FOM - 15.0320

Annual report 2014

FOM programme nr. i26
'Topological quantum computation'

Foundation for Fundamental Research on Matter
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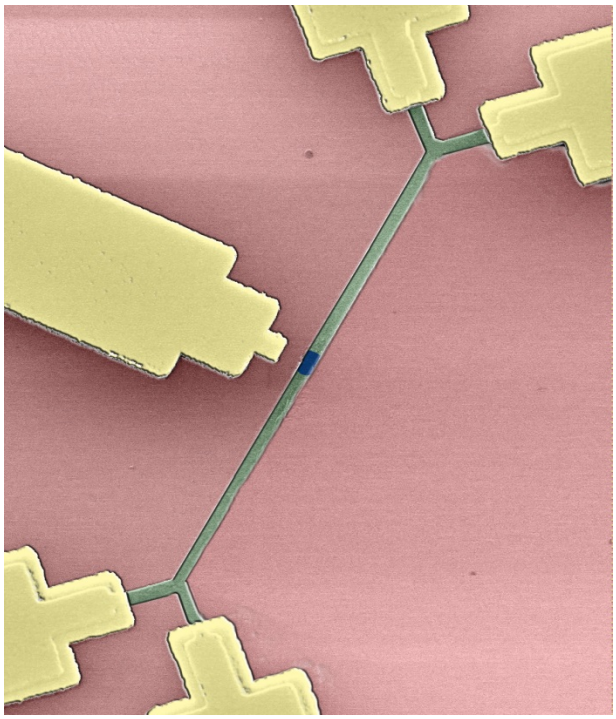

Cooperpair Box with band gap engineering of the superconducting gap resulting in a parity lifetime on the central island (blue center) of more than a minute. Blue is NbTiN; Green is Al; Yellow is Au.

May 2015

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1. Scientific results 2014

The current state of the art in Majorana research is the observation of zero-bias anomalies. This signature for Majoranas has been observed by several research groups and has been reproduced in many different device geometries. An important next step is to demonstrate that Majoranas can have topological properties. The topological protection in this case corresponds to an even or odd parity in the particle number in the device structure. In other words, do we have an even or an odd number of electrons in our nanowire-superconductor devices? The stability or lifetime of the parity constitutes the Majorana qubit lifetime.

We have measured parity lifetimes of order minutes in a Cooperpair box made of NbTiN. This long lifetime was achieved by engineering the spatial dependence of the superconducting gap using combinations of NbTiN, Al and Au, effectively creating on-chip, integrated coolers for quasi-particles. (This work has been accepted for publication in Nature Physics; see also figure.)

Signatures of Majoranas have been found in 1D semiconductor wires connected to a superconductor. An alternative approach starts with a 2D topological insulator (TI) that can be connected to a superconductor. Options for a 2D TI are HgTe-based II-VI materials, or our choice of the inverted bandgap system made out of InAs/GaSb. We have demonstrated new devices with multiple gate structures to obtain a tunability from trivial to topological phases. (This work has been accepted for publication in Phys.Rev.Letters.)

We have connected InAs/GaSb to a superconductor and studied induced superconductivity and its dependence on the phase of the semiconductor. If tuned to a trivial phase we observe a homogeneous distribution of the supercurrent (i.e. Fraunhofer interference). Strikingly, when tuned to the topological phase we observe induced superconductivity at the sample edges only (i.e. SQUID-like interference). These results clearly demonstrate phase-tunability, which by itself is an important observation. (This work has been published in Nature Nanotechnology.) Future work will focus on an explicit demonstration that the edge mode conduction is carried by helical edge states, the unambiguous result of a topological phase.

The Beenakker group in Leiden has proposed schemes that allow for a demonstration of initialization of Majorana qubits, manipulation by an exchange, or braiding gate, and a readout of the final state. These schemes would allow for a demonstration that Majoranas obey non-Abelian statistics. We have realized already the readout part of this circuit. This part is a superconducting resonator (i.e. a microwave high-quality cavity) especially designed for operation in a magnetic field of 1 Tesla.

2. Added value of the programme

This IPP comes with a partnership with the Microsoft Station Q team that is headed by Dr. M. Freedman. This Q team is of exceptional quality and all meetings are very inspiring.

3. Personnel

The PhDs are on schedule with their projects. In 2014 Önder Gul was in his second year of his PhD, Daniel Szombati was in his third PhD year and Kun Zuo reached his final year. Kun Zuo and Daniel Szombati are expected to obtain their doctorate in 2015.
Postdoc Fanming Qu and Hao Zhang both started on this project in August 2014.
Michael Wimmer has organized a workshop on "Topological nanodevice modeling" in Delft, focusing on this new emerging research line. This workshop resulted in several new collaborations, for example with Zuerich and Regensburg.

