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Exploring the Structural, Electronic, and Charge Transport Properties of Reduced Graphene Oxide (rGO) and Its Nanocomposites for Advanced Energy and Electronic Applications

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Abstract: *Reduced graphene oxide (rGO), a new member of the family, has been already reported to display wide range of tunable structural and electronic properties and therefore has been considered a promising material suitable for energy, sensors, catalysis and electronic applications. Unlike in case of pristine graphene in which the conduction is purely band-like, a wide variety of charge transport mechanisms are observed in rGO including band, hopping (nearest-neighbor and variable range), tunneling and percolation process [19]. Those effects are regulated by the synthetic protocols, reduction levels, residual oxygen groups, and defect concentration. Structural-transport correlations are discussed through experimental techniques like DC/AC conductivity, Hall effect, impedance spectroscopy, Raman, XPS and temperature-dependent I–V characterization. Furthermore, the "synergistic interfacial interaction" based on rGO with its nanocomposites has also been developed in combination with polymers, metals, semiconductors, and 2D/3D hybrid architectures to gain an improvement in the charge transfer efficiency. These composites have shown great promise in supercapacitors, lithium-ion batteries, fuel cells, solar cells, biosensors, flexible electronics and photocatalysis. Although some progresses have been made, challenges facing controlled reduction, morphological uniformity, reproducibility, and stability in practical applications are still open. Future work should emphasize controlled syntheses at the next level, interface engineering, in situ characterization of active devices and data-based modeling to reach common understanding for charge transport. This review summarizes the basic mechanisms, characterization methods, and applications of rGO and its nanocomposites, as well as introduces new possibilities for their incorporation into advanced energy (batteries or supercapacitors), electronic (FETs) and environment-related devices.*

Keywords*--Reduced graphene oxide (rGO); Charge transport; Nanocomposites; Hopping conduction; Tunneling; Percolation theory; Energy storage; Sensors; Flexible electronics; Photocatalysis*

1. Introduction

Two-dimensional (2D) monolayer graphene, composed of sp^2-hybridized carbon atoms in a honeycomb lattice, is one of the most studied materials during the past two decades, owing to its extraordinary properties such as electrical, thermal and mechanical properties (Novoselov et al., 2004; Geim & Novoselov, 2007). Among these, graphene oxide (GO) and reduced graphene oxide (rGO) have been intensively researched due to their easy processing, adjustable bandgap, and good compatibility with other functional materials (Stankovich et al., 2007; Dreyer et al., 2010). Reduced graphene oxide (rGO) suffers a partially restored conjugated structure and a controlled amount of defects as well as oxygen-containing functionalities (Pei & Cheng, 2012); it is fabricated through the C reduction of GO by means of chemical, thermal or electrochemical strategies. Such structural alterations have great implications on its electrical conduction, mobility of charge carriers and electronic density of states making rGO material a promising material for future electronic and optoelectronics (Eda & Chhowalla, 2010). While knowledge of the charge transport in rGO is critical, the charge transport is greatly impacted by the

competition of intrinsic defects, disorder and interfacial interactions with other materials (Bagri et al., 2010). Moreover, arena with compositing formation in hybrid structure of reduced graphene oxide (rGO) with polymers, metals, semiconductors or other nanostructures, their global charging transfer feature would be considerably changed as a result of synergistic effect where particular functionalities could be designed for various purposes (Wang et al., 2015; Liu et al., 2018). This review aims to provide a comprehensive discussion on various charge transport theories in rGO and its nanocomposites based on their structure–electronic correlations and device applicability. In particular, we focus on the effects of hopping conduction, tunneling and percolation in charge transport. New tools and theories employed in the fields of chemistry, biology and materials science to probe charge transport at the nanometer scale are also covered, including in the areas of energy storage, sensing, catalysis and electronic devices.

2. Structural and Electronic Properties of rGO

The structural and electronic properties of reduced graphene oxide (rGO) are strongly governed by its method of synthesis, degree of reduction, and the presence of residual oxygen functionalities. These factors directly influence the charge transport mechanism, making it crucial to understand the structural–electronic correlations in rGO.

