I4BAGs Public Workshop, 16.05.2024:

Development of innovative processing and characterisation solutions for microelectronics and battery applications

Reduced graphene oxide-based electrodes: application perspectives in energy storage systems

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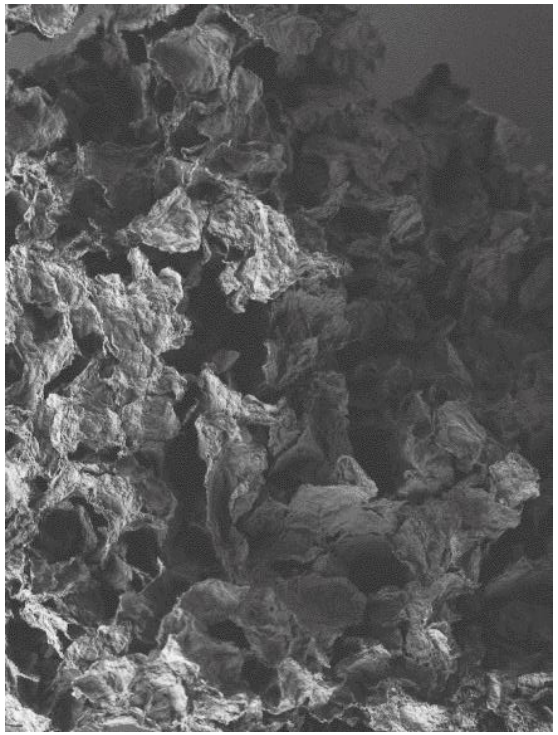
Instytut Mikroelektroniki
i Fotoniki

Introduction



G-Flake

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- **2024–2030** forecast for global graphene market: **35.1% CAGR** [1]
- Graphene oxide market: **30% CAGR (2023–2030)** [2]

- **47% revenue share for graphene oxide in 2023** [1]

- **Application perspective:** composites, energy storage materials, sensors, photovoltaics

Source:
1. https://www.grandviewresearch.com/industry-analysis/graphene-industry
2. https://univdatos.com/report/graphene-oxide-market/
Illustrations: undraw.co
Image: G-Flake marketing materials

Definitions & Standards

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Comment | Published: 15 March 2021

The importance of international standards for the graphene community

Charles A. Clifford, Erlon H. Martins Ferreira, Toshiyuki Fujimoto, Jan Herrmann, Angela R. Hight Walker, Denis Koltsov, Christian Punckt, Lingling Ren, Gregory J. Smallwood & Andrew J. Pollard

Nature Reviews Physics **3**, 233–235 (2021) | Cite this article

825 Accesses | **19** Citations | **58** Altmetric | Metrics

If graphene and related 2D materials are to be used commercially, buyers need to have confidence in the measured properties of the material they obtain from suppliers. Scientists from international standards committees describe how the first joint ISO/IEC measurement standard, published this month, will help.

ISO/TS 21356-1:2021

Nanotechnologies

Structural characterization of graphene

Part 1: Graphene from powders and dispersions

Status : **Published**

→ This standard will be replaced by ISO/AWI 21356-1

ISO/AWI 21356-1

Nanotechnologies

Structural characterization of graphene

Part 1: Graphene from powders and dispersions

Status : **Under development**

ISO/AWI TS 23879

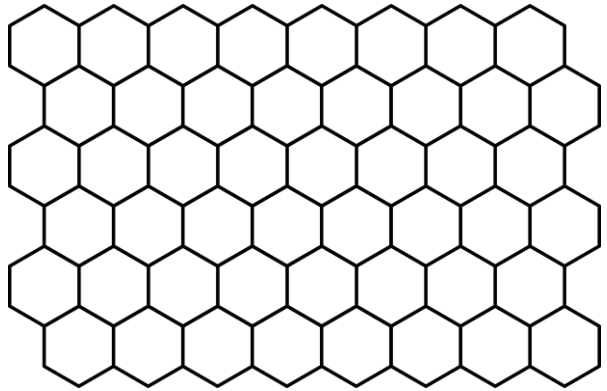
Nanotechnologies

Structural characterization of graphene oxide flakes: thickness and lateral size measurement using AFM and SEM

