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Nanotube micro-opto-mechanical systems

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Abstract

While there have been numerous reports on the electromechanical actuation of carbon nanotubes (CNTs), devices based on the photomechanical actuation of CNTs have been elusive until now. In this paper, we report the integration of single-wall carbon nanotube ensembles into micro-mechanical systems to realize a new carbon nanotube micro-opto-mechanical system (CNT-MOMS). CNT-MOM grippers were fabricated using CMOS compatible techniques involving nanotube film forming, wafer bonding, photolithography, plasma etching and dry release. A MOM-gripper displacement of ∼24 μm was obtained from a gripper of 430 μm in length under infrared laser stimulus and continuous operation of more than 140 000 cycles was acquired. The optical power consumption of the gripper operation was estimated to be as small as ∼240 μW. Manipulation of polystyrene microspheres in air was demonstrated using CNT-MOMS grippers. This study is one good example of how nanomaterials could be integrated into CMOS compatible techniques for applications in high performance MEMS and nanoscale actuation technologies.

1. Introduction

Materials that can reversibly change their physical properties upon application of external stimulus are used as sensors and actuators in many applications such as robotics, switches, prosthetic devices, micro-mechanical and microfluidic devices and various sensor applications. The best-known materials used today for actuation are piezoelectrics, electrostrictive materials, conducting polymers and shape memory alloys (SMA) [1–3]. However, electrostrictive materials are limited by the high driving voltages and low work density per cycle; Faradaic processes involving ionic diffusion encountered in conducting polymers present limitations on the actuation rate and cycle life in this actuation material [4]; SMA based actuation has been widely used in many applications and can be configured to give high strain capabilities; however, a cyclic mechanical deformation mechanism is needed for repeatable operation. It must be appreciated that all the above actuation technologies have already been successfully employed in a wide variety of practical applications, giving that different actuation materials match certain application requirements while their drawbacks are not a critical issue in such an application. However, most of them are not suitable in fabricating low cost, high performance miniature actuators for future nanotechnology, bio-nanotechnology and biomedical applications, where batch fabrication capability, scalability into nanoscales, ease of operation, remote controllability and high performance are all critical issues. Also, as devices become smaller (μm–nm), electrical connections are often complicated, requiring additional wiring circuits on different length scales.

Carbon nanotubes (CNT) and porous metallic nanoparticles and CNT/Pt hybrid nanowires have been recently proposed as new classes of actuator materials that require only small voltages for actuation compared to piezoelectric and ferroelectric materials [4–6]. However, current applications of these nanomaterials for mechanical energy conversion are based solely on electrochemical and electromechanical processes that require the use of electrolytes or external electronics, respectively, for their operation and thus are not capable of operating in a massively parallel fashion and in a remotely controlled environment. While CNTs have been shown to have better electromechanical properties than many known materials, there have been no reports on the use of the actuation properties of CNT with MEMS devices that shows simplicity of integration and achieves similar or better performance compared to their electrostatic MEMS counterparts. Part of the reason is due to a lack of proper integration techniques of nanotubes with CMOS/MEMS processes.

