Wafer-scale nanofabrication of single telecom quantum emitters in silicon

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LEAPS meets Quantum Technology

15-20 May 2022

FWIM - Quantum Technology and Materials
PhD Student

Partner von DRESDEN concept exzellenz-dresden.de

HZDR

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Outline

1. **Motivation**

2. **State of the art: G-center in Silicon**
   - Atomic configuration
   - Creation

3. **Experimental setup**
   - Single-defect spectroscopy (CFM)
   - Hanbury-Brown & Twiss (HBT) experiment

4. **Experimental results**
   - FIB writing of single telecom quantum emitters (FIB)
   - Wafer-scale fabrication of single telecom quantum emitters (PMMA)

5. **Outlook**

6. **Summary**

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On-chip quantum photonics in a silicon on insulator (SOI) platform

Single-photon source

Can SOI host single-defects ?

Single-photon detector 1 (SNSPD)

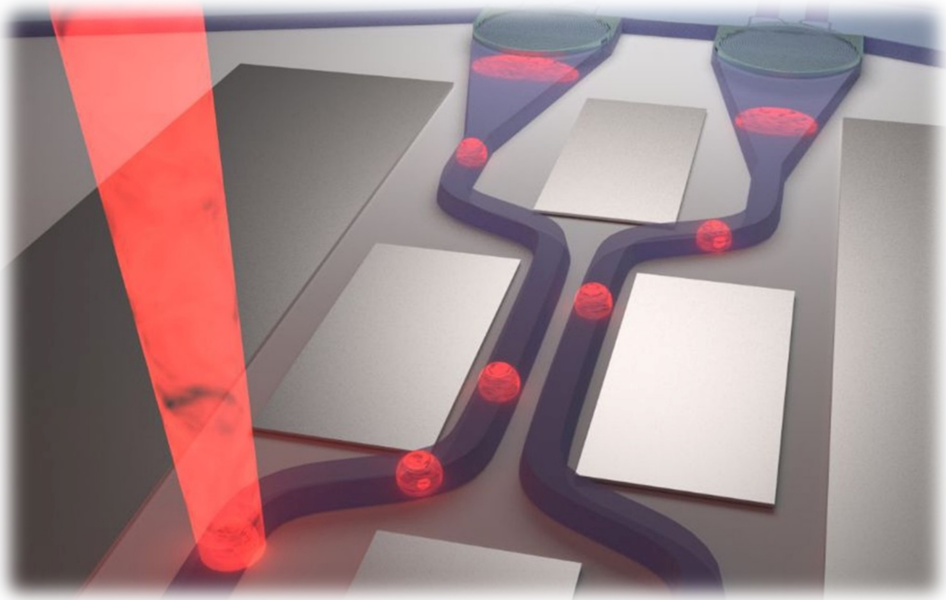
Single-photon detector 2 (SNSPD)

Existing in SOI

Required properties of single-photon emitters:

↓

- Purity
- On-Demand
- Brightness
- Stability



M. Schwartz et al. Nano Lett. 2018, 18, 11, 6892–6897

Optical circuits / routing (waveguides & beamsplitters)

Existing in SOI

Monolithic semiconductor - superconductor quantum circuit in silicon

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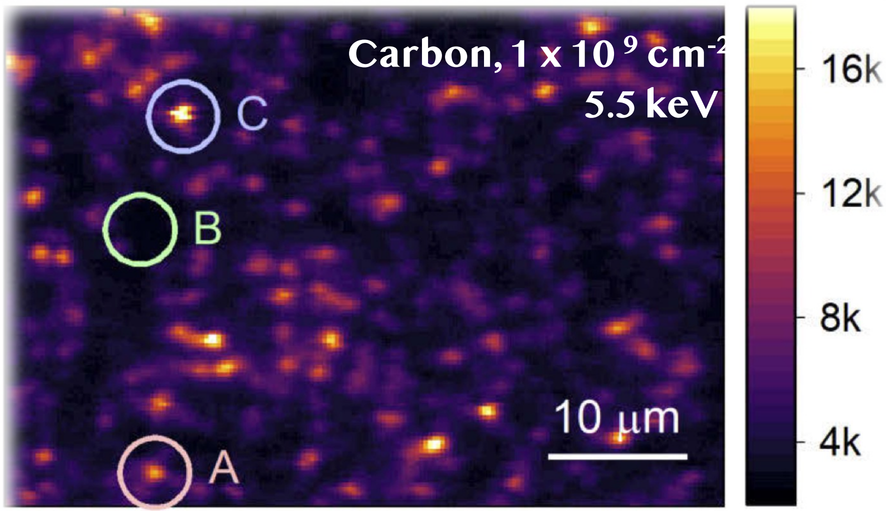

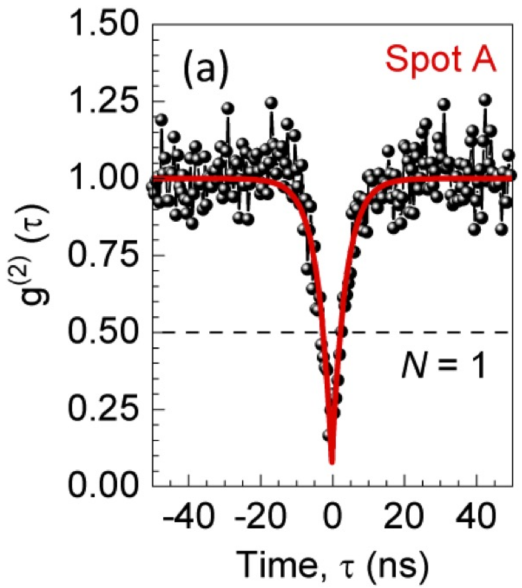

M. Hollenbach et al. :“Engineering telecom single-photon emitters in silicon for scalable quantum photonics“, Optics Express Vol. 28, Issue 18, pp. 26111-26121 (2020)

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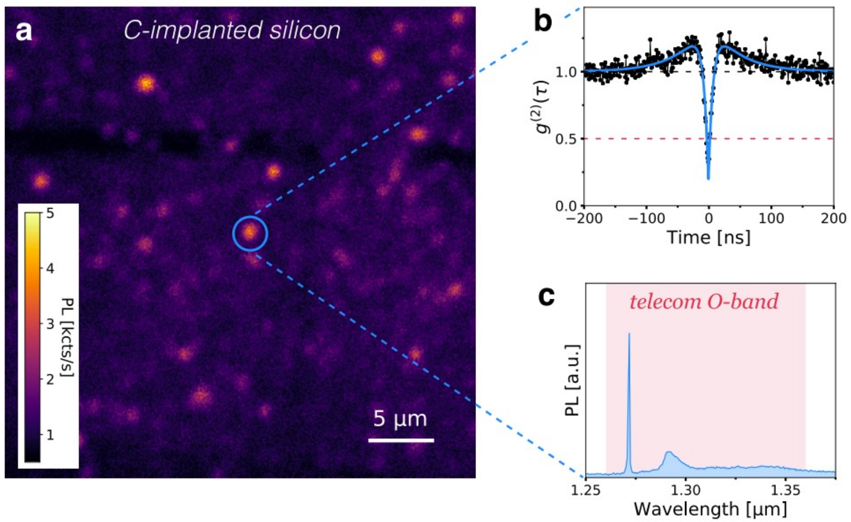
How to create "artificial atoms" in an SOI wafer?

Laboratoire Charles Coulomb, France

Single artificial atoms in silicon emitting at telecom wavelengths
Methods

W. Redjem[1],* A. Durand[1],* T. Herzig[2], A. Benali[3], S. Pezzagna[2], J. Meijer[2], A. Yu. Kuznetsov[4], H. S. Nguyen[5], S. Cueff[5], J.-M. Gérard[6], I. Robert-Philip[1], B. Gil[1], D. Caliste[6], P. Pochet[6], M. Abbarchi[3], V. Jacques[1], A. Dréau[1],† and G. Cassabois[1]
Laboratoire Charles Coulomb, Université de Montpellier and CNRS, 34095 Montpellier, France



⇒ High fluence C-broad-beam irradiation + RTA at 1000 °C (5x 10^{13} cm^{-2}, 36 keV)

Nature Electronics volume 3, pages 738–743 (2020)

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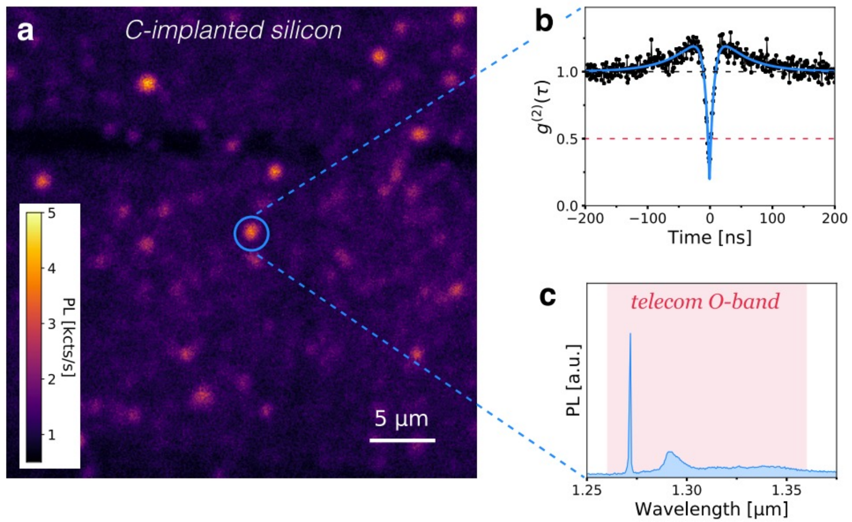

