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Bending of Graphene Via Electrostatic Actuation

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ABSTRACT

Recent advanced sensors and actuators are transducers that rely on micro and nano components to perform an actuation or sensing with high performance. Three factors must be taken into consideration when designing an actuator: actuation mechanism, driving voltage, and energy efficiency. Relatively low energy efficiency, high driving voltage, design complexity, and low flexibility are the most common obstacles related to traditional materials in actuators. To overcome the problems of using conventional materials, a thin, flexible, and strong graphene material has been introduced. From an actuation point of view, graphene can be driven into actuation electrostatically, electrothermally, or optically. Electrostatic actuation has been proven to be an efficient approach, enabling the actuator to achieve large displacement with high sensitivity. In this review, properties, actuation mechanisms, and synthesis methods are discussed. Moreover, we have briefly reviewed the recent actual applications, challenges, and future perspectives of graphene-based electrostatic actuators.

INTRODUCTION

The simplest definition of the actuator is that it is a type of transducer that enables the transformation of a specific form of energy, usually mechanical, into electrical energy. An important element of the actuator is the actuation material. The material should be able to sense/respond to any external stimulus [1]. There are many forms of external stimuli. They could be mechanical strain, heat, light, electric field, or magnetic field [2]. When such external stimuli are applied to the actuator, the sensitive material will respond in a way that is translated to a change in shape or modulus. Therefore, choosing materials for the actuator is strongly attributed to the material's ability to respond to the external stimulus. From an operational point of view, mechanisms of actuation are described as electrostatic, piezoelectric, magnetic, and thermal [3]. Electrostatic actuation has been found in most recent sensors and actuators. This approach has several benefits, including, for example, low power consumption, simple configuration, compatibility with micro- and nanoelectromechanical systems (MEMS/NEMS), and relative ease of fabrication. These features make electrostatic actuation preferable over other actuation mechanisms. Numerous micro/nano electrostatic actuators, such as switches, resonators, and filters, have been created and used in a broad range of applications [4,5]. That being said, there are some drawbacks associated with electrostatic actuation, the most common of which are high driving voltage and non-linearity. Pull-in instability is an undesired situation that has been identified as a restriction of electrostatically operated devices [6].

Although silicon is widely used in micro/nano actuators, other materials such as metals, polymers, ceramics, alloys, glasses, and carbon-based elements have also been successfully applied [7]. The constraint that limits the use of piezoelectric ceramics is that they require high operating voltage. In addition, polymer-based soft actuators suffer from low energy conversion efficiency and slow response. These challenges have led to the need to choose alternative materials that are more suitable for high-performance actuators. In order to develop a robust actuator that operates at low voltages with a rapid response, carbon-based materials have been introduced recently [7–10]. A possible competitive candidate for actuation materials is graphene.

Graphene was discovered in 2004 when a single sheet of an array of carbon atoms was isolated. What makes graphene very desirable in sensors and actuators are its unbeaten properties. Characteristics such as large surface area, flexibility, mechanical strength, and high conductivity have made graphene an ideal material for a wide range of applications [11]. In recent years, plenty of advanced MEMS/NEMS devices have been created using graphene and its derivatives [12]. It was also found that the performance of graphene-based actuators can be further enhanced by combining graphene with other materials. For instance, fast response and low power consumption have been achieved for a graphene-polymer electromechanical actuator. Additional advantages of using graphene-based actuators are their scalability and compatibility with existing fabrication and synthesis technologies. Attempts to develop graphene-based actuators have already been made by groups of scientists and researchers [13–20]. Nevertheless, the future of advanced and reliable actuators of graphene is still promising. Research efforts are focused on developing high-quality, scalable, and mass-produced graphene. In this review, we aim to provide a brief description of graphene, its properties, synthesis methods, actuation mechanisms, and potential applications. The main topic that will be covered in this review is electrostatic actuators based on graphene.

RESEARCH METHOD

The configuration of an electrostatic actuator is simply two plates separated from each other by an insulting layer. This configuration works similarly to a capacitor, where the attraction between opposite charges on the plates leads to the creation of an electric field in the capacitor. From a design point of view, an electrostatic actuator is normally made from a fixed electrode and a moveable membrane/film/beam [21]. In the case of graphene, the actuator is made from a layer of graphene (i.e. usually suspended) and an actuation electrode made from a metallic material. To set the actuator in motion, an electric field is applied. Accordingly, a force will be exerted on the graphene film, causing the film to undergo deformation or bending. A simple representation of the electrostatic actuation of graphene is schematically shown in Figure 1.

The electrostatic force (F_{es}) that describe the graphene actuator is given by [22]:

$$F_{es} = \frac{1}{2}\epsilon_0\left(\frac{V^2}{d^2}\right)A \qquad (1)$$

Where d is the distance separating graphene from the actuation electrode, ϵ_0 is free space permittivity, V is the applied voltage, and A is the effective area of the membrane. It is clear that the greater the electric field, the greater the displacement of the actuator. Therefore, the actuation can be controlled by modulating the voltage applied across the capacitor or changing the distance between the electrodes. Depending on how the system is configured in graphene-based actuators, the force generated by the electrostatic fields may induce the graphene material to stretch or bend.