Michael Wimmer has recently been awarded a Vidi grant.

4. Publications

In 2014 the following articles have been published:

- I. van Weperen, B. Tarasinski, D. Eeltink, V.S. Pribiag, S.R. Plissard, E.P.A.M. Bakkers, L.P. Kouwenhoven, **M. Wimmer**.
  Spin-orbit interaction in InSb nanowires
  arXiv:1412.0877.
- M. Diez, J.P. Dahlhaus, **M. Wimmer**, C.W.J. Beenakker.
  Emergence of massless Dirac fermions in graphene's Hofstadter butterfly at switches of the quantum Hall phase connectivity.
  Phys. Rev. Lett. **112**, 196602 (2014).
- I. Adagideli, **M. Wimmer**, A. Teker.
  Inducing topological order in dirty wires: Majorana fermions from scattering.
  Phys. Rev. B **89**, 144506 (2014).
- D.I. Pikulin, T. Hyart, Shuo Mi, J. Tworzydlo, **M. Wimmer**, C.W.J. Beenakker.
  Disorder and magnetic-field induced breakdown of helical edge conduction in an inverted electron-hole bilayer.
  Phys. Rev. B **89**, 161403(R) (2014).
- M. Raith, C. Ertler, P. Stano, **M. Wimmer**, J. Fabian.
  Electric control of tunneling energy in graphene double dots.
  Phys. Rev. B **89**, 085414 (2014).

5. Valorisation and outreach

In 2014 the following talks have been given:

- *Electrostatics and Majoranas (it matters)*
  Numerics meeting at Station Q, Santa Barbara, USA, 7 December 2014
- *Simulating topological nanodevices with Kwant*
  Mini-workshop *Topological nanodevice modeling,* Delft, Netherlands, 26 September 2014
- *Disordered topological superconducting wires*
  DPG spring meeting, Dresden, Germany, 2 April 2014
- *Kwant - a software package for quantum transport*
  DPG spring meeting, Dresden, Germany, 31 March 2014
- *Designing and controlling topological hybrid systems*
  Institute of Andvanced Studies, Technische Universität München, 17 February 2014
- *Kwant - a software package for quantum transport*
  IAS workshop on *Topological Matter, Superconductivity and Majorana,* Hong Kong, China, 17 January 2014
- *Disordered topological superconducting wires*
  IAS workshop on *Topological Matter, Superconductivity and Majorana,* Hong Kong, China, 17 January 2014

6. Vacancies

There are no vacancies. All positions have been filled.

FOM – 11.0620/6
datum: 01-01-2015

APPROVED INDUSTRIAL PARTNERSHIP PROGRAMME

Number	i26.
Title (code)	Topological quantum computation (TQC)
Executive organisational unit	BUW
Programme management	Prof.dr.ir. L.P. Kouwenhoven
Duration	2011 - 2018
Cost estimate	M€ 4.0
Partner(s)	Microsoft

Concise programme description

a. Objectives

The realization of a quantum computer depends on the suppression of decoherence. Most qubit designs have ways to protect the information-carrying quantum state as much as possible but the protection is never complete. This makes the lifetime of a quantum superposition finite and qubit operations subject to errors. There is one exception to this inherent obstacle: topologically protected qubits; in short top-qubits. The intrinsic design of top-qubits is such that deformations do not change the qubit state. This intrinsic protection is the same as the protected winding-number of a belt with a single twist; deformations without breaking the belt cannot undo a single twist. It is obviously advantageous to build a complex quantum computer based on infinitely lived qubit states. Top-qubits have yet to be realized and currently exist only on paper in various theoretical proposals. Nevertheless, Microsoft Station Q has chosen to focus their qubit activities entirely on this approach. This IPP proposes to realize topologically-protected qubits in nanoscale solid state devices.

b. Background, relevance and implementation

Recent theoretical proposals have developed new schemes for top-qubits based on nanodevices with semiconductor nanowires and superconducting electrodes. It turns out that the leading proposals by Lutchyn *et al.* (2010) and Oreg *et al.* (2010) are based on previously realized devices (2006) by the Kouwenhoven group. The Kouwenhoven group thus has all the necessary expertise for upgrading their earlier devices into top-qubit devices. For this reason Microsoft Station Q intends to finance experimental research in Kouwenhoven's group.
This IPP aims at understanding and solving various scientific questions concerning the character of topological phases and states in condensed matter systems. The motivation of addressing these questions is the technological goal of a new form of computing, which is based on two new ingredients: quantum mechanics and topology. The realization of a full-scale quantum computer falls outside the timescale of this IPP. Within this programme we focus on the initial required steps: the

realization and manipulation of top-qubits based on the development of solid state Majorana Fermions. Within the first tranche of this programme signatures of Majorana Fermions have been observed in 2012 (10.1126/science.1222360).

