Graphene based nano-composites for efficient energy conversion and storage in Solar cells and Supercapacitors : A Review.

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ABSTRACT

Due to unique properties, ease of synthesis and functionalization, graphene-based nanocomposites show great potential in energy storage and conversion. These hybrid materials have excellent characteristics like high carrier mobility, faster recombination rate and long-time stability. In this review, the recent progresses in the synthesis and applications of graphene and its composites in the fields of energy storage (supercapacitors) and conversion (Solar cells) are summarized. This article highlights the challenges of the practical applications of graphene-based materials in supercapacitors and solar cells. Future research to develop new methodologies for the design and the synthesis of graphene-based nanocomposite are also proposed.

ARTICLE HISTORY

Received 23 August 2020 Revised 15 October 2020 Accepted 11 November 2020

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KEYWORDS

Graphene; nano-composites; solar cells; supercapacitors

1. Introduction

The energy requirement of world is rising day by day and it is estimated that energy requirement will be double by 2050. Besides that, the energy production from conventional ways creates pollution of environment. So, renewable energy storage and conversion materials as well as their devices are topics of intense research.^[1] To make the effective use of renewable energy, it is necessary to develop high-performance, low-cost and eco-friendly energy conversion and storage devices. Carbon materials are of great interest in research related to electrochemical devices due to abundance, stability and eco-friendliness. their Among different allotropes of carbon, graphene, is emerged as an excellent candidate for energy conversion and storage applications because of its unique properties, including high specific surface area (2630 m²/g), good chemical stability and excellent electrical conductivity.^[2]

2. History of graphene

Graphene appears frequently in our day to day life and it is topic of intense research for more than six decades, but the pioneer efforts were of two scientists from the University of Manchester, Prof. Andre Geim and Prof. Kostya Novoselov who successfully carried out the cleavage of one atom thick single layer of graphene from graphite. This was a milestone discovery in history of nanotechnology as it practically demonstrates the concept of single atom components from theory closer to reality. The various events in the discovery of single-layer graphene are as follows^[3]:

- Simonio and Lyndiana Bernacotti developed the first pencil in 1560.
- John Desmond Bernal described the layered structure of graphite in 1924.
- The theoretical study of electronic properties of a single graphite layer was initiated by Philip Wallace in 1947.

3. J. W. McClure proposed the equation of wave function for single graphite layer in 1956

• In 1987, S. Mouras used the term graphene for the first time as a virtual expression of unit structure in graphite instead of a realistic form of carbon nanomaterials.

In 2004, Andre Geim and Konstantin Novoselov published very first article about the synthesis of graphene by mechanical exfoliation method in the Science magazine. For their groundbreaking experiments in the synthesis and characterization of this two-dimensional material Graphene, they received the Nobel Prize in Physics 2010.

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Figure 1. Top-down and bottom-up graphene synthesis approaches^[96] (Adopted from Mahmoudi, T., Wang, Y., and Hahn, Y. B. (2018). Graphene and its derivatives for solar cells application. Nano Energy, 47, 51–65).



Figure 2. Band structure of different materials (Adopted from https://whitenoise.kinja.com/graphene-miracle-material -1575961841^[97].

4. Synthesis of graphene

The amazing properties of graphene are mainly due to the defect of less pristine graphene. structural defects occur during growth and processing steps of graphene which alters their properties. Several scientists reported innovations in the mass and low-cost production of graphene with minimal defects for various applications. The approach for the synthesis of graphene is classified into two types:

(1) In top-down approach, the stack of graphene precursor (graphite) dissociates into individual atomic



Figure 3. Device structure of polymer solar cell^[73].

layer graphene sheet by overcoming Vander Waals forces of attraction.

(2) In bottom-up approach, carbon molecules obtained from various resources are used to develop the honeycomb structure of graphene sheet.

Various methods reported worldwide by many researchers for synthesis of graphene are given below:

4.1. Mechanical exfoliation

This is top-down approach to produce high-quality graphene with minimal defects and high electron mobility. It is a repeated peeling process used to break weak Vander Waals forces present between the stacked layers of graphite to produce individual graphene sheets.^[4-7]

4.2. Chemical exfoliation

Using this technique, good quality graphene suspension can be obtained from graphite by using aqueous electrolyteThis technique can be used for the production of conductive inks, transparent conducting oxides and electrodes for batteries and supercapacitors but cannot be used to generate large sheets of graphene required for device applications.^[8–10]

4.3. Hummer's method

Synthesis of graphene oxide is reported by placing graphite in concentrated acid in the presence of an oxidizing agent. In this process, potassium permanganate is used in a solution of graphite, sodium nitrate, and sulfuric acid to generate graphene oxide and the reaction is terminated with the help of hydrogen peroxide. Many modifications are reported to make it more efficient and environmentally friendly.^[11-13]



Figure 4. Charge and discharge processes of an EDLC.^[98] (Adopted from Notarianni, M., Liu, J., Vernon, K., and Motta, N. (2016). Synthesis and applications of carbon nanomaterials for energy generation and storage. *Beilstein journal of nanotechnology*, *7*(1), 149–196.).

4.4. Chemical vapor deposition(CVD)

It involves pyrolysis of the precursor material to form carbon which is used to form the structure of graphene. This process is carried out in an inert environment by passing the gases like N_2 /Ar.^[14,15]

5. Properties of graphene

Major properties of graphene are as follows.^[3,16,17]

- Graphene is considered as the first two dimensional crystalline material developed in lab.
- Graphene is a zero-gap semiconductor and it shows conductivity higher than copper.
- Graphene is a highly transparent material with great flexibility and stretchability.
- Graphene can be stretch up to 120% of its length and can recover its original shape.
- At room temperature, the thermal conductivity of Graphene is found to be more than diamond, graphite and any other known material.

This is a thinnest material **and** it can transmit up to 98% of light.

• Graphene is very strong. Graphene is 200 times stronger as compared to steel.

Graphene is a two-dimensional atomic sheet with sp²hybridized carbon atoms arranged in a Hexagonal manner. The s, p_x and p_y orbitals involve in σ -bond formation with neighbouring carbon atoms while p_z orbital forms π -bond . This makes one electron free. The C-C bond length is reported as 0.142 nm and the thickness of single layer of graphene is found to be 0.35 nm. The graphene is stable due to strong interatomic bonds present in the material which helps to overcome the thermal fluctuations and does not create dislocations or other crystal defects even at high temperatures

5.1. Electrical and thermal properties of graphene

Graphene is a zero-gap semiconductor or semi-metal. Its conduction band and valence band are same as semiconductor with no band gap. Here, holes and electrons act as charge carrier which leads to a very high electrical conductivity (more than copper). The π -bonds have high mobile pi (π) electrons that overlap together to form bonding π (valence) and antibonding π^* (conduction) bands. The free moving electrons show high mobility and hence travel sub-micrometer distances without any scattering (ballistic transport). The electron mobility in graphene is found to be 15,000 $\text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ and its theoretical potential limits are 200,000 $\text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ mainly due to the quality of graphene and the substrate. Graphene also shows the highest value of thermal conductivity because of the highly stable sp² bonding pattern and a two-dimensional nature. The experimental values are found to be in the range of $3000-5000 \text{ Wm}^{-1}\text{K}^{-1}$.

5.2. Thermal and mechanical properties of graphene

The study of mechanical properties of single-layer graphene was done by atomic force microscopy technique and it is reported as strongest material ever tested. Thermal conductivity was found in the range of 3000–5000 $Wm^{-1}K^{-1}$. Graphene shows an extraordinary tensile strength, i.e.,130 GPa which is found to be higher than 0.4 GPa of A36 steel and 0.375 GPa of Kevlar (Aramid) fibers. The values of Spring constant and Young's modulus values were reported to be 1–5 Nm^{-1} and 1TPa respectively.

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Table 1. Summary of Supercapacitor work based on graphene-based composite.