2.1 Synthesis Methods of rGO

Several methods have been used to produce rGO from GO, which result in varying degree of reduction, defect density, and conductivity. It is known that chemical reduction method is commonly used which the reducing agent, e.g. hydrazine, sodium borohydride, ascorbic acid and hydroquinone was employed to eliminate oxygen-containing group of GO (Stankovich et al., 2007; Pei & Cheng, 2012). Thermal reduction by high temperature annealing (>500 °C) is another approach which reestablishes sp^2 carbon over layers, but can also create defects such as carbon atom rearrangement (Eda & Chhowalla, 2010). Electrochemical reduction is a more sustainable and adjustable approach, in which the reduction reaction occurs in an electrochemical cell upon applying potential bias to GO films (Zhou et al., 2014). Nowadays, some green reducing materials achieved many attentions, such as the plant extracts, amino acids and the microorganisms (Pham et al., 2015), they have been prepared in large quantities at low costs and lower toxicity.

2.2 Structural Defects, Oxygen Functionalities, and Their Influence on Charge Transport

Reduction of GO to rGO seldom brings the pristine graphene back perfectly. Residual species of oxygen belonging to hydroxyl and epoxide groups, as well as those forming carbonyl and carboxyl functionalities remain upon exfoliation and are responsible for the coexistence of sp^2 conductive carbon-based regions within an insulating sp^3-like environment (Bagri et al., 2010). Structural imperfections vacancies and grain boundaries; as well as, SW defects also affect the charge transport by serving as scattering sites. Reported in the literature is that, because of their structural defects, graphene-based conductors show percolative transport behavior where carrier hops or tunnels through an insulating medium consisting of random networks of closely space sp^2 domains with remote weak linkages between them (Liu et al. 2018).

2.3 Bandgap Modulation and Density of States in rGO

Graphene pristine graphene, white aero -4M has an Abs st zero bandgap semiconductor which have l inear DISPERSION relation etc. around the dirac point result higher c arrier mobility. Main advantage of Graphene: a. In contrast, rGO has the ability to alter its band gap which is attributed to the broken of π–π conjugation and presence of some oxygenated groups. Depending on reduction degree, the band-gap can vary from few hundreds of meV to ~2 eV (Eda & Chhowalla, 2010). The electronic DOS is strongly renormalized, presenting localized states close to the Fermi energy that participate in hopping conduction at low temperature and variable range hopping in disordered areas (Kim et al., 2010). Such tunability renders rGO a remarkably versatile candidate for electronic, sensing and energy devices.

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2.4 Comparison with Pristine Graphene and Graphene Oxide

In comparison with pure graphene, rGO has the reduced conductivity owning to the structural disorder as well as incomplete reduction. Mobilities of graphene exceed 10,000 $cm^2/V{\cdot}s$ (Bolotin et al., 2008) and are in the range of 1–100 $cm^2/V{\cdot}s$ for rGO, depending on the synthesis method used and amount of reduction applied. In contrast, rGO is much more conductive than graphene oxide because the latter becomes highly insulating as a result of disruption to sp^2 carbon networks (Dreyer et al., 2010). As a result, rGO acts as an in-between material with compromised processability and tunable properties but with decent conductivity for nanocomposites and device integration applications.

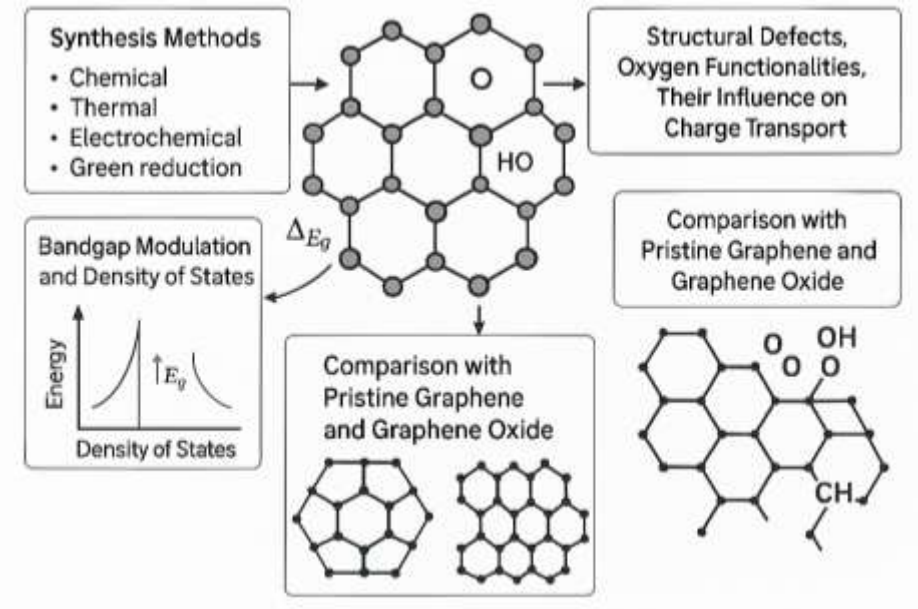

Fig. 1. Structural and Electronic Properties of rGO

Table 1: Summary of Key References on rGO Synthesis, Properties, and Charge Transport