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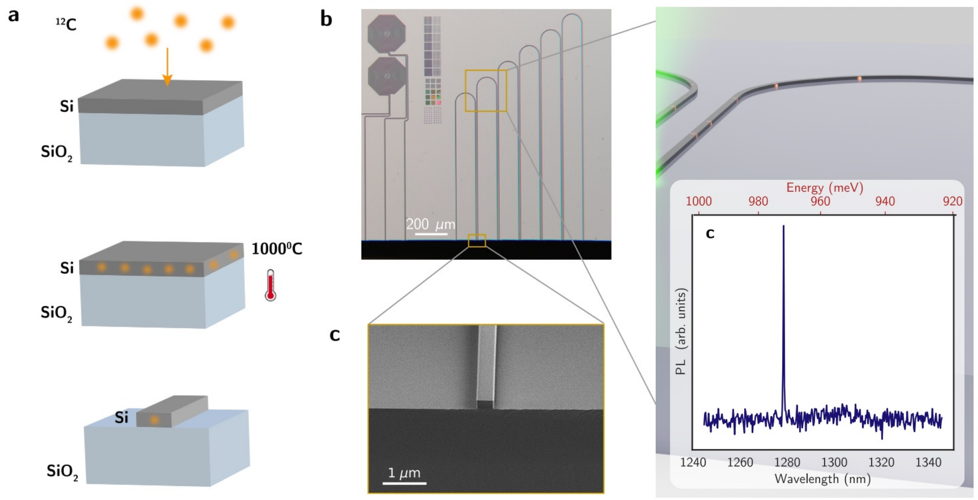
Nature Electronics volume 3, pages 738–743 (2020)

Massachusetts Institute of Technology, USA

Individually Addressable Artificial Atoms in Silicon Photonics

Mihika Prabhu[1,†], Carlos Errando-Herranz[1,2,†], Lorenzo De Santis[1,3], Ian Christen[1], Changchen Chen[1], and Dirk Englund[1,*]
[1] *Massachusetts Institute of Technology, Cambridge, USA*
[2] *University of Münster, Münster, Germany*
[3] *QuTech, Delft University of Technology, Delft, Netherlands*



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arXiv:2202.02342v1 (2022)

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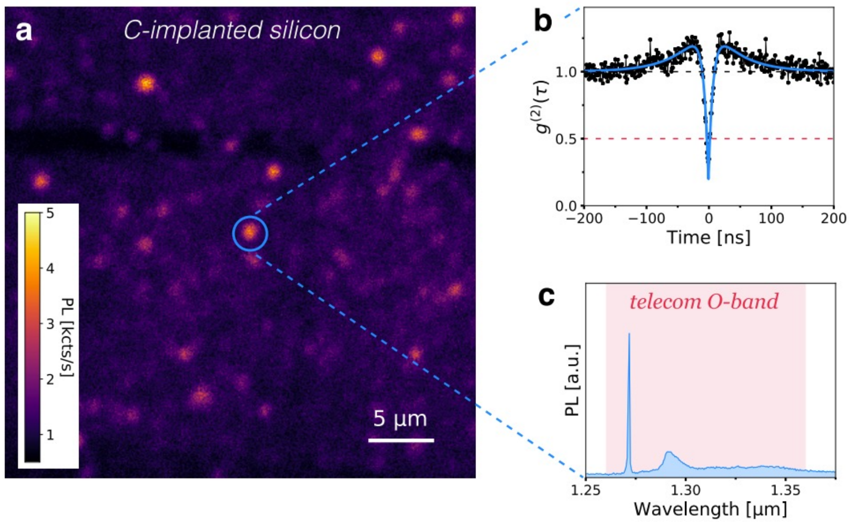

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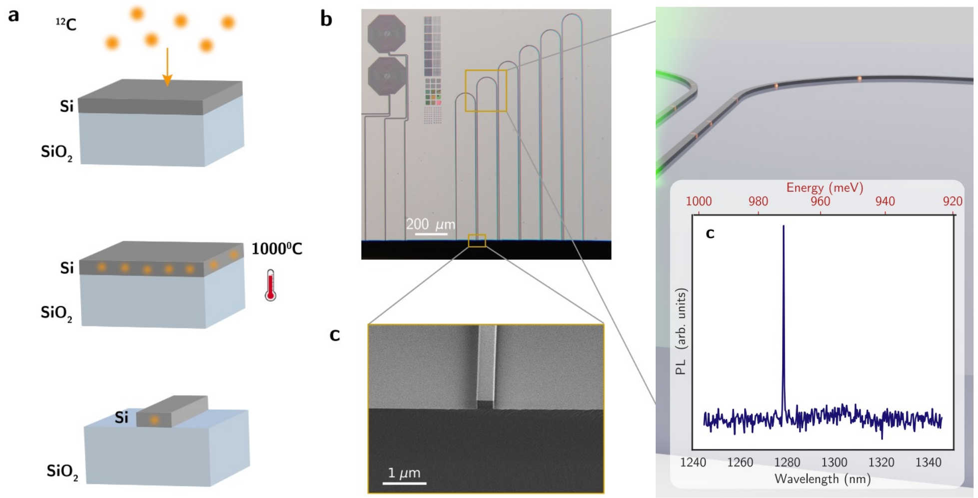


⇒ High fluence C-broad-beam irradiation + RTA at 1000 °C (1x 10^{13} cm^{-2}, 36 keV)

Random positioning of single defects - No controlled creation !

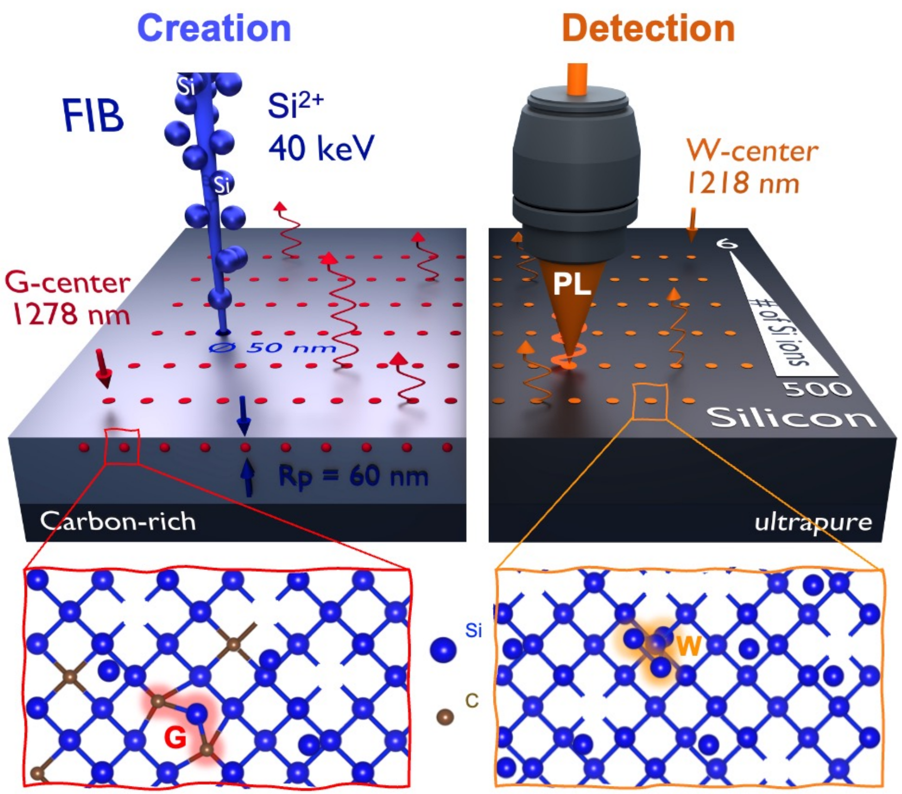
On-chip quantum photonics in a silicon on insulator (SOI) platform

Can we create single defects in silicon at desired locations ?

Required properties of single-photon emitters:

↓

- Purity
- On-Demand
- Brightness
- Stability



Requirements for very large-scale integrated Silicon photonics:

↓

- Local creation
- Scalability
- Accuracy
- Efficiency

Focus of the talk: Controllable creation of single G-centers with sub-100-nm precision

M. Hollenbach et al. :"Wafer-scale nanofabrication of telecom single-photon emitters in silicon", arXiv:2204.13173 (April 2022)

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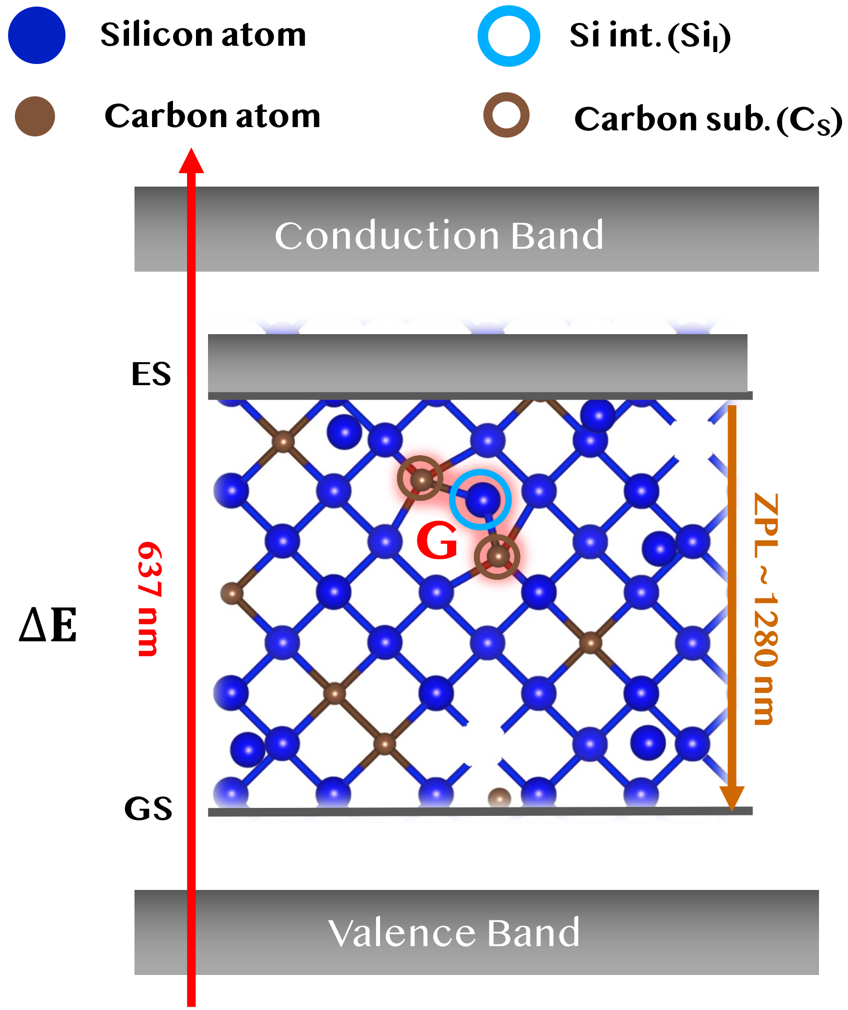
What is the G-center ?... carbon related atomic-sized luminescence center in silicon

