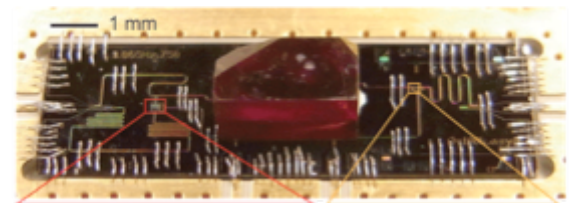


Quantum Information with NV-Centers (QINVC)

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

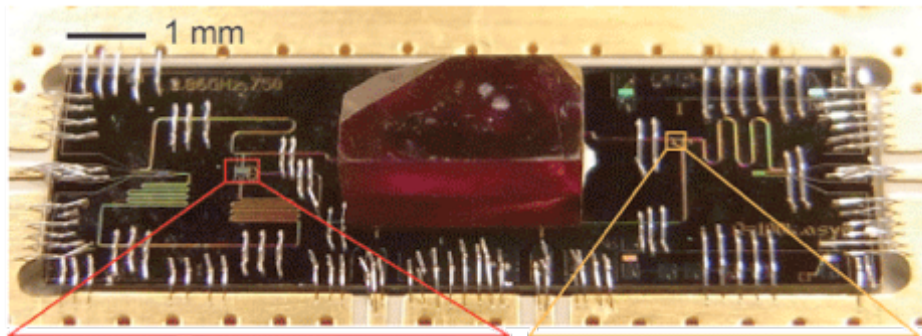
Research Group in
Quantum Electronics,
CEA-Saclay, France



Expertise:
Superconducting quantum circuits
Mesoscopic physics
Hybrid systems

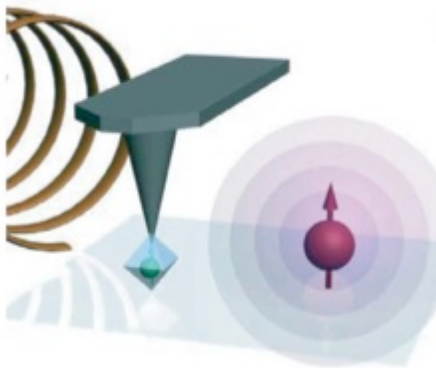
Daniel Esteve (Coordinator)

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



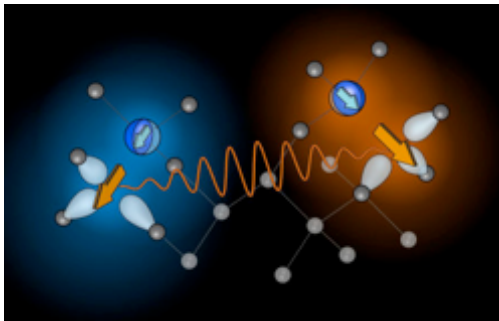
Partner 3: Uni Stuttgart (Germany)
Jörg Wrachtrup group

Expertise:
Spin physics and spin properties
Direct coupling

Inventor of the NV centers as quantum device



Jörg Wrachtrup



Partner 4: University Leipzig (Germany)
J. Meijer group

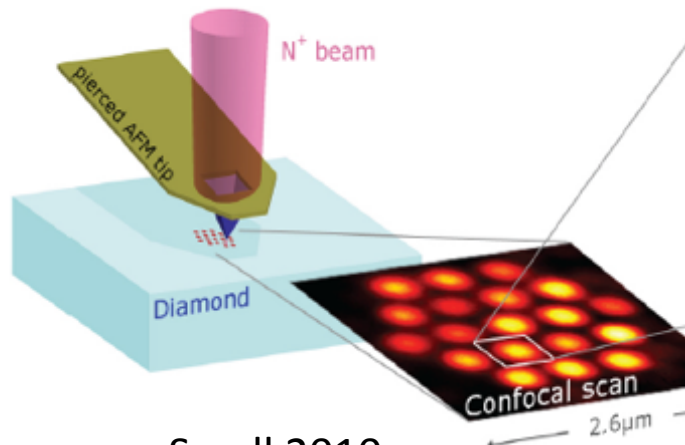
Expertise:
Single ion Implantation
First creation of artifical NV centers



S. Pezzagna



J. Meijer



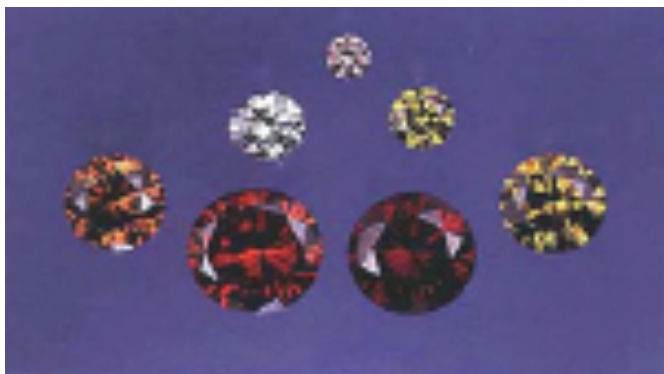
S. Pezzagna Small 2010



(Former Prof. Butz group)

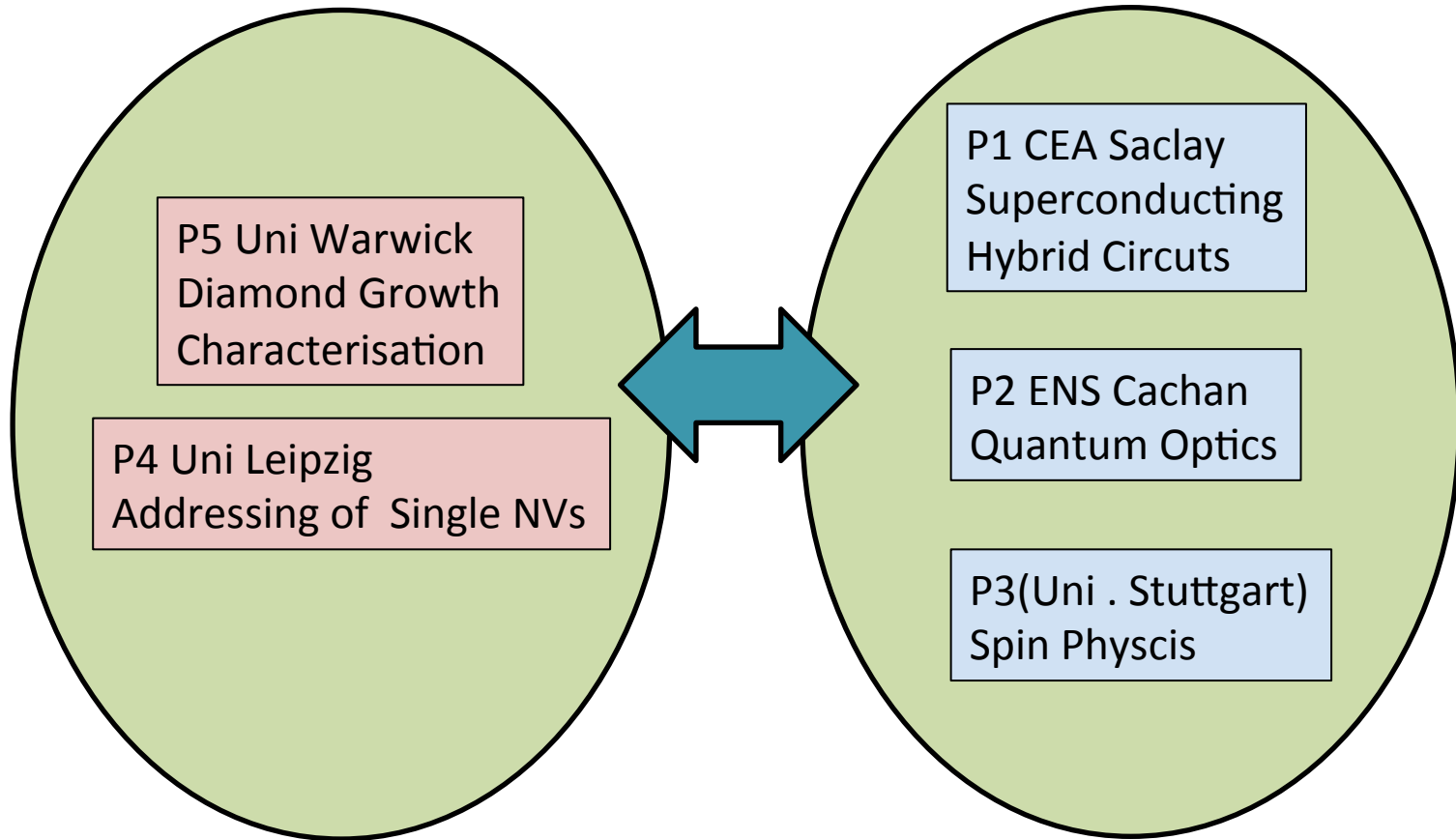
Partner 5: Uni. Warwick (United Kingdom)
Mark Newton group

Expertise:
Diamond crystal grown (E6)
NMR, ESR



Material Science Group

Solid state quantum Physics



Start 2011 ; Duration 36 month

Quantum Information with NV-Centers (QINVC)



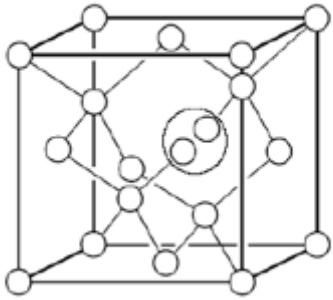
Why NV Centers ?



