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The manipulation and assembly of CuO nanorods with line optical tweezers

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Abstract
We present a simple technique for manipulating and assembling one-dimensional (1D) CuO nanorods. Our technique exploits the optical trapping ability of line optical tweezers to trap, manipulate and rotate nanorods without physical contact. With this simple and versatile method, nanorods can be readily arranged into interesting configurations. The optical line tweezers could also be used to manipulate an individual nanorod across two conducting electrodes. This work demonstrates the potential of optical manipulation and assembly of 1D nanostructures into useful nanoelectronics devices.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

In recent years, one-dimensional (1D) nanostructures such as nanowires, nanorods, nanobelts, nanotubes, and even linearly stretched DNA molecules, have attracted great interest due to their unique properties and potential for interesting applications. Such applications include nanoelectronic circuits [1, 2], ultraviolet lasers [3], chemical sensors [4], and optical switches [5]. One of the most important challenges faced by incorporating nanowires/nanorods into devices is to be able to manipulate and arrange the nanowires into desired formations or patterns. A variety of techniques have been developed for this purpose. Some of these techniques made use of microfluidic channels in flow alignment [6, 7], liquid crystal templates in organizing carbon nanotubes (CNTs) [8], a scanning probe in manipulating nano-mechanical switches [9], and patterned surfaces for locating and orientating individual carbon nanotubes [10]. In addition, the positioning of semiconductor [11] and metallic nanowires [12] has been realized using electric fields, and the alignment of magnetic nanowires [13, 14] has been realized using magnetic fields.

Over the years, optical tweezers, pioneered by Ashkin *et al* [15], have continually been developed into a versatile technique that facilitates the contactless manipulation of micro-sized or nano-sized particles [16]. In addition to the manipulation of spherical micro-objects, optical tweezers have been successfully employed to manipulate non-spherical and elongated structures, examples of which include flat particles [17], DNA [18], *E. coli* bacteria [19], microdisks [20], and the fused assembly of silica spheres [21]. In a recent effort, Plewa *et al* [22] demonstrated the trapping and manipulating of carbon nanotubes by holographic optical tweezers. Their finding suggests a new possibility with the application of optical tweezers onto 1D nanostructures and it is natural to further explore the possibility of using the optical tweezers to manipulate semiconductor nanowires/nanorods, which exhibit much more attractive properties as a building block compared with CNTs [2]. In order to achieve more effective control of the position and orientation of the nanorods, it is worthwhile to make use of appropriately shaped optical tweezers. In this work, we report the demonstration of line optical tweezers to trap and manipulate individual semiconductor copper (II) oxide (CuO) nanorods. With such system, we are able to

(i) control the motion and position of a single nanorod;

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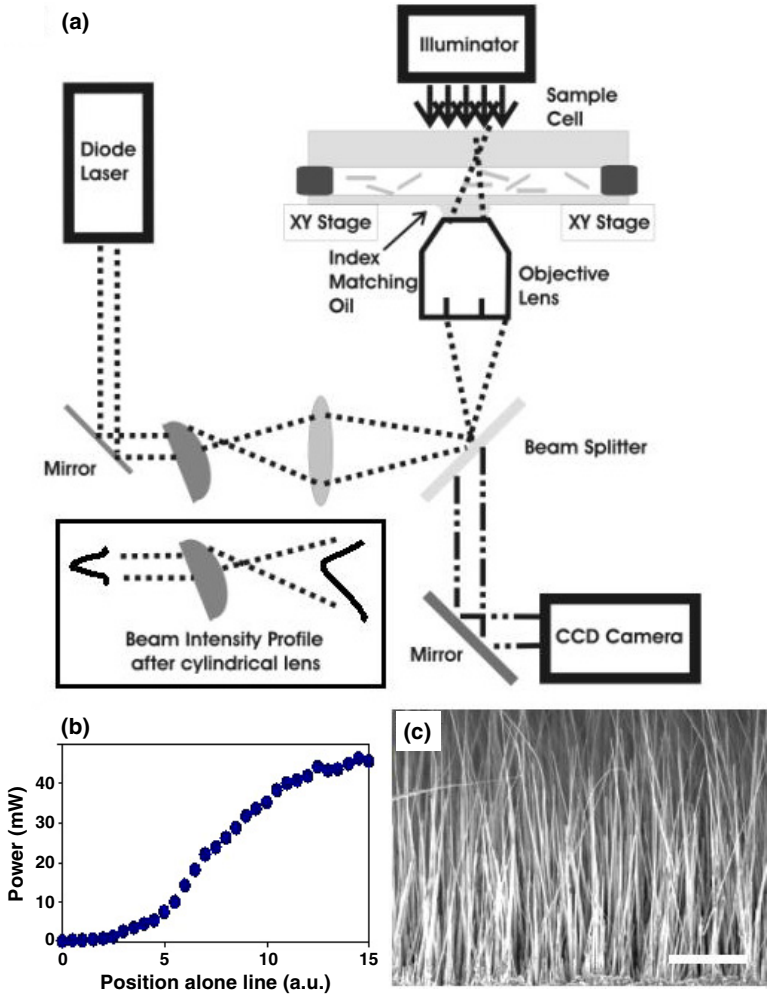

