Review on graphene oxide-based nanocomposites for resistive switching applications

Nipom Sekhar Das[1], Koustav Kashyap Gogoi[1], and Avijit Chowdhury[1]*

[1]Organic Electronics and Sensor Laboratory, Department of Physics, National Institute of Technology Silchar, Assam-788010, India

Email: avijitiacs@gmail.com, nipomsekhardas21@gmail.com

Abstract

Graphene and graphene oxide (GO) have attracted growing attention in the field of resistive switching memory due to their extraordinary structural, physical and electronic characteristics. Moreover, properties such as excellent charge carrier mobility, high mechanical strength, and outstanding thermal properties make the graphene-based materials suitable for a broad range of other exploitations and many technological applications such as in sensors, energy storage devices, batteries, photocatalysis, electronic devices, supercapacitors etc. The limiting factors such as low storage density and scaling capabilities in silicon-based memories have led the researchers to explore other alternatives for developing the next generation cost effective data storage devices. The article summarises the recent advances in the field of resistive switching memory and tries to focus mainly on the use of graphene-based semiconductor heterostructure devices. The article further includes a brief comparison of the memory performances of graphene/GO nanocomposites with various insulating polymers and semiconducting materials.

Keywords: *Graphene, electronic devices, resistive switching, non-volatile*

1. Introduction

Graphene has been reported to be the thinnest yet the strongest material to exist in nature with a two-dimensional honeycomb structure of carbon atoms as displayed in Fig. 1 [1].

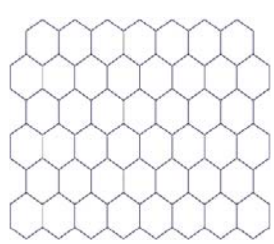

FIG 1. Schematic diagram of graphene.

It possesses various extraordinary properties like high mechanical strength, high electron mobility, Young's modulus, optical transmittance, thermal conductivity, and surface area [2-4]. Owing to such properties, graphene has found numerous applications in the fields of solar cell technology, polymer nanocomposite, supercapacitor [5]. However, the zero-band gap of graphene stands out as a major limitation for its application in the field of data storage device [6]. Furthermore, the low solubility of graphene also possesses a major constraint to its ease of processability which further limits its use in electronic devices [7]. On the other hand, the derivatives of graphene such as GO or reduced graphene oxide (rGO) display an increased band gap, enhanced solubility and so forth while simultaneously maintaining the excellent mechanical and electrical characteristic of graphene. While graphene oxide is the oxidised form of graphene, reduced graphene oxide can be prepared directly from graphene oxide by removing some of the oxygen functionalities. The presence of these oxygen functionalities is responsible for opening of a band gap and better solubility of these materials [8-10]. As such, GO and rGO find a much wider range of exploitations such as in catalysis, energy storage, nanocomposite materials and data storage devices [11]. A diagram of graphene oxide is schematically displayed in Fig. 2.

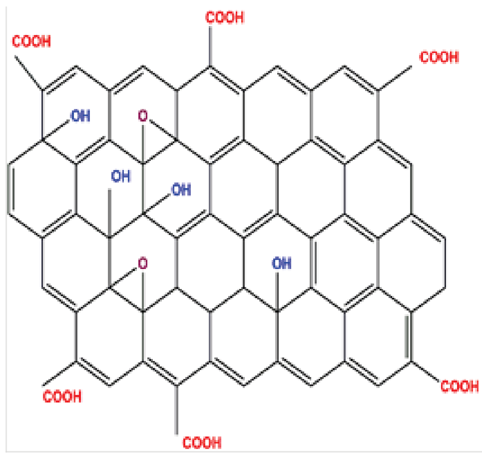

FIG 2. Schematic diagram of graphene oxide (GO)

Both GO and rGO have been reported to possess various defects states that are introduced during the synthesis processes. Thus, in the context of data storage devices, these materials can be used for both charge blocking as well as charge trapping purposes [12]. Furthermore, the amount of defect sites can be tuned depending on the degree of oxidation or reduction which in turn changes the charge blocking and trapping capabilities of both the materials [13, 14]. Research shows that among the various currently developed data storage devices such as phase change resistive random-access memory (PCRAM), magnetoresistive random access memory (MRAM), ferroelectric random-access memory (FRAM) and resistive random-access memory (RRAM), the RRAM technology possesses the highest potential to replace the gradually dating Si type flash memory technology as mentioned in Fig.3 [15]. Although the flash memory technology exhibits high operating speeds and storage densities, but the physical constraint of scaling down to few tens of nanometers without compromising with the storage density possesses a challenge [16]. Such limitations can however be overcome through the 3D stacking in the RRAM devices [17]. As such, much effort has been paid by the researchers for exploiting the resistive switching properties in graphene oxide and its derivatives. There have been numerous reports where graphene oxide is mixed with various polymers for resistive switching applications [18]. Some other works report the resistive switching properties of GO composites with various conducting and semiconducting materials [19]. A detailed investigation on the resistive switching properties of various graphene, GO and rGO nanocomposites is given in section 2.