- **G-Center: substitutional-substitutional carbon pairs (C_S - C_S) with interstitial silicons (Si_I)**
- **Localization within Si bandgap: Optically active**
- **Zero-phonon line (ZPL) emission at 1278 nm**
- **Spectrally narrowest ZPL in solid state (^{28}Si)**
- **Low-temperature emission in the Telecommunication O-Band**

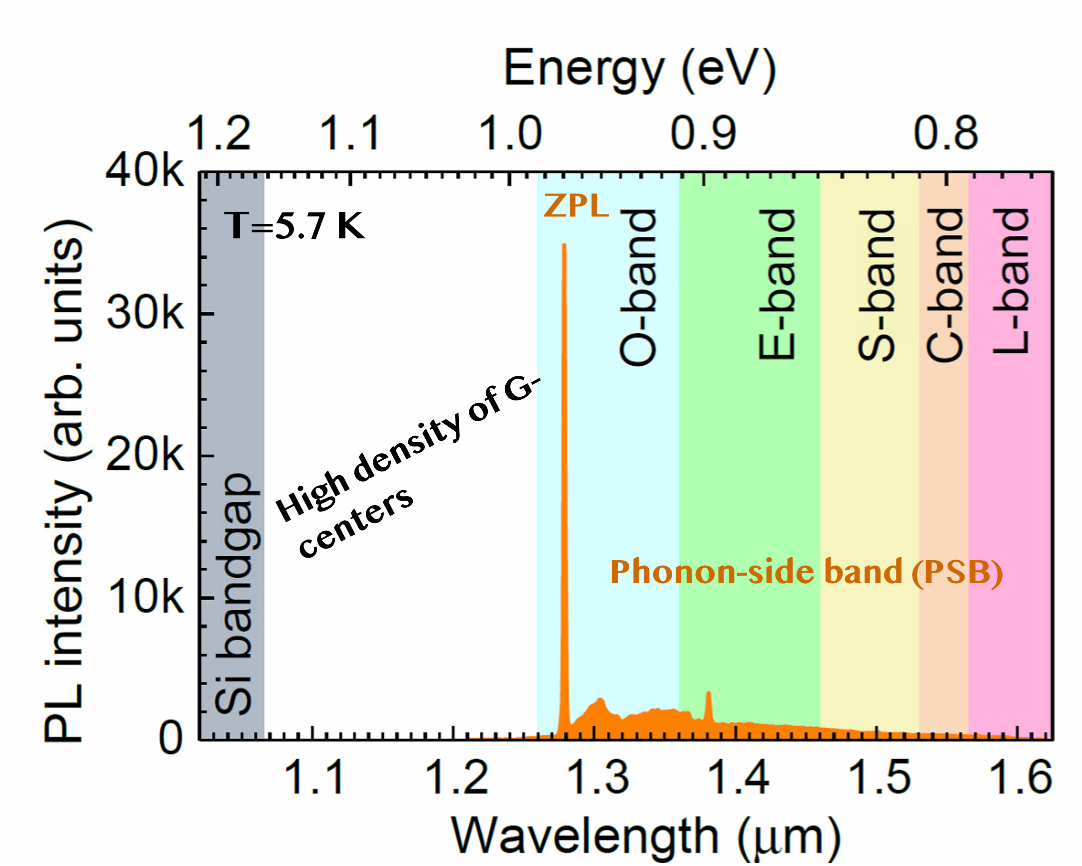
Atomic configuration / Energy level



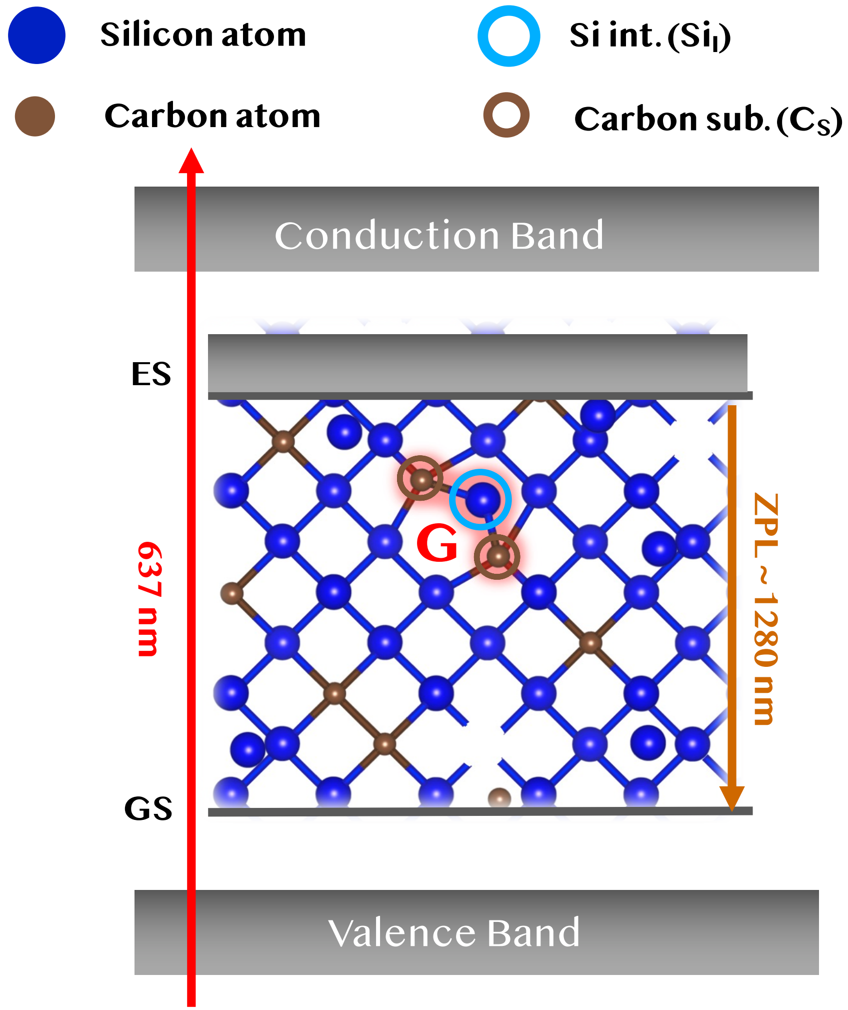
P. Udvarhelyi et al. :"Identification of a Telecom Wavelength Single Photon Emitter in Silicon", Phys. Rev. Lett. 127, 196402 (2021)

What is the G-center ?... emitting in the telecom O-band (1260 – 1360 nm)

Spectroscopic fingerprint of the G-center



Atomic configuration / Energy level



⇒ **Excellent light source for fiber-optic communications**

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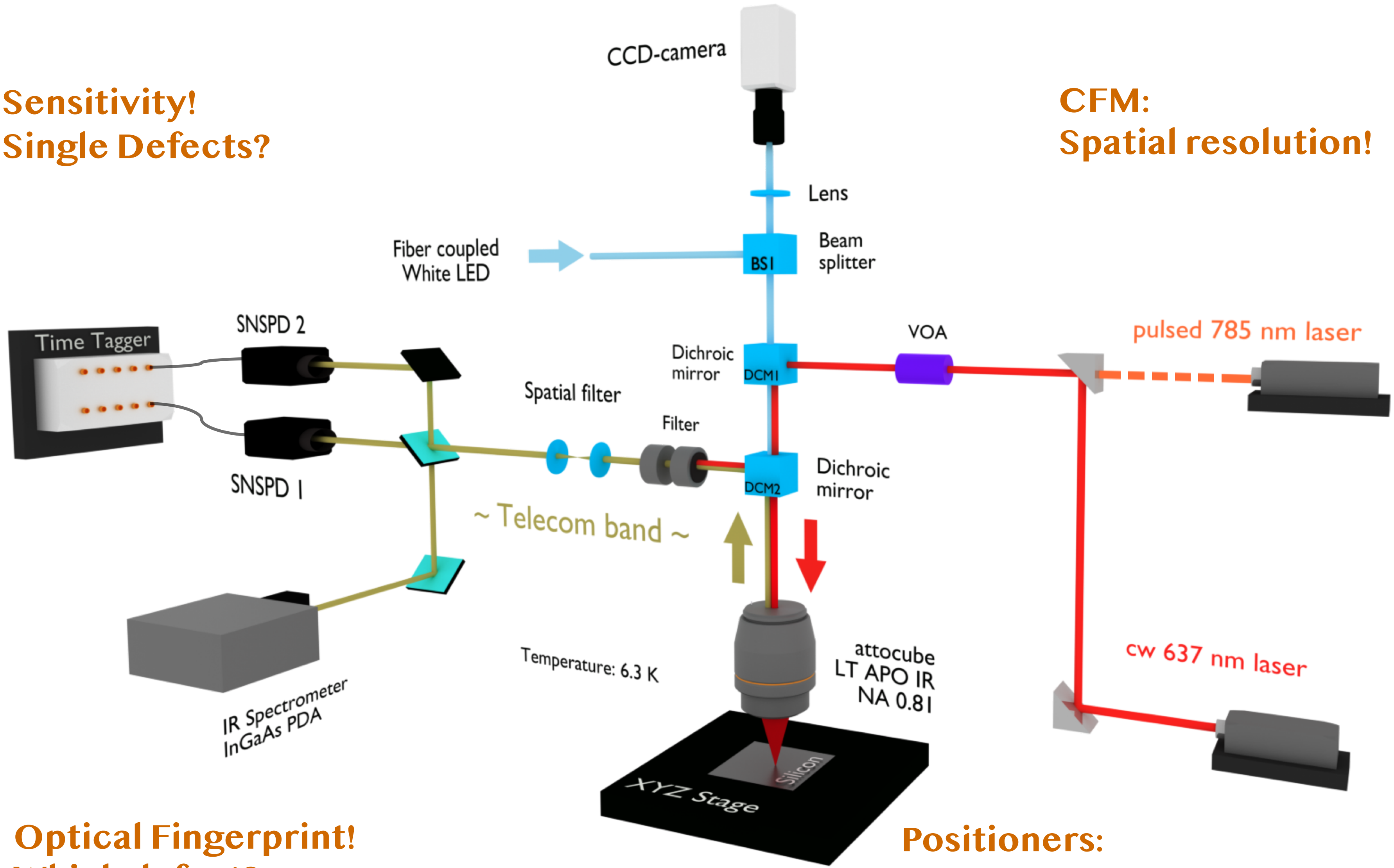
How to read-out the G-center ? ...home-built LT confocal microscope (CFM)

Sensitivity!
Single Defects?

