Research article

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Microsphere-assisted manipulation of a single Ag nanowire

<https://doi.org/10.1515/nanoph-2021-0234>

Received May 12, 2021; accepted June 24, 2021;

published online July 9, 2021

Abstract: Metal nanowires are promising building blocks for optoelectronic nanodevices, so their independent and precise manipulation is urgently needed. However, the direct optical manipulation methods are severely hampered due to the high absorption and scattering characteristics of the metal nanowires. Here, a microsphere-assisted indirect optical manipulation method is proposed, and precise manipulation of a single Ag nanowire is demonstrated in liquid. The microsphere is actuated to rotate to generate a microvortex by dynamic optical traps. Under the action of shear stress, the Ag nanowire within the microvortex can be controllably rotated and accurately orientated. By manipulating the position of the microsphere using a single optical trap, a precise positioning of the nanowire can be achieved under the action of pushing force. On this basis, the Ag nanowire-based structures were assembled. This indirect optical manipulation avoids the direct interaction between the light and the nanowires, which makes it independent of both the laser (power, wavelength) and the nanowire (material, size, and shape). Hence, the microsphere-assisted manipulation method is simple and general for independent and precise manipulation of a single nanowire, which is of great significance to the fabrication of optoelectronic nanodevices.

Keywords: Ag nanowire; manipulation; optical tweezers.

1 Introduction

The independent and precise manipulation of nanostructures is a prerequisite for fully exploiting the potential of nanodevices in various applications [1–6], especially for the anisotropic nanostructures, nanowires for example [2–5], of which the chemical and physical properties are highly dependent to their orientation and position [7, 8]. At present, several nanowire manipulation techniques have been investigated based on the magnetic field [9], electric field [10, 11], optical field [12, 13], and others [14, 15], most of which were performed in a liquid environment to prevent the adhesion of nanowires to substrates. Among them, the optical field-based manipulation technique, represented by optical tweezers [16], has attracted widespread attention for its high precision, great flexibility, and versatility, and succeeded in trapping and manipulating various nanowires, such as SnO₂, Ag, Au, and Si nanowires [12, 17–19]. However, it typically encountered technical obstacles in manipulating metal nanowires for their high scattering and high absorption characteristics. One of the manipulation techniques of metal nanowires based on the optical field was achieved by constructing a special laser beam [17, 20]. For example, the rotation of a single Ag nanowire has been realized using vortex beams produced by modulating a linearly polarized Gaussian beam [17]. However, some attractive forces must be introduced on the substrate to counteract the scattering force from the vortex beam. As a result, the nanowires were confined near the substrate, which is not conducive to their further movement and positioning. Besides, the high photothermal effect resulting from the high absorption of light by the metal nanowires will reduce the stability of the manipulation. Another manipulation technique was based on the plasmonic tweezers [18]. Due to the field enhancement effect of the surface plasmon resonance [21], the gradient force acted on the nanowires was increased and then the manipulation stability was improved. However, plasmonic tweezers needed to be implemented on a metallic surface, whose high-loss characteristics limited the operating range

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(usually tens of nm) [22, 23], and the photothermal effect resulting from the interaction of the metallic surface and incident light was not neglected. Thus, the direct optical manipulation techniques are inevitably affected. Additionally, certain requirements for the laser and metal nanowires usually are needed to meet the manipulation conditions (exciting plasmon resonance for example). Hence, a simple, versatile, flexible, and stable technique for manipulating a single metal nanowire precisely is urgently needed.

Transparent dielectric microspheres have been trapped and actuated by the optical tweezers and the technique was very simple and mature [24–26]. In this work, we take the microspheres as “micron robots” or “micromanipulators” and propose a microsphere-assisted manipulation technique to orientate and position a single metal nanowire. Taking 10- μm -diameter SiO_2 microspheres as an example, under their “command”, the rotation, orientation, and translation of a single Ag nanowire were achieved. This indirect optical manipulation method was further used in manipulating nanowires with different types, sizes, and shapes, proving the universality of this method. Moreover, the method combined microflow and optical field-based manipulation, which provides a new perspective on the nanostructure assembly and adjustment.