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GO/PANI GO/PANI: 527 g ⁻¹ from CV at a scan [110] RGO/PANI rate of 1 mVs ⁻¹ RGO/PANI: 125 g ⁻¹ from CV at a (111) GO/PANI 320 fg ⁻¹ at 0.1 Ag ⁻¹ (111) (111) RGO/PANI 320 fg ⁻¹ at 0.1 Ag ⁻¹ (111) GO/PANI 320 fg ⁻¹ at 0.1 Ag ⁻¹ (111) GG/PANI 480 Fg ⁻¹ at 0.1 Ag ⁻¹ (113) GGO/PANI 361 Fg ⁻¹ at 0.3 Ag ⁻¹ (113) Graphene/PANI 763 Fg ⁻¹ at 1.4 Gg ⁻¹ (114) Paper 763 Fg ⁻¹ at 0.1 Ag ⁻¹ (114) GO/PANI 257 Fg ⁻¹ at 0.1 Ag ⁻¹ (116) GO/PANI 448 Fg ⁻¹ at 0.5 Ag ⁻¹ (116) GO/PANI 438.8 Fg ⁻¹ at 0.5 Ag ⁻¹ (116) GO/PANI 438.8 Fg ⁻¹ at 0.1 Ag ⁻¹ (117) GO/PANI 438.8 Fg ⁻¹ at 0.5 Ag ⁻¹ (118) Gaphene/PPy 100 mVs ⁻¹ (107) GO/PPANI 438.8 Fg ⁻¹ at 0.5 Ag ⁻¹ (119) GO/PPY 420 Fg ⁻¹ at 0.4 Ag ⁻¹ (120) GO/PPY 420 Fg ⁻¹ at 0.4 Ag ⁻¹ (121)	Graphene/PANI	233 Fg ⁻ '	[110]
RGO/PANI rate of 1 mVs ⁻¹ RGO/PANI: 1129 Fg ⁻¹ from CV at a scan rate of 1 mVs ⁻¹ GO/PANI 320 Fg ⁻¹ at 0.1 Ag ⁻¹ (11) GO/PANI 320 Fg ⁻¹ at 0.1 Ag ⁻¹ (11) Gorphene/PANI 1046 Fg ⁻¹ from CV at a scan rate (112) GO/PANI 361 Fg ⁻¹ at 0.3 Ag ⁻¹ (113) Gorphene/PANI 763 Fg ⁻¹ at 0.1 Ag ⁻¹ (114) Paper (119) (119) RGO/PANI 257 Fg ⁻¹ at 0.1 Ag ⁻¹ (119) GO/PANI 257 Fg ⁻¹ at 0.1 Ag ⁻¹ (119) GO/PANI 257 Fg ⁻¹ at 0.1 Ag ⁻¹ (119) GO/PANI 257 Fg ⁻¹ at 0.1 Ag ⁻¹ (119) GO/PANI 257 Fg ⁻¹ at 0.1 Ag ⁻¹ (119) GO/PANI 257 Fg ⁻¹ at 0.1 Ag ⁻¹ (119) Go/PANI 438 Fg ⁻¹ at 0.5 Ag ⁻¹ (119) Go/PANI 438 Fg ⁻¹ at 0.3 Ag ⁻¹ (119) Go/PANI 165 Fg ⁻¹ at 1.4 G ⁻¹ (120) GO/PANI 438 Fg ⁻¹ at 0.3 Ag ⁻¹ (120) GO/PPY 400 Fg ⁻¹ at 3.4 G ⁻¹ (120) GO/PPY 267 Fg ⁻¹ at 0.4 Ag ⁻¹ (120) Go/PPY	GO/PANI	GO/PANI: 827 Fg^{-1} from CV at a scan	[110]
GO/PANI Scan rate of 1 mVs ⁻¹ [11] GO/PANI 320 fg ⁻¹ at 0.1 Ag ⁻¹ [11] GG/PANI 320 fg ⁻¹ at 0.1 Ag ⁻¹ [11] GGAPten/PANI 480 Fg ⁻¹ at 0.1 Ag ⁻¹ [11] GGO/PANI 361 Fg ⁻¹ at 0.3 Ag ⁻¹ [11] Graphene/PANI 763 Fg ⁻¹ at 0.3 Ag ⁻¹ [11] Graphene/PANI 763 Fg ⁻¹ at 0.1 Ag ⁻¹ [11] GO/PANI 257 Fg ⁻¹ at 0.1 Ag ⁻¹ [11] GO/PANI 448 Fg ⁻¹ at 0.5 Ag ⁻¹ [11] GO/PANI 448 Fg ⁻¹ at 0.5 Ag ⁻¹ [11] GO/PANI 438.8 Fg ⁻¹ at 0.5 Ag ⁻¹ [11] GO/PANI 438.8 Fg ⁻¹ at 0.5 Ag ⁻¹ [11] GO/PANI 438.8 Fg ⁻¹ at 0.5 Ag ⁻¹ [11] GO/PANI 400 fs ⁻¹ g ⁻¹ from CV (scan rate: [11] GO/PPy 267 Fg ⁻¹ for CV (scan rate: [12] GO/PPy 249 Fg ⁻¹ at 0.3 Ag ⁻¹ [12] GO/PPy 249 Fg ⁻¹ at 0.3 Ag ⁻¹ [12] GO/PPy 249 Fg ⁻¹ at 0.4 Gg ⁻¹ [12] GO/PPy 249 Fg ⁻¹ at 0.3 Ag	RGO/PANI	rate of 1 mVs ⁻¹	
GO/PANI 320 Fg ⁻¹ at 0.1 Ag ⁻¹ [111] RGO/PANI 480 Fg ⁻¹ at 0.1 Ag ⁻¹ [112] Graphene/PANI 1046 Fg ⁻¹ from CV at a scan rate [112] Graphene/PANI 361 Fg ⁻¹ at 0.1 Ag ⁻¹ [113] GO/PANI 361 Fg ⁻¹ at 0.3 Ag ⁻¹ [113] GO/PANI 763 Fg ⁻¹ at 0.1 Ag ⁻¹ [113] GO/PANI 257 Fg ⁻¹ at 0.1 Ag ⁻¹ [116] GO/PANI 448 Fg ⁻¹ at 0.5 Ag ⁻¹ [116] Crumpled graphene/ 456 Fg ⁻¹ at 0.1 Ag ⁻¹ [117] Crumpled graphene/ 438.8 Fg ⁻¹ at 0.5 Ag ⁻¹ [118] GO/PANI 438.8 Fg ⁻¹ at 0.5 Ag ⁻¹ [119] GO/PANI 1000th cycle [119] Go/PANI 1000th cycle [119] Go/PPy 165 Fg ⁻¹ at 0.4 Ag ⁻¹ [120] GO/PPY 160 Fg ⁻¹ at 0.4 Ag ⁻¹ [121] GO/PPY 165 Fg ⁻¹ at 0.4 Ag ⁻¹ [121] GO/PPY 165 Fg ⁻¹ at 0.4 Ag ⁻¹ [121] GO/PPY 240 Fg ⁻¹ at 0.4 Ag ⁻¹ [221] Go/PPY 240 Fg ⁻¹ at 0.4		RGO/PANI: 1129 Fg ⁻¹ from CV at a	
GO/PANI 320 fg ⁻¹ at 0.1 Ag ⁻¹ [11] GRO/PANI 400 fg ⁻¹ at 0.1 Ag ⁻¹ [12] GG/PANI 046 Fg ⁻¹ from CV at a scan rate [12] GG/PANI 361 Fg ⁻¹ at 0.3 Ag ⁻¹ [11] Graphene/PANI 763 Fg ⁻¹ at 0.3 Ag ⁻¹ [11] Graphene/PANI 763 Fg ⁻¹ at 0.1 Ag ⁻¹ [11] GO/PANI 257 Fg ⁻¹ at 0.1 Ag ⁻¹ [11] GO/PANI 257 Fg ⁻¹ at 0.1 Ag ⁻¹ [11] GO/PANI 257 Fg ⁻¹ at 0.1 Ag ⁻¹ [11] GO/PANI 448 Fg ⁻¹ at 0.5 Ag ⁻¹ [11] GO/PANI 438.8 Fg ⁻¹ at 0.5 Ag ⁻¹ [11] GO/PANI 438.8 Fg ⁻¹ at 0.3 Ag ⁻¹ [11] GO/PANI 438.8 Fg ⁻¹ at 0.3 Ag ⁻¹ [11] GO/PPy 165 Fg ⁻¹ at 0.3 Ag ⁻¹ [11] GO/PPy 407 Fg ⁻¹ from CV (scan rate: [11] GO/PPy 249 Fg ⁻¹ at 0.3 Ag ⁻¹ [12] RGO/PPy 249 Fg ⁻¹ at 0.3 Ag ⁻¹ [12] RGO/PPy 249 Fg ⁻¹ at 0.3 Ag ⁻¹ [12] RGO/PPy 700 mVs ⁻¹ [22] Fg ⁻¹ at 0.5 Ag ⁻¹ [12] [2		scan rate of 1 mVs ⁻¹	
RGO/PANI 490 Fg ⁻¹ at 0. Ag ⁻¹ [12] Graphene/PANI of 1 mVs ⁻¹ [13] RGO/PANI 361 Fg ⁻¹ at 0. Ag ⁻¹ [14] Paper 763 Fg ⁻¹ at 0. Ag ⁻¹ [14] Paper 763 Fg ⁻¹ at 0. Ag ⁻¹ [15] RGO/PANI 257 Fg ⁻¹ at 0.1 Ag ⁻¹ [16] Crumpled graphene/ 456 Fg ⁻¹ at 0.1 Ag ⁻¹ [16] CTI/PANI 438.8 Fg ⁻¹ at 0.5 Ag ⁻¹ [16] GO/PANI 438.8 Fg ⁻¹ at 0.1 Ag ⁻¹ [17] RGO/PANI 438.8 Fg ⁻¹ at 0.3 Ag ⁻¹ [18] Graphene/PPy 105 Fg ⁻¹ at 0.1 Ag ⁻¹ [19] RGO/PANI 438.8 Fg ⁻¹ at 0.3 Ag ⁻¹ [18] Graphene/PPy 105 Fg ⁻¹ at 0.3 Ag ⁻¹ [19] Go/PPy 100 mVs ⁻¹) 267 Fg ⁻¹ at 0.3 Ag ⁻¹ [19] Go/PPy 200 Fg ⁻¹ at 0.3 Ag ⁻¹ [12] 27 RGO/PPy 200 Fg ⁻¹ at 0.3 Ag ⁻¹ [20] 20 RGO/PPy 20 Fg ⁻¹ at 0.3 Ag ⁻¹ [21] 20 RGO/PPy 20 Fg ⁻¹ at 0.3 Ag ⁻¹ [22] 27 RGO/PPy 31 Fg ⁻¹ at 0.3 Ag ⁻¹ <td< td=""><td>GO/PANI</td><td>320 Fg^{-1} at 0.1 Ag^{-1}</td><td>[111]</td></td<>	GO/PANI	320 Fg ^{-1} at 0.1 Ag ^{-1}	[111]
Graphene/PANI 1046 F_{g}^{-1} from CV at a scan rate of 1 mVs ⁻¹ 112 RGO/PANI 31 F_{g}^{-1} at 0.3 A_{g}^{-1} 113 Graphene/PANI 763 F_{g}^{-1} at 0.1 A_{g}^{-1} 113 Paper 257 F_{g}^{-1} at 0.1 A_{g}^{-1} 115 GO/PANI 257 F_{g}^{-1} at 0.1 A_{g}^{-1} 116 Crumpled graphene/ 448 F_{g}^{-1} at 0.5 A_{g}^{-1} 116 Crumpled graphene//PANI 438.8 F_{g}^{-1} at 0.5 A_{g}^{-1} 117 RGO/PANI 438.8 F_{g}^{-1} at 0.5 A_{g}^{-1} 118 Graphene/PPy 105 F_{g}^{-1} at 0.5 A_{g}^{-1} 118 RGO/PANI 438.8 F_{g}^{-1} at 0.5 A_{g}^{-1} 119 GO/PANI 438.8 F_{g}^{-1} at 0.5 A_{g}^{-1} 119 GO/PANI 438.8 F_{g}^{-1} at 0.5 A_{g}^{-1} 119 GO/PPy 100 mVs ⁻¹) 267 F_{g}^{-1} at 0.3 A_{g}^{-1} 120 GO/PPy 249 F_{g}^{-1} at 0.3 A_{g}^{-1} 121 RGO/PPy 249 F_{g}^{-1} at 0.3 A_{g}^{-1} 121 RGO/PPy 249 F_{g}^{-1} at 0.3 A_{g}^{-1} 121 RGO/PPy 249 F_{g}^{-1} at 0.3 A_{g}^{-1} 121	RGO/PANI	480 Fg^{-1} at 0.1 Ag^{-1}	