Figure 1. (a) Schematic of a line optical tweezers system and a sample cell. (b) Measured profile of the power of line tweezers. (c) SEM image of the side view of as-grown CuO nanorods. Scale bar = 5 μm.

(ii) arrange several nanorods into a line or other configurations; and
(iii) arrange a nanorod across two electrodes.

Such line optical tweezers facilitate better control in terms of orientational arrangement as compared to single spot optical tweezers. This is a potentially useful technique in the fabrication of nanoelectronics devices.

2. Experimental details

Line optical tweezers can be created by (i) scanning a laser beam [23, 24]; (ii) dynamic holographic optical tweezers [25]; (iii) asymmetrical aperture [21] and (iv) inserting a cylindrical lens in the optical path of the trapping beam [19]. In this work, we adopted the simple technique of inserting a cylindrical lens in the path of the laser beam to create the line optical tweezers. Figure 1(a) shows a schematic of the experimental setup used in this work. It was a typical setup for an optical tweezers system with an additional cylindrical lens inserted in the laser beam path to achieve line tweezers with non-uniform intensity profile. The sample cell was placed on the sample stage of an inverted Nikon TE300 microscope that was equipped with an oil-immersion objective lens (100×, NA = 1.3). A SUWTech LDC-2500 Diode Laser emitting laser beam with a wavelength of 1064 nm and a maximum power of 500 mW was utilized as the laser source. As shown in figure 1(a), the laser beam was directed towards a tilted cylindrical lens in an off-axis manner. As a result, the laser spot spread out into a line. In addition, the originally symmetrical Gaussian intensity profile became skewed, as shown in the inset in figure 1(a). The diverging laser line passed through a biconvex lens before it entered the side-port of the inverted microscope. The beam was then reflected by a beam-splitter towards the objective lens. Since the beam spot was spread out into a line, as shown in figure 1(a), only half of the laser line passed through the oil-immersion objective lens before it was focused down to form the line optical tweezers. In this way, the resultant line tweezers would have a non-uniform and monotonously increasing intensity profile. Figure 1(b) shows a plot on the measured profile of the power of the line tweezers. The sample cell was illuminated in transmission mode with a halogen light source from the top. The image was captured using a Hamamatsu CCD camera. The images were recorded onto videotapes or fed directly to a computer.

The semiconductor cupric oxide (CuO) nanorods used in this work were synthesized by a simple method detailed

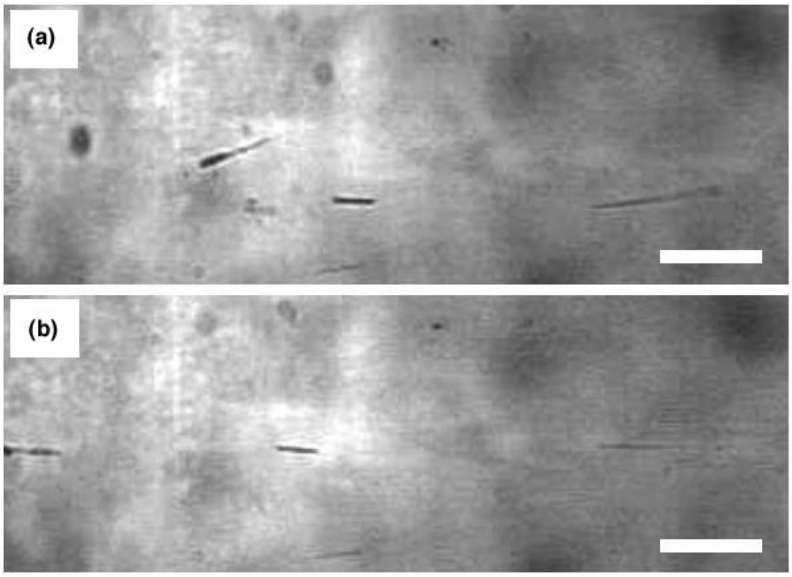

Figure 2. Optical micrographs showing (a) CuO nanorods in the field of view in the absence of the line tweezers. (b) Nanorods lined up in a single line due to the influence of the line tweezers. Scale bars = 15 μm.

