Silicon Carbide: Device Integration for Quantum Technologies

863. WE-Heraeus-Seminar

9 - 13 August 2026

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 863. WE-Heraeus-Seminar:

Developing quantum technologies is a top global research priority. Recently, silicon carbide (SiC) has emerged as a next-generation CMOS-compatible platform, combining state-of-the-art photonics, electrical control with optically active solid-state defects ("color centers") that can be used as quantum bits.

In this WE-Heraeus seminar, we will explore the opportunities and challenges related to the integration of color centers into photonic and electronic nanofabricated devices, a key topic in scaling this platform. The program spans materials science, nanofabrication, photonics, electronics, and quantum sensing, combining perspectives from leading figures in academia, industry, and policy.

Early-career researchers will be at the heart of the event, with numerous contributed talks and a dynamic poster session. The seminar aims not only to share the latest advances but also to forge new collaborations, strengthen global networks, and align efforts between silicon carbide defect physics and device engineering.

By fostering synergy between established industries and the rapidly growing quantum field, this meeting will help define the roadmap toward large-scale, practical silicon carbide-based quantum technologies.

Introduction

Scientific Organizers:

Dr. Guido van de Stolpe	Stanford University Stanford, CA, USA
Dr. Di Liu	Massachusetts Institute of Technology Cambridge, MA, USA
Prof. Dr. Roland Nagy	Friedrich-Alexander-Universität Erlangen-Nürnberg Erlangen, Germany

Administrative Organization:

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Introduction

Venue:

Physikzentrum
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Registration:

Nadine Mock (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday morning

Program

Program

Sunday, 09 August 2026

17:00 - 21:00	Registration
18:00 - 19:30	*BUFFET SUPPER*
19:30	**Networking**

Program

Monday, 10 August 2026

07:30 - 09:00	*BREAKFAST*	
09:00 - 09:10	Scientific Organizers	**Opening talk**
09:10 – 09:25	Scientific Organizers / or Stefan Jorda	**Video "About the Wilhelm and Else Heraeus Foundation"**
09:25 - 10:15	**- Keynote talk -** Vadim Vorobyov	**Building a nuclear spin register with V2 center in SiC**
10:15 - 10:35	Viktor Ivady	**Accurate hyperfine tensors of quantum defects in SiC**
10:35 - 11:05	*COFFEE BREAK*	
11:05 - 11:35	Marianne Bathen	**Defect generation, integration and control: Theory and experiment combined**
11:35 - 11:55	Laurens Feije	**Laser-induced creation of coherent V2 centers in bulk-grown silicon carbide**
11:55 - 12:15	Maximilian Hollendonner	**Impact of Strain on the Spin Dynamics of Silicon Vacancy Centers in 4H Silicon Carbide**
12:15 - 12:25	CONFERENCE PHOTO (in front of the main entrance)	
12:30 - 14:00	*LUNCH*	
14:00 - 14:30	Michael Trupke	**Spin Centres in Silicon Carbide for Scalable Spin-Photon Interfaces**
14:30 - 15:00	Georgy Astakhov	**Chlorine defects in silicon carbide: A new platform for telecom quantum memory**

Program

Monday, 10 August 2026

15:00 - 15:20	Jin-Shi Xu	**High-yield engineering and identification of oxygen-related modified divacancies in 4H-SiC**
15:20 - 15:50	Patrick Berwian	**Developing a pilot line for integrated SiC quantum devices: From process modules to AI-driven color center characterization**
15:50 - 16:20	*COFFEE BREAK*	
16:20 -16:40	Katja Höflich	**Direct is beautiful: exploiting the full potential of focused electron and ion beams**
16:40 -17:00	Jonah Heiler	**Spectrally stable near-surface silicon vacancies in silicon carbide through surface passivation**
17:00 -17:20	Aurora Teien	**Cathodoluminescene mapping of band bending effects from different 4H-SiC Schottky diodes for defect spin control**
17:30 - 18:00	**Poster flash talks**	
18:00 - 19:30	*DINNER*	
19:30	**Poster session**	