r of 1 mVs ⁻¹ RGO/PANI 361 Fg ⁻¹ at 0.3 Ag ⁻¹ [113] Graphene/PANI 73 Fg ⁻¹ at 0.1 Ag ⁻¹ [114] Paper 257 Fg ⁻¹ at 0.1 Ag ⁻¹ [115] GO/PANI 448 Fg ⁻¹ at 0.5 Ag ⁻¹ [116] Crumpled graphene/ 448 Fg ⁻¹ at 0.5 Ag ⁻¹ [117] CT/TPANI 438 Fg ⁻¹ at 0.5 Ag ⁻¹ [118] Go/PANI 438 Fg ⁻¹ at 0.5 Ag ⁻¹ [118] Graphene/PPy 165 Fg ⁻¹ at 0.5 Ag ⁻¹ [118] Go/PANI 438 Fg ⁻¹ at 0.5 Ag ⁻¹ [119] GO/PPN 1000th cycle [119] GO/PPY 100 mVs ⁻¹) 267 Fg ⁻¹ from CV (scan rate: 100 mVs ⁻¹) GO/PPy 249 Fg ⁻¹ at 0.3 Ag ⁻¹ [120] RGO/PPy 249 Fg ⁻¹ at 0.3 Ag ⁻¹ [121] Adv Fg ⁻¹ at 0.3 Ag ⁻¹ [121] [122] Graphene/PPy 240 Fg ⁻¹ at 0.2 Ag ⁻¹ [121] RGO/PPy 249 Fg ⁻¹ at 0.2 Ag ⁻¹ [122] Graphene/PPy 240 Fg ⁻¹ at 0.3 Ag ⁻¹ [121] RGO/PPy 240 Fg ⁻¹ at 0.2 Ag ⁻¹ [122] Graphene/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ <td>Graphene/PANI</td> <td>1046 Fg^{-1} from CV at a scan rate</td> <td>[112]</td>	Graphene/PANI	1046 Fg^{-1} from CV at a scan rate	[112]
RGO/PANI 361 Fg ⁻¹ at 0.3 Ag ⁻¹ [113] Graphene/PANI 763 Fg ⁻¹ at 1.4 g ⁻¹ [114] Paper 257 Fg ⁻¹ at 0.1 Ag ⁻¹ [115] GO/PANI 257 Fg ⁻¹ at 0.1 Ag ⁻¹ [116] GO/PANI 448 Fg ⁻¹ at 0.5 Ag ⁻¹ [116] GO/PANI 448 Fg ⁻¹ at 0.5 Ag ⁻¹ [117] GO/PANI 456 Fg ⁻¹ at 0.5 Ag ⁻¹ [118] GO/PANI 165 Fg ⁻¹ at 0.5 Ag ⁻¹ [118] Go/PANI 165 Fg ⁻¹ at 0.5 Ag ⁻¹ [118] Go/PANI 165 Fg ⁻¹ at 0.5 Ag ⁻¹ [118] Go/PANI 100 mVs ⁻¹) 267 Fg ⁻¹ at 0.5 Ag ⁻¹ [119] GO/PPy 100 mVs ⁻¹) 267 Fg ⁻¹ at 0.5 Ag ⁻¹ [120] GO/PPy 249 Fg ⁻¹ at 0.5 Ag ⁻¹ [121] [121] GO/PPy 249 Fg ⁻¹ at 0.5 Ag ⁻¹ [121] RGO/PPy 351 Fg ⁻¹ at 0.5 Ag ⁻¹ [121] Graphene/PPy 351 Fg ⁻¹ at 0.2 Ag ⁻¹ [121] RGO/PPy 351 Fg ⁻¹ at 0.2 Ag ⁻¹ [121] Exfoliated graphene/ 351 Fg ⁻¹ at 0.2 Ag ⁻¹ [121] RGO/PPy 14 Gg ⁻¹ at 0.2 Ag ⁻¹ [1	•	of 1 mVs ^{-1}	
Graphene/PANI 763 F_9^{-1} at 1 A_9^{-1} [114] Paper	RGO/PANI	361 Fg^{-1} at 0.3 Ag^{-1}	[113]
Paper 257 Fg^{-1} at 0.1 Ag^{-1} [19] RGO/PANI 257 Fg^{-1} at 0.1 Ag^{-1} [110] Cumpled graphene/ 436 Fg^{-1} at 0.5 Ag^{-1} [110] CNT/PANI 488 Fg^{-1} at 0.5 Ag^{-1} [110] GO/PANI 438.8 Fg^{-1} at 0.5 Ag^{-1} [111] GO/PANI 438.8 Fg^{-1} at 0.5 Ag^{-1} [118] GG/PANI 105 Fg^{-1} from CV (scan rate: [119] GO/PPy 100 mVs^{-1}) 267 Fg^{-1} from CV (scan rate: [119] GO/PPy 249 Fg^{-1} at 0.3 Ag^{-1} [120] RGO/PPy 249 Fg^{-1} at 0.3 Ag^{-1} [120] RGO/PPy 249 Fg^{-1} at 0.1 Ag^{-1} [121] RGO/PPy 249 Fg^{-1} at 0.2 Ag^{-1} [122] RGO/PPy 351 Fg^{-1} at 2.5 Ag^{-1} [122] Exfoliated graphene/ 728 Fg^{-1} at 0.2 Ag^{-1} [122] PPy 514 Fg^{-1} at 0.2 Ag^{-1} [123] RGO/PPy 301 Fg^{-1} at 0.3 Ag^{-1} [124] Nanotubes 420 Fg^{-1} at 1.4 g^{-1} [123] RGO/PPy 400 FG^{-1} at 1.4 g^{-1} [124] <	Graphene/PANI	763 F_{g}^{-1} at 1 Ag^{-1}	[114]
$\begin{array}{c} RGO/PANI & 257 \ Fg^{-1} at 0.1 \ Ag^{-1} & (115) \\ GO/PANI & 448 \ Fg^{-1} at 0.5 \ Ag^{-1} & (116) \\ Crumpled graphene/ & 438 \ Fg^{-1} at 0.5 \ Ag^{-1} & (117) \\ CNT/PANI & 338 \ Fg^{-1} at 0.5 \ Ag^{-1} & (118) \\ Go/PANI & 438 \ Fg^{-1} at 0.5 \ Ag^{-1} & (118) \\ Graphene/PPy & 165 \ Fg^{-1} at 1 \ Ag^{-1} at end of & (111) \\ 1000 \ th cycle & (119) \\ 1000 \ th cycle & (119) \\ 1000 \ th cycle & (119) \\ 267 \ Fg^{-1} \ from CV (scan rate: & (119) \\ 100 \ mVs^{-1}) & 267 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (120) \\ RGO/PPy & 420 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (120) \\ RGO/PPy & 420 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (122) \\ RGO/PPy & 420 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (122) \\ RGO/PPy & 420 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (122) \\ RGO/PPy & 420 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (122) \\ RGO/PPy & 420 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (122) \\ RGO/PPy & 420 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (122) \\ RGO/PPy & 420 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (122) \\ RGO/PPy & 420 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (122) \\ RGO/PPy & 420 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (122) \\ RGO/PPy & 420 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (122) \\ RGO/PPy & 351 \ Fg^{-1} \ at 1.3 \ G^{-1} & (122) \\ Graphene/PPy & 440 \ mFcm^{-2} \ at 0.5 \ Ag^{-1} & (123) \\ RGO/PPy & 440 \ mFcm^{-2} \ at 0.3 \ Ag^{-1} & (124) \\ Graphene/PPy & HCl & 304 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (124) \\ Graphene/PPy & HCl & ad 0 \ mVs^{-1} & Hcl \\ Graphene/PPD & HCl & 304 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (124) \\ Graphene/PEDOT & (20 \ Fg^{-1} \ ft 0.3 \ Ag^{-1} & (124) \\ Graphene/PEDOT & (20 \ Fg^{-1} \ ft 0.3 \ Ag^{-1} & (124) \\ Hcl & ad 0.5 \ Ag^{-1} & (127) \\ Graphene/PEDOT & 270 \ Fg^{-1} \ at 0.3 \ Ag^{-1} & (128) \\ Graphene/PEDOT & (20 \ FGO^{-1} \ at 0.5 \ Ag^{-1} & (128) \\ Hcl & Ad 0.5 \ Ag^{-1} & (128) \\ Hc$	Paper	5 5 5	
GO/PANI 448 Fg ⁻¹ at 0.5 Åg ⁻¹ (116) Crumpled graphene/ 456 Fg ⁻¹ at 0.5 Åg ⁻¹ (117) CMT/PANI 438.8 Fg ⁻¹ at 0.5 Åg ⁻¹ (118) Go/PANI 438.8 Fg ⁻¹ at 0.5 Åg ⁻¹ (118) Graphene/PPy 165 Fg ⁻¹ at 1 Åg ⁻¹ at end of (111) GO/PANI 438.8 Fg ⁻¹ at 0.5 Åg ⁻¹ (118) Graphene/PPy 165 Fg ⁻¹ at 1 Åg ⁻¹ at end of (111) GO/PPy 167 Fg ⁻¹ from CV (scan rate: (119) 100 mVs ⁻¹) 267 Fg ⁻¹ from CV (scan rate: (120) RGO/PPy 249 Fg ⁻¹ at 0.3 Åg ⁻¹ (121) RGO/PPy nanowire 728 Fg ⁻¹ at 0.3 Åg ⁻¹ (121) Pry 351 Fg ⁻¹ at 0.2 Åg ⁻¹ (122) Graphene/PPy 514 Fg ⁻¹ at 0.2 Åg ⁻¹ (123) PPy 514 Fg ⁻¹ at 0.2 Åg ⁻¹ (124) Go/PPy 514 Fg ⁻¹ at 0.2 Åg ⁻¹ (124) Nanotubes 420 Fg ⁻¹ at 1 Åg ⁻¹ (124) RGO/PPy 514 Fg ⁻¹ at 0.2 Åg ⁻¹ (125) Sulfonated 310 Fg ⁻¹ at 0.3 Åg ⁻¹ (125) Graphene/PPy Graphene/PPDOT HCI: 304 Fg ⁻¹ from CV at a scan	RGO/PANI	257 Fg^{-1} at 0.1 Ag^{-1}	[115]
Crumpled graphene/ (CNT/PANI 155 F_g^{-1} at 0.1 A_g^{-1} [177] RGO/PANI 438.8 F_g^{-1} at 0.5 A_g^{-1} [18] Graphene/PPy 165 F_g^{-1} at 0.5 A_g^{-1} [19] GO/PPy 417 F_g^{-1} from CV (scan rate: 100 mVs ⁻¹) [19] RGO/PPy 249 F_g^{-1} at 0.3 A_g^{-1} [120] RGO/PPy 249 F_g^{-1} at 0.3 A_g^{-1} [121] RGO/PPy 249 F_g^{-1} at 0.4 A_g^{-1} [121] RGO/PPy 240 F_g^{-1} at 0.4 A_g^{-1} [121] RGO/PPy 240 F_g^{-1} at 0.4 A_g^{-1} [121] RGO/PPy 240 F_g^{-1} at 0.4 A_g^{-1} [122] Exfoliated graphene/ 728 F_g^{-1} at 0.4 A_g^{-1} [123] PPy 11 F_g^{-1} at 0.2 A_g^{-1} [123] PPy 11 A_g^{-1} [124] Nanotubes 420 F_g^{-1} at 0.2 A_g^{-1} [123] RGO/PPy 514 F_g^{-1} at 0.2 A_g^{-1} [124] Nanotubes 420 F_g^{-1} at 0.3 A_g^{-1} [123] Graphene/PPy 10 F_g^{-1} at 0.3 A_g^{-1} [124] Graphene/PEDOT 100 F_g^{-1} at 0.3 A_g^{-1} [125] <	GO/PANI	448 Fg^{-1} at 0.5 Ag $^{-1}$	[116]