Compared to electromechanical transduction, photomechanical actuation offers an alternative way to couple energy into actuator structures and brings distinctive advantages such as wireless actuation, remote controllability, electrical–mechanical decoupling, low noise, easier scaling down and elimination of electrical circuits. Unfortunately, few material systems have been shown to exhibit photomechanical actuation properties and are often not compatible with CMOS processing techniques. Photostrictive materials such as PLZT ceramics [7, 8] and chalcogenide glasses [9, 10] were deemed as traditional photomechanical actuation materials. However they only show small strains and they are not compatible with CMOS/MEMS integration techniques. Recently, increasing evidence indicates that CNTs have novel photomechanical actuation properties, showing promising potentials to achieve optical–mechanical energy transduction in CNTs and CNT/polymer composite systems. In the recent past, it was reported that single-wall carbon nanotube/acrylic elastomer composite structures exhibited reversible light-induced elastic strain of up to 0.3% [11]. Light-induced reversible photomechanical actuation from multiwall carbon nanotube/polymer mixtures was also reported and further the direction of actuation was controlled by the pre-strain of the composite and by the alignment of CNTs [12–15]. Theoretical models revealed that photon-induced deformation of CNTs along the tube axis could be as large as 20% when embedded in a polymer matrix, showing the benefits of nanotubes in photomechanical actuation technologies [13]. Besides these experimental works based on CNT/polymer composite systems, pure CNTs in the form of 'bucky' paper or fibres have also been shown to exhibit photomechanical properties. Zhang *et al* reported the elastic responses of single-wall carbon nanotube bundles and fibrous networks under light illumination [16]. While this report was one of the first to show photomechanical actuation of nanotubes, it was not clear whether such light-induced deformations were of any practical import. Recently systemic studies on bucky paper and aligned CNT fibres also show the intrinsic photomechanical deformation properties from both single-wall and multiwall carbon nanotubes under infrared light stimulus. While there is growing interest in the photomechanical actuation of CNTs, practical micro- and nano-devices that utilize this principle have been elusive until now. Nanotube based nano-tweezers were reported in the past that showed the benefits of nanotubes for measuring electrical properties of materials at nanoscales [17]. However, the actuation mechanism of these tweezers was still electrical in nature requiring precise wire bonding, not compatible with working in liquid environments and not compatible with batch fabrication techniques.

In this paper, we report the integration of CNT ensembles into micro-mechanical systems by a CMOS/MEMS compatible fabrication process involving CNT film formation, film bonding to substrate, lithographic patterning and plasma etching of CNT. Utilizing the photomechanical properties from CNT ensembles, a new CNT based MOMS is demonstrated, where nanotubes exhibit multiple functionalities of both structural materials and actuation mechanisms. A novel CNT-MOMS gripper was fabricated based on surface micromachined SU8/CNT structures, which operated under infrared laser stimulus. While they operate due to photomechanical energy transduction, the MOMS grippers do not need any complicated electrical energy supply circuits, offering the opportunity of decoupling the electrical signals from mechanical actuation for better sensing/actuation applications requiring high signal to noise ratio. Because of the absence of driving circuits, the devices could potentially be scaled down beyond the range of electrical actuators which need additional patterning for wire bonding and electrical connections to the macroscale world. The MOMS grippers show comparable performance as their electrically driven counterparts. By controlling the laser illumination below ~800 mW, gripper openings of ~24 μm are readily obtained in a gripper of ~430 μm in length, which would not be possible in most micro-electromechanical tweezers without high driving voltages. The CNT-MOMS grippers are ideal for micro- and nano-manipulation and sensing applications such as nanoparticle assembly and probing, and live cell manipulation and sensing. As one example, the CNT-MOMS gripper was used to successfully manipulate and position polystyrene microspheres.

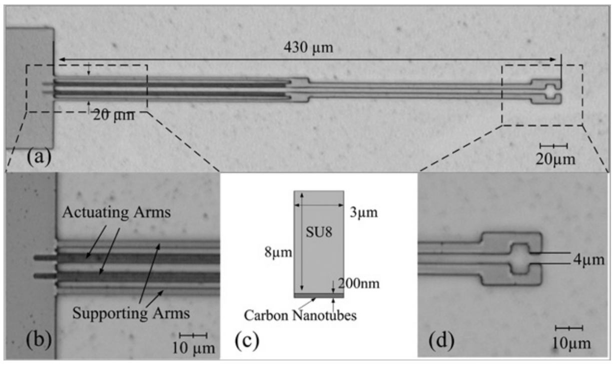


Figure 1. Design of the CNT-MOMS gripper. (a) A 'double arm' gripper with 430 μm in length and 20 μm in width; (b) the 'supporting arm' (2 μm in width)–'actuating arm' (3 μm in width) structure, The region with deep grey colour in the actuating arm indicates the CNT layer underneath the actuating arms; (c) cross-sectional view of actuating arms showing the SU8 frame of 8 μm in height and 3 μm in width on top of a 200 nm thick CNT film; (d) the gripper tips with a 4 μm initial opening.