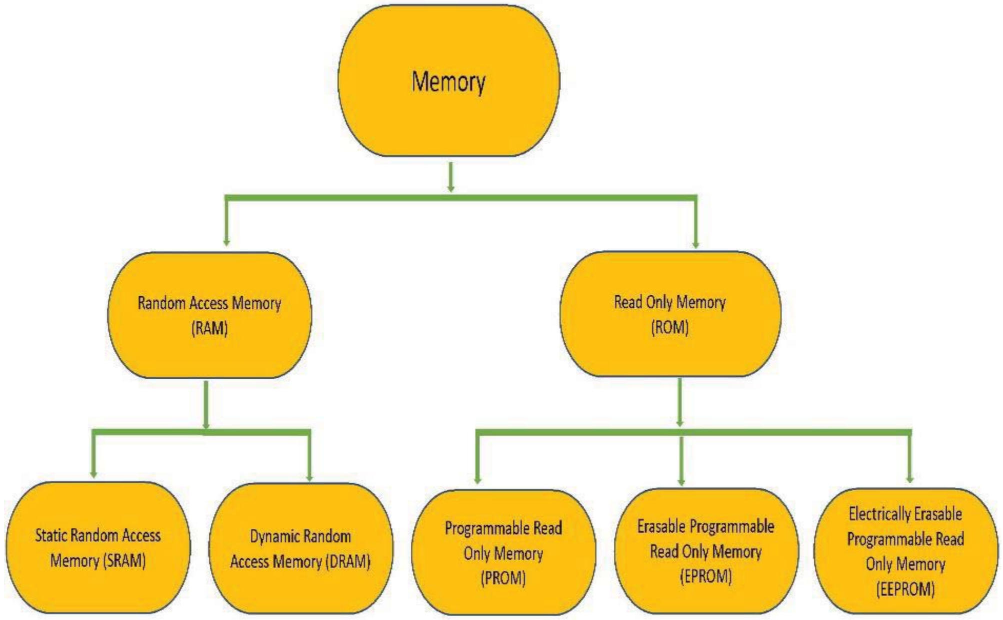

FIG 3. Classification of memory devices

2. Graphene oxide-based nanomaterial for non-volatile memory devices

2D graphene and its functional derivative GO and rGO have gained utmost attention for non-volatile memory devices because of their impressive physical, structural and electrical properties. Graphene oxide as mentioned earlier is a layered nanomaterial and possesses high solubility which in turn contributes to its ease of processability. There have been numerous reports where graphene, GO and rGO have been exploited for resistive switching applications [20,21]. For example, Gogoi *et al.* fabricated the polymer based multi-stacked memory device (ITO/PMMA/GOs/PMMA/Al) by taking GO as an active material and studied the memory characteristics by variation of GO concentration. The multi-stacked device showed the electrical hysteresis because of the presence of charge trapping layers [22]. Khurana *et al.* reported the thermally stable bipolar resistive switching in memory device (Pt/GO/ITO) that is composed of GO deposited on ITO coated glass substrate and the device exhibited I_{ON}/I_{OFF} ratio 10^4 at room temperature and endurance cycle 100 and retention up to 10^4 [23]. Jeong *et al.* prepared graphene oxide thin film by spin casting technique and the device (Al/GO/Al/PES) showed bipolar resistive switching with decent endurance cycle up to 10^2 and retention 10^5 sec [24]. Li *et al.* fabricated the ITO/GO-PEDOT/Al device that exhibited non-volatile rewritable memory with I_{ON}/I_{OFF} ratio 10^4 and retention 10^4 sec [25]. Wu *et al.* fabricated the device Ag/PI/GO: PI/PI/ITO that showed multilevel resistive switching characteristics with I_{ON}/I_{OFF} ratio 10^5 and retention 10^3 sec and endurance cycle up to 10^2 [26]. Kapitanova *et al.* reported the graphene/GO/ZnO heterostructure with I_{ON}/I_{OFF} ratio 10^3 and low operating voltage (<1V) [27]. Yin *et al.* reported the ITO/MoS_2 -GO/Al memory device that showed rewritable non-volatile switching with V_{SET} and V_{RESET} are -1.2 and 1.5V, respectively and I_{ON}/I_{OFF} ratio 10^2 [28].