CharlesDescriptionDescriptionDescriptionRGO/PANI438.8 F_{g}^{-1} at 0.5 Ag^{-1} [118]Graphene/PPy165 Fg^{-1} at 1 Ag^{-1} at end of[111]GO/PPy417 Fg^{-1} from CV (scan rate:[119]GO/PPy417 Fg^{-1} from CV (scan rate:[119]GO/PPy249 Fg^{-1} at 0.3 Ag^{-1} [120]RGO/PPy249 Fg^{-1} at 0.3 Ag^{-1} [121]RGO/PPy240 Fg^{-1} at 0.3 Ag^{-1} [121]RGO/PPy240 Fg^{-1} at 0.5 Ag^{-1} [122]RGO/PPy nanowire728 Fg^{-1} at 0.5 Ag^{-1} [122]Exfoliated graphene/351 Fg^{-1} at 1 Ag^{-1} [123]Py1140140 FG^{-1} at 0.4 g^{-1} [124]Nanotubes420 Fg^{-1} at 0.2 Ag^{-1} [125]Sulfonated310 Fg^{-1} at 0.3 Ag^{-1} [126]Graphene/PPy440 mEm^{-2} at 0.5 $mAcm^{-2}$ [125]Sulfonated310 Fg^{-1} at 0.3 Ag^{-1} [111]graphene/PPy420 Fg^{-1} at 0.3 Ag^{-1} [126]Graphene/PEDOTHC: 304 Fg^{-1} from CV at a scan rate[126]Graphene/PEDOT108 Fg^{-1} at 0.3 Ag^{-1} [127]Graphene/PEDOT108 Fg^{-1} at 0.3 Ag^{-1} [128]RGO/PEDOT108 Fg^{-1} at 0.3 Ag^{-1} [128]RGO/PEDOT213 Fg^{-1} at 0.3 Ag^{-1} [129]Hallow RGO/PEDOT203 Fg^{-1} at 0.5 Ag^{-1} [130]Hallow RGO/PEDOT204 Fg^{-1} at 0.4 G^{-1} [131]	Crumpled graphene/	456 Fg^{-1} at 0.1 Ag ⁻¹	[117]
BCO/PANI 438.8 F_{g}^{-1} at 0.5 A_{g}^{-1} [118] Graphene/PPy 165 F_{g}^{-1} at 1 A_{g}^{-1} at end of [111] GO/PPy 417 F_{g}^{-1} from CV (scan rate: [119] 100 mVs^{-1}) 267 F_{g}^{-1} from CV (scan rate: [119] RGO/PPy 249 F_{g}^{-1} at 0.3 A_{g}^{-1} [120] RGO/PPy 249 F_{g}^{-1} at 0.3 A_{g}^{-1} [121] RGO/PPy 240 F_{g}^{-1} at 0.3 A_{g}^{-1} [122] RGO/PPy 420 F_{g}^{-1} at 0.3 A_{g}^{-1} [123] RGO/PPy 420 F_{g}^{-1} at 0.2 A_{g}^{-1} [124] RO/PPy 514 F_{g}^{-1} at 0.2 A_{g}^{-1} [123] PPy 514 F_{g}^{-1} at 0.2 A_{g}^{-1} [124] Nanotubes 420 F_{g}^{-1} at 0.2 A_{g}^{-1} [124] Nanotubes 420 F_{g}^{-1} at 1 A_{g}^{-1} [124] Nanotubes 420 F_{g}^{-1} at 0.2 A_{g}^{-1} [124] Nanotubes 420 F_{g}^{-1} at 0.2 A_{g}^{-1} [124] Nanotubes 420 F_{g}^{-1} at 0.2 A_{g}^{-1} [125] Sulfonated 310 F_{g}^{-1} at 0.3 A_{g}^{-1} [111] graphene/PPD Higo	CNT/PANI		
Int OF Anti- Graphene/PPy 165 G ⁻ at 1 A G ⁻¹ at end of [111] GO/PPy 100 CV (scan rate: [119] BOO/PPy 100 mVs ⁻¹) RGO/PPy 249 Fg ⁻¹ at 0.3 Ag ⁻¹ [120] RGO/PPy 249 Fg ⁻¹ at 0.3 Ag ⁻¹ [121] RGO/PPy 240 Fg ⁻¹ at 0.3 Ag ⁻¹ [121] RGO/PPy 240 Fg ⁻¹ at 0.3 Ag ⁻¹ [121] RGO/PPy 240 Fg ⁻¹ at 0.3 Ag ⁻¹ [122] RGO/PPy 240 Fg ⁻¹ at 0.2 Ag ⁻¹ [122] RGO/PPy 240 Fg ⁻¹ at 0.2 Ag ⁻¹ [122] RGO/PPy 351 Fg ⁻¹ at 1 Ag ⁻¹ [123] RGO/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [123] PPy 100 mVs ⁻¹ Graphene/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 1 Ag ⁻¹ [123] Graphene/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 1 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 0.3 Ag ⁻¹ [124] RGO/PPy 440 mFcm ⁻² at 0.5 mAcm ⁻² [125] Sulfonated 310 Fg ⁻¹ at 0.3 Ag ⁻¹ [124] RGO/PPDOT HCI: 304 Fg ⁻¹ at 0.3 Ag ⁻¹ [127] Graphene/PEDOT HCI: 304 Fg ⁻¹ at 0.3 Ag ⁻¹ [128] RGO/PEDOT 270 Fg ⁻¹ at 0.3 Ag ⁻¹ [128]	BGO/PANI	438.8 Eq ⁻¹ at 0.5 Aq^{-1}	[118]
GO/PPy 100 ftg view 100 mVs ⁻¹ GO/PPy 417 Fg ⁻¹ from CV (scan rate: [119] 100 mVs ⁻¹) 267 Fg ⁻¹ from CV (scan rate: 100 mVs ⁻¹) RGO/PPy 249 Fg ⁻¹ at 0.3 Ag ⁻¹ [120] RGO/PPy 249 Fg ⁻¹ at 0.1 Ag ⁻¹ [121] RGO/PPy 240 Fg ⁻¹ at 0.3 Ag ⁻¹ [122] RGO/PPy 240 Fg ⁻¹ at 0.5 Ag ⁻¹ [122] RGO/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [123] PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] RGO/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 0.3 Ag ⁻¹ [124] RGO/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 0.3 Ag ⁻¹ [124] RGO/PPy 514 Fg ⁻¹ at 0.3 Ag ⁻¹ [126] Graphene/PPy 310 Fg ⁻¹ at 0.3 Ag ⁻¹ [111] graphene/PPy 100 mVs ⁻¹ [126] Graphene/PEDOT 10 mVs ⁻¹ [127] Graphene/PEDOT 270 Fg ⁻¹ at 1 Ag ⁻¹ [128] RGO/PEDOT 270 Fg ⁻¹ at 1 Ag ⁻¹ [128] RGO/PEDOT 213 Fg ⁻¹ at 0.5 Ag	Granbene/PPv	165 Eg^{-1} at 1 Ag^{-1} at end of	[111]
GO/PPy 417 Fg ⁻¹ from CV (scan rate: [119] 100 mVs ⁻¹) 267 Fg ⁻¹ from CV (scan rate: 100 mVs ⁻¹) RGO/PPy 249 Fg ⁻¹ at 0.3 Ag ⁻¹ [120] RGO/PPy 249 Fg ⁻¹ at 0.1 Ag ⁻¹ [121] 240 Fg ⁻¹ at 0.3 Ag ⁻¹ [122] RGO/PPy 420 Fg ⁻¹ at 0.3 Ag ⁻¹ [122] RGO/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [123] PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] RGO/PPy 440 mFcm ⁻² at 0.5 mAcm ⁻² [125] Sulfonated 310 Fg ⁻¹ at 0.3 Ag ⁻¹ [111] graphene/PPy 440 mFcm ⁻² at 0.5 mAcm ⁻² [125] Sulfonated 310 Fg ⁻¹ at 0.3 Ag ⁻¹ [111] graphene/PPy 420 Fg ⁻¹ at 0.3 Ag ⁻¹ [111] Graphene/PEDOT 10 mVs ⁻¹ [126] Graphene/PEDOT 270 Fg ⁻¹ at 0.3 Ag ⁻¹ [127] Graphene/PEDOT 270 Fg ⁻¹ at 0.5 Ag ⁻¹ [128] RGO/PEDOT 270 Fg ⁻¹ at 0.5 Ag ⁻¹ [129] Hallow RGO/PEDOT 270 Fg ⁻¹ at 1 Ag ⁻¹ [128] RGO/PEDOT	Suprement y	1000th cycle	
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RGO/PPy 267 Fg^{-1} from CV (scan rate: 100 mVs^{-1}) 120 RGO/PPy 249 Fg^{-1} at 0.3 Ag^{-1} 120 RGO/PPy 420 Fg^{-1} at 0.3 Ag^{-1} 121 RGO/PPy nanowire 249 Fg^{-1} at 0.3 Ag^{-1} 122 RGO/PPy nanowire 728 Fg^{-1} at 0.5 Ag^{-1} 122 Exfoliated graphene/ 675 Fg^{-1} at 2.5 Ag^{-1} 123 PPy 514 Fg^{-1} at 0.2 Ag^{-1} 123 Graphene/PPy 514 Fg^{-1} at 0.2 Ag^{-1} 124 Nanotubes 420 Fg^{-1} at 0.2 Ag^{-1} 124 RGO/PPy 514 Fg^{-1} at 0.2 Ag^{-1} 124 Nanotubes 420 Fg^{-1} at 0.3 Ag^{-1} 111 graphene/PPy 514 Fg^{-1} at 0.3 Ag^{-1} 1111 graphene/PPy 675 Fg^{-1} at 0.3 Ag^{-1} 1111 graphene/PPy 675 Fg^{-1} at 0.3 Ag^{-1} 1111 graphene/PPy 675 Fg^{-1} at 0.3 Ag^{-1} 125 Suffonated 310 Fg^{-1} from CV at a scan rate 126 of 10 mVs^{-1} H_2SO4: 261 Fg^{-1} from CV at a scan rate 126 raphene/PEDOT 108 Fg^{-1} at 0.3 $Ag^{$	30/11 y	$100 \text{ m}/(c^{-1})$	
