Annual report 2016

FOM programme nr. i39
'Scalable circuits of majorana qubits'

MBE-ALD during installation at QuTech lab

May 2017
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1. **Scientific results 2016**

The current state of the art in Majorana research is the characterization of the properties of single Majorana bound states or pairs of bound states. The next milestone is to show the non-Abelian statistics of Majorana bound states through braiding. There are two main proposals for a braiding circuit in the literature: On the one hand there is the approach of braiding by changing the coupling between Majorana bound states (either by flux, Hyart et al. Phys. Rev. B 88, 035121 (2013) or with gates, Aasen et al. Phys. Rev. X 6, 031016 (2016)). On the other hand is the recent proposal of measurement-based braiding from the station Q group (T. Karzig, arxiv:1610.05289). We are pursuing both approaches.

The demonstration of braiding requires proper materials that allow for Majorana fermions with negligible quasiparticle poisoning. A prerequisite for that is a 'hard' induced superconducting gap. For nanowires, previous results from the group of C. Marcus in Copenhagen have indicated that epitaxial interfaces between semiconductor and superconductor are essential.

To this end, a novel ultra-high vacuum (UHV) deposition cluster tool has been developed, manufactured and started to be installed at QuTech during 2015. It will serve to develop and produce nanowire based devices for the QuTech topological quantum computing roadmap, with a level of materials integration, design and cleanliness that is not possible with the current technology. Indeed, the cluster has been designed to allow the deposition of a variety of pure crystalline materials by means of both Molecular Beam Epitaxy (MBE) and Atomic Layer Deposition (ALD) technology, and to promote the best integration of different epitaxial materials (i.e. semiconductor and superconductor) in the same nanodevice without altering the material interface cleanliness. In addition, a special care has been taken to minimize the introduction of particle contamination in the cluster and the cross contamination in-between different. The cluster installation has finished in 2016, and initial calibrations as well as the first growth of nanowires has been done.

All the different proposals for braiding circuits require the fabrication of separate superconducting islands, possibly together with electrostatic gates. Epitaxial semiconductor/superconductor wires form a challenge as established lithographic fabrication techniques cannot be used to pattern the superconductor. In the last year we have worked towards improved etch recipes for creating gated junctions in InSb and InAs nanowires with epitaxial Al shells, as well as investigated wire shadowing as an alternative technique for creating junctions. Essential part of controlling Majorana overlap is a control of the charging energy of superconducting islands. To this end, we have started to develop graphene based Josephson junctions that are very robust against in-plane magnetic field.

The measurement-based braiding circuits rely on interference between different conductance pathways in the nanowire system. This implies that such circuits must consist of phase coherent loops. Together with the group of Erik Bakkers in Eindhoven we have developed and measured nanowires grown such that they form interconnected networks. We have measured the Aharonov-Bohm effect in such nanowire loops and extracted a phase coherence length of several microns. This makes these systems very promising for the measurement-based braiding design.

The braiding circuit that was put forward by the group of Carlo Beenakker in Leiden relies on the read-out of the topological qubit formed by Majorana fermions with microwave spectroscopy of transmons. We have successfully installed the high frequency microwave equipment required for operating a magnetic field compatible transmon. Initial testing of traditional flux-tunable transmon qubits has revealed the challenges associated with operating these sensitive devices within a magnetically unshielded environment. As an alternative, we have developed the fabrication of gate-tunable nanowire transmons with sputtered contacts (published in Phys. Rev. Lett.). Using nanowires with an epitaxial aluminum shell has since then significantly improved the relaxation and coherence times. In the coming years we plan to further develop transmons with magnetic field compatible junctions, and demonstrate their performance in magnetic fields.

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


Postdoc Fanning Qu finished his work on 14 August 2016, Jie Shen will work on this project till 1 November 2017. John Watson has an extension for another two years.

Postdocs who started in 2016 are: Dominique Laroche, Sebastian Heedt, Kevin van Hoogdalem, Avradeep Pal and Srijit Goswami.

Per 1 May 2016 a new technician Olaf Benningshof started on this project. The other two technicians are still working on this project, Jason Mensingh from 15 June 2015 and Siebe Visser from 1 October 2015.

4. Publications

14SCMQ01

a. Scientific (refereed) publications


b. Presentations at (inter)national scientific conferences


14SCMQ02

a. Scientific (refereed) publications

14SCMQ03
a. Scientific (refereed) publications

b. Presentations at (inter)national scientific conferences

5. PhD defences
No PhD defences in 2016 for these projects.

6. Valorisation, outreach and patents
- Towards Majorana QuBits, L.P. Kouwenhoven, 15–19 June, 2016 Station Q, Santa Barbara
- Quantum Computer, L.P. Kouwenhoven, 13 May 2016, RTLZ tv interview
- Quantum Computer, L.P. Kouwenhoven, 10 June 2016, NOS Hilversum, interne bijeenkomst met gastspekers
- Quantum Computer, L.P. Kouwenhoven, 27 September 2016, Opname TV college NPO3