2 Experiment

The Ag nanowires (diameter: 150–500 nm, length: 6–30 μm) used here are chemically synthesized and purchased from Nanjing XFNANO Materials Tech. Co., Ltd. The microspheres used here are SiO_2 microspheres with a diameter of $\sim 10 \mu\text{m}$, purchased from Wuhan Huake Weike Tech. Co., Ltd. A detailed schematic diagram of the experimental device is shown in Figure S1 in Supplementary Material. Ag nanowires and SiO_2 microspheres were suspended in water and with the assistance of an injector, the suspension was transferred into a 100- μm -thick sample chamber that consists of two coverslips (size: $24 \times 50 \text{ mm}$, thickness: 0.13–0.16 mm) separated by an annular adhesive spacer. Then the sample chamber was placed on the three-dimensional (3D) platform of the scanning optical tweezers system (Tweez250si, Aresis, Europe) equipped with a solid-state Nd:YAG laser (wavelength of 1064 nm). The laser beam was focused by a 60 $\times$ water immersion objective lens (numerical aperture [NA] = 1.0) onto the chamber from the bottom side and it can be modulated as multiple quasi-static or dynamic optical traps through an acousto-optic-deflector. Further, each optical trap could be set with a predefined trajectory by programming in MATLAB.

2.1 Working principle

Figure 1(a) is the schematic diagram for the microsphere-assisted manipulation of a single Ag nanowire. Here, the microsphere (purple) can be easily captured and actuated by optical traps, which is acted as a “micron robot” or “micromanipulator” and can further accomplish the rotation, orientation, and translation of the nanowire, as follows. To translate the nanowire, the microsphere controlled by a single optical trap is needed to contact the target nanowire; by moving the optical trap, the trapped microsphere can move synchronously, and then the contacted nanowire will be translated under the action of thrust force. To rotate the nanowire, a circular scanning optical trap (marked by a green dotted circle) with the midpoint of nanowire as the center is needed to be set, and the microsphere could be actuated to orbit along the circular path at a constant speed when the laser is on. In a low Reynolds number environment where the viscous force plays a dominant role, the uniform circular motion of the microsphere further forms a steady microvortex within the circular trajectory. Thus, the target nanowire at the center of microvortex will be rotated under the action of hydrodynamic shear stress. Moreover, the rotation direction and speed of the nanowire can be controlled by adjusting the scanning frequency and direction of the scanning optical trap. Once the laser is turned off, the rotating nanowire will be orientated and positioned.

To investigate this above interaction deeply, a finite-element method (COMSOL Multiphysics) was used for simulation. A two-dimensional axisymmetric model composed of a SiO_2 microsphere, an Ag nanowire, and a water environment was built. Both the pre-defined fluid-structure interaction and laminar flow models were used to simulate the movement of the microsphere and the nanowire in the fluid. Figure 1(b) shows the distribution of water flow around the target Ag nanowire when the microsphere is rotating (taking the laser-on time $t = 0.1 \text{ s}$ as an example). Here, the fluid material was water and the density, viscosity, and temperature were set as $1 \times 10^3 \text{ kg m}^{-3}$, $0.9 \times 10^{-3} \text{ Pa s}$, and 25°C , respectively. The Ag nanowire was set as 400-nm diameter and 15- μm length with a refractive index of $n = 0.04 + 5.57i$, and the SiO_2 microsphere was set as 10- μm diameter with its revolution speed of 1.5 rps and orbit radius of 25 μm . The above data were consistent with the following experiment. The direction and size of the white arrows represent the direction and speed of the water flow, respectively. It can be seen that, when the microsphere orbited along the circular trajectory, a micro vortex was formed. The velocity of water flow continuously changed from the boundary to the center of

Figure 1: (a) Schematic diagram for the microsphere-assisted manipulation of a single Ag nanowire. MS and NW represent the SiO_2 microsphere and the Ag nanowire, respectively. (b) Simulated water flows distribution around Ag nanowire at $t = 0.1$ s. The white arrows represent the velocity of the water flow. (c) The rotation angle of the nanowire at different times. The inset in the upper left shows the trajectory of the midpoint of the nanowire during 10 s. The inset in the lower right shows the rotation speed of the nanowire (f_{NW}) and orbit radius (r) of the microsphere.

