particle, relative velocity, density of medium, and viscous coefficient, respectively), where the drag force overwhelms [1–3]. Consider a nanowire 10 μm in length and 0.3 μm in diameter suspended in deionized (DI) water, for which the Reynolds number is only about 10^{-5}. Such a small Reynolds number dictates that, in the absence of other external forces, the drag force alone will stop a moving nanowire at 100 μm/sec in 10^{-6} sec within a short distance of 1 Å. By the same token, disproportionately large forces are required to overcome the drag force and to initiate appreciable motion. Under a constant external force, the nanowire reaches the terminal velocity essentially instantly with no apparent acceleration.

It is even more challenging to controllably rotate nanoscale entities, especially with high rotation speeds. The problem is further compounded by the fact that the terminating torque due to the viscous drag force, that ultimately dictates the rotation of a small rotating object in small Reynolds numbers, is not well known. These difficulties notwithstanding, a rotating magnetic field has been used to rotate ferromagnetic nanowires, such as Ni, albeit with low rotation rates [4,5]. Optical tweezers using circularly polarized light and elaborate instrumentation can also rotate small particles, usually one particle at a time [6].

In contrast, the electric (E) field provided by patterned microelectrodes can accommodate force variations on the μm scale necessary for motion of small entities, and equally important, involves no moving parts. We have recently shown [7] that nanowires in suspension can be driven by an ac electric field to execute linear motion with high efficiency despite extremely low Reynolds number at the level of 10^{-5}. We have determined the functional form of the force and its dependence on the voltage and frequency of the ac field. In this work, we demonstrate a versatile method for executing controllable high-speed rotation in nanowires using a rotating electric field provided by ac voltages applied to multiple electrodes. The rotation of the nanowires can be instantly switched on or off with precisely controlled chirality, rotation speeds [to at least 1800 revolution per minute (rpm)], and total angle of rotation. This method also allows the determination of the viscous torque on nanowires of the same diameter but different lengths. We further show that this method can rotate various elongated metallic entities, including nonmagnetic and magnetic nanowires as well as multiwall carbon nanotubes (MWCNT). We have also demonstrated a micromotor using a bent Au nanowire in a rotating electric field, of relevance to small fluidic or mechanical devices, such as microelectromechanical systems (MEMS) [8,9].

The gold (Au), platinum (Pt), and nickel (Ni) nanowires used in this work, 300 nm in width and lengths from 2 μm to 30 μm, were fabricated by electrodeposition through nanoporous alumina templates as described previously [7,10]. After the alumina template was dissolved in a 4 M NaOH solution, the nanowires were sonicated, centrifuged alternately in DI water and ethanol twice, and then suspended in DI water with a low conductivity of 2.4 μSiemens/cm. The electrodes used to rotate the nanowires were made of Au patterned by laser micromachining on quartz substrates. Small amounts of 2–4 μl nanowires suspended in DI water were applied in the regions of Au electrodes as shown in Fig. 1(a) for executing rotational motion of the nanowires.

We used four separate electrodes with a gap distance between the opposite electrodes of about either 150 μm or 320 μm. Four ac voltages of the same magnitude and frequency but with a sequential phase shift of 90° were simultaneously applied at the electrodes as shown in Fig. 1(a). These voltages give rise to a rotating electric

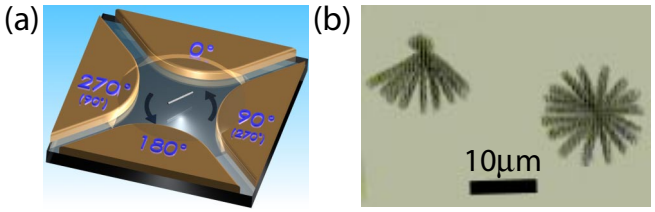

FIG. 1 (color online). (a) Schematics of a nanowire suspended in DI water set to rotation by quadruple electrodes, at which four phase-shifted ac voltages are simultaneously applied but with a sequential phase shift of 90°. (b) Overlapped images at 1/30 sec interval of free (right) and one end fixed (left) rotating Au nanowires at 2.5 V, 80 kHz.