2. Experimental details

To design the CNT-MOMS gripper, a double arm structure consisting of 'an actuating arm and a supporting arm' is employed to translate the photomechanical actuation in a CNT/polymer composite structure into the gripper's operations. Figure 1 shows the gripper design, which is similar to the traditional 'hot arm and cold arm' actuators [18–20]. As shown in figure 1(a), the gripper has the dimensions of 430 μm in length and 20 μm in width. The long actuator beams serve to amplify the gripper openings. The double arm design is better seen in figure 1(b), where the inner two arms are actuating arms (3 μm in width) and the outer two arms are supporting arms (2 μm in width). The region with deep grey colour in the actuating arm indicates the CNT layer underneath the actuating arms. In traditional 'hot arm and cold arm' actuators, the hot arm expands more than the cold arm when there is a temperature difference between the two arms, so that a length difference between the arms results, causing the bending and

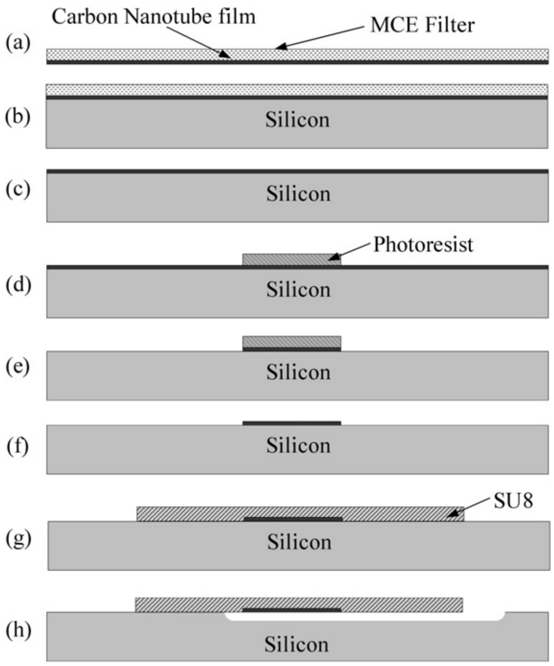


Figure 2. The fabrication processes of CNT-MOMS grippers. (a) CNT film formed on MCE filter after vacuum filtration; (b) CNT film together with MCE filter being transferred onto silicon substrate; (c) MCE filter dissolved to leave pure CNT film on silicon; (d) patterning photoresist for CNT plasma etching; (e) O_2 plasma etching of CNT film; (f) photoresist striped; (g) patterning SU8 photoresist for MOMS gripper frame; (h) XeF_2 dry etching to release the gripper.

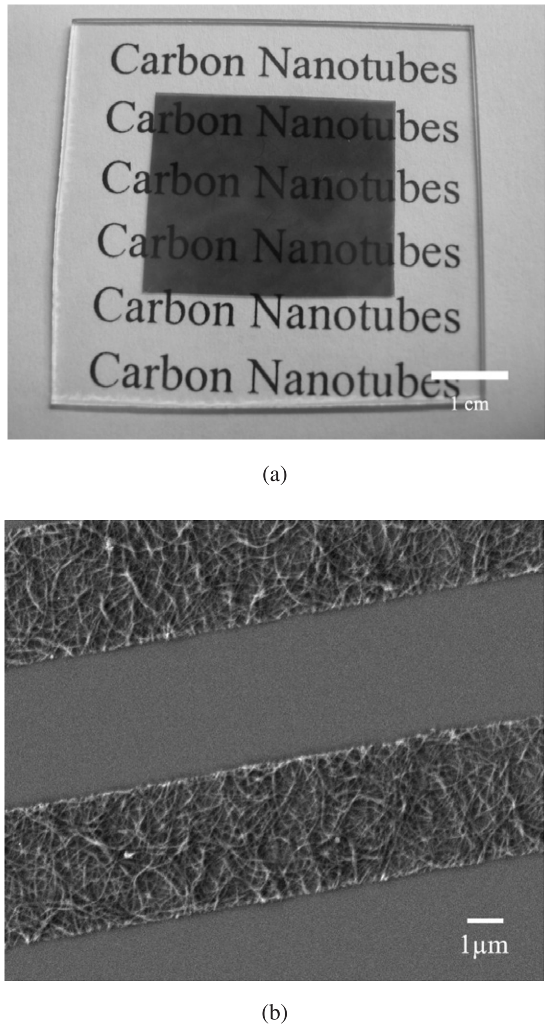


Figure 3. (a) A rectangular semi-transparent CNT film of ∼200 nm in thickness transferred onto glass substrate; (b) SEM image of CNT film patterns after O_2 plasma etching.