Author(s), Year	Focus of Study	Method/Approach	Key Insights/Findings
Novoselov et al., 2004	Discovery of graphene	Mechanical exfoliation	Graphene exhibits extraordinary electronic properties with zero bandgap and high mobility.
Geim & Novoselov, 2007	Rise of graphene research	Review	Highlighted unique 2D properties and applications of graphene.
Stankovich et al., 2007	rGO synthesis	Chemical reduction using hydrazine	Demonstrated scalable synthesis of graphene nanosheets via reduction of GO.
Dreyer et al., 2010	Chemistry of GO	Review	Discussed GO functionalities and their role in structural/electronic properties.
Pei & Cheng, 2012	Reduction strategies	Chemical/thermal reduction methods	Classified various reduction techniques and their influence on conductivity.
Eda & Chhowalla, 2010	rGO thin films	Chemical/thermal reduction	Showed tunable bandgap and conductivity of rGO; highlighted disorder-induced transport.
Bagri et al., 2010	Electronic structure of rGO	Computational/theoretical study	Reported how structural defects and oxygen groups influence charge transport.
Zhou et al., 2014	Electrochemical reduction	Electrochemical GO reduction	Environmentally friendly reduction with controlled properties.
Pham et al., 2015	Green synthesis	Plant extract-based reduction	Proposed sustainable, eco-friendly route for rGO production.
Kim et al., 2010	Bandgap modulation	Large-scale graphene films	Demonstrated band structure engineering and electronic tunability.
Bolotin et al., 2008	Transport in graphene	Suspended graphene transport measurements	Reported ultrahigh electron mobility (>10,000 $cm^2/V \cdot s$) in pristine graphene.
Wang et al., 2012	Nitrogen-doped graphene	Doping & modification	Improved catalytic/electronic performance in composites.
Liu et al., 2018	rGO composites	Review	Comprehensive review on rGO–based composites for energy storage.

3. Charge Transport Mechanisms in rGO

The charge transport in reduced graphene oxide (rGO) is a highly challenging issue due to its heterogeneity, which is composed of the conducting sp^2 domains among the disordered and insulating sp^3 regions with oxygen functionalities, existing simultaneously [1]. Unlike highly mobile pristine graphene that conducts in a band-like manner, the transport in rGO exhibits a number of regimes that depends on the reduction level as well as the measurement temperature and frequency.

3.1 Theoretical Frameworks for Charge Transport

Band Conduction: In undoped graphene, carriers in the conduction band occupy a linear dispersion relation around the Dirac point and are known to yield remarkably high mobilities (ref. 36 Novoselov et al., 2004; ref.37 Bolotin et al, 2008). However, in the case of rGO band-like transport is still possible within large and connected enough sp^2-domains. Against this, structural disorder and scattering from the oxygen groups are dominant limitations to carrier delocalization (Bagri et al., 2010).

Hopping Conduction: In highly disordered rGO, charge transport is dominated by hopping between localized states. Two main hopping regimes are observed

- **Nearest-Neighbor Hopping (NNH):** Electrons hop between adjacent localized states, usually active at higher temperatures (Mott, 1969).
- **Variable Range Hopping (VRH):** At lower temperatures, carriers minimize hopping energy by choosing sites at varying distances, described by Mott's VRH model or Efros–Shklovskii VRH in systems with strong Coulomb interactions (Efros & Shklovskii, 1975; Joung et al., 2011).

Tunneling Conduction: Charge carriers may tunnel through potential barriers created by insulating oxygen-rich regions separating conductive sp^2 domains. Tunneling becomes prominent in partially reduced rGO films and nanocomposites, where the conductive pathways are interrupted by residual functional groups (Xu et al., 2010).

Percolation Theory in Disordered Systems: The conductivity of the rGO may also be explained as percolation theory where the transport of electrons is over a network of percolating sp^2 clusters distributed in an insulating matrix. When the ratio of conductive structures exceeds a certain critical percolation threshold, long-range conduction paths appear and result in the enhancement of conductivity (Stauffer & Aharony, 1994; Das et al., 2014).

