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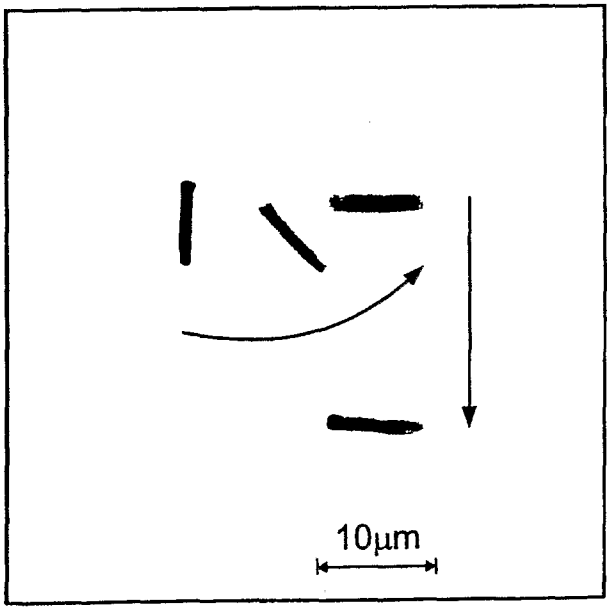
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(54) Title: SYSTEM AND METHOD FOR PROCESSING NANOWIRES WITH HOLOGRAPHIC OPTICAL TWEEZERS



(57) Abstract: A system and method for manipulating and processing nanowires in solution with arrays of holographic optical traps. The system and method of the present invention is capable of creating hundreds of individually controlled optical traps with the ability to manipulate objects in three dimensions. Individual nanowires with cross-sections as small as 20 nm and lengths exceeding 20 μm are capable of being isolated, translated, rotated and deposited onto a substrate with holographic optical trap arrays under conditions where single traps have no discernible influence. Spatially localized photothermal and photochemical processes induced by the well-focused traps can also be used to melt localized domains on individual nanowires and to fuse nanowire junctions.

WO 2007/084114 A2

SYSTEM AND METHOD FOR PROCESSING NANOWIRES WITH HOLOGRAPHIC OPTICAL TWEEZERS

[0001] This application is an application claiming the benefit under 35 USC 119(e) US Application 60/643,384, filed 01/12/2005, incorporated herein by reference in its entirety.

[0002] This work was supported by the National Science Foundation through Grant Numbers DMR-0233971 and DBI-0450878.

FIELD OF THE INVENTION

[0003] The present invention relates generally to semiconductor and metallic nanowires. More particularly, the present invention relates to the manipulating and processing of semiconductor and metallic nanowires in solution with arrays of holographic optical traps.

BACKGROUND OF THE INVENTION

[0004] Semiconductor and metallic nanowires are one-dimensional structures with unique electrical and optical properties that are used as building blocks in nanoscale devices. Their low dimensionality means that they exhibit quantum confinement effects. For this and other reasons, such nanowires are therefore versatile building blocks for assembling functional electronic and photonic devices. Realizing their potential requires efficient methods for assembling them into complex and specifically organized architectures.

SUMMARY OF THE INVENTION

[0005] It is therefore an object of the invention to provide an improved system and method for manipulating semiconductor and metallic nanowires.

[0006] It is another object of the present invention to provide an improved system and method for increasing the amount of force that can be exerted on semiconductor and metallic nanowires while minimizing radiative damage.

[0007] It is an additional embodiment of the present invention to provide an improved system and method for translating semiconductor and metallic nanowires.

[0008] In accordance with the above objects and others explained hereinafter, the present invention involves a system and method for using holographic optical tweezer arrays to assemble nanowires into precisely organized two and three-dimensional structures.

Individual nanowires with cross-sections as small as 20 nm and lengths exceeding 20 μm are capable of being isolated, translated, rotated, manipulated in other ways and deposited onto a substrate with holographic optical trap arrays under conditions where single traps have no discernible influence. Spatially localized photothermal and photochemical processes induced by the well-focused traps can also be used to melt localized domains on individual nanowires and to fuse nanowire junctions.

[0009] These and other objects, advantages and features of the invention, together with the organization and manner of operation thereof, will become apparent from the following detailed description when taken in conjunction with the accompanying drawings, wherein like elements have like numerals throughout the several drawings described below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. 1(a) is an image showing a focused light beam from a linear sixty-trap array; and

[0011] FIG. 1(b) is an image showing multiple exposures of a single CdS nanowire being rotated and translated by the optical trap array.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0012] The present invention provides for a system and method for manipulating and processing nanowires in solution with arrays of holographic optical traps. In one embodiment of the present invention, CdS and Si nanowires are dispersed in water for implementation of the present invention. In this particular embodiment, the CdS nanowires have a nominal diameter of 80 nm and lengths up to 20 μm, while the Si nanowires have even more substantial aspect ratios, with diameters as small as 20 nm. These samples are charged into slit pores about 40 μm thick formed by sealing the edges of clean glass coverslips to the surfaces of microscope slides. Both materials are substantially more dense than water ($\rho_{CdS} = 4.8g/cm^3, \rho_{Si} = 2.3g/cm^3$) and rapidly sediment onto the lower glass wall, with the CdS samples lying essentially perfectly in the plane. In this embodiment of the invention, sealed samples are mounted for observation and manipulation on the stage of a Zeiss Axiovert S100-TV microscope outfitted with a 100x NA 1.4 S-Plan Apo oil-immersion objective. This lens is used both to create bright-field images of the dispersed nanowires and also to focus light from a continuous wave (CW) frequency doubled Nd:YVO_4 laser operating at 532 nm (Coherent Verdi) into optical traps.