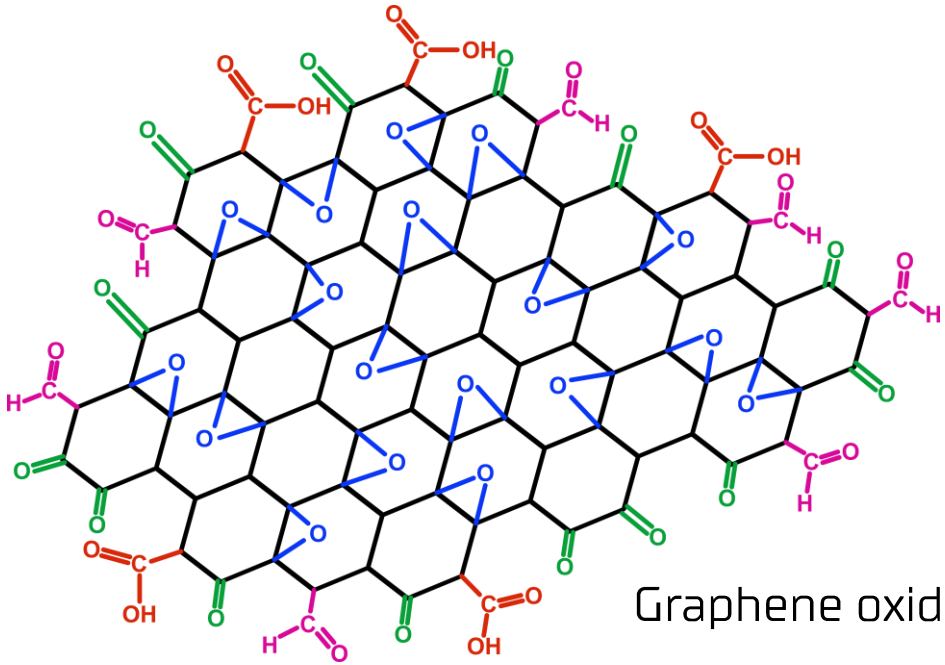
Status : **Under development**

Sources:
1. DOI: 10.1038/s42254-021-00278-6
2. https://www.iso.org/standard/70757.html
3. https://www.iso.org/standard/87572.html
4. https://www.iso.org/standard/84861.html