RGO/PPy 249 Fg ⁻¹ at 0.3 Ag ⁻¹ [120] RGO/PPy 420 Fg ⁻¹ at 0.3 Ag ⁻¹ [121] 240 Fg ⁻¹ at 0.1 Ag ⁻¹ [121] 240 Fg ⁻¹ at 5 Ag ⁻¹ [122] RGO/PPy nanowire 728 Fg ⁻¹ at 0.5 Ag ⁻¹ [122] Exfoliated graphene/ 728 Fg ⁻¹ at 0.2 Ag ⁻¹ [123] PPy 351 Fg ⁻¹ at 1 Ag ⁻¹ [123] Graphene/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 1 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 0.3 Ag ⁻¹ [124] RGO/PPy 440 mFc ⁻² at 0.5 mAcm ⁻² [125] Sulfonated 310 Fg ⁻¹ at 0.3 Ag ⁻¹ [111] graphene/PPy 440 mFc ⁻² at 0.3 Ag ⁻¹ [126] Graphene/PPy 675 Fg ⁻¹ from CV at a scan rate [126] Graphene/PEDOT HCI: 304 Fg ⁻¹ from CV at a scan rate [126] Graphene/PEDOT 108 Fg ⁻¹ at 0.3 Ag ⁻¹ [127] Graphene/PEDOT 270 Fg ⁻¹ at 1 Ag ⁻¹ [128] RGO/PEDOT 213 Fg ⁻¹ at 0.5 Ag ⁻¹ [129] Hallow RGO/PEDOT 304.5 mFc ⁻¹ at 1 Ag ⁻¹ [130] Hallow AGO/P		$267 \mathrm{Fg}^{-1}$ from CV (scan rate)	
RGO/PPy 249 Fg ⁻¹ at 0.3 Ag ⁻¹ [120] RGO/PPy 249 Fg ⁻¹ at 0.1 Ag ⁻¹ [121] 240 Fg ⁻¹ at 0.1 Ag ⁻¹ [121] 240 Fg ⁻¹ at 0.5 Ag ⁻¹ [122] RGO/PPy nanowire 728 Fg ⁻¹ at 0.5 Ag ⁻¹ [122] Exfoliated graphene/ 731 Fg ⁻¹ at 0.5 Ag ⁻¹ [123] PPy 351 Fg ⁻¹ at 0.2 Ag ⁻¹ [123] Graphene/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 1 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Sulfonated 310 Fg ⁻¹ at 0.3 Ag ⁻¹ [125] Sulfonated 310 Fg ⁻¹ at 0.3 Ag ⁻¹ [111] graphene/PPy 440 mFcm ⁻² at 0.5 mAcm ⁻² [126] Graphene/PEDOT HCI: 304 Fg ⁻¹ from CV at a scan rate [126] of 10 mVs ⁻¹ H ₂ SO ₄ : 261 Fg ⁻¹ from CV at a scan rate of 10 mVs ⁻¹ RGO/PEDOT 108 Fg ⁻¹ at 0.3 Ag ⁻¹ [127] Graphene/PEDOT 270 Fg ⁻¹ at 1 Ag ⁻¹ [128] RGO/PEDOT 213 Fg ⁻¹ at 0.5 Ag ⁻¹ [129] Hallow RGO/PEDOT 304.5 mFcm ⁻² at 0.08 mAcm ⁻² [131] <		207 Fy from CV (scall rate:	
RGO/PPy 249 Fg at 0.3 Ag 121 RGO/PPy 420 Fg ⁻¹ at 0.1 Ag ⁻¹ 121 240 Fg ⁻¹ at 0.5 Ag ⁻¹ 122 RGO/PPy nanowire 728 Fg ⁻¹ at 0.5 Ag ⁻¹ 122 675 Fg ⁻¹ at 5.4 Gg ⁻¹ 123 PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ 123 PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ 124 Nanotubes 420 Fg ⁻¹ at 0.2 Ag ⁻¹ 124 RGO/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ 124 Nanotubes 420 Fg ⁻¹ at 0.2 Ag ⁻¹ 124 RGO/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ 124 Nanotubes 420 Fg ⁻¹ at 0.2 Ag ⁻¹ 124 RGO/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ 124 Sulfonated 310 Fg ⁻¹ at 0.3 Ag ⁻¹ 111 graphene/PPy 440 mFcm ⁻² at 0.5 mAcm ⁻² 125 Sulfonated 310 Fg ⁻¹ at 0.3 Ag ⁻¹ 1111 graphene/PEDOT Hcl: 304 Fg ⁻¹ from CV at a scan rate 126 of 10 mVs ⁻¹ 128 127 128 Graphene/PEDOT 270 Fg ⁻¹ at 0.3 Ag ⁻¹ 128 RGO/PEDOT 270 Fg ⁻¹ at 1 Ag ⁻¹ 128		100 mVs)	[120]
RGO/PPy 240 Fg at 0.1 Ag 122 RGO/PPy nanowire 728 Fg ⁻¹ at 0.5 Ag ⁻¹ [122] 675 Fg ⁻¹ at 2.5 Ag ⁻¹ 675 Fg ⁻¹ at 2.5 Ag ⁻¹ [123] PPy 351 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] RGO/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] RGO/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Sulfonated 420 Fg ⁻¹ at 0.3 Ag ⁻¹ [111] graphene/PPy 440 mEcm ⁻² at 0.5 mAcm ⁻² [125] Sulfonated 310 Fg ⁻¹ at 0.3 Ag ⁻¹ [111] graphene/PEDOT HCI: 304 Fg ⁻¹ from CV at a scan rate [126] of 10 mVs ⁻¹ H ₂ SO ₄ : 261 Fg ⁻¹ from CV at a scan rate of 10 mVs ⁻¹ RGO/PEDOT 108 Fg ⁻¹ at 0.3 Ag ⁻¹ [127] Graphene/PEDOT 270 Fg ⁻¹ at 1.3 g ⁻¹ [128] RGO/PEDOT 213 Fg ⁻¹ at 0.5 Ag ⁻¹ [129] Hallow RGO/PEDOT 304.5 mEcm ⁻² at 0.08 mAcm ⁻² [130] Hallow RGO/PEDOT 364.5 mEcm ⁻² at 1.00 [130]	RGO/PPy	249 Fg at 0.3 Ag	[121]
RGO/PPy nanowire 728 Fg ⁻¹ at 0.5 Ag ⁻¹ [122] Exfoliated graphene/ 675 Fg ⁻¹ at 0.5 Ag ⁻¹ [123] PPy 351 Fg ⁻¹ at 1 Ag ⁻¹ [123] Graphene/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 1 Ag ⁻¹ [124] RGO/PPy 514 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 1 Ag ⁻¹ [124] RGO/PPy 440 mFcm ⁻² at 0.5 mAcm ⁻² [125] Sulfonated 310 Fg ⁻¹ at 0.3 Ag ⁻¹ [111] graphene/PPy 111 [111] Graphene/PEDOT HCl: 304 Fg ⁻¹ from CV at a scan rate [126] of 10 mVs ⁻¹ H2SO4: 261 Fg ⁻¹ from CV at a scan rate [126] Graphene/PEDOT 108 Fg ⁻¹ at 0.3 Ag ⁻¹ [127] Graphene/PEDOT 108 Fg ⁻¹ at 0.3 Ag ⁻¹ [127] Hallow RGO/PEDOT 270 Fg ⁻¹ at 1 Ag ⁻¹ [128] RGO/PEDOT 213 Fg ⁻¹ at 0.5 Ag ⁻¹ [129] Hallow RGO/PEDOT 304.5 mFcm ⁻² at 0.08 mAcm ⁻² [130]	RGO/PPy	420 Fg at 0.1 Ag	
RGO/PPy nanowire 728 Fg ⁻¹ at 0.5 Ag ⁻¹ [123] Exfoliated graphene/ 351 Fg ⁻¹ at 1 Ag ⁻¹ [123] Ppy 351 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 0.2 Ag ⁻¹ [124] Nanotubes 420 Fg ⁻¹ at 0.2 Ag ⁻¹ [125] Sulfonated 310 Fg ⁻¹ at 0.3 Ag ⁻¹ [111] graphene/PPy HCI: 304 Fg ⁻¹ from CV at a scan rate [126] Graphene/PEDOT HCI: 304 Fg ⁻¹ from CV at a scan rate [126] Graphene/PEDOT HCI: 304 Fg ⁻¹ at 0.3 Ag ⁻¹ [111] graphene/PEDOT HCI: 304 Fg ⁻¹ at 0.3 Ag ⁻¹ [128] RGO/PEDOT 108 Fg ⁻¹ at 0.3 Ag ⁻¹ [129] RGO/PEDOT 270 Fg ⁻¹ at 1 Ag ⁻¹ [128] RGO/PEDOT 213 Fg ⁻¹ at 0.5 Ag ⁻¹ [129] Hallow RGO/PEDOT 304.5 mFcm ⁻² at 0.08 mAcm ⁻² [130]		240 Fg at 5 Ag $^{-1}$	[122]
$675 \text{ Fg}^{-1} \text{ at } 2.5 \text{ Ag}^{-1}$ [123] PPy $351 \text{ Fg}^{-1} \text{ at } 1 \text{ Ag}^{-1}$ [124] Nanotubes $420 \text{ Fg}^{-1} \text{ at } 0.2 \text{ Ag}^{-1}$ [124] Nanotubes $420 \text{ Fg}^{-1} \text{ at } 1 \text{ Ag}^{-1}$ [125] Sulfonated $310 \text{ Fg}^{-1} \text{ at } 0.3 \text{ Ag}^{-1}$ [111] graphene/PPy HCI: $304 \text{ Fg}^{-1} \text{ from CV at a scan rate}$ [126] Graphene/PEDOT HCI: $304 \text{ Fg}^{-1} \text{ from CV at a scan rate}$ [126] Graphene/PEDOT HCI: $304 \text{ Fg}^{-1} \text{ at } 0.3 \text{ Ag}^{-1}$ [111] graphene/PEDOT HCI: $304 \text{ Fg}^{-1} \text{ at } 0.3 \text{ Ag}^{-1}$ [126] Graphene/PEDOT 108 \text{ Kg}^{-1} \text{ at } 0.3 \text{ Ag}^{-1} [127] Graphene/PEDOT 108 fg^{-1} \text{ at } 0.3 \text{ Ag}^{-1} [128] RGO/PEDOT 270 fg^{-1} \text{ at } 1 \text{ Ag}^{-1} [128] RGO/PEDOT 213 fg^{-1} \text{ at } 0.5 \text{ Ag}^{-1} [129] Hallow RGO/PEDOT 304.5 mFcm^{-2} \text{ at } 0.08 mAcm^{-2} [130] RGO/PEDOT 304.5 mFcm^{-2} \text{ at } 1.0 \text{ cm}^{-1} [131]	RGO/PPy nanowire	728 Fg ' at 0.5 Ag '	[122]
