Single Wall Carbon Nanotube Optical Actuators: Towards Optical Artificial Muscles

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ABSTRACT

Optically driven nanotube actuators have been fabricated from single wall carbon nanotube -acrylic elastomer bimorph sheets. They were shown to generate higher stress than natural muscles and higher strains than high-modulus ferro-electric materials. Strain measurements revealed about 0.3% elastic strain under visible light intensities of 120mW/cm^2. A nanotube gripper based on this optical actuation principle is demonstrated to show manipulation of small objects. The principle of actuation is based on a combination of optical, thermal, electrostatic and elastic effects in the nanotube–elastomer sheets. Optically driven actuators using nanomaterials may eventually provide higher strains and lower power requirements than currently known actuation technologies.

Keywords: carbon nanotubes, acrylic elastomer, optical actuator

1 INTRODUCTION

The direct conversion of different types of energy to mechanical energy is of importance in many applications such as robotics, artificial muscles, optical displays, prosthetic devices, optical communication, micro-mechanical and microfluidic devices. Although piezoelectric ceramics, shape memory alloys, magnetostrictive materials are well known and their applications commercialized, they are handicapped by the maximum allowable operational temperatures, requirement of high voltages, and limitations on the work densities per cycle. In recent years, carbon nanotubes [1], metallic nano-particles [2] and polymer actuators [3, 4] have been proposed to be attractive alternatives to overcome these problems. Of these materials systems, polymer materials, which have stroke, force, and efficiency similar to that of human muscles, are very promising because of their low cost and wide choice of polymer materials.

Since its discovery, single wall carbon nanotubes (SWNTs) have attracted much attention owing to their excellent electrical, mechanical, optical and thermal properties [5-8]. A combination of the excellent optical and thermal properties of SWNTs could form the basis for future applications in the field of opto-thermal transduction at the micro- and nano-scale.

Many attempts have been made in the past to combine polymer material systems with SWNTs aiming to improve the properties of either system. They have been combined to improve electrical properties [9], mechanical properties of the composite [10], strain response of polymer actuator [11] and used as the functional layer in organic light emitting diodes [12,13]. However, the entire spectrum of polymer nanotube composite actuators has not been fully explored.

The new actuators we describe here use carbon nanotube-acrylic elastomer bimorph structure to realize the conversion from optical to mechanical energy. It is different from nanotube reinforced polymer actuators described recently [14] as the nanotubes are not mixed with the polymer materials to form composites but mechanically bonded to the acrylic elastomer to form a bimorph structure, which doesn't change the properties of polymer material. The primary mechanism of actuation is a combination of thermal and electrostatic mechanisms that are evidenced in nanotubes upon light absorption. The actuators overcome some of the fundamental limitations over piezoelectric, ferroelectric actuator materials and carbon nanotube based electro-chemical actuation technologies. The actuators respond to any remote source of light causing movements, eliminating the complicated electrical connections needed for electrically driven actuators.

2 EXPERIMENTAL AND DISCUSSION

The optically driven nanotube actuators as described here were surprisingly simple to fabricate. 16mg of SWNTs commercially obtained from Carbon Nanotechnologies was dispersed in 100ml iso-propyl alcohol and agitated for 20 hours to disperse the nanotubes uniformly in the solution to a final concentration of 0.16mg/ml. The SWNT suspension was then vacuum filtered through a poly (tetrafluoroethylene) filter (47 mm in diameter) [1]. The resulting SWNT sheet on the filter was rinsed twice with iso-propyl alcohol and DI water and then dried at 80ºC for 2 hours to remove any remaining organic residues in the sheet. After drying, the SWNT sheet was peeled off the filter with a final thickness ranging from 30µm to 40 µm and a bulk density of about 0.3g/cm^3. Figure 1(a) shows the optical image of a free standing SWNT sheet or "Bucky Wafer" made by vacuum filtration. Figure 1 (b) is the scanning electron microscope (SEM) image of the SWNT sheet composed of highly entangled SWNT bundles. This SWNT sheet was used in making the bimorph actuator without further optimization. The acrylic elastomer was purchased from 3M, sold as137DM-2. The material is available as a precast adhesive tape with 12.5mm in width and about 80 µm in thickness. A thin acrylic elastomer film derived from the adhesive tape, 30µm thick and 30mm×2mm in dimensions, was attached to a piece of SWNT sheet of similar dimensions by direct physical contact. The resulting bimorph structure was used to study the light induced actuation.