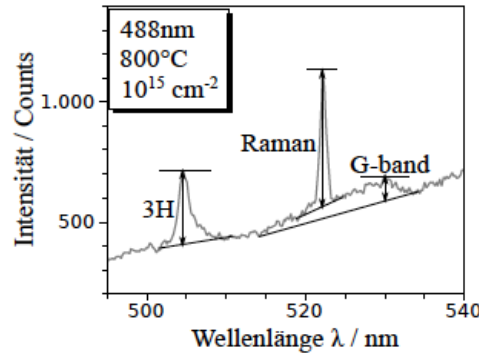
Color centers in diamond

G-Band: sp^2 -Inclusion

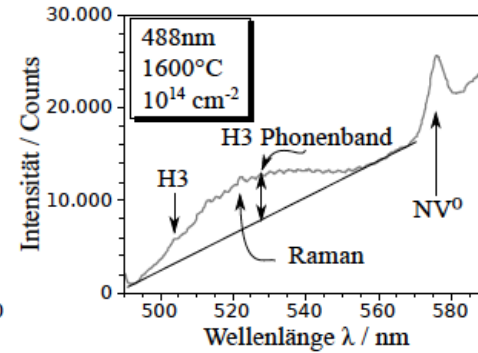
H3-center



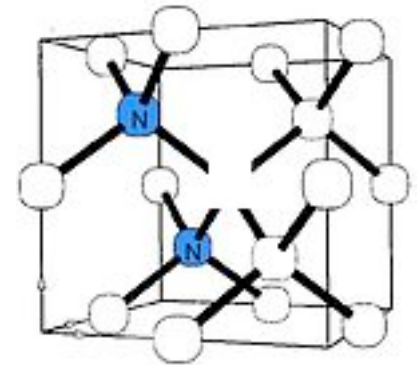
3H-Center



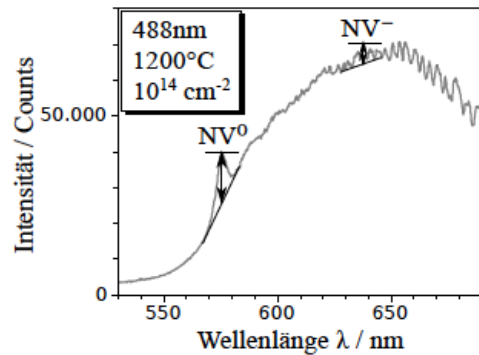
(a) 3H Zentrum, Ramanlinie und G-Band



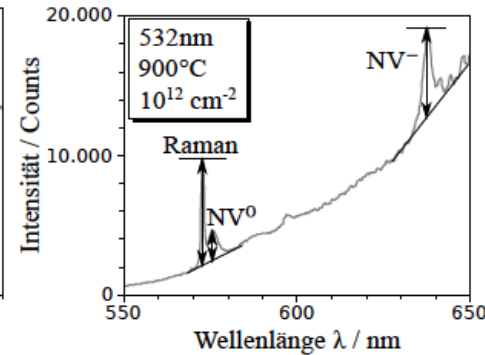
(b) H3 Zentrum



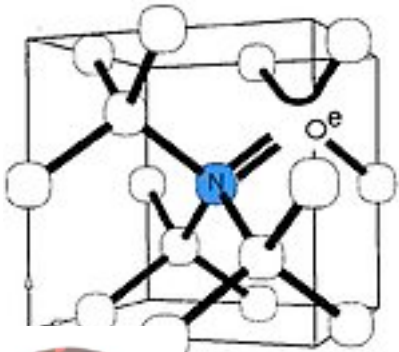
b



(c) NV-Zentren



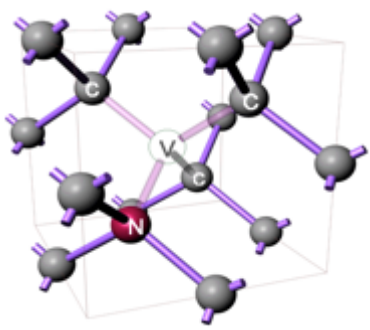
(d) NV-Zentren



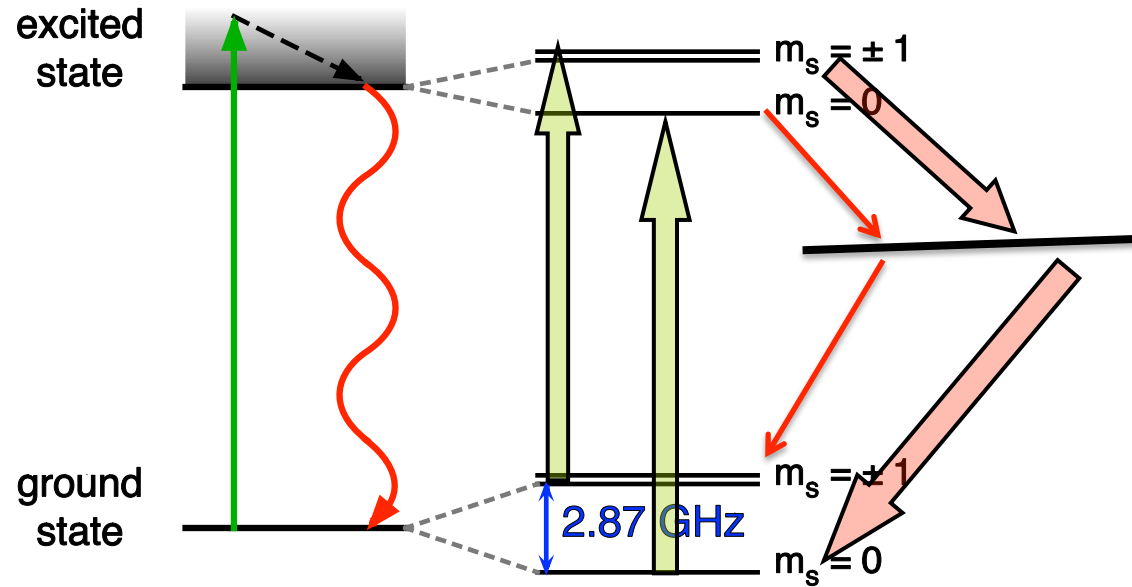
NV-center

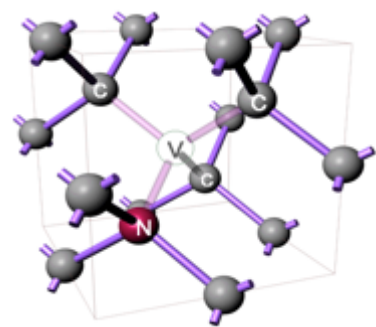


Pink star: 62 Mio. Euro

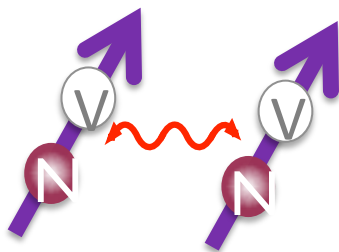
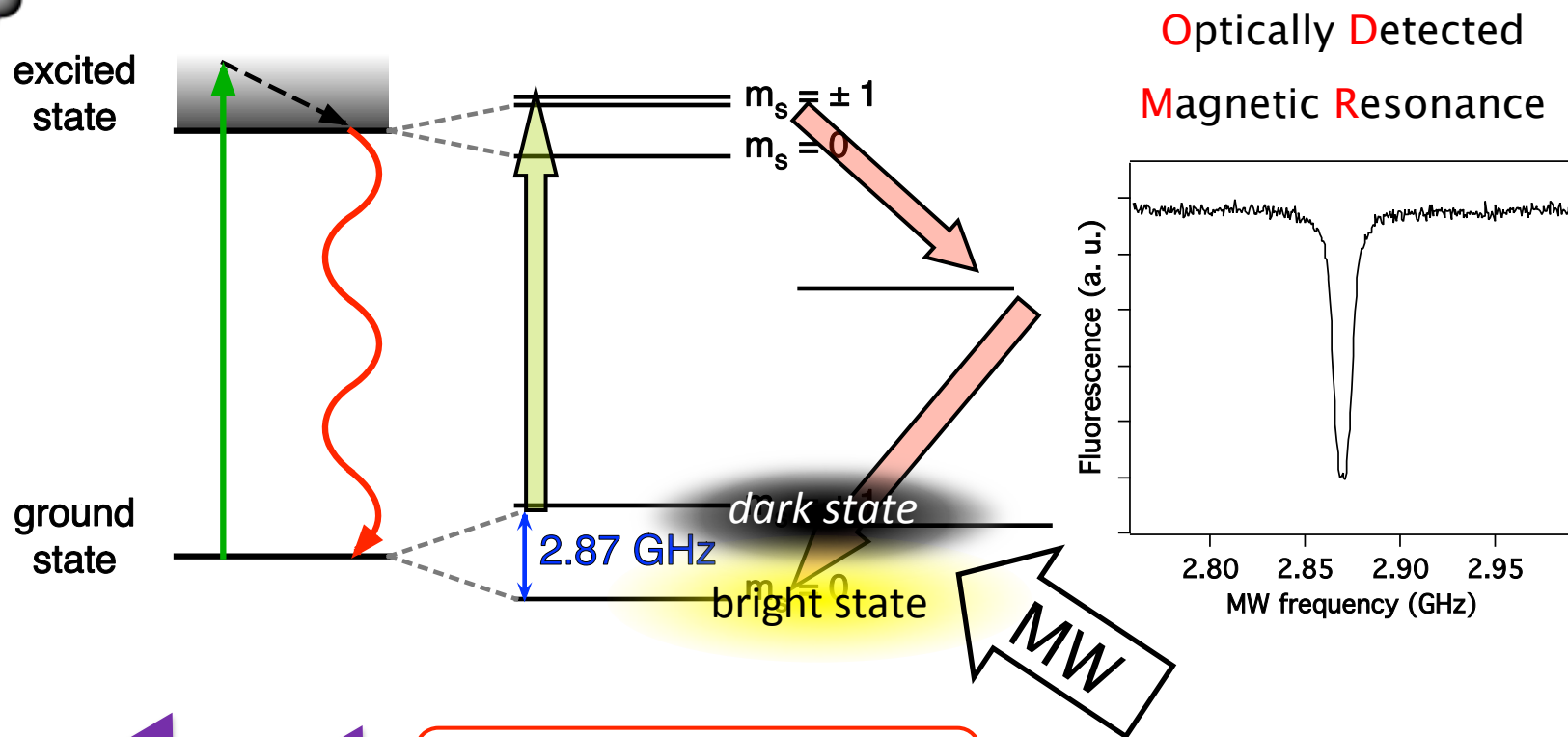


NV properties





NV Spin properties



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

Lesik et al
2013

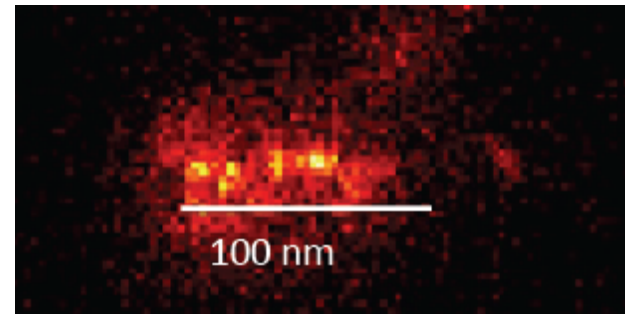
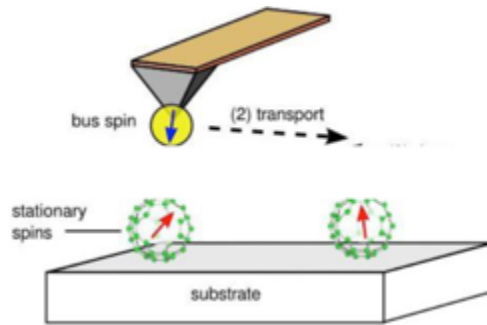
NV-centers

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

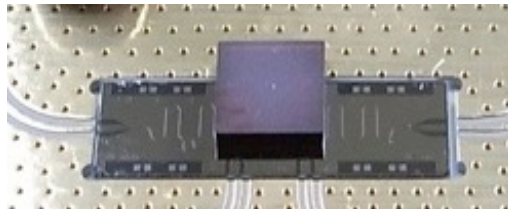
-> DiVincenzo criteria to build a quantum computer

Two Strategies:

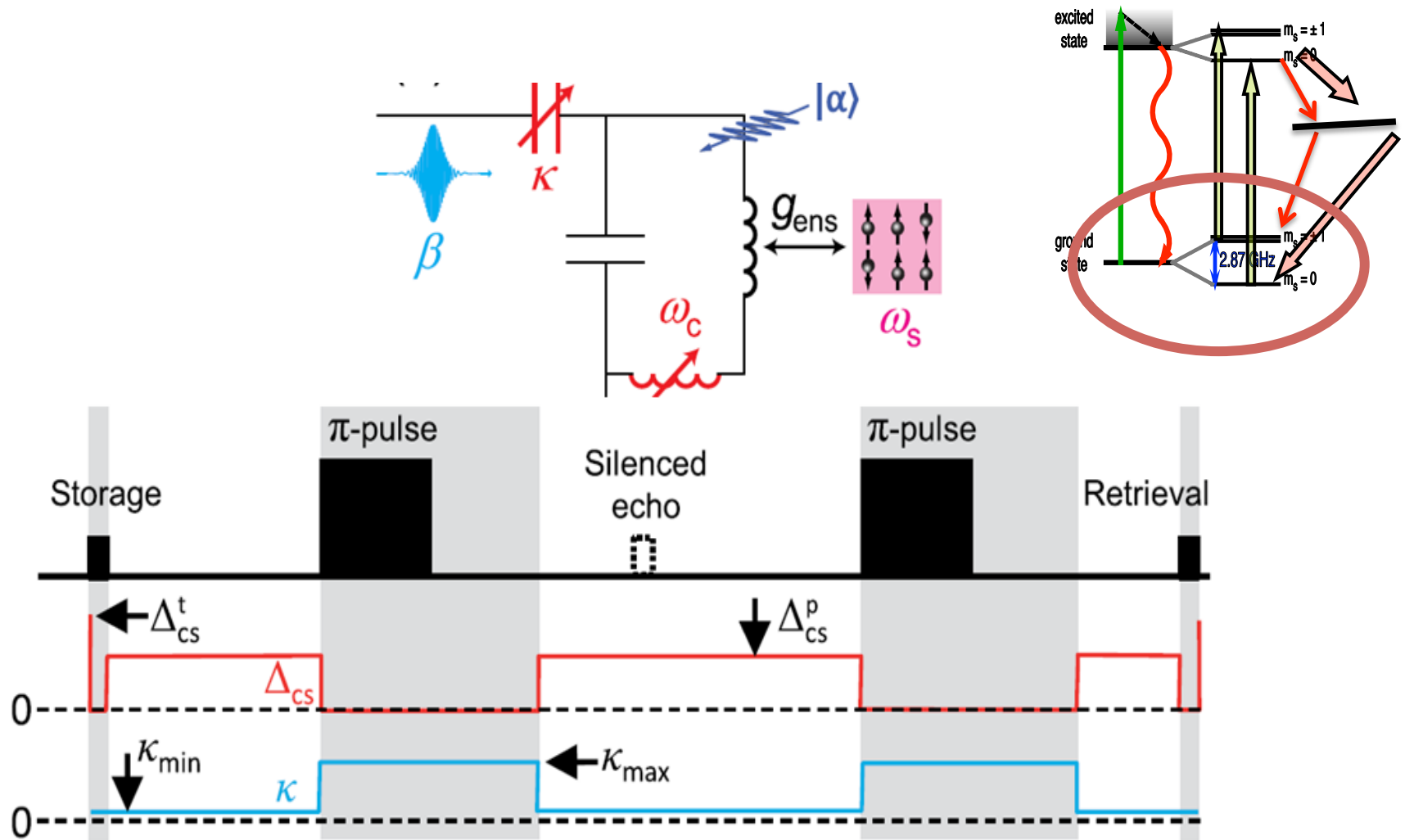
- AFM Quantum Bus

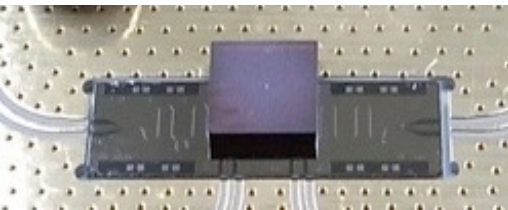


- hybrid system with superconducting qubits

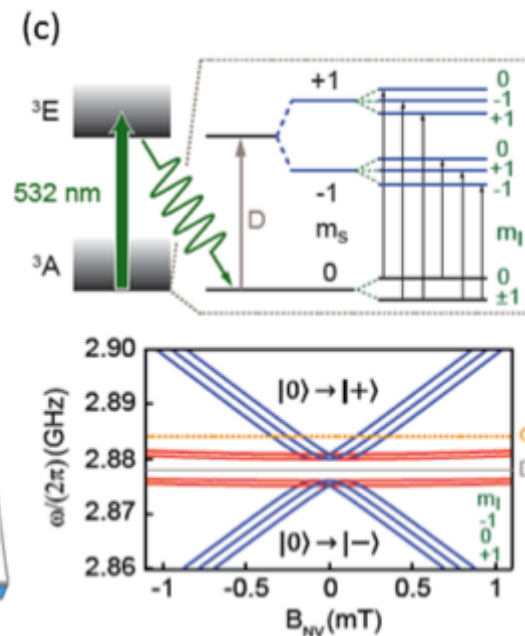
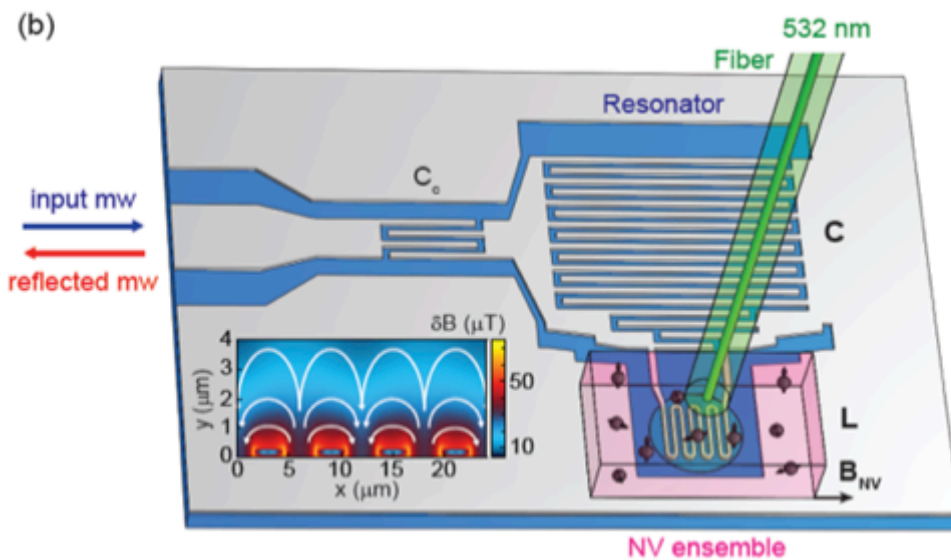
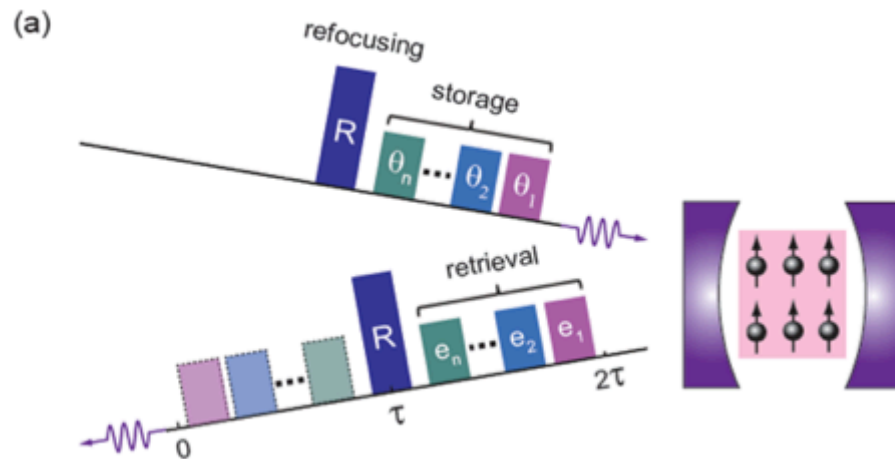


Hybrid Quantum Computer

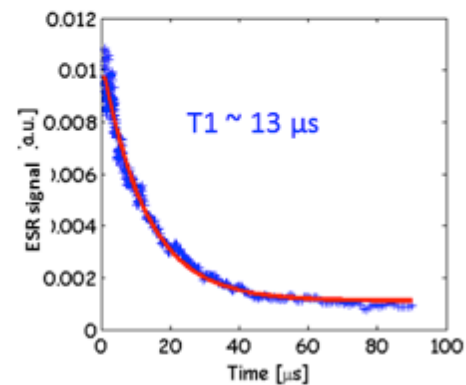
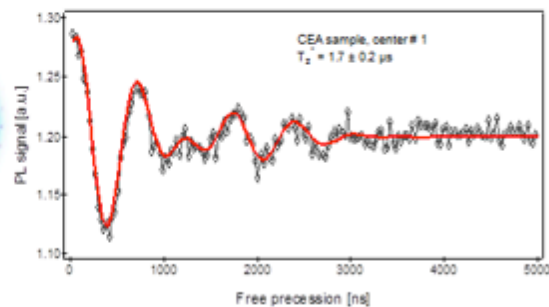
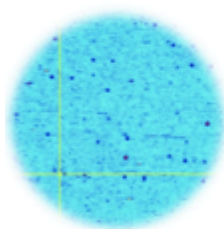
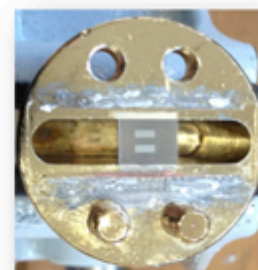
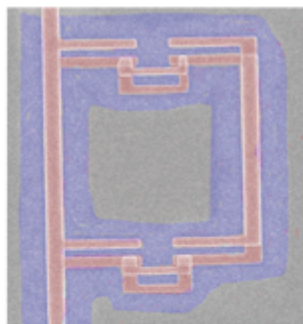
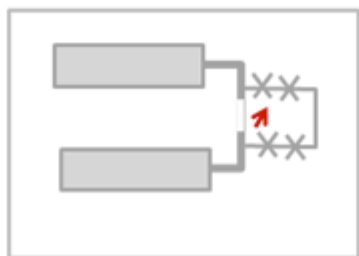




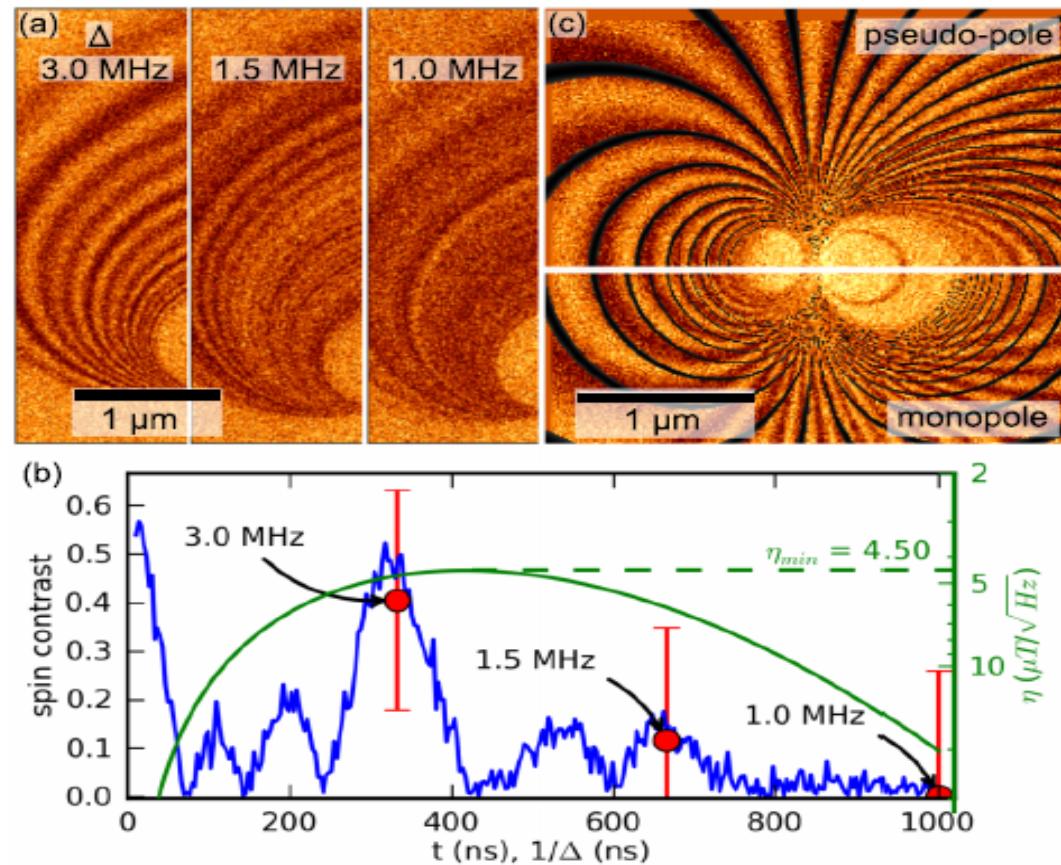
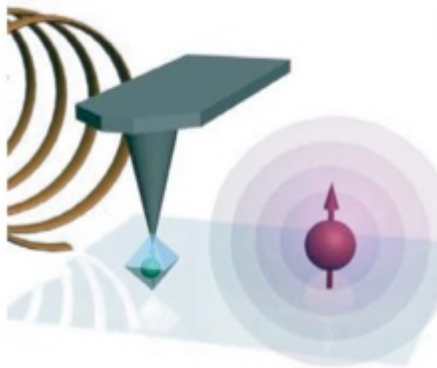
Hybrid System



Single Spin Coupling



AFM Quantum Bus



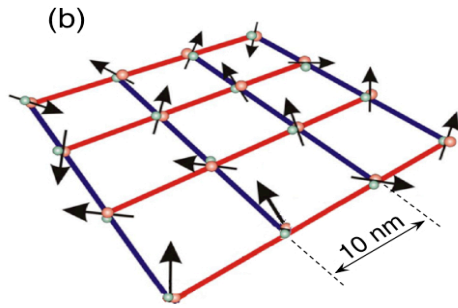
Realization idea: production of NV-centers by N implantation into diamond

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

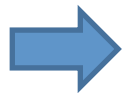
Shallow centres

“bulk” centres

*Conversion
efficiency*

Charge state

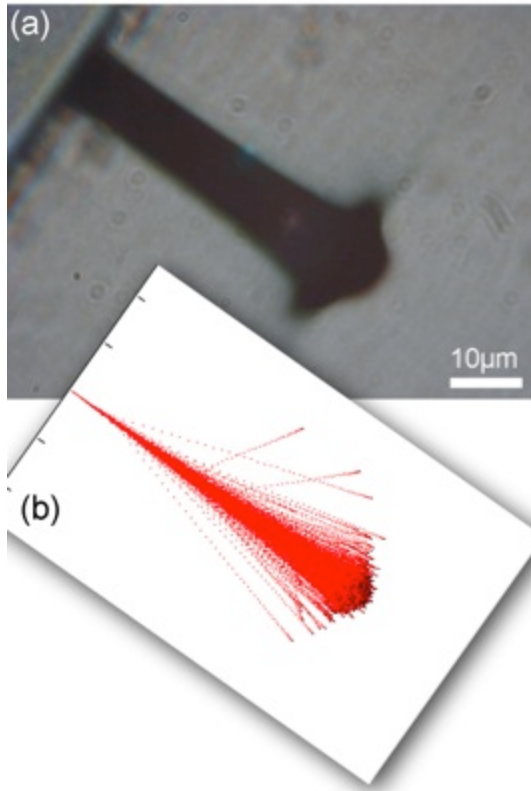
*Overall
properties*



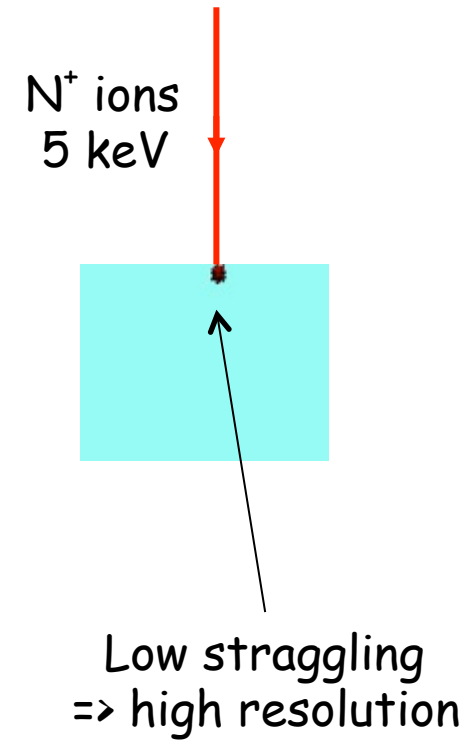
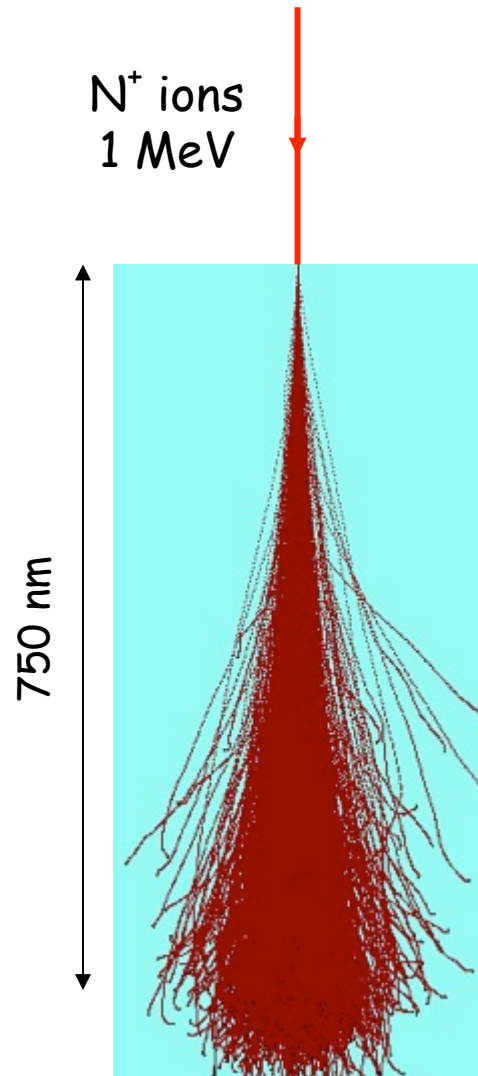
Using **Nitrogen** ion implantation

