Supplementary Information for:

In-plane trapping and manipulation of ZnO nanowires by hybrid plasmonic field

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Excitation of the LP-SPP field. When a LP laser beam is focused by a high-numerical-aperture objective lens (100×, NA=1.49) into a coupling-type glass plate that has been top-coated with a 45-nm-thick gold film, SPPs are excited at the surface plasmon resonance angle (~44.5°), which results in near-zero reflection at the excitation positions. Fig. S1a and b show the reflected light at the rear focal plane of the objective lens for different incident polarization directions. The dark arcs correspond to the near-zero reflectance that resulted from SPP excitation. The LP-SPP polarization direction is determined by the incident polarization direction. Fig. S1c shows the spatial mapping of SPP field generated under a LP laser beam with two focal spots that had uniform intensity distributions, which is in good agreement with the calculated SPP field. This LP-SPP field has a large transmission range (>5 μm from the center), providing a trapping force for the sample in a large-area.

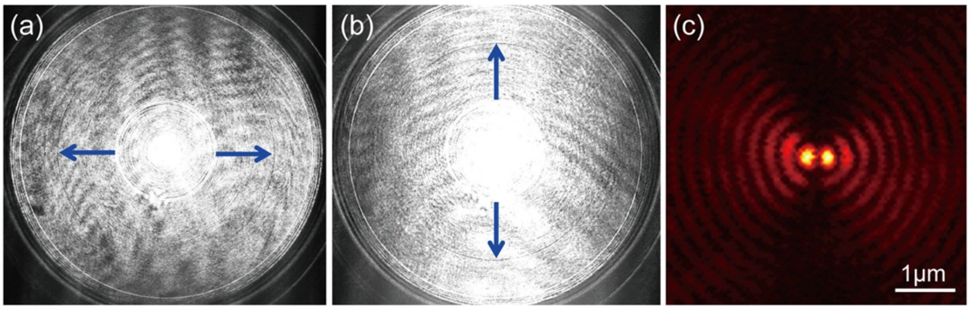

Fig. S1 (a) and (b) Captured reflected images on the rear focal plane of the objective lens with orthogonal incident polarization direction at a wavelength of 1064 nm. The very thin dark arcs (indicated by the solid blue arrows) correspond to the low reflectance regions, and the solid blue arrows lie along the linear polarization direction of the incident laser beam. (c) The spatial mapping of SPP field generated under a linearly-polarized Gaussian beam. The scale bar length represents 1 μm.

Trapping of ZnO nanowires of different lengths using plasmonic tweezers. Trapping experiments with ZnO nanowires of various lengths were performed using the focused plasmonic tweezers. The results show that the SPP field can attract nanowires with lengths ranging from 2 to 15 μm to the center of the field, as shown in Fig. S2, thus demonstrating the robust trapping forces of our proposed configuration for semiconductor nanowire manipulation.

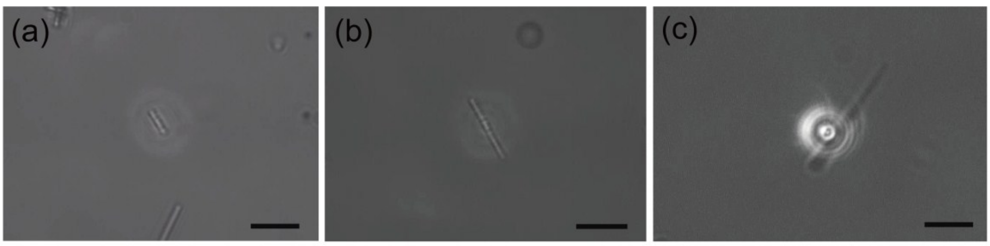

Fig. S2 ZnO nanowires of different lengths trapped using focused plasmonic tweezers on a metallic surface. The scale bar length represents 5 μm.