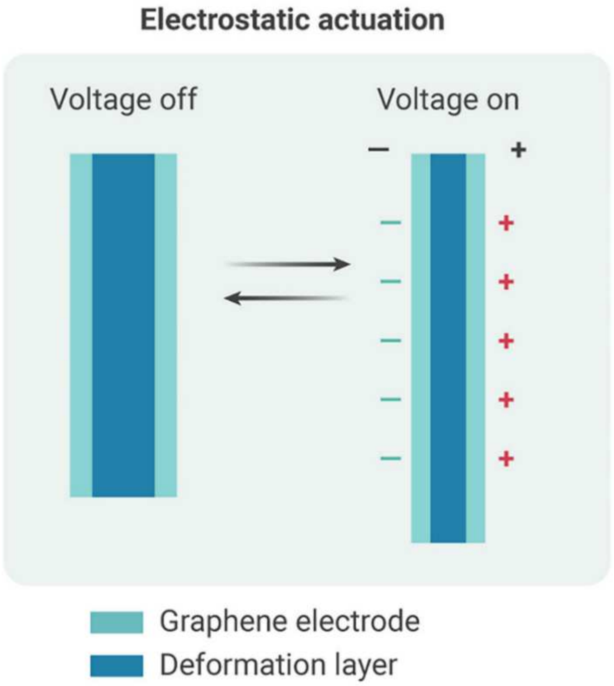

Figure 1. Illustration of electrostatic actuation of graphene. Reproduced with permission from [23] . Copyright 2021, Elsevier.

The deformation of the graphene film when subjected to an electrostatic force can be described using the classical plate theory as follows:

$$w(x,y) = \frac{F_{es}}{D}\left(\frac{x^2+y^2}{L^2}\right) \qquad (2)$$

where $w(x,y)$ is the graphene displacement, D is the flexural rigidity of the membrane, and L is the characteristic length scale. The flexural rigidity of the graphene membrane can be determined in terms of Young's modulus (E), Poisson's ratio (v), and thickness (h) [24]:

$$D = \frac{Eh^3}{12\,(1-v^2)} \qquad (3)$$

It seems from above that, to control the movement of the graphene actuator, we can either adjust the voltage applied across the actuator electrodes or modify the size/shape of the membrane itself. By tuning these parameters, we can precisely control how much the graphene bends/ deflects [25].

$$F = \frac{1}{2}\epsilon_0\left(\frac{V^2}{d^2}\right)A \qquad (4)$$

RESULTS AND DISCUSSION

Fabrication

In order to use graphene in sensors and actuators, it must first be manufactured in ways that are compatible with the designs and functions of those sensors and actuators. For most sensing or actuation applications, synthesizing high-quality graphene in large quantities is essential. The term synthesis is simply a procedure followed to extract graphene with specific properties and sizes for use in the appropriate application. Several methods can be used to synthesize graphene [26–28]. The first fundamental approach is mechanical exfoliation [29]. Recently, many synthesis approaches have been developed. The recently used methods for synthesizing graphene, applications, and the pros and cons of each method have been highlighted in Table 1.

Importantly, the goal of diversifying and innovating new manufacturing methods for graphene is to ensure that the graphene produced is of high quality and pristine. In other words, the graphene should be free of cracks, defects, wrinkles, or contamination. However, that is not always possible because of the fact that most fabrication or post-fabrication processes cause undesirable defects. Graphene cannot be directly deposited and processed using semiconductor processing technology like traditional materials such as silicon. This is due to complications associated with post-synthesis conditions. The general route is by growing graphene on transition metal substrates such as (e.g., copper or nickel).

Table 1. Synthesis methods of graphene.

Method	Advantages	Disadvantages	Applications
Mechanical Exfoliation	High-quality, inexpensive	Low yield, difficult to scale up	Research, small-scale devices
Chemical Exfoliation	Scalable, simple	Lower quality, dispersion challenges	Composites, coatings, energy storage
CVD on Metal Substrates	High-quality, scalable	Requires high temperature, expensive	Electronics, photodetectors
Reduction of GO	Simple, scalable, cost-effective	Quality compromised, defect-prone	Supercapacitors, sensors
CVD on SiC	High-quality, no catalyst needed	High temperatures, expensive	High-speed electronics
Hydrothermal/Solvothermal	Scalable, moderate temperature	Low-quality, less control over size	Energy storage, catalysis
Epitaxial Growth on Metal	High-quality, ordered graphene	High pressure, temperature	Electronics, photonics

One of the biggest challenges facing graphene is that it cannot be used directly while it is still on the initial substrate on which it was synthesized. Therefore, graphene must be transferred from the deposition substrate to the target substrate to be ready for further processing. Despite all efforts to develop an efficient and damage-free transfer method of graphene, unaddressed challenges remain [30–33]. Recently, attempts have been devoted to introducing innovative methods by which graphene can be grown directly on flexible, and non-metallic substrates [34,35]. A comparison of methods used to transfer graphene is presented in Table 2.

Table 2. Graphene transfer methods. Reproduced with permission from [36]. Copyright 2021, Springer.