the trajectory and the nanowire was rotated by 27° at $t = 0.1$ s compared with the initial position (marked by yellow dotted line). Taking the water flow velocities at the ends of the nanowire (marked as A and B point) as an example, they had the opposite direction with a speed of 3.75×10^{-5} and 3.42×10^{-5} m/s, respectively, which means the opposite direction of the viscous shear stress and can act as a torque to drive the rotation of the nanowire. Under the action of torque, the nanowire exhibits a linear rotation with a calculated speed of 0.69 rps, as shown in Figure 1(c). It should be pointed out that, the speed discrepancy of the water flow at the ends, which means that the forces acted on the two ends of the nanowire are not completely balanced, can result in a displacement of the nanowire midpoint during the rotation process. As shown in the inset (upper left in Figure 1(c)), the nanowire center shows the highest offset of $x_{\max} = 0.83 \mu\text{m}$, $y_{\max} = 0.80 \mu\text{m}$ within 10 s. Even so, the position deviation of the nanowire midpoint in the experiment can be corrected by moving the center of the circular optical trap in real time. Besides, by changing the revolution speed and orbit radius of the microsphere, the velocity of water flow around the nanowire will be changed, resulting in the changing rotation speed of the

nanowire, as shown in the inset (lower right in Figure 1(c)). It can be seen that the rotation speed (f_{NW}) of the nanowire was linearly related to the revolution speed (f_M) of the microsphere. And at the same revolution speed f_M , the smaller the orbit radius of the microsphere, the greater the rotation speed of the nanowire. In addition, the movement of target nanowires in water could be affected by the diameter d of the microsphere. Here, different diameters of SiO_2 microspheres-actuated rotation of the Ag nanowire were further simulated (Figure S2, Supplementary Material). The results show that, with the increasing diameter of the microsphere, the rotation speed of the target nanowire increases. However, the corresponding standard error also increases. In order to obtain the stable and effective rotation of the nanowires, 10 μm -diameter microspheres were chosen as the orbiting particle in our experiment.

3 Results and discussion

Figures 2(a) and (b) show the optical images for the microsphere-assisted counterclockwise and clockwise

Figure 2: Microsphere-assisted rotation of a single Ag nanowire. Optical images of counterclockwise (a) and clockwise (b) rotation. The scale bar is 10 μm . (c) The rotation angle of the nanowire at different times with different orbit radius of the microsphere. (d) Rotation speed of the nanowire (f_{NW}) at different revolution speed (f_M) of the microsphere. The orbit radius of the microsphere is 25 μm . The plus or minus of the value represents the counterclockwise and clockwise rotation, respectively.

rotation of a single Ag nanowire, respectively. The target Ag nanowire is 15 μm length and 400 nm diameter, and the SiO_2 microsphere is 10 μm diameter. A spatial scanning optical trap was set as a circular path (marked by yellow dotted circles) with a radius of 25 μm . In order to observe the rotation of the nanowire more clearly, one end of the nanowire is marked with a star. When the laser was on with an optical power of 25 mW, the microsphere was actuated to orbit along the circular path with a revolution speed of 1.5 rps. To actuate the microspheres to rotate smoothly, an optical power threshold of the trapping laser was required. In our experiment, the threshold was measured as 25 mW/1.5 rps for the 10- μm -diameter SiO_2 microspheres. Under the action of the viscous shear stress, the nanowire was rotated in the same direction (indicated by green arrows) (Movie 1). Counterclockwise (Figure 2(a)) and clockwise (Figure 2(b)) 360° rotation of the nanowire

was completed using 6.90 and 7.15 s, respectively. The different time required is mainly attributed to the disturbance of the water environment and the instability of the laser source. Besides, the center of the nanowire would be drifted slightly due to the unbalanced forces acting on the ends of the nanowire during its rotating process (as the simulated result shows in Figure 1(c)), which could also result in the difference in the rotation period. The rotation of the nanowire in a rotation period is not uniform; however, in a long time, the rotation angle of the nanowire shows a linear relationship with time, as shown in Figure 2(c). By changing the orbit radius of the microsphere, the rotation rate of the nanowire was changed. By averaging three experimental values from three videos, the average rotation angle at different times could be calculated as shown in Figure 2(c). By linear fitting, the average rotation rate can be calculated as 0.31 ± 0.007 ,