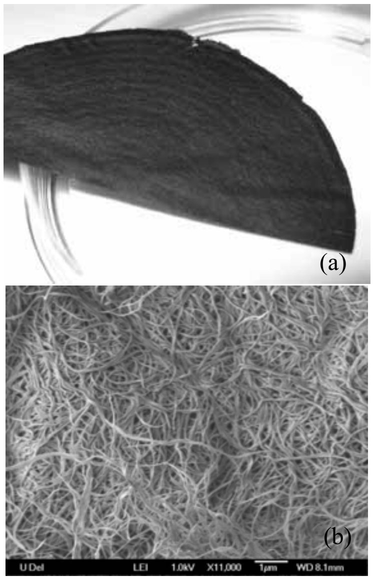

Figure 1: (a) SWNT sheet made by vacuum filtration. (b) SEM image of SWNT sheet composed of highly entangled SWNTs bundles.

As a first demonstration of actuation, a cantilever structure was made by attaching the bimorph actuator to a 100 µm thick PVC film. Figure 2(a) shows the schematic arrangement of the entire setup with the cantilever structure anchored on a base that bends in a direction normal to the cantilever surface. The structure of the bimorph actuator is shown in the inset. A halogen lamp of tunable intensity was used as the light source and was incident normal to the surface of the cantilever. The light intensity was recorded using Newport 1815-C intensity meter. A digital camera was used to characterize the displacement of the bimorph structure.

The displacement of the cantilever under optical illumination is shown in Figure 2(b). An intensity of 60mW/cm^2 was used to actuate the cantilever for four cycles. During the period of light exposure, the structure bends to the PVC side, indicating an increase in the length of the bimorph structure. Once the light source was turned off, the bimorph structure contracted back to its original length and the cantilever to its initial position, suggesting elastic deformations of the actuator upon illumination. The actuation was quite repeatable from cycle to cycle with nearly the same displacement amplitude. A maximum displacement of 4.3mm was achieved for a cantilever length of 30mm.

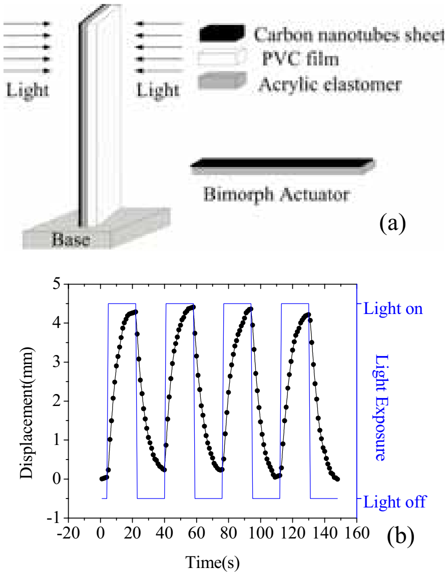

Figure 2: (a) Shows a cantilever vertically anchored on a base. The cantilever composed of a bimorph actuator (shown in the right lower part) and a 100µm thick PVC film. (b) Shows the displacement of the cantilever measured when light was turned "on" and "off".

In order to characterize the strain instead of the displacement suffered by the actuator under optical illumination, another experiment was set up as shown in Figure 3(a), in which the bimorph actuator was doubly clamped between a vertical anchor and the PVC film. The PVC film was 100µm thick and was fixed vertically to the base. The stress on the bimorph actuator (30mm×2mm), due to light incident normal to its surface, bent the PVC film. The displacement of the PVC film was recorded by a digital camera and was used to characterize the change in length of the bimorph actuator. Figure 3 (b) shows six cycles of strain response of the actuator under different light intensities. The strain cycles were quite repeatable with nearly the same strain amplitude for any given intensity. It can be seen that the strain values are positive suggesting that the SWCNT – acrylic elastomer bimorph actuator expands during optical exposure and returns back to its original strain free position when the source is turned off.