Method	Advantages	Disadvantages
Wet transfer	Non-destructive, laboratory-scale	Contamination, time-consuming, expensive
Electrochemical bubble transfer	Repeatable, scalable, less etching chemicals	Low quality, dispersion challenges
Non-electrochemical bubble transfer	Applied to metallic and non-metallic substrates	Relatively slow
Roll-to-roll transfer	Compatible, low cost, short processing time	Limited to flexible substrates, possible cracks
Dry transfer	High-quality, scalable, short processing time	Signs of cracks
Support-free transfer	Residue-free, low cost, short processing time	Risk of damage

Design of Graphene Actuator

Once graphene has been synthesized and transferred successfully, graphene-based electrostatic actuators can be fabricated. The fabrication process includes several steps such as patterning and etching of graphene as well as integrating the graphene film with actuation electrodes and other actuator components. It is very important to take into consideration the geometry of the actuator. The geometry of graphene-based electrostatic actuators is critical because it can influence their performance and functionality. Depending on the desired application, some key geometric factors can be considered when designing graphene-based electrostatic actuators. The first factor is the thickness of the graphene. Although a single-layer sheet of graphene provides fast actuation and high sensitivity, it is more prone to mechanical failure [37,38]. To overcome the challenges related to mechanical damage, multilayer graphene membranes have been developed [39–42].

Another influential factor is the graphene surface area. A possible effective way to improve the actuator performance is by increasing the surface area of the membrane. When such a scenario occurs, an enhancement in electrostatic interactions is granted[43], [44]. The configuration of the actuator can also impact the deformation of the graphene membrane. Depending on the configuration, the actuator may bend, twist, or expand linearly [45]. Different behavior is expected when the actuator is designed with different geometric shapes, such as circular or rectangular. Furthermore, the distance separating the electrodes must be carefully designed to ensure that no pull-in instability occurs in the actuator [46,47]. Additionally, it is possible to combine one or more layers of graphene with other materials. For example, if a flexible layer is attached to graphene, substantial deformation in the actuator is highly expected.

So far, several graphene-based electrostatic actuators have been developed. Most of these devices rely on graphene suspended in the form of a membrane [25,48] or beam [49–51]. In a membrane-based actuator, a thin film of graphene is transferred to a target substrate and then patterned in a particular shape, usually drum-like. When an electric potential is applied across the graphene–actuation electrodes, the electrostatic force generated induces a deflection in the membrane. In a similar way, graphene can be patterned into a beam structure (e.g., cantilever beam, doubly-clamped beam). The beam will bend (upwards, downwards, or buckling) in response to the external stimulus. Figure 2 shows diagrams and scanning electron microscope (SEM) images of drum-based and beam-based actuators of graphene.

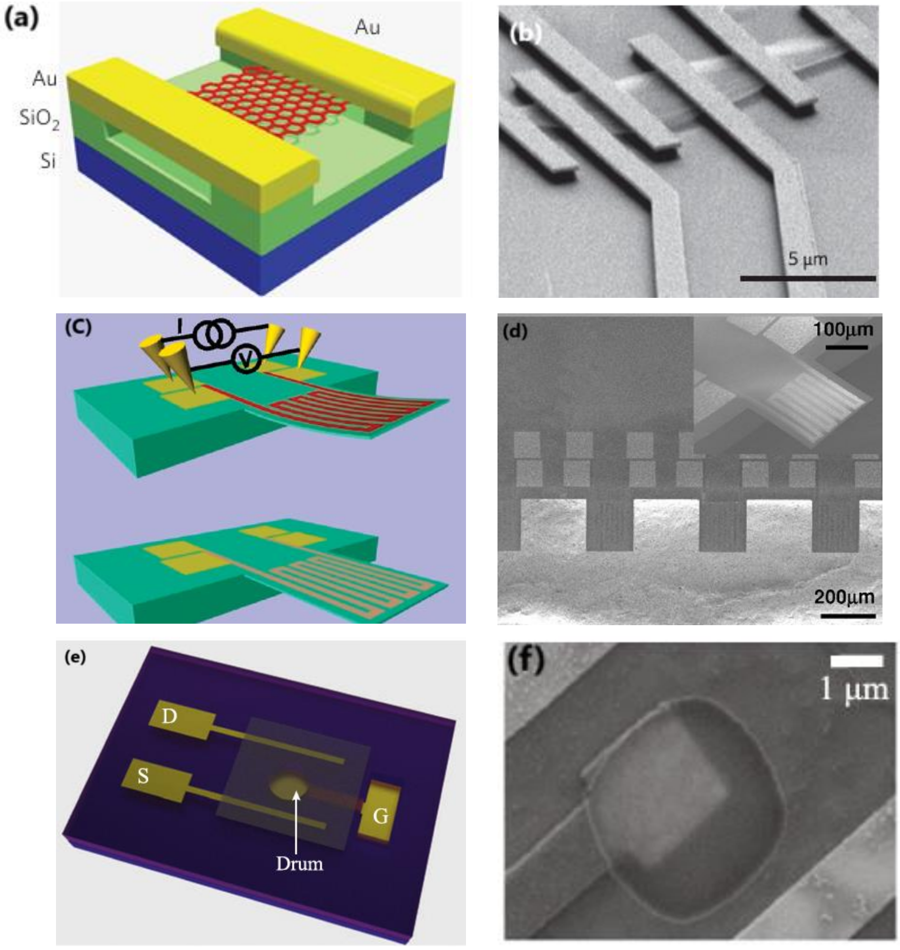

Figure 2. (a) Illustration of a doubly clamped beam of graphene. (b) SEM snapshot of graphene beam. Reprinted with permission from ref. [52]. Copyright 2009, Nature. (c) Schematic diagram of four array graphene/epoxy cantilever beam. (d) SEM image of graphene/epoxy cantilever beam. Reproduced with permission from ref.[53] Copyright 2011, ACS. (e) Sketch of drum-like graphene actuator. (f) SEM image of graphene drum

suspended over an actuation electrode. Reproduced with permission from ref. [54]. Copyright 2016, IOP.