Ion implantation - straggling

Proton beam (3 MeV) in diamond

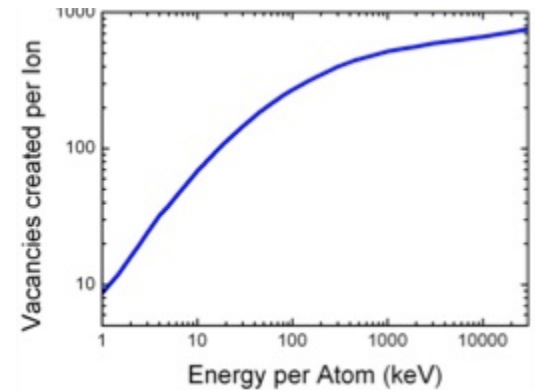
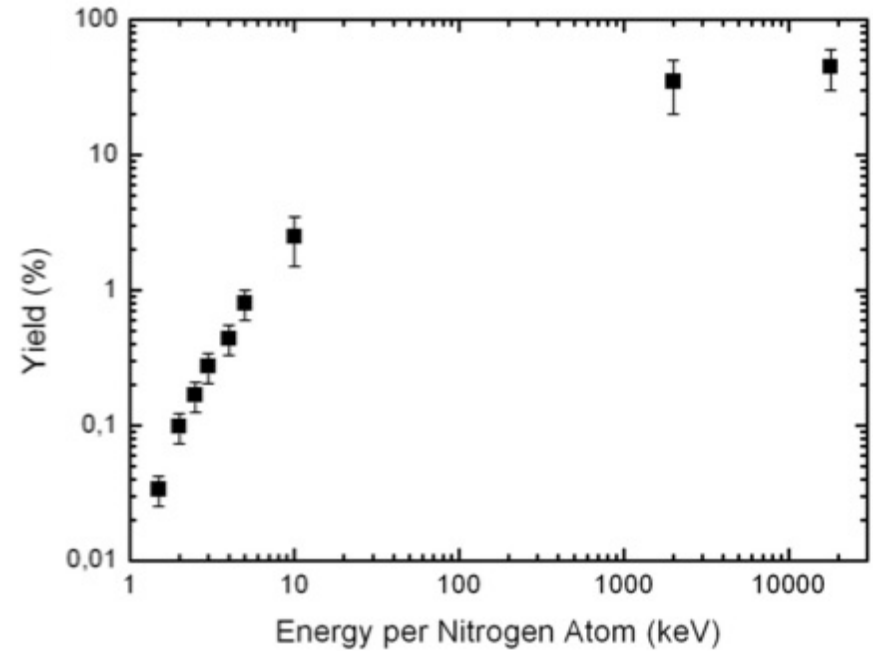
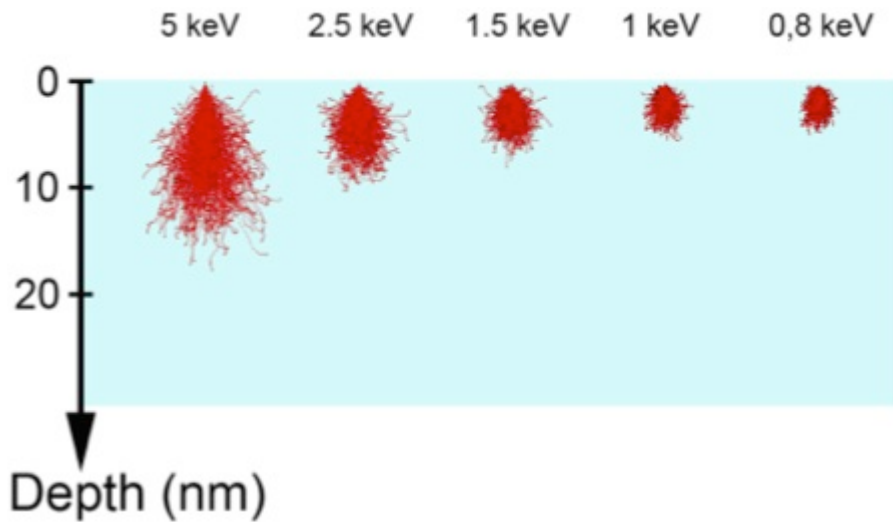
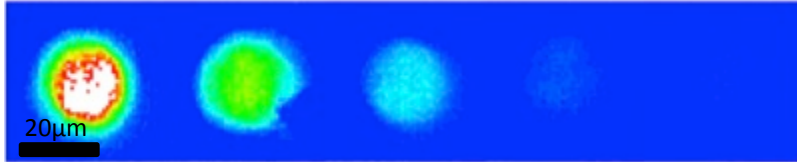


Simulation with SRIM
J. Ziegler, <http://srim.org>

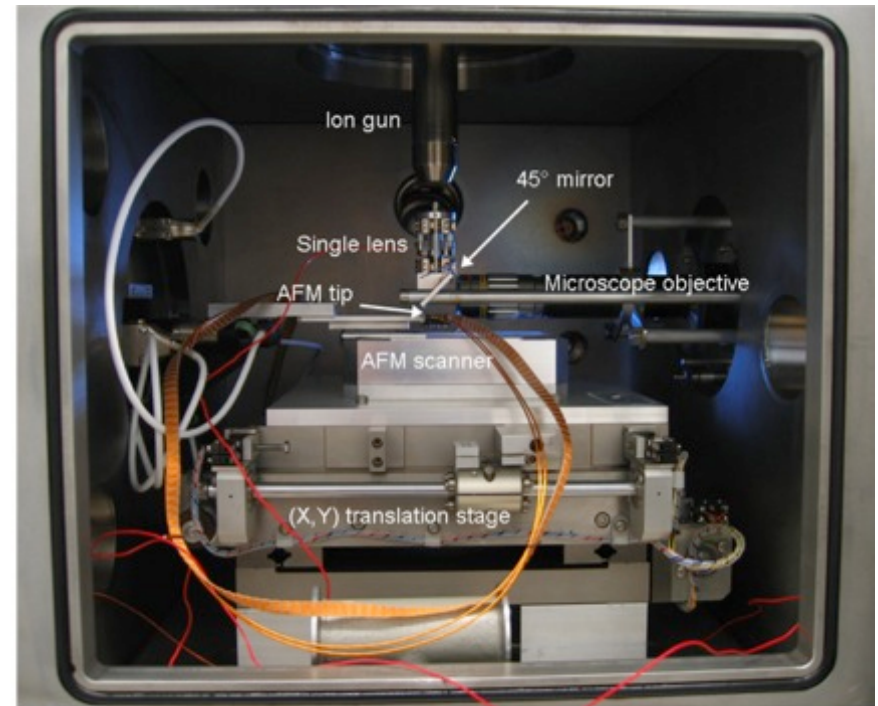
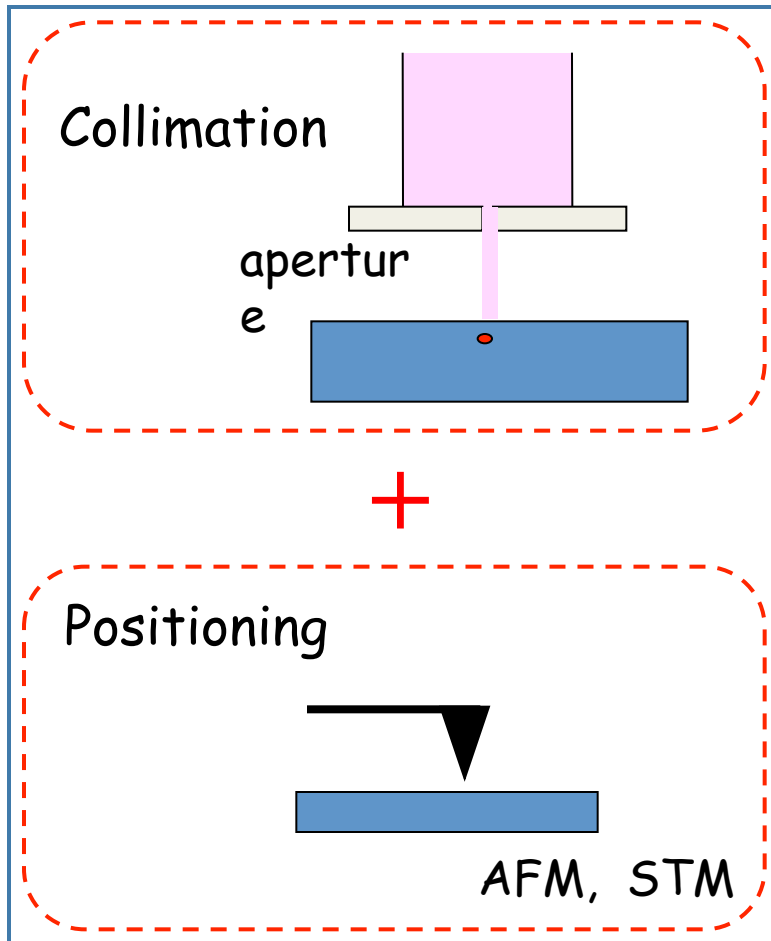


Creation efficiency ($N \rightarrow NV$)

Scan of the diamond surface implanted with 1×10^{13} nitroaen/cm²



Ion implantation towards nm resolution

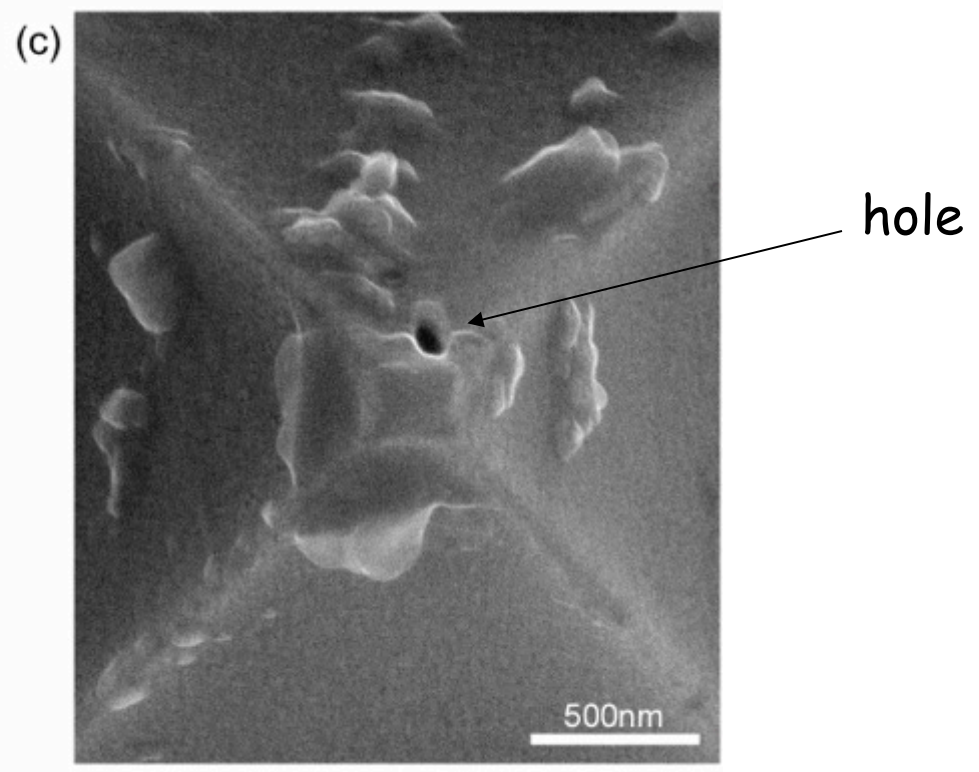
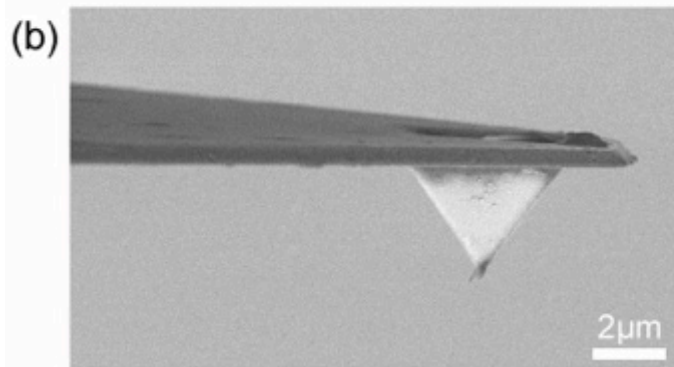
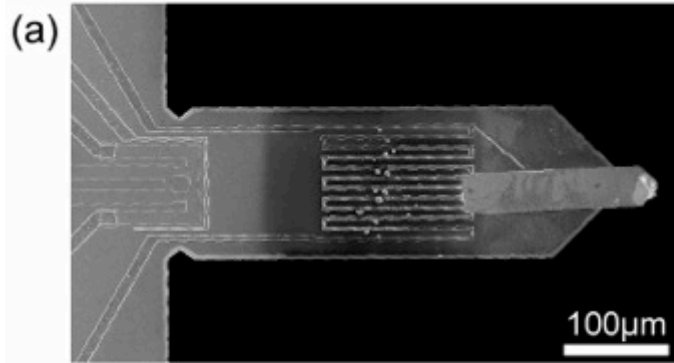
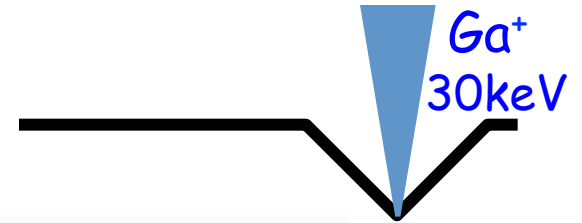