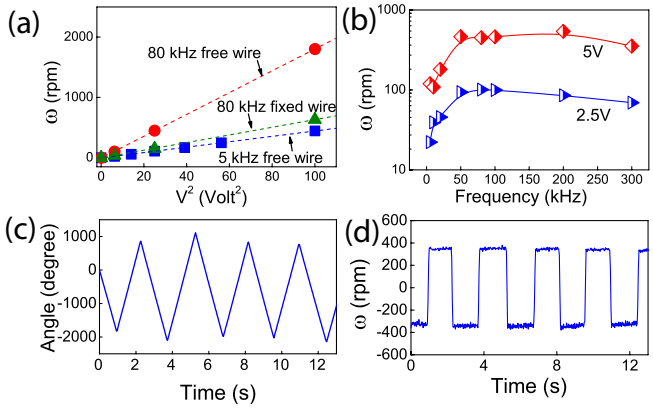

FIG. 2 (color online). (a) Rotation speed ω of free Au nanowires at 5 and 80 kHz, and Au nanowires with one end fixed at 80 kHz as a function of V^2. (b) Semilog plot of rotation speed ω vs ac frequency at 2.5 and 5 V for free Au nanowires. (c) Angle of rotation and (d) rotation speed of Au nanowires at 5 kHz and 10 V under repeated reversal of chirality.

(E) field that compels all the suspended nanowires in the central region to rotate simultaneously. An optical microscope equipped with a video system with 30 frames per second captured the rotational motion of the nanowires. The angular speed (ω) of an individual nanowire was determined by measuring the amount of rotation in fixed time intervals.

Most of measurements have been made using Au nanowires of the same length of 15 μm in quadruple electrodes with a 150 μm gap. Both freestanding nanowires and nanowires with one end fixed by the thoil chemical linkage to the quartz substrate [11,12] can be rotated. Under the same ac voltage with the same frequency, freestanding nanowires always rotate faster than those with one end fixed to the substrate as shown in Fig. 1(b), where snapshots taken 1/30 sec intervals under $V_{ac} = 2.5$ V at 80 kHz are overlapped.

The measured rotation speed ω of a nanowire depends both on the magnitude and the frequency of the applied ac voltage. The rotation rate increases quadratically with voltage as shown in Fig. 2(a) with slopes of 4.5 rpm/V^2 at 5 kHz, 18.1 rpm/V^2 at 80 kHz for free nanowires, and 6.3 rpm/V^2 at 80 kHz for nanowires with one end fixed. The V^2 dependence is particularly advantageous for achieving high rotation speeds. Indeed, we have achieved very high rotation rates of 1803 rpm for free nanowires and 445 rpm for nanowires with one end fixed at 10 V and $f =$ 80 kHz as shown in Fig. 2(a). We have detected no limitation in the rotation speed up to 1800 rpm, beyond which our video system with 30 frames per second could not accurately track the rotation. The value of ω also depends on the frequency of the ac voltage. As shown in Fig. 2(b), at $V_{ac} = 2.5$ V and 5 V, the rotation rate of a free nanowire increases sharply below 50 kHz before leveling off and then decreasing slightly from 50 to 300 kHz.

The ability to control the chirality of rotation for all the nanowires within the region of the electrodes is an important attribute. Since the phase-shifted ac voltages applied to the quadruple electrodes set the rotation, the chirality of rotation is likewise determined by the phases of the ac voltages. Using the geometry shown in Fig. 1(a), the rotation chirality is always the same as that of the field rotation but opposite to the phase shift direction of the ac voltages. The rotation is clockwise (or counterclockwise) when the phase shift was $-90°$ (or 90°). This fact has been verified in the frequency range of 5 to 300 kHz.

To further illustrate the ability to control the rotation chirality, we repeatedly reversed the phase shifts of the applied ac E field. The nanowires responded to the reversed chirality and instantly reached the constant terminal rotation speeds as shown in Fig. 2(c), with no apparent acceleration and deceleration detected within 1/30 sec. Furthermore, the rotation starts and stops as soon as the electric field was switched on and off. This apparent instant response is due to the extremely small Reynolds number of 10^{-5} for nanowires suspended in DI water. These results show that we can use the ac voltages to instantly switch on and off the rotation of nanowires, precisely control the rotation speed, the chirality of rotation, and the total angle of rotation.

The rotation of nanowires is due to the interaction [13] between the ac E field and the induced electric dipoles of the nanowires. The charge carriers in a metallic entity are polarized by the electric field resulting in a charge distribution and subsequently an electric dipole moment, $\boldsymbol{p} = \hat{l} \int_{-L/2}^{L/2} x\rho(x)dx$, where $\boldsymbol{p}$ is the induced dipole moment, $\hat{l}$ is the unit vector directed along the wire, $\rho(x)$ is the charge density induced in the wire, and the integration is conducted over the wire length $[-\frac{L}{2}, \frac{L}{2}]$. The value $\boldsymbol{p}$ depends on charge distribution due to the material properties, the geometrical shape of the object, and the applied E field. The induced dipole moment of a metallic sphere can be readily calculated. The dipole moment is substantially enhanced for an elongated ellipsoid, to which a metallic nanowire can be approximated. The large aspect ratio of