CFM:
Spatial resolution!



Optical Fingerprint!
Which defect?

Positioners:
2D Scans

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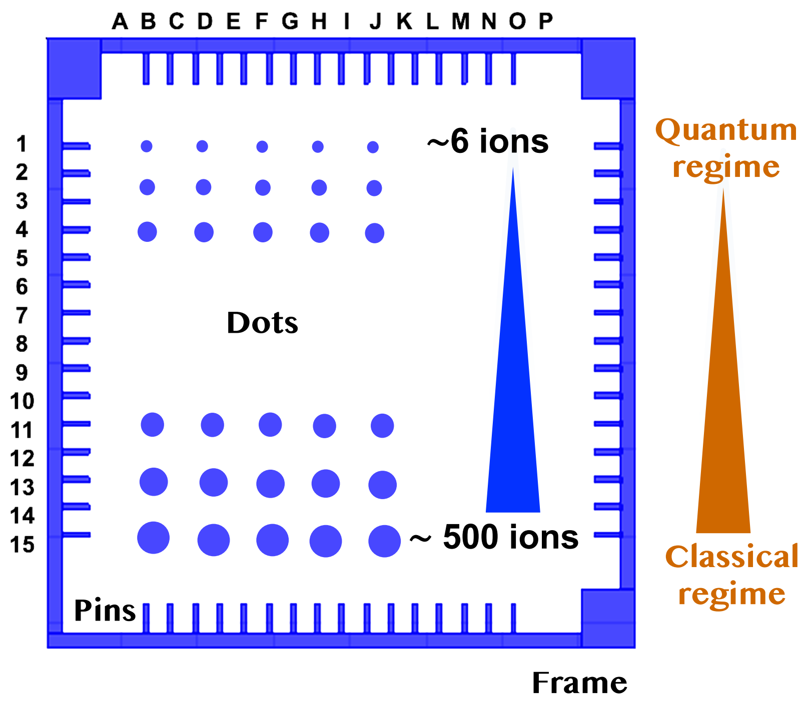
Focused ion-beam writing of G-centers using Si-FIB (LMAIS)

Irradiation layout



Single dot writing
(15 x 16 spots)

Special thanks to N. Klingner and L. Bischoff

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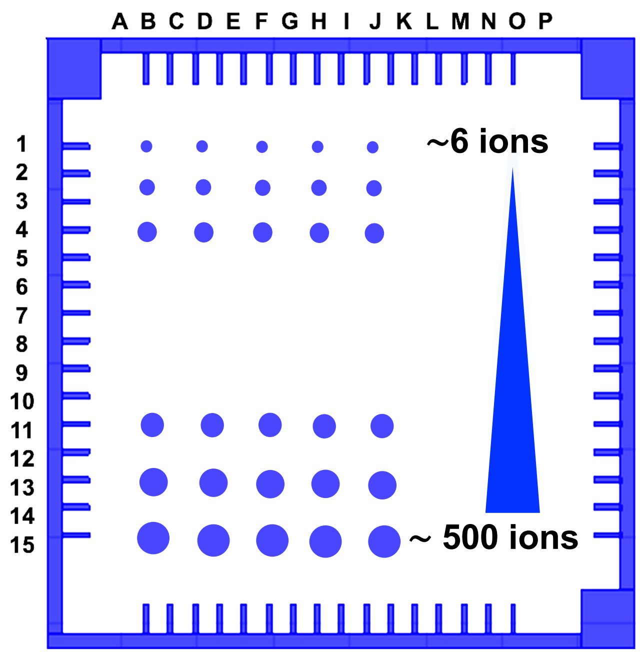

Single dot writing
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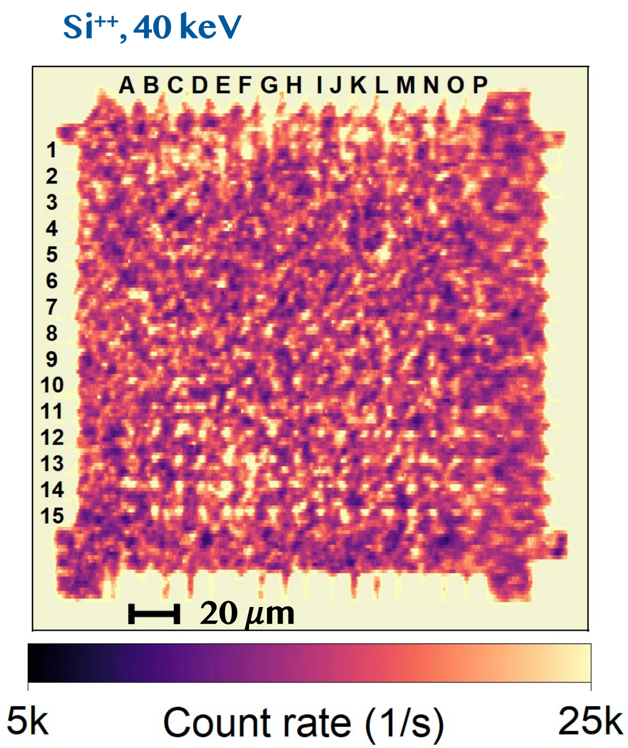
2D confocal photoluminescence maps



LP 1250 nm

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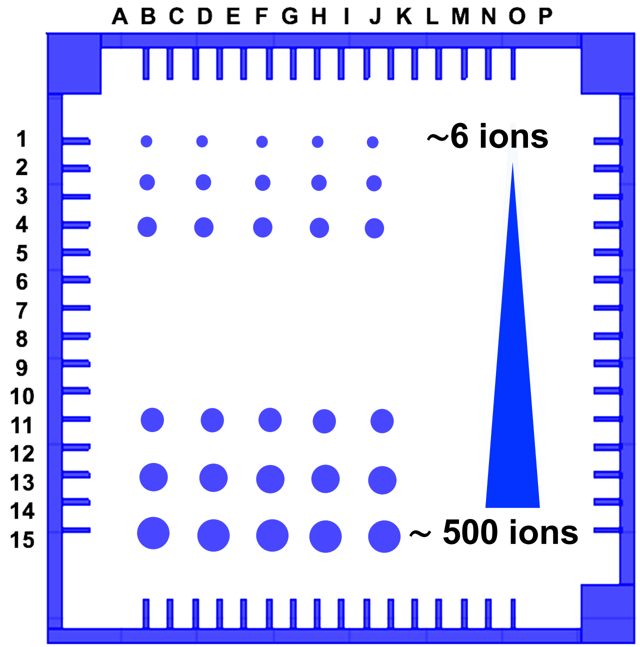

Single dot writing
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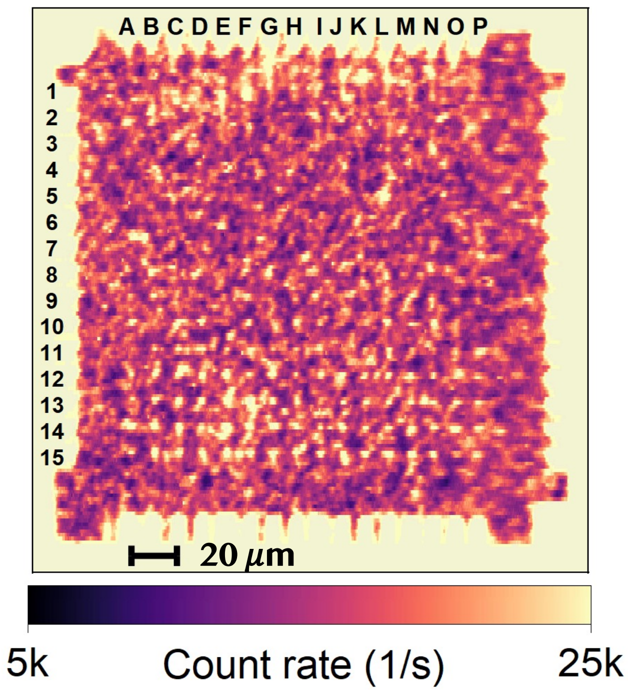
2D confocal photoluminescence maps

Si^{++}, 40 keV



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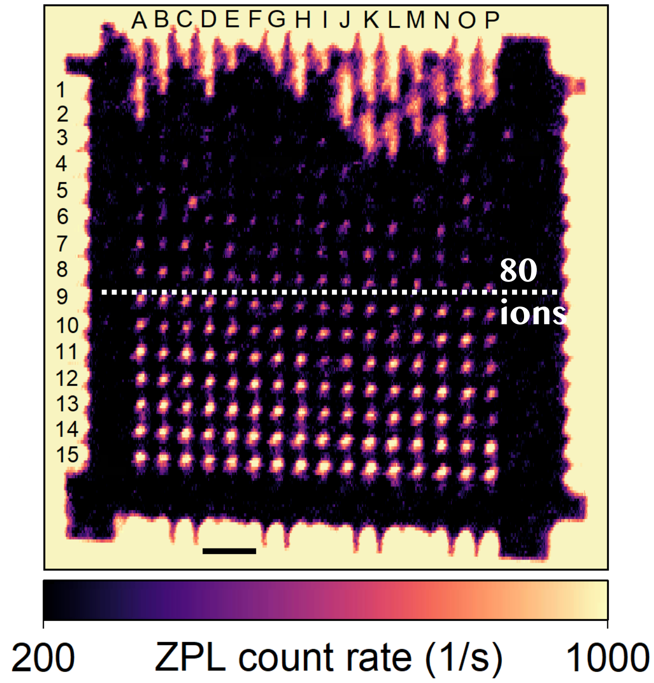

1nm Bandpass
tuned to the ZPL

Local irradiation sites are masked by the background fluorescence ⇒ 1nm BP filter