Exfoliated graphene/ $351 \text{ Fg}^{-1} \text{ at } 1 \text{ Ag}^{-1}$ [123] PPy $514 \text{ Fg}^{-1} \text{ at } 0.2 \text{ Ag}^{-1}$ [124] Nanotubes $420 \text{ Fg}^{-1} \text{ at } 0.2 \text{ Ag}^{-1}$ [124] RGO/PPy $514 \text{ Fg}^{-1} \text{ at } 0.2 \text{ Ag}^{-1}$ [125] Sulfonated $420 \text{ Fg}^{-1} \text{ at } 0.3 \text{ Ag}^{-1}$ [111] graphene/PPy $440 \text{ mFcm}^{-2} \text{ at } 0.5 \text{ mAcm}^{-2}$ [125] Sulfonated $310 \text{ Fg}^{-1} \text{ at } 0.3 \text{ Ag}^{-1}$ [111] graphene/PPy HCI: $304 \text{ Fg}^{-1} \text{ from CV at a scan rate}$ [126] of 10 mVs^{-1} H_2SO_4: 261 \text{ Fg}^{-1} \text{ from CV at a scan rate} [127] Graphene/PEDOT 108 \text{ Fg}^{-1} \text{ at } 0.3 \text{ Ag}^{-1} [127] Graphene/PEDOT 270 \text{ Fg}^{-1} \text{ at } 0.3 \text{ Ag}^{-1} [129] Hallow RGO/PEDOT 213 \text{ Fg}^{-1} \text{ at } 0.5 \text{ Ag}^{-1} [129] Hallow RGO/PEDOT 304.5 mFcm^{-2} at 0.08 mAcm^{-2} [130]		675 Fg ' at 2.5 Ag '	[122]
PPy $514 \text{ Fg}^{-1} \text{ at } 0.2 \text{ Ag}^{-1}$ [124] Nanotubes $420 \text{ Fg}^{-1} \text{ at } 1 \text{ Ag}^{-1}$ [125] RGO/PPy $440 \text{ mFcm}^{-2} \text{ at } 0.5 \text{ mAcm}^{-2}$ [125] Sulfonated $310 \text{ Fg}^{-1} \text{ at } 0.3 \text{ Ag}^{-1}$ [111] graphene/PPy HCI: 304 Fg^{-1} from CV at a scan rate [126] of 10 mVs^{-1} H_2SO_4: 261 Fg^{-1} from CV at a scan rate [127] RGO/PEDOT 108 Fg^{-1} at 0.3 Ag^{-1} [127] Graphene/PEDOT 108 Fg^{-1} at 0.3 Ag^{-1} [128] RGO/PEDOT 108 Fg^{-1} at 0.5 Ag^{-1} [129] Hallow RGO/PEDOT 213 Fg^{-1} at 0.5 Ag^{-1} [130] RGO/PEDOT 304.5 mFcm^{-2} at 0.08 mAcm^{-2} [130]	Exfoliated graphene/	351 Fg ⁻ ' at 1 Ag ⁻ '	[125]
Graphene/PPy $514 \text{ Fg}^{-1} \text{ at } 0.2 \text{ Ag}^{-1}$ $[124]$ Nanotubes $420 \text{ Fg}^{-1} \text{ at } 1 \text{ Ag}^{-1}$ [125] Sulfonated $310 \text{ Fg}^{-1} \text{ at } 0.3 \text{ Ag}^{-1}$ [111] graphene/PPy HCI: 304 Fg^{-1} from CV at a scan rate [126] of 10 mVs^{-1} H_2SO4: 261 Fg^{-1} from CV at a scan [127] RGO/PEDOT 108 Fg^{-1} at 0.3 Ag^{-1} [127] Graphene/PEDOT 108 Fg^{-1} at 0.3 Ag^{-1} [129] RGO/PEDOT 270 Fg^{-1} at 1 Ag^{-1} [129] Hallow RGO/PEDOT 304.5 mFcm^{-2} at 0.08 mAcm^{-2} [130]	РРу		[124]
Nanotubes $420 \text{ Fg}^{-1} \text{ at } 1 \text{ Ag}^{-1}$ RGO/PPy $440 \text{ mFcm}^{-2} \text{ at } 0.5 \text{ mAcm}^{-2}$ [125] Sulfonated $310 \text{ Fg}^{-1} \text{ at } 0.3 \text{ Ag}^{-1}$ [111] graphene/PPy $HCI: 304 \text{ Fg}^{-1} \text{ from CV at a scan rate}$ [126] of 10 mVs^{-1} $H_2SO_4: 261 \text{ Fg}^{-1} \text{ from CV at a scan rate}$ [127] RGO/PEDOT 108 Fg^{-1} at 0.3 Ag^{-1} [127] Graphene/PEDOT 270 Fg^{-1} at 1 Ag^{-1} [128] RGO/PEDOT 213 Fg^{-1} at 0.5 Ag^{-1} [129] Hallow RGO/PEDOT 304.5 mFcm^{-2} at 0.08 mAcm^{-2} [130]	Graphene/PPy	514 Fg ⁻ ' at 0.2 Ag ⁻ '	[124]
RGO/PPy 440 mFcm ⁻² at 0.5 mAcm ⁻² [125] Sulfonated $310 \text{ Fg}^{-1} \text{ at } 0.3 \text{ Ag}^{-1}$ [111] graphene/PPy (126) (127) Graphene/PEDOT HCI: 304 Fg ⁻¹ from CV at a scan rate (126) of 10 mVs ⁻¹ H ₂ SO ₄ : 261 Fg ⁻¹ from CV at a scan rate (127) RGO/PEDOT 108 Fg ⁻¹ at 0.3 Ag ⁻¹ [128] RGO/PEDOT 270 Fg ⁻¹ at 1 Ag ⁻¹ [128] RGO/PEDOT 213 Fg ⁻¹ at 0.5 Ag ⁻¹ [129] Hallow RGO/PEDOT 304.5 mFcm ⁻² at 0.08 mAcm ⁻² [130]	Nanotubes	420 Fg ⁻¹ at 1 Ag ⁻¹	(
Sulfonated $310 \text{ Fg}^{-1} \text{ at } 0.3 \text{ Ag}^{-1}$ [11] graphene/PPy (111) Graphene/PEDOT HCI: 304 Fg^{-1} from CV at a scan rate (126) of 10 mVs^{-1} H ₂ SO ₄ : 261 Fg^{-1} from CV at a scan rate (127) RGO/PEDOT 108 Fg^{-1} at 0.3 Ag^{-1} (127) Graphene/PEDOT 270 Fg^{-1} at 0.3 Ag^{-1} (128) RGO/PEDOT 213 Fg^{-1} at 0.5 Ag^{-1} (129) Hallow RGO/PEDOT 304.5 mFcm^{-2} at 0.08 mAcm^{-2} (130) RGO/PEDOT 367 Fg^{-1} at 1 Ag^{-1} (131)	RGO/PPy	440 mFcm ⁻² at 0.5 mAcm ⁻²	[125]
graphene/PPy Graphene/PEDOT HCl: 304 Fg ⁻¹ from CV at a scan rate of 10 mVs ⁻¹ [126] Mail of 10 mVs ⁻¹ H2SO4: 261 Fg ⁻¹ from CV at a scan rate of 10 mVs ⁻¹ [127] RGO/PEDOT 108 Fg ⁻¹ at 0.3 Ag ⁻¹ [128] Graphene/PEDOT 270 Fg ⁻¹ at 0.3 Ag ⁻¹ [128] RGO/PEDOT 213 Fg ⁻¹ at 0.5 Ag ⁻¹ [129] Hallow RGO/PEDOT 304.5 mFcm ⁻² at 0.08 mAcm ⁻² [130]	Sulfonated	310 Fg^{-1} at 0.3 Ag^{-1}	[111]
Graphene/PEDOT HCI: 304 Fg ⁻¹ from CV at a scan rate [126] of 10 mVs ⁻¹ H2SO4: 261 Fg ⁻¹ from CV at a scan rate [127] RGO/PEDOT 108 Fg ⁻¹ at 0.3 Ag ⁻¹ [127] Graphene/PEDOT 270 Fg ⁻¹ at 0.3 Ag ⁻¹ [128] RGO/PEDOT 213 Fg ⁻¹ at 0.5 Ag ⁻¹ [129] Hallow RGO/PEDOT 304.5 mFcm ⁻² at 0.08 mAcm ⁻² [130]	graphene/PPy		
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RGO/PEDOT $H_2SO_4: 261 \text{ Fg}^{-1} \text{ from CV at a scan}$ rate of 10 mVs^{-1} rate of 10 mVs^{-1} Graphene/PEDOT 108 Fg^{-1} at 0.3 Ag^{-1} [127] GRO/PEDOT 270 Fg^{-1} at 1 Ag^{-1} [128] RGO/PEDOT 213 Fg^{-1} at 0.5 Ag^{-1} [129] Hallow RGO/PEDOT 304.5 mFcm^{-2} at 0.08 mAcm^{-2} [130] RGO/PEDOT- 267 Eg^{-1} at 1 Ag^{-1} [131]		of 10 mVs ⁻¹	
rate of 10 mVs ⁻¹ rate of 10 mVs ⁻¹ RGO/PEDOT 108 Fg ⁻¹ at 0.3 Ag ⁻¹ [127] Graphene/PEDOT 270 Fg ⁻¹ at 1 Ag ⁻¹ [128] RGO/PEDOT 213 Fg ⁻¹ at 0.5 Ag ⁻¹ [129] Hallow RGO/PEDOT 304.5 mFcm ⁻² at 0.08 mAcm ⁻² [130] RGO/PEDOT- 367 Eg ⁻¹ at 1 Ag ⁻¹ [131]		H_2SO_4 : 261 Fg ⁻¹ from CV at a scan	
RGO/PEDOT 108 Fg ⁻¹ at 0.3 Ag ⁻¹ [127] Graphene/PEDOT 270 Fg ⁻¹ at 1 Ag ⁻¹ [128] RGO/PEDOT 213 Fg ⁻¹ at 0.5 Ag ⁻¹ [129] Hallow RGO/PEDOT 304.5 mFcm ⁻² at 0.08 mAcm ⁻² [130] RGO/PEDOT: 367 Fg ⁻¹ at 1 Ag ⁻¹ [131]		rate of 10 mVs ^{-1}	
Graphene/PEDOT 270 Fg ⁻¹ at 1 Ag ⁻¹ [128] RGO/PEDOT 213 Fg ⁻¹ at 0.5 Ag ⁻¹ [129] Hallow RGO/PEDOT 304.5 mFcm ⁻² at 0.08 mAcm ⁻² [130] RGO/PEDOT:PSS 367 Fg ⁻¹ at 1 Ag ⁻¹ [131]	RGO/PEDOT	108 Fg^{-1} at 0.3 Ag^{-1}	[127]
RGO/PEDOT 213 Fg ⁻¹ at 0.5 Ag ⁻¹ [129] Hallow RGO/PEDOT 304.5 mFcm ⁻² at 0.08 mAcm ⁻² [130] RGO/PEDOT:PSS 367 Fcr ⁻¹ at 1 Ag ⁻¹ [131]	Graphene/PEDOT	270 Fg^{-1} at 1 Ag $^{-1}$	[128]
Hallow RGO/PEDOT 304.5 mFcm^{-2} at 0.08 mAcm ⁻² [130] RGO/PEDOT:PSS 367 Fcm^{-1} at 1.4 cm^{-1} [131]	RGO/PEDOT	213 Fg^{-1} at 0.5 Ag ⁻¹	[129]
BG0/PEDT-PSS 367 En ⁻¹ at 1 An ⁻¹ [¹³]	Hallow RGO/PEDOT	304.5 mFcm^{-2} at 0.08 mAcm ⁻²	[130]
10/ FU // L MU	RGO/PEDOT:PSS	367 Fg^{-1} at 1 Ag ⁻¹	[131]