3.2 Temperature and Frequency Dependence of Conductivity

The temperature-dependent conductivity of rGO yields the information regarding the controlling transport mechanism. At higher temperatures, band conduction or NNH prevails whereas at lower temperatures VRH becomes dominant (Joung et al., 2011). Frequency dependent transport behavior is found from AC conductivity measurements. Normally, the conductivity follows the universal dielectric response that results in a plateau at low frequency (DC transport) and power-law behaviour at high frequencies caused by hopping or tunnelling among localised states (Dyre & Schrøder, 2000).

3.3 Role of Defects, Disorder, and Functional Groups

Imperfections and disorder dominate charge transport in rGO. π-conjugation is disrupted by oxygen functionalities, and charge carriers are localized; and structural defects such as vacancies, grain boundaries, Stone–Wales defects operate as scattering centers (Bagri et al., 2010; Eda & Chhowalla, 2010). The density and distribution of these defects determine whether charge carriers follow extended bands or localized hopping/tunneling processes. Optimizing the electrical performance of rGO for desired applications is an endeavor that necessitates improving reduction methods tailored toward modulating defect density and removing oxygen.

Table 2: Comparative Overview of Charge Transport Mechanisms in rGO

Mechanism	Governing Equation / Model	Temperature Dependence	Frequency Dependence	Applicability to rGO	References
Band Conduction	$\sigma = ne\mu\ (where\ n = carrier\ density, e = charge, \mu = mobility)$	Conductivity decreases with increasing T due to phonon scattering	Weak frequency dependence	Dominant in relatively defect-free sp^2 domains; rare in disordered rGO	Novoselov et al., 2004; Bagri et al., 2010
Nearest-Neighbor Hopping (NNH)	$\sigma \propto exp(-Ea/kBT)\ (Arrhenius-type)$	Strongly thermally activated; dominant at high T	Weak frequency response	Occurs between adjacent localized states separated by oxygen/defect sites	Mott, 1969
Variable Range Hopping (VRH) (Mott)	$\sigma \propto exp[-(T0/T)\text{^}(1/(d+1))]\ (d = dimension)$	Weak T-dependence compared to NNH; dominant at low T	Stronger frequency response than NNH	Describes disordered rGO with localized states; common at low temperatures	Mott, 1969; Joung et al., 2011
Efros–Shklovskii VRH (ES-VRH)	$\sigma \propto exp[-(TES/T)\text{^}(1/2)]$	Follows T^−1/2 law due to Coulomb gap	Frequency-dependent hopping	Applies in systems with strong Coulomb interactions and defects	Efros & Shklovskii, 1975
Tunneling Conduction	$I \propto exp(-2\alpha d)\ (\alpha = decay\ constant, d = barrier\ width)$	Weak T-dependence; quantum tunneling possible	High-frequency assisted tunneling	Occurs across oxygen-rich insulating barriers separating sp^2 clusters	Xu et al., 2010
Percolation Conduction	$\sigma \propto (p - pc)\text{^}t\ (p = volume\ fraction\ of\ conduc = threshold, t = exponent)$	Weak T-dependence; percolation threshold governs	Frequency scaling depends on network connectivity	Explains transition from insulating to conductive state in partially reduced GO	Stauffer & Aharony, 1994; Das et al., 2014
Universal Dielectric Response (UDR)	$\sigma(\omega) = \sigma DC + A\omega\text{^}s\ (0 < s < 1)$	DC part follows VRH/NNH laws; AC part weakly T-dependent	Strong frequency dependence; σ increases with ω	Observed in disordered rGO films under AC conductivity studies	Dyre & Schrøder, 2000; Joung et al., 2011

4. rGO-Based Nanocomposites

As a result of the tunable conductivity, high surface area and easy functionalization of rGO, it has been widely used as part of various nanocomposites. When combined together with polymers, metals, semiconductors or other nanostructures, rGO can be used as an electron mediator and/or structural support to improve the charge transfer abilities. The transport of charges in such systems is predominantly controlled by interfacial effects, defect-driven engineering and percolation mechanisms.