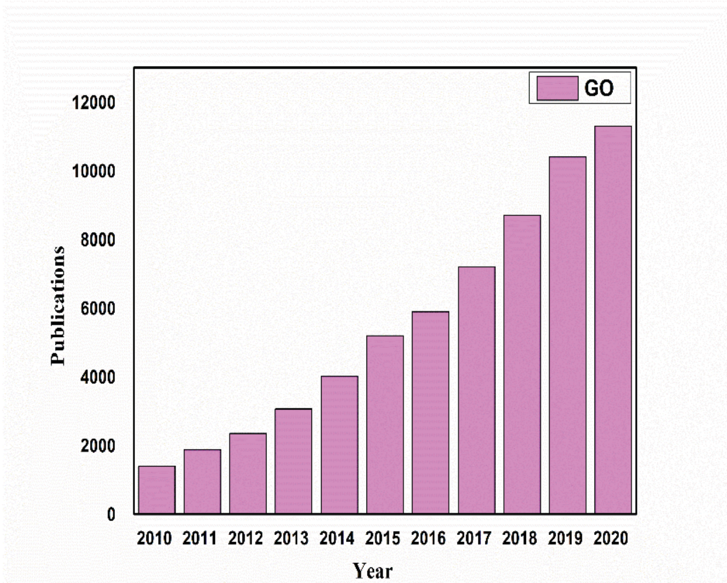

FIG 4. Publication vs Year graph of graphene oxide (GO) based memory device (Data obtained from Google Scholar)

Figure 4 shows the publications related to graphene oxide (GO) based memory devices over the past ten years. The growing demand of GO exploited for memory devices increases year by year.

Table 1. Non-volatile memory devices using graphene-based nanomaterial

Authors	Structure of the device	Method of fabrication	V_{set} (volt)	V_{reset} (volt)	I_{ON}/I_{OFF}	Endurance cycles	Retention (sec)	Memory effect	Publication Year	References
Khurana *et al.*	ITO/GO-ZnO/Al	Spin coating method	2.1	-2.0	10^2	10^2	10^4	The device showed bipolar resistive switching behaviour.	2014	29
He *et al.*	Cu/GO/Pt	Vacuum filtration method	0.80	-0.75	20	10^2	$>10^4$	The device exhibited bipolar resistive switching behaviour.	2009	30
Kim *et al.*	Au/PVA-GOs-PVA -PVA/Au	Spin coating method	3.5± 0.29	-1.81± 0.10	10^4	100	$>10^3$	The device showed bipolar nature.	2019	31

Gogoi *et al.*	ITO/PMMA-GOs/Al	Spin coating method	-1.87	-	10^4	30	10^4	The device showed WORM nature.	2019	32
Sun *et al.*	ITO/PS-GO/Al	Spin coating method	-0.80	3.67	10^3	10^4	10^5	The device exhibited non-volatile ternary memory characteristics.	2017	33
Zhuang *et al.*	ITO/TPAPAM-GO/Al	Spin coating method	-1.0	3.5	$>10^3$	10^8	3 hours	The device showed non-volatile unipolar nature.	2010	34
Bhattacharjee *et al.*	ITO/Graphene-MoS2+PMMA/Cu	Spin coating method	-1	1	$>10^4$	10^4	10 days	The device showed non-volatile, rewritable and flexible memory characteristics.	2018	35
Gogoi *et al.*	ITO/PMMA/rGO/CuS/PMMA/Al	Spin coating method	-0.44 ± 0.10	0.50 ± 0.10	10^3-10^4	10^3	10^4	The device exhibited bipolar-resistive switching characteristics.	2020	36

3. Conclusion

Graphene has attracted increasing attention in non-volatile resistive memory devices and become an important part in modern electronic devices. In summary, we briefly discussed the recent progresses of monolayer graphene and its derivative, graphene oxide (GO) in non-volatile resistive switching memory devices. Because of the spectacular and unique characteristics of graphene and GO-based nanocomposites, many researchers have found potential applications in various fields of research. High I_{ON}/I_{OFF} ratio, high retention, low switching voltage can find potential applications in transparent and flexible high density, multilevel non-volatile resistive switching memory devices.