5.3. Optical properties of graphene

In Graphene, there is no gap between the conduction and valence band and it touches each other at Dirac point which leads to strong interaction of Dirac Fermions with electromagnetic radiation. Pristine graphene layer has thickness equal to only one atom and it can absorb 2.3% of the white light. The wide range of spectral absorption of pristine graphene is due to the

Table 2. Performance summary	of solar	cells	studied	by	differe	nt
research groups.						

· ·		
Cell structure	Eff (%)	Reference
TiO ₂ — graphene	6.49%	[132]
TiO ₂ - graphene	6.49%	[133]
TiO ₂ - graphene	15.6%	[134]
TiO_2 – graphene sulfide	1.68%	[135]
Silicon	17%	[136]
Organic molecules or polymers	5%	[136]
Hybrid solar cell	22-23%	[136]
Graphene nanoplatelets	5%	[137]
rGO–PANI	6.15%	[138]
TiO2/RGO	7.46	[81]
Dve-sensitized solar cells based on TiO ₂	4.81%	[139]
nanoparticles		
Dve-sensitized solar cells based on PANI/graphene	7 70	[140]
Dye-sensitized solar cells based on PANI-BGO	7 84	[141]
Dye-sensitized solar cells based on Pny/RGO	6.45	[142]
Dye-sensitized solar cells based on PANI/graphene	6.09	[143]
dve-sensitized solar cells (DSSC) were fabricated	4 78%	[144]
using graphene-TiO2composite	4.2070	
2D graphene	6 07%	[145]
Dvo Sonsitized Solar Colls by using GraphonaTiO	6 960/	[146]
Compositor	0.00%	
A due consitized color coll (DSSC) based on	4 200/	[147]
A uye-sensitized solar cell (DSSC) based on	4.20%	
$Graphene-10_2$ composite photoelectrode	2 1 1 0/	[147]
DSSC based on pure IIO_2 photoelectrode	3.11%	[148]
Dye-sensitized Solar Cell using Graphene-110 ₂	7.1%	[82]
. DSSCs based on TIO2@RGO hybrid photoanodes	7.68%	[02]
with a graphene content of 1.6 wt %		[149]
DSSC based on Polyaniline/graphene (1 wt%)	6./1	[140]
complex		[149]
DSSC based on Polyaniline/graphene (8 wt%)	/./8	[140]
complex		[149]
DSSC based on Polyaniline/graphene (15 wt%)	6.89	[140]
complex		[150]
DSSC based on Polyaniline-graphene (10 wt%)/GO)	7.88	[150]
n (n = 10)		[150]
DSSC based on Polyaniline-graphene (10 wt%)/GO)	6.61	[150]
n (n = 5)		[100]
DSSC based on Polyaniline-graphene (8 wt%)/GO)	7.83	[150]
n (n = 10)		[1 50]
DSSC based on Polyaniline-graphene (8 wt%)/GO)	6.03	[150]
n (n = 5)		[150]
DSSC based on Polyaniline-graphene (4 wt%)/GO)	6.38	[150]
<i>n</i> (<i>n</i> = 10)		F a a a
DSSC based on Polyaniline-graphene (4 wt%)/GO)	4.21	[150]
n (n = 5)		
DSSC based on Graphene/TiO ₂	9.2	[151]
DSSC based on TiO ₂ /graphene nanocomposite	5.41	[152]
(0.5 wt%)		
DSSC based on TiO ₂ only	4.11	[152]
DSSC based on TiO ₂ /graphene nanocomposite	3.69	[152]
(1.6 wt%)		
DSSC based on TiO ₂ /graphene nanocomposite	2.82	[152]
(0.4 wt%)		
DSSC based on TiO ₂ only	2.49	[152]
DSSC based on Graphene (1.5 wt%)/TiO ₂	4.20	[153]
DSSC based on TiO_2 only	3.17	[153]
]DSSC based on TiO ₂ /graphene composite	3.98	[153]
DSSC based on TiO_2 only	1.45	[153]

contribution from both interband and intraband optical transitions. The optical absorption of single-layer graphene in visible region takes place mainly due to interband transitions which are independent of frequency. The optical absorption in the far-infrared region is mainly due to intraband transitions or free carrier absorption. Hence, graphene shows excellent thermal management applications especially in micro- and nanoelectronics.

6. Solar cells

A solar cell, or photovoltaic cell, is an electrical device which is used to converts the energy of light into electricity. In electric power generation by use of renewable energy resources instead of conventional fossil-fuels is rapidly increasing. Among renewable energy resources which are used for electric power generation, solar photovoltaics (PVs) are the fastest growing resource.^[18] After hydro and wind energy, solar energy is the third largest renewable energy resource of electric power generation in the world.^[19]

The motivating factors for the replacement of conventional fossil-fuels by solar PVs for electric power generation are

Price of fossil fuels is increasing day by day and they are limited while the source of solar energy is free and abundant.^[20,21]

Use of Fossil-fuels pollutes the environment while solar PV's does not release any pollutant.^[22,23]

Use of fossil-fuels contribute to global warming while solar PV's mitigate this issue.

Solar PV's requires less maintenance and operational costs.^[24]

Among renewable energy sources, solar PVs provide the highest power density. $^{\left[25,26\right] }$

More than 100 countries in the world are using solar $\mathrm{PVs.}^{[24]}$

In order to encourage investments, governments declared financial assistance for solar electricity generation.^[27-31] PV cell is the basic component of PV systems. Basically, PV cell is a semiconductor diode in which P–N junction is exposed to the light.^[32]

Despite all the above advantages of solar PV systems, there are some challenges.

PV systems do not create emissions during their operation, but these technologies are not completely emission-free. A lifecycle assessment (LCA) of solar PV cells is found to be divided into three phases; manufacturing, operation and recycling. It is observed that, Manufacturing phase is responsible for most of GHG emissions (around 90 percent) while recycling phase lowers GHG emissions^[33]

Currently, the efficiency of solar PV cells is low, hence cost of electricity produced from them is high. Hence, researchers are taking effort to increase the efficiency of solar cells so as to reduce the cost of produced electricity.^[19–22]

Another challenge of solar PV cells is their handling after end of their lifecycle. Research is going on to for recycling of solar modules and its different parts involved in manufacturing after the end of their life cycle. ^[23] Once recycled, solar companies can use it again to build new modules so as to reduce their cost of manufacturing.^[23]

The power generated by solar PV cells is depend on environmental parameters such as irradiation and temperature which are not controllable.^[34–36] To overcome this issue, storage devices are integrated into PV systems.

6.1. Working principles of solar cells

6.1.1 Exciton formation

After the phenomenon of light absorption, Inorganic semiconductors immediately produce free carriers, while organic semiconductors require additional process known as exciton formation.^[37]

6.1.2 Exciton transport

The next step is exciton transport, which is in competition with other decay process such as Luminescence or radiative recombinations to ground state.

6.1.3 Charge Separation

Creation of charge is one of the important steps in conversion of sunlight into electric energy. In most PV cells, charges are produced by photoinduced electron *transfer from* a donor (D) to acceptor (A) by using additional input energy of absorbed photon.

6.1.4 Charge transport

The next step is charge transport phenomenon where charge carriers go towards electrodes.

6.1.5 Charge collection

The collection of charge carriers at electrodes is done by a transparent conductive oxide (TCO) such as ITO on one side and a metal contact on another side.

Thus, A built-in-potential barrier in the cell activates the electrons to produce a voltage, to drive a current through a circuit.^[38–40]

7. Supercapacitor

Electrochemical capacitors (ECs) are also known as "ultracapacitors" or "power capacitors" but currently the most recognized name is "supercapacitors". The term supercapacitor was proposed by NEC, since it was the first company to introduce a device with the name SupercapacitorTM in 1971.^[41] Supercapacitors

are under development since 1957 when Becker^[42] first time used carbon flooded with a sulfuric acid electrolyte for charge storage at the interface of these two materials. However, in 1969 that the company SOHIO^[43] first launched this technology into the market. The real success of supercapacitors research started in the 1990s when government programs in the United States donated funds for this technology to incorporate it into hybrid vehicles to provide necessary power for acceleration.^[44] Supercapacitors show a higher power density but a smaller energy density compared to traditional batteries, which make them attractive for applications where instantaneous power is necessary. The other characteristics of supercapacitors are: ability to chargedischarge within seconds; a long lifetime of more than 106 cycles; ecofreindlyness and stability at various temperatures.^[45] Thus, supercapacitors are electrochemical devices that can store energy and release it with high power capability and high current density within a short time interval.^[46] So, supercapacitors are the perfect complement for batteries or fuel cells in various applications, such as automobiles and high-performance portable electronics.^[47] Electrode materials which are intensively studied for supercapacitors are carbon, metal oxides, and conducting polymers, with a recent focus on CNTs and graphene.^[48-50]

7.1. Working principles of supercapacitors

Supercapacitors are broadly divided into two types: electric double-layer capacitors (EDLCs) and pseudocapacitors. One more subcategory known as hybrid capacitors can be identified if the EDLCs and the pseudo-capacitors are combined together into a single device. EDLCs store the energy at the electrode/electrolyte interface. During the charging, an external electric field is applied to the device responsible to move the ions at the electrode/electrolyte interface.^[45,51]

Positive and negative ions are accumulated at this interface, typically on the order of 5–10 $A^{0\ .[52]}$

The thickness (d) of the interface is very small (on the order of A^0), while the surface area (A) of the electrode usually varies due to the choice of porous structures with a large internal surface area. In this way, the capacitance can increase to a high value (>10 μ F/cm²).^[53] In contrast, pseudo-capacitors are such a devices in which the charge is not stored electrostatically but electrochemically, as in conventional lithium ion batteries. Pseudocapacitive materials such as conducting polymers (e.g., polyaniline (PANI)) or metal oxides (e.g., ruthenium oxide (RuO₂)) can have 10–100 times larger capacitance as compared to EDLCs but they show poor stability, short lifetime and their synthesis is expensive.