Acrylic elastomers have earlier been used as dielectric electroactive polymers as they produce higher strain and possess higher elastic energy density than any other dielectric elastomer [4, 15-17]. In the case of optical actuation, bonding the nanotube sheets with acrylic elastomer results in a new type of actuator that utilizes the opto-thermal transitions and electrostatic effect in carbon nanotubes. SWNTs are prefect black bodies and exhibit excellent optical and thermal absorption properties. Ajayan *et. al.* showed that fluffy SWNTs can burn when exposed to the flash light of a photographic flash camera [6]. This suggests that SWNTs can absorb significant amount of photon energy and convert it to thermal energy. When SWNTs absorb photons, the temperature of nanotube bundles increases dramatically owing to their extremely high thermal conductivity along the tube axis [18, 19]. According to Savas *et.al.*, the room temperature thermal conductivity of isolated SWNTs is 6600W/mK, much larger than that of pure diamond [18]. Although the thermal conductance is significantly lowered in SWNT bundles because of the anisotropic nature of thermal conductivity and thermal barriers between nanotubes, they are still very good thermal conductors [20]. In the presence of oxygen, nanotubes burn out at temperatures around 600^{o}C. If the nanotube bundles are 'fluffy', then the dissipation of heat between nanotubes would be poor and lead to a drastic increase in localized heating achieving high temperatures. And in the presence of oxygen, the enormous heat confinement can burn the nanotubes. However, if the SWNTs were packed tightly together and were in close contact with each other, or if there was a substrate which could absorb the heat and act as a sink, then the thermal energy generated by the SWNTs can be rapidly dissipated to the other nanotubes or the substrate and make the bundles less prone to burning. Under optical illumination, nanotubes absorb the photons thereby causing the localized heating of nanotubes. But the temperature of the nanotubes never really increases drastically as the heat is readily transferred to the acrylic elastomer which is in direct contact with the nanotube sheet. This leads to a thermal expansion of the elastomer causing strain and thus actuating the bimorph structure. An SEM of the SWNT sheet was performed after two hundred cycles of exposure to light to see if the nanotubes had burned. The images obtained were similar to those obtained before light exposure showing no signs of any physical damage to the nanotubes. Figure 3(b) shows the strain in the actuator under light intensities of 70mW/cm^2, 40mW/cm^2 and 20mW/cm^2. It is apparent that the higher the intensity of light incident on the sample, the greater is the strain amplitude measured. Figure 3(c) shows the curve of strain versus incident light intensity ranging from 0 to 120mW/cm^2. It can be construed that for smaller intensities the rate of strain induced is higher than at higher intensities. At higher intensities, optical scattering and reflection and heat dissipation due to the temperature rise become more serious and in turn slow down the rate of increase of strain. A maximum strain of ~0.3% is acquired under visible light intensities of 120mW/cm^2, which is comparably larger than that from piezo-electric materials.

Having shown the origins of thermal effects, the stretching of carbon nanotubes sheets as well as acrylic elastomer due to electrostatic effects was also investigated. The reason for such investigation stems from Zhang et al [7] found that SWNTs could stretch when shining light on it, which is quite similar to the stretching under static electrical field. They concluded that the stretching was due to the locally imbalance in the charge density due to the intertube interaction, the charge transfer from metallic tubes to the semiconductor ones, interbundle or intertube barriers and poor intertube and interbundle contacts, which results in local electrical field inside the SWNTs bundles.

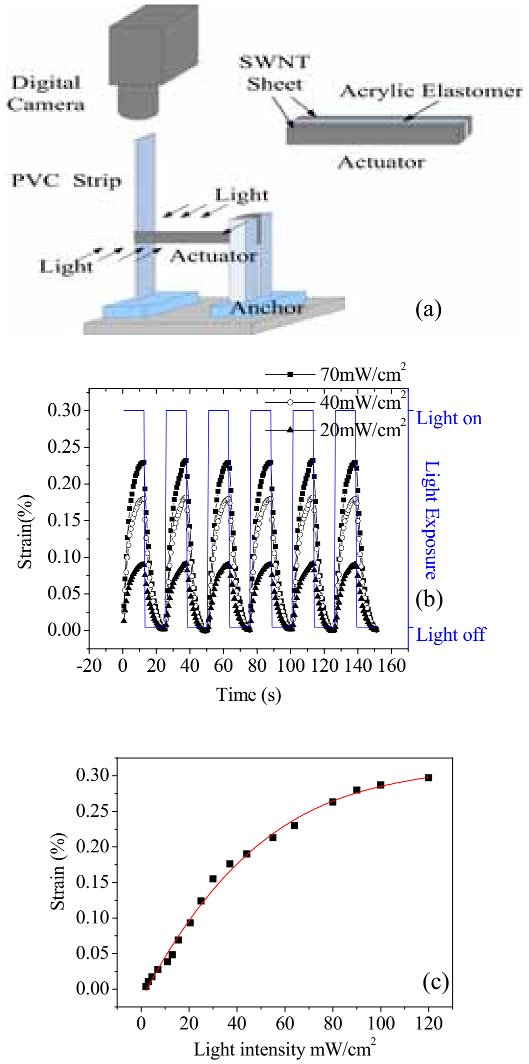

Figure 3: (a) Experimental setup for strain characterization. (b) Strain in the actuator measured under light intensities of 70mW/cm^2 (square), 40mW/cm^2 (circle), 20mW/cm^2 (triangle). (c) The strain as a function of light intensity.