M Multimedia showing the nanorod manipulation process can be found at stacks.iop.org/Nano/15/1732

elsewhere [26, 27]. CuO is a p-type semiconductor with a narrow band gap (1.4 eV) [28]. Figure 1(c) shows an SEM image of the side-view of as-grown and aligned CuO nanorods grown on a substrate. Typically the diameter of the CuO nanorods ranges from 50 to 100 nm, and the average length of the CuO nanorods used in this work is 20 μm. The bottom layer where the CuO nanorods grow is Cu_2O, the precursor for the growth of CuO [26, 29]. In order to make the sample cell as shown in figure 1(a), a small piece of the as-grown sample (Cu_2O thin layer with CuO nanorods) was suspended in deionized water. After 5 min of ultrasonic agitation, some nanorods became detached from the substrate and suspended freely in the deionized water. Three droplets of the suspension were dropped onto a glass slide and covered by a coverglass. The edges of the glass slide and coverglass were sealed with optical adhesive. Once assembled, the sandwich-like sample cell with the aqueous suspensions of CuO nanorods between the glass slide and coverglass was subjected to the tests.

3. Results and discussion

In the presence of the line tweezers, the nanorods were readily trapped by the line tweezers and aligned with their long axis in the line-shaped optical field. In addition, they were found to travel readily along the line tweezers towards the end with higher intensity. Since the strength of the optical trapping depends on the power of the laser beam, one can readily tune the trapping force with variation in the power of the laser beam. Figure 2 shows the optical micrographs of arranging several CuO nanorods into a line formation by optical line tweezers. Initially, the orientations and the positions of the CuO nanorods were random in the absence of the line tweezers (figure 2(a)). Once the line tweezers were turned on, the nanorods lined up in a single line, as shown in figure 2(b), thereby maximizing the volume of the nanorods in the region of highest electric field. This behaviour is typical of non-spherical objects, as reported in references [17, 19–21]. Once lined up, the nanorods were found to travel along the line tweezers towards the left end with higher measured power. This is mainly due to the varying magnitude in the trapping force induced by the increasing intensity profile of the line tweezers. Videoclips of the nanorod manipulation process with line optical tweezers can be found at the website [30].

With attractive properties, such as rectifying behaviour [10] and individually addressable device function [7], crossed nanowires play a significant role as basic building blocks for integrated nanodevices. We can use the line optical tweezers to arrange the CuO nanorods into a crossed formation. Figure 3 shows sequential optical micrographs that demonstrate the manipulation of CuO nanorods into a crossed formation. First, we trapped and aligned a nanorod with the line tweezers. Second, moving the sample stage with respect to the tweezers, we positioned the nanorod at the desired level. Lastly, the nanorod travelled along the line tweezers towards the high-power end where a pre-selected vertically oriented nanorod was located. Once the crossed formation was achieved, the line tweezers were turned off or the sample was moved rapidly away from the optical line tweezers. Thus, using this optical line tweezers, we can trap a nanorod, move it to a pre-selected nanorod, and obtain a cross formation. Using this technique, we can manipulate the nanorods and form some basic shapes, such as 'T', 'L', and a triangle. Videoclips of the formation of some of these configurations can be found at the website [30].

To study and measure the electrical transport properties of individual or crossed nanowires/nanorods, it is required to bridge the nanowires/nanorods across conducting electrodes. Sometimes the nanowires/nanorods were randomly deposited on a substrate and then followed by the deposition of the electrodes across both ends of nanowires/nanorods with the aid of electron beam lithography [31]. Therefore, the precise deposition of the electrodes in an ultra-fine space is required.

