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Nanomaterials in Actuators—A Review

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This review compiles the past and recent development of nanomaterial research in relation to the improvement of performance characteristics of actuators. Representative nanomaterials such as carbon nanotubes (CNT), CNT based composites, CNT sheets, nanoparticle based composites, nano films and coatings as well as nanowires are discussed. Taking advantage of the increased surface area and enhanced mechanical and electrical properties, various research groups demonstrated microscale and nanoscale actuators with a large displacement and a rapid response at low operating voltages and temperatures. New actuation mechanisms and accompanying design approaches were also often found in those actuators. Deriving from the traditional actuator configurations, researchers have designed and fabricated cantilevers, tweezers, resonators and switches for moving objects or routing electrical signals. Their research expanded further to create artificial muscles using nanomaterial composites. The impact of nanomaterials could be found in, for example, improved Young's modulus, electrical conductivity and thermal conductivity, all of which are parameters closely related to the conversion process between electrical and mechanical energy. As a result, many devices could be operated with increased static and dynamic responses at very low power consumption. Additionally due to the reduced scale of the materials and devices, the precise generation and control of sub atto Newton force and the high frequency operation are foreseeable. The prospect of the research as well as desired characteristics is discussed. Light yet strong, simple yet powerful actuators fabricated with newly developed nanomaterials based on various actuation methods are reviewed and summarized.

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KEYWORDS: Actuators, Nanomaterials, Single Walled Carbon Nanotubes, Multi Walled Carbon Nanotubes, Nano Composites, Nano Particles, Nano Wires, Nano Coatings.

CONTENTS

1. INTRODUCTION

As the nanotechnology science and engineering progresses at the unprecedented speed, there are significant efforts in the field to produce various working devices and systems based on newly synthesized nanoscale materials and their properties. Among those, microscale actuators are considered as a good candidate due to their size and well-developed production infrastructure. Actuators are used as a hosting device for nanomaterials as well as a tool for manipulating and testing nanomaterials, e.g., in scanning tunneling microscope and atomic force microscope (AFM). This review will focus on actuators which take advantage of current developments in nanomaterials research.

The fabrication of actuators with mechanical functionality on the nanoscale by implementing top-down fabrication methods such as electron beam lithography or bottom-up chemical synthesis methods is a highly active research area. The size of the devices which are fabricated by the top-down fabrication methods are limited by several factors, more importantly the resolution of lithography system. The use of nanomaterials in conjunction with high resolution lithography is considered as a promising solution to this challenge. Another active research topic is the exploitation of unique properties of nanomaterials for improving the performance of existing

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actuators or providing a new working mechanism. Notably, the carbon nano tubes (CNTs) are widely studied due to their excellent mechanical and electrical properties such as high Young's modulus and electrical conductivity. The conversion of electrical energy to mechanical energy, thereby obtaining movable structures, has been demonstrated in micro and nano electromechanical devices in which CNTs, CNT/polymer based composites, CNT sheets or buckypapers were used. The recent studies show that the addition of nanomaterials such as nanotubes and nanoparticles into the polymer matrix could significantly improve the mechanical and electrical properties of the polymer nanocomposites. The active field of study also includes nanofilms such as graphene sheets and nanocrystalline diamond. The nanowires with a diameter scale of 100 nm and a length scale of 10 μm have been utilized in fabrication of bimorph cantilevers and nanotweezers with enhanced flexibility and force sensitivity which are devised in high frequency resonators and manipulation of nanoparticles and nanoscale objects. Examples of different types of nanomaterials used in actuation are shown in Figures 1(A)–(I).

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2. HISTORY

Since the discovery of single walled carbon nanotubes (SW CNTs) by Iijima in 1991,[1,2] CNTs have been the subject of many studies due to their unique mechanical and electrochemical actuation properties. The mechanical response of the SW CNTs bundles to optical stimulus have also been first reported by Zhang and Iijima.[3] Nanotweezers based on CNT arms were developed by Akita and Nakayama. They demonstrated the actuation by applying a dc voltage to CNT arms.[4] Individual carbon nanotubes were investigated by Roth et al. as a promising candidate to form electromechanical nanoactuators.[5] An electromechanical switchable multi-walled carbon nanotube (MW CNT)-based device was devised by Ke et al. which consists of a cantilever CNT clamped to a top electrode and is actuated by a bottom electrode.[6] Nanoactuators in the form of sandwiched MW CNT structures were fabricated by Ikuno et al. which show repeatable thermally induced nanomechanical deflection.[7] Most recently the individual MW CNTs are utilized by Sul et al. to form bimorph nanoactuator which generates a μN force at its tip, and by Lim et al. to form arrays of elastic vertically aligned MW CNTs as microactuators which are reversibly actuated using a focused laser beam system.[8,9]

Landi et al. synthesized the SW CNT-Nafion composite bimorph cantilever actuators by efficient distribution of the high aspect ratio and conductive SW CNTs within the polymer matrix.[10,11] A hybrid electro-active paper (EAPap) actuator is synthesized by coating a composite of SWNT/polyaniline/Dopant on the both sides of electroactive paper to enhance its low force output and frequency band.[12] Mazzoldi et al. fabricated a microactuator from CNTs enclosed in partially cross-linked polyvinyl alcohol (PVA) and polyallylamine (PAA), using micromolding method.[13] Hu et al. reported a study of an electroactive biopolymer/SW CNT composite actuator operating at low voltage in an atmospheric condition.[14]

Shi et al. reported an actuator based on MWNT hydrogels composite in 2005.[15] The electrothermal actuators

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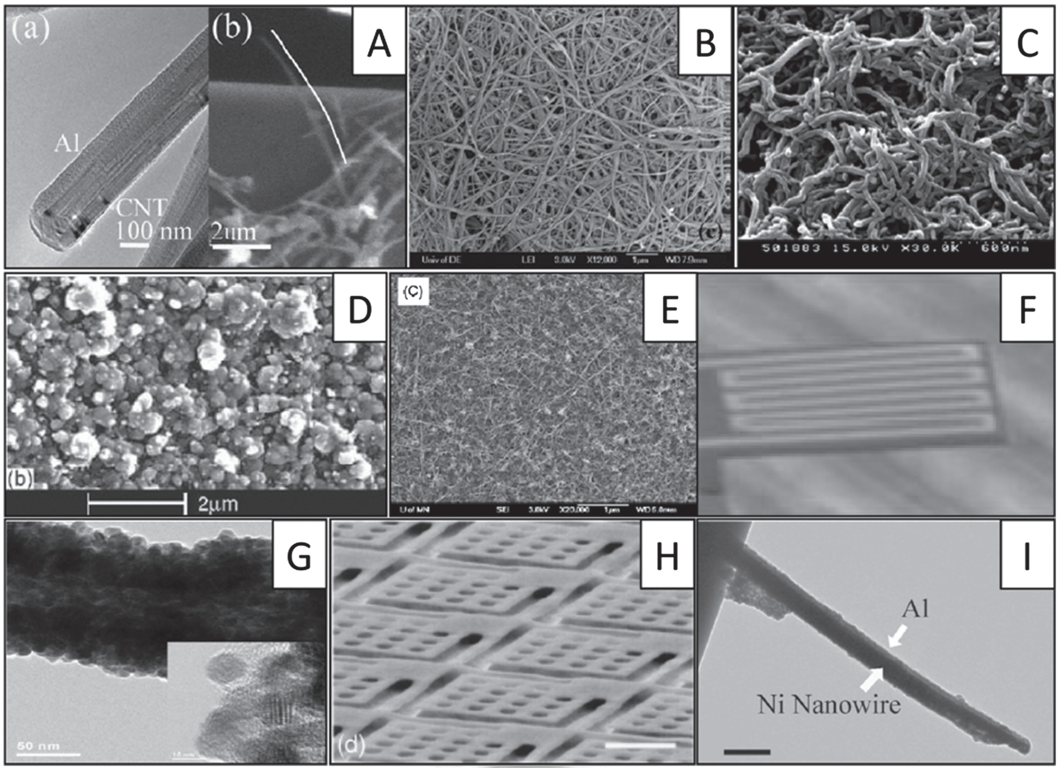

Fig. 1. Nanomaterials used in synthesis and enhancement of performance of actuators: (A) Nanoactuators fabricated using a MWNT with a uniform PLD-based Al film: (a) TEM image on MWNT–Al bimorph nanoactuators at a side view angle. (b) SEM image of a nanoactuator from the same PLD batch. A white line displays the entire length of the bimorph. Reprinted with permission from [8], O. Sul and E.-H. Yang, A multi-walled carbon nanotube-aluminum bimorph nanoactuator. *Nanotechnology* 20, 095502 (**2009**). © 2009, IOP Publishing Ltd. (B) SEM image showing the entanglement of nanotubes in SWCNTs composite. Reprinted with permission from [50], S. Lu and B. Panchapakesan, Photomechanical responses of carbon nanotube/polymer actuators. *Nanotechnology* 18, 305502 (**2007**). © 2007, IOP Publishing Ltd. (C) SEM images of the MWNT/PANI composite with sonication time of 2 hours. Reprinted with permission from [18], S. Yun and J. Kim, Multiwalled-carbon nanotubes and polyaniline coating on electro-active paper for bending actuator. *Journal of Physics D-Applied Physics* 39, 2580 (**2006**). © 2006, IOP Publishing Ltd. (D) SEM images of a PPy film with TiO_2 nanoparticles electrochemically prepared. Reprinted with permission from [22], X. He and G. Shi, Electrochemical actuator based on monolithic polypyrrole-TiO_2 nanoparticle composite film. *Sensors and Actuators B-Chemical* 115, 488 (**2006**). © 2006, Elsevier Ltd. (E) SEM image of the SWNT network in the transparent conductive thin film of the SWCNT sheet. Reprinted with permission from [33], X. Yu, et al., Carbon nanotube-based transparent thin film acoustic actuators and sensors. *Sensors and Actuators a-Physical* 132, 626 (**2006**). © 2006, Elsevier Ltd. (F) SEM image of a serpentine pattern of graphene on a SU-8 epoxy based layer. Reprinted with permission from [42], S.-E. Zhu, et al., Graphene-based bimorph microactuators. *Nano Letters* 11, 977 (**2011**). © 2011, ACS. (G) The TEM image shows the platinum nanoparticles attaching to the nanotube templates to form electrochemical hybrid metallic nanowire actuator based on self assembling the platinum nanoparticles. The inset shows platinum nanoparticles of size ranging from 5 to 10 nm. Reprinted with permission from [45], S. Lu and B. Panchapakesan, Hybrid platinum/single-wall carbon nanotube nanowire actuators: Metallic artificial muscles. *Nanotechnology* 17, 888 (**2006**). © 2006, IOP Publishing Ltd. (H) ESEM image (bar $= 50\ \mu$m) of released squares of a patterned nanoparticle gold film on polyimide. Reprinted with permission from [38], E. J. Wilhelm, et al., Nanoparticle-based microelectromechanical systems fabricated on plastic. *Appl. Phys. Lett.* 85, 6424 (**2004**). © 2004, AIP. (I) TEM image of a nickel nanowire coated with aluminum. The scale bar is 500 nm. Reprinted with permission from [48], O. Sul, et al., Fabrication and characterization of a nanoscale NiAl bimorph for reconfigurable nanostructures. *Nanoscience and Nanotechnology Letters* 2, 181 (**2010**). © 2010, ASP.