4.1 Types of Nanocomposites

rGO–Polymer Composites: The inclusion of rGO in conductive and insulating polymers can improve charge conducting by establishing the network for conducting percolation. For example, in PANI/rGO composites, the π–π bonding between polymer chains and rGO will enhance the conductivity and charge storage capability (Xu et al., 2010). Another group of insulating polymers such as polyvinyl alcohol (PVA) also become electrically conductive upon blending them with rGO possessing a high level of electrical conductivity, which is useful for flexible electronics and dielectric devices (Kumar et al., 2014).

rGO–Metal/Metal Oxide Composites: Metal (Ag, Au, Pt) and metal oxide (TiO_2, ZnO, Fe_3O_4, MnO_2)-rGO composites have higher electron transfer and catalytic activities. rGO acts as a conductive matrix to promote electron tunneling and reduce recombination. For rGO composites, rGO–Ag composites have high electrical conductivity and plasmonic effects (Zhang et al., 2012), while the superior performance of supercapacitors is attributed to the improved ion diffusion pathways in rGO–MnO_2 composites (Liu et al., 2018).

rGO–Semiconductor Composites: Mixing rGO with semiconductors (such as TiO2, ZnO, MoS2 and CdS) greatly improves photocatalytic and optoelectric properties. The rGO phase works as an electron sink, which reduces the recombination losses and prolongs the carrier lifetimes. For example, rGO–TiO_2 materials show enhanced photocatalytic performance under visible light owing to effective interfacial electron transfer (Zhou et al., 2011).

rGO–2D/3D Hybrid Structures: The hybrid systems (built from other 2D materials, including MoS_2,WS_2, insulating h-BN, or three-dimensional (3D) scaffolds, including CNTsand porous carbon frames) rely on the synergistic effect. The sufficient surface contact area for charge transfer of 2D–2D composites, and the mechanical stability as well as ion/electron pathways of 3D hybrids, contribute to the applicability of these structured composites in energy storage and sensor devices (Wang et al., 2015).

4.2 Interfacial Interactions and Their Effect on Charge Transfer

The performance of rGO nanocomposites are driven by interfacial interactions [3]. Non-covalent interactions, including π–π stacking, van der Waals interactions, and hydrogen bonding, enhance miscibility and retain the conjugation paths. However, while covalent linkages are more toxic to π-conjugation, they may increase stability and modulate charge transport (Pei & Cheng, 2012). A well-matched interfacial charge transfer would be great for reducing recombination loss in photo catalysts, improving conductivity in polymer mixtures, and providing better electrochemical response in sensor elements (Xu et al., 2010; Liu et al., 2018).

4.3 Strategies to Tune Charge Transport in Nanocomposites

Several strategies are employed to optimize charge transport in rGO-based nanocomposites:

Controlled reduction: Tuning oxygen content and defect density to balance conductivity and functionalization.

Doping and functionalization: Introducing heteroatoms (N, B, S) to enhance carrier density and catalytic properties (Wang et al., 2012).

Optimizing filler content: Achieving percolation thresholds where conductive rGO pathways are maximized without agglomeration.

Hybrid structuring: Integrating rGO with nanostructured metals, semiconductors, or polymers to create synergistic effects.

Interface engineering: Using surface modifiers, coupling agents, or molecular linkers to promote efficient electron transfer across the rGO–matrix interface.

These approaches collectively enable the design of nanocomposites with tailored charge transport properties suited for applications in energy storage, catalysis, electronics, and sensing.

Table 3: Comparative Overview of rGO-Based Nanocomposites

Type of Nanocomposite	Representative Systems	Interfacial Interactions	Dominant Charge Transport Mechanism	Key Applications	References
rGO–Polymer Composites	$rGO-PANI, rGO-PVA, rGO-PEDOT:PSS$	π–π stacking, H-bonding, van der Waals	Percolation conduction, hopping transport	Flexible electronics, sensors, supercapacitors	Xu et al., 2010; Kumar et al., 2014
rGO–Metal/Metal Oxide Composites	$rGO-Ag, rGO-Au, rGO-MnO_2, rGO-Fe_3O_4, rGO-ZnO$	Electron tunneling, electrostatic interaction, surface anchoring	Tunneling + band conduction through metal/oxide–rGO interface	Catalysis, supercapacitors, fuel cells, antimicrobial coatings	Zhang et al., 2012; Liu et al., 2018
rGO–Semiconductor Composites	$rGO-TiO_2, rGO-ZnO, rGO-MoS_2, rGO-CdS$	Charge transfer at heterojunction, covalent functionalization	Band conduction + interfacial electron trapping, reduced recombination	Photocatalysis, solar cells, photodetectors	Zhou et al., 2011; Wang et al., 2015
rGO–2D/3D Hybrid Structures	$rGO-CNTs, rGO-MoS_2, rGO-porous\ carbon, rGO-WS_2$	2D–2D van der Waals stacking, 3D scaffold anchoring	Percolation + hybrid band/hopping conduction	Energy storage, high-performance sensors, flexible devices	Wang et al., 2015; Pei & Cheng, 2012
Doped/Functionalized rGO Composites	$N-doped\ rGO, S-rGO-metal\ oxides$	Covalent bonding, substitutional doping	Enhanced band conduction due to increased carrier density	Electrocatalysis, batteries, gas sensors	Wang et al., 2012; Liu et al., 2018