Performance Analysis

The performance of graphene-based electrostatic actuators can be evaluated by considering several factors. The key feature of the actuator is the mechanical strain or displacement. When the device is electrostatically actuated through the application of a DC bias voltage between the actuation electrode and the suspended graphene membrane, the membrane undergoes vertical deflection as shown in Figure 3. It can be seen that the membrane deflects upwards, with a maximum value achieved at the center/middle of the membrane. Also, Figure 3b indicates that the higher the voltage applied across the actuator, the larger the displacement. Most graphene-based actuators can achieve mechanical stress in the range of a few nanometers to micrometers, depending on the dimensions of the actuator [24, 25].

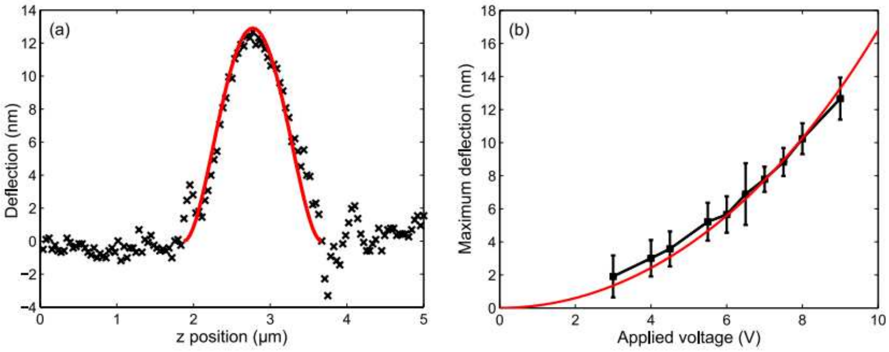

Figure 3. (a) Deflection profile versus the length of an 8.1 nm thick graphene membrane actuated at DC bias of 9 V. (b) Maximum deflection of the membrane under different DC bias voltages. Reprinted/adapted with permission from [55]. Copyright 2013, AIP.

A critical parameter that influences the performance of graphene-based electrostatic actuators is the response time. In some applications such as artificial muscles, energy harvesting, and robotics, rapid actuation is highly required. Since the capacitance of the actuator is affected to some extent by the distance between the graphene electrode and actuation electrode as well as the geometry of the actuator, the response time will be impacted accordingly. Graphene is well-known for its low mass density and high mechanical strength, which enable the graphene-based actuator to deform rapidly when it is driven in actuation, see Figure 4.

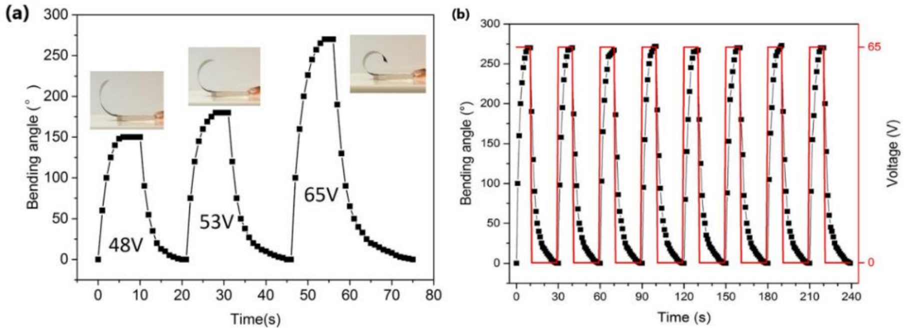

Figure 4. (a) Bending angles over time for a U-shaped graphene-based actuator. (b) Cyclic actuation of the actuator under a voltage of a 65 V square wave. Reprinted/adapted with permission from [56]. Copyright 2017, AIP Publishing.

Applications

When it comes to the applications of graphene and graphene-based devices, they are simply countless. Graphene-based electrostatic actuators in particular have useful applications in many aspects of our daily life. These actuators can be integrated into diverse technologies, including MEMS/NEMS, flexible electronics, and biomedical devices. In some devices, such as accelerometers and pressure sensors that require precision in measurements, graphene can be exploited for this purpose by employing its extreme sensitivity to any applied change. The market for wearable and flexible devices has become popular nowadays. Benefiting from being lightweight and flexible, actuators based on graphene are now part of daily gadgets such as conformable displays and soft robotics. Moreover, the sector of prosthetics has been advanced significantly. For such a goal, graphene-based actuators can serve as artificial muscles, performing their function in a precise and controllable manner. The biocompatibility of graphene is an attractive merit to be used in drug delivery systems and implantable medical devices. In some delicate surgical procedures, an ultra-sensitive material is necessary. That explains why graphene-based actuators can be used in the biomedical field as wearable sensors and to detect biomarkers of medical conditions. To sum up, the possible potential applications of graphene-based electrostatic actuators are presented in Table 3.