REFERENCES

[1] A K Geim, Science 324, 5934 (2009)

[2] V B Mohan, K-t Lau, D Hui and D Bhattacharyya, Composites Part B 142, 200 (2018)

[3] S N Alam, N Sharma and L Kumar, Graphene 6, 1 (2017)

[4] A T Smith, A M LaChance, S Zeng, B Liu and L Sun, Nano Materials Science 1, 31 (2019)

[5] R K Gupta, Z A Alahmed and F Yakuphanoglu, Materials Letters 112, 75 (2013)

[6] G G Gebreegziabher, A S Asemahegne, D W Ayele, M Dhakshnamoorthy and A Kumar, Materials Today Chemistry 12, 233 (2019)

[7] D W Johnson, B P Dobson and K S Coleman, Current Opinion in Colloid & Interface Science 20, 367 (2015)

[8] S Biswal, D S Bhaskaram and G Govindaraj, Mater. Res. Express 5, 086104 (2018)

[9] H Huang, Z Li, J She and W Wang, J. Appl. Phys. 111, 54317 (2012)

[10] R Roy, R Thapa, S Chakrabarty, A Jha, P R Midya, E M Kumar and K K Chattopadhay, Chemical Physics Letters 677, 80 (2017)

[11] Y Zhu, S Murali, W Cai, X Li, J W Suk, J R Potts and R S Ruoff, Adv. Mater. 22, 3906 (2010)

[12] Z Ma, C Wu, D U Lee, F Li and T W Kim, Organic Electronics 28, 20 (2016)

[13] A Rani, J M Song, M J Lee and J S Lee, Appl. Phys. Lett. 105, 223301 (2014)

[14] L Li, Micromachines 10, 151 (2019)

[15] A Midya, N Goguria and S K Ray, Current Applied Physics 15, 706 (2015)

[16] R Bez, E Camerlenghi, A Modelli and A Visconti, Proceedings of the IEEE 91, (2003)

[17] B Hwang and J S Lee, Adv. Electron. Mater. 5, 1800519 (2019)

[18] A Rani and D H Kim, J. Mater. Chem. C 4, 11007 (2016)

[19] R Singh, R Kumar, A Kumar, D Kumar and M Kumar, Mater. Res. Express 6, 105621 (2019)

[20] S K Pradhan, B Xiao, S Mishra, A Killam and A K Pradhan, Scientific Reports 6, 26763 (2016)

[21] D Y Yun and T W Kim, Carbon 88, 26 (2015)

[22] K K Gogoi, N S Das and A Chowdhury, Mater. Res. Express 6, 085108 (2019)

[23] G Khurana, P Misra and R S Katiyar, Journal of Applied Physics 114, 124508 (2013)

[24] H Y Jeong, J Y Kim, J W Kim, J O Hwang, J E Kim, J Y Lee, T H Yoon, B J Cho, S O Kim, R S Ruoff and S Y Choi, Nano Lett. 10, 4381 (2010)

[25] Y Li and X Ni, RSC Adv. 6, 16340 (2016)

[26] C Wu, F Li, Y Zhang, T Guo and T Chen, Appl. Phys. Lett. 99, 042108 (2011)

[27] O O Kapitanova, G N Panin, O V Kononenko, A N Baranov and T W Kang, Journal of the Korean Physical Society 64, (2014)

[28] Z Yin, Z Zeng, J Liu, Q He, P Chen and H Zhang, Small 9, 727 (2013)

[29] G Khurana, P Misra and R S Katiyar, J. Phys. Chem. C 118, 21357 (2014)

[30] C L He, F Zhuge, X F Zhou, M Li, G C Zhou, Y W Liu, J Z Wang, B Chen, W J Su, Z P Liu, Y H Wu, P Cui and R W Li, Applied Physics Letters 95, 232101 (2009)

[31] T Kim, D-K Kim, J Kim and J J Pak, Semiconductor Science and Technology 34, (2019)

[32] K K Gogoi and A Chowdhury, J. Appl. Phys. 126, 025501(2019)

[33] Y Sun, D Wen, X Bai, J Lu and C Ai, Scientific Reports 7, 3938 (2017)

[34] X-D Zhuang, Y Chen, G Liu, P-P Li, C-X Zhu, E-T Kang, K G Neoh, B Zhang, J H Zhu and Y-X Li, Advanced Materials 22, (2010)

[35] S Bhattacharjee, U Das, P K Sarkar and A Roy, Organic Electronics 58, (2018)

[36] K K Gogoi, S Das, S Maiti and A Chowdhury, ACS Applied Nano Materials 3, (2020)