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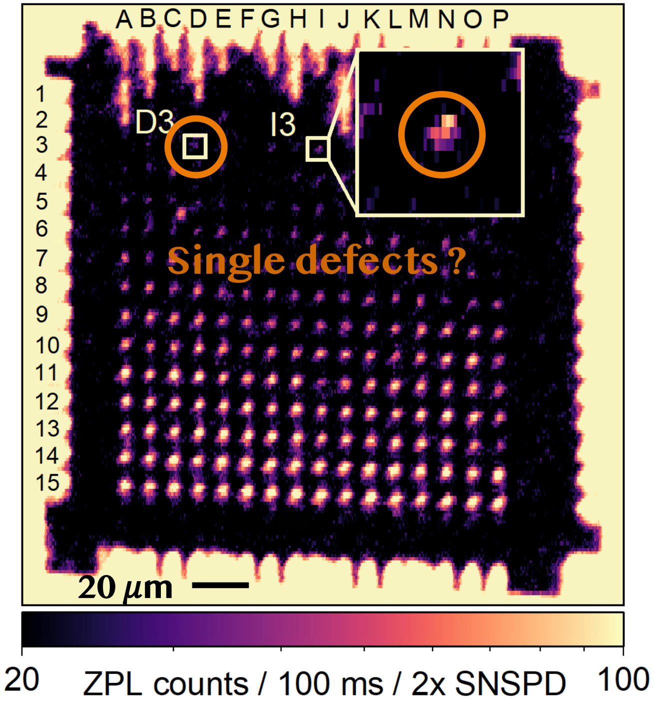
Focused ion-beam writing of G-centers using Si-FIB (LMAIS)

2D confocal PL map

Line 3: (25 ± 5) Si ions/spot



1nm Bandpass

Diffraction-limited spots = single telecom photon emitter ?

Member of the Helmholtz Association
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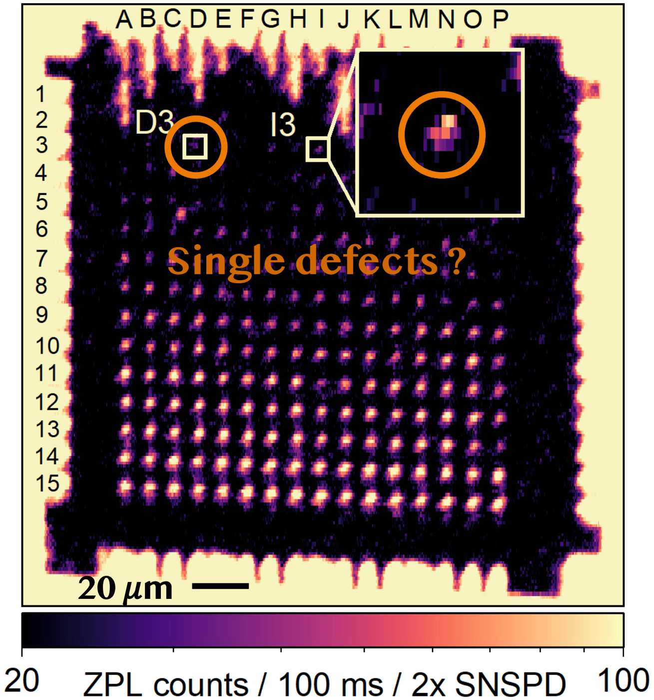
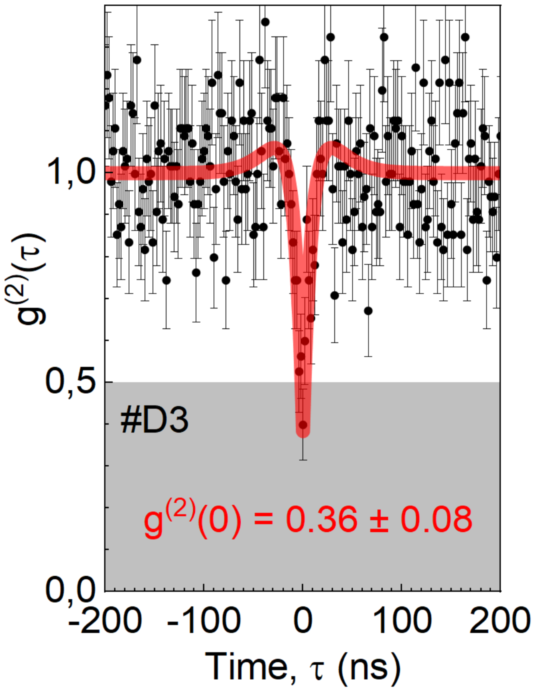


1nm Bandpass

HBT - Interferometry



1nm Bandpass

Single Emitter : Never two photons at a time = no coincident counts at zero time delay

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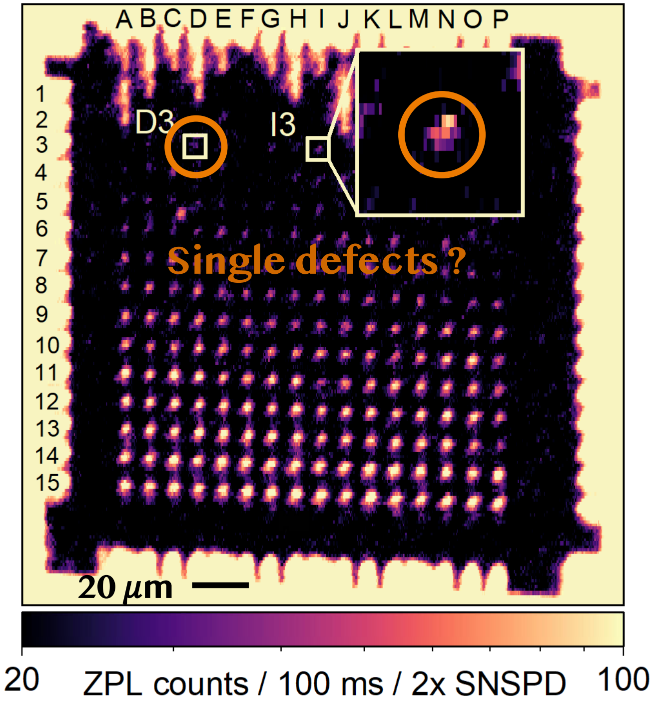

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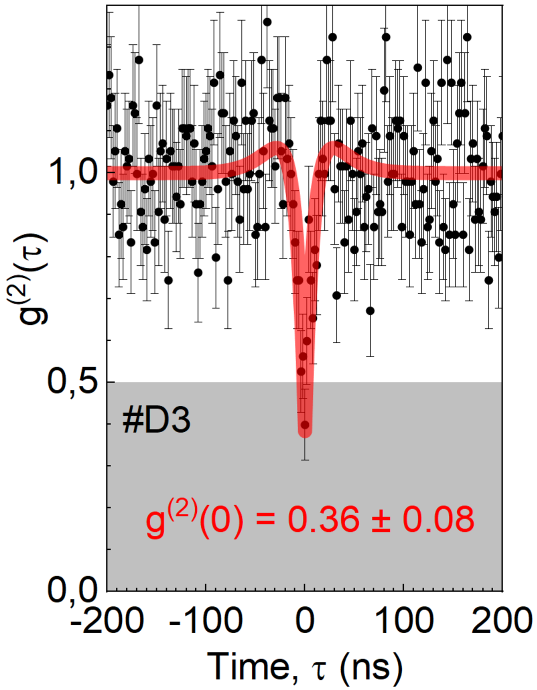
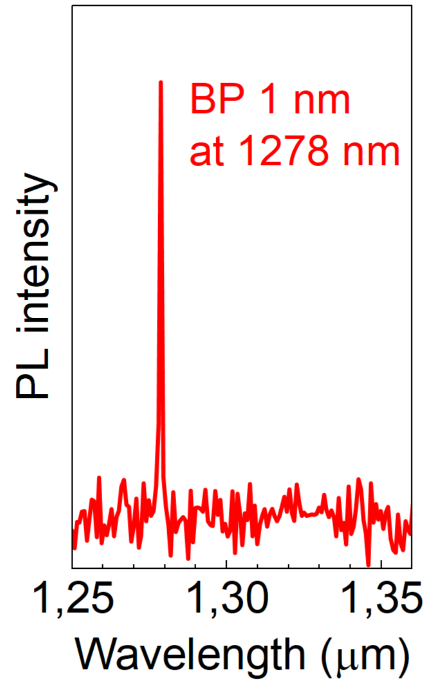


1nm Bandpass

ZPL contribution to the PL spectrum



1nm Bandpass

First demonstration of controllable fabrication of single-telecom photon emitters in Si !

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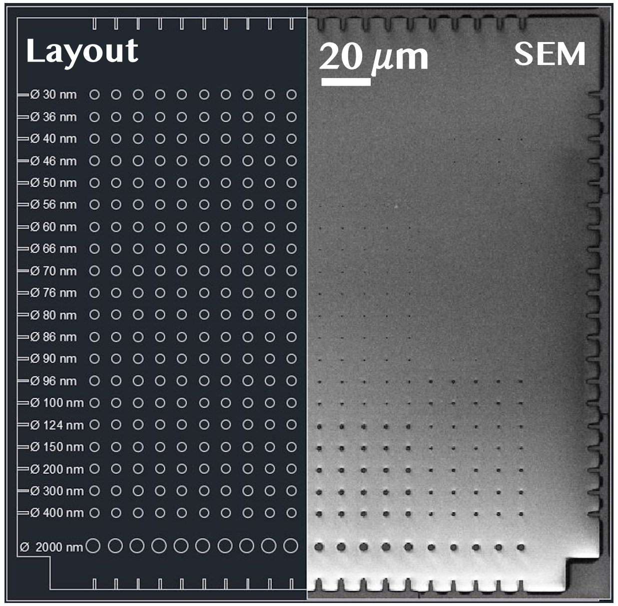
DRESDEN concept HZDR

Wafer-scale nanofabrication of single telecom quantum emitters – Broad beam Si ions

PMMA design / SEM image

Si^{++}, 1x 10^{12} cm^{-2}, 40 keV



Nanohole layout
Mask implantation (20 x 20 sites)