Table 3. Applications of graphene-based actuators.

Application	Description	Ref.
MEMS Devices	Used in microelectromechanical systems, switches, resonators, and sensors	[57]
Sensors	High-sensitivity pressure sensors, accelerometers, and sensing devices	[58]
Artificial Muscles	Utilized in robotics and prosthetics for precise control and movement	[59]
Smart Windows	Integrated into systems for controlling light and heat transmission	[60]
Energy Harvesting	Converts mechanical energy into electrical energy, such as in vibration energy harvesters	[57]
Medical Devices	Applied in minimally invasive surgical tools and drug delivery systems	[42]
Robotic Systems	Incorporated into micro- and nanorobots for precise manipulation and movement.	[61]
Intelligent Switches	Used in creating switches that respond to electrical stimuli for various electronic applications	[40]

Environmental Monitoring	Gas sensors, chemical sensors	[62]
Wireless Communication	RF switches, tunable antennas, RF filters	[63]

Challenges

Although graphene has tremendous potential in electrostatic-based devices, there are still many challenges that must be overcome and appropriate solutions must be found for them. The manufacturing of pure and high-quality film of graphene is not an easy task. There are also some difficulties in the realization of graphene on a large scale without incorporating significant imperfections. When considering the actual utilization of graphene-based actuators in practical commercial applications, the development of mass and scalable fabrication methods becomes essential. Graphene, although capable of achieving substantial deflections when subjected to voltage, the actuation efficiency—the process of converting electrical energy into mechanical movement—needs to be improved. In some particular applications that require the device to operate for a long and continuous period, more efforts must be made to ensure that the performance of graphene-based actuators remains stable during the operation. Additional challenges to address are the integration and compatibility of graphene with other materials like metals or polymers.

CONCLUSION

The growing interest in graphene material and graphene-based is attributed to its remarkable properties. The deformation of a thin film of graphene has been exploited in the realization of different types of sensors and actuators. In a graphene-based actuator, the film is set into actuation when the system is exposed to a stimulus. Here, we have briefly discussed the main mechanisms of graphene actuators, highlighting the merits and limitations of each approach. Displacement of graphene-based electrostatic actuators has been comprehensively explored. We have also described the electrostatic actuation mechanism, synthesis methods, challenges, and applications of graphene and its derived actuators.

REFERENCES

[1] A.S. Algamili, M.H.Md. Khir, J.O. Dennis, A.Y. Ahmed, S.S. Alabsi, S.S. Ba Hashwan, M.M. Junaid, A Review of Actuation and Sensing Mechanisms in MEMS-Based Sensor Devices, Nanoscale Res Lett 16 (2021) 16. https://doi.org/10.1186/s11671-021-03481-7.

[2] D.J. Bell, T.J. Lu, N.A. Fleck, S.M. Spearing, MEMS actuators and sensors: observations on their performance and selection for purpose, Journal of Micromechanics and Microengineering 15 (2005) S153–S164. https://doi.org/10.1088/0960-1317/15/7/022.

[3] P.K. Sekhar, V. Uwizeye, Review of sensor and actuator mechanisms for bioMEMS, in: MEMS for Biomedical Applications, Elsevier, 2012: pp. 46–77. https://doi.org/10.1533/9780857096272.1.46.

[4] D. Young, C. Zorman, M. Mehregany, MEMS/NEMS Devices and Applications, in: Springer Handbook of Nanotechnology, Springer Berlin Heidelberg, Berlin, Heidelberg, 2007: pp. 415–442. https://doi.org/10.1007/978-3-540-29857-1_15.

[5] Y. Yan, Y. Hu, L. Wang, X. Qian, W. Zhang, K. Reda, J. Wu, G. Zheng, Electrostatic sensors – Their principles and applications, Measurement 169 (2021) 108506. https://doi.org/10.1016/j.measurement.2020.108506.

[6] W.M. Zhang, H. Yan, Z.K. Peng, G. Meng, Electrostatic pull-in instability in MEMS/NEMS: A review, Sens Actuators A Phys 214 (2014) 187–218. https://doi.org/10.1016/j.sna.2014.04.025.

[7] V.T. Srikar, S.M. Spearing, Materials selection for microfabricated electrostatic actuators, Sens Actuators A Phys 102 (2003) 279–285. https://doi.org/10.1016/S0924-4247(02)00393-X.

[8] R. Shabani, H.J. Cho, Nanomaterials in Actuators—A Review, Reviews in Nanoscience and Nanotechnology 1 (2012) 85–102. https://doi.org/10.1166/rnn.2012.1006.

[9] W.A.D.M. Jayathilaka, K. Qi, Y. Qin, A. Chinnappan, W. Serrano-García, C. Baskar, H. Wang, J. He, S. Cui, S.W. Thomas, S. Ramakrishna, Significance of Nanomaterials in Wearables: A Review on Wearable Actuators and Sensors, Advanced Materials 31 (2019). https://doi.org/10.1002/adma.201805921.

[10] L. Chang, D. Wang, A. Jiang, Y. Hu, Soft Actuators Based On Carbon Nanomaterials, Chempluschem 87 (2022). https://doi.org/10.1002/cplu.202100437.