thus the actuation in the structure. In our gripper design, there is also a length difference developed between the actuating arm and the supporting arm during gripper operation. However, it is due to the photomechanical actuation of CNT in the actuating arm instead of resistive heating of the hot arm that results in the operation of the gripper. Simulation by ANSYS shows the effectiveness of translating photomechanical actuation of the actuating beam into the gripper operation, while the out-of-plane bending of the gripper is small with optimized structure thickness.

In recent years, SU8 has been widely used in fabricating micro-mechanical structures because of its excellent mechanical properties, high glass transition temperature, excellent bio-compatibility and compatibility with CMOS processing techniques. However, the application of SU8 in actuators is quite limited due to the difficulties of implementing and integrating a reliable actuation mechanism into SU8 structures [20]. Resistive heating for thermal actuation [19], pneumatic actuation [21] and shape memory alloy [22] actuation mechanisms have been investigated with SU8 structures. Here, by incorporating CNTs into SU8 structures, the photomechanical actuation mechanism was successfully implemented to accomplish the SU8 actuation. Figure 1(c) shows the schematic view of a cross-section area of the actuating arm, in which a thin layer of CNTs is attached to the SU8 frame. The slim actuating arms bear the height of ∼8 μm and width of ∼3 μm, which gives an appropriate aspect ratio of the structure to minimize the out-of-plane bending of the gripper, while avoiding beam warping or gripper 'bite' problems in the released grippers. By careful control of the fabrication process, the device yield was as high as 95%, which is partially due to the small residual stress in the CNT film and SU8 structure after fabrication. The dry release process employed here also contributes to this high device yield, which minimizes the effects of fabrication process and leaves intact device structures. An optical image of the gripper tips in the shape of a holder is shown in figure 1(d). A 4 μm opening is designed in the gripper 'close' state, which can be tuned to match the size of objects for micro- and nanoscale manipulation technologies.

To fabricate the CNT-MOMS gripper, we have developed a process consisting of a CNT film formation/film transfer/film patterning/structure release steps [23]. Single-wall carbon nanotubes are first dispersed uniformly into isopropyl alcohol by ultrasonication, followed by vacuum filtration to produce uniform CNT films of ∼200 nm thick on a mixed cellulose ester (MCE) filter, as shown in figure 2 step (a). The CNT film on a MCE filter is transferred onto silicon substrate by compressive loading and moderate temperate (80 °C) annealing to form intimate contact between CNTs and substrate as shown in figure 2 step (b). The MCE filter is then

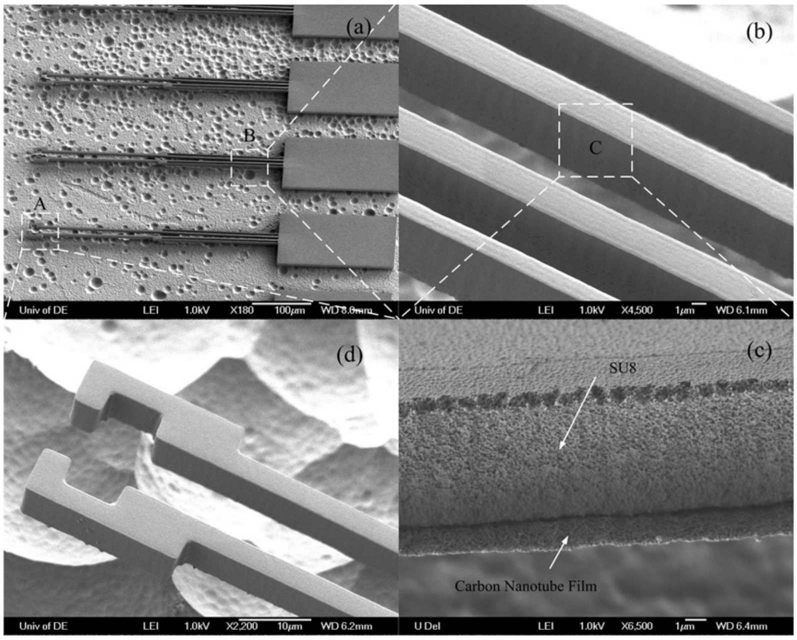


Figure 4. SEM images of CNT-MOMS grippers released from the substrate. (a) Gripper arrays; (b) magnified square B in figure (a) showing the actuating arms and the supporting arms; (c) magnified square C in figure (b) showing the cross-sectional view of the actuating arms; (d) the magnified square A in figure (a) showing the structure of the gripper tips.