Special thanks to
N. Jagtap, C. Fowley and U. Kentsch

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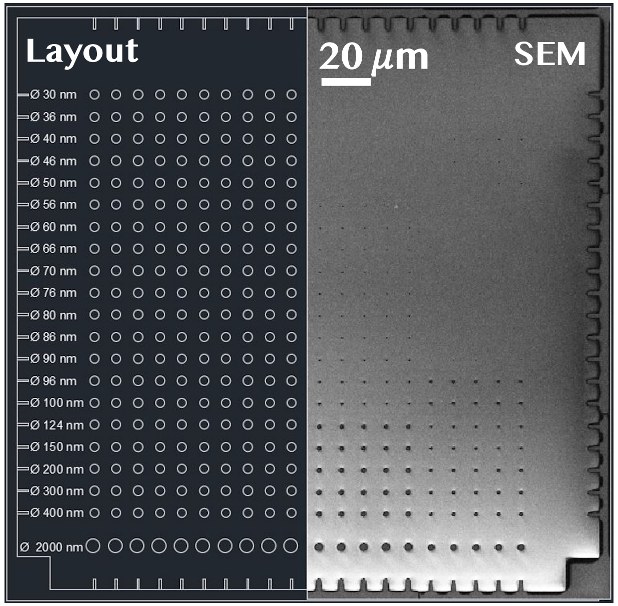

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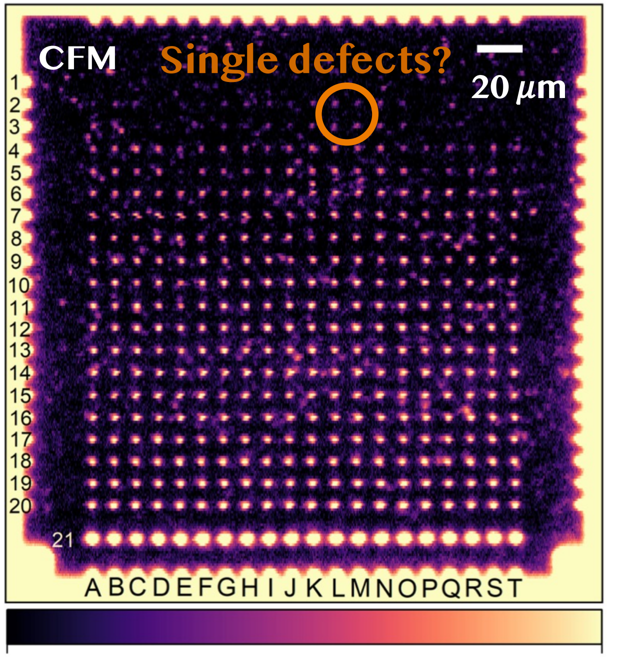

RTA Annealing,
BP 1275/50 nm

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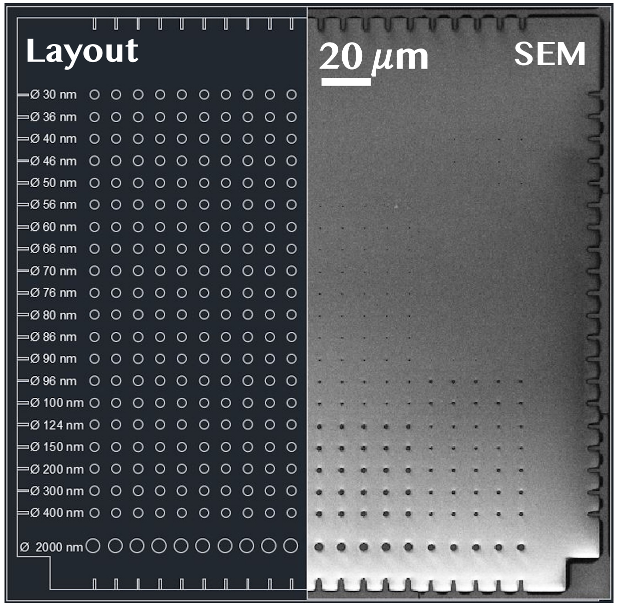
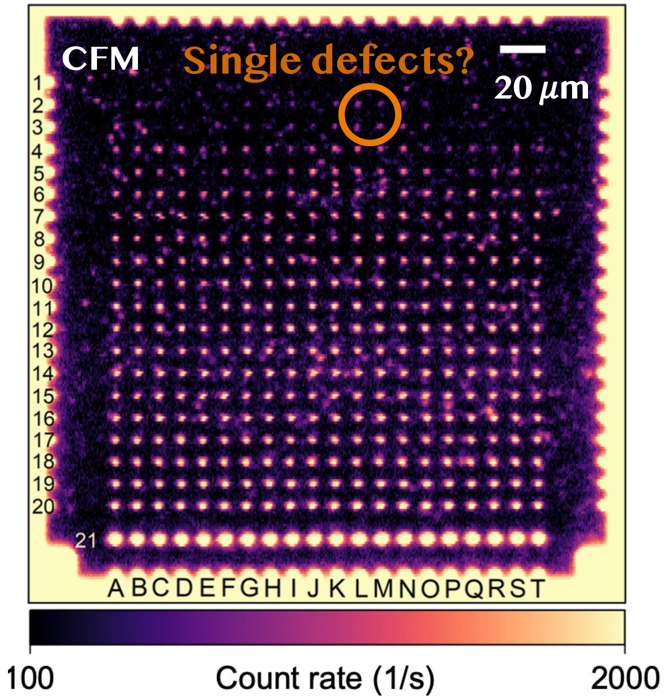


Nanohole layout
Mask implantation (20 x 20 sites)

2D confocal PL map

t_{int} ~ 2 days



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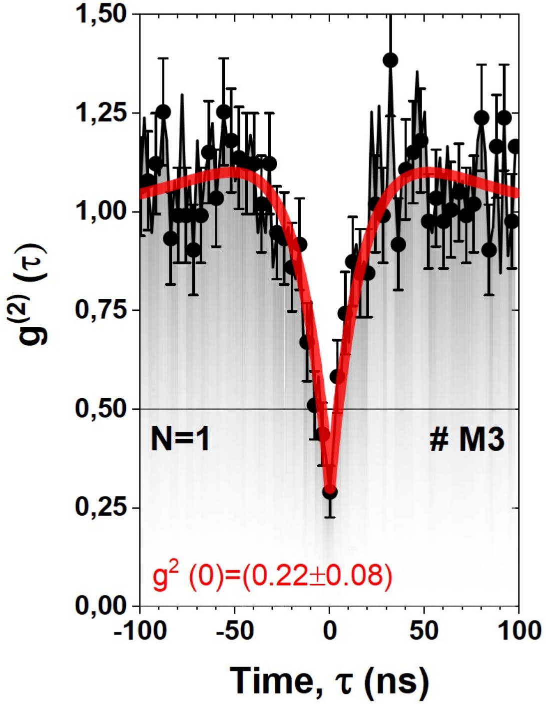
HBT- Interferometry



RTA Annealing,
BP 1275/50 nm

⇒ CMOS compatible fabrication method of single telecom photon emitters

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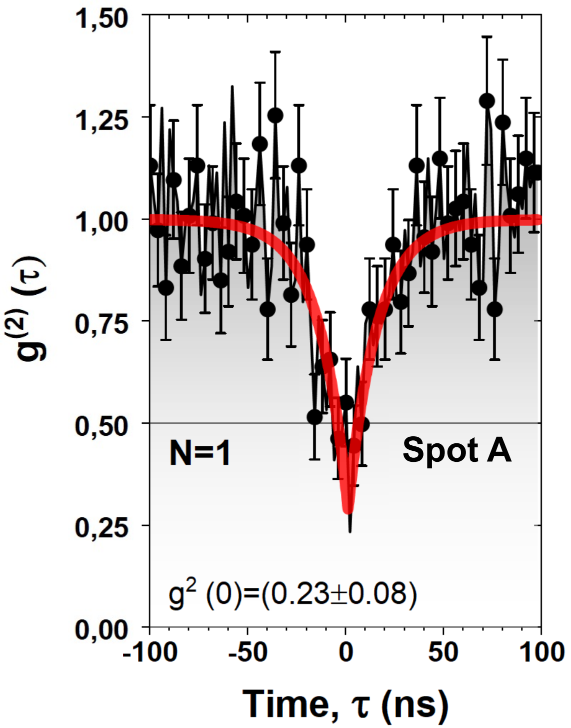
Wafer-scale nanofabrication of single telecom quantum emitters – Broad beam Si ions

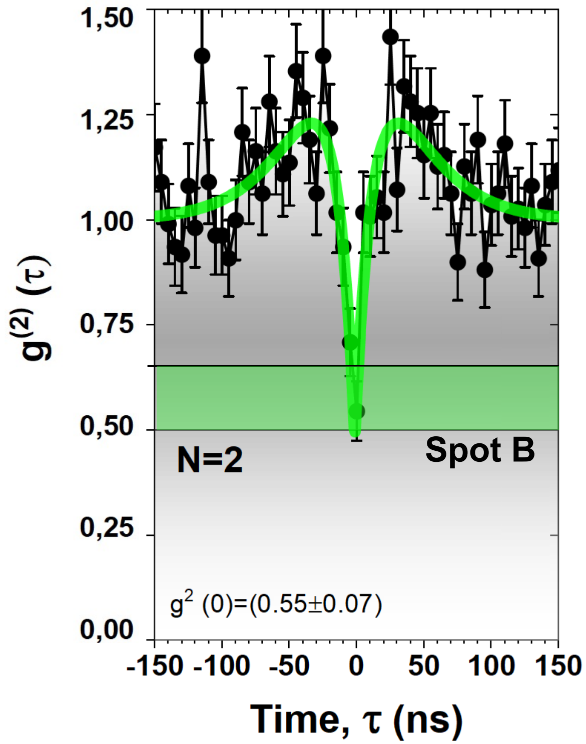
HBT Interferometry – Statistics

Emitter condition:

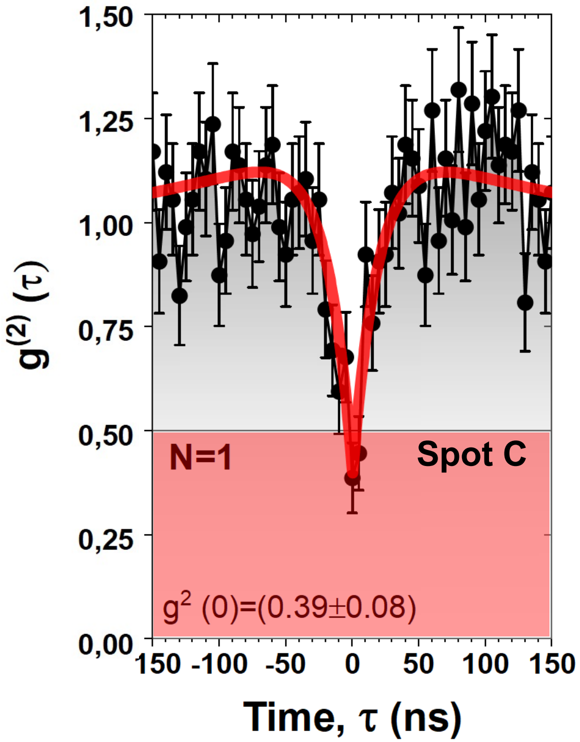
$$g^{(2)}(0) = \frac{N-1}{N}$$



If $0.5 < g^{(2)}(0) < 0.67$
⇒ N=2



If $g^{(2)}(0) < 0.5$
⇒ N=1



We measure the g^2 function of many spots to

1. **determine the number of emitters N**
2. **calculate the creation probability**

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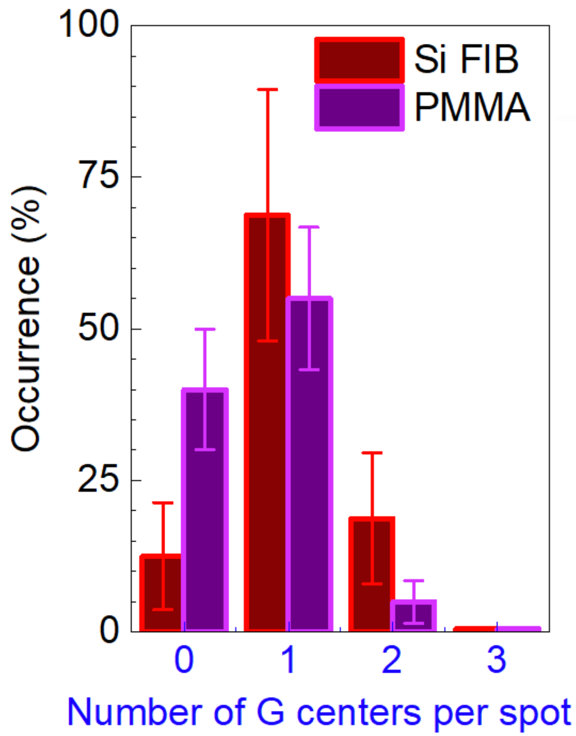
Wafer-scale nanofabrication of single telecom quantum emitters – Broad beam Si ions vs. Si FIB

Statistics histogram



⇒ **Creation probability > 50%**

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Optical & spectral properties of single telecom emitters

Statistics histogram

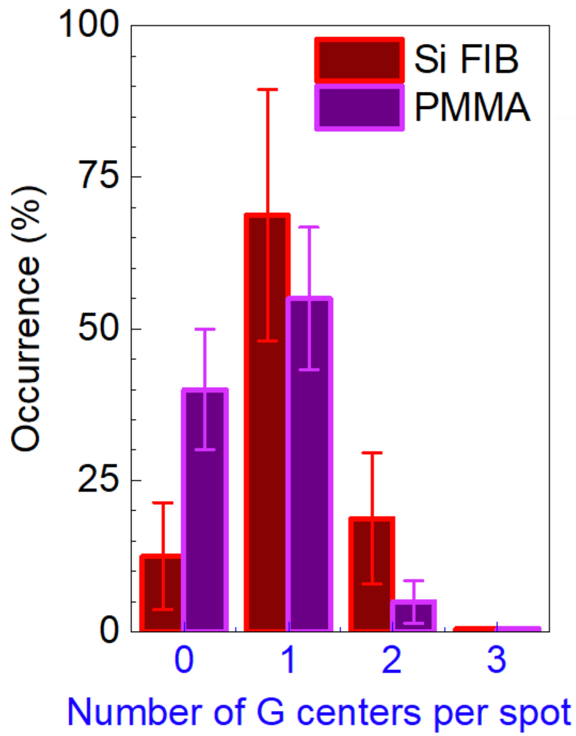
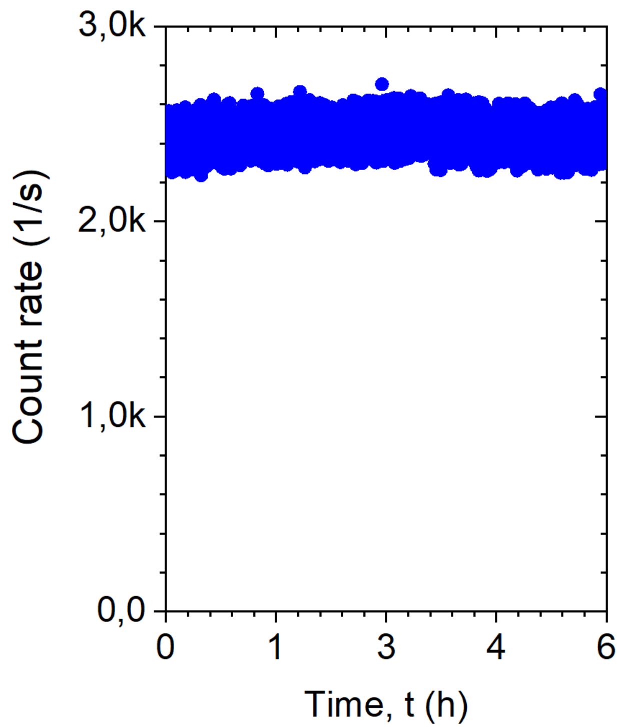


Photo- stability



⇒ **Long-term stability over days of operation - No blinking , no bleaching**

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Optical & spectral properties of single telecom emitters

Statistics histogram

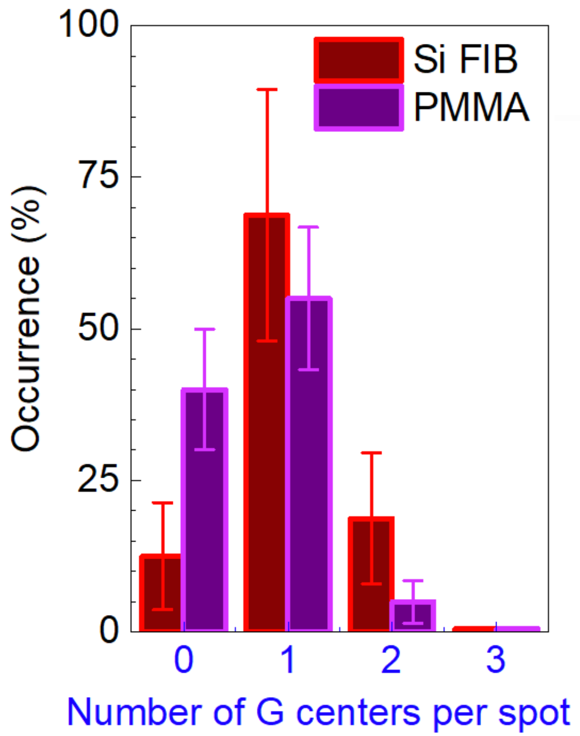
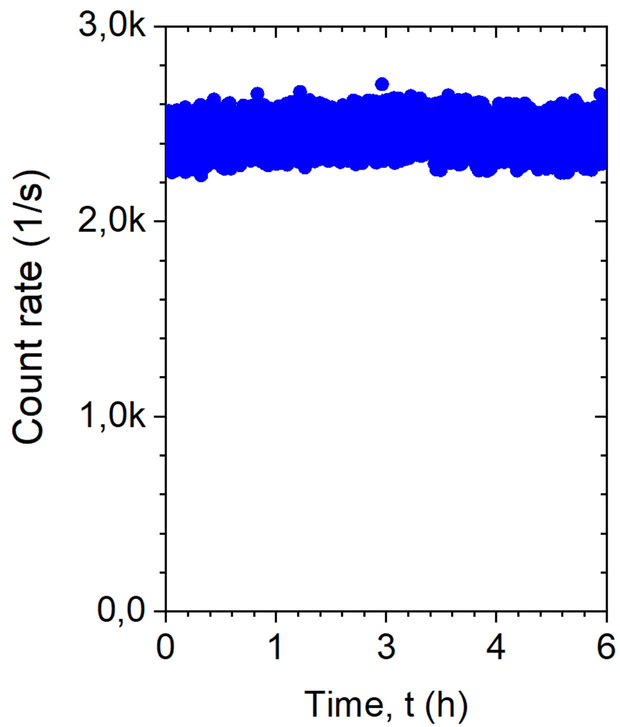
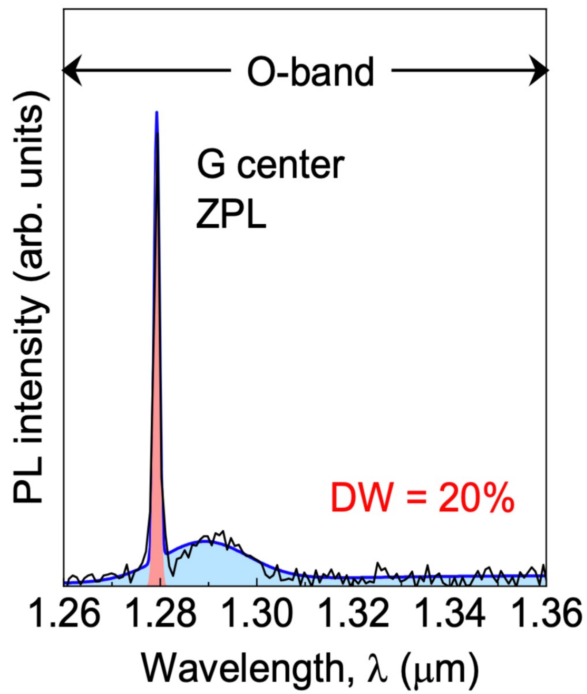


Photo- stability



PL Spectrum of single defect



⇒ **No spectral diffusion, spectral position of ZPL nearly equal compared to ensemble**

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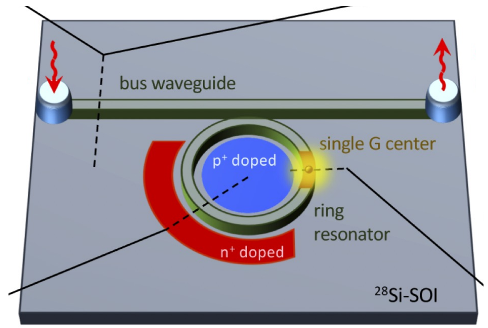
1 Creation of G-centers using FIB in photonic integrated circuits?