[11] A. D. Ghuge, A. R. Shirode, V. J. Kadam, Graphene: A Comprehensive Review, Curr Drug Targets 18 (2017) 724–733. https://doi.org/10.2174/1389450117666160709023425.

[12] Z.H. Khan, A.R. Kermany, A. ï¿½chsner, F. Iacopi, Mechanical and electromechanical properties of graphene and their potential application in MEMS, J Phys D Appl Phys 50 (2017) 053003. https://doi.org/10.1088/1361-6463/50/5/053003.

[13] Z. Kolka, V. Biolkova, D. Biolek, Z. Biolek, Modeling Electrostatic MEMS Actuator, in: 2021 28th IEEE International Conference on Electronics, Circuits, and Systems (ICECS), IEEE, 2021: pp. 1–5. https://doi.org/10.1109/ICECS53924.2021.9665561.

[14] S. Nabavi, M. Menard, F. Nabki, Surface Micromachined Out-of-plane Electrostatic MEMS Actuator Integrated with Displacement Sensor, in: 2021 IEEE Sensors, IEEE, 2021: pp. 1–4. https://doi.org/10.1109/SENSORS47087.2021.9639643.

[15] T. Cea, P.A. Pantaleón, N.R. Walet, F. Guinea, Electrostatic interactions in twisted bilayer graphene, Nano Materials Science 4 (2022) 27–35. https://doi.org/10.1016/j.nanoms.2021.10.001.

[16] G. Abbas, F.J. Sonia, M. Jindra, J. Červenka, M. Kalbáč, O. Frank, M. Velický, Electrostatic Gating of Monolayer Graphene by Concentrated Aqueous Electrolytes, J Phys Chem Lett 14 (2023) 4281–4288. https://doi.org/10.1021/acs.jpclett.3c00814.

[17] F. Wang, L. Wang, Z. Wu, W. Wang, A low-voltage electro-ionic soft actuator based on graphene nanoplatelets-sulfonated cellulose nanowhisker combined with microfibrillated cellulose, J Mater Sci 58 (2023) 466–477. https://doi.org/10.1007/s10853-022-08061-3.

[18] S. Nair, V. Kumar, R. Kumar, V.K. Jain, S. Nagpal, Electrostatic graphene oxide-based biosensor for rapid direct detection of *E. coli*, International Journal of Materials Research 113 (2022) 560–568. https://doi.org/10.1515/ijmr-2021-8288.

[19] J. Chen, Y. Cao, J. Pei, H. Zhao, Multifunctional Actuator Based on Graphene/PDMS Composite Materials with Shape Programmable Configuration and High Photothermal Conversion Capability, ACS Appl Mater Interfaces 15 (2023) 31917–31926. https://doi.org/10.1021/acsami.3c06041.

[20] G.J. Verbiest, M. Goldsche, J. Sonntag, T. Khodkov, N. von den Driesch, D. Buca, C. Stampfer, Tunable coupling of two mechanical resonators by a graphene membrane, 2d Mater 8 (2021) 035039. https://doi.org/10.1088/2053-1583/ac005e.

[21] R.C. Batra, M. Porfiri, D. Spinello, Review of modeling electrostatically actuated microelectromechanical systems, Smart Mater Struct 16 (2007) R23–R31. https://doi.org/10.1088/0964-1726/16/6/R01.

[22] W.C. Chuang, H.L. Lee, P.Z. Chang, Y.C. Hu, Review on the modeling of electrostatic MEMS, Sensors 10 (2010) 6149–6171. https://doi.org/10.3390/s100606149.

[23] Y.-L. Zhang, J.-C. Li, H. Zhou, Y.-Q. Liu, D.-D. Han, H.-B. Sun, Electro-responsive actuators based on graphene, The Innovation 2 (2021) 100168. https://doi.org/10.1016/j.xinn.2021.100168.

[24] I.E. Berinskii, A.M. Krivtsov, A.M. Kudarova, Bending stiffness of a graphene sheet, Physical Mesomechanics 17 (2014) 356–364. https://doi.org/10.1134/S1029959914040134.

[25] N. Lindahl, D. Midtvedt, J. Svensson, O.A. Nerushev, N. Lindvall, A. Isacsson, E.E.B. Campbell, Determination of the Bending Rigidity of Graphene via Electrostatic Actuation of Buckled Membranes, Nano Lett 12 (2012) 3526–3531. https://doi.org/10.1021/nl301080v.

[26] A. Gutiérrez-Cruz, A.R. Ruiz-Hernández, J.F. Vega-Clemente, D.G. Luna-Gazcón, J. Campos-Delgado, A review of top-down and bottom-up synthesis methods for the production of graphene, graphene oxide and reduced graphene oxide, J Mater Sci 57 (2022) 14543–14578. https://doi.org/10.1007/s10853-022-07514-z.

[27] F. Zhang, K. Yang, G. Liu, Y. Chen, M. Wang, S. Li, R. Li, Recent advances on graphene: Synthesis, properties and applications, Compos Part A Appl Sci Manuf 160 (2022). https://doi.org/10.1016/j.compositesa.2022.107051.