Because of such drawbacks, they are generally combined with carbon materials which are known as hybrid supercapacitors.^[54,55] In study the electrical properties of a supercapacitor, three electrochemical measurement techniques are generally used: cyclic voltammetry (CV), galvanostatic charging/discharging and electrochemical impedance measurements.^[56]

Some important characteristics of an EDLC which should be considered to maximize the performance of the device are:

- The appropriate specific surface area of the electrodes so as to increase the capacitance
- The conductivity of the electrodes to minimize the power density losses
- The resistance to any oxidation/reduction at the surface of the electrode to achieve good stability and performance
- Sufficient size distribution of the pores so that it should match with the size of the electrolyte ions
- Good electrochemical stability of the electrolyte material in the voltage operating range of the device
- Low interconnected resistance of the electrolyte material
- Good wettability of the electrolyte material on the electrode.^[52]

8. Challenges associated with manufacture and use of graphene

- (i) Graphene is expensive and it is difficult to manufacture.
- (ii) It is difficult to obtain monolayer graphene every time during synthesis of Graphene. If thickness of graphene is more than 10 layers of graphene, the properties resemble graphite more than graphene.
- (iii) Because of above reasons, results of graphene synthesis are not very reproducible.
- (iv) Graphene is not suitable for its application as a transistor since it does not have an off state and it cannot be switched off completely.
- (v) Graphene is a hydrophobic material and hence it cannot be used in water-oriented applications like in humidity sensor, water filters.

9. Applications of graphene

Graphene has wide range of applications. During the last decade, graphene is a topic of interest in the field of research due to their exceptional electrical, optical and mechanical properties. Graphene can significantly improve the properties of existing products and to develop new materials with novel functionalities. Some of the applications are^[5, 57–59]:

9.1. Graphene – metal oxide/graphene – polymer composites for supercapacitor study

Energy storage is the major topic of interest for researchers and scientists. Graphene has extremely high surface area of ${\sim}2600~m^2g^{-1}$ and it is an ideal material for electrostatic charge storage such as in supercapacitors. Supercapacitors are different from capacitors as charge storage is not done by the insulator material which is present in between the electrodes but by the electrodes which are dipped in the electrolytic solution. Graphene with high surface area and high porosity can store more ions as compared to activated carbon. The specific capacitance of a Graphene-based supercapacitor is found to be five times more than of the activated carbon-based supercapacitor. Researchers are working for lightweight, low-cost, elastic with high mechanical strength graphene-based supercapacitors to reduce and ultimately replace the use of fossil fuels for energy.

The performance of hybrid structures is found to be better than those of pure graphene, GO, rGO, or pure metal oxides due to synergistic effects of both graphene and Metal-oxides. The graphene in the hybrid-structure has various advantages such as high surface area, ultra-thin thickness, excellent electrical and thermal conductivity, mechanical flexibility, while metal oxides have high chemical functionality, and other electrochemical properties. Consequently, graphene can be an ideal 2D membrane for growing tiny nanoparticles with very distinct structures and precious morphologies for constituting a threedimensional interconnected conductive porous network, with enhanced the electrical conductivity and the charge transport. The other advantages of using hybrid structures are:

It can prevent the volume change and particle agglomeration of metal-oxides during the process of chargingdischarging;

2) Oxygen-containing functional groups on GO, rGO imparts good interfacial bonding and electrical contacts between graphene and metal oxides; and

3) Metal-oxide nanoparticles suppress the re-stacking of graphene layers to get continuous, porous, interconnected network structure is with highest achievable power density and capacitance in supercapacitors. Thus, graphene-metal oxide hybrid-materials with all remarkable properties turn it into a more efficient material for supercapacitor electrode applications.^[58]

Hybrid nanocomposites obtained from graphene and polymers also show excellent mechanical, electrical properties and large specific surface areas are particularly suitable for supercapacitor applications. Polymers with a good electrical conductivity and a high pseudo-capacitance are required to prepare such nanocomposites. Such hybrid materials show enhanced electrochemical performance in supercapacitor devices due to the synergetic effects of graphene and polymers which combines the unique properties of the individual components.^[60,61]Thus Along with energy conversion, energy storage (as in supercapacitors and batteries) is also important and for many practical applications, high energy-storage capability, high power-delivery capability, and long cycle life are necessary. Due to the unique characteristics of graphene, much effort has been taken to study the applications of graphene in highperformance supercapacitors and batteries.^[46,62-66] Metal oxide shows high specific capacitance and low resistance makes it simpler to construct supercapacitors with high energy and power. A special attention was toward manganese dioxide MnO₂ as an electrode material for supercapacitors because of their low cost, excellent capacitive performance in aqueous electrolytes and environmental benignity. Different conducting polymers are widely used as supercapacitor electrode material due to its ease of production and low cost. Conducting polymers shows a relatively high conductivity, capacitance and equivalent series resistance as compared to carbon-based electrode materials. In conducting polymers reduction-oxidation process stores and releases charge.^[67] So, graphene - metal oxide/graphene polymer composites are topic of interest for supercapacitor study.

Researchers have been working on a pathway to improve the performance of supercapacitors, and meet that demand for increased storage capacity. Recently, Mojtaba et al suggested a new path to develop further miniaturized on-chip energy storage systems, which are compatible with silicon electronics and can support the power demand to operate integrated smart systems.^[68]

9.2. Graphene-metal oxide/graphene-polymer composites for photovoltaic study

Inorganic semiconductor materials, such as amorphous silicon, gallium arsenide, and sulfide salts, have been widely used in conventional photovoltaic cells, where free electrons and holes are generated directly upon photon absorption. Although a power conversion efficiency (PCE) of more than 40% is achieved by using inorganic semiconductor materials in solar cells, the widespread use of inorganic solar cells is still limited due to difficulties in modifying the bandgap of inorganic semiconductors and high costs associated with the elaborate fabrication processes including elevated temperature and high vacuum. These inorganic solar cells are very much expensive than the conventional grid electricity. Alternative approaches with organic or polymer materials have gained considerable attention due to their low cost, light weight, flexibility, and solution processability.^[61, 69–74]

9.3. Dye-sensitized solar cells (DSSCs)

As compared to other types of solar cells, DSSCs are different. They consist of a semiconducting material (e.g. TiO_2) with a photosensitive dye as the anode which is coupled with an electrolyte solution and a pure metal cathode (e.g. Platinum). Graphene has a number of favorable properties so that the loading efficiency of the dye molecules can be increased by increasing the interfacial area and enhancing the conductivity of the electrons. The proper ratio of graphene and TiO_2 is necessary for achieving an efficient system. The valence electrons from graphene get excited to the TiO₂ conduction band through the Graphene-TiO₂ interface, so as to separate the holes and the electrons. So, about 1% graphene is needed for this separation and the introduction of higher graphene concentrations into the matrix reduces the transmittance. The use of graphene in DSSCs increases the light scattering phenomenon at the photoanode, provides an efficiency that is 39% greater than that of pure TiO₂ electrodes and efficiently disperses the dye molecules.^[74] In the photovoltaic study done by Morais et_al, the influence of different amounts of RGO in the TiO₂ film was investigated and it was compared to pristine TiO₂ films. The best solar cells made up of TiO₂/RGO films were obtained with 2.0 wt % RGO.^[75] At the national level, several national laboratories and universities have been working on PV cell based on graphene-metal oxide nanocomposites.^[76–86]

Thus, Dye-sensitized solar cells have gained attention in field of research because of their low production costs, ease of fabrication, lighter weight property, ecofriendliness and recyclable advantages, optical properties regardless of its low-efficiency output as compared to conventional silicon solar cell.^[87] Dye-sensitized solar cells containing TiO2 are found to be more efficient. It consists of a dye-sensitized nanocrystalline TiO₂ film, an electrolyte with an I-/I3-redox couple and a Pt counter-

electrode. In addition to practical applications as an alternative energy source, these devices are also useful from a scientific point of view, as it converts light in to electrical energy through complex energy and charge transfer processes. The overall energy conversion efficiency depends on the individual properties of the constituents of the cell. To enhance their performance requires better understanding of processes in energy conversion and controlling the properties of each component.^[88] ICPs are organic polymers which conduct electricity. It may have metallic conductivity or can be semiconductors. The advantage of ICPs is their pro-^{89–94]}So, dispersion.^{[53,} by cessability, mainly Graphene - metal oxide/Graphene - Polymer composites are topic of interest for Photovoltaic study.

Typical efficiency of Polycrystalline silicon solar cells is 13% to 16%. Thin-Film solar cells (TFSC), are made by depositing one or several thin layers of photovoltaic material onto a substrate. Different types of TFSCs are categorized by which photovoltaic material is deposited onto the substrate: Amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIS/ CIGS), polymer solar panels and organic photovoltaic cells (OPC). Thin-film modules have reached efficiencies of 7–13%. Recently, researchers have used graphene to develop a perovskite-silicon solar cell – a promising new solar technology – with an impressive conversion efficiency of 26.3%.^[95]

10. Conclusion

As discussed herein, the extensive study of graphenebased nanocomposite with unique structure and properties offer a great opportunity to deal with challenges of energy conversion and storage. Many of fundamental properties of graphene are discovered, but there are still much new discoveries to be made in properties of graphene-based materials and in their applications. Due to unique properties, ease of synthesis and functionalization, graphene-based nanocomposites show great potential in energy storage and conversion. These hybrid materials have excellent characteristics like excellent mechanical, electrical properties and large specific surface areas and long-time stability. So, it is interesting to study the graphene to open up new possibilities to produce graphenebased nanocomposites and to better understand their properties as well as related phenomenon.

Disclosure statement

No potential conflict of interest was reported by the authors.

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