[0013] A single beam of light brought to a tight focus forms an optical trap known as an optical tweezer that can capture a mesoscopic object in three dimensions. At laser powers below roughly 1 W, however, an individual optical tweezer appears to be incapable of moving either type of semiconductor nanowire. Rapid heating at higher powers leads to the evolution of vapor bubbles whenever the focal point passes through a nanowire. Such rapid heating also leads to visible changes in the nanowires themselves, including bending, formation of nodules, and even scission. This is consistent with heating due to optical absorption in the substantial photon flux passing through the focal volume.

[0014] To exert more force on the nanowires while minimizing radiative damage, a large numbers of diffraction-limited optical traps are projected using the dynamic holographic optical tweezer technique. This approach uses a spatial light modulator (SLM) (Hamamatsu X7550 PAL-SLM) to imprint a computer-designed phase-only hologram encoding the desired array of traps onto the laser beam's wavefront before focusing. Each trap in the array can be translated independently in three dimensions by projecting a sequence of holograms encoding the sequence of intermediate trapping configurations.

[0015] The image in FIG. 1(a) shows the focused light from a linear sixty-trap array, which is shown moving a CdS nanowire in FIG. 1(b). In this case, the array was focused into the plane of the nanowire to within 0.5 μm and powered by 3 mW per trap. The nanowire, which initially was oriented perpendicular to the optical trap array, rotates into registry within a few seconds, even at such a comparatively low laser power. Given the intertrap separation of 0.4 μm, roughly 15 traps are trained on this nanowire simultaneously in its final configuration.

[0016] Given the above conditions, once the nanowire is aligned with the array, it can be translated at speeds up to roughly $u = 10$ μm/sec by moving the array across the field of view or by moving the sample stage relative to the array. It should be noted that the nanowire can be translated at speeds beyond $u = 10$ μm/sec by increasing the power, optimizing the laser wavelength, or any of a variety of other mechanisms for increasing the effective force per trap. The drag on a cylinder of length L and radius a translating through an unbounded fluid of viscosity η at low Reynolds number is approximately

$$F_{\infty} = 4\pi\eta\left(\varepsilon + 0.193\varepsilon^2 + 0.215\varepsilon^3\right)Lu, \qquad (1)$$

where $\varepsilon = [\ln(L/A)]^{-1}$, which sets a lower limit on the optically applied force of 0.2 fN/trap for CdS nanowires of this cross-sectional area. The actual drag on this nanowire is

substantially enhanced by the bounding glass surface at distance h ≈ 0.5 μm from the nanowire's center, and is given to lowest order in *a/h* by

$$F(h) = \frac{4\pi\eta L u}{\ln\left(\frac{2h}{a}\right)}, \qquad (2)$$

which increases the estimate for the trapping force by at least a factor of two.

[0017] The above estimates suggest that a single optical tweezer should be able to move a nanowire. Even if this were the case, however, the nanowire would rotate into an orientation that minimizes the drag force in the direction of motion, and thus would escape from the trap. The spatially extended trapping potential provided by the holographic optical tweezer array maintains the nanowire's orientation and thus makes controlled translation possible.

[0018] The conventional nature of the nanowires' response to optical tweezers is further demonstrated when an individual trap is transformed into an optical vortex, by imposing a helical phase profile $\varphi\left(\vec{r}\right) = \ell\theta$ onto the trapping laser's wavefront with the SLM. In this situation, $\vec{r} = (r,\theta)$ is a polar coordinate in a plane normal to the beam relative to the beam's axis and ℓ is an integer winding number defining the wavefront's helicity. The effect of this modulation is to transform a point-like optical tweezer into a ring-like trap whose radius scales linearly with the winding number, and whose photons each carry an orbital angular momentum of $\ell\hbar$, in addition to their intrinsic spin angular momentum. This angular momentum can be transferred to objects illuminated by the ring of light, resulting in a net torque proportional to the light's intensity.

[0019] Both Si and CdS nanowires tend to align themselves tangent to the ring of light. Once oriented tangentially, the cross-section that is subject to radiation pressure becomes larger and they get pushed away radially. Nevertheless, while in the region of the optical vortex trap, nanowires do get propelled around the circumference in the same direction as conventional micrometerscale dielectric spheres. These observations are consistent with the interpretation that nanowires experience optical tweezers as conventional optical gradient force traps despite their extremely small cross-sectional areas.

