University of Groningen

Design and Study of Pillared Graphenes and Nanoporous Carbon Materials for Energy, Environmental and Catalytic Applications

Thomou, Eleni

DOI:

[10.33612/diss.192214050](https://doi.org/10.33612/diss.192214050)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version

Publisher's PDF, also known as Version of record

Publication date:

2021

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Thomou, E. (2021). *Design and Study of Pillared Graphenes and Nanoporous Carbon Materials for Energy, Environmental and Catalytic Applications*. [Thesis fully internal (DIV), University of Groningen]. University of Groningen. <https://doi.org/10.33612/diss.192214050>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Design and Study of Pillared Graphenes
and Nanoporous Carbon Materials for
Energy, Environmental and Catalytic
Applications

university of
 groningen

faculty of science
 and engineering

zernike institute for
 advanced materials

Design and Study of Pillared Graphenes and Nanoporous Carbon Materials for Energy, Environmental and Catalytic Applications

Eleni Thomou

The work presented in this thesis was performed in the Ceramics and Composites Laboratory of the University of Ioannina (Greece) and the Surfaces and Thin Films Group (Zernike Institute for Advanced Materials) of the University of Groningen (the Netherlands).

The research work was supported by the Hellenic Foundation for Research and Innovation (HFRI) and the General Secretariat for Research and Technology (GSRT), under the HFRI PhD Fellowship grant (GA. no. 1829).

H.F.R.I.
Hellenic Foundation for
Research & Innovation

GSRT
GENERAL SECRETARIAT FOR
RESEARCH AND TECHNOLOGY

The author was also financially supported by a PhD scholarship grant from the Ubbo Emmius programme at the University of Groningen during PhD studies at the Zernike Institute for Advanced Materials.

Cover: SEM image of pillared graphene oxide

Printed by ProefschriftMaken

Zernike Institute PhD thesis number: 2021-25

ISSN: 1570-1530

university of
 groningen

UNIVERSITY
OF IOANNINA

Design and Study of Pillared Graphenes and Nanoporous Carbon Materials for Energy, Environmental and Catalytic Applications

PhD Thesis

to obtain the degree of PhD of the University of Groningen
on the authority of the Rector Magnificus Prof. C. Wijmenga
and in accordance with the decision by the College of Deans

and

to obtain the degree of PhD of the University of Ioannina
on the authority of the Rector Prof. T. A. Albanis
and in accordance with the decision of the General Meeting of
the Department of Materials Science and Engineering

Double PhD degree

This thesis will be defended in public on

Friday 26 November 2021 at 11:00 hours

by

Eleni Thomou

born on 27 May 1988
in Ioannina, Greece

Supervisors

Prof. P. Rudolf
Prof. D. Gournis

Assessment committee

Prof. P. Pescarmona
Prof. A. Paipetis
Prof. G. Froudakis
Prof. C. Casiraghi

«The acceptance of Doctoral Dissertation by the Department of Materials Science and Engineering of University of Ioannina does not imply the acceptance of the author's opinion» (Law 5343/1932, article 202).

Table of Contents

Chapter 1: Introduction	1
1.1. Porous materials	1
1.2. Carbon	2
1.2.1. Graphene	2
1.2.2. Graphene oxide	3
1.2.2.1. Graphene Pillaring.....	3
1.2.2.2. Silsesquioxanes as pillaring agents	4
1.2.3. Porous Carbons	4
1.2.3.1. Hierarchical Porous Carbons.....	5
1.2.3.2. Porous Carbon Cuboids.....	5
1.3. Applications	6
1.3.1. Energy	6
1.3.2. Environmental remediation	6
1.3.3. Catalytic Applications	6
1.4. Thesis Outline	6
References	8
Chapter 2: Characterization techniques.....	11
2.1. X-Ray Diffraction	12
2.2. Fourier Transform Infrared Spectroscopy	12
2.3. Surface Area and Porosity Measurements	13
2.4. X-Ray Photoelectron Spectroscopy	17
2.5. Thermal Analysis	18
2.6. Scanning Electron Microscopy	19
2.7. CO ₂ adsorption measurements.....	20
2.8. Anion exchange chromatography.....	21
References	22
Chapter 3: New Porous Heterostructures Based on Organo-Modified Graphene Oxide for CO ₂ capture	23

3.1. Introduction	24
3.2. Experimental Section	26
3.2.1. Materials.....	26
3.2.2. Graphene Oxide Synthesis	26
3.2.3. Organo-Modified Graphene Oxide	27
3.2.4. Silica-GO Heterostructures	27
3.3. Results and Discussion.....	28
3.4. Conclusions.....	41
References	43
Chapter 4: A diamino-functionalized silsesquioxane pillared graphene oxide for CO ₂ capture	47
4.1. Introduction	48
4.2. Experimental Section	50
4.2.1. Materials.....	50
4.2.2. Graphene Oxide Synthesis	50
4.2.3. Formation of the pillaring agent.....	51
4.2.4. Preparation of silsesquioxane pillared graphene oxide	51
4.3. Results and Discussion.....	52
4.4. Conclusions.....	66
References	67
Chapter 5: H ₂ S removal by copper enriched and porous carbon cuboids	71
5.1. Introduction	72
5.2. Materials and methods	73
5.2.1. Materials.....	73
5.2.2. Materials synthesis	74
5.2.2.1. PCC synthesis	74
5.2.2.2. PCC-Cu synthesis	74
5.2.3. H ₂ S adsorption experiments.....	74
5.3. Results and discussion	76

5.3.1. Structural and morphological characterization of the sorbents .	76
5.3.2. H ₂ S removal study	85
5.3.3. Possible reactions – proposed mechanism	91
5.4. Conclusions	93
References	94
Chapter 6: Hierarchical porous carbon structures derived from sugar and coffee waste	97
6.1. Introduction	98
6.2. Materials and methods	100
6.2.1. Materials	100
6.2.2. Materials synthesis	100
6.2.3. CO ₂ activation	102
6.3. Results and Discussion	103
6.4. Conclusions	116
References	117
Summary	121
Samenvatting	125
Περίληψη	129
Acknowledgements	133
List of publications	141
The author	143