Nano Energy (2015) **16**, 488–515

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/nanoenergy

REVIEW

Graphene oxide: A promising nanomaterial for energy and environmental applications

Fen Li[a], Xue Jiang[a], Jijun Zhao[a,b,*], Shengbai Zhang[c,]**

[a]*Key Laboratory of Materials Modification by Laser, Ion and Electron Beams (Dalian University of Technology), Ministry of Education, Dalian 116024, China*
[b]*Beijing Computational Science Research Center, Beijing 100089, China*
[c]*Department of Physics, Applied Physics, and Astronomy, Rensselaer Polytechnic Institute, Troy, NY 12180, USA*

Received 25 May 2015; received in revised form 17 July 2015; accepted 17 July 2015
Available online 26 July 2015

KEYWORDS
Graphene oxide;
Hydrogen energy;
Lithium battery;
Supercapacitor;
Gas capture;
Water purification

Abstract
Graphene oxide (GO), the functionalized graphene with oxygen-containing chemical groups, has recently attracted resurgent interests because of its superior properties such as large surface area, mechanical stability, tunable electrical and optical properties. Moreover, the surface functional groups of hydroxyl, epoxy and carboxyl make GO an excellent candidate in coordinating with other materials or molecules. Owing to the expanded structural diversity and improved overall properties, GO and its composites hold great promise for versatile applications of energy storage/conversion and environment protection, including hydrogen storage materials, photocatalyst for water splitting, removal of air pollutants and water purification, as well as electrode materials for various lithium batteries and supercapacitors. In this review, we present an overview on the current successes, as well as the challenges, of the GO-based materials for energy and environmental applications.

Contents

*Corresponding author at: Key Laboratory of Materials Modification by Laser, Ion and Electron Beams (Dalian University of Technology), Ministry of Education, Dalian 116024, China.
**Corresponding author.
E-mail addresses: zhaojj@dlut.edu.cn (J. Zhao), zhangs9@rpi.edu (S. Zhang).

http://dx.doi.org/10.1016/j.nanoen.2015.07.014

Introduction

As the global concerns in the development of human civilization, the scientific and technological issues of energy utilization and environment protection are currently facing challenges. Nowadays, enormous energy demands of the world are mainly met by the nonrenewable and environmental unfriendly fossil fuels. To replace the conventional energy platform, pursuit of the renewable and clean energy sources and carriers, including hydrogen storage, lithium batteries, and supercapacitors, has become extremely urgent. Additionally, long-term industrial and agricultural activities induce serious environmental pollution (such as greenhouse and toxic gases, heavy metal ions and organic species) in air and water to deteriorate the ecological balance and the daily human health.

GO is a monolayer of graphite oxide, which can be obtained by exfoliating graphite oxide into layered sheets through sonicating or mechanical stirring [1]. The graphene-based lattice and existence of various oxygen-containing groups (mainly epoxy and hydroxyl groups) enable GO abundant fascinating properties. First, the functional groups on GO surface act as effective anchoring sites to immobilize various active species. Furthermore, GO possesses tunable electronic properties. Typically, GO is insulating due to the large portion of sp^3 hybridized carbon atoms bonded with the oxygen-containing groups, which results in a sheet resistance of $\sim 10^{12}\ \Omega\ sq^{-1}$ or higher [2]. However, after reduction, the sheet resistance of reduced GO (namely, RGO) can be degraded by several orders of magnitude, hence transforming the material into a semiconductor or even into a graphene-like semimetal [3]. It has been demonstrated that band gap of GO can be tailored by controlling coverage, arrangement, and relative ratio of the epoxy and hydroxyl groups [4-8].

Besides, GO also displays excellent optical and mechanical properties for a wide landscape of applications. The optical transmittance of GO films can be continuously tuned by varying the film thickness or the extent of reduction [9]. Generally, a suspension of GO films in water is dark brown to light yellow, depending on the concentration, whereas that of reduced graphene oxide (RGO) thin films (with a thickness less than 30 nm) is semitransparent [10]. The optical absorption of GO is dominated by the π-π^* transitions, which typically give rise to an absorption peak between 225 and 275 nm (4.5-5.5 eV). During reduction, the strength of optical absorption increases while the plasmon peak shifts to $\sim$270 nm, reflecting an increased π-electron concentration and structural ordering [11]. Usually, the mechanical properties of GO rely on the details of sample, such as the oxidation degree (especially coverage of the epoxy and hydroxyl groups) and thickness [12-15]. The reported Young's modulus and intrinsic strength of GO sheets show a wide range of distributions of 6-42 GPa and 76-293 MPa, respectively [16]. More details about the fundamental physical properties of GO can be found in a recent book and a review article [1,17].

Despite the aforementioned fascinating properties, there are still some drawbacks of GO for practical applications. The combination of structural defects, poor dispersion, restacking and multilayer thickness can affect the electrical properties and high surface area of GO materials [18]. The insulating nature of regular GO also limits its applications in electronic devices and energy storage. Furthermore, the residual defects and holes degrade the electronic quality of RGO [19,20]. Fortunately, the oxygenated groups can largely expand the structural/chemical diversity of GO by further chemical modification or functionalization, which offer an effective way to tailor the physical and chemical properties of GO to expected extents. As a consequence, GO and GO-based composites have shown great potentials in the applications of energy storage/conversion and environment protection. Figure 1 shows the numbers of journal publications searched by ISI with some relevant keywords. One can see that there have been tremendous efforts in developing GO-based materials for various kinds of Li batteries and supercapacitors, whereas there are also certain activities on hydrogen generation/storage as well as purification of water and air by using GO-based materials. This review aims to highlight the recent progresses on the energy and environmental applications of GO/RGO-based materials and their composites.