

University of Groningen

Electron spin transport in graphene and carbon nanotubes

Tombros, Nikolaos

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:

2008

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

Citation for published version (APA):

Tombros, N. (2008). *Electron spin transport in graphene and carbon nanotubes*. s.n.

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).

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.

Electron spin transport
in graphene and carbon nanotubes

Nikolaos Tombros



University of Groningen
**Zernike Institute
for Advanced Materials**

Zernike Institute PhD thesis series 2008-15

ISSN 1570-1530

ISBN 978-90-367-3474-5

ISBN (electronic version) 978-90-367-3475-2

The work described in this thesis was performed in the research group Physics of Nanodevices of the Zernike Institute for Advanced Materials at the University of Groningen, the Netherlands. This work is part of the research programme of the 'Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)'

Cover photo: Kish graphite on a SiO_2 substrate. The graphite layer (light green) next to the text "Nikolaos Tombros" is two graphene layers thick and has dimensions $\sim 1 \times 1 \text{ mm}^2$.

Printed by: PrintPartners Ipskamp, Enschede

RIJKSUNIVERSITEIT GRONINGEN

Electron spin transport
in graphene and carbon nanotubes

Proefschrift

ter verkrijging van het doctoraat in de
Wiskunde en Natuurwetenschappen
aan de Rijksuniversiteit Groningen
op gezag van de
Rector Magnificus, dr. F. Zwarts,
in het openbaar te verdedigen op
maandag 16 juni 2008
om 14:45 uur

door

Nikolaos Tombros

geboren op 2 februari 1978
te Jeruzalem, Israël

Promotor: Prof. dr. ir. B. J. van Wees

Beoordelingscommissie: Prof. dr. P. Rudolf
Prof. dr. ir. J. C. Maan
Prof. dr. P. Kim

Contents

1	Introduction	1
1.1	Spintronics: from metals, semiconductors to organics	1
1.2	Motivation and Outline	5
	References	7
2	Theoretical aspects	9
2.1	Spin injection and detection	10
2.1.1	All electrical spin injection and detection	10
2.1.2	Spin injection and detection, the non-local technique	11
2.1.3	Spin precession and conductivity mismatch	13
2.1.4	Definition of the R value	20
2.2	Spin relaxation	22
2.2.1	Relaxation and dephasing time	23
2.2.2	Spin-orbit interaction	23
2.3	Graphene	26
2.3.1	Graphene electronics	26
2.3.2	Graphene spintronics	29
2.4	Carbon nanotubes	33
2.4.1	Carbon nanotube electronics and spintronics	33
	References	35
3	Experimental techniques	37
3.1	Electron Beam Lithography	38
3.2	Fabrication steps	38
3.2.1	Markers	39

3.2.2	Fabrication of a single-walled carbon nanotube device . . .	39
3.2.3	Fabrication of a Sn nanowire device for superconducting measurements	42
3.2.4	Fabrication of a graphene spintronic device	43
3.3	Selection of graphene flakes	45
3.3.1	Optical microscopy	45
3.3.2	Raman Spectroscopy	51
3.3.3	Atomic Force Microscopy	54
3.4	Electrical characterization setup	55
	References	57
4	Separating spin and charge transport in single wall carbon nan- otubes	59
4.1	Introduction	60
4.2	Non-local spin transport in a single wall nanotube	60
4.3	Discussion and conclusions	65
	References	67
5	The magneto-Coulomb effect in spin valve devices	69
5.1	Introduction	70
5.2	Magneto-Coulomb effect, definition	70
5.3	Magneto-Coulomb effect, magnetization switching	72
5.4	Magneto-Coulomb effect in a carbon nanotube	75
5.5	Discussion and conclusions	76
	References	77
6	Electronic spin transport and spin precession in single graphene layers at room temperature	79
6.1	Spin transport in Graphene	80
6.2	Discussion and conclusions	87
6.3	Methods	87
	References	89
7	Anisotropic spin relaxation in graphene	91
7.1	Introduction	92
7.2	Experiment	93
7.3	Conclusions	99
	References	101

8	Electronic spin drift in graphene field effect transistors	103
8.1	Introduction	104
8.2	Experiment	104
8.3	Conclusions	112
	References	113
9	Charge transport in a single superconducting tin nanowire encapsulated in a multiwalled carbon nanotube	115
9.1	Introduction	116
9.2	Experiment	116
9.3	Conclusions	124
	References	125
A	Spin transport in a SWNT, Resistor Model	127
B	EBL recipes	133
B.1	EBL Recipe: fabrication of markers	134
B.2	Single-walled carbon nanotube device on a SiO ₂ substrate	135
B.3	Tin nanowire device on a SiO ₂ substrate	137
B.4	Graphene spintronic device on a SiO ₂ substrate	139
	Summary	141
	Samenvatting	145
	Acknowledgments	149
	List of Publications	151