Force distribution on the centrally-positioned ZnO nanowire inplasmonic tweezers. Unlike the force distributions around the off-center nanowires (Figure 3b), the force distributions on the centrally-positioned ZnO nanowire in the y-z plane are manifested as shown in Fig. S3. The vertical forces in the z direction are attractive forces that pull the nanowires toward the Au film.

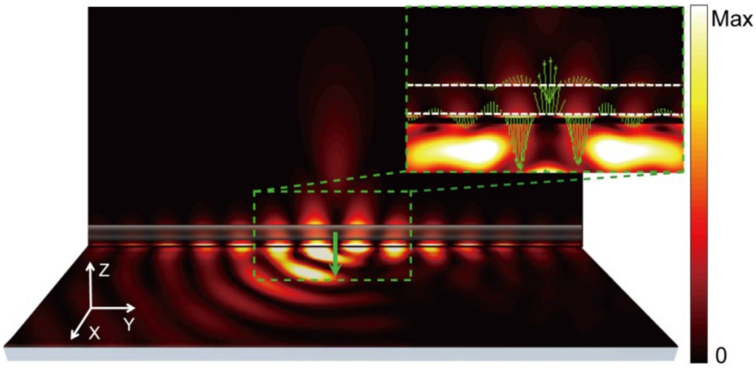

Fig. S3 Force distribution on centrally-located ZnO nanowire in the vertical y-z plane. The polarization direction of the incident laser is at an angle of 45° to the long axis of the nanowire. The background is the electric field distribution. The single green arrow shows the direction of the total force, and the smaller green arrows in the enlarged inset show the detailed distribution of the forces that are exerted on the nanowire surface.

Optical field distribution excited by single focused laser beam. To analyze the trapping phenomenon of a ZnO nanowire in the conventional optical tweezers system, we calculate the optical field distributions and the direction of gradient force of the focused laser beam, as shown in Fig. S4. The focused laser field is primarily distributed along the z-axis, and thus provides the gradient trapping forces required to align the nanowire to be upright along the z-axis.

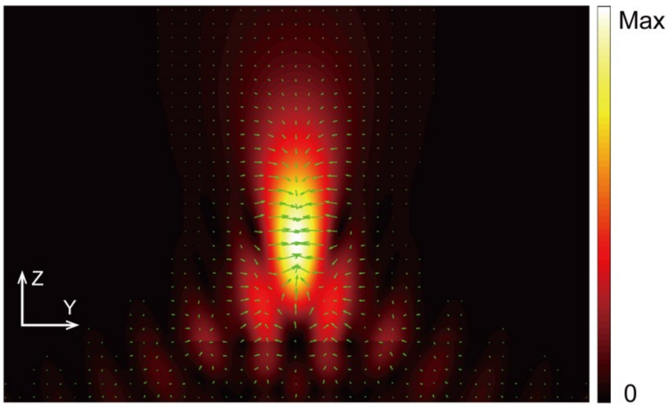

Fig. S4 Optical field distribution and the direction of gradient force (green arrows) excited by a single focused laser beam in the y-z plane.

Forces and torque analysis on ZnO nanowire in plasmonic tweezers. An asymmetric force acting on the ZnO nanowire will induce a torque and cause angular acceleration. Fig. S5a–d show the torques acting on the nanowire for different included angles of 0°, 30°, 60°, and 90°, and this indicates that the ZnO nanowire will rotate toward the orientation parallel to the polarization direction. As the angle increases from 0° to 90°, the nanowire rotates in a counterclockwise direction. The torque is near zero at 90°, indicating that the ZnO nanowire also reaches a balance when the nanowire is perpendicular to the polarization direction. This balance is formed by two opposing forces acting vertically relative to the nanowire (Fig. S5d). Therefore, a slight disturbance can break this balance and cause the nanowire to rotate until it lies parallel to the polarization direction. Fig. S6a-e shows the forces exerted on the off-center wires with different sizes at included angles 45°. It can be seen that the total resultant forces of all wires will attract the wire to the center of the excited SPP field, despite the magnitude of the forces is slightly different. Fig. S7a-e shows the forces exerted on centrally located ZnO nanowires with different sizes at same included angles 45°. It turns out that all nanowires will stably be trapped and rotated parallel to the polarization direction, in concordance with the experimental results in the main text. As a result, the size and geometry of the nanowire only have some influence on the magnitude of the forces and troques, but not a key factor for the trapping.

