

University of Groningen

Low-dimensional solution-processable electronics

Talsma, Wytse

DOI:
[10.33612/diss.182730251](https://doi.org/10.33612/diss.182730251)

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):

Talsma, W. (2021). *Low-dimensional solution-processable electronics: from field-effect transistor to artificial synapse*. [Thesis fully internal (DIV), University of Groningen]. University of Groningen.
<https://doi.org/10.33612/diss.182730251>

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.

**LOW-DIMENSIONAL SOLUTION-PROCESSABLE
ELECTRONICS**
From field-effect transistor to artificial synapse

Wytse Talsma



university of
 groningen

faculty of science
 and engineering

zernike institute for
 advanced materials

Zernike Institute PhD thesis series 2021-30

ISSN: 1570-1530

DOI: <https://doi.org/10.33612/diss.182730251>

The work described in this thesis was performed in the Photophysics and Opto-Electronics research group of the Zernike Institute for Advanced Materials at the University of Groningen, the Netherlands. This work was supported by NanoLab NL, CogniGron and the Zernike Institute for Advanced Materials. Reuse of any materials published in this thesis is only permitted following the copyright license of the publication mentioned on the corresponding chapter title page.

Cover design: Filiberto Augusto Bautista Moreno (*The Figure Wizard*).

Original concept by Wytse Talsma.

Printed by: Gildeprint, Enschede

© Wytse Talsma 2021. All rights reserved.



university of
 groningen

Low-dimensional solution-processable electronics

From field-effect transistor to artificial synapse

PhD thesis

to obtain the degree of PhD at 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.

This thesis will be defended in public on

Friday 5 November 2021 at 9:00 hours

by

Wytse Talsma

born on 5 May, 1990
 in Groningen

Supervisors

Prof. M. A. Loi

Prof. L. J. A. Koster

Assessment committee

Prof. B. Noheda

Prof. T. Anthopoulos

Prof. E. Menna

wijd oan heit, mem en Crystal

Abstract

Modern-day computing has irreversibly impacted our way of living. Nowadays, we are surrounded by computers that become smarter and more connected every day. The demand for more powerful hardware increases, while physical limitations already come into play. Pushing the boundaries of hardware development requires a new strategy, especially for (visual) pattern recognition. For this, a novel material candidate is semiconductive single-walled carbon nanotubes (s-SWCNTs). They promise inexpensive and scalable production methods for electronics. This thesis focuses on experimental research for the preparation and utilisation of these s-SWCNTs.

We optimised s-SWCNT ink preparation by substituting the applicator-solvent in a colloidal dispersion of polymer-wrapped s-SWCNT. This resulted in improved shelf-life, field-effect transistor (FET) performances and device reproducibility. Also, we successfully demonstrated three newly designed low-bandgap polymers that wrap and select s-SWCNT. This resulted in FETs with improved energy-band alignment, potentially lowering energy consumption. More insight is provided into the relationship between the polymer structure and the dispersion capability for s-SWCNT, subsequently, the final inks' physical properties. Finally, we demonstrated that sufficient plasticity arises to obtain a functional artificial synapse using simple pulse-shapes by utilising the hysteresis commonly found in bottom-gate structure SWCNT FETs. As synapses are the functional connection between neurons and are believed to be the units enabling learning and computing, our finding enables usage in more energy-efficient computing architecture.

We conclude that our improved inks can be easily industrially applied. The artificial synapse can potentially be used by neuromorphic computing for everyday pattern recognition tasks, enabling more powerful hardware.

Contents

1	Introduction	1
1.1	Semiconductors: the past, present and future of all electronics	1
1.2	Carbon nanotubes and their exciting properties	2
1.2.1	Discovery of carbon nanotubes	2
1.2.2	Dive into the basics: graphene	2
1.2.3	Carbon nanotube synthesis methods	7
1.2.4	Sorting semiconducting from metallic single-walled carbon nanotubes	10
1.2.5	Primary optical characterisation of the semiconductive single-walled carbon nanotubes ink	14
1.3	The fundamentals of hybrid perovskites	15
1.4	Field-effect transistors and their characterisation	18
1.4.1	Ambipolar transport	20
1.4.2	Characterisation of field-effect transistors	21
1.5	Deposition techniques	26
1.6	Applications	30
1.7	Beyond conventional computing technologies	31
1.8	Outline of the thesis	32
	Bibliography	33
2	Remarkably Stable, High-Quality Semiconducting Single-Walled Carbon Nanotube Inks for Highly Reproducible Field-Effect Transistors	55
2.1	Introduction	56
2.2	Procedure of obtaining stable inks	57
2.3	Optical characterization	59
2.4	Electrical characterization using Field Effect Transistors	61

2.5	Surface effects and morphologies	63
2.6	Conclusion	66
2.7	Experimental	66
	Bibliography	69
3	Efficient Selective Sorting of Semiconducting Carbon Nanotubes Using Ultranarrow-Bandgap Polymers	75
3.1	Introduction	76
3.2	Synthesis and Characterization	79
3.3	Optical and Electrochemical Properties	81
3.4	s-SWCNT ink characterization	84
3.5	Thin-film transistor performance	88
3.6	Energy level alignment and FET hysteresis	90
3.7	Conclusion	92
3.8	Experimental	93
	Bibliography	94
4	Field effect transistors based on formamidium tin triiodide perovskite	101
4.1	Introduction	102
4.2	Perovskite film characterization	104
4.3	Perovskite field-effect transistors	108
4.4	Tuning the perovskite film composition	113
4.5	Field effect transistors in staggered configuration	115
4.6	Conclusion	118
4.7	Experimental	118
	Bibliography	121
5	Synaptic plasticity in semiconducting single-walled carbon nanotubes transistors	125
5.1	Introduction	126
5.2	Working principle	128
5.3	Fabrication principle	129
5.4	Achieving electrical plasticity	130
5.5	Signs of learning capability: STDP rules	135
5.6	Conclusion	139
5.7	Experimental	139
	Bibliography	140
	Summary	145
	Samenvatting	149

Contents

Curriculum Vitae	153
Publications	155
Acknowledgements	158