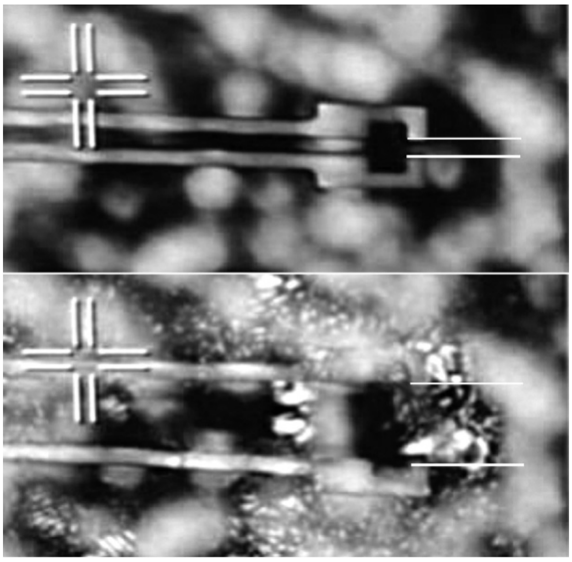
removed by multi-baths of acetone rinse to leave pure CNT film on top of the substrate (figure 2 step (c)) [23, 24]. Through these processes, uniform CNT films of desired thicknesses were readily produced on various substrates. Nanotube films that are less than 300 nm start showing a high degree of transparency. By varying the film thickness and the transparency one can tune the photomechanical actuation properties in CNTs. Such transparent CNT films can also be employed as passive or active optical components in MEMS and nanoscale actuation technologies after patterning. After nanotube film forming, a standard lithography was used to pattern the CNT film, followed by oxygen plasma etching in a ICP system and masking photoresist removal process, as indicated in figures 2(d)–(f). A second lithography is then applied to form SU8 structural layers, as indicated in figure 2(g). Finally the gripper structures are released from the silicon substrate by XeF_2 dry etching [23], shown in figure 2(h). A blind cut of substrate also help to get a better view of the grippers during operation.

Figure 3(a) shows a semitransparent uniform CNT film on top of a piece of glass, which was produced by the above described CNT film formation and transfer processes. Fine patterns of CNT films produced by plasma etching were shown in the SEM image in figure 3(b). The above described simple double lithography process is used to fabricate the CNT-MOMS grippers with high throughputs. Micro-gripper arrays were fabricated, in which all the grippers operate simultaneously under illumination from a single light source. This is not possible with most MEMS based tweezers operating on the electrostatic actuation principle. Figure 4(a) shows the SEM pictures of a gripper array after being released from the substrate. The wider actuating arm and narrower supporting arm are clearly seen in figure 4(b). Figure 4(c) depicts the cross-sectional view of the actuating arms, which shows the SU8 structure on top of the thin CNT layer. The gripper tips are shown in figure 4(d). Being far away from the actuating arms, the gripper tips are separated away from light stimulus, ensuring minimal light-induced effects on the objects being manipulated during gripper operation.

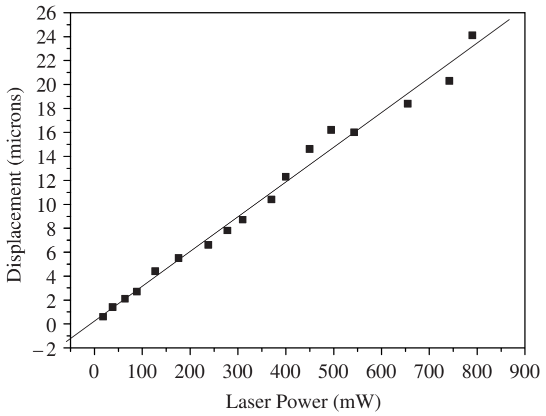
Following the fabrication, the CNT-MOMS grippers were tested under light illumination. An 808 nm semiconductor laser focused into a $\sim$5 mm $\times$ 1 mm spot is used as the light source. A CCD camera mounted on an optical microscope is used to measure the displacement of the gripper tips. To test the ability of the gripper for micro-manipulation, polystyrene microspheres of $\sim$16 μm in diameter were used as the micro-objects.