are synthesized by Chao et al. using Ni-P-CNTs nanocomposite films and by Tsai et al. using Ni-CNTs nanocomposite.[16, 17] Concurrently a hybrid actuator is made of MW CNT and Polyaniline (PANI) composite by Yun et al. which is coated on an EAPap.[18] A MW CNT/polymer composite based bimorph actuator is synthesized by Bartholome et al.[19] An electromechanical actuator in the form of a reinforced membrane made of surface modified MW CNTs based composite is synthesized by Du et al.[20]

The incorporation of diamond nanoparticles in nickel matrix was reported[21] in which the nanocomposite overall stiffness was enhanced by the hardness and the stiffness of the nanoparticles. He et al. reported the fabrication of a microactuator based on a polypyrrole (PPy)–TiO_2 nanoparticle composite.[22] Huang et al. made a magnetic microactuator based on a nanocomposite film by incorporating the ferromagnetic Ni nanoparticles in Cu matrix.[23] An electroactive polymer (EAP) actuator film was synthesized using conductive carbon nanoparticles (CNPs).[24]

The application of sheets of SW CNTs in electromechanical actuators was first reported by Baughman et al. in 1999.[25] In 2002, Fraysse et al. investigated a bimorph cantilever actuator with a sandwiched structure using strips of SW CNTs sheets as electrodes in an electrochemical cell.[26] In the following year, Barisci et al. reported an increased actuation rate of electromechanical CNT sheets based actuators[27] and Tahhan et al. investigated electrochemical actuators based on a SW CNT mat.[28] The actuation mechanism of electrochemical actuators based on charge transfer dynamics on the surface of SW CNT sheets was investigated by Gupta et al.[29] Lu et al. reported optically driven actuators made of highly entangled nanotubes in the form of sheets.[30] Actuators with various driving methods such as electrochemical, optomechanical and acoustic actuators were synthesized using CNT sheet.[31–33] Yuan et al. implemented the SW CNT electrodes to improve the performance of the actuators based on the acrylic adhesive films (3M, VHB 4910) and Suppiger et al. used SW CNT mats as electromechanical actuators.[34, 35] Xi et al. reported electrochemical pneumatic actuators utilizing CNT electrodes.[36]

Another effort was made to reduce friction and wear in microactuators using nano-film coatings.[37] Wilhelm et al. fabricated the electrostatic actuators by printing a nanoparticle colloid of gold on a polyimide substrate.[38] Kusterer et al. utilized diamond film to synthesize a thermal bi-stable cantilever beam actuator for generating micro Newton forces.[39] Lu et al. reported application of CNT film coating in fabrication of grippers.[40] Liang et al. reported fabrication of the optical triggered actuators based on polymeric nanocomposite films made of sulfonated-graphene homogenously incorporated in thermoplastic polyurethane (TPU) matrix.[41] Most recently in 2011, thin films of graphene are used in fabrication of electrothermal bimorph actuators.[42]

Husain et al. synthesized a very high frequency resonator in 2003 using single platinum nanowires.[43] In 2006, Berdichevsky et al. investigated electrically controlled actuation of conductive polypyrrole nanowires, fabricated using template synthesis, in an aqueous solution.[44] Concurrently Lu and Panchapakesan synthesized a hybrid nanowire actuator by self assembling the platinum nanoparticles on SW CNT template.[45] Lee et al. utilized individual polypyrrole nanowires for constructing nanoscale actuators.[46] Change et al. reported fabrication of straight and bent nanotweezers from two carbon nanowires.[47] A nanoscale nickel-aluminum (Ni-Al) bimorph actuator made of individual nickel nanowires was reported by Sul et al. recently.[48]

3. NANOMATERIALS

3.1. Carbon Nanotube (CNT) as an Actuator

An individual multiwalled carbon nanotube itself has been used to comprise micro- and nanoactuators with various configurations such as free standing nanotube fixed at two ends,[5] cantilever nanotube,[6] bimorph cantilever nanotube,[8] sandwiched nanotube structure,[7] an array of vertically aligned elastic nanotubes[9] and two arms of nanotubes in the form of nanotweezers.[4, 49] A variety of actuation methods are investigated to operate the individual CNT based actuators such as electromechanical,[4–6, 49] thermal[7, 8] and optomechanical[9] actuation mechanisms.

In one configuration, a trench is etched in a silicon chip and a free standing nanotube is placed on nanostructured blocks across the trench which is actuated using a conductive AFM tip with a relative length change of less than 1% and a tip deflection of about 1 nm. The electrons are injected into the nanotube from the conducting AFM tip. The tip is touching the nanotube and a square wave potential of ± 1 V is applied between the tip and the silicon substrate in vacuum or under air. Since there is only one nanotube, a compensation of charge with a double layer is not needed and the doped silicon substrate is used as a gate in the configuration of a field effect transistor. The nanotube expands in air depending on the polarity in a similar way as the buckypaper in an electrolyte, and is attracted toward the silicon substrate due to electrostatic forces. The structure of a nanotube seems like a graphite layer rolled into a tube. Graphite could be intercalated by alkali metals inserted between its layers. In this process the distance between the graphite layers and between two carbon atoms of the same layer increases. The latter increase is used to drive the actuator and the change of the nanotube length is monitored by the displacement of the AFM tip (Fig. 2(A)).[5]

In addition to the free standing nanotube (fixed at two ends to the supporting base and bent in the middle), a cantilever configuration is also investigated which is fixed to the base at one end and is free to move at the other end. A switchable CNT-based device which consists of a cantilever CNT clamped to a top electrode is actuated by a bottom electrode. For device fabrication MW CNT is used as a cantilever and is clamped on a microfabricated step. By increasing the voltage applied to the setup the system becomes unstable in which the electrostatic force is not balanced by the elastic force from the deflection of the CNT cantilever. The CNT switches from the upper equilibrium position to the lower position toward the bottom electrode (Fig. 2(B)). The applications of the CNT-based switchable device are NEMS switches, random-access memory elements, logic devices, electron counters, and gap sensing devices.[6]

MW CNT is utilized to form bimorph nanoactuator with a length scale in the order of 1 μm (Fig. 2(C)).[8] A μN force is generated at its tip and for a temperature change from 290 K to 690 K, a deflection of 550 ± 200 nm is achieved. A pulsed laser deposition (PLD) technique was used to uniformly deposit a thin aluminum film with a thickness in the order of 10 nm on the sidewalls of MW CNTs. The MW CNT cantilevers are formed on the edge of a silicon substrate by dehydration of a droplet of a suspension of nanotubes on the substrate.

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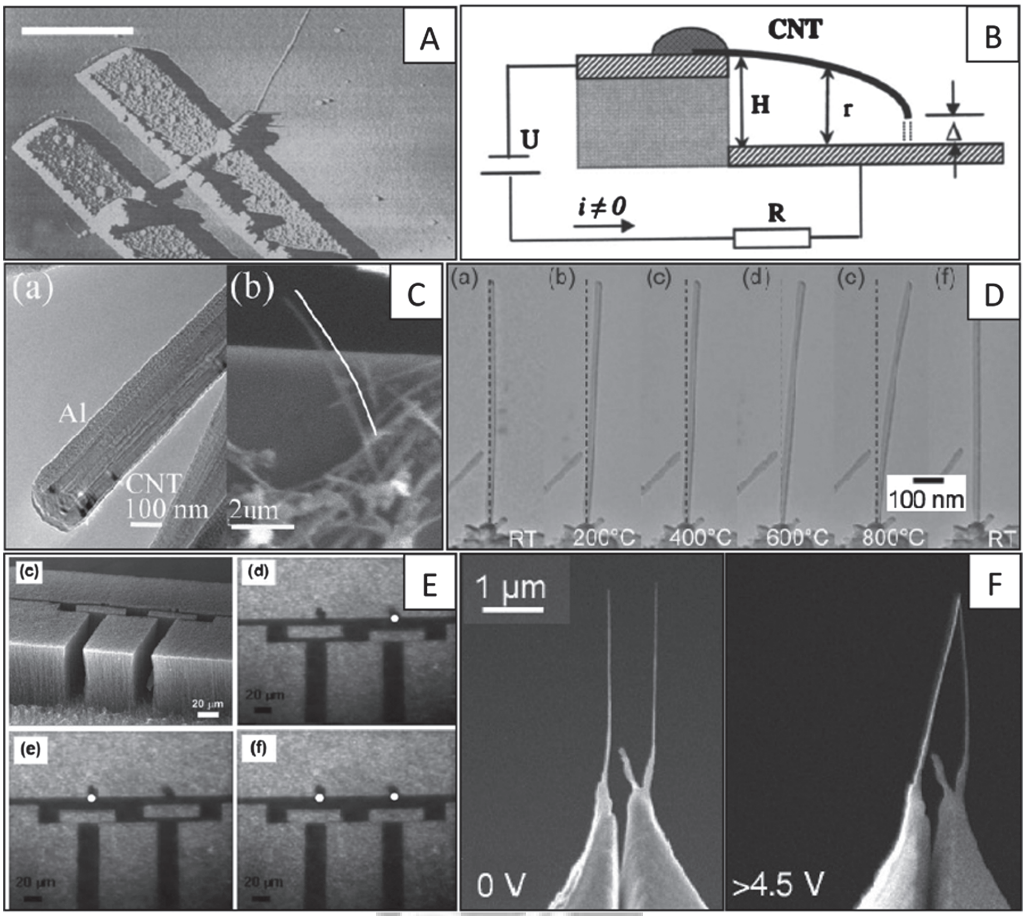