Program

Tuesday, 11 August 2026

07:30 - 09:00	*BREAKFAST*	
09:00 - 09:50	**- Keynote Talk -** Marina Radulaski	**Color center integration with photonic devices for quantum networking and analog simulation**
09:50 - 10:20	Florian Kaiser	**Quantum photonics for colour centres in silicon carbide**
10:20 - 10:50	*COFFEE BREAK*	
10:50 - 11:20	Tim Schröder	**Nanophotonic Solid-State Spin-Photon Interfaces**
11:20 - 11:40	Yu Zhou	**Wafer-scale monolithic integration of coherent spins in semiconductor photonics**
11:40 - 12:00	Joshua Bader	**Room temperature purcell enhanced photon-emission of single erbium defects in silicon-carbide-on-insulator microring resonators**
12:00 - 12:20	Roman Dimov	**Deterministic Placement of Silicon-Vacancy Centers and High-Q Photonic Crystal Cavities in Thin-Film Silicon Carbide**
12:30 - 14:00	*LUNCH*	
14:00 - 14:50	**- Keynote talk -** Eva Weig	**Towards spin-based quantum technologies in hybrid nanomechanical systems based on silicon carbide**
14:50 - 15:10	Heiko Weber	**Tuning of on-chip mechanical resonators by bending-induced stress**
15:10 - 15:40	Carlos Errando-Herranz	**Hybrid integration of quantum building blocks onto photonic integrated circuits**
15:40 - 16:00	Fedor Hrunski	**Hong-Ou-Mandel Interference of Spatially Separated Silicon Vacancy Centers in 4H-SiC**

Program

Tuesday, 11 August 2026

16:00 - 16:30	*COFFEE BREAK*	
16:30 - 16:50	Xiaoyi Lai	**Key building blocks for a quantum repeater node based on silicon carbide**
16:50 - 17:20	Christina Spaegele	**Silicon Carbide Waveguides for Augmented Reality and Beyond**
17:20 - 17:45	**Poster flash talks**	
18:00 - 19:30	*DINNER*	
19:30	**Poster session**	

Program

Wednesday, 12 August 2026

07:30 - 09:00	*BREAKFAST*	
09:00 - 09:50	**- Keynote talk -** Tim Taminiau	**Towards distributed quantum computation with SiC color centers**
09:50 - 10:20	Takeshi Oshima	**Local area sensing in silicon carbide devices using silicon vacancy introduced by particle beam writing**
10:20 - 10:50	*COFFEE BREAK*	
10:50 - 11:20	Naoya Morioka	**Photoelectrical probing of spin defects in SiC**
11:20 - 11:50	Heinrich Heiss	**Highly Integrated Quantum Sensors: From Quantum Physics to System-in-Package Solutions**
11:50 - 12:10	Junfeng Wang	**In-situ magnetic sensing based on silicon carbide color centers**
12:10 - 12:30	Jun-Jae Choi	**Time-domain crosstalk analysis for multilevel control and readout of silicon-vacancy qudits in 4H-SiC**
12:30 - 14:00	*LUNCH*	
14:00 - 14:15	Oscar Diez	**Shaping Europe's Quantum Future: Policy Support for Industrial Leadership**
14:15 - 15:15	**Roundtable discussion**	
15:15 - 18:30	**Excursion**	
18:30	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Thursday, 13 August 2026

07:30 - 09:00	*BREAKFAST*	
09:00 - 09:30	Christopher Anderson	**Photonically integrated low-noise SiC qubits**
09:30 - 09:50	Lin Jin	**Integrated Photonic Components and Single-Photon Detection in Silicon Carbide for Scalable Quantum Information Processing**
09:50 - 10:10	Kingshuk Mallick	**Engineering vacancy defects in SiC for precision timing and sensing**
10:10 - 10:30	Ben Haylock	**Electrical Spin State Readout in Thin Film Silicon Carbide on Insulator**
10:30 - 11:00	*COFFEE BREAK*	
11:00 – 11:30	Christian Bonato	**Engineering photonic structures in SiC for improved spin-photon interfacing**
11:30 - 12:00	**Closing and poster prize**	
12:00 - 14:00	*LUNCH*	

End of the seminar and departure

Posters

Posters

Andrei Anisimov	**Optically addressable spin centers in the telecom window based on chlorine defects in SiC**
Daniil Ansimov	**Diamond membrane platform for scalable photonic crystal cavities**
Thomas Astner	**Quantum Photonics with Vanadium in Silicon Carbide**
Sounak Sinha Biswas	**Silicon Carbide Nanocrystals for Quantum Sensing**
Michel Bockstedte	**The spin- & photo physics of prototypical color centers in SiC using quantum embedding methods**
Philipp Bredol	**The best of two worlds: hexagonal boron nitride exfoliated on stressed silicon carbide string resonators**
Fabio Candolfi	**Towards Spin-Resolved Electrical Detection**
Dominic Catanzaro	**Electro-Optic Tunability of 4H Silicon Carbide Photonics for Quantum Applications**
Rosa Diaz	**Atomic-Scale Characterization of Silicon Carbide Interfaces: Key Step for Device Integration in Quantum Technologies.**
Adil Han Dogan