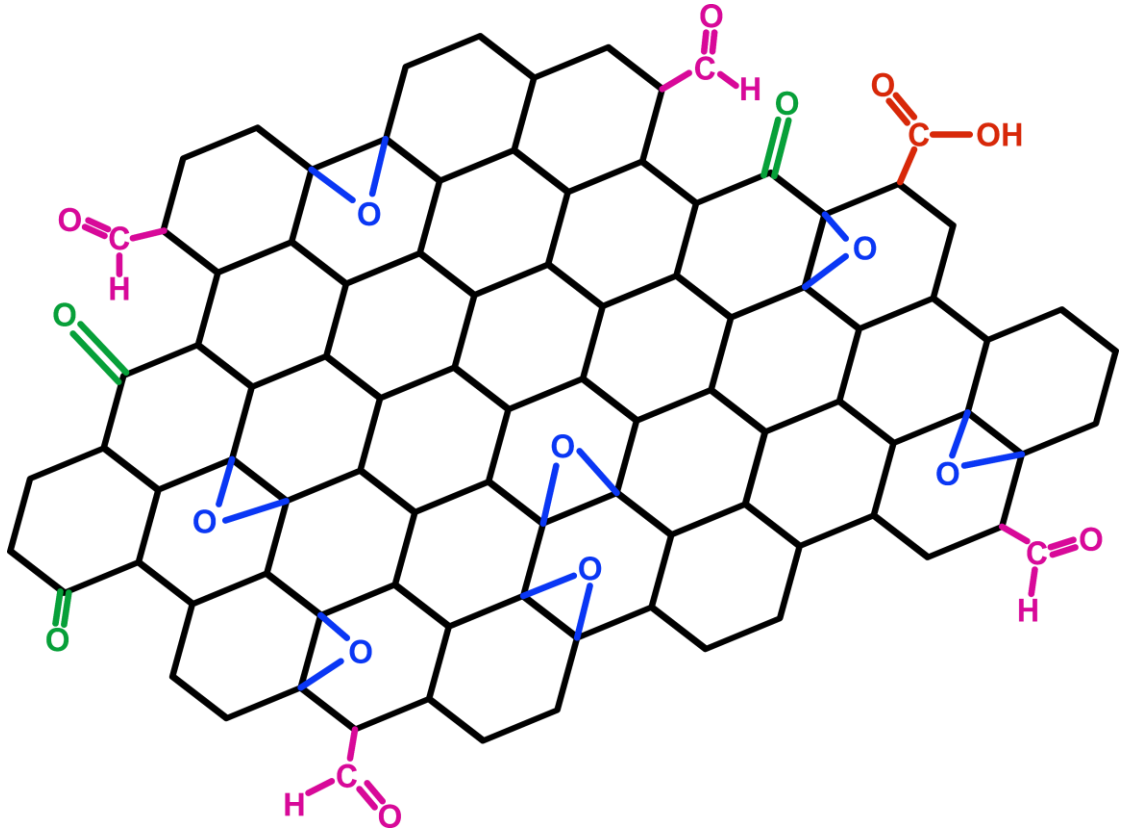
Definitions & Standards



Graphene



Graphene oxide



Reduced graphene oxide

Graphene materials

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General properties

GO – graphene oxide

- Hydrophilicity
- Specific surface area: 5–12 m^2/g
- Elemental composition:
  - C (40–42 %),
  - O (45–52 %),
  - others

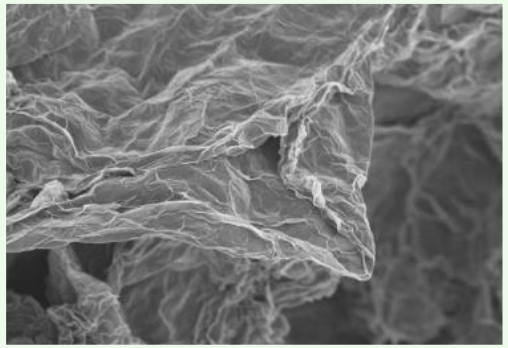
rGO – reduced graphene oxide:

- hydrophobicity
- **Electric (92 S/cm)** and thermal **conductivity**
- **Specific surface area: 264–266 m^2/g**
- **Elemental composition:**
  - **C (70–80 %),**
  - **O (15–20 %),**
  - others

Reduced graphene oxide: general properties

rGO – reduced graphene oxide:

- hydrophobicity
- **Electric (92 S/cm)** and thermal **conductivity**
- **Specific surface area: 264–266 m^2/g**
- **Elemental composition:**
  - **C (70–80 %),**
  - **O (15–20 %),**
  - S (<1 %)
  - N (<0.3 %)
  - H (<2 5)



- **Bulk density: 0.019 g/cm^3**
- Flake size (lateral): 10.3 ± 3.8 µm

ADVANCED ENGINEERING MATERIALS

Research Article

Hybrid Epoxy Composites Based on Basalt Fabric: A Case Study of Low-Temperature Plasma Treatment and Reduced Graphene Oxide Flakes Addition

Stefan Marynowicz, Agata Romanowska, Magdalena Baran, Tomasz Strachowski, Ewelina B. Możdżyńska, Adrian Chlanda

First published: 08 March 2024 | https://doi.org/10.1002/adem.202301920

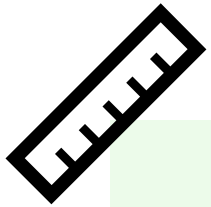
Graphene Oxide Paper as a Lightweight, Thin, and Controllable Microwave Absorber for Millimeter-Wave Applications

Publisher: IEEE | Cite This | PDF

Agata Romanowska ; Stefan Marynowicz ; Tomasz Strachowski ; Konrad Godziszewski ; Yevhen Yashchyshyn ; Adrian Racki ; ... All Authors

58 Full Text Views

Controllable material – tailoring rGO properties



Flake size

- Various diameter ranges available
- Capacity, specific surface area and electrical properties improvement due to optimized flake size [1]

Reduction

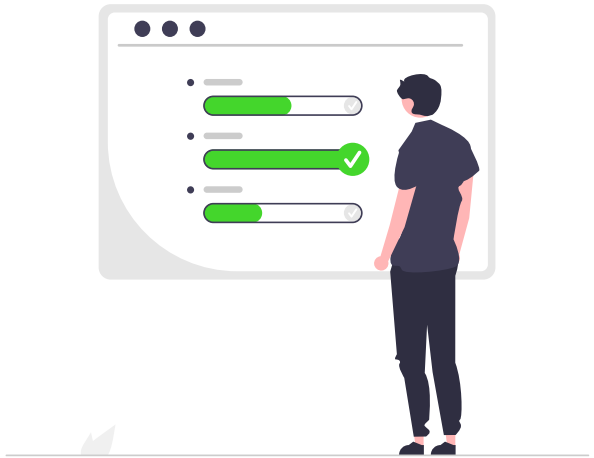
- Various methods
- Oxygen percentage control: capacity improvement [1–3]
- Specific surface area improvement
- Structural properties: defects formation