Fig. 2. Individual carbon nanotube based actuators: (A) An individual carbon nanotube standing free between two metal blocks. The actuation is made by injection of charges. Scale bar is 1 lm. Reprinted with permission from [5], S. Roth and R. H. Baughman, Actuators of individual carbon nanotubes. *Curr. Appl. Phys.* 2, 311 (**2002**). © 2002, Elsevier Ltd. (B) Schematic of MW CNT based nanocantilever device with tunneling contacts. Reprinted with permission from [6], C. Ke and H. D. Espinosa, Feedback controlled nanocantilever device. *Appl. Phys. Lett.* 85, 681 (**2004**). © 2004, AIP. (C) Nanoactuators fabricated using a MWNT with a uniform PLD-based Al film: (a) TEM image on MWNT–Al bimorph nanoactuators at a side view angle. (b) SEM image of a nanoactuator from the same PLD batch. A white line displays the entire length of the bimorph. Reprinted with permission from [8], O. Sul and E.-H. Yang, A multi-walled carbon nanotube-aluminum bimorph nanoactuator. *Nanotechnology* 20, 095502 (**2009**). © 2009, IOP Publishing Ltd. (D) Series of TEM video images showing mechanical deflection as a function of specimen (AlOx/WOx hybrid NW using CNT template) temperature (a–f). Reprinted with permission from [7] T. Ikuno, et al., Thermally driven nanomechanical deflection of hybrid nanowires. *Appl. Phys. Lett.* 87, 213104 (**2005**). © 2005, AIP. (E) A microactuator based on an array of vertically aligned individual MW CNTs. (c) SEM image of a two-actuators system individually controlled by focused laser beams. (d–f) Optical microscopy images of the system in action. (d) Focused laser beam on the right switched on. (e) Focused laser beam on the left switched on. (f) Both beams on. Reprinted with permission from [9], Z. H. Lim and C.-H. Sow, Laser-induced rapid carbon nanotube micro-actuators. *Adv. Funct. Mater.* 20, 847 (**2010**). © 2010, John Wiley and Sons. (F) Nanotweezers consisting of two arms of MW CNTs. SEM images of the motion of nanotube arms in a pair of nanotweezers as a function of the applied voltage are shown. Reprinted with permission from [49], S. Akita, et al., Nanotweezers consisting of carbon nanotubes operating in an atomic force microscope. *Appl. Phys. Lett.* 79, 1691 (**2001**). © 2001, AIP.

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Sandwiched CNT structures are also studied as nanoactuators. A MW CNT in the form of a nanowire sandwiched between two different oxide materials is used to fabricate a nanoactuator. The MW CNTs are made by an arc discharge method. An aluminum oxide (ALO_x) layer on one side and a tungsten oxide (WO_x) layer on the other side were deposited by PLD. The nanoactuator shows a thermally induced mechanical deflection similar to a thermostat switch (Fig. 2(D)).[7]

Lim and Sow reported the individual CNT based microactuators synthesized in the form of arrays of vertically aligned elastic MW CNTs with a height of 40–60 μm which could be reversibly actuated using a focused laser beam system. The laser induced actuating microstructure is durable and shows a rapid response which could oscillate up to 40 kHz and exert a sub-micro-Newton force to bend. The optomechanical actuation mechanism is based on the laser induced electrostatic interaction. The intense radiation of the focused laser beam results in a local polarization of the sample around the laser spot and an electric field perpendicular to the CNTs alignment direction is generated. The actuator is deflected due to the electrostatic repulsion from the opposite array of CNTs (Fig. 2(E)). The investigated CNT microstructures show potential applications in electrical switching, resonant oscillations, and bending of nanowires.[9]

Akita et al. reported a method to combine two arms of MW CNTs and form electromechanical nanotweezers. The nanotubes are synthesized by an arc discharge method with a length of 1 to 5 μm and an average diameter of 10 nm. The nanotube arms were coated with an insulating thin carbon film with a thickness of several nanometers. The nanotube arms approach to each other without plastic deformation by applying a dc voltage which reduces the separation from 500 nm to zero. The bend of the nanotube arms is the result of a balance between the electrostatic attraction and the bending momentum of the nanotubes. The proposed nanotweezers could be used for manipulating nanoscale objects, investigating the interaction between the nanomaterials, and measuring the mass and electrical conduction of nanomaterials (Fig. 2(F)).[4,49]

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3.2. Single Walled Carbon Nanotube (SW CNT) Composites

The CNT/polymer based composites are promising for enhancing the characteristics of micro and nanoactuators in comparison to their counterparts made from polymers. The composites were made by dispersing CNTs in polymer matrices such as chitosan (CS) biopolymer,[14] Nafion,[10,11] partially cross-linked PVA and PAA,[13] polyaniline with two dopants of Cl– and ClO–4 (PANI/Dopant)[12] and Polydimethylsiloxane (PDMS) silicone elastomer.[50]

Hu et al. reported an electroactive biopolymer/SW CNT composite actuator which is controlled by a low voltage in atmospheric condition.[14] A conductive CNT network is formed by dispersing SW CNTs in the biopolymer matrix (chitosan) which debundles the CNTs at very high concentration. The pure CS matrix does not show any displacement and by increasing the CNTs contents, larger displacements are generated. The SW CNTs with excellent electrical and thermal conductivity increase the electrical and thermal conductivity of the composite. In combination with an active cooling system, a steady state displacement at a constant voltage was observed (Fig. 3(A)). An artificial muscle type of applications could be envisioned.

The CNT based composites are also used to make bimorph actuators which resemble muscle fibers. The SW CNT-Nafion composite bimorph cantilever actuators are synthesized for 0.1–18% w/w doping of purified SW CNTs within the polymer matrix to achieve an efficient polymer actuation. The interaction between the nanotubes and Nafion matrix results in debundling of the purified nanotubes and enhances their dispersion throughout the membrane. By adding SW CNTs dopants, the conductivity of the membrane is improved which highly enhances the deflection. The chemical reduction of platinum ions on the Nafion membrane surface is utilized to achieve an electrical contact to the membrane surface. The electrical contacts are sealed and the SW CNT-Nafion composite bimorph actuator is immersed in an aqueous lithium chloride solution. A square wave excitation voltage in the range of 0.1 to 2.0 V is applied to the electrodes, with a stepping frequency of 1 to 50 Hz. A tip deflection of 4.5 mm is measured by optical deflection analysis for the doping level of 18% (Fig. 3(B)).[11]

Microactuators in the form of a sandwiched structure were also investigated.[13] A microactuator is fabricated from CNTs enclosed in partially cross-linked PVA and PAA, using micromolding method. A CNT-PVA-PAA composite active layer and a solid polymer electrolyte layer are sandwiched between two conductive electrode layers through which a voltage difference is applied. The microactuator has a bending mechanism based on the longitudinal strain in nanotubes which is induced by the charging process. As a double layer is formed around the nanotubes, a strain is induced which is proportional to the charge on their accessible surface. However no strain is induced in the PVA matrix and the resulting mechanical unbalance causes the actuator to bend.

A hybrid EAPap actuator was synthesized by coating a composite of SWNT/polyaniline with two dopants of Cl– and ClO–4 (SWNT/PANI/Dopant) on the both sides of electroactive paper to enhance its low force output and frequency band. A suspension of SW CNTs is mixed with the dopants and spin-coated on both sides of EAPap as conductive layer. The hybrid actuator shows improved force and resonance frequency due to enhanced stiffness, from the interaction between the nanotubes and PANI with dopants. The low power consumption is a promising factor for achieving ultralight-weight smart actuators (Fig. 3(C)).[12] For preparing the CNT/Polymer composite films with a thickness of 60 μm, the nanotubes are mixed with the PDMS monomer at the weight ratio of 0.2%, then the cross linker is added to the mixture with a weight ratio of 1:10. For preparation of the CNT/polymer multilayer structure, the PDMS monomer is mixed with the curing agent with a weight ratio of 10:1 and a pure PDMS polymer film is formed. Then CNTs/IPA suspension is formed, and using air brushing method, a nanotube film with a thickness of 350 nm is formed on polymer film. A similarity in the trends of contraction under large prestrains and expansion under small prestrains were observed for all four samples and at all the light intensity levels. This indicates that the photomechanical effect is an intrinsic behavior of both SW CNTs and MW CNTs. For the four samples the photomechanical stress decreases in response to light under small prestrains which leads to sample expansion, and increases under large prestrains which results in sample contraction (Fig. 3(D)).[50]