the Au nanowires used here gives rise to an enhancement factor of about 380, which greatly increases the efficiency in rotating the nanowires [7]. The rotation of a nanowire is due to the torque $T_e = \int_{-L/2}^{L/2} x\rho(x)[\hat{l} \times \boldsymbol{E}(x)]dx$, where $\boldsymbol{E}(x)$ is the applied electric field. In the experiments, we only analyze those nanowires (micrometers in length) rotating in the center of the electrodes (hundreds of micrometers across). Our simulation shows that the variation of $\boldsymbol{E}$ in a small area (20 μm $\times$ 20 μm) in the center of our electrodes (320 μm across) is less than 5% [14]; therefore, $\boldsymbol{E}$ can be treated as constant. The rotary torque, T_e, can be simplified as $\boldsymbol{p} \times \boldsymbol{E}$, where $\boldsymbol{p}$ is the induced dipole moment along the nanowire axis and $\boldsymbol{E}$ the rotating electric field. Hence the torque varies as E^2. For a conducting metallic nanowire of length L and radius a suspended in a medium of permittivity of ε_m, the magnitude of the torque is [15]

$$T_e \approx \frac{\pi L^3}{12} \frac{\varepsilon_m}{\ln(\frac{L}{a}) - 1} E^2 \qquad (1)$$

for $L \gg a$. The E^2 dependence accounts for the observed V^2 dependence of the rotation rate as experimentally observed.

The actual rotation speed ω of the rotating nanowire is dictated by $T_e = T_\eta$, where T_η is the torque due to the fluidic drag force. Because of the low Reynolds number, at each ac E field, the rotating nanowire reaches a terminal angular velocity essentially instantaneously. Consequently, the rotation of the nanowire can be instantly switched on and off. Also due to the large drag force, the nanowires cannot synchronize its rotation with that of the rotating field. There is always a lag between the nanowire rotation and the E field. The chirality of rotation is determined by the charge relaxation times of the nanowire relative to that of the medium in which the nanowires are embedded. When the charge relaxation time of the nanowire is shorter than that of the medium, as in the case of Au nanowire in DI water, the Au nanowires always rotate in the same chirality as that of the E field as observed for the frequency range of 5 to 300 kHz.

For a sphere of radius R, the torque T_η has the form of $\eta\omega(8\pi R^3)$, where η is the viscous coefficient, ω the rotation speed, and the last term is the geometrical factor for spheres. For small entities of other shapes, including nanowires, the geometrical factor is not theoretically well known. For nanowires of the same diameter, T_η has the form of $\eta\omega f(L)$, in which $f(L)$ depends only on the length L. Since the driving torque T_e due to the ac field is known, we can in turn experimentally determine $f(L)$ by noting $T_\eta = \eta\omega f(L) = T_e \approx CL^3V^2$ from Eq. (1), where C is a constant. For this purpose, we have measured the values of ω of various Au nanowires of the same diameter of 300 nm with lengths ranging from 1.7 μm to 11 μm in quadruple electrodes with a 320 μm gap at 10 kHz applied voltages. The measured dependence of ω/V^2 on L is shown in Fig. 3(a). The value of ω/V^2 is weakly dependent on L showing a maximum at $L = 6$ μm. To extract $f(L)$, we fit ω/V^2 to $L^3/g(L)$, where the best-fit form is $g(L) = -0.00052L^6 + 0.0138L^5 - 0.11L^4 + 0.41L^3$, shown by the solid curve in Fig. 3(a). We then plot $L^3V^2/\omega = g(L) = (\eta/C)f(L)$, which increases monotonically with L as shown by the solid curve in Fig. 3(b). In this manner, the elusive geometrical factor $f(L)$ for nanowires with 300 nm in diameter and length L has been determined experimentally. Note that within the length range, the L^3 term is the dominant one in $f(L)$ with the largest coefficient. However, if $f(L)$ strictly includes only the L^3 term, then ω/V^2 would have been independent of L. Thus the variation of ω/V^2 showing in Fig. 3(a) is a direct consequence of higher order terms in addition to the L^3 term in $f(L)$.