Same electro-static effect could also happen in our actuator. The excess charge induced by light exposure on the carbon nanotubes distribute unevenly in the bundles and could induce local electrostatic fields, which stretch the carbon nanotubes sheet and increase its total length. Since the nanotubes are randomly aligned, the contribution of electrostatic strain in our actuator may be small compared to thermal actuation effects. However, for single nanotube actuators or small bundles of nanotubes, the electrostatic effects may dominate more than thermal effects in the actuator [7]. Further, the local electrical field at the surface between the SWNTs sheet and acrylic elastomer film could also exert Maxwell stress on the acrylic elastomer and result in the stretching of acrylic elastomer, which add up to the total strain in our samples.

The nanotube sheets that we used for our experiments were produced by the same methods as described in Reference [1]. Assuming the same value of Young's modulus of 1 Gpa for the nanotube sheets, and 0.5 Mpa for the Young's modulus of the acrylic elastomer, the Young's modulus of the bimorph structure can be calculated to be ~ 270 Mpa. The maximum stress generated in the actuator for a maximum strain of 0.3% was therefore 0.8 Mpa which is significantly higher than the peak capacity of human skeletal muscles (0.3 Mpa) and similar to the first electro-chemically driven nanotube actuators. For more optimized nanotube sheets and using ceramic materials instead of elastic polymers, one can improve the Young's modulus of the bimorph that can result in higher stress than for the non-optimized nanotube bundles as reported here. For making higher strength nanotube sheets, new processing methods are needed compared to the vacuum filtration technique which has its limitations.

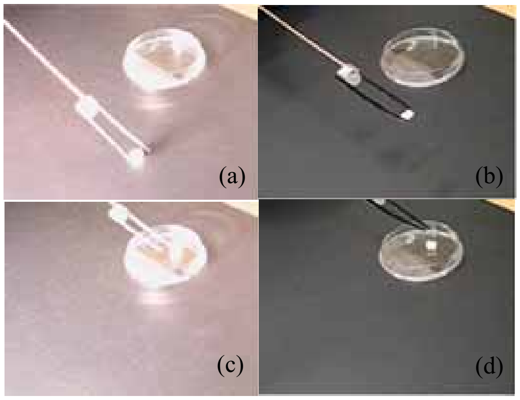

Figure 4: Showing a simple demonstration of a gripper manipulating small objects.

As a simple demonstration of the potential of this technology in different fields, a millimeter scale gripper was fabricated using the bimorph actuator which was subsequently used to manipulate small objects. The sequence of gripper manipulation is shown in Figure 4. The dimensions and structure of the bimorphs in the gripper are the same as discussed earlier and shown in Figure 2(a). The bimorph structures are attached to either side of a probe station arm such that the gripper is closed when the light source is switched off and open when the light is turned on. This setup was used to grip a piece of aluminum oxide, 4mm x 2mm in dimension and 0.3gms in weight and place it on a petri dish as shown in the Figure 4. When light is shining on the gripper, it is opened to grip the particle. After the particle is moved to the position above the petri dish, the gripper was again opened by light exposure to release the particle from it.

The demonstrations of these millimeter-scale grippers are the first prototypes showing the ability to manipulate small objects very easily using this technique. Much more work is required before the potential advantages of this technology can be experimentally assessed in practical devices. With just modest improvements, one can use this technology for cell manipulation and optically driven micro-cantilevers for medical catheter applications. The actuators are easy to fabricate and versatile compared to many other actuation technologies. It can be integrated with optical sources such as semiconductor lasers and LEDs directly to form devices on a single chip as the fabrication techniques of these are quite mature. Robotic structures from nanotubes could also be possible and could be driven optically that can be used for interplanetary space explorations.

3 ACKNOWLEDGEMENTS

Funding for this research was partially supported by the National Science Foundation Grant CCR: 0304218

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