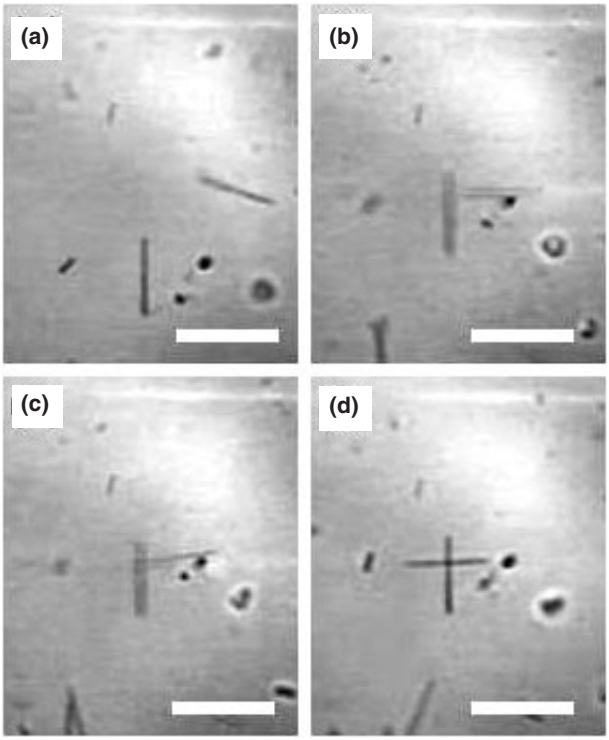

Figure 3. Sequential optical micrographs of the manipulation of nanorods into a cross formation with the line tweezers. Scale bars = 15 μm.

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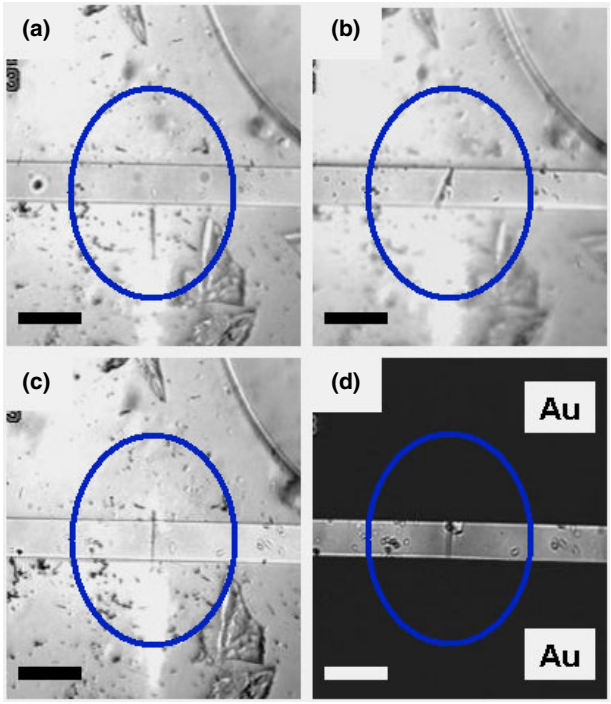

Figure 4. (a)–(c) Sequential optical micrographs of manipulating a CuO nanorod to bridge across Au electrodes with line tweezers. (d) Optical micrographs in transmission mode. Scale bars = 15 μm.

M Multimedia showing the trapping and manipulation of the CuO nanorod across the electrodes can be found at stacks.iop.org/Nano/15/1732

Here we present an alternative method to bridge a nanorod across electrodes with line optical tweezers. Figure 4 shows a demonstration of manipulating and bridging a CuO nanorod across two electrodes using the line tweezers. Prior to the fabrication of the sample cells, gold electrodes were first deposited onto a glass slides using electron-beam evaporation deposition. The optical line tweezers were set up in a direction that was orthogonal to the gap between two gold (Au) electrodes. When a suitable nanorod was identified, it was trapped and moved towards the gap and eventually bridged across the gap. In this particular case, we found that the nanorod remained in this bridging position for an extended period (7 days) even after the laser had been turned off. It was presumably held in position by the van der Waals force between the Au substrate and the nanorod. Compared with previous works, this simple method provides the flexibility and ease of selection of suitable nanorods with the desired length (to fit the gap in the electrodes). In addition, to a lesser extent, one can choose the nanorod with the desired diameter. An added advantage is that the whole process can be visually monitored.

4. Conclusions

In summary, we report our preliminary efforts in the trapping and manipulation of CuO nanorods with optical line tweezers. With this simple method, the motions, positions and directions of these nanorods can be precisely controlled. A cross formation and some basic shapes of such nanorods were formed. We have also demonstrated an alternative method to manipulate and bridge nanorods across Au electrodes. Future experiments include the formation of more extended network of nanorods; the formation and stabilization of the nanorod patterns while the solution is slowly drained or evaporated away; addition of multiple laser beams for more control; manipulation of nanorods in non-polar solvents; and manipulation of other 1D nanostructures.

Acknowledgments

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