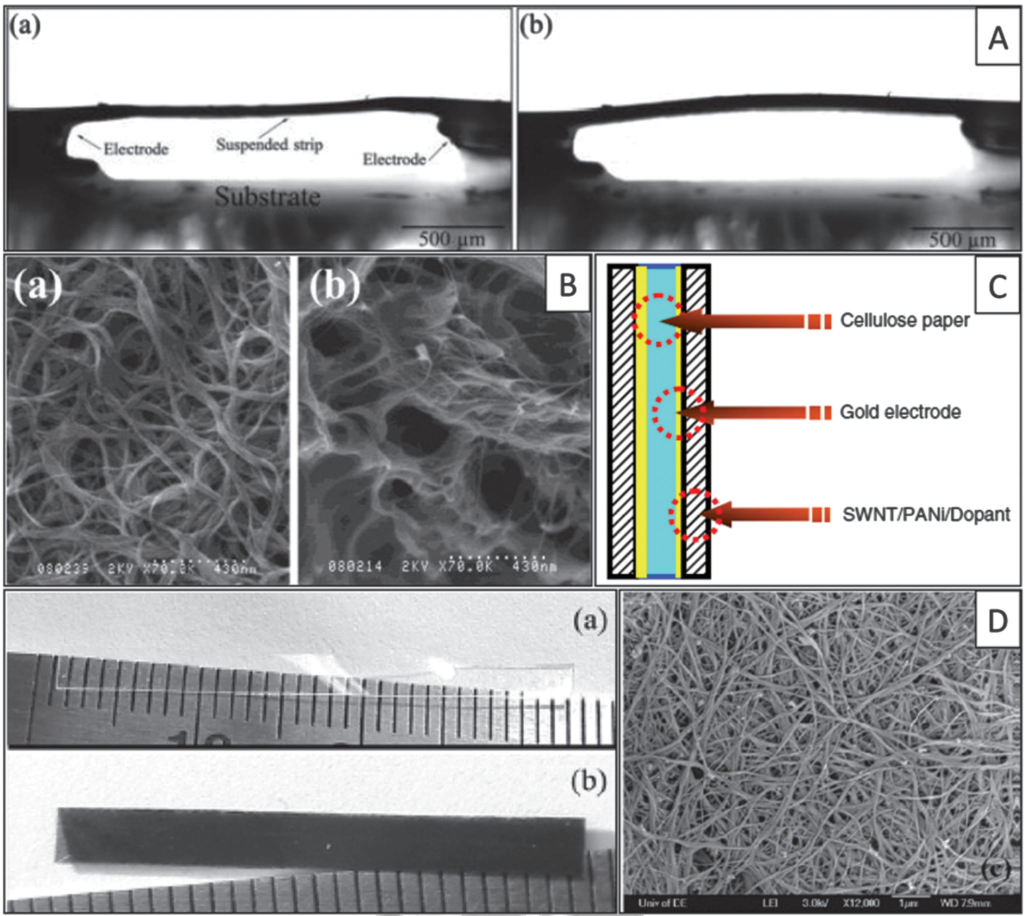

Fig. 3. Single walled carbon nanotube composite based actuators: (A) An actuator based on SW CNTs/CS biopolymer composite. Optical images of the side view of suspended strip with the voltage off (a) and on (b). The lower part is the glass substrate, and the black line is the 25 wt % SWCNT/CS composite. The applied voltage is 0.1 Hz alternating sine wave voltage of 5 V. Reprinted with permission from [14], Y. Hu, et al., Electromechanical actuation with controllable motion based on a single-walled carbon nanotube and natural biopolymer composite. *ACS Nano* 4, 3498 **(2010)**. © 2010, ACS. (B) FESEM images of SW CNT/Nafion composites depicting a 5-fold reduction in h-SWNT bundle diameter from (a) high purity, compared to (b) 10% w/w dispersion in Nafion. Reprinted with permission from [11], B. J. Landi, et al., Single wall carbon nanotube-Nafion composite actuators. *Nano Letters* 2, 1329 **(2002)**. © 2002, ACS. (C) Schematic of a hybrid EAPap actuator based on SWNT/PANI/Dopant composite. Reprinted with permission from [12], S. Yun, et al., Single-walled carbon nanotube/polyaniline coated cellulose based electro-active paper (EAPap) as hybrid actuator. *Smart Mater. Struct.* 15, N61 **(2006)**. © 2006, IOP Publishing Ltd. (D) (a) pure PDMS silicone elastomer and (b) samples from SWCNT/PDMS/SWCNT multilayered structure. (c) SEM image showing the entanglement of SWCNTs. The spacing between grid lines is 1 mm. Reprinted with permission from [50], S. Lu and B. Panchapakesan, Photomechanical responses of carbon nanotube/polymer actuators. *Nanotechnology* 18, 305502 **(2007)**. © 2007, IOP Publishing Ltd.

3.3. Multi Walled Carbon Nanotube (MW CNT) Composites

The MW CNTs are used in the form of individual CNTs as nanoactuators in many researches. Here composite materials based on MW CNTs dispersed in polymers are reviewed as promising candidates in enhancement of actuators performance. The MW CNTs are dispersed in polymer matrixes such as PVA,[19] PANI,[18] PVA hydrogels[15] and mixture of poly (sodium 4-styrenesulfonate-co-acrylic acid) PSA and PVA,[20] or incorporated in metallic films such as nickel,[17] to form composites. The MW CNT composites were utilized to fabricate devices in the form of bimorph actuator,[19] hybrid EAPap actuator,[18] gel strip,[15] reinforced membrane[20] and electrothermal resonator.[17]

Bartholome et al. investigated a CNT/polymer composite based bimorph actuator which generates a maximum stress of 1.8 MPa. The MW CNTs are oxidized in nitric acid and are dispersed in water and mixed with PVA which has high tensile strength and flexibility. One face of the composite is coated with gold to enhance the conductivity and uniform actuation, and a PVA layer is added on top of the composite to form bimorph actuator which is deformed due to swelling of the oxidized CNT/polymer composite sheet. The crystallization of polymer is improved by the CNTs and this leads to the enhancement of the stress and the strain of the failure as well as the Young modulus of the composites (Fig. 4(A)).[19]

A hybrid actuator was made of MW CNT and PANI composite which is coated on an EAPap. It is actuated by

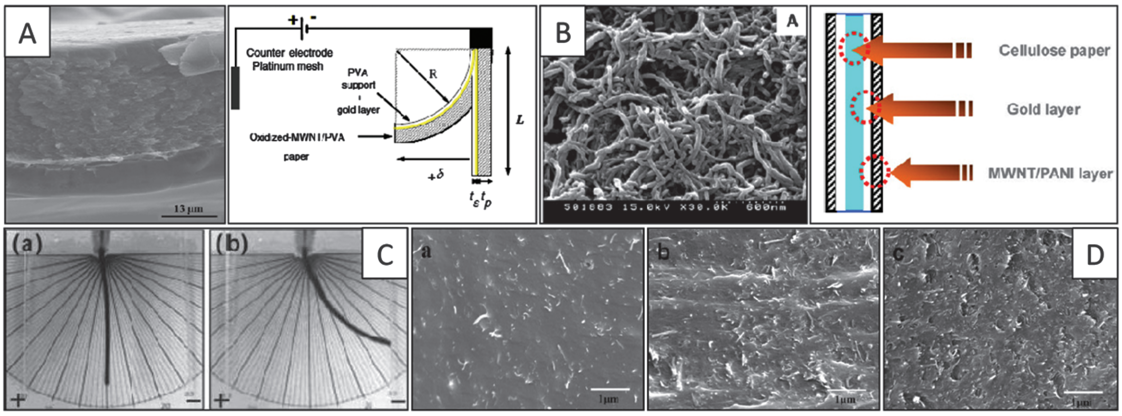

Fig. 4. Multi-walled carbon nanotube composite based actuators: (A) SEM micrograph of the bimorph section. At the top of the image the oxidized-MWNT/PVA paper, then the layer of gold and finally the inert PVA layer. Schematic of the MW CNT/ polyvinyl alcohol based composite bimorph actuator. Reprinted with permission from [19], C. Bartholome, et al., Electromechanical properties of nanotube-PVA composite actuator bimorphs. *Nanotechnology* 19, 325501 (**2008**). © 2008, IOP Publishing Ltd. (B) SEM images of the MWNT/PANI composite with sonication time of 2 hours. Schematic diagram of the MWNT/ PANI composite coated hybrid EAPap actuator. Reprinted with permission from [18], S. Yun and J. Kim, Multiwalled-carbon nanotubes and polyaniline coating on electro-active paper for bending actuator. *Journal of Physics D-Applied Physics* 39, 2580 (**2006**). © 2006, IOP Publishing Ltd. (C) Photographs of the Na-MWNT/PVA composite hydrogel strip with 10% (w/w) loading of Na-MWNT at different times in 3 mM of Na2CO3 aqueous solution at 10 V/cm DC electric field at (a) 0 and (b) 30 s. Reprinted with permission from [15], J. Shi, et al., Actuator based on MWNT/PVA hydrogels. *Journal of Physical Chemistry B* 109, 14789 (**2005**). © 2005, ACS. (D) PSA-g-MWNTs reinforced PSA/PVA membranes with the PSA-g-MWNTs loading content of (a) 5 wt %, (b) 10 wt %, and (c) 20 wt%. Reprinted with permission from [20], F.-P. Du, et al., Carbon nanotube enhanced gripping in polymer-based actuators. *Journal of Physical Chemistry C* 113, 7223 (**2009**). © 2009, ACS.

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an electric field and shows an improvement of 250% in the output force, 160% in the resonance frequency and 50% in the efficiency. The MW CNT/PANI coating enhances the bending actuation and the mechanical stiffness of the actuator due to the high Young's modulus of the MW CNTs which results in improved force output. The investigated actuator mimics biological muscles (Fig. 4(B)).[18]

Shi et al. investigated the application of MW CNT hydrogels for actuators. It was shown that salts of carboxylic MWNTs exhibit excellent actuation properties through hydrogelation with PVA. For making MWNT/PVA hydrogels, nanotubes are purified and sonicated with nitric-sulfuric acid and then converted to sodium salts (Na-MWNT). A mixture of PVA and Na-MWNT aqueous solutions are repeatedly frozen and thawed to form the Na-MWNT/PVA composite hydrogels. The Na-MWNTs act as polyelectrolytes in the composite and by applying a DC electric field, the Na-MWNT/PVA hydrogel strips are significantly and rapidly bent toward the cathode like the artificial muscles. The microstructure in the form of a gel strip is bent like a bimetal due to the osmotic pressure difference between the positive electrode side and the negative electrode side which has a smaller pressure. This is due to the migration of the mobile ions in the solution, toward their counter electrodes. As a result the gel strip near the positive electrode swells and the gel strip near the negative electrode side shrinks and the microstructure is bent like a bimetal (Fig. 4(C)).[15]

An electromechanical actuator in the form of a reinforced membrane based on a composite is made of ionic polymer membrane which is cast from the mixture of PSA and PVA and the surface modified MW CNTs as the strengthen elements (Fig. 4(D)). The MW CNTs surface is coated by a 12 nm thick PSA layer. The composite membrane with uniform dispersion of the surface modified nanotubes and removed interface mismatch between the nanotubes and the polymer membrane generates enhanced gripping of the actuator. The electrical conductivity of the membrane is improved by several orders of magnitude due to the uniform dispersion of nanotubes and their high thermal conductivity. The proposed reinforced membrane exhibits enhanced mechanical toughness, a relatively constant value of ion-exchange capacity, and high structure integrity after water uptake. For the loading ratio of higher than 10 wt% of the PSA-g-MW nanotubes the small oscillation of the actuator's mechanical output disappears.[20]

An electrothermal microactuator with enhanced performance and reliability and power efficiency is fabricated based on Ni-CNTs nanocomposite. An electrolyte nickel deposition process is used to form a well-dispersed Ni-CNTs colloidal solution, and using acid oxidative method for the surface modification of the MW CNTs, a Ni-CNTs nanocomposite is made. A microscale movement is generated by electrically resistive heating of the microactuator which has two connected cantilevers made of the same material but with different lengths. Incorporation of nanotubes into the Ni film does not change the surface smoothness but increases the Modulus of elasticity to the density ratio (E/ρ) of the film. A Ni-CNTs nanocomposite based actuator shows more than 95% power savings compared to the power required for a pure nickel actuator.[17]

3.4. Nanoparticle Composites

The use of nanoparticles such as diamond nanoparticles,[51] nanodiamond powders,[16] ferromagnetic Ni nanoparticles,[23] titanium dioxide (TiO_2) nanoparticles[22] and conductive CNPs[24] in metallic films, e.g., nickel and copper and polymers, e.g., monolithic PPy and EAPs to produce composite materials has been reported. The nanoparticle composites are utilized in actuators with improved magnetic, electrothermal and electrochemical properties.

A Ni-diamond nanocomposite- based microactuator was investigated in order to reduce power consumption, increase operation reliability and achieve a longer reversible displacement range.[51] Diamond nanoparticles could enhance the actuator's mechanical strength due to their high hardness and Young's modulus. No hysteresis or degradation was observed in the forward and backward displacement of the device. The microactuator consists of two connected cantilevers with different arm lengths, which was curled toward the shorter one due to the unequal coefficient of thermal expansions (CTE) of the arms of the beams upon resistive heating. The composite material contributed to enhanced output force and displacement as well as better energy conversion.