Resolution of the table
~ 1 nm

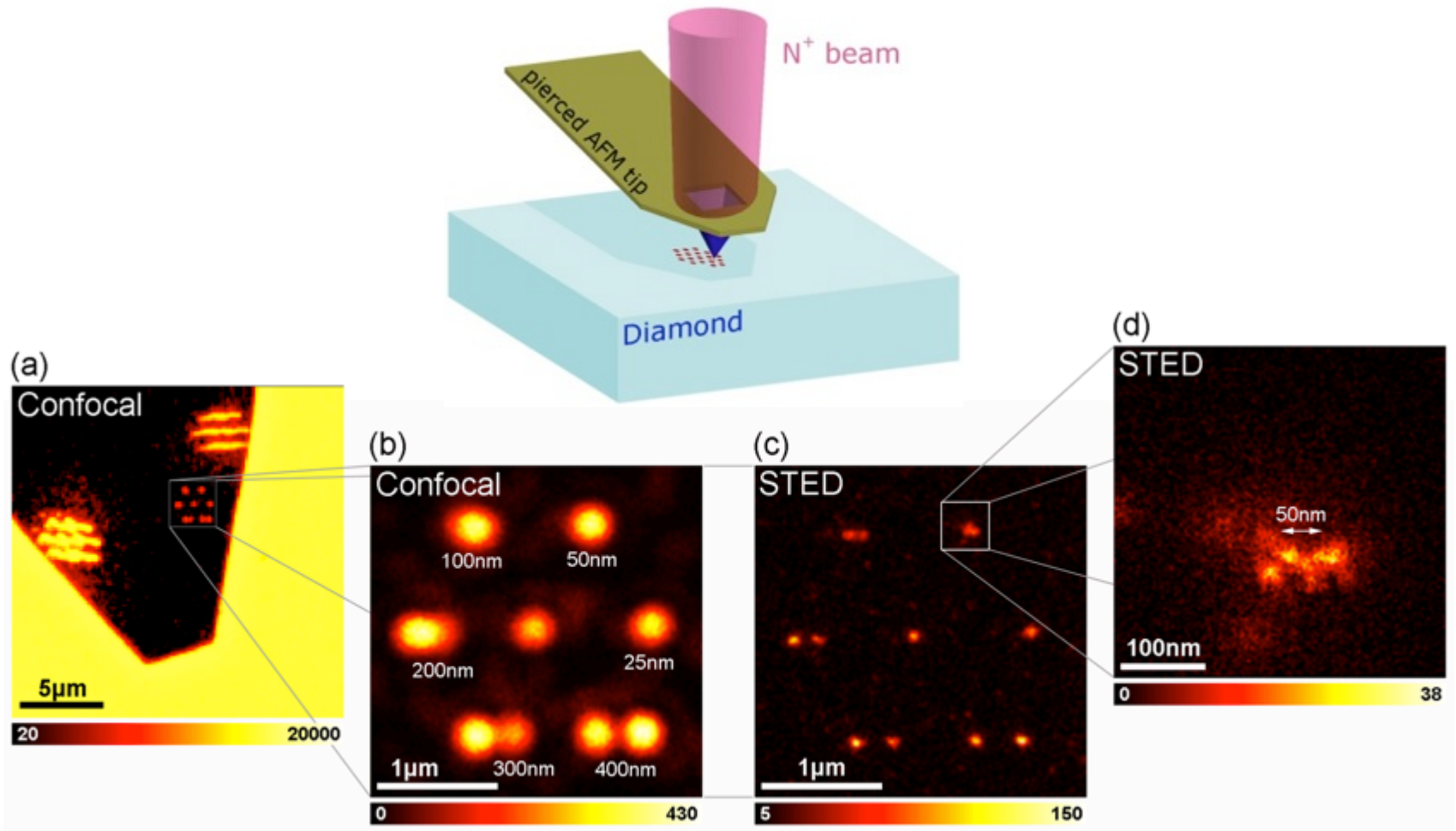
Atomic force microscope



Hole made by Focussed Ion Beam

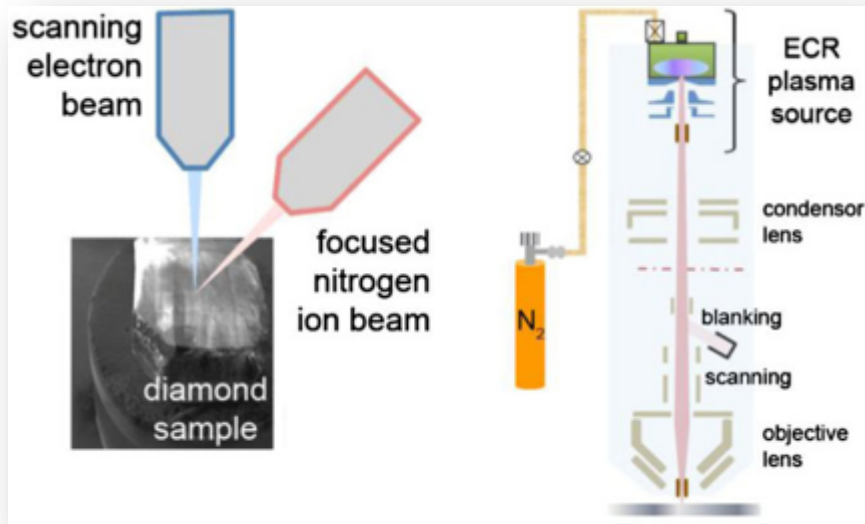


Reduced hole => below 20 nm

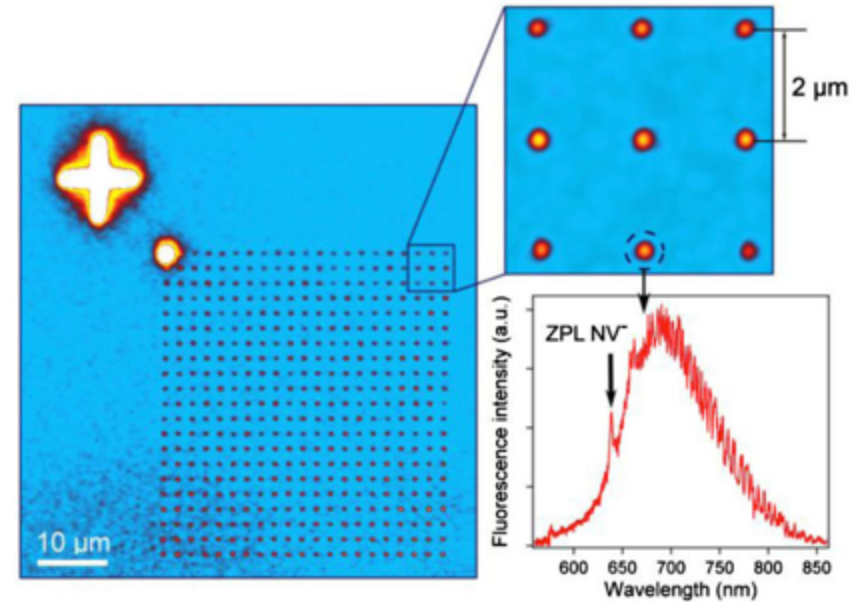


Non Contact Mode: We can implant into pillars, photonic crystals etc.

Nitrogen Focused Ion Beam (FIB)

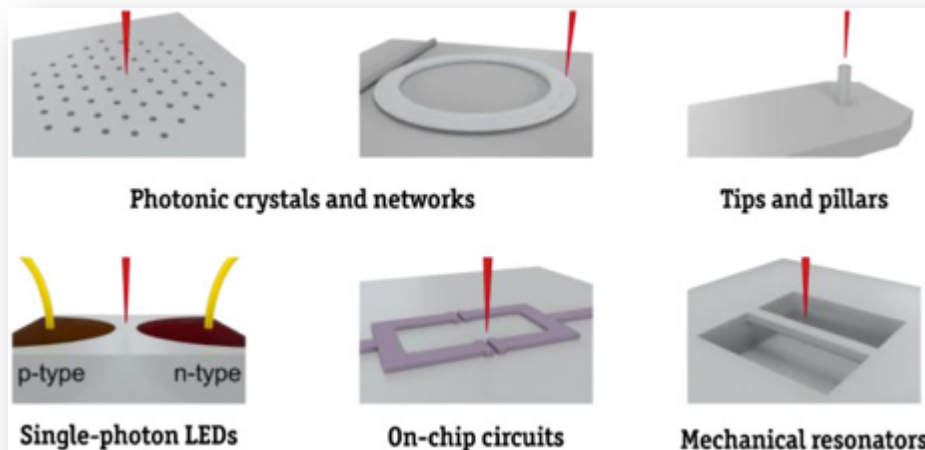


In collaboration with Orsay Physics



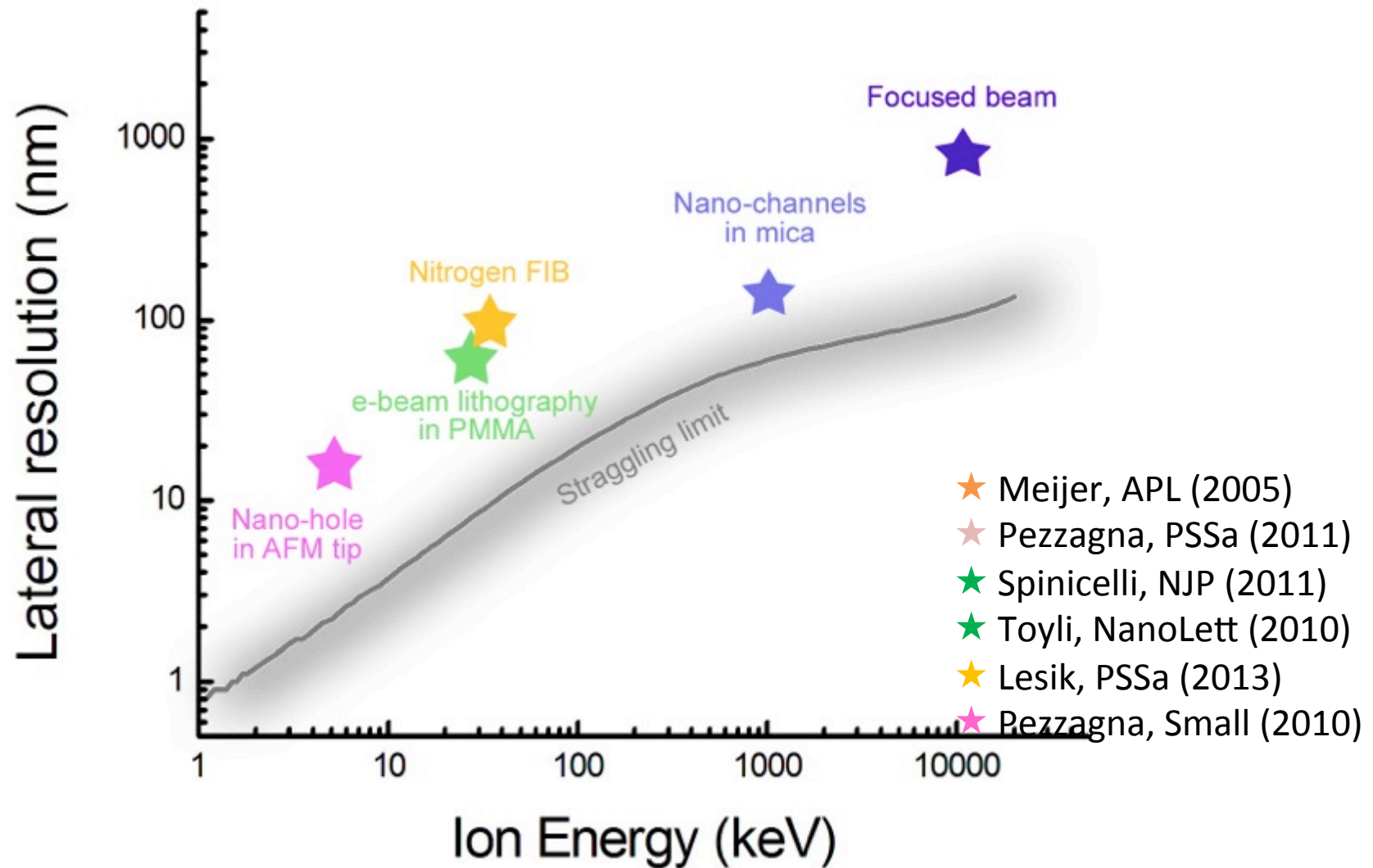
Lesik *et al.*, Phys. Stat. Sol. A (2013)

A wide range of applications...