3. Results and discussion

Successful operation of micro-grippers based on SU8 polymeric structures is guaranteed by the reliable photomechanical actuation from CNT/polymer composite structures, which serves to couple the photonic energy directly into the microstructures, transforms it into mechanical energy and ensures enough mechanical deformation to occur in the rigid polymer structure. A typical optical image of the gripper tips in the ‘close’ state is shown in figure 5(a). When infrared laser light of $\sim$550 mW is directed to the actuating arms, the gripper tips open to $\sim$20 μm, resulting in $\sim$16.5 μm displacement, as shown in figure 5(a). In our gripper, the photomechanical actuation of the actuating arms causes the elongation of this arm and a length difference between the actuating arm and the supporting arm, resulting in the gripper opening. We have reported that a released CNT/SU8 cantilever exhibits a ‘Z’ direction displacement normal to the cantilever surface under light illumination [23]. However, the ‘Z’ direction actuation is not suitable for the integration of the actuation mechanism with



(a)



(b)

Figure 5. (a) Snapshots showing the closing and opening of the gripper tips under laser illumination. (b) Displacement of the CNT-MOMS gripper tips as a function of the laser illumination. The straight line is the linear fit of the experimental data.

surface micro-machined structures. By employing an 'actuating arm and supporting arm' double arm structure, the photomechanical actuation can be transferred into the horizontal 'X–Y' plane as shown by the gripper example, which brings more compatibility of this photomechanical actuation with surface micro-machined structures. Theoretically, many electrically driven MEMS structures that involve movable structures such as micro-motors, micro-gears, micro-stages and micro-mirrors can be implemented using this nanotube photomechanical actuation principle without requiring electrostatic actuators. The advantages of this actuation principle are the ease and simplicity of implementation, low power of operation, capable of working in liquid, air and vacuum environments [11], remote controlled actuation and capable of operation in a massively parallel fashion using one light source. Further, the photomechanical actuation mechanism reduces the complexity compared to MEMS based electrostatic actuators and can be easily removed from the substrate for 3D manipulation.

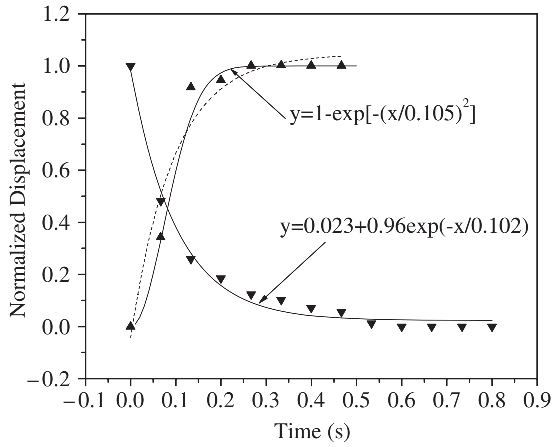


Figure 6. The transient response of normalized displacement (opening) of the gripper during light switching period. (▲) During light 'on' period, the displacement data follows a compressed exponential function: $y = 1 - \exp[-(t/0.105)^2]$, as indicated by the solid line, while a simple exponential function cannot fit the data, as shown by the dashed line. (▼) During light 'off' period, the displacement data follows a simple exponential function: $y = 0.023 + 0.96 \times \exp(-t/0.102)$.