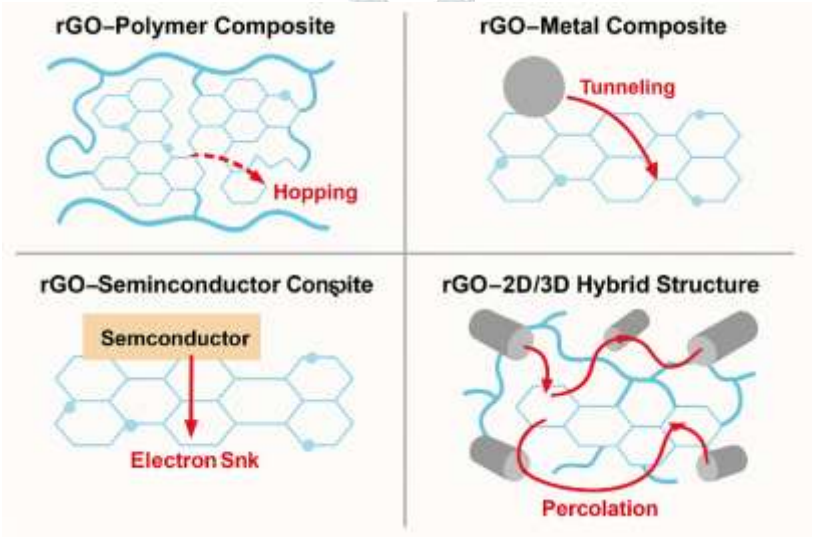

Fig. charge transfer in rGO nanocomposites:

This diagram gives a summary of the charge transfer in rGO nanocomposites: (a) rGO–polymer presents hopping conduction through localised states; (b) rGO–metal describes an electron tunneling across barriers; (c) rGO–

semiconductor, showing that rGO acts as an electron sink to impede recombination and finally to gain the photo-generated charges; d) Other hybrids show percolation pathways, leading to improved conductivity and efficient charge flow along interconnected networks.

5. Experimental Techniques for Studying Charge Transport

The combined roles of the band conduction, hopping, tunneling, and percolation mechanisms at and near the percolation threshold in reduced graphene oxide (rGO) complicate the situation in such a manner that multiple experimental techniques are necessary in order to disentangle charge transport in rGO. They produce mutually of information on conductivity, carrier dynamics, interface behaviour, and defects.

5.1 Electrical Conductivity Measurements (DC, AC, Four-Probe Method): DC conductivity measurements are simple techniques for studies of electrical properties of rGO films and nanocomposites Compared to 2-probe method detailed above, fourth point probe method is beneficial as the contact resistances between probe tip and surface are reduced, therefore providing authentic values of resistivity (Das et al., 2014). Likewise, (3) AC conductivity measurements yield a wealth of information regarding the hopping-and tunneling conduction at different frequency ranges typically fitted with the universal dielectric response model (Dyre & Schrøder, 2000; Koung et al., 2011).

5.2 Hall Effect Measurements: An important parameter, charge carrier density, is extracted 1) from Hall effect measurements with these other parameters like Charge carrier mobility (how fast an electron or hole can move) [e or h = electron or hole] also be determined from Hall effect measurements and Charge carrier nature is determine from Hall effect measurements. Mobility in rGO is limited by orders of magnitude as compared to pristine graphene due to scattering on defects and residual oxygen functionalities (Bolotin et al., 2008). The Hall data therefore give direct information on the disorder and the relevance of the branches of the carrier transport (Kim et al., 2010).

5.3 Spectroscopic Methods (Raman, XPS, UPS): Although indirect, spectroscopies give some of the most informative type of information associated when it comes to electronic and structural properties. Disorder and defect density are measured from the intensity ratios of D-marked bands to G-band with reduction efficiency, using differential Raman spectroscopy method. X-ray photoelectron spectroscopy (XPS) is used to reveal the different oxygen functionalities and bonding environment that can be correlated to the conductivity chemical states (Dreyer et al., 2010) on the one hand, whereas ultraviolet photoelectron spectroscopy (UPS) explores work function and density of states that can give information about the band alignment in rGO and its derivatives (Pei & Cheng, 2012).