Cachan, ULeip

High resolution ion implantation



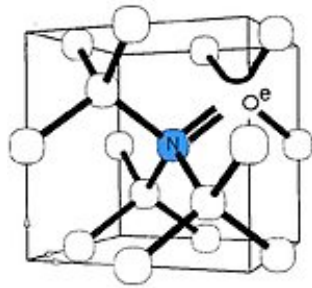
Realization idea: production of NV-centers by N implantation into diamond

requirements:

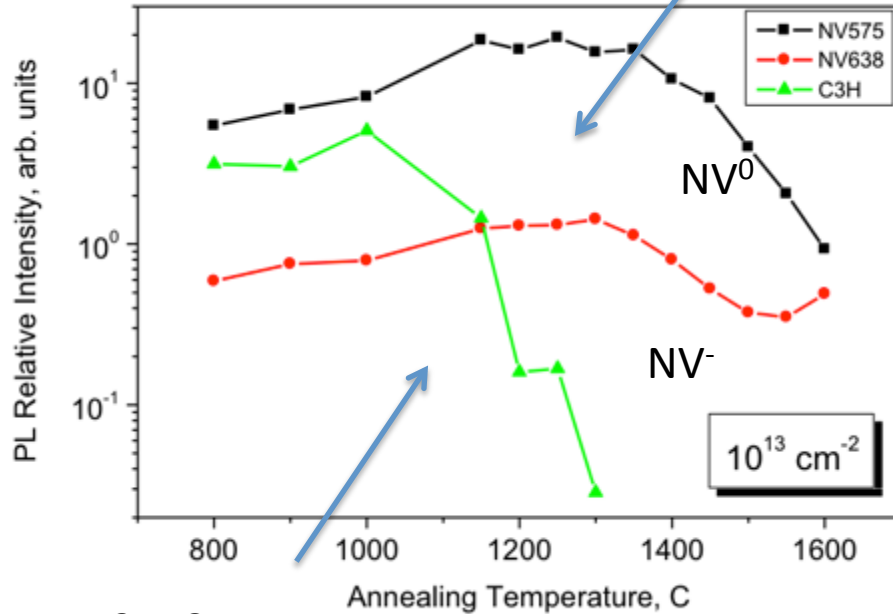
**technical solutions to implant countable single
ions with nm spatial resolution**

**Physical solution: high yield production of NV
centers, charge state control, mobility of NV**

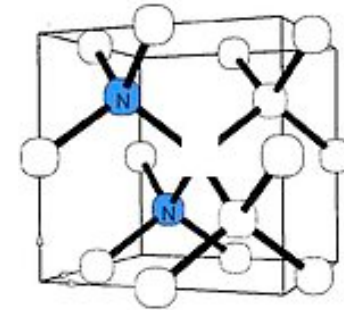
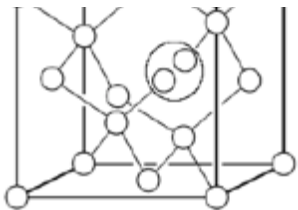
Material: E6: 3x3 mm (100)
optical grade!
100kV CN⁻ Implantation



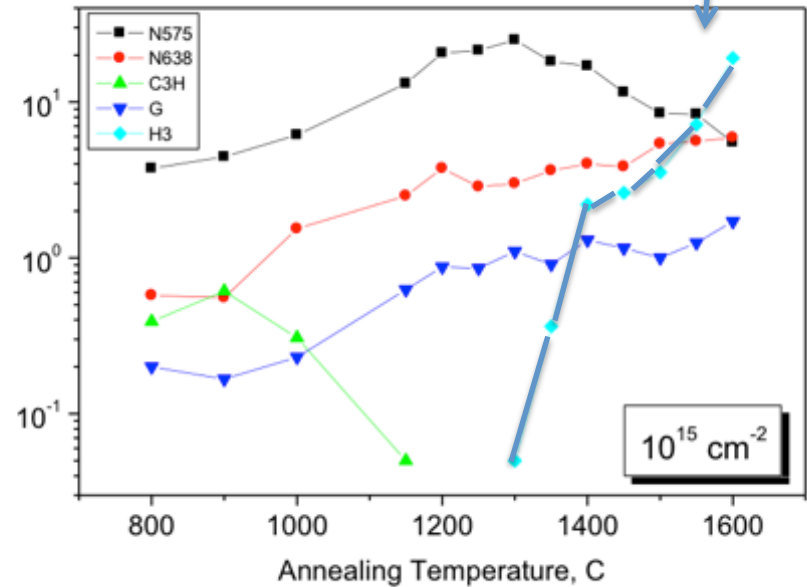
NV-center



3H-Center

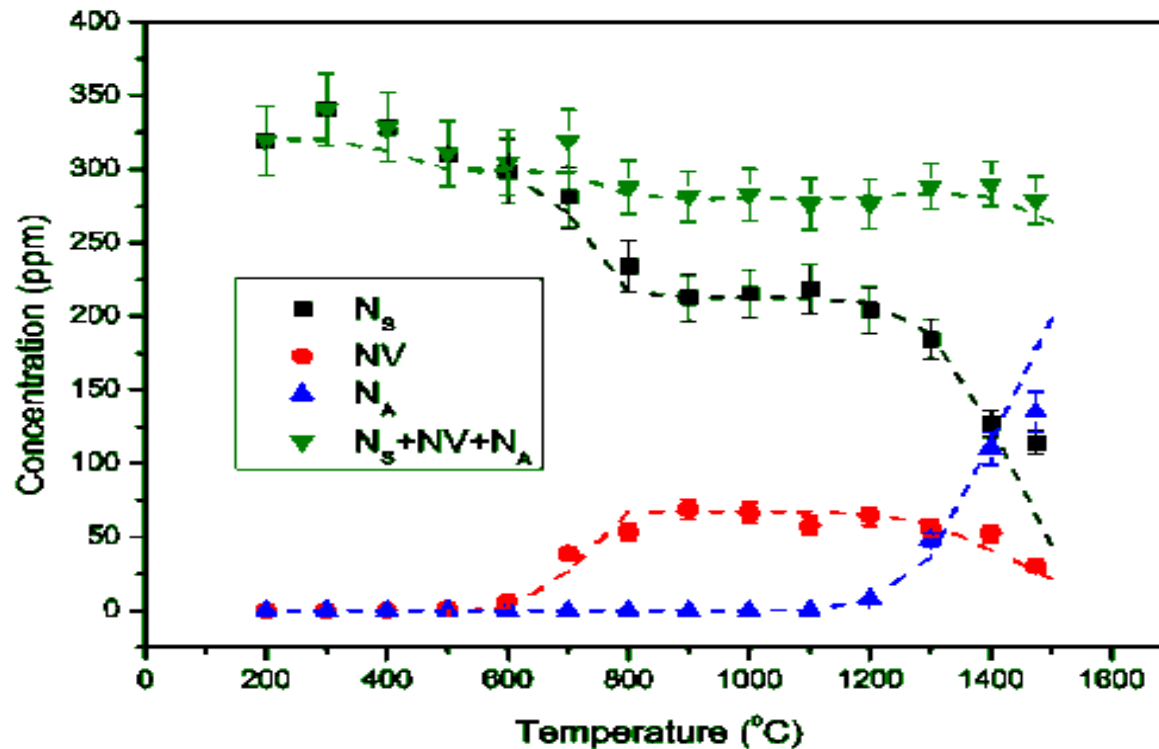


H3-center



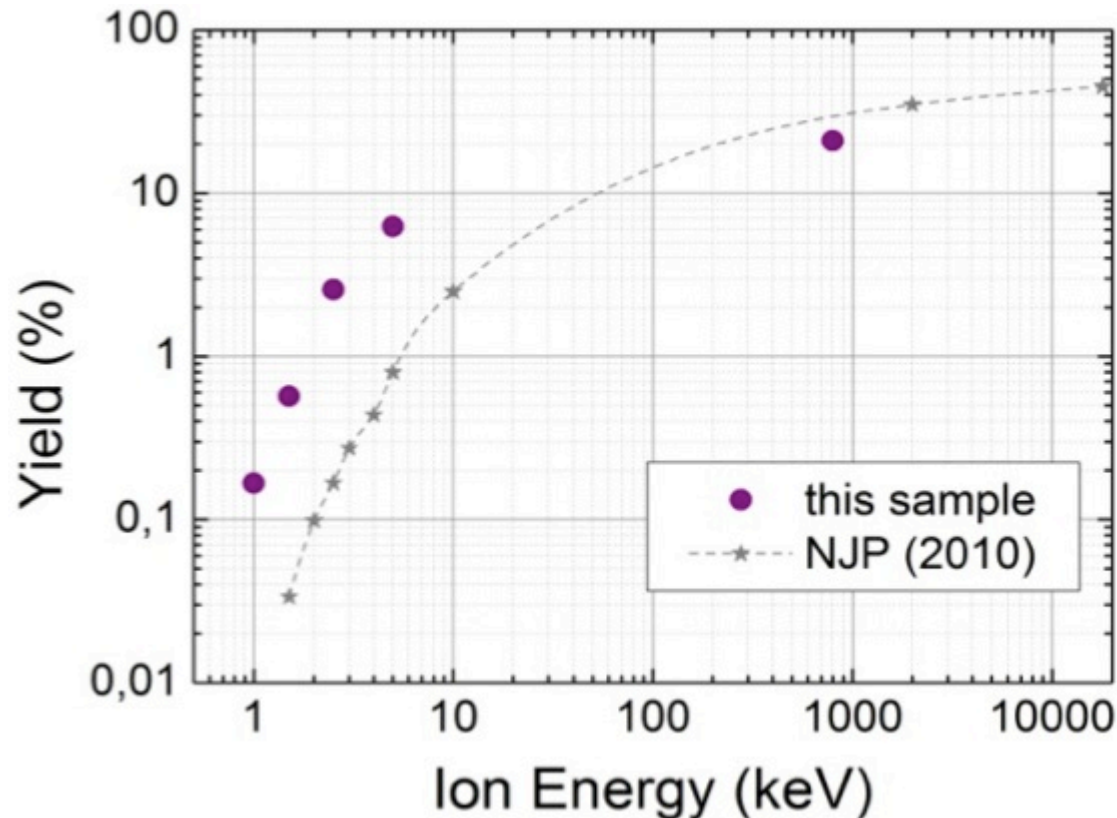
ULeip, UStutt

Creation Efficiency



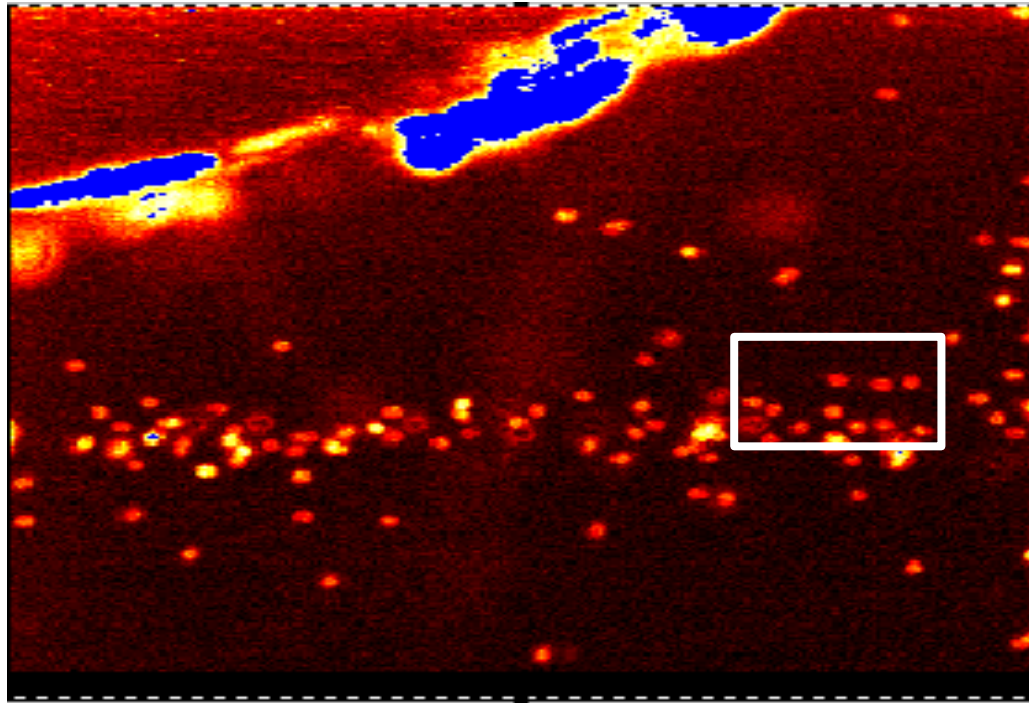
Creation Efficiency

10x Improvement by annealing optimization



Diffusion of single NV?