Funding
salarispeil cao per 01-07-2012

bedragen in k€	≤ 2014	2015	2016	2017	2018	2019	≥ 2020	Totaal
FOM-basisexploitatie	1.204	324	172	100	100	-	-	1.900
FOM-basis investeringen	-	-	-	-	-	-	-	-
Doelsubsidies NWO	-	-	-	-	-	-	-	-
Doelsubsidies derden	-	-	-	-	-	-	-	-
- Microsoft*)	1.991	-	-	-	-	-	-	1.991
- TKI-toeslag	200	-	-	-	-	-	-	200
Totaal	3.395	324	172	100	100	-	-	4.091

*) Microsoft draagt in totaal k$ 2.600 bij. De exacte bedragen in euro's worden bepaald volgens de koers op de dag dat de middelen worden overgemaakt. Daarnaast draagt Microsoft circa 35 k$ *in kind* bij.

Source documents and progress control

a) Original programme proposal: FOM-11.0404[1)], FOM-12.0252[2)], FOM-13.0013[3)]
b) Ex ante evaluation: FOM-11.0478[1)], FOM-11.0643[1)], FOM-12.0641[2)], FOM-13.0789[3)]
c) Decision Executive Board: FOM-11.0644[1)], FOM-12.0699[2)], FOM-13.0904[3)]
d) Contracts: FOM-11.0744[1)], FOM-11.0745[1,2)], FOM-11.0746[1)], FOM-12.0540[2)], FOM-12.0711[2)], FOM-13.1055[3)], FOM-13.1056[3)]

[1)] concerns first tranche
[2)] concerns second tranche
[3)] concerns third tranche

Remarks

The final evaluation of this programme will consist of a self-evaluation initiated by the programme leader and is foreseen in 2018.

MH par. HOZB

Subgebied: 100% NANO

Historical overview of input en output

Input	personnel (in fte)				finances* (in k€)
	WP/V	WP/T	PhD	NWP	
2010	-	-	0.1	-	
2011	-	1.2	1.3	-	524
2012	-	0.9	2.5	-	1.166
2013	-	1.2	3.0	-	1.115
2014	-	1.8	3.0	-	335

Output	PhD theses	refereed publications	other publications & presentations	patents
2012	-	12	25	-
2013	-	7	16	-
2014	-	4	8	-

* After closing the financial year.

PhD defences

2012
None.

2013
None.

2014
None.

Patents (new/changes)

2013
None.

2014
None.

Overview of projects and personnel

Workgroup FOM-D-41

Leader	Prof.dr.ir. L.P. Kouwenhoven
Organisation	Delft University of Technology
Project leader	Prof. Y. Nazarov
Programme	Topological quantum computation
Project (title + number)	Topological quantum computation 5 12TQC05

FOM employees on this project

Name	Position	Start date	End date
M.T. Wimmer	postdoc	01 October 2013	30 September 2018

Leader	Prof.dr.ir. L.P. Kouwenhoven
Organisation	Delft University of Technology
Programme	Topological quantum computation
Project (title + number)	Topological quantum computation 3 12TQC03

FOM employees on this project

Name	Position	Start date	End date
O. Gul	PhD	01 January 2013	31 December 2016
F. Qu	postdoc	1 August 2014	31 January 2015

Leader	Prof.dr.ir. L.P. Kouwenhoven
Organisation	Delft University of Technology
Programme	Topological quantum computation
Project (title + number)	Topological quantum computation 1 11TQC01

FOM employees on this project

Name	Position	Start date	End date
D.B. Szombati	PhD	01 September 2011	31 August 2015
K. Zuo	PhD	01 July 2011	08 February 2015

Leader	Prof.dr.ir. L.P. Kouwenhoven
Organisation	Delft University of Technology
Project leader	Prof. Y. Nazarov
Programme	Topological quantum computation
Project (title + number)	Topological quantum computation 5 12TQC07

FOM employees on this project

Name	Position	Start date	End date
H. Zhang	postdoc	1 August 2014	31 July 2016