Nanopillars, SILS, Cavities, waveguides,...

⇒ Locally down to single level?

⇒ On-chip control?

Local integration & Brightness

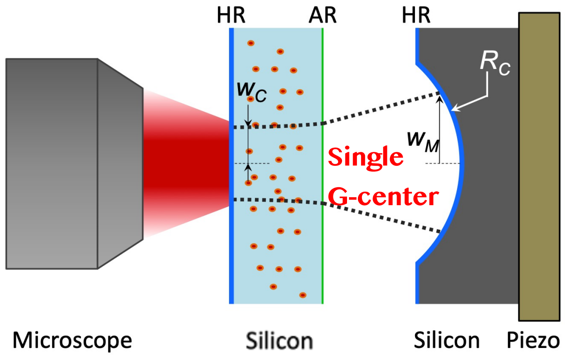


2 Coupling of single G-centers to a Fabry-Pérot microcavity?

PL enhancement?

Spectral stability & lifetime-limited optical linewidth?

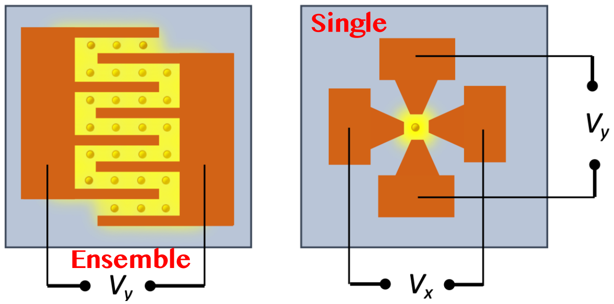
Maximize coupling efficiency



3 Tuneability of ZPL emission of single G-center?

Electrical control via Stark-Effect?

Indistinguishability



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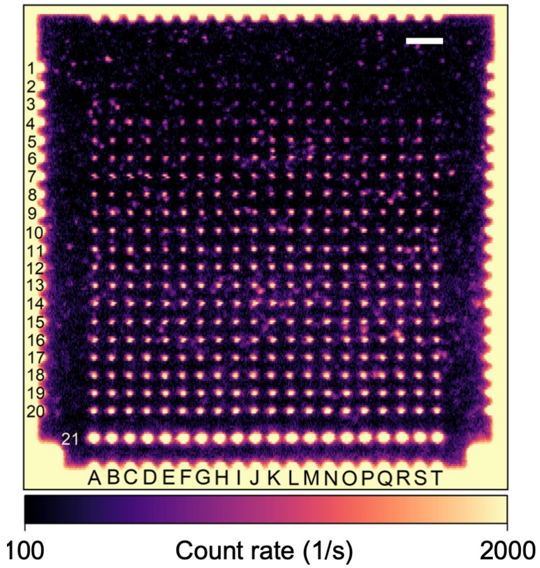
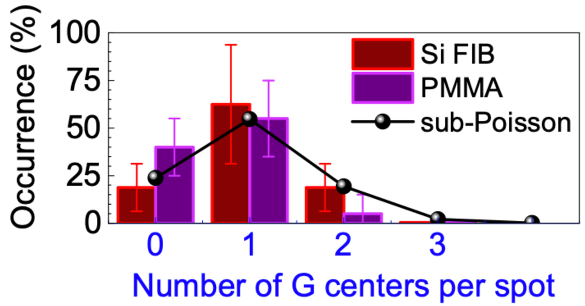
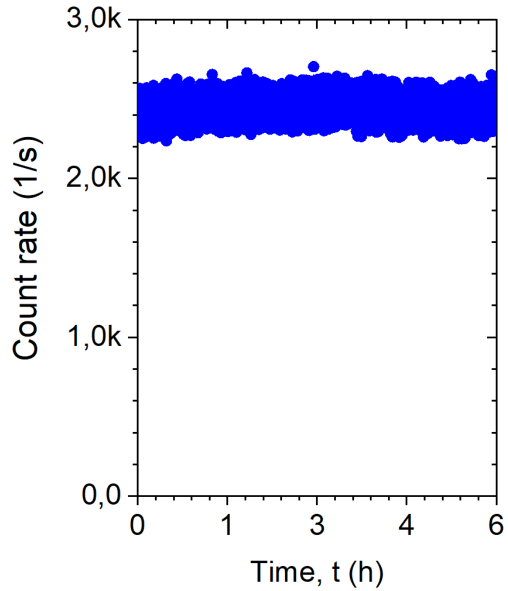
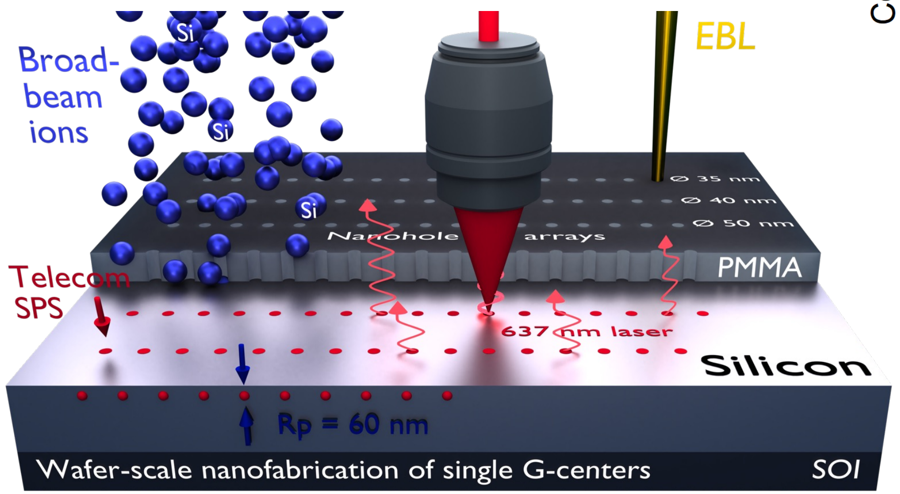
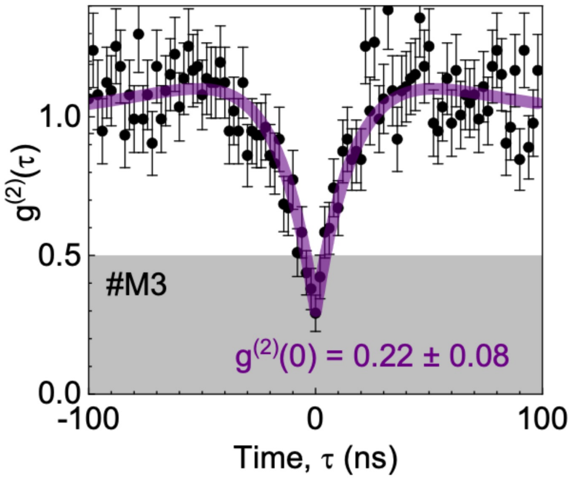
Wafer-scale nanofabrication of single telecom quantum emitters in silicon











Scalability!

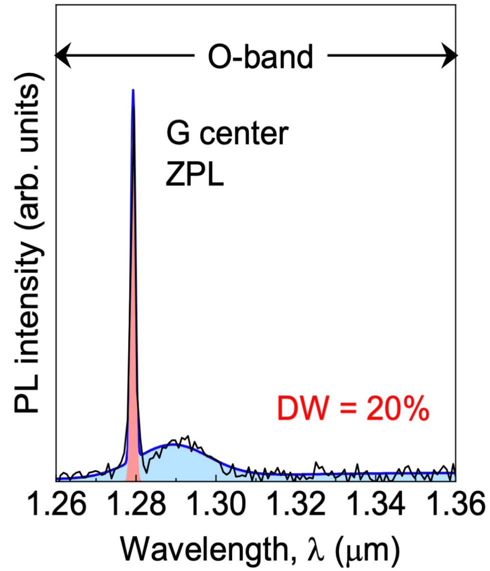
Accuracy!

Controlled creation!

Single telecom photon Emitter!

Brightness!

Long-term Stability!



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Thank you for your attention!

Acknowledgement:

Y. Berencén
G. V. Astakhov
S. Zhou
M. Helm
U. Kentsch
G. Hlawacek
N.V. Abrosimov
N. Klingner
L. Bischoff
N. Jagtap
C. Fowley
L. Rebohle
D. Sobiella
A. Erbe
I. Skorupa

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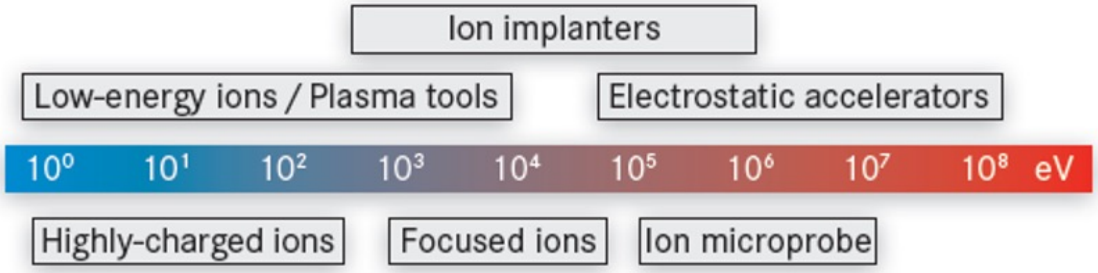

ION BEAM ANALYSIS

- Elemental mapping and depth profiling
- Light element analysis
- Hydrogen analysis and depth profiling
- Crystal damage analysis
- In-situ process characterization
- Ion microscopy
- Long-lived radionuclides
- Analysis using reactive gases or liquids
- External proton beam

ION BEAM MODIFICATION

- Ion implantation and doping
- Ion-induced ordering/disordering
- Nanostructure fabrication
- Thin-film modification
- Surface patterning
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