Optical detection of single NVs:

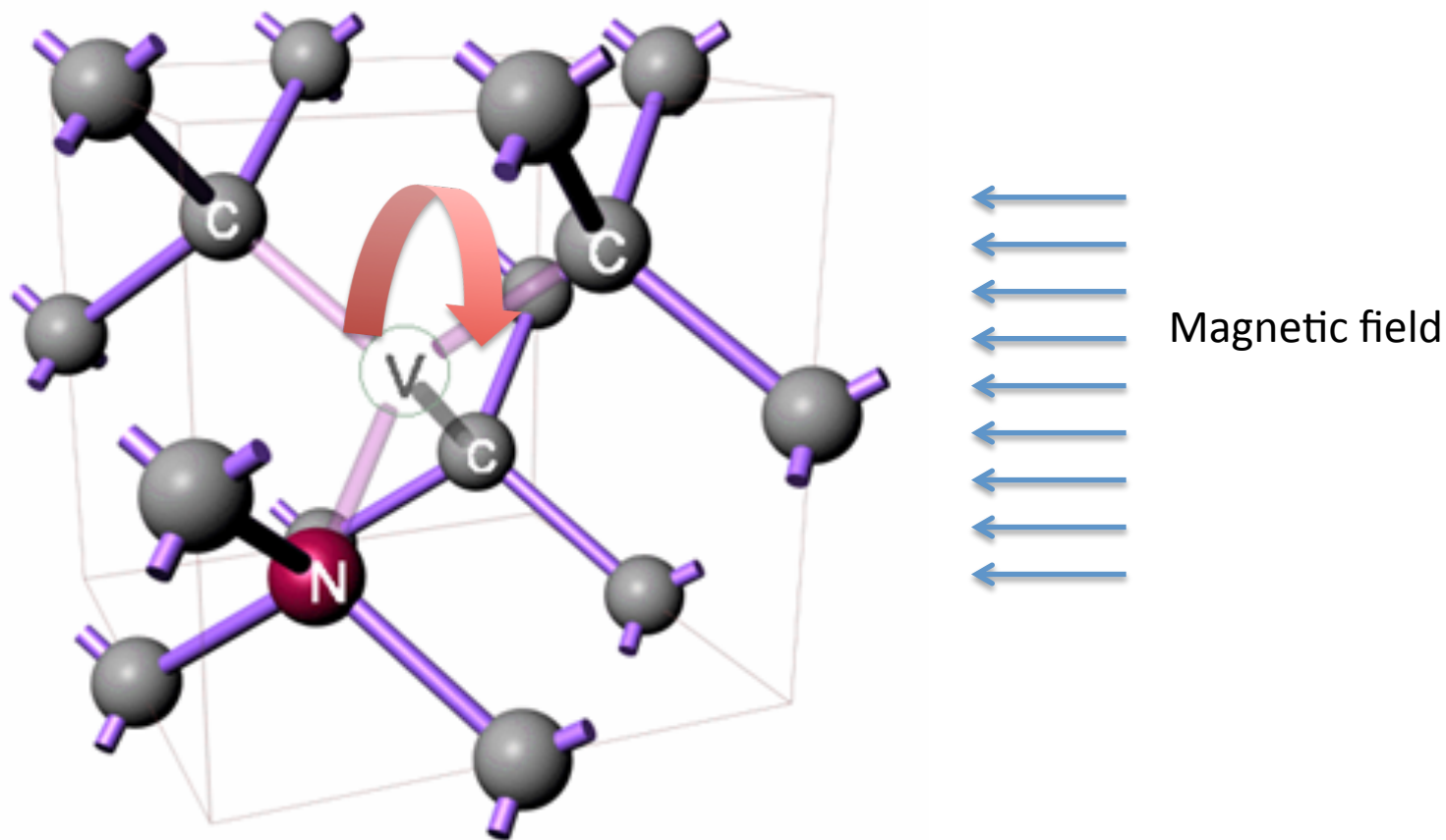


No change @ 1100° C 90 min
resolution 5 nm

Cachan, ULeip

Wildanger, Roch, Meijer 2012 in prep.

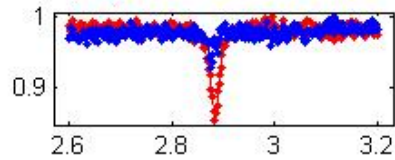
ODMR for orientation control



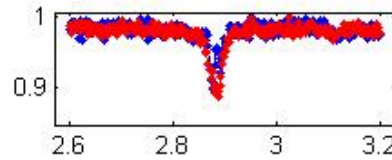
Orientation of single NVs?

ODMR:

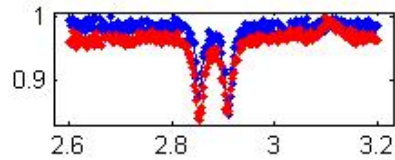
Title, Report 2012-03-13 19-14-56.xml



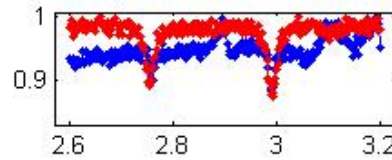
Title, Report 2012-03-14 16-05-11.xml



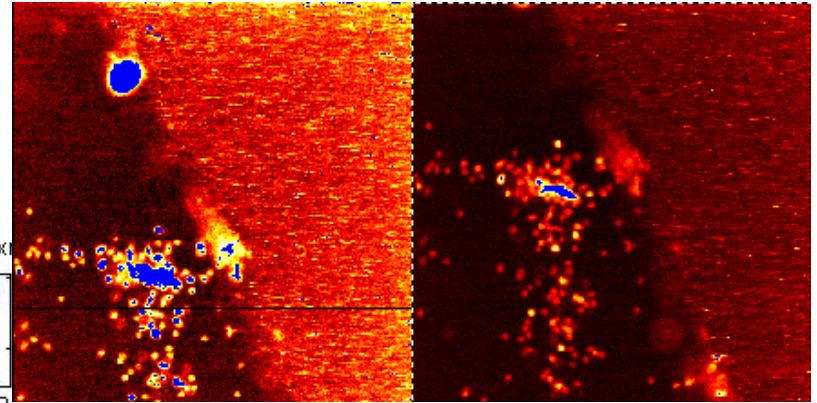
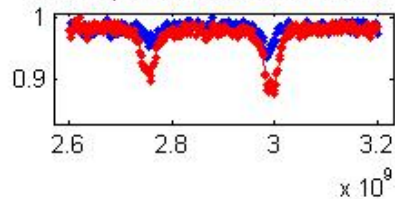
Title, Report 2012-03-14 15-53-24.xml



Title, Report 2012-03-14 16-18-18.xml



Title, Report 2012-03-14 16-37-16.xml



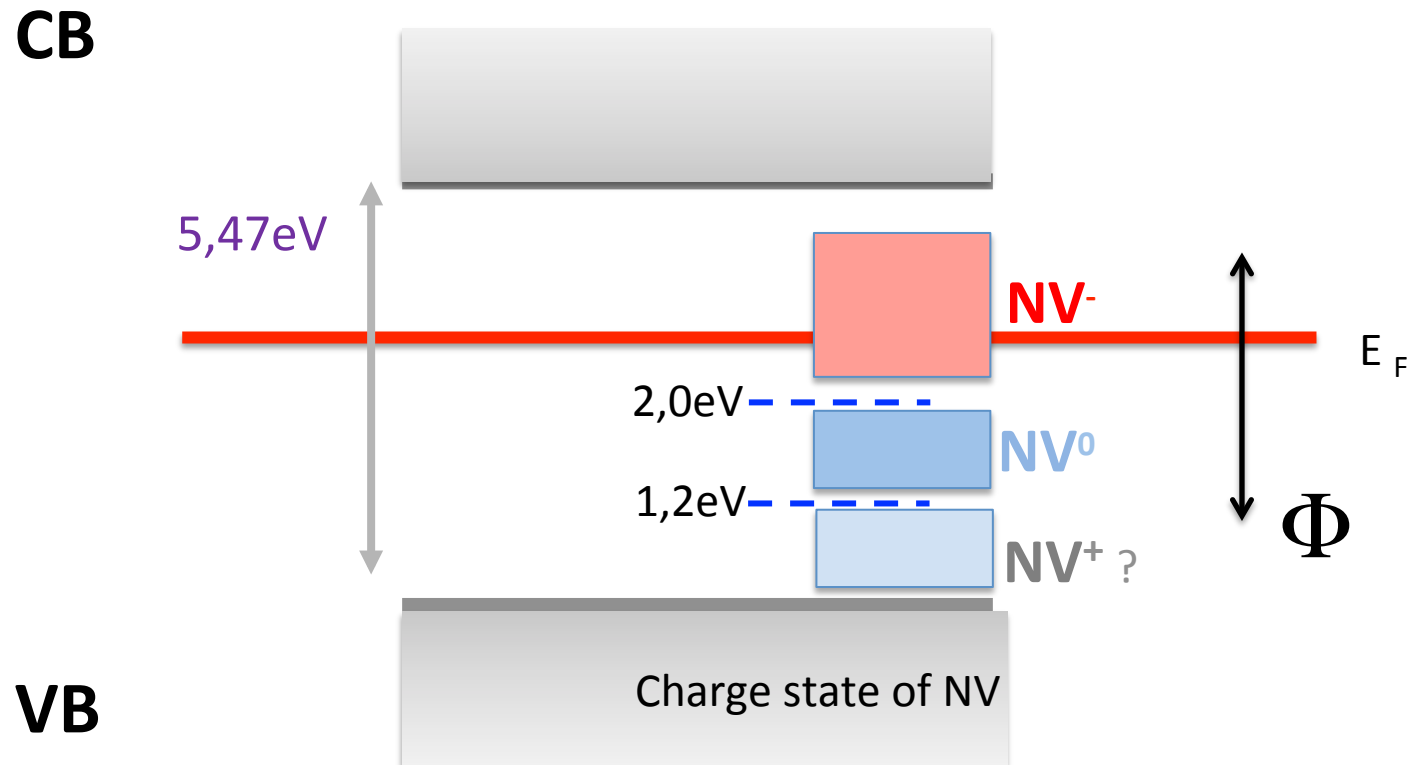
No change @ 1100° C 90 min

Charge state control

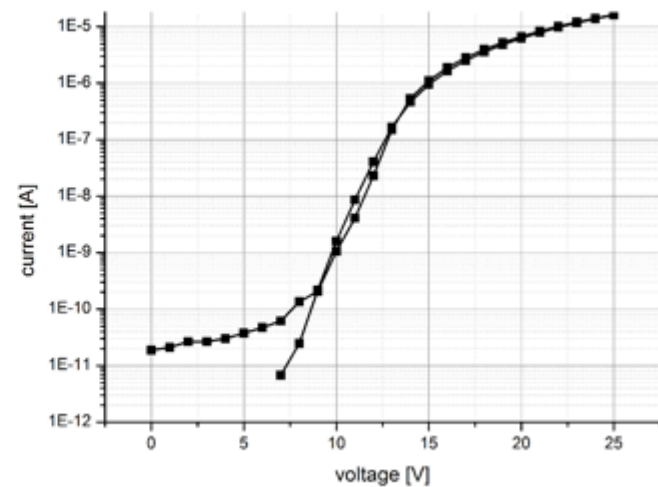
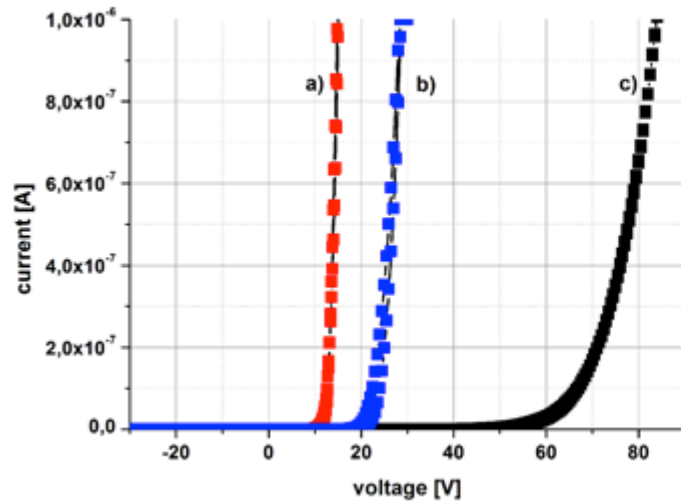
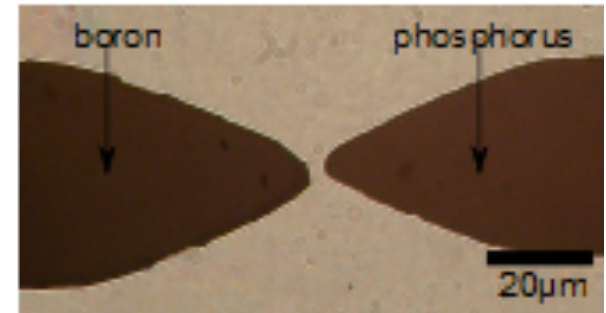
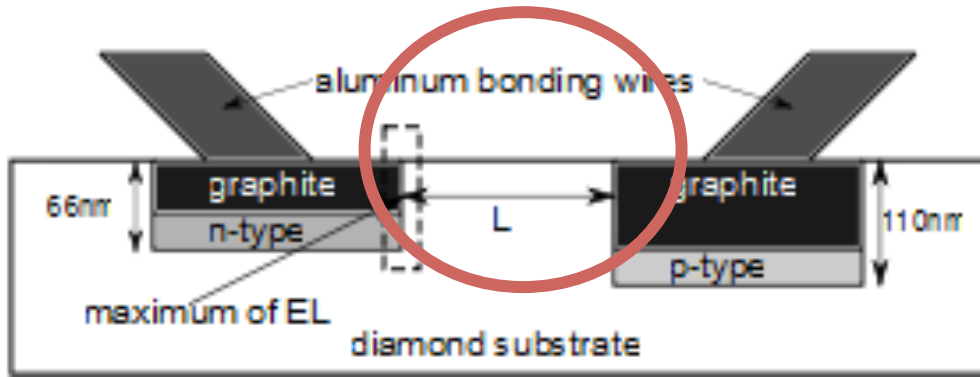
“Active control by applied voltage”

