AMBIPOLAR QUANTUM DOTS IN PLANAR SILICON

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Silicon quantum team
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Matthias Brauns
Chris Spruijtenburg
Sergey Amitonov
Wilfred van der Wiel
Reliable and scalable quantum devices:
Understand and manipulate spin states and topological states in silicon

- Develop new concepts for high-quality devices
- Unravel fundamental physics
- Partners with scaling abilities (IMEC, Intel, LETI, nanoPHAB)

- State-of-the-art silicon processing (ultra-clean line)
- Thin film growth, e.g. ALD dielectrics
- Low-temperature electron transport

*Embracing the quantum limit in silicon computing*
Morton et al., Nature 2011

*Silicon quantum electronics*
Zwanenburg et al., RMP 2013
**SILICON QUANTUM ELECTRONICS**

**SILICON SPIN QUBIT MILESTONES** (not exhaustive)

- Single-shot readout of electron spin
- Electron and P nuclear spin Qubits
- Singlet-triplet qubit in Si/SiGe quantum dot
- 39 min quantum info storage in P nuclear spins
- Hybrid qubit in Si/SiGe quantum dot
- Spin qubit in Si/SiGe quantum dot
- Electron spin qubit in Si quantum dot
- 2-qubit logic gate in Si quantum dot
- CMOS Si spin qubit
- 2-qubit algorithms in Si/SiGe quantum dot
- High-fidelity spin qubit in Si/SiGe quantum dot
- Coherent spin–photon interface in Si/SiGe QD
- Spin-photon coupling in Si/SiGe QD
- Ge hole spin qubit
- ...
Ge/Si nanowires
- Single & double quantum dots
- Supercurrent transistor

Ambipolar nanoMOSFET quantum dots
- Ambipolar charge sensing
- Gates and oxides
- Depletion-mode quantum dots

Nanowire supercurrent transistor

Pauli spin blockade in double QDs

Low-disorder quantum dots with Pd gates

Depletion-mode quantum dots in undoped silicon
QUANTUM DOTS AND SUPERCONDUCTIVITY IN Ge/Si NANOWIRES

- Clean and robust QDs, highly tuneable
  - Brauns et al., APL 2016
  - Conesa-Boj et al., Nano Lett 2016
  - Froning et al., APL 2018
  - Brauns et al., PRB (R) 2016

- Shell filling in double quantum dot

- Pauli spin blockade
  - Brauns et al., PRB (R) 2016

- Supercurrent transistor

- Josephson junction x quantum dot

- Shapiro steps
  - Ridderbos et al., Adv. Mat. 2018
  - De Vries et al., Nano Lett 2018
  - Ridderbos et al., Phys Rev Materials 2019
  - Ridderbos et al., in review 2019
SCALABLE TOPOLOGICAL STATES WITH Ge-Si NANOWIRES

New FET OPEN project
(1 Dec 2019)

TOPSQUAD:
Topologically protected and
Scalable quantum bits

Address qubit fragility:
- Topologically protected states in Ge wires

Address scalability:
- Making nanowire research scalable

PhD / Post-doc vacancies

Nanowire supercurrent transistor

Nanowire architecture on Si wafers

SemiCon München Nov 2019
### TOPSQUAD PIs

<table>
<thead>
<tr>
<th>UNIVERSITY OF TWENTE.</th>
<th>Universität Basel</th>
<th>IST Austria</th>
<th>Basel Precision Instruments</th>
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<tr>
<td>Floris Zwanenburg</td>
<td>Dominik Zumbühl</td>
<td>Christian Schönberger</td>
<td>Georgios Katsaros</td>
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<td>Alexander Brinkman</td>
<td>Jelena Klinovaja</td>
<td>Daniel Loss</td>
<td>Parisa Fallahi</td>
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**SemiCon München Nov 2019**
Ambipolar QDs: few-charge regime
Mueller et al., Nano Lett 2015, APL 2015
Sousa de Almeida et al., in preparation 2019

Accumulation-mode and depletion-mode hole quantum dots
Spruijtenburg et al., APL 2013
Amitonov et al., APL 2017

`Si QD cookbook`: low-disorder QDs and single defect characterization
Spruijtenburg et al., Scientific Reports 2018
Brauns et al., Scientific Reports 2018
Spruijtenburg et al., Nanotechnology 2018
Electron version introduced by Angus et al, Nano Lett 2008: workhorse for UNSW results (Morello, Dzurak, Hamilton)

Compare holes and electrons in one and the same device, i.e. with the same silicon, oxide, metal and impurities.