Figure 5(b) shows the gripper tip displacements as a function of light intensity. A nearly linear relationship was found and there was no saturation of displacement in the whole testing range. For laser light of ∼800 mW, a large displacement of ∼24 μm was obtained from a gripper of 430 μm in length. These results indicate that the performance of the MOMS grippers is comparable to their electrically driven MEMS counterparts, but only driven by photomechanical actuation [17, 19, 20]. The light intensity being used for the gripper operation is qualitatively high, ranging from 0.6 to 20 W cm^{-2}, taking into account the small laser spot size after focusing and collimation. However, due to the small area of the gripper (∼600 μm^2), the driving photonic energy was estimated to be as small as 240 μW per gripper during operation, assuming that all the photonic energy illuminated on the actuating arm is absorbed. Low power optical sources well focused into small spots would be enough for gripper operation, expanding the potential application of this MOMS gripper.

The operation mechanism of this CNT-MOMS gripper involves electrostatic, elastic and photomechanical effects in the nanotube–polymer films [11]. Opto-thermal effects of the structure can also contribute to the total actuation. From previous works conducted on macro-size samples, the thermal effects were estimated to be smaller than 25% of the total actuation, showing that it is the competing mechanisms between elastic, electrostatic, photomechanical and opto-thermal effects that cause the actuation [11–13]. Figure 6 shows the transient response of the gripper displacement during the light switching period. When the light is switched on, a fast increase of the displacement is witnessed, which follows a compressed exponential function: $y = 1 - \exp[-(t/0.105)^2]$. A simple exponential function fails to fit the experimental data, as shown by the dashed line in the figure. The reaction of the CNT/polymer structure upon light stimulus is faster than the classical Debye relaxation in a

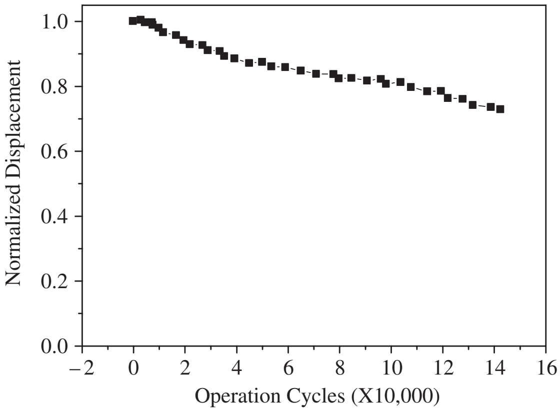


Figure 7. Stability of the CNT-MOM gripper during continuous operation under 350 mW laser stimuli at 5 Hz actuation rate.

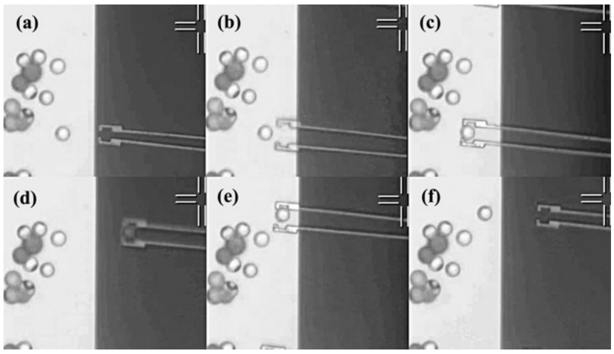


Figure 8. Sequence of a CNT-MOMS gripper attached to a mechanical manipulator to manipulate a micro-polystyrene sphere of ∼16 μm in diameter. (a) Closed gripper approaching the microsphere; (b) gripper opened under light illumination; (c) gripper closed to grasp the microsphere; (d) the microsphere lifted from the substrate and transferred to destination; (e) microsphere being released to the destination under light illumination on gripper; (f) gripper removed and closed.

polymer matrix. When light is switched off, the relaxation of the gripper displacement follows a slower exponential function of time: $y = 0.023 + 0.96 \times \exp(-t/0.102)$. These results qualitatively agree with the photomechanical actuation and relaxation of multiwall carbon nanotube/polymer composites observed previously [14], indicating that the gripper operation is dominated by the photomechanical actuation mechanism instead of infrared heating of the structure. The time constant of the gripper operation is ∼105 ms, progressively faster than that observed from macroscopic samples [11–13]. This may indicate that micro- and nanoscopic samples may operate faster than macroscopic samples through photomechanical transduction, as the stress transfer and relaxation inside the CNT networks and polymer matrix take shorter times in micro- and nanoscopic samples. Further experimental observations indicate that the actuation rate of the structures could potentially be improved by increasing the degree of alignment of CNT networks, which will be addressed elsewhere.

