Quantum Information with NV-Centers (QINVC)

Jan Meijer (Uni –Leipzig)

Cooperation between

CEA Saclay          France,
ENS Cachan          France,
University Stuttgart Germany,
University Leipzig   Germany,
University Warwick   United Kingdom
Partner 1: CEA-Saclay, Paris
D. Esteve group

Research Group in Quantum Electronics, CEA-Saclay, France

Expertise:
Superconducting quantum circuits
Mesoscopic physics
Hybrid systems

Daniel Esteve (Coordinator)  Patrice Bertet
Partner 2: ENS Cachan, Paris
J.-F. Roch group

Expertise:
Quantum optics
Optical and spin properties of NV centers
AFM with NV-centers

Jean-Francois ROCH
Partner 3: Uni Stuttgart (Germany)  
Jörg Wrachtrup group

Expertise:  
Spin physics and spin properties  
Direct coupling

Inventor of the NV centers as quantum device
Partner 4: University Leipzig (Germany)
J. Meijer group

Expertise:
Single ion Implantation
First creation of artificial NV centers

S. Pezzagna
J. Meijer

(Former Prof. Butz group)
Partner 5: Uni. Warwick (United Kingdom)
Mark Newton group

Expertise:
Diamond crystal grown (E6)
NMR, ESR
Material Science Group

- P5 Uni Warwick
  Diamond Growth Characterisation

- P4 Uni Leipzig
  Addressing of Single NVs

Solid state quantum Physics

- P1 CEA Saclay
  Superconducting Hybrid Circuits

- P2 ENS Cachan
  Quantum Optics

- P3 (Uni. Stuttgart)
  Spin Physics

Start 2011; Duration 36 month
Quantum Information with NV-Centers (QINVC)
Color centers in diamond

3H-Center

G-Band: Sp$^2$-Inclusion

H3-center

NV-center

Pink star: 62 Mio. Euro

J. Rödiger, A. Zaitsev, J. Meijer et al. 2013 Unpubl,
NV properties

Excited state

Ground state

2.87 GHz

\[ m_s = \pm 1 \quad m_s = 0 \]
NV Spin properties

The main goal to do spin-spin coupling (for the distance < 20 nm with $T_2 \sim 1$ ms)

P. Neumann et al., Nature Physics 6, 249–253 (2010)
NV-centers

• Easy to initialized
• Long T2 times, low decoherence
• Single shot readout
• Quantum gate operation
• Scalable

-> DiVincenzo criteria to build a quantum computer
Two Strategies:

• AFM Quantum Bus

• hybrid system with superconducting qubits
Hybrid Quantum Computer
Hybrid System

CEA Sacley
Single Spin Coupling

CEA Sacley
AFM Quantum Bus

Cachan, UStutt
Realization idea: production of NV-centers by N implantation into diamond

requirements:

technical solutions to implant countable single ions with nm spatial resolution

Physical solution: high yield production of NV centers, charge state control, mobility of NV
Our aims for NV centres

Nanoscalability

Nanometer placement

Scalability / Reproducibility

Shallow centres

“bulk” centres

Conversion efficiency

Charge state

Overall properties

Using Nitrogen ion implantation
Proton beam (3 MeV) in diamond

Simulation with SRIM
J. Ziegler, http://srim.org
Creation efficiency ($N \rightarrow NV$)

Scan of the diamond surface implanted with $1 \times 10^{13}$ nitrogen/cm$^2$

- Yield vs. Energy per Nitrogen Atom (keV)
- Vacancies created per ion vs. Energy per Atom (keV)

Pezzagna et al., *New Journal of Physics* 2010, 12, 065017
**Ion implantation towards nm resolution**

**Positioning**

Collimation

aperture

AFM, STM

**Resolution of the table**

~ 1 nm

Atomic force microscope

Hole made by Focussed Ion Beam

Ga\(^+\) 30keV

hole
Reduced hole => below 20 nm

Non Contact Mode: We can implant into pillars, phtomic crystalls etc.

Pezzagna et al., Small. 6, 2117 (2010)
Nitrogen Focused Ion Beam (FIB)

In collaboration with Orsay Physics

A wide range of applications...


Cachan, ULeip
High resolution ion implantation

Pezzagna et al., New J Phys. 13, 035024 (2011)
Realization idea: production of NV-centers by N implantation into diamond

requirements:

technical solutions to implant countable single ions with nm spatial resolution

Physical solution: high yield production of NV centers, charge state control, mobility of NV
Material: E6: 3x3 mm (100)
optical grade!
100kV CN⁻ Implantaion

NV-center

H3-center

J. Rödiger, A. Zaitsev, J. Meijer et. al. 2013
Unpubl,
Creation Efficiency

![Graph showing concentration vs temperature]
Creation Efficiency
10x Improvement by annealing optimization
Diffusion of single NV?

Optical detection of single NVs:

No change @ 1100° C 90 min
resolution 5 nm

Cachan, ULeip
Wildanger, Roch, Meijer 2012 in prep.
ODMR for orientation control

Wildanger, Roch, Meijer 2012 in prep.
Orientation of single NVs?

ODMR:

No change @ 1100° C 90 min

Wildanger, Roch, Meijer 2012 in prep.
Charge state control

“Active control by applied voltage”
Individual Adressing
“Active control by applied voltage”

Charge state of NV

CB

5.47 eV

2.0 eV

1.2 eV

NV⁻

NV⁰

NV⁺ ?

VB
Bipolar: In-plane PIN-Diode

Lohrmann, et al. APL 2011
SP-LED by growing: N. Mizuochi et al.
Nature photonics 2012
PL-Intensity of a single NV from NV\textsuperscript{-} to NV\textsuperscript{0}

May be a dynamic process? better NV\textsuperscript{+} -> NV\textsuperscript{-}?

Lohrmann et al unpubl.
Addressing of NVs by active charge control

Initialization
Addressing of NVs by active charge control

Initialization
Addressing of NVs by active charge control

Initialization
Addressing of NVs by active charge control

Initialization
Conclusion

• Material science:
  – Optimization in NV production
  – Addressing of NV within 15 nm
  – NVs stable until 1300° C
  – No diffusion @ 1100° C

• First results in coupling NV and superconducting qubits

• Optimization of the AFM-bus system
Thank You!

cooperation with I. Rangelow, Ilmenau and L. Bischop FZR