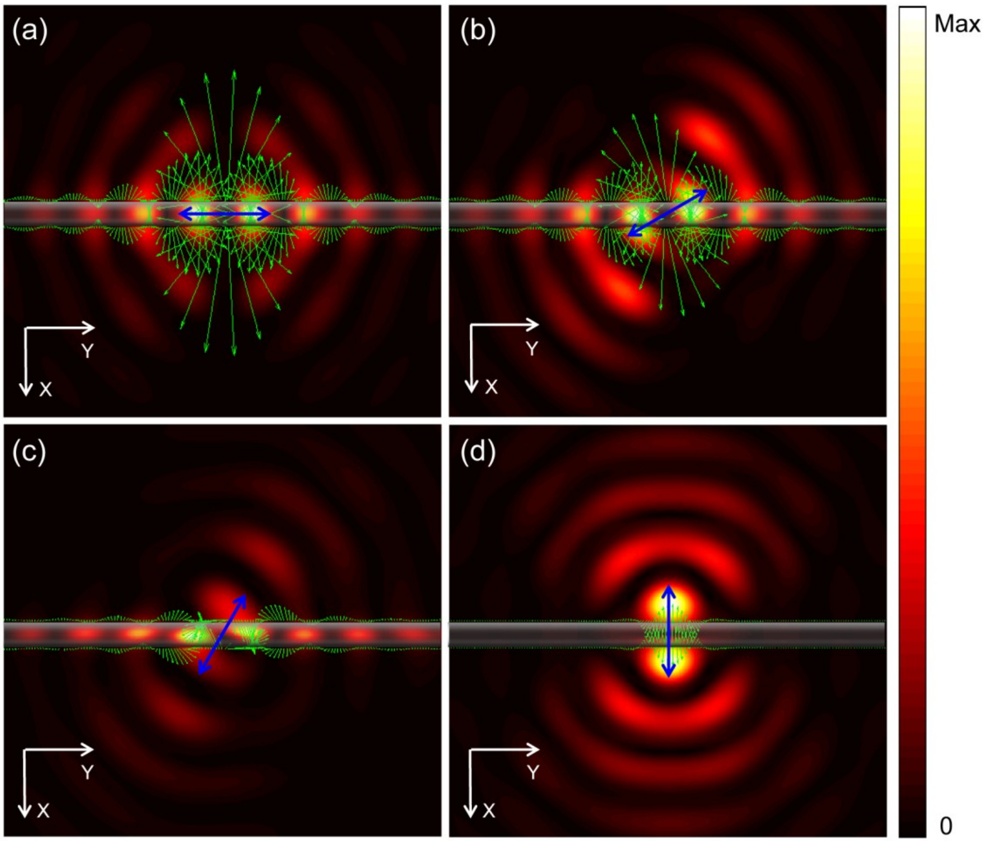

Fig. S5 Horizontal force distributions (green arrows) exerted on a centrally located ZnO nanowire in the x-y plane. (a), (b), (c) and (d) Horizontal forces exerted on the ZnO nanowire with included angles of 0°, 30°, 60°, and 90°, respectively (indicated by the blue arrows). These results suggest that the ZnO nanowire will rotate toward the orientation parallel to the polarization. The lengths and the orientations of the green arrows represent the magnitudes and directions of the forces. The background is the resulting electric field amplitude.