[0020] Optical tweezers also can move single nanowires vertically along the optical axis, and can press them against substrates. Unless particular care is taken to stabilize the nanowires against deposition, this results in the nanowire being irreversibly affixed to the

substrate by van der Waals interaction. In cases where the nanowires are stabilized, for example by a layer of adsorbed polymer surfactant, they still can be fixed in place by selective photochemical or photothermal processes. The simplest of these involves increasing the laser power until the stabilizing layer is desorbed or destroyed. Such selective contact deposition can provide the basis for controlled assembly of nanowires onto prefabricated functional substrates. A more aggressive form of such optical processing can be used to selectively melt the contacts between nanowires, thereby fusing them into permanent structures. A more precise variant might use linear or nonlinear photochemical processes to selectively induce photochemical changes at nanowire junctions to create specific functionality.

[0021] Nanowires of the type described herein can also be modified by projecting light of a specified intensity or specified wavelength onto the nanowires. The respective intensity and wavelength are chosen to affect specific changes along the length of the nanowire. Changes that can be effectuated include melting of the nanowire, cutting of the nanowire, and chemical transformation. These changes can all occur at the junction between nanowires comprising similar or different materials. Such transformations can also result in the forming of mechanical, electrical, or optical contacts between nanowires, as well as between nanowires and other substrates.

[0022] The results presented here demonstrate that holographic optical tweezer arrays can be used to assemble semiconductor nanowires into precisely organized two and three-dimensional structures. This process can be optimized by tuning the laser wavelength to enhance the optical trapping force, and will become substantially faster and more highly parallel with advances in holographic trapping technology.

[0023] The foregoing description of embodiments of the present invention have been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the present invention to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the present invention. The embodiments were chosen and described in order to explain the principles of the present invention and its practical application to enable one skilled in the art to utilize the present invention in various embodiments and with various modifications as are suited to the particular use contemplated.

WHAT IS CLAIMED IS:

1. A method of processing nanowires by providing at least a first nanowire, the improvement comprising the steps of inputting a plurality of beams of light, forming a plurality of optical traps, projecting the plurality of optical traps onto the first nanowire, and processing the at least first nanowire.

2. The method of claim 1, wherein the step of processing the at least first nanowire includes at least one of manipulating, isolating, heating and chemically transforming the at least first nanowire.

3. The method of claim 1, wherein the at least first nanowire comprises at least one of a metallic nanowire and a semiconductor nanowire.

4. The method of claim 1, wherein the at least first nanowire comprises at least one of CdS and Si.

5. The method of claim 1, further comprising the step of translating the at least first nanowire by altering the position of the array of optical traps relative to the at least first nanowire.

6. The method of claim 1, further comprising the steps of:

providing a second nanowire; and

fusing the at least first nanowire to the second nanowire by increasing the power projected by at least one of the array of optical traps.

7. The method of claim 1, further comprising the steps of:

transforming at least one of the plurality of optical traps into at least one optical vortex; and

using the at least one optical vortex to radially translate the at least first nanowire.

8. The method of claim 1, wherein the plurality of beams of light possess a predetermined wavelength in order to cause the at least partial change in the at least first nanowire.

9. The method of claim 1, wherein the plurality of beams of light possesses a predetermined intensity in order to cause the at least partial change in the at least first nanowire.

10. The method of claim 1, wherein the at least first nanowire and the second nanowire are selected from the group of identical materials and different materials.

11. The method of claim 1, wherein the change forms a contact between at least two of the at least first nanowire and the second nanowire, the second nanowire and a non-nanowire substrate, and the at least first nanowire and the non-nanowire substrate, wherein the contact is selected from the group consisting of a mechanical contact, an electrical contact, and an optical contact.



FIG. 1A

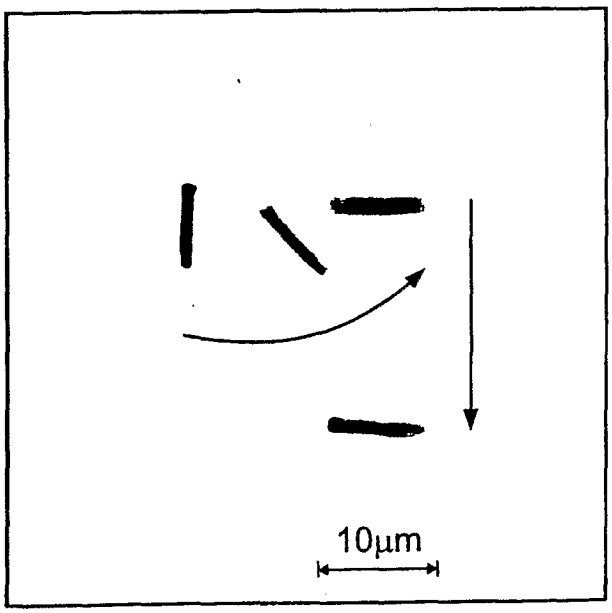


FIG. 1B