0.15 ± 0.005 , and 0.08 ± 0.0007 rps when the radius is 20, 25, and 30 μm , respectively. Besides, the rotation rate of the nanowire can also be changed by changing the revolution rate of the microsphere. By averaging three experimental values (each value was taken over 6 to 10 rotation periods) from three videos, the corresponding rotation rate can be calculated as shown in Figure 2(d) (the orbit radius of the microsphere is 25 μm). The plus or minus of the value represents the counterclockwise and clockwise rotation, respectively. It can be seen that the rotation rate f_{NW} of the nanowire increases with the increasing revolution rate f_{M} of the microsphere and the data can be well fitted by a linear equation of $f_{\text{NW}} = 0.094 f_{\text{M}}$. The above results are corresponding to the simulation results, while the rotation rate of the nanowire in the experiment is lower than the simulated results, which is mainly attributed to the disturbance of the liquid environment and the stability of the laser source. Besides, the good stability and repeatability of the results were further proved (Figure S3, Supplementary Material).

Based on the above microsphere-assisted rotation of the nanowire, the arbitrary orientation of the nanowire can be achieved by turning off the laser, as shown in Figure 3 and Movie 2. Taking the orientation of the Ag nanowire in Figure 3(a) as the initial orientation, that is, $\theta = 0$ at $t = 0$ s. As the laser was on, the nanowire was rotated with the assistance of the microsphere. Turning off the laser at $t = 1.8$ s, the nanowire immediately stopped rotating and it was oriented with a rotated angle of 80° (Figure 3(b)). The nanowire held its orientation until the laser was turned on again at $t = 5.3$ s (Figure 3(c)). Once the laser was on, the nanowire began to rotate immediately and a rotated angle of 180° was achieved at $t = 7.7$ s (Figure 3(d)). The results show that, with the assistance of microsphere, the rotation of nanowire is controllable and the arbitrary orientation of nanowire can be achieved in theory, which is of great significance for the assembly of nanowire-based nanostructures.

Besides the rotation and orientation manipulation of the Ag nanowire, its translation was also demonstrated, as shown in Figure 4 and Movie 3. Here, a 10- μm -diameter SiO_2 microsphere was controlled by a single optical trap. By moving the optical trap, the microsphere was moved synchronously to contact and then push the target nanowire. Under the action of the thrust force, the translation of nanowire was achieved. When the nanowire reached the desired position, the microsphere was pulled quickly to separate from the nanowire, that is, a process of release. As Figure 4(a) shows, with the assistance of the microsphere, a 23- μm -length Ag nanowire completed an up-and-down translation (marked by a yellow dotted line). To verify the effectiveness of this method, Ag nanowires with different lengths of 15 and 10 μm were translated by the microsphere, as shown in Figures 4(b) and (c). When the nanowires were moved to the desired position, the orientations of the Ag nanowires were changed, which is mainly attributed to the translational trajectories were not straight lines. The orientation of the nanowire was further adjusted to the original state by the above rotation method. The above results show that the metal nanowires can be precisely and independently positioned and orientated by a controllable microsphere. Here, it should be mentioned that a microsphere with a larger diameter would reduce the translating accuracy and a microsphere with a smaller diameter would affect the translation stability. Due to the small size (5 μm diameter in Movie 4), the target Ag nanowire was easily irradiated by the laser beam and pushed away by a strong scattering light. So, the 10 μm -diameter microsphere was also suitable for the precise and stable translation of Ag nanowires.

Here, it should be mentioned that, due to their density and gravity, the Ag nanowires quickly settled to the bottom coverslip. However, the nanowires did not become irreversibly bound to the surface by van der Waals forces for about 30 min. Therefore, the Ag nanowires could be regarded to suspend in the aqueous solution very close to

Figure 3: Microsphere-assisted orientation of the Ag nanowire. The scale bar is 10 μm .

Figure 4: Microsphere-assisted translation of a single Ag nanowire.

(a) The optical images of the movement process for a single Ag nanowire with lengths of 23 (a), 15 (b), and 10 μm (c). The scale bar is 10 μm .

the bottom coverslip within the 30 min (time window for manipulating Ag nanowire). Thus, most of the Ag nanowires maintain a horizontal or slightly oblique state in the aqueous solution. However, in some special cases, the Ag nanowires could be also actuated to “stand up” by the microsphere-assisted method, as shown in Figure S4 and the corresponding Movie 5. The result shows that the rotation of a single nanowire in 3 dimensions could also be achieved by the proposed method.