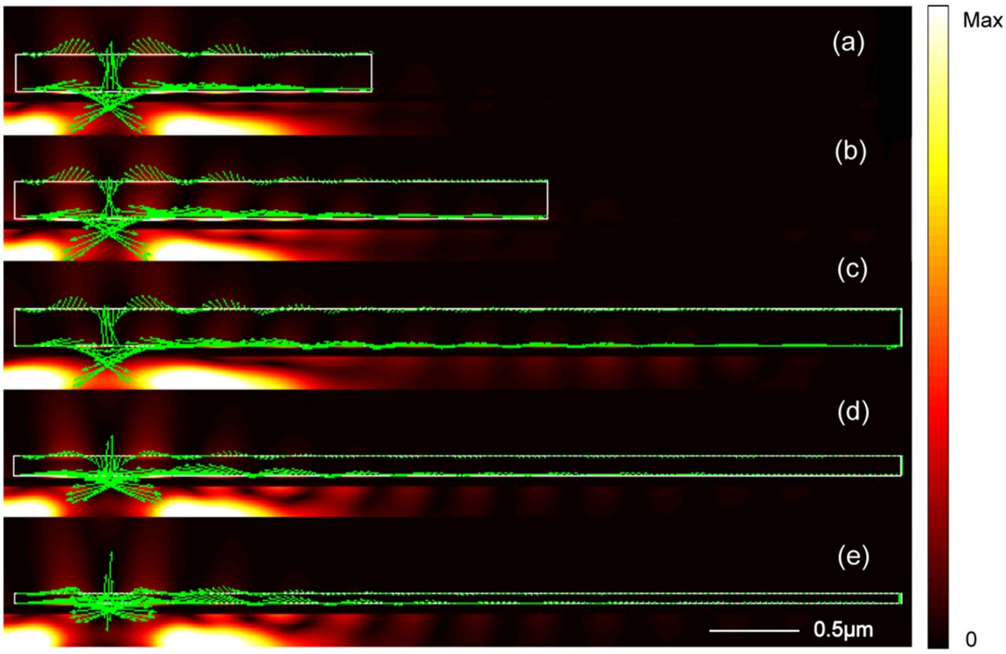

Fig. S6 Force distribution exerted on the off-center ZnO nanowires with different lengths and diameters in the vertical x-y plane at included angles 45°. (a)-(c) The lengths are 1 μm, 3 μm and 5 μm, respectively, with the same diameter of 200nm. (d)-(e) The diameters are 100 nm and 50 nm with the same length of 5 μm. The background is the electric field distribution. The length and orientation of the arrows represent the magnitude and direction of the force.