Individual Addressing

“Active control by applied voltage”



Bipolar: In-plane PIN-Diode



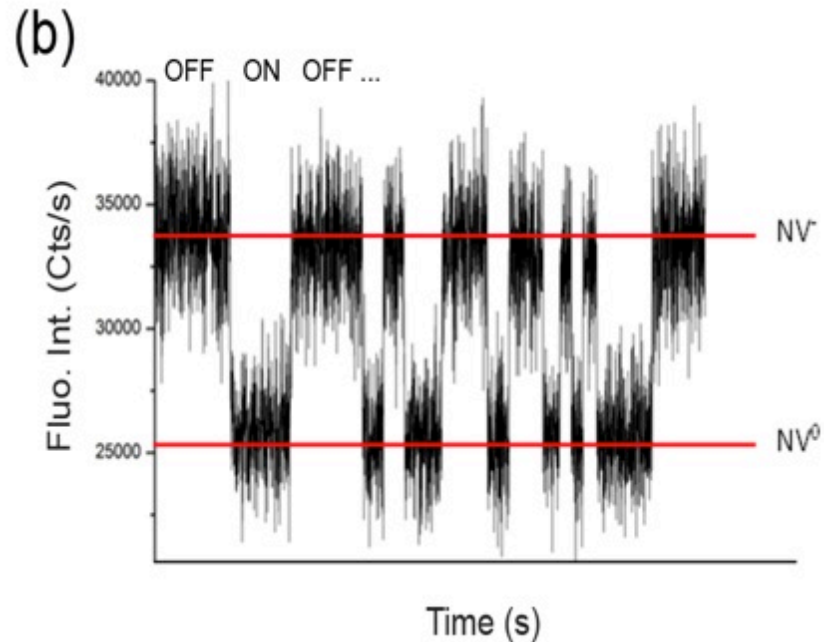
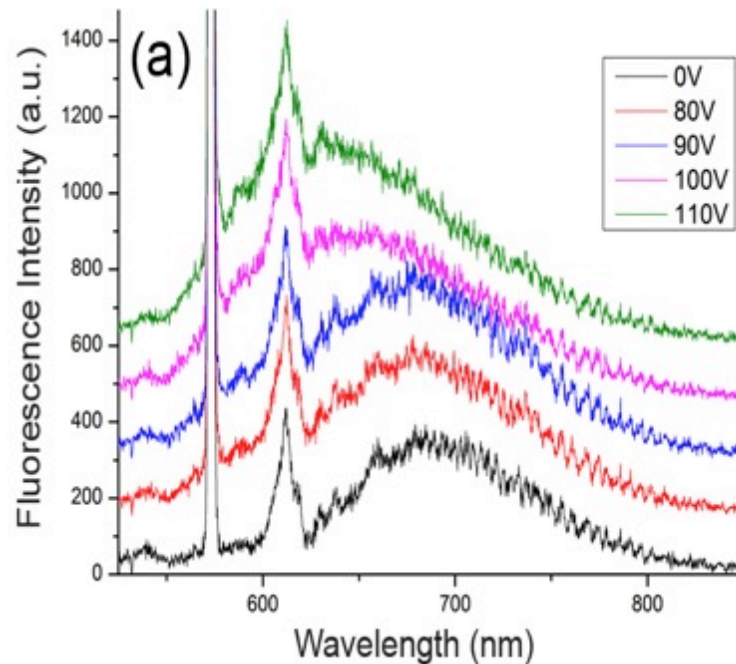
Lohrmann, et al. APL 2011

SP-LED by growing: N. Mizuochi et al.

Nature photonics 2012

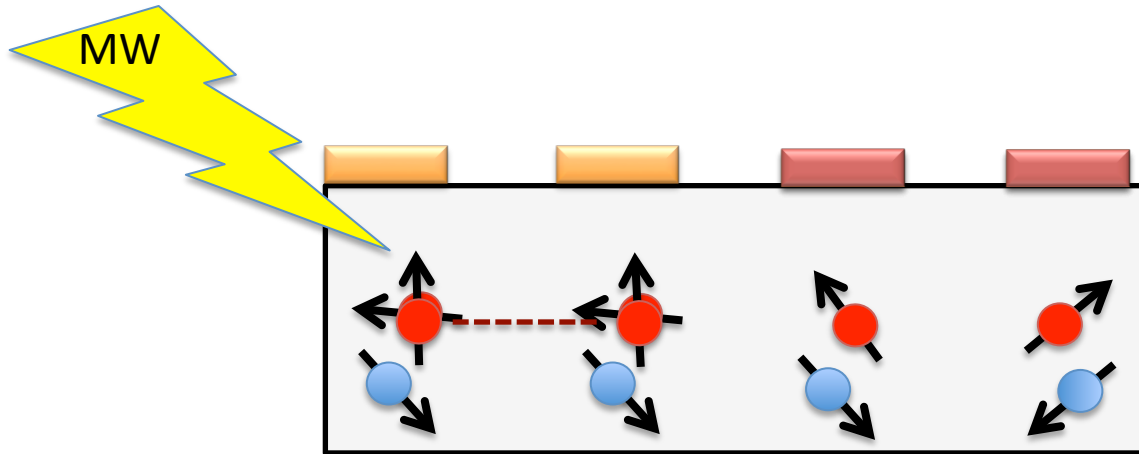
PL-Intensity of a single NV

from NV^- to NV^0



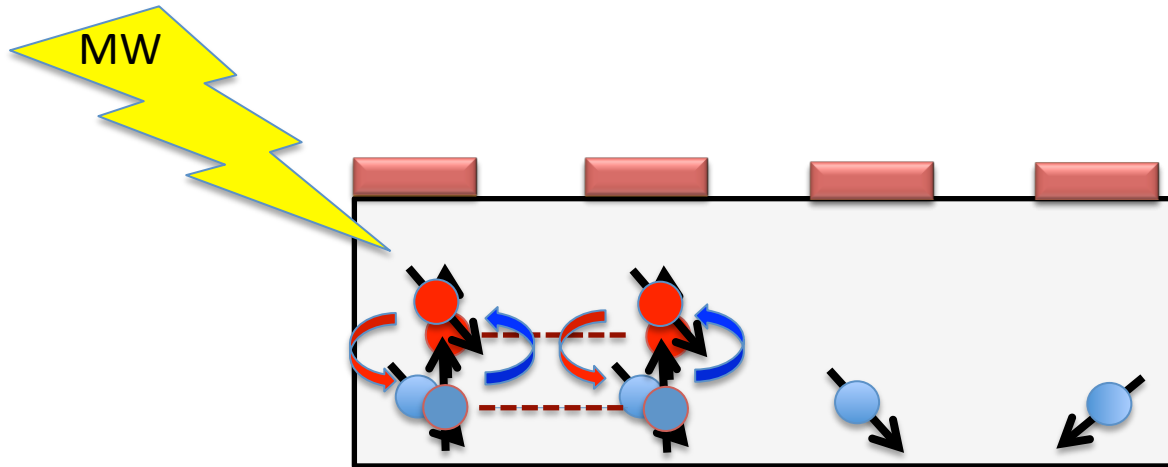
May be a dynamic process?
better $\text{NV}^+ \rightarrow \text{NV}^-$?

Addressing of NVs by active charge control



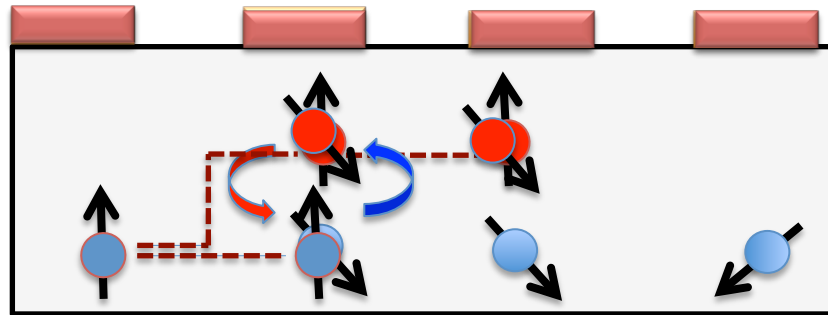
Initialization

Addressing of NVs by active charge control



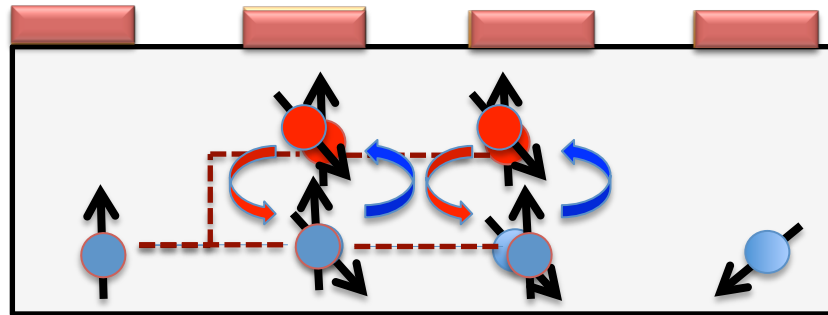
Initialization

Addressing of NVs by active charge control



Initialization

Addressing of NVs by active charge control

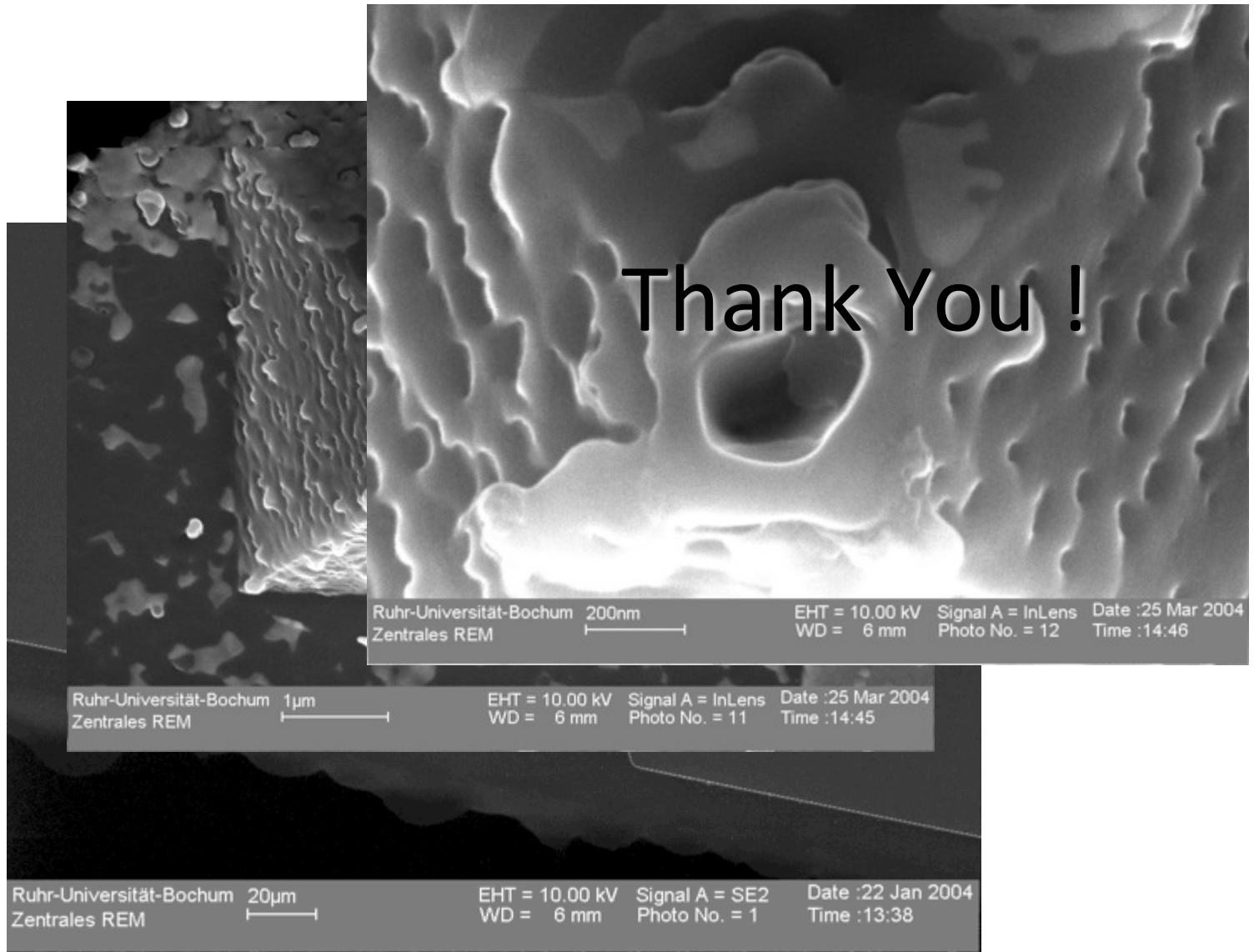


Initialization

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. Bishop FZR