We have also used this versatile method to rotate other elongated entities including Au, Pt, and Ni nanowires (300 nm in diameter and 9 μm in length), and MWCNT (50 nm in diameter and 5 μm in length) shown in Fig. 4(a), with images taken every 1/15 sec, at 6 V, 10 kHz. Using a quadruple electrode with 320 μm in separation and at 10 kHz, we have found in these cases that the rotation speed is likewise linearly dependent on V^2, but with different slopes of 5.4 rpm/V^2, 4.7 rpm/V^2, 4.5 rpm/V^2, and 3 rpm/V^2 for Au, Ni, Pt, and MWCNT, respectively, as shown in Fig. 4(b). The difference among the Au, Ni, and Pt nanowires with the same geometrical shape scales roughly with their conductivities, since a higher conduc-

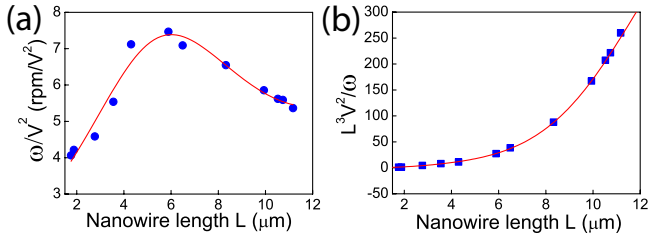

FIG. 3 (color online). (a) The dependence of ω/V^2 and (b) L^3V^2/ω on the length L of Au nanowires with 300 nm diameter. The curves are best-fit results to the data (see text).

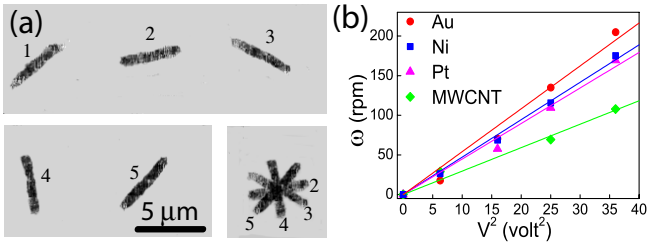

FIG. 4 (color online). (a) Snapshots of enhanced images, every 1/15 sec, of a multiwall carbon nanotube rotating at 6 V, 10 kHz. (b) Rotation speed ω of Au, Ni, and Pt nanowires and multiwall carbon nanotubes as a function of V^2.

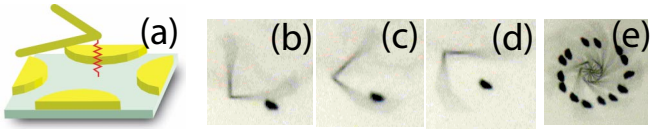

FIG. 5 (color online). (a) Schematics of a bent nanowire attached to the surface. Snap shots (b)–(d) of rotating bent nanowires taken every 1/30 sec and (e) overlapped images taken within 1.8 sec under 10 V at 20 kHz illustrating a bent nanowire as a micromotor driving a dust particle.

tivity facilitates a higher induced polarization, hence a higher rotation speed. The rotation speed of MWCNT is slower and can be attributed to the less polarization of MWCNT. It is also noted that both ferromagnetic (Ni) and nonmagnetic (Au, Pt, and MWCNT) entities can be rotated.

For demonstration purposes, we have made a nanowire motor [16] by attaching the kink of a bent nanowire onto the quartz substrate through the covalent bonding between Au and thiolated substrate. In analogy to an electric motor, the bonding between the kink of nanowire and the substrate anchors the axel of the motor as shown in Fig. 5(a). The bent nanowire serves as the rotor while the four Au electrodes serve as the stator. After the application of a rotating ac voltage of 10 V at 20 kHz, a dust particle was being whipped, driven, and occasionally missed by the two arms of about 16 μm in length of the bent nanowire [Figs. 5(b)–5(d)]. Note that the dust particle moves only when driven by the nanowire and hence maintains a circular motion [Fig. 5(e)]. The relevance of such a micromotor to microfluidic devices, microstirrer, and MEMS [8] is apparent.

In summary, we have demonstrated a method of rotating metallic nanowires in suspension by using ac voltages applied to multiple electrodes. Nanowire in suspension can be rotated with a specific chirality, rotation speed, and total angle of rotation. The rotation can be instantly switched on or off by the application of the ac voltages. We have used this method to determine the viscous torque on nanowires with different length. This method can also be used to explore other phenomena occurring in systems with very low Reynolds numbers, from transport of small entities, the studies of motion of microorganism, to MEMS.

This work has been supported by NSF Grant No. DMR00-80031.

*Electronic address: clc@pha.jhu.edu

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[16] See EPAPS Document No. E-PRLTAO-95-006527 for controllable nanowire rotation and a rotating bent nanowire driving a dust particle into circular motion. A direct link to this document may be found in the online article's HTML reference section. The document may also be reached via the EPAPS homepage (http://www.aip.org/pubservs/epaps. html) or from ftp.aip.org in the directory /epaps/. See the EPAPS homepage for more information.