Functionalization

- Further properties improvement: active sites accessibility improvement, limitation of agglomerates formation, cyclability improvement, solubility, film forming capability [4–6]

Sources:
1. DOI: 10.1021/acs.energyfuels.0c04126
2. DOI: 10.1007/s10008-018-4021-0
3. DOI: 10.1039/c2nr32703a
4. DOI: 10.1016/j.jpowsour.2018.03.055
5. DOI: 10.1016/j.jpowsour.2021.230712
6. DOI: 10.1016/j.pnsc.2018.02.001

Controllable material: reduction process



Methods:

- Chemical
- Thermal
- Combined

Oxygen percentage control

Conductivity/sheet resistance

Specific surface area

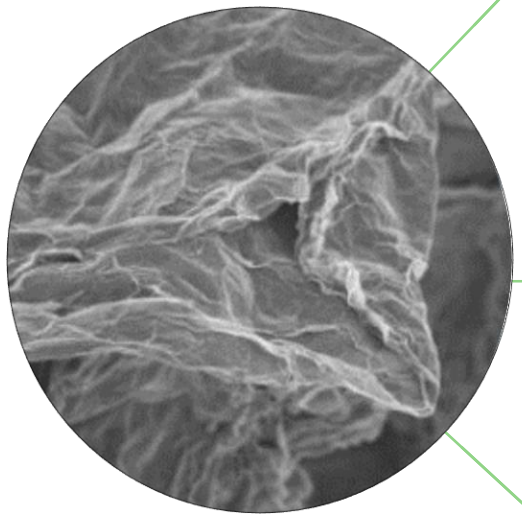
Controllable material: functionalization

Terminology: **doping** or **functionalization?**

Element/compound	Effect	Source
Fe_3O_4	High cycling stability and rate performance	[1]
MoS_2/SnS_2	Offsetting the impact of volume change during charge/discharge cycling	[2]
Thiophene-sulfur	Conductivity enhancement (20.2 S/cm vs 4.8 S/cm)	[3]
Boron/phosphorous	Thermal stability improvement	[4]
Nitrogen/amine	Limitation of agglomerates formation, improved capacity	[5]
Tin oxide	High and stable capacity	[6]
V_2O_5 film	Cathode material incorporation	[7]

Sources:
1. DOI: 10.1002/celc.202000134
2. DOI: 10.1021/acsami.7b06572
3. DOI: 10.1039/c3nr05061k
4. DOI: 10.1016/j.carbon.2016.01.080
5. DOI: 10.1016/j.electacta.2021.139241
6. DOI: 10.1016/j.electacta.2018.09.059
7. DOI: 10.1039/c0ee00640h

Application perspectives: role of rGO materials



Current collectors

- Replacement of Al/ Cu foils [1]

Active material

- Capacity provided due to oxygen containing groups taking part in redox reactions [1, 2]

Composite filler

- Conductive filler [3]

Sources:
1. DOI: 10.1016/j.carbon.2019.05.017
2. DOI: 10.1021/am40444147
3. DOI: 10.3390/nano11102771

RGO-based electrode materials: literature data

Material design	Description	Source
rGO-S composite film	Cathode material with 1208 mAh/g (after 50 cycles with 0.1 C)	[1]
Graphene aerogel	Anode material: capacity of 568 mAh/g at 100 mA/g after 100 cycles	[2]
Graphene paper	Anode material: 180 mAh/g capacity after 100 cycles	[3]
rGO/PANI composite films	Supercapacitor electrode: 1182 F/g	[4]
rGO/CB film	Supercapacitor current collector: rGO film	[5]

Sources:
1. DOI: 10.1002/adma.201602262
2. DOI: 10.1002/adma.201104691
3. DOI: 10.1016/j.electacta.2012.12.106
4. DOI: 10.1016/j.jpowsour.2016.11.068
5. DOI: 10.1021/acsomega.0c04530

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