To test the reliability of the actuation mechanism of the MOMS gripper, the grippers were operated continuously under laser intensity of 350 mW. The laser pulses had 50% duty cycle and were operated at 5 Hz. Figure 7 shows the stability of the MOM gripper displacements which was normalized by the initial gripper displacement at the beginning of the testing. The gripper was continuously operated for more than 140 000 cycles. The degradation of the gripper displacement was within ∼28% of the initial value, showing the robustness of actuation in the nanotube/SU8 polymer. The performance degradation of the gripper may be attributed to the relaxation of CNT networks, the degradation of the contacts of CNT and polymer at their interfaces and also mechanical fatigue of the SU8 polymer. By dynamic control of the light intensity used to drive the gripper, the degradation of the gripper displacements can be dynamically compensated to remain at a constant performance. Low power light sources, when employed to actuate the gripper, can also improve the stability even further. This MOMS gripper could potentially be used in many areas such as micro- and nano-manipulation and assembly. Successful manipulation of polystyrene microspheres of ∼16 μm diameter in air was demonstrated as shown in figure 8. Figures 8(a)–(f) shows the sequence of the gripper during manipulation of the microsphere. The released micro-gripper is attached to the arm of a mechanical manipulator, which first approaches the microsphere (figure 8(a)). Upon approaching the microsphere, the gripper is then opened by light stimulus as shown in figure 8(b). The gripper is then closed by switching off the light to grasp the objects (figure 8(c)). The microsphere is then lifted from the substrate and transported to the destination (figure 8(d)), where the gripper is opened again by light stimulus to release the object, as indicated in figure 8(e). Finally it is closed and removed from the microsphere to finish the manipulation (figure 8(f)). Although the manipulation shown here is two dimensional, the gripper is released and fully free from the substrate unlike most MEMS based electrostatic grippers that are anchored in plane. By improving the gripper design to accommodate a 'Z' direction actuation mechanism, three-dimensional manipulations are also possible through CNT photomechanical actuation.

While the CNT-MOMS gripper is successful in manipulating the microscale objects, structural optimization of the gripper may show better performance compared to their electrically driven counterparts. With little modification one can use these grippers for biological manipulation of cells without having to worry about electrolytic currents that are often a problem in electrically driven tweezers. By making design modifications one can potentially extend the performance of the same grippers for nano-manipulation down to sub-hundred nanometres using optical actuation principles. Further, many other potential MOMS applications can be made possible by the integration of CNT photomechanical actuation with the micromachined structures, which will render the micro-devices new properties and new potential applications. We believe that systems based on optical actuation of CNTs could be a nice alternative to MEMS based electrostatic actuators. For sensing and actuation applications in nanoscale, this actuation technique would show favorable scaling properties due to the lack of electrical driving circuits, which overcomes the complicated high resistive wiring problems and electro- and thermo-migration problems encountered in nanoscale electrically driven sensors and actuators.

4. Conclusion

The integration of CNTs into micro-mechanical systems results in a novel CNT based micro-opto-mechanical system. By incorporating CNT with SU8, a photomechanical actuation mechanism is introduced to SU8 polymer structures, resulting in a new CNT-MOMS gripper. We found that the optical actuation principle is simple, easier to implement, low power consumption, remotely controllable and compatible with MEMS/CMOS batch fabrication techniques. Tip opening of $\sim$24 μm is obtained from a gripper of 430 μm in length under $\sim$800 mW of laser stimulus, showing comparable performance to the electrically driven counterparts. However, the gripper consumed only $\sim$240 μW of the total optical power due to its small area. The grippers were used to successfully manipulate and position micro-polystyrene spheres in air. We believe that CNT-MOMS will extend the promising potentials of CNT based actuation technologies and will bring more opportunities in designing various optically driven micro-and nano-mechanical systems such as micro/nano surgical tools, micro/nano robotics, micro/nano resonators, micro/nano manipulation and positioning systems based on photomechanical effects in CNTs. This study is a good example of how new types of MOMS devices of practical import can be created by the integration of nanomaterials with MEMS/CMOS processes.

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