This method could be further used in nanowire-based structure assembly. As an example, Figure 5 shows a swallow-tail structure assembled with two Ag nanowires. For simplification, an Ag nanowire fixed on the substrate was chosen as the target location. Under the assistance of a microsphere, a free Ag nanowire was translated to close the target nanowire. When one end of the free nanowire touched the fixed nanowire, the electrostatic attraction force between the nanowires can offset some of the Brownian motion, resulting in a relatively static state of the nanostructure. Because the optical force exerted on the trapped microsphere is linearly related to the optical power

Figure 5: A swallow-tail nanostructure assembled with two Ag nanowires. The scale bar is 10 μm .

of the trapping laser, hence, it can be increased by increasing the optical power, and correspondingly, the extreme value of the thrust force applied on the nanowires will also be increased. When the thrust force is greater than the electrostatic attraction between the two nanowires, the

Table 1: The geometrical characteristics, properties, and manipulating behaviors of nanowires.

Material	Shape	Diameter (nm)	Length (μm)	Orientable?	Removable?
Ag		150–500	6–30	Yes	Yes
Ag		70–100	15–30	Yes	Yes
Ag		150–500	10–30	Yes	Yes
Au		150–500	6–30	Yes	Yes
Al ₂ O ₃		150–500	10–30	Yes	Yes

position of the free nanowire can be adjusted with the assistance of the microsphere. After reaching the required position, the free nanowire is slowly adsorbed to the substrate under the action of gravity and electrostatic attraction (between the nanowire and substrate), forming a stable nanostructure (~30 min). This process could be repeated to fabricate more complex nanowire-based structures. This provides experimental evidence of the great potential of the microsphere-assisted method in the micro/nanofabrication for lab-on-a-chip devices.

Due to the indirect interaction between the laser and nanowires, the proposed microsphere-assisted manipulation method was independent of the nanowire sizes and materials. Therefore, it can be further used to manipulate other nanowires, such as the Ag nanowires with different diameters, folded Ag nanowires (Movie 6), Au nanowires, and Al₂O₃ nanowires. The results were shown in Table 1. Obviously, the microsphere-assisted manipulation method is a simple and universal method to manipulate nanowires. Besides, experiments for manipulating sphere and discoid objects were also performed (Figure S5 in Supplementary Material), indicating that the same strategy can be used in the manipulation of target objects with different shapes.

4 Conclusion

In summary, a microsphere-assisted manipulation method based on an optical tweezer system was proposed to realize the controllable rotation, orientation, and translation of single Ag nanowires, and the assembly of Ag nanowire-based structure. This method combined microflow and optical field-based manipulation. Compared with the direct control by optical tweezers system, the indirect control of metal nanowires through microspheres remained the flexibility and controllability of optical tweezers and the harmlessness of hydrodynamic force, while it could also overcome some key limitations of optical tweezers. Firstly, the proposed method can avoid direct interaction between the metal nanowires and the

laser beam, thereby avoiding a series of problems such as thermal effect and strong scattering force due to light absorption and scattering, resulting in a more stable, precise, and harmless manipulation of the metal nanowires. Secondly, it is simple enough and easy to operate, which doesn't require specially modulated or special wavelength laser beams or specially fabricated metal nanostructures exciting highly focused plasmonic field. Thirdly, it can be applied for manipulating not only different shapes of metal nanostructure but also other materials such as semiconductors, polymers, and biological cells. Last but not least, the formed microvortex's location is reconfigurable and highly localized, which makes this method have no significant spatial limitation and leave other objects in the sample largely unperturbed. Overall, the proposed method is beneficial to the 3D construction of nanowire-based structures, provides a new perspective on the micro/nanostructure manipulation, and has an importation contribution to nanowire-based devices for nano-optoelectronics, spectroscopy, and sensing applications.

Author contribution: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: This work was supported by the National Natural Science Foundation of China (NSFC) (11974435 and 12004444) and the Natural Science Foundation of Guangdong Province (2018A030313498, 2016A030313339).

Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

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Supplementary Material: The online version of this article offers supplementary material (<https://doi.org/10.1515/nanoph-2021-0234>).