[28] M.J. Allen, V.C. Tung, L. Gomez, Z. Xu, L.M. Chen, K.S. Nelson, C. Zhou, R.B. Kaner, Y. Yang, Soft transfer printing of chemically converted graphene, Advanced Materials 21 (2009) 2098–2102. https://doi.org/10.1002/ADMA.200803000.

[29] E. Gao, S.Z. Lin, Z. Qin, M.J. Buehler, X.Q. Feng, Z. Xu, Mechanical exfoliation of two-dimensional materials, J Mech Phys Solids 115 (2018) 248–262. https://doi.org/10.1016/J.JMPS.2018.03.014.

[30] S. Ullah, X. Yang, H.Q. Ta, M. Hasan, A. Bachmatiuk, K. Tokarska, B. Trzebicka, L. Fu, M.H. Rummeli, Graphene transfer methods: A review, Nano Res 14 (2021) 3756–3772. https://doi.org/10.1007/s12274-021-3345-8.

[31] Y. Song, W. Zou, Q. Lu, L. Lin, Z. Liu, Graphene Transfer: Paving the Road for Applications of Chemical Vapor Deposition Graphene, Small 17 (2021). https://doi.org/10.1002/smll.202007600.

[32] Y. Gao, J. Chen, G. Chen, C. Fan, X. Liu, Recent Progress in the Transfer of Graphene Films and Nanostructures, Small Methods 5 (2021). https://doi.org/10.1002/smtd.202100771.

[33] P. Wu, W. Zhang, Z. Li, J. Yang, Mechanisms of Graphene Growth on Metal Surfaces: Theoretical Perspectives, Small 10 (2014) 2136–2150. https://doi.org/10.1002/smll.201303680.

[34] Q. Shi, K. Tokarska, H.Q. Ta, X. Yang, Y. Liu, S. Ullah, L. Liu, B. Trzebicka, A. Bachmatiuk, J. Sun, L. Fu, Z. Liu, M.H. Rümmeli, Substrate Developments for the Chemical Vapor Deposition Synthesis of Graphene, Adv Mater Interfaces 7 (2020). https://doi.org/10.1002/admi.201902024.

[35] M. Li, P. Zou, Z. Chen, R. Zhao, C. Tang, S. Wang, Y. Ma, L. Ma, Wafer-Scale Graphene Growth on Si/SiO $_2$ Substrates via Metal-Free Chemical Vapor Deposition, ACS Appl Nano Mater 6 (2023) 10817–10825. https://doi.org/10.1021/acsanm.3c01956.

[36] S. Ullah, X. Yang, H.Q. Ta, M. Hasan, A. Bachmatiuk, K. Tokarska, B. Trzebicka, L. Fu, M.H. Rummeli, Graphene transfer methods: A review, Nano Res 14 (2021) 3756–3772. https://doi.org/10.1007/s12274-021-3345-8.

[37] A. Genoese, A. Genoese, N.L. Rizzi, G. Salerno, Buckling Analysis of Single-Layer Graphene Sheets Using Molecular Mechanics, Front Mater 6 (2019). https://doi.org/10.3389/fmats.2019.00026.

[38] R. Ansari, S. Ajori, B. Motevalli, Mechanical properties of defective single-layered graphene sheets via molecular dynamics simulation, Superlattices Microstruct 51 (2012) 274–289. https://doi.org/10.1016/J.SPMI.2011.11.019.

[39] C. Zhang, T. Zhai, C. Zhan, Q. Fu, C. Ma, Actuation Behavior of Multilayer Graphene Nanosheets/Polydimethylsiloxane Composite Films, Polymers (Basel) 10 (2018) 1243. https://doi.org/10.3390/polym10111243.

[40] G.W. Rogers, J.Z. Liu, Graphene Actuators: Quantum-Mechanical and Electrostatic Double-Layer Effects, J Am Chem Soc 133 (2011) 10858–10863. https://doi.org/10.1021/ja201887r.

[41] C. Zhang, T. Zhai, C. Zhan, Q. Fu, C. Ma, Actuation Behavior of Multilayer Graphene Nanosheets/Polydimethylsiloxane Composite Films, Polymers (Basel) 10 (2018) 1243. https://doi.org/10.3390/polym10111243.

[42] B. Li, Y. Zhang, T. Li, H. Yu, Q. Guo, M. Hu, J. Yang, Multilayer Graphene/PDMS Composite Gradient Materials for High-Efficiency Photoresponse Actuators, Macromol Mater Eng 307 (2022). https://doi.org/10.1002/mame.202100868.

[43] T. Tungkavet, N. Seetapan, D. Pattavarakorn, A. Sirivat, Graphene/gelatin hydrogel composites with high storage modulus sensitivity for using as electroactive actuator: Effects of surface area and electric field strength, Polymer (Guildf) 70 (2015) 242–251. https://doi.org/10.1016/j.polymer.2015.06.027.

[44] X. Xie, L. Qu, C. Zhou, Y. Li, J. Zhu, H. Bai, G. Shi, L. Dai, An Asymmetrically Surface-Modified Graphene Film Electrochemical Actuator, ACS Nano 4 (2010) 6050–6054. https://doi.org/10.1021/nn101563x.

[45] A.K. Al-Mashaal, G.S. Wood, A. Torin, E. Mastropaolo, M.J. Newton, R. Cheung, Dynamic behavior of ultra large graphene-based membranes using electrothermal transduction, Appl Phys Lett 111 (2017) 243503. https://doi.org/10.1063/1.5007327.