Electron QD

Hole QD

Müller et al, Nano Lett 2015, APL 2015
AMBIPOlar Si NANO-MOSFETs

Ambipolar device functionality

Müller et al, Nano Lett 2015, APL 2015
AMBIPOLAR Si NANO-MOSFETs

Ambipolar device functionality

Holes
Electrons

Müller et al, Nano Lett 2015, APL 2015
Compare holes and electrons in one and the same device, i.e. with the same silicon, oxide, metal and impurities.
AMBIPOLAR CHARGE SENSING

Capacitively coupled SET and SHT

A.J. Sousa de Almeida, in preparation
AMBIPOLAR CHARGE SENSING

Electron current | Hole current

See also: Yang et al. AIP Advances 2011

SHT sensing electrons

A.J. Sousa de Almeida, in preparation
AMBIPOLAR CHARGE SENSING

Electron current

Hole current

SET sensing holes

See also: Yang et al. AIP Advances 2011

A.J. Sousa de Almeida, in preparation
AMBIPOLAR CHARGE SENSING

Active charge sensing of electrons with SHT

Hole current

Electron current

See also: Yang et al. AIP Advances 2011

SHT sensing electrons

A.J. Sousa de Almeida, in preparation
AMBIPOlar Charge Sensing

Data from May 2019

Active charge sensing of holes with SET

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See also: Liles et al. Nat. Comms 2018

A.J. Sousa de Almeida, in preparation
Nanowire supercurrent transistor

Ge/Si nanowires
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Pauli spin blockade in double QDs

Low-disorder quantum dots with Pd gates

Ambipolar charge sensing

Depletion-mode quantum dots in undoped silicon

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Electron layout introduced by Angus et al, Nano Lett 2008: workhorse for UNSW results (Morello, Dzurak, Hamilton)
SI QUANTUM DOTS WITH ALUMINIUM GATES

➢ Ambipolar quantum dots
➢ Probe single defects
➢ Low level of disorder >> long hole quantum dots

Spruijtenburg et al, Nanotechnology 2018
SI QUANTUM DOTS WITH PALLADIUM GATES

- Ambipolar quantum dots
- Probe single defects
- Low level of disorder >> long hole quantum dots

Brauns et al, Scientific Reports 2018
SI QUANTUM DOTS WITH PALLADIUM GATES

Low-disorder quantum dot

Brauns et al, Scientific Reports 2018
SI QUANTUM DOTS WITH PALLADIUM GATES

Reproducibility:
3 chips from 3 different fabrication runs

Brauns et al, Scientific Reports 2018
Pauli spin blockade in double QDs

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DEPLETION-MODE HOLE QUANTUM DOTS IN INTRINSIC SILICON

Serendipity:

2DHG in \textit{undoped} silicon

- Annealing can create fixed charge in $\text{Al}_2\text{O}_3$ $\gg$ 2DHG
- UV-ozone can remove charges

Amitonov et al, APL (2017)
DEPLETION-MODE HOLE QUANTUM DOTS IN INTRINSIC SILICON

- Basic pinch off
- Quantum dot formation in undoped silicon

Amitonov et al, APL (2017)
**DEPLETION-MODE ELECTRON QUANTUM DOTS IN UNDOPED SILICON**

PO$_x$/Al$_2$O$_3$ stacks: Highly effective surface passivation of crystalline silicon with a large positive fixed charge

Lachlan E. Black$^a$ and W. M. M. (Erwin) Kessels$^b$

*APPLIED PHYSICS LETTERS 112, 201603 (2018)*

- Positive fixed charge in PO$_x$/Al$_2$O$_3$ $\gg$ 2DEG
- Depletion-mode electron quantum dots?

Collaboration: Kessels group (TU Eindhoven)

- (ugly) QD behaviour
- Charge density too high

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GATES AND OXIDES

- Large grains (-)
- Eats into SiO₂ (+/-)
- Native oxide (+)

- Easy evaporation (+)
- Does not stick well (-)
- Uniform interface (+)

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TWENTE SILICON QUANTUM TEAM – PAST & PRESENT

COLLABORATIONS

TU Eindhoven: Sonia Conesa-Boj, Ang Li, Erik Bakkers, Willem-Jan Berghuis, Lachlan Black, Erwin Kessels

TU Delft: Fokko de Vries, Jie Shen, Leo Kouwenhoven

University of Basel: Florian Froning, Mirko Rehmann, Floris Braakman, Timothy Camenzind, Kristopher Cerveny, Dominik Zumbühl, Daniel Loss