A remote-controlled transparent large-area graphene-based robot

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Since the discovery of C_{60} in 1985 by Richard Smalley and co-workers[1], several novel carbon nanomaterials have been isolated, including carbon nanotubes (CNTs)[2] in 1991 and graphene[3] in 2004. CNTs and graphene, with their superb electrical, thermal, mechanical and optical properties, can function as promising hosts for various device applications. With the availability of these two carbon nanomaterials, there has been a great surge in the development of new mechanical actuators that convert external stimuli such as thermal, light, electrical or chemical energy to mechanical energy. CNTs and their composites are good actuator materials and it has been demonstrated that CNT aerogel sheets are the sole component of new artificial muscles that provide giant elongations and elongation rates[4]. The extraordinary mechanical, optical and electrical properties of graphene have been exploited by many scientists in the past three years to develop actuators based on this 2D carbon nanomaterial. Park *et al.*[5] prepared a bilayer paper composed of adjacent graphene oxide and multi-walled carbon nanotube (MWCNT) layers with the thickness of the graphene oxide and MWCNT layers approximately 10 mm each, and demonstrated a macroscopic graphene-based actuator (curling). The papers curl depending on humidity and/or temperature. While graphene–thermoplastic polyurethane composite exhibited infrared-triggered actuation behaviour[6], electromechanical performance of ionic polymer–metal composite based on graphene oxide–Nafion nanocomposite actuators using CNT as electrodes displayed dramatic enhancement of actuation properties[7]. Xie *et al.*[8] designed a graphene film actuator by asymmetric surface modification of the two opposite sides of the monolithic graphene film with hexane and O_2 plasma respectively. The actuation motion was induced through asymmetric electrochemical charging and discharging. Recently a bimorph micro-actuator has been developed based on graphene-on-orgnic (epoxy) film hybrid[9]. The graphene-on-organic film actuator generates a flapping and bending movement that could be controlled by changing the frequency and duration of the applied voltage.

The current interest and demand for transparent flexible electronic devices not only invigorated scientists to use graphene for this purpose but also for the development of soft actuators, as well as in the construction of the transparent soft-robot models. In this context the recent report by Wu *et al.*[10] that describes the fabrication of a robot by employing a large-area transparent graphene as the actuator garners greater attention. The actuator can curl and uncurl in the absence and presence of infrared (IR) radiation (*vide infra*). This behaviour has been successfully employed to develop a remote-controlled graphene-based robot that picks up an object, moves it to a desired location and then drops it by the remote control of IR irradiation. In addition, the fabricated robot from large-area graphene also exhibits worm-like motion triggered by IR irradiation [a symmetric shape changing behaviour of contracting (IR off) and stretching (IR on); see also Figure 1]. This motion is reminiscent of the movement of a fullerene-wheeled azobenzene incorporated nanovehicle (nanoworm)[11] in which a *cis–trans* photoisomerization of azobenzene chromophore is responsible for the generation of worm-like motion on a surface. Wu *et al.*[10] employed a large-area graphene as it enhanced the actuating performance of the bimorph actuator. This happens because of photothermal conversion efficiency of IR radiation keeping high transparency. They fabricated a transparent soft actuator, based on incorporation of large-area graphene in a new bilayer configuration constructed with chitosan and polyethylene (PE; Figure 1 *a*). Graphene, obtained from hydrazine reduction of graphite oxide, dispersed in water was mixed with an aqueous solution of chitosan. The graphene–chitosan mixture (0.05 ml) was then directly coated onto the PE film. Before this coating, the PE film on a glass plate was made hydrophilic by treatment with a mixture of sulphuric and nitric acids. The graphene–chitosan was homogeneously spread to form the transparent graphene–chitosan/PE bimorph configuration. After completely drying at 90°C in vacuum, a 3 mm × 12 mm strip of the graphene–chitosan/PE transparent thin film was peeled-off from the glass and this strip acted as an actuator (Figure 1).

The study of spatial temperature distribution of the chitosan/PE film with and without the addition of graphene before and after IR irradiation of chitosan/PE biomorph clearly revealed that graphene effectively absorbs IR light and then converts the light energy to thermal energy efficiently, ensuring high

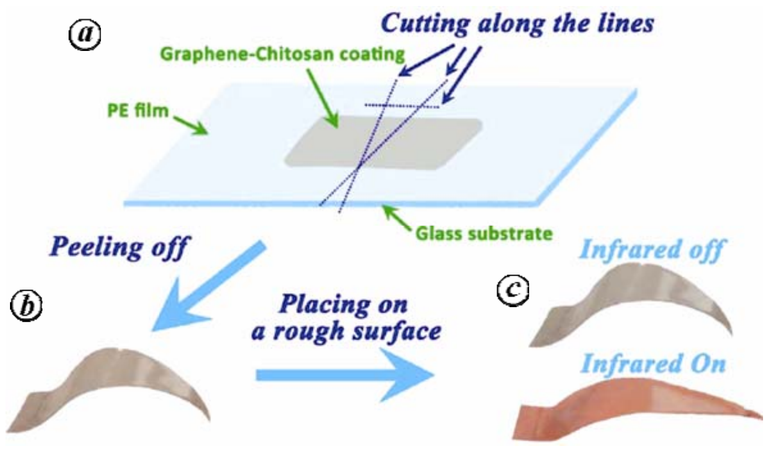

Figure 1. Schematic procedure for the fabrication of infrared-triggered artificial worms. ***a***, Triangle-shaped area was cut out as is shown by dashed lines. ***b***, The cut-out area was peeled off, after which the strip automatically transformed into a curled state. ***c***, The two different states with and without IR irradiation, which shows a typical crawling mechanism like the real worms. From Wu *et al.*[10]. Reproduced by permission of The Royal Society of Chemistry.