5.4 Impedance Spectroscopy: Electrochemical impedance spectroscopy (EIS) is applied to obtain parameters such as charge transfer resistance (Rct), capacitance (C), and ion diffusion in rGO-based composites. Nyquist plots effectively separate bulk resistance from interfacial resistance in rGO electrodes for supercapacitors, batteries, and sensors (Liu et al., 2018) and thus, are particularly suited for EIS.

5.5 Temperature-Dependent I–V Characterization: The dominant transport mechanism can be extracted from comparing I–V metrics measured at different temperatures (e.g. [35]). The Arrhenius plots show different behaviours at low and high temperatures: at high temperatures the curves indicate thermally activated nearest-neighbour hopping and at low temperature range variable range hopping (VRH) are seen (Mott, 1969; Efros & Shklovskii, 1975). The T-affine random-in-the-box model can also be used to distinguish tunnelling conduction versus percolation in disordered networks which will help as a based temperature dependent I – V analysis(Das et al.,2014).

Table 4: Comparative Overview of Experimental Techniques for Charge Transport in rGO

Technique	Measured Parameter(s)	Information Gained	Relevance to rGO Charge Transport	Key References
DC Conductivity (Four-Probe Method)	Electrical resistivity, sheet resistance	Eliminates contact resistance; provides intrinsic conductivity	Determines baseline conductivity of rGO and	Das et al., 2014

			composites; useful for percolation studies	
AC Conductivity	Frequency-dependent conductivity	Identifies hopping, tunneling, universal dielectric response	Reveals conduction mechanism at different frequency regimes	Dyre & Schrøder, 2000; Joung et al., 2011
Hall Effect Measurement	Carrier type, density, and mobility	Distinguishes between electron/hole transport; quantifies mobility	Shows effect of defects/functional groups on carrier dynamics	Bolotin et al., 2008; Kim et al., 2010
Raman Spectroscopy	D/G band ratio, 2D band	Measures defect density, crystallinity, and disorder	Links structural defects to charge transport pathways	Dreyer et al., 2010
XPS (X-ray Photoelectron Spectroscopy)	Chemical bonding states, oxygen functional groups	Tracks degree of reduction and functionalization	Correlates chemical composition with conductivity changes	Pei & Cheng, 2012
UPS (Ultraviolet Photoelectron Spectroscopy)	Work function, density of states near Fermi level	Determines electronic band alignment	Explains electron injection/transfer efficiency in composites	Pei & Cheng, 2012
Impedance Spectroscopy (EIS)	Nyquist plot: charge transfer resistance, capacitance	Separates bulk vs. interfacial transport	Important for energy devices (batteries, supercapacitors, sensors)	Liu et al., 2018
Temperature-Dependent I–V	Current vs. temperature and voltage	Distinguishes conduction regime: NNH, VRH, tunneling, percolation	Identifies dominant charge transport mechanism in rGO	Mott, 1969; Efros & Shklovskii, 1975

6. Applications of rGO and its Nanocomposites

The inherent properties of reduced graphene oxide (rGO) and its nanocomposites such as high surface area, tunable conductivity, mechanical flexibility, and versatility of functional groups make them suitable for various applications. However, the performance of these systems is ultimately limited by the efficiency of charge transport, amenable to optimization by rational composite design.

6.1 Energy Storage and Conversion

Supercapacitors: rGO-based supercapacitors leverage high surface area and conductivity to enable rapid charge/discharge cycles. Incorporation with metal oxides (MnO_2, RuO_2) or conducting polymers (PANI, PEDOT: PSS) further enhances pseudocapacitance and cycling stability (Liu et al., 2018).

Lithium-Ion Batteries (LIBs): In LIBs, rGO acts as a conductive additive and flexible matrix, improving electron/ion transport and buffering volume changes in electrodes. rGO–metal oxide (e.g., Fe_3O_4, TiO_2) composites have demonstrated high specific capacity and improved cycle life (Wang et al., 2015).

Fuel Cells: Nitrogen-doped rGO serves as an efficient, low-cost catalyst support, replacing expensive platinum electrodes. Its enhanced conductivity and active sites promote oxygen reduction reactions (Wang et al., 2012).

Solar Cells: rGO improves charge transport and reduces recombination in dye-sensitized and perovskite solar cells. As a transparent conductive layer, rGO provides flexibility and scalability compared to traditional ITO electrodes (Roy-Mayhew & Aksay, 2014).

6.2 Sensors and Biosensors

Electrochemical Sensors: rGO's large surface area and functional groups enable immobilization of biomolecules and catalytic nanostructures, improving sensitivity. Practical uses are for glucose sensing and detection of heavy-metal ions (Huang et al., 2011).