[46] X. Liu, N.G. Boddeti, M.R. Szpunar, L. Wang, M.A. Rodriguez, R. Long, J. Xiao, M.L. Dunn, J.S. Bunch, Observation of pull-in instability in graphene membranes under interfacial forces, Nano Lett 13 (2013) 2309–2313. https://doi.org/10.1021/nl401180t.

[47] A.K. Al-mashaal, G. Wood, E. Mastropaolo, R. Cheung, Electrostatically driven long-microbeams for low-frequency applications, Electron Lett 54 (2018) 372–374. https://doi.org/10.1049/el.2017.4534.

[48] J. Xu, G.S. Wood, A.K. Al-Mashaal, E. Mastropaolo, M.J. Newton, R. Cheung, Realization of Closed Cavity Resonator Formed by Graphene-PMMA Membrane for Sensing Audio Frequency, IEEE Sens J 20 (2020) 4618–4627. https://doi.org/10.1109/JSEN.2020.2966415.

[49] H. Rokni, W. Lu, Effect of Graphene Layers on Static Pull-in Behavior of Bilayer Graphene/Substrate Electrostatic Microactuators, Journal of Microelectromechanical Systems 22 (2013) 553–559. https://doi.org/10.1109/JMEMS.2012.2230315.

[50] D.I. Caruntu, L. Luo, Bifurcation and pull-in voltages of primary resonance of electrostatically actuated SWCNT cantilevers to include van der Waals effect, Meccanica 52 (2017) 849–859. https://doi.org/10.1007/s11012-016-0461-8.

[51] J. Sun, M. Muruganathan, N. Kanetake, H. Mizuta, Locally-Actuated Graphene-Based Nano-Electro-Mechanical Switch, Micromachines (Basel) 7 (2016) 124. https://doi.org/10.3390/mi7070124.

[52] C. Chen, S. Rosenblatt, K.I. Bolotin, W. Kalb, P. Kim, I. Kymissis, H.L. Stormer, T.F. Heinz, J. Hone, Performance of monolayer graphene nanomechanical resonators with electrical readout, Nat Nanotechnol 4 (2009) 861–867. https://doi.org/10.1038/nnano.2009.267.

[53] S.E. Zhu, R. Shabani, J. Rho, Y. Kim, B.H. Hong, J.H. Ahn, H.J. Cho, Graphene-based bimorph microactuators, Nano Lett 11 (2011) 977–981. https://doi.org/10.1021/nl103618e.

[54] R.N. Patel, J.P. Mathew, A. Borah, M.M. Deshmukh, Low tension graphene drums for electromechanical pressure sensing, 2d Mater 3 (2016) 011003. https://doi.org/10.1088/2053-1583/3/1/011003.

[55] N. Sridi, B. Lebental, J. Azevedo, J.C.P. Gabriel, A. Ghis, Electrostatic method to estimate the mechanical properties of suspended membranes applied to nickel-coated graphene oxide, Appl Phys Lett 103 (2013). https://doi.org/10.1063/1.4817301.

[56] T.-Y. Zhang, Q. Wang, N.-Q. Deng, H.-M. Zhao, D.-Y. Wang, Z. Yang, Y. Liu, Y. Yang, T.-L. Ren, A large-strain, fast-response, and easy-to-manufacture electrothermal actuator based on laser-reduced graphene oxide, Appl Phys Lett 111 (2017). https://doi.org/10.1063/1.5003610.

[57] B. Sajadi, F. Alijani, D. Davidovikj, J. (Hans) Goosen, P.G. Steeneken, F. van Keulen, Experimental characterization of graphene by electrostatic resonance frequency tuning, J Appl Phys 122 (2017). https://doi.org/10.1063/1.4999682.

[58] J. Xue, Z. Gao, L. Xiao, The Application of Stimuli-Sensitive Actuators Based on Graphene Materials, Front Chem 7 (2019). https://doi.org/10.3389/fchem.2019.00803.

[59] Y. He, Y. Sun, Z. Wang, S. Ma, N. Zhang, J. Zhang, S. Soh, L. Wei, Pristine graphene oxide film-based contactless actuators driven by electrostatic forces, J Mater Chem C Mater 5 (2017) 9534–9539. https://doi.org/10.1039/C7TC03043F.

[60] L. Xu, I.K. Oh, Study on the graphene-based actuator, Composites 7978 (2011) 79781V-79781V–9. https://doi.org/10.1117/12.880649.

[61] Y. Huang, J. Liang, Y. Chen, The application of graphene based materials for actuators, J Mater Chem 22 (2012) 3671. https://doi.org/10.1039/c2jm15536b.

[62] A. Nag, A. Mitra, S.C. Mukhopadhyay, Graphene and its sensor-based applications: A review, Sens Actuators A Phys 270 (2018) 177–194. https://doi.org/10.1016/j.sna.2017.12.028.

[63] X. Song, M. Oksanen, M.A. Sillanpää, H.G. Craighead, J.M. Parpia, P.J. Hakonen, Stamp transferred suspended graphene mechanical resonators for radio frequency electrical readout, Nano Lett 12 (2012) 198–202. https://doi.org/10.1021/nl203305q.

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