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Huang et al. reported a magnetic microactuator made of Cu-Ni nanocomposite film with reduced power consumption, improved actuation displacement, low driving voltage and large output force.[23] By incorporating the ferromagnetic Ni nanoparticles with a size of 50 nm in Cu matrix, the magnetic property of the Cu film is modified from diamagnetic to ferromagnetic and by increasing the amount of nanoparticles, the saturated magnetism of the Cu-Ni nanocomposite is increased. A low temperature synthesis method is utilized to form the Cu-Ni nanocomposite, by heating up a colloidal solution with well dispersed nanoparticles to 40 °C and putting itself into Cu plating bath (Fig. 5(A)).

Electrothermal actuators are also synthesized using Ni-P-diamond and Ni-P-CNTs nanocomposite films (Fig. 5(B)).[16] Their distinct characteristics and device performance are compared due to the difference in the shapes and sizes of the granular diamond and the fibrous CNTs. By resistively heating the electrothermal actuators, which consist of two connected cantilevers with different lengths and CTEs, the actuators are bent toward the shorter beam and lateral actuations are generated. The Young's modulus and the hardness of Ni-P-CNT nanocomposite film are higher than those of pure nickel contrary to the Ni-P-diamond nanocomposite film. The degradation in the Ni-P-diamond nanocomposite is related to the formation of voids and cracks on the surface of the nanocomposite (due to nanodiamond powders) contrary to the Ni-P-CNT nanocomposite which has a smooth surface with no observable defects. The average roughness of the Ni-P-diamond composite film is about 10 times higher than that of the Ni-P-CNT composite and the pure Ni-P films. Although the cracks in nanocomposite cause reliability problems and require more processing steps to prevent defect formation, the nanodiamond powders do not require complex chemical treatment and the preparation of the nanocomposite is much simpler. The actuators made of Ni-P-CNT and Ni-P-diamond nanocomposites provide larger displacements with lower input powers as compared to pure Ni-P actuator. The Young's modulus to density ratio, which is an important factor for the design of high frequency and resonant devices, is about three times higher in actuators made of Ni-P-CNT and Ni-P-diamond nanocomposites compared to the actuator made of pure Ni-P film. This makes the nanocomposites suitable candidates for high frequency applications.

The fabrication of a microactuator from a monolithic PPy composite film which has a pure PPy zone on one side and a PPy–TiO_2 nanoparticle composite zone on the other side was investigated (Fig. 5(C)).[22] The PPy composite film shows a high response rate and a long lifetime and bends uniformly in two directions with a bending angle of more than 90° for low driving voltages. The incorporation of the TiO_2 nanoparticles improves the performance of the actuator in aqueous solution. The actuator is able to be bent in two directions due to its anisotropic structure contrary to the actuator made of pure PPy film. The presented actuator made of a composite film uniformly bends to the TiO_2 free side direction when oxidized and to the TiO2 rich side direction when reduced. There is no interface between the two sides of the film which reduces the friction and extends the lifetime of the actuator.

An EAP actuator film was made of conductive CNPs and solid electrolyte binder polymer (Nafion) composite (Fig. 5(D)).[24] The CNPs are dispersed into Nafion solution and used to form a composite film. The film is actuated in electrolyte solution in a charge accumulation mode or in the air in a self-heating mode. In the charge accumulation mode of actuation, charges are accumulated on the electric double layer formed at the surface of the CNPs and thereby the strain is induced to the film. A small amount of energy is required to maintain the deformation. The polymer in this case needs to be electrolyte. In the self-heating mode, the Joule heating upon applying the voltage to both ends of the actuator film causes the expansion.

3.5. Single Walled Carbon Nanotube (SW CNT) Sheets as Electrodes

Sheets of SW CNTs could be used as electrodes in an electrochemical cell[25,26,33,35] to fabricate actuators with various actuation mechanisms, e.g., electromechanical actuation,[25,27,34] dry and wet electrochemical actuation,[28,29,32] electrochemical pneumatic actuation,[36] optically-driven actuation[30,31] and acoustic actuation.[33] The actuators based on SW CNTs electrodes are made and studied in the form of bimorphs[25] cantilevers,[26,30] nanotube grippers[30] and speakers.[33] The SW CNTs sheets with

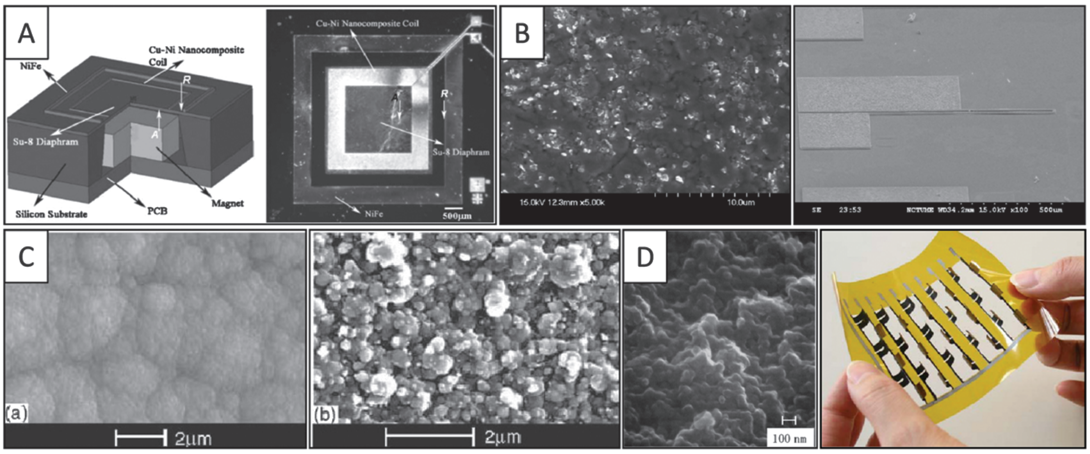

Fig. 5. Nanoparticle nanocomposite based actuators: (A) Diagram of a magnetic microactuator made of Cu-Ni nanocomposite film and the top view of as-fabricated SU-8 diaphragm with magnetic Cu–Ni nanocomposite coil. Reprinted with permission from [23], Y. W. Huang, et al., Power consumption reduction scheme of magnetic microactuation using electroplated Cu-Ni nanocomposite. *Applied Physics Letters* 90, 244105 (**2007**). © 2007, AIP. (B) The SEM photo of Ni–P–diamond film surface and the fabricated Ni-P-diamond electrothermal microactuator. Reprinted with permission from [16], T.-Y. Chao, et al., Comparative study of Ni-P-diamond and Ni-P-CNT nanocomposite films. *Journal of the Electrochemical Society* 153, G98 (**2006**). © 2006, ECS. (C) SEM images of (a) a PPy film without TiO_2 and (b) a PPy–TiO_2 film electrochemically prepared. Reprinted with permission from [22], X. He and G. Shi, Electrochemical actuator based on monolithic polypyrrole-TiO_2 nanoparticle composite film. *Sensors and Actuators B-Chemical* 115, 488 (**2006**). © 2006, Elsevier Ltd. (D) SEM image of CNP composite film and fabricated unimorph actuators. Reprinted with permission from [24], M. Kato and M. Ishibashi, Carbon nanoparticle composite actuators. *Journal of Physics: Conference Series* 127, 012003 (**2008**). © 2008, IOP publishing Ltd.

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randomly oriented nanotubes mimic the natural muscles[25] and could generate a higher stress than that of natural muscles.[26]

The SW CNT electrodes are implemented to improve the performance of the actuators based on the VHB films (dielectric elastomers). The dielectric elastomer is strained by 200% in area expansion and the fault tolerance of the actuators is enhanced. Electric arc is used to partially remove the SW CNT and form electrically isolated patches which consist of a network of SW CNTs. The punctured fault is thus isolated from the rest of the active area and accounts for the improved fault tolerance of the actuators. The SW CNTs increase the reliability of the actuators by preventing dielectric failure caused by defects while accommodating a strain over large area films. An aqueous solution of purified P3 SW CNTs could be sprayed onto the acrylic elastomer films (3 M VHB adhesive tapes, biaxially prestrained) to form a SW CNT-based coating (Fig. 6(A)).[35]

Baughman et al. reported an electromechanical actuator based on SW CNT sheets, as electrolyte-filled electrodes of a supercapacitor, which generates higher stresses than natural muscle[52] and higher strains than high-modulus ferroelectrics. The actuator is operated by applying low operating voltages which injects electric charge into a SW CNT electrode. This is compensated by the ions in electrolyte at the nanotube-electrolyte interface. The presented actuators could provide higher work densities per cycle than any other actuators by optimizing the SW CNT sheets. The nanotubes sheet based actuators which are arrays of nanofiber actuators mimic the natural muscle and generate a stress of 0.75 MPa which is significantly higher than that of human skeletal muscle (0.3 MPa) (Fig. 6(B)).[25]

A bimorph cantilever actuator was investigated which is composed of two strips of SW CNTs sheets as electrodes separated by an adhesive film in an electrochemical cell. The applied voltage of a few volts between the electrodes generates a displacement of several millimeters by inducing electronic charge injection into the SW CNTs and the formation of double layer at the nanotube- electrolyte (1 M NaCl aqueous solution) interface. The SW CNTs sheet which is composed of randomly entangled bundles and ropes of several hundreds of nanotubes, was formed by vacuum filtration of a nanotube suspension, and was peeled off from the filter after drying. One of the electrodes is charged negatively and expands more than the other electrode, which is charged positively, and causes the whole structure to bend. By switching the polarity of the applied voltage the cantilever is bent to the other direction. In compare to the piezoelectric devices, the buckypaper actuators show a relatively larger deformation at a lower operation voltage. The reported actuators do not need ion intercalation which limits the life and the rate of the actuator contrary to conducting polymers. The isometric contraction of SW CNT sheet generates a higher stress of 0.75MPa than the human natural muscle[52] of 0.3 MPa, but it consists of billions of randomly oriented actuator units, unlike the muscular fibers. The alignment of nanotubes is a goal to achieve optimized actuation (Fig. 6(C)).[26]

Moreover optically driven millimeter-scale actuators are made of highly entangled nanotubes in the form of sheets, bonded by direct physical contact to an acrylic elastomer

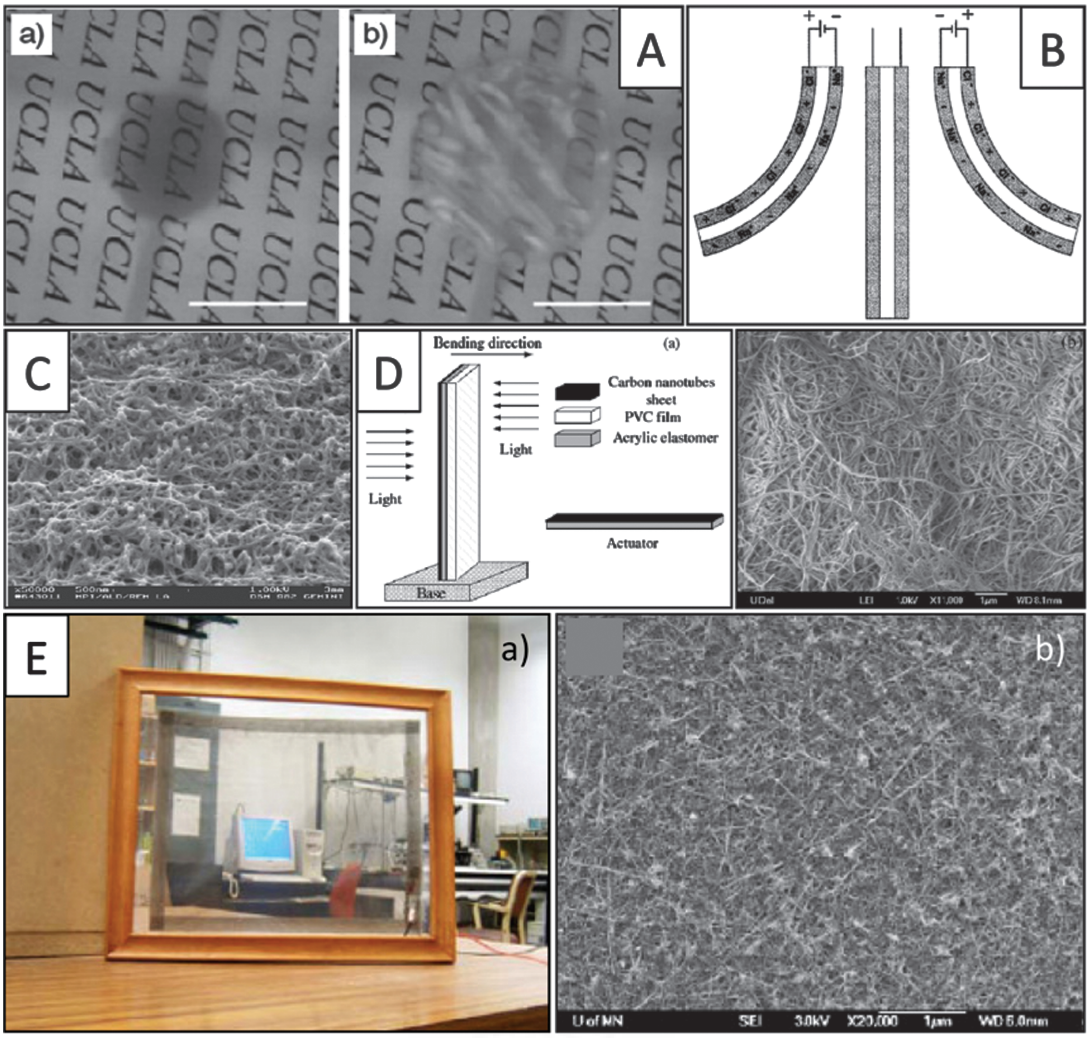

Fig. 6. Single-walled CNTs sheet based actuators: (A) Circular strain test measuring the expansion of a 300% biaxially prestrained VHB 4910 film with SWNT electrodes on both surfaces. A 200% area strain obtained from (a) no voltage applied, and (b) voltage at 5 kV. The scale bars are 10 mm. Reprinted with permission from [35], W. Yuan, et al., Fault-tolerant dielectric elastomer actuators using single-walled carbon nanotube electrodes. *Advanced Materials* 20, 621 (**2008**). © 2008, John Wiley and Sons. (B) Schematic edge view of a cantilever-based actuator operated in aqueous NaCl, which consists of two strips of SWNTs (shaded) that are laminated together with an intermediate layer of double-sided Scotch tape (white). Reprinted with permission from [25], R. H. Baughman, et al., Carbon nanotube actuators. *Science* 284, 1340 (**1999**). © 1998, AAAS. (C) Electron micrograph of the Buckypaper surface. Reprinted with permission from [26], J. Fraysse, et al., Carbon nanotubes acting like actuators. *Carbon* 40, 1735 (**2002**). © 2002, Elsevier Ltd. (D) A cantilever vertically anchored on a base. The cantilever is composed of an actuator (shown in the right lower part) and a 100 μm thick PVC film. SEM image of SWNT sheet composed of highly entangled SWNTs bundles. Reprinted with permission from [30], S. Lu and B. Panchapakesan, Optically driven nanotube actuators. *Nanotechnology* 16, 2548 (**2005**). © 2005, IOP Publishing Ltd. (E) A 250 mm $\times$ *l*90 mm transparent thin film actuator/sensor. SEM image of the SWNT network of the transparent conductive thin film. Reprinted with permission from [33], X. Yu, et al., Carbon nanotube-based transparent thin film acoustic actuators and sensors. *Sensors and Actuators a-Physical* 132, 626 (**2006**). © 2006, Elsevier Ltd.

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sheet with a thickness of 30 μm. They generate a maximum elastic strain of 0.3% and a maximum stress of 0.9 MPa due to electrostatic and thermal effects under visible light. The optically driven actuator is also used in the form of a nanotube gripper which works in dry and wet environments. There is no need for high voltages, electrochemical solutions or mechanical energy storage. A new type of actuation is investigated for the conversion of optical energy to electrostatic, thermal and elastic energy in nanotube sheets which are fabricated by vacuum filtration. The cantilever actuator with a length of 30 mm is elastically deformed upon illumination with a maximum displacement of 4.3 mm. The Young's modulus of the composite made of nanotube sheet with a Young's modulus of ~1 GPa bounded to an acrylic elastomer sheet with a Young's modulus of 0.5 MPa is 350 MPa (Fig. 6(D)).[30]

Yu et al. investigated a transparent acoustic transducer made of a piezoelectric poly(vinylidene fluoride) PVDF thin film coated with CNT based transparent conductors which is utilized as an acoustic actuator (speaker)

(Fig. 6(E)).[33] The transparent actuators which are flexible, extremely thin and light show excellent and smooth acoustic response from 50 Hz to 3 kHz and a resonant frequency of 150 Hz. The SWNTs electrodes are used to develop transparent transducers which contrary to ITO thin films are not brittle and do not need high processing temperatures. The CNT based acoustic actuators are durable and do not need high voltage amplifier and have low power consumption.

3.6. Films and Coatings

Films and coatings made of various materials such as graphene,[42, 53] carbon nanotubes,[40] nanocrystalline diamond,[39] diamond-like-carbon (DLC), metal doped DLC (Me-DLC), carbon- nitride (CNx), boron-nitride (BN), alumina (Al_2O_3),[37, 39] and nanoparticle colloid of gold[38] are utilized in actuators. Moreover polymeric nanocomposites made of sulfonated-graphene, isocyanate treated graphene oxide and fully reduced graphene-based sheets which are homogenously incorporated in TPU matrix,[41] are used in the form of thin films for fabrication of actuators. The described films are coated on a variety of substrates e.g., epoxy based materials, polymeric microparts, photoresist structures as well as silicon, steel, ceramic and polyimide substrates. Electrothermal,[39, 42] electrostatic[38] and optomechanical actuation methods[40, 41] are utilized to derive the actuators in the form of bimorph cantilevers,[42] bi-stable double anchored cantilevers[39] and cantilevers pinned at one corner.[38]

Zhu et al. utilized a thin film of graphene to form bimorph microactuators. The distinctive mechanical, thermal and electrical properties of graphene are implemented to generate a relatively large displacement at a low temperature and with low power consumption. A very thin film with an average number of 9 graphene layers with negative CTE of $-6.9 \pm 0.6 \times 10^{-6}$ (/°C) is coated on an epoxy based material with positive CTE and causes an upward deflection upon heating the graphene layer. Ni catalyst layer is used to grow graphene layer on SiO_2/Si wafer and is patterned using photolithography and O_2 plasma reactive ion etching (RIE). The reported actuator works in an elastic structural regime and is utilized for sensing while actuating by measuring the change in the electrical resistance (Fig. 7(A)).[42]

A bi-stable diamond microbridge for hybrid integration which is based on the thermal bi-metal actuation was used for generating large switching forces in the range of hundreds of μN. The actuator consists of a double anchored diamond cantilever beam and a base plate, which switches between two bi-stable positions by thermal actuation and a threshold voltage of 12 V. The diamond film is compressively pre-stressed and the use of nanocrystalline diamond film with a homogenous grain size and grain distribution allows the deposition of a uniform vertical stress distribution. The large switching forces, the mechanical stability and the chemical inertness are due to the use of diamond (Fig. 7(B)).[39]

Nano-films of DLC, Me-DLC, carbon- nitride (CNx), boron-nitride (BN) and alumina (Al_2O_3) are coated, with a thickness of 20 to 500 nm and a hardness of 10 to 60 GPa, on polymeric microparts, photoresist structures as well as silicon, steel and ceramic substrates to reduce friction and wear in microactuators with sufficient adhesion in all cases. Sputtering is used for carbon- nitride (CNx), boron-nitride (BN) and alumina (Al_2O_3) film preparation and plasma enhanced chemical vapor deposition (PECVD) is used for DLC film formation which allows deposition at low temperatures. The reported films have an amorphous or nanocrystalline structure and are highly wear resistant against abrasive and adhesive treatments. The micro-areal pin-on-disc measurement is implemented for friction measurement. The critical load of the first onset of irreversible surface deformation or film failure is derived in an elastic regime and at the onset of the wear.[37]

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The electrostatic actuators are fabricated with a size of 45 to 100 μm by printing a nanoparticle colloid of gold on a polyimide substrate with a thickness of 75 μm using offset liquid embossing (OLE). The polyimide substrate is then under-etched using oxygen plasma through etch holes. The released gold film is bent away from the polyimide substrate due to the residual stresses and is attracted toward the substrate using electric field of about 2 V/μm to modulate light by switching at several hundred cycles per second. The polyimide substrate acts as a mechanical substrate and a dielectric layer between the gold film and a second electrode fabricated from gold nanoparticles on the other side of the substrate. The released cantilevers, pinned at one corner form zipping electrostatic actuators which allow large displacement and high force by electrostatic actuation. The electrostatic actuators could be run for greater than 10^8 cycles with no degradation in the amplitude of the modulated light (Fig. 7(C)).[38]

The optical triggered actuator is based on polymeric nanocomposite which is made of sulfonated-graphene, with unusual mechanical, thermal and optical properties, homogenously incorporated in TPU matrix. The actuator exhibits excellent light-triggered actuation and an enhancement in mechanical property for its nanocomposite. Other graphene materials such as isocyanate treated graphene oxide and fully reduced graphene-based sheets are also incorporated into TPU matrix and three kinds of nanocomposites are fabricated by a solution mixing process. The comparative study of the nanocomposites shows that the infrared-triggered actuation depends on the integrity of the graphene's aromatic network and on the dispersion state of graphene within the matrix. The nanocomposite actuator exhibits repeatable infrared-triggered actuation which generates a force of 0.21 N on exposure of infrared light. The great improvement in mechanical properties of graphene nanocomposites with homogeneous dispersion is

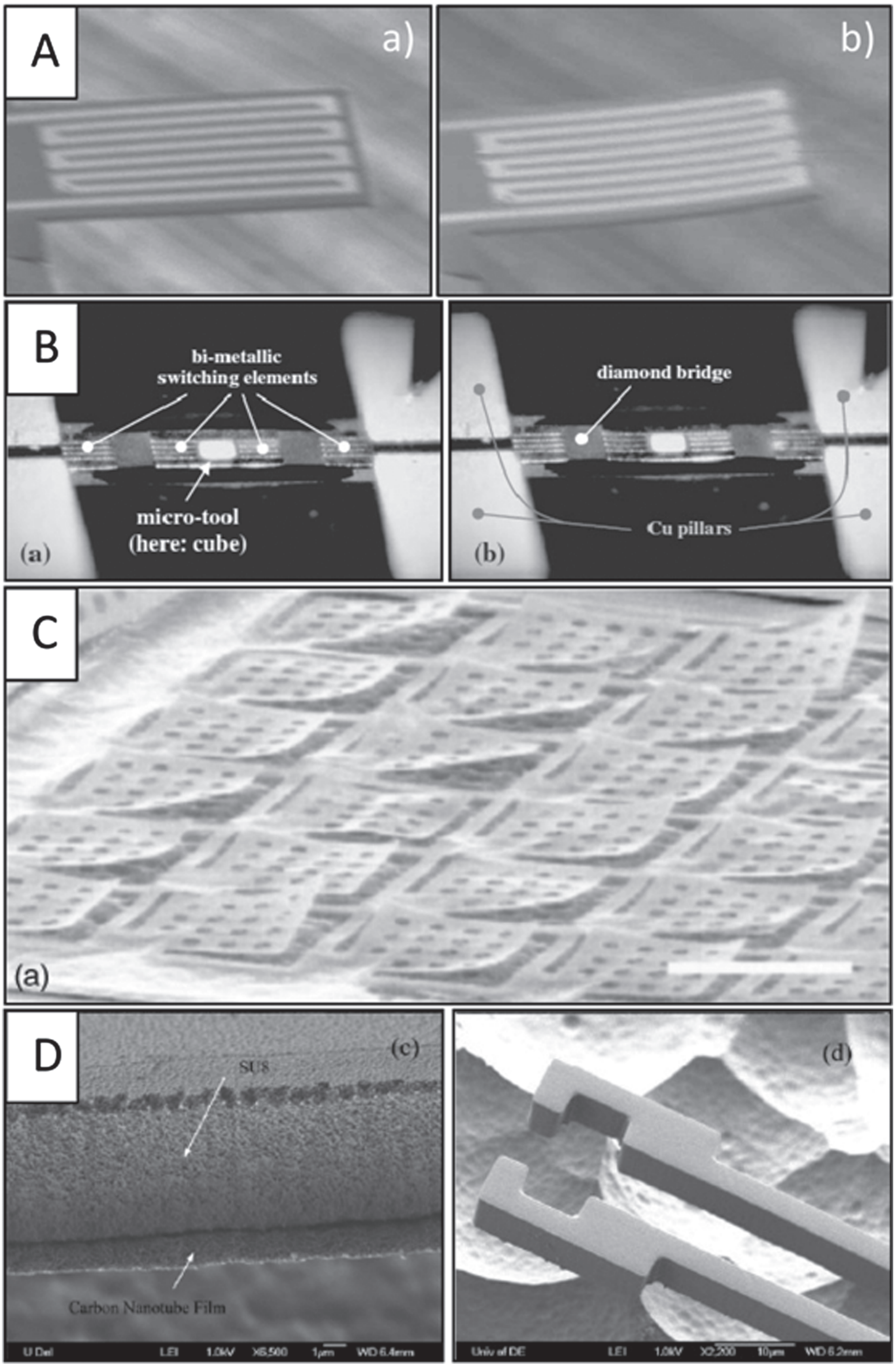

Fig. 7. Nano films (coatings) based actuators: (A) A graphene based bimorph microactuator: the SEM images of the initial position of the cantilever beam (a) and bend up state upon applying electrical power (b). Reprinted with permission from [42], S.-E. Zhu, et al., Graphene-based bimorph microactuators. *Nano Letters* 11, 977 (**2011**). © 2011, ACS. (B) An electrothermal bi-stable double anchored cantilever actuator made of nanocrystalline diamond film. Buckling of diamond beam due to compressive stress results in two quasi-stable positions. Fabricated diamond micro-bridge in upper (a) and lower (b) position. Reprinted with permission from [39], J. Kusterer, et al., Bi-stable micro actuator based on stress engineered nano-diamond. *Diamond and Related Materials* 15, 773 (**2006**). © 2006, Elsevier Ltd. (C) ESEM image (bar = 50 μm) of released squares of a patterned nanoparticle gold film on polyimide. Reprinted with permission from [38], E. J. Wilhelm, et al., Nanoparticle-based microelectromechanical systems fabricated on plastic. *Appl. Phys. Lett.* 85, 6424 (**2004**). © 2004, AIP. (D) CNT-MOMS gripper was fabricated based on surface micromachined SU8/CNT structures. (c) the cross-sectional view of the actuating arms; (d) the structure of the gripper tips. Reprinted with permission from [40], S. Lu, et al., Nanotube micro-opto-mechanical systems. *Nanotechnology* 18, 065501 (**2007**). © 2007, IOP.

evidenced by the increase of Young's modulus by 120% at only 1 wt% loading of sulfonated functionalized graphene sheets.[41]

Lu et al. reported fabrication of a micro-optomechanical gripper using CMOS compatible techniques such as nanotube film forming by incorporating a film of SW CNTs with a thickness of 200 nm on a SU8 structure with a thickness of 8 μm. It consists of actuating and supporting arms and has a length of 430 μm and a width of 20 μm. The double arm gripper was tested under infrared laser stimulus and showed a linear behavior with the change in the laser input power. A tip opening of about 24 μm was obtained with a very small power consumption of 240 μW. The CNT-MOMS grippers were utilized in manipulation and positioning of the polystyrene microspheres with a size of 16μm in air and showed a comparable performance to the electrically driven counterparts (Fig. 7(D)).[40]

3.7. Nano Wire Actuators

Nanowires with a diameter scale of 100 nm and a length scale of 10 μm are made of different materials such as nickel nano wire with aluminum deposited on one side,[48] conductive polypyrrole coupled with gold,[44] individual polypyrrole,[46] self assembled platinum nanoparticles,[45] carbon[47] and platinum.[43] They are utilized for high frequency resonators,[43] nanotweezers and nanoactuators.[44–46, 48] Actuators with various actuation mechanism and configuration such as thermally actuated bimorph cantilevered nanowires,[48] electrically controlled bimorph actuators,[44] electrochemical hybrid core–shell structures,[45] electrostatic nanotweezers[47] and doubly clamped beams[43] were produced. The nanowires such as nickel nanowire are also incorporated in polymers such as cellulose to form nanocomposites suitable for actuators synthesis.[54]

Sul et al. reported a nanowire based nickel-aluminum (Ni-Al) bimorph actuator with a length of 18 μm. It is actuated by increasing the temperature from 295 K to 675 K to generate a maximum deflection of 700 nm. The nanoactuator which is made of individual nanowires as opposed to nanowire bundles has applications in reconfigurable nanoantenna technology. The Ni nanowires are electrochemically deposited on an anodized aluminum oxide (AAO) membrane and are extracted by dissolving the membrane in sodium hydroxide. They are then suspended in water and a droplet of the suspension is dispensed on a silicon substrate and dehydrated. To form the cantilevered nanowires at the substrate edge, the substrate is broken into smaller pieces. The aluminum deposition is done on one side of the nanowire using a PLD (Fig. 8(A)).[48]

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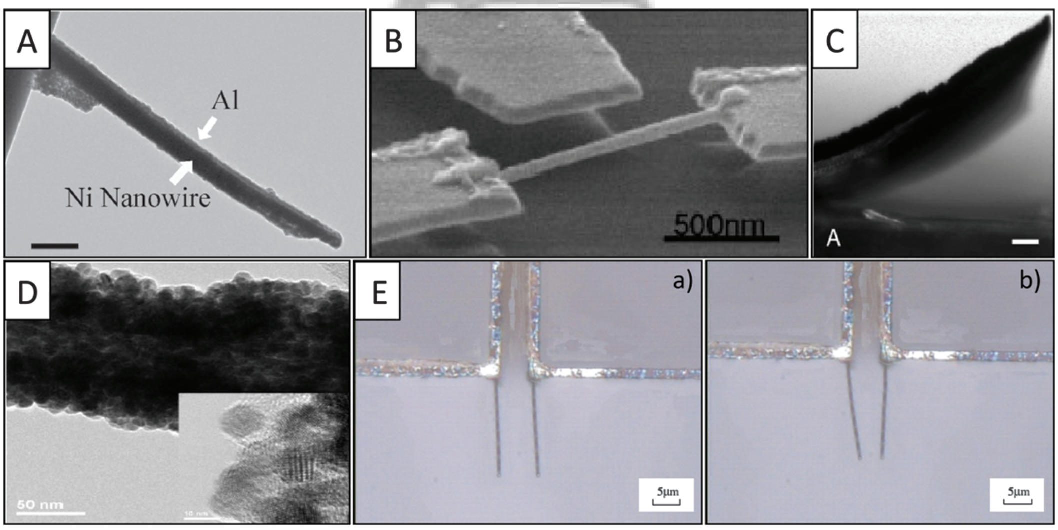

Fig. 8. Nanowire based actuators: (A) TEM image of a cantilever bimorph nanoactuator made of nickel nanowire coated with aluminum. The scale bar is 500 nm. Reprinted with permission from [48], O. Sul, et al., Fabrication and characterization of a nanoscale NiAl bimorph for reconfigurable nanostructures. *Nanoscience and Nanotechnology Letters* 2, 181 (**2010**). © 2010, ASP. (B) SEM image of an electromechanical very-high-frequency suspended resonator based on Nanowire, 1.3 mm long and 43 nm in diameter. Reprinted with permission from [43], A. Husain, et al., Nanowire-based very-high-frequency electromechanical resonator. *Appl. Phys. Lett.* 83, 1240 (**2003**). © 2003, AIP. (C) Micrograph showing the curving electrically actuated bimorph nanoactuator based on polypyrrole nanowires (on top) coupled with gold (on the bottom). Scale bar represent 50 μm. Reprinted with permission from [44], Y. Berdichevsky and Y.-H. Lo, Polypyrrole nanowire actuators. *Advanced Materials* 18, 122 (**2006**). © 2006, John Wiley and Sons. (D) The TEM image shows the platinum nanoparticles attaching to the nanotube templates to form electrochemical hybrid metallic nanowire actuator based on self assembling the platinum nanoparticles. The inset shows platinum nanoparticles of size ranging from 5 to 10 nm. Reprinted with permission from [45], S. Lu and B. Panchapakesan, Hybrid platinum/single-wall carbon nanotube nanowire actuators: Metallic artificial muscles. *Nanotechnology* 17, 888 (**2006**). © 2006, IOP Publishing Ltd. (E) Electrostatically actuated carbon nanowires straight type nanotweezers, 300 nm in diameter and 20 μm in length. (a) No applied voltage. (b) Maximum deflection is achieved when the tip distance is 3.5 μm under 101 V. Reprinted with permission from [47], J. Chang, et al., Electrostatically actuated carbon nanowire nanotweezers. *Smart Mater. Struct.* 18, 065017 (**2009**). © 2009, IOP Publishing Ltd.

Table I. Summary of nanomaterials for actuators.

Individual CNTs	Actuation methods	Electromechanical, thermal, optomechanical (focused laser beam)
	Actuator structures	Cantilevers, simply supported beam, bimorph cantilevers, sandwiched CNT structures, arrays of elastic vertically aligned CNTs, nanotweezers
	Enhanced properties	μN force, linear deflection, reduced size actuators, rapid response
	Fabrication and synthesis	Pulsed laser deposition (PLD), dehydration of a droplet of a suspension of nanotubes on the substrate, arc discharge method
	Applications	NEMS switches, random-access memory elements, logic devices, electron counters, and gap sensing devices, artificial muscles, thermometer, thermostat, and thermosensor, electrical switching, resonant oscillations, and bending of nanowires, constructing three-dimensional structures, for investigating the interaction between the nanomaterials, and for measuring the mass and electrical conduction of nanomaterials, manipulates nanomaterials in an atomic force microscope
Single-walled CNTcomposites	Actuation methods	Electrothermal, electromechanical, photomechanical
	Actuator structures	Bimorph cantilever, sandwiched structure, hybrid configuration
	Enhanced properties	Displacement, electrical conductivity, thermal conductivity, conversion efficiency, force output, frequency band, stiffness, power consumption, resonance frequency
	Fabrication and synthesis	Compatible to CMOS/MEMS processes, ultrasonic treatment, micromolding, mixing and sonication
	Applications	Biomimmetic muscle-like actuators, MEM switches and artificial muscle fibers, ultra light weight smart actuators
Multi-walled CNTcomposites	Actuation methods	Electromechanical, electrothermal
	Actuator structures	Bimorph, hybrid, gel strip, reinforced membrane, connected cantilevers made of the same material but with different lengths
	Enhanced properties	Maximum stress, stress and the strain of the failure, Young modulus, Output force, resonance frequency, efficiency, stiffness, electrical conductivity, enhanced gripping, toughness, structural integrity, reliability, power efficiency, Modulus of elasticity to the density
	Fabrication and synthesis	Oxidized in nitric acid, mixing and sonication, mixing and casting, electrolyte nickel deposition, acid oxidative method
	Applications	Mimics biological muscles, resonators
Nanoparticle composites	Actuation methods	Electrothermal, Magnetic, electrochemical
	Actuator structures	Two connected cantilevers with different lengths, anisotropic structure
	Enhanced properties	Power consumption, reliability, reversible displacement, mechanical strength, CTE, output force, energy conversion, Young's Modulus, hardnesss, Young's modulus to density ratio, resistivity, response rate, life time
	Fabrication and synthesis	CMOS-compatible, heating up colloidal solution in a Cu plating bath, mixing and sonication, casting
	Applications	High frequency microresonators, MEMS fabrication due to CMOS compatibility, biomedical
Single-walled CNT sheets	Actuation methods	Electromechanical, electrochemical, optically driven, acoustic
	Actuator structures	Bimorph actuator, bimorph cantilevers
	Enhanced properties	Reliability, dielectric strength, stresses and strains, deflection, deformation, displacement, Young's modulus
	Fabrication and synthesis	Spraying aqueous solution of purified P3 SW CNTs, vacuum filtration of nanotube suspension and peeling off the dried sheets
	Applications	Mimics the natural muscles, load speaker and for active noise cancellation
Nanofilms and coatings	Actuation methods	Electrothermal, electrostatic, optical triggered (infrared light)
	Actuator structures	Bimorph cantilever, bi-stable double anchored cantilever, cantilevers pinned at one corner
	Enhanced properties	Displacement, large switching force, chemical inertness, Young's modulus
	Fabrication and synthesis	Photolithography, O2 plasma reactive ion etching(RIE), sputtering, plasma enhanced chemical vapor deposition (PECVD), offset liquid embossing (OLE)
	Applications	Sensing while actuating, biomimetic actuators, membranes, and skins, medical devices, high performance MEMS and nanoscale actuation technologies, live cell manipulation and sensing
Nanowires	Actuation methods	Thermally actuated, electrochemical, electromechanical, electrostatic
	Actuator structures	Bimorph cantilevers, hybrid core–shell structure, doubly clamped beam, nanotweezers
	Enhanced properties	Stress, maximum reversible strain, flexibility, high strength, Modulus of elasticity, force sensitivity
	Fabrication and synthesis	Electrochemical deposition, Dehydration of the suspension of the nanowires, template synthesis, Self assembly of nanoparticles on nanotube template, focused ion beam chemical vapor deposition
	Applications	Very high frequency resonators, nanotweezers, nanoactuators, reconfigurable nanoantenna technology, operation in blood plasma and salt water, artificial muscle, manipulation of the nanoparticles and nanoscale objects

A very high frequency resonator is made of single platinum nanowire. The electrodeposition of platinum into a nanoporous polycarbonate membrane with a pore size of 20 nm is utilized to form nanowires. The platinum nanowire could be optimized for high compliance and high force sensitivity. The nanowire resonator with small dimensions and high compliance demonstrates the use of a nonlinear device for mixing and parametric amplification (Fig. 8(B)).[43]

Electrically controlled actuation of conductive polypyrrole nanowires, fabricated using template synthesis, is investigated in an aqueous solution. By applying voltage a bundle of nanowires could reversibly expand/contract by about 3% of their initial length which is amplified by coupling the nano wire with gold to form a bimorph structure. The movement of the dopant ions which are incorporated into the polymer induces the contraction when oxidized and expansion when reduced. This actuation is consistent with the bimorph behavior of polypyrrole nanowires coupled with gold. By measuring the current versus time it is observed that the nanowires on the edge of the sample show a faster response in compare to the ones in the middle of the sample. The nanoactuators are suitable for operation in environments such as blood plasma and salt water in which a small amount of positively charged ions are present (Fig. 8(C)).[44]

A hybrid metallic nanowire actuator is synthesized with high surface area to volume ratio, which generates a stress of 12 MPa for a maximum reversible strain of 0.31% at low voltages and could be used as artificial muscle. The nanowire actuators with a diameter of 50 to 170 nm are fabricated by self assembling the platinum nanoparticles with an average diameter of 5–8 nm on SW CNT template. This core–shell structure is assembled into sheets (Young's modulus of 3.8 GPa) consisting of millions of nanowire actuators using a vacuum filtration system. A hybrid platinum/SWNT nanowire sheet with a thickness of 70 μm was attached to strip of PVC with a thickness of 100 μm which was vertically anchored in a 1M KOH solution. The high surface to volume ratio of nanowires which results in a high accessible surface area for double layer charging is crucial to achieve large actuation response. When the nano wire sheet was biased a potential difference was formed at the interface between the nanowire and the solution which results in an electrochemical double layer at the interface. Moreover the use of nanotubes as cores gives flexibility and high strength to actuators (Fig. 8(D)).[45]

Chang et al. fabricated the straight and bent nanotweezers from two carbon nanowires, using focused ion beam chemical vapor deposition (FIB-CVD). The nanowires are constructed on batch processed microelectrodes made from silicon on insulator (SOI) wafer. The tweezing motion is generated by direct deformation of the nanowires due to electrostatic attraction forces. A voltage is applied between the ground and the driving microelectrodes which causes the electrostatic attraction between the nanowires. The tweezing range is measured to be about one third of the initial gap between each tweezers. By applying a voltage of 30 V a continuous gap closing movement of 0.6–1.2 μm is generated. The proposed nanotweezers could be used for manipulation of the nanoparticles and nanoscale objects (Fig. 8(E)).[47]

4. PROSPECT

Based on the active research reviewed in the field, it is predicted that future research will yield

(a) development of more elaborate fabrication methods of actuators

(b) understanding of dynamic response of devices and

(c) implementation of actuation mechanisms into practical applications.

Generation and control of sub atto Newton force, for example, could be one of the expected outcomes.

Some of the nanomaterials change their shape when electrically charged and this property could be used as complicated and more efficient nanomechanical devices. The challenges lie in detection of minuscule motion of high impedance structures. Recently for the production of high performance actuators such as MEMS switches and artificial muscles, composites enabled by nanomaterials, e.g., SW CNTs are actively studied. The low power consumption of the hybrid actuators is a promising trait for developing ultra light weight smart actuators. For example, CNT/biopolymer composite based actuators exhibit great actuation performance with ease of fabrication, low driving voltage, reliability and biocompatibility which makes them a good candidate for artificial muscles in microrobots and actuators for microfluidic devices. More study is needed to further improve electrical to mechanical energy conversion. CNTs are uniquely positioned as the most widely used material in various actuating devices due to their mechanical and electrical properties. Graphene will gain the same position and will be more commonly used in upcoming years as it provides the same characteristics with the ease of film based process. Another interesting topic in this area is the improvement of existing devices employing nanofilms and nanocoatings obtained by optimization of material properties. A substantial reduction in power consumption and improvement in fatigue life are expected out of successful implementation of this work.

5. SUMMARY

Nanomaterials are used for fabrication of nanoscale actuators as well as improvement of performance characteristics of microscale actuators. Carbon nanotubes have been most widely used due to their superb electrical and mechanical properties. A variety of composites have been derived by dispersing CNTs and other nanoparticles in polymer

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matrices and used for fabricating actuators in the form of cantilever beams, suspended beams and membranes. Films and coatings, such as graphene sheets have been used as an additive layer to form hybrid structures actuated by thermal, electrical or optical stimuli. Nanowires in their stand-alone configurations could be used for manipulating other nanoscale objects. Due to their scale and versatility, nanomaterials are well-suited to current and future applications of miniaturized actuators. A variety of nanomaterials currently reported and used for actuators are summarized based on their actuation methods, structures, enhanced properties and fabrication methods in Table I.

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