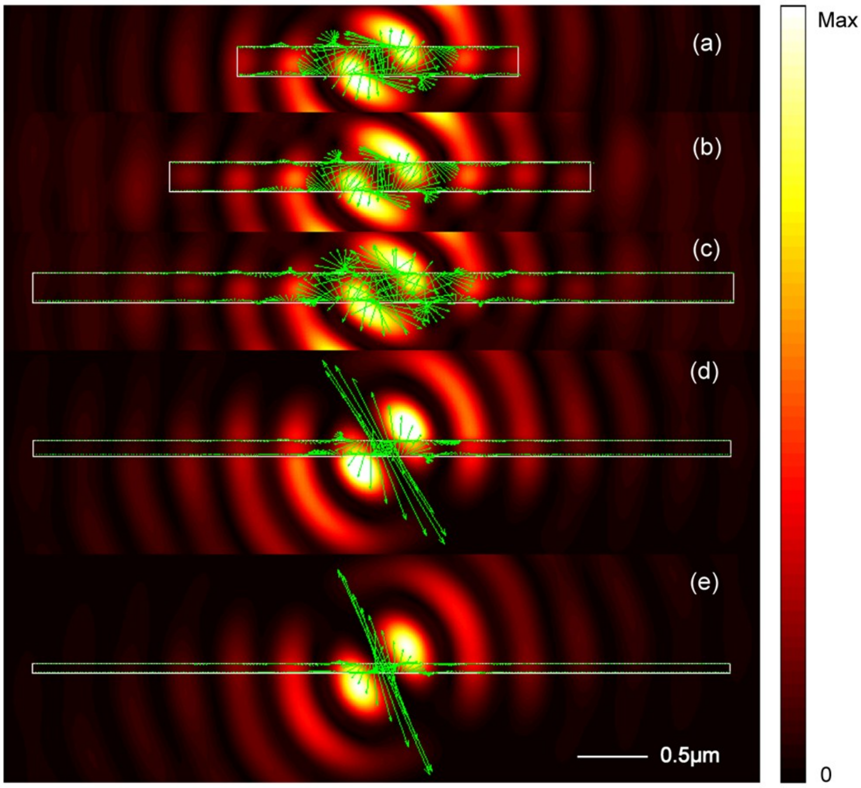

Fig. S7 Force distribution exerted on the centrally located ZnO nanowires with different lengths and diameters in the vertical x-y plane at included angles 45°. (a)-(c) The lengths are 1 μm, 3 μm and 5 μm, respectively, with the same diameter of 200nm. (d)-(e) The diameters are 100 nm and 50 nm with the same length of 5 μm. The background is the electric field distribution. The length and orientation of the arrows represent the magnitude and direction of the force.

Temperature distribution and thermal convection. Heating effects (including thermophoresis and convection) are always supposed to play a complicated role in plasmonic trapping systems. In our experiments, the highest incident power of the laser is ~100 mW and the efficient power is about 10 mW due to only a small amount of that power can be coupled to the SPPs (shown as dark arcs in the Supporting Information, Fig. S1). The metal film is usually located a few micro-meters below the focal plane, as a result, the average intensity of the light spot on the metal film is about 9.47 mW/μm^2. Thus, in the simulation, we chose an illumination intensity of 9.47 mW/μm^2. The calculated result is shown in Fig. S8. It can be seen that maximum temperature increase is only about 2.4 K and the highest thermal convection is 2.06×10^{-9} m/s, which is quite small compared with the optical force. Therefore, the influence of thermal effect can be ignored for the manipulation.

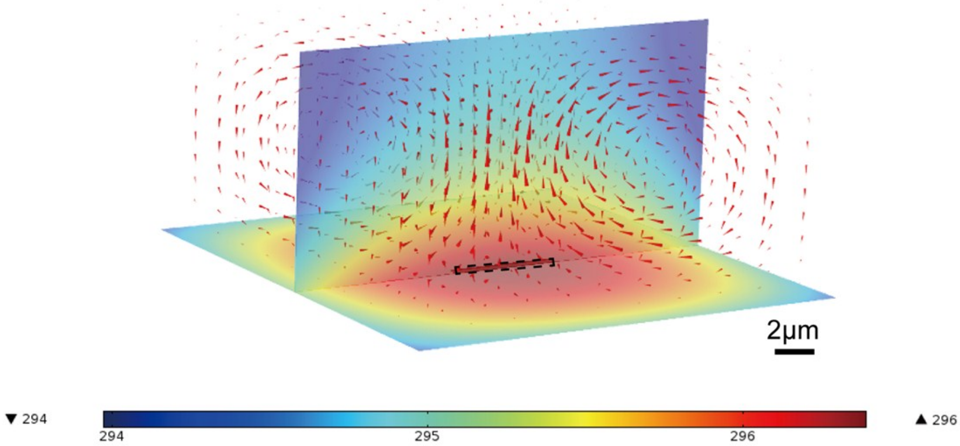

Fig.S8 3D distribution of thermal convection velocity near the central ZnO nanowire. The background shows the temperature distribution, and the arrows indicate the direction of the convection in water. The result of thermal convection currents demonstrates that the circulating fluid provides an ignorable influence.

Movies

Supplementary Video1 shows the in-plane trapping of a single ZnO nanowire with the focused plasmonic tweezers on the Au film surface.

Supplementary Video 2 shows the trapping process of a single ZnO nanowire with the conventional tweezers.

Supplementary Video 3 shows the rotational processof a single ZnO nanowire stimulated by changing the incident polarization direction.