Gas and Humidity Sensors: The key to the strong adsorption of gases such as NO2, NH3 and relative humidity in rGO is that oxygen functionalities play an important role in rGO to provide adsorption sites, while its tunable conductivity gives rGO a real-time response (Zhu et al., 2012).

Biomedical Sensing Applications: In particular, the biocompatibility and fast electron transfer (Geim & Novoselov, 2007; Xu et al., 2010) of rGO composites with enzymes, antibodies or DNA probes have been used for biomarker detection, point-of-care diagnostics and wearable biosensor.

6.3 Electronics and Optoelectronics

Thin-Film Transistors (TFTs): Graphene oxide (GO) reduction (rGO) films represent scalable, flexible, but less conductive alternatives as TFT channels compared with the pristine graphene. They also provide tunable bandgap, allowing switching control (Eda & Chhowalla, 2010).

Flexible Electronics: Due to their bending flexibility, stable conductivity under bending, rGO–polymer nanocomposites show up to be suitable for wearable electronics, smart textiles, and roll-to-roll devices (Kim et al., 2010).
Photodetectors: In rGO–semiconductor hybrids (ZnO, MoS_2), rGO acts as an electron sink, enhancing responsivity and response speed in UV-visible photodetectors (Wang et al., 2015).

6.4 Catalysis and Environmental Applications

rGO–metal and rGO–semiconductor composites have been explored for photocatalysis, water splitting, and pollutant degradation. In wastewater treatment, rGO enhances adsorption of dyes and heavy metals due to its oxygen functional groups and large surface area (Zhou et al., 2011). As a catalytic support, rGO stabilizes nanoparticles, facilitating reactions such as hydrogen evolution and CO_2 reduction (Liu et al., 2018).

7. Conclusion and Future Work

Reduced graphene oxide (rGO) and rGO-based nanocomposites are grouped under a tailorable class of materials characterized by distinct structural, electronic, and surface properties which can be exploited through synthesis and interface design. The charge conduction mechanism is critical to their functioning in applications ranging from energy storage and conversion, sensors, electronics to catalysis. In stark contrast to pristine graphene, where conduction is band-only, rGO exhibits the coexistence of conduction mechanisms: band conduction in its 3(sp^2 domains)+hopping through localized states tunnelling through oxygen-rich barriers and percolation in disordered systems. These transport mechanisms are highly sensitive to the fabrication technique, reduction level, defect density, and type of interfacial interactions present in the materials.
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From experimental DC/AC conductivity, Hall effect as well as spectroscopic studies and impedance spectroscopy, correlations between structure, electronic states and transport pathways have been gained. Comprising rGO with polymers, metals, semiconductors and 2D/3D hybrids, interest in nanocomposites is largely based on the idea of benefiting from synergy to maximize the interfacial charge transfer or recombination inhibition as well as facilitate effective percolation pathways. Thus, rGO based systems have been widely used in supercapacitors, lithium ion batteries, fuel cells, solar cells, flexible electronics, biosensors and catalytic reactors. Despite the remarkable advancement, there are still several challenges. The control over reduction degrees, defect sites and oxygen functionalities is not enough for producing an expectedly uniform transport property. Furthermore, scalability, reproducibility and long-term stability under the operating environment still limit its practical application on a large scale. A unified theoretical basis that includes conduction by band, hopping, and tunneling models as well as percolation have not been extrapolated to experimental measurements.

Future research directions may include:
• **Advanced synthesis control:** Developing greener, scalable reduction methods with precise control of defect density and oxygen functional groups.
• **Interface engineering:** Customised heterostructures and nanocomposites; tuning charge transfer routes via chemical doping, functionalization, and surface modification.
• **Field spectro-microscopy:** using operando spectroscopy and microscopy to directly measure charge transport dynamics at relevant electrochemical conditions.
• **AMMML:** Combining multiscale simulations with data-driven techniques to predict transport behavior and aid material design.

•**New applications:** Growing rGO-quantum transport, neuromorphic devices, next-generation optoelectronic and environmental remediation.

Due to their tunable properties, rGO and its nanocomposites fill the gap between high conductivity pristine graphene and high functionality graphene oxide, making them indispensable in many technologies. Essential for unlocking the full potential of these materials and the last ray of hope of competing these materials for next-generation energy, electronic, and environmental applications is a deeper understanding of their charge transport mechanisms, as well as advancements in synthesis and interface engineering.

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