7. Vacancies
At this moment there are no vacancies.
## APPROVED INDUSTRIAL PARTNERSHIP PROGRAMME

<table>
<thead>
<tr>
<th>Number</th>
<th>i39.</th>
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<tbody>
<tr>
<td>Title (code)</td>
<td>Scalable circuits of Majorana qubits (SCMQ)</td>
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<td>Executive organisational unit</td>
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<tr>
<td>Programme management</td>
<td>Prof.dr.ir. L.P. Kouwenhoven</td>
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<tr>
<td>Duration</td>
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<tr>
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<td>M€ 16.2</td>
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<td>Partner(s)</td>
<td>Microsoft</td>
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### Concise programme description

#### a. Objectives

The potential realization of a quantum computer depends on the ability to suppress decoherence. One of the most promising proposed designs is based on so-called Majorana-state qubits. The longterm objective of this Industrial Partnership Programme is to develop scalable Majorana circuits of qubits with topological protection. The main scientific challenge is to demonstrate non-Abelian statistics through braiding, using circuits of Majorana qubits. In the future these topologically protected qubits are a possible building block for large-scale quantum computing.

#### b. Background, relevance and implementation

The promise of using Majoranas for scalable quantum circuits is that quantum decoherence can be circumvented by using topological protection. The topological protection is guaranteed as long as the fermionic parity of the system remains constant; i.e. the number of electrons in the system has to remain either an even or an odd number. This parity can be viewed as a qubit and can be denoted as the 'Majorana state'. Qubit operations involve exchanging different Majoranas around each other, called a 'braiding operation'. Strikingly, the expected exchange statistics is not fermionic, nor bosonic, but instead 'non-Abelian'. It is this non-Abelian statistics that makes these Majoranas so interesting. First, of all it would be the first (quasi) particle ever to show non-Abelian statistics. Second, the non-trivial exchange statistics provide a mean for manipulating quantum states useful for quantum computation. Most importantly, and absolutely stunning, is the notion that as long as topological protection works the Majorana state cannot decohere, i.e. quantum mechanics without decoherence!

The experimental challenge is to control parity conservation. Even-odd parity effects were studied in the '90's on superconducting nanostructures employing the stabilizing effect of Coulomb blockade. The current challenge is to repeat these experiments, however, Coulomb blockade cannot be used since this interaction in fact provides a coupling between different parities. We therefore have to control even-odd occupations of an open system.

Microsoft has chosen topologically protected qubits as their approach towards large scale quantum computing. The collaboration between Microsoft and the Kouwenhoven group at TU Delft was established in 2010. An
earlier FOM-Microsoft IPP (TQC, nr. i26) was already granted and currently running, and resulted in the first discovery of the Majorana fermion. The current IPP puts a strong emphasis on technology development and making the transition from individual Majorana samples towards Majorana circuits.

**Funding**

salarispeil cao per 01-01-2016

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1) Microsoft zal in totaal naar schatting M$ 22.5 bijdragen, de helft in-cash en de andere helft in de vorm van apparatuur die rechtstreeks aan TU Delft geleverd wordt. De exacte bedragen worden jaarlijks vastgesteld, en het bedrag in Euro's is afhankelijk van de actuele dollarkoers.

2) In 2015 heeft Microsoft de bijdrage van 2016 voldaan (in totaal k$ 7.700 in-cash).

3) Exact bedrag is afhankelijk van de actuele dollarkoers.

4) Microsoft draagt k$ 600 bij als matching voor de inzet van de TKI-toeslag gegenereerd over 2014

5) TKI-toeslag wordt jaarlijks toegekend. De Microsoft bijdragen in apparatuur leveren ook TKI-toeslag op. De bedragen over 2014 en 2015 zijn inclusief TKI-toeslag die verworven is over programma i26 -TQC (ook met partner Microsoft) en binnen dit programma wordt geadmineerd.

**Source documents and progress control**

a) Original programme proposal: FOM-14.0849
b) Ex ante evaluation: FOM-14.1258; FOM-14.1569
c) Decision Executive Board: FOM-14.1636

**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
Overview of projects and personnel

Workgroup FOM-D-41

Leader
Prof.dr.ir. L.P. Kouwenhoven

Organisation
Delft University of Technology

Project leader(s)

Project (title + number)
Scalable circuits of Majorana qubits - tranche 1 (14SCMQ01)

FOM employees on this project

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Leader
Prof.dr.ir. L.P. Kouwenhoven

Organisation
Delft University of Technology

Project leader(s)

Project (title + number)
Scalable Circuits of Majorana Qubits - NWO/FOMdeel (14SCMQ02)

FOM employees on this project

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Leader
Prof.dr.ir. L.P. Kouwenhoven

Organisation
Delft University of Technology

Project leader(s)
Dr. L. DiCarlo

Project (title + number)
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