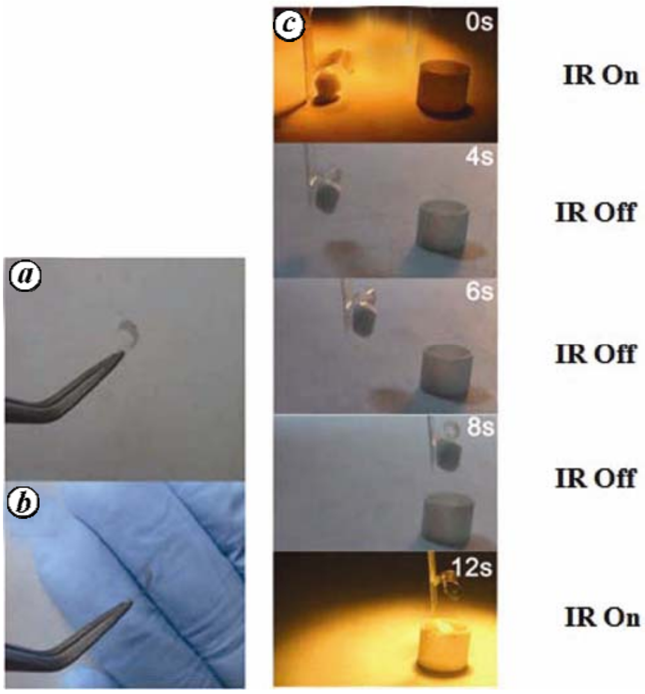

Figure 2. ***a***, ***b***, Even under the very weak IR irradiation by the hand approaching, the actuator exhibits the contracting-to-stretching behaviour with high sensitivity (also see supplementary movie in Wu *et al.*[10] – 'Actuating behaviour under weak IR irradiation'). ***c***, Developing the large-area graphene-based bimorph actuator for 3D robotic motions. Time course of a typical gripping–releasing process based on the actuating behaviour. The photographs show the microrobot picking, lifting, moving and placing the object in a nearby container by turning on and off the infrared light. (also see supplementary movie in Wu *et al.*[10] – 'Gripping/releasing process'). (From Wu *et al*.[10]. Reproduced by permission of The Royal Society of Chemistry.)

sensitivity and high energy conversion efficiency during the actuating process[10]. The team found that the strip curled in the absence of IR light (off) and uncurled by switching the IR light (on; Figure 1 *c*). A continuous on–off switching of IR radiation leads to a worm-like movement – a walking worm induced by IR light. (see the supplementary movie entitled 'Walking under alternating IR stimulus' in Wu *et al.*[10]). It is amazing to observe that when an alternating IR stimulus with a power density of 10 mW cm^{-2} was applied at a frequency of 1 Hz, the actuator strip underwent a contracting-to-stretching motion with a maximum displacement of 1.8 mm. It may be noted that the large-area graphene-based transparent actuator strip displays a high shape-changing stability in response to external IR stimulus and the contracting–stretching states are fully reversible. It is interesting that even under the very weak IR irradiation from an approaching hand, the actuator still exhibits the contracting-to-stretching behaviour with high sensitivity (Figure 2 *a* and *b*; also see supplementary movie 'Actuating behaviour under weak IR irradiation' in Wu *et al.*[10]).

As the strip uncurled in the presence of IR radiation, switching the IR light on and off, it became possible to transform the strip into a moving robot. Wu *et al.*[10] could develop from this actuator a remote controlled graphene-based robot that picks up an object, moves it to a desired location and then drops it. The bimorph film acts as the 'hand'. When the graphene film curls in the absence of IR light, it can act as a gripper for carrying an object. On exposure to IR irradiation due to uncurling, the object can be dropped. It may be realized that the two ends of the actuator strip could close and open under the off–on state of IR irradiation, which offers the driving force to grip/release the object respectively. Therefore, the graphene actuator can exhibit gripping–releasing action of a robot with a remote control of IR stimulus. The robotic action of picking, lifting, moving and placing the object in a nearby container by turning on and off the IR light (30 mW cm^{-2}) is illustrated in Figure 2 *c* (also see supplementary movie 'Gripping/releasing process' in Wu *et al.*[10]). To start with the bimorph 'hand' opened upon IR irradiation. Then on switching off the IR light, the object was steadily gripped due to the contracting (curling) action of the actuator strip. With the object in its grip, the strip was moved to a container, the IR light was switched on and the 'hand' opened to drop its cargo. Thus Wu *et al.*[10] have clearly demonstrated that 'the multiple synergic advantages of large-area graphene, especially its excellent IR absorption ability and 2-dimensionality, successfully result in the excellent actuating sensitivity with high transparency, accompanied by fascinating advantages of remote control and high energy conversion efficiency'[10].

The robot developed by Wu *et al.*[10] is undoubtedly an elegant and important demonstration of photothermal energy conversion by graphene-based actuators. It could possibly pave the way for the design of several such micro-robots for a variety of applications, including transparent artificial muscles. The photomechanical actuation of graphene is likely to kindle interest in exploring other exciting applications of this system.

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