Translation and manipulation of silicon nanomembranes using holographic optical tweezers

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Abstract
We demonstrate the use of holographic optical tweezers for trapping and manipulating silicon nanomembranes. These macroscopic free-standing sheets of single-crystalline silicon are attractive for use in next-generation flexible electronics. We achieve three-dimensional control by attaching a functionalized silica bead to the silicon surface, enabling non-contact trapping and manipulation of planar structures with high aspect ratios (high lateral size to thickness). Using as few as one trap and trapping powers as low as several hundred milliwatts, silicon nanomembranes can be rotated and translated in a solution over large distances.

Keywords: optical trapping, silicon nanomembrane, nanofabrication, directed assembly

Introduction
Silicon nanomembranes are flexible, single-crystalline sheets with thicknesses ranging from less than ten up to several hundred nanometers [1,2]. These materials are extremely attractive for use in fast-flexible-electronic, optoelectronic, and nanophotonic applications. This broad potential derives from the unique properties imparted by the membranes' thinness relative to silicon wafers, including robustness, flexibility, and bondability. The structures can also be strain engineered to enhance individual electronic and mechanical properties or to produce unique tubular and helical nanostructures [2-6]. Successful integration of these structures into next-generation devices will require new paradigms for their assembly. The most promising methods for transferring and manipulating silicon nanomembranes to date include wet transfer (whereby nanomembranes are moved from the original substrate in a solution via adhesive attachment to a new host), dry transfer, and stamp printing processes [7-9]. As nanomembranes are made thinner and thus become more difficult to handle, mechanical means of manipulation are limited in their precision with regards to controllably placing individual membranes.

Holographic optical trapping [10-13] offers a promising new approach for manipulating silicon nanomembranes with a high degree of accuracy and precision that may circumvent some of the above issues. Optical tweezers use a single, tightly focused beam of light to manipulate micro- and nanoscale objects in three dimensions. The technique enables precise positional control in a non-contact and non-invasive fashion without damage to the trapped object [14]. Holographic optical trapping uses an array of traps to extend these same capabilities to multiple points in space. Each trap can be independently and dynamically controlled in real time. Although holographic optical tweezers have been used to manipulate microspheres, nanowires, and arbitrarily shaped biological molecules [15-18], application to two-dimensional (planar) geometries has been limited to objects with low aspect ratios and with dimensions less than approximately 5-10 × 5-10 μm [19,20]. The nanomembranes used for this work have thicknesses of 220 nm and in-plane dimensions of 50 × 50 μm, giving edge length-to-thickness aspect ratios of over 200. We believe this is the first time high-aspect-ratio planar materials have been successfully manipulated using non-contact techniques.

Most recent work on trapping and manipulating semiconductor materials has focused on one-dimensional nanowires [21,22], where the large index of refraction...
mismatches with the fluid medium complicates direct manipulation with the beam. Nanowires also tend to align along the axis of the laser and can be completely ejected from the trap, because of the overwhelming scattering force. This problem was recently circumvented for high-index vanadium oxide nanowires [23] using silica beads as a handle, the optical trapping of which has been well described in the literature [24]. The attachment of beads is commonly used when working with biological materials, where the arbitrary shape of the molecule or damage from laser heating can preclude trapping [25,26]. Wider application to directed assembly is limited, however, because removal of the handle has remained an issue: the manipulated object needed to be laser cut or damaged to achieve detachment or in other cases the covalently bonded bead could not be detached at all.

We present here a significant step forward, extending this initial work to the silicon nanomembranes described above. By attaching a single bead to the edge of a membrane, we achieve full three-dimensional control of large-area planar objects using optical tweezers. We furthermore succeed in reversible detachment of the handle bead without damage to the membrane, providing a substantial advantage over previous work. These capabilities will enable new, flexible routes for assembly of a variety of two-dimensional thin sheets of direct relevance to semiconductor, biotechnology, and sensor technologies.

**Results and discussion**

Attachment of silica microsphere handles is shown in Figure 1. The nanomembranes were dispersed in a deionized water solution with trace amounts of isopropyl alcohol. 3 mL of this suspension was pipetted into an open sample well with a glass coverslip bottom. The membranes submerge to an equilibrium distance several hundred micrometers below the surface of the liquid. After a suitable membrane was identified, commercially available 10-μm diameter silica beads with an amine terminated (-NH₂) surface functionalization (Sicastar®, Micromod Partikeltechnologie GmbH, Rostock-Warnemünde, Germany) were attached to the membrane using the optical trapping system. The functionalized microspheres, dispersed in de-ionized water, were added to the nanomembrane suspension. A single suspended bead was stably trapped at a power of approximately 300 mW and the submerged nanomembrane moved towards it using a Prior ProScan II (Rockland, MA, USA) motorized microscope stage. The bead was directed to near the desired attachment point and slowly brought to the edge of the nanomembrane using the microscope stage.

As the microsphere is brought into the immediate vicinity of the desired location on the nanomembrane, a strong van der Waals attraction causes immediate attachment. The bead attaches to the side of the nanomembrane, as evidenced by both objects remaining in the same focal plane and the final location of the bead at the very edge. A thin layer of silicon dioxide readily forms on silicon in the presence of water or alcohols at room temperature [27]. The oxygen-terminated surface of the nanomembrane reacts at multiple sites with the hydrogen from the amine-functionalized bead. The resulting bond, shown in Figure 2 at a single attachment site for clarity, has a relatively weak energy of around 20 kJ/mol per bond [28] but is strong enough to allow the simultaneous manipulation of the microsphere and membrane without detachment. The multiple bonds are also strong enough to rotate the nanomembrane into an equilibrium position immediately upon attachment while the bead remains firmly fixed in the trap, also shown in the figure.

Once attached, the bead functions as a nanoscale trailer hitch, facilitating manipulation of the bead together with the nanomembrane. Using a single optical trap and the motorized stage, the nanomembrane can be translated laterally over millimeter distances with laser powers on the order of 200 to 700 mW as measured at the sample. Higher powers allow larger gradient forces and permit the trapped bead to be moved at greater velocities.
At powers higher than approximately 700 mW, we observe a break in the bond between the nanomembrane and microsphere, and the two structures become decoupled. Detachment is observed only if the laser power is greater than this minimum, and we reason that this results from laser heating in the immediate vicinity of the bead-silicon nanomembrane attachment site, weakening the coupling moiety, but we cannot at this stage determine where the break occurs. Most importantly, this decoupling process does not damage the nanomembrane and we can reattach the membrane to this or a new bead. The reversibility of our procedure is very encouraging for future work in nanomembrane assembly using optical tweezers.

In the above range of trapping powers, the nanomembrane can be transported using the optical tweezers/motorized-stage system at velocities reaching 200 μm/s. Above this limit, the microsphere and nanomembrane tandem fall out of the optical trap. We observe a similar maximum velocity when laterally translating identical beads without attachment to a nanomembrane, suggesting that the hydrodynamic drag resulting from the unique shape of the nanomembranes is minimal. An order-of-magnitude estimate of the fluid drag force on the planar nanomembrane is calculated from

\[ F_D = C_D \frac{V^2}{2} \rho A, \]  

where \( C_D \) is the drag coefficient for a rectangular sheet as a function of area and Reynolds number, \( V \) is the velocity, \( \rho \) is the density of the solution, and \( A \) is the surface area of the nanomembrane [29,30]. The resulting drag force at maximum velocity for the nanomembranes used in this work is approximately 0.5 pN, two orders of magnitude lower than the approximately 20 pN calculated for a 10-μm microsphere using Stokes's law, \( F_D = 6\pi \mu RV \) [30]. We expect that this magnitude difference allows for lateral translation of nanomembranes having much larger surface areas, with minimal effect on motion at similar high velocities.

Finer-scale, more precise manipulation can be achieved using either diffracted traps from holographic optical tweezers or a steering mirror placed at a conjugate plane with respect to the objective lens. Figure 3 shows a trapped membrane being transported along a circular path that was predefined using the control software for the spatial light modulator. This motion occurs approximately 50 μm above the bottom of the sample well. Holographic optical tweezers offer exceptional control over individual trap positioning and velocity. Nanometer level manipulation at Angstrom-scale resolutions has been demonstrated for single optical traps [31], and this precision can be extended to multiple traps and multiple structures [32,33]. The benefits of this level of control are offset in part by the limited range of positioning that can be achieved within a single field of view of the ×20 microscope objective, approximately 350 × 450 μm. In comparison, the range afforded by our motorized microscope stage is several centimeters with 10-nm resolution and motion is limited only by the lateral dimensions of the sample well. Combining holographic optical tweezers with a motorized microscope stage offers unparalleled nanomembrane manipulation abilities over a large range of motion.

We investigated other methods of membrane manipulation using holographic optical trapping abilities to demonstrate the versatility of this approach. We found that the in-plane orientation of a single nanomembrane can be controlled about a single point of rotation, by harnessing the deleterious scattering force that otherwise precludes direct manipulation of membranes without an attached bead. Figure 4 shows this rotation. The two-part structure is held in position using a stationary optical trap that secures the attached microsphere in place while a second dynamically generated holographic optical trap is used to direct and rotate the object in place. Once the second optical trap is removed, the membrane remains in its configured position barring heavy flow in the immediate vicinity. Thus the trapped microsphere functions as a kind of nanoscale hinge.
Conclusions

In summary, we have used a functionalized-bead handle technique to translate and rotate high-lateral-size-to-thickness-aspect-ratio planar silicon nanomembranes in solution with holographic optical tweezers. The handle technique enables non-contact optical trapping of two-dimensional planar objects that could not otherwise be manipulated directly. Our approach permits individual nanomembrane positioning and transfer with unprecedented lateral control. The use of microspheres allows motion with well-documented nanometer-scale precision [14], while employing holographic optical trapping facilitates computer control of trajectories and enhanced positioning accuracy. We also demonstrated reversible attachment and detachment of handle beads without cutting or damaging the silicon material. We expect that this trapping method can be extended to manipulating silicon nanomembranes having larger lateral dimensions and differing thicknesses, in addition to the directed assembly of various other shapes and material compositions of planar objects with exceedingly small thickness [34-37]. The ability to tune the bond strength for membranes having different surface terminations may provide a future path for more selective, simultaneous manipulation of a variety of different planar materials. The successful use of holographic optical tweezers demonstrated here could be expanded to include massively parallel control over multiple nanomembranes, thus making heterostructure stacking and assembly a realizable goal. This simple proof of concept could eventually enable more advanced non-contact nanofabrication using nanomembranes as building blocks for two- and three-dimensional optical and electronic devices.

Methods

Fabrication of Si nanomembranes

The silicon nanomembranes, 220 nm thick, were fabricated from the template (outermost crystalline silicon) layer of commercially procured silicon-on-insulator (SOI) wafers (SOITEC S.A., Bernin, France) [38,39]. The wafers were cleaned with acetone, methyl alcohol, and isopropyl alcohol prior to patterning with electron beam lithography to define the square boundaries of each nanomembrane. Reactive ion etching was employed to etch the template silicon layer along these boundaries followed by a wet etch in 49% hydrofluoric acid for 4 h to dissolve the underlying SiO2 layer. The wet etch causes the patterned, thin silicon membranes to release and settle on the silicon handle wafer, the bottom layer of the SOI. The patterned membranes were then
removed from the handle wafer by immersion in isopro-pyl alcohol and re-suspended in de-ionized water via a solvent exchange, where they remained stably dispersed for several weeks.

**Experimental system**

The holographic optical trapping system consists of a linearly polarized IPG Photonics YLR-10-1064-LP (Oxford, MA, USA) Ytterbium fiber laser operating at 1,067 nm with a maximum output power of 10 W. The laser is reflected off a Hamamatsu Photonics LCOS-SLM X10468 (Hamamatsu City, Japan) spatial light modulator (SLM), aligned through beam expanding optics, and finally directed into an Olympus IX71 inverted microscope (Olympus America, Inc., Center Valley, PA, USA), as shown in Figure 5. The beam diameter is expanded to slightly overfill the back aperture of the Olympus objective lens used for all

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**Figure 4** Extracted video frames showing laser actuated rotation of an optically trapped silicon nanomembrane. The silicon membrane is held in place using a single static trap directed at the attached functionalized bead. Frames (a) through (c) show membrane rotation about this coordinate using a second dynamic optical trap. The second trap does not directly interact with the nanomembrane but instead uses the optical scattering force to direct its motion. This indirect approach prevents damage to the strongly scattering silicon object.

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**Figure 5** Experimental setup. The schematic diagram shows expansion of linearly polarized fiber laser light onto a spatial light modulator (SLM) using lenses F1 ($f = 100$ mm) and F2 ($f = 200$ mm). A second telescope (lenses F3 and F4, $f = 500$ mm) produces a plane conjugate to the surface of the SLM at the back aperture of the microscope objective (20x objective lens shown). CCD = charge coupled device, for recording images.
experiments [26], ×20, numerical aperture (NA) = 0.5. Holographic optical traps were generated and dynamically controlled using a customized LabVIEW program adapted from a freeware SLM control code available from the University of Glasgow [40,41]. This interface gives us full three-dimensional spatial (translation and rotation) as well as temporal control over as many as 100 generated traps. Live power measurements were made continuously at the location of the beam dump, as shown in Figure 5, with more accurate measurements periodically made after the objective lens. All imaging was done using bright-field microscopy with a Lumenera Infinity 2 (Ottawa, Canada) digital microscope camera.

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Authors’ contributions
SMO and JRSP performed the translation and manipulation experiments. RBJ and SMO carried out the experiments [26], ×20, numerical aperture (NA) = 0.5.

Competing interests
The authors declare that they have no competing interests.

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References
1. Cavallo F, Lagally MG: Semiconductors Turn Soft: Inorganic Nanomembranes. Soft Matter 2010, 6:439-455.
2. Scott SA, Lagally MG: Elastic strain-sharing nanomembranes: flexible and transferable strained silicon and silicon-germanium alloys. J Phys D Appl Phys 2007, 40:R75-R92.
3. Yuan HC, Wang G, Ma Z, Roberts MM, Savage DE, Lagally MG: Flexible thin-film transistors on biaxial- and uniaxial-strained Si and SiGe membranes. Semicond Sci Technol 2012, 27:527-575.
4. Roberts WM, Klein LJ, Savage DE, Slinker KA, Friesen M, Celler G, Eriksson MA, Lagally MG: Elastically Relaxed Free-Standing Strained-Silicon Nanomembranes. Nat Mater 2006, 5:388-393.
5. Kim DH, Rogers JA: Stretchable electronics: materials strategies and devices. Adv Mater 2008, 20:4887-4902.
6. Huang MH, Boone C, Roberts M, Savage DE, Lagally MG, Shaji N, Qin H, Blick R, Nairn JA, Liu F. Nanomechanical architecture of strained bilayer thin films: from design principles to experimental fabrication. Adv Mater 2015, 17:2860-2864.
7. Menard E, Nuzzo RG, Rogers JA: Bendable single crystal silicon thin film transistors formed by printing on plastic substrates. Appl Phys Lett 2005, 86.
8. Yuan HC, Shin JH, Qin GX, Sun L, Bhattacharya P, Lagally MG, Celler G, Ma ZQ. Flexible photodetectors on plastic substrates by use of printing transferred single-crystal germanium membranes. Appl Phys Lett 2009, 013102.
9. Peng WN, Roberts MM, Nordberg EP, Flack FS, Colavita PE, Hamers RJ, Savage DE, Lagally MG, Eriksson MA: Single-crystal silicon/silicon dioxide multilayer heterostructures based on nanomembrane transfer. Appl Phys Lett 2007, 90:183107.
10. Dufresne ER, Spalding GC, Dearing MT, Sheets SA, Grier DG: Computer-generated holographic optical tweezer arrays. Rev Sci Instrum 2001, 72:1810-1816.
11. Dufresne ER, Grier DG: Optical tweezer arrays and optical substrates created with diffractive optics. Rev Sci Instrum 1998, 69:1974-1977.
12. Curtis JE, Koss BA, Grier DG: Dynamic holographic optical tweezers. Opt Commun 2002, 207:169-175.
13. Grier DG, Roichman Y: Holographic optical trapping. Appl Opt 2006, 45:880-887.
14. Grier DG: A revolution in optical manipulation. Nature 2003, 424:810-816.
15. Agarwal R, Ladavac K, Roichman Y, Yu GH, Lieber CM, Grier DG: Manipulation and assembly of nanowires with holographic optical traps. Opt Express 2005, 13:8906-8912.
16. van der Horst A, Campbell AI, van Vugt LK, Vanmaekelbergh DM, Dogterom M, van Blaaderen A: Manipulating metal-oxide nanowires using counter-propagating optical line tweezers. Opt Express 2007, 15:11629-11639.
17. Plewa J, Tanner E, Mueth DM, Grier DG: Processing carbon nanotubes with holographic optical tweezers. Opt Express 2004, 12:1978-1981.
18. Dholakia K, Reece P: Optical micromanipulation takes hold. Nano Today 2006, 1:18-27.
19. Galajda P, Ormos P: Orientation of flat particles in optical tweezers by linearly polarized light. Opt Express 2003, 11:446-451.
20. Rodrigo PJ, Kelemen L, Alonzo CA, Perch-Nielsen IR, Dam JS, Ormos P, Gluckstad J: 2D optical manipulation and assembly of shape complementary planar microstructures. Opt Express 2007, 15:9009-9014.
21. Pauzauskie PJ, Radenovic A, Trepagnier E, Shroff H, Yang PD, Liphardt J: Optical trapping and integration of semiconductor nanowire assemblies in water. Nat Mater 2006, 5:897-101.
22. Jackish A, Pauzauskie PJ, Schuck PJ, Ohta AT, Chiou PY, Jou Y, Yang PD, Wu MC. Dynamic manipulation and separation of individual semiconductor and metallic nanowires. Nat Photonics 2008, 2:85-89.
23. Hernandez-Pozosi JL, Lee WM, Vera-Robles LL, Campero A, Dholakia K: Controlled three-dimensional manipulation of vanadium oxide nanotubes with optical tweezers. Appl Phys Lett 2008, 93:243107.
24. Ashkin A, Dziedzic JM, Bjorkholm JE, Chu S. Observation of a single-beam gradient force optical trap for dielectric particles. Opt Lett 1986, 11:288-290.
25. Kuro SC, Sheetz MP: Force of single kinesin molecules measured with optical tweezers. Science 1993, 260:232-234.
26. Sveboda K, Block SJ: Biological applications of optical forces. Annu Rev Biophys Biomol Struct 1994, 23:247-285.
27. Salonen J, Lehto VP, Laine E: The room temperature oxidation of porous silicon. Surf Sci Forum 1997, 120.
28. Jeffrey GA: An Introduction to Hydrogen Bonding (Topics in Physical Chemistry) Oxford: Oxford University Press; 1997.
29. Mohanty SK, Mohanty KS, Gupta PK: Dynamics of interaction of RBC with optical tweezers. Appl Phys Lett 2005, 87:1434-451.
30. White FM: Fluid Mechanics. 4 edition. Boston: McGraw Hill, 1999.
31. Moffitt JR, Chemla YR, Ihahlky D, Bustamante C: Differential detection of dual traps improves the spatial resolution of optical tweezers. Proc Natl Acad Sci USA 2006, 103:9006-9011.
32. Martin-Badosa E, Montes-Usategui M, Carrinchar, Andilla J, Plegueuzuelos E, Juvells I: Design strategies for optimizing holographic optical tweezers set-ups. J Opt A Pure Appl Opt 2007, 9:S57-3277.
33. Engstrom D, Bengtsson J, Eriksson E, Gokcer M: Improved beam steering accuracy of a single beam with a 1D phase-only light spatial modulator. Opt Express 2008, 16:18275-18287.
34. Reina A, Jia X, Ho J, Newich D, Son H, Bulovic V, Dresselhaus MS, Kong J: Large area, few-layer graphene films on arbitrary substrates by chemical vapor deposition. Nano Lett 2009, 9:30-35.
35. Obratzsov AN, Obratzsova EA, Tyumin AV, Zolotukhin AA: Chemical vapor deposition of thin graphite films of nanometer thickness. Carbon 2007, 45:2017-2021.
36. Park I, Ko SH, Pan H, Gregoropoulos CP, Picano AR, Fretwell J, Lee ES, Jeong JH: Nanoscale patterning and electronics on flexible substrates by direct nanoinprinting of metallic nanoparticles. Adv Mater 2008, 20:4898+.
37. McAlpine MC, Friedman RS, Lieber CM: High-performance nanoelectronics and photonics and nanoscale patterning on flexible plastic substrates. Proc IEEE 2005, 93:1357-1363.
38. Bruel M: Silicon-on-insulator material technology. Electron Lett 1995, 31:1201-1202.
39. Bruel M, Aspar B, Auberton-Herve AJ: Smart-Cut: A New Silicon on Insulator Material Technology Based on Hydrogen Implantation and Wafer Bonding. 1996 International Conference on Solid State Devices and Materials (SSDM 96), Yokohama, Japan, Aug 26-29 Japan J Applied Physics: Yokohama, Japan, 1996, 1636-1641.
40. Leach J, Wulff K, Sinclair G, Courtal J, Thomson L, Gibson G, Karunwi K, Cooper J, Laczik ZJ, Padgett M: Interactive approach to optical tweezers control. Appl Optics 2006, 45:897-903.
41. Padgett M: SLM Control-Optical Tweezers at Glasgow University. [http://www.physics.gla.ac.uk/Optics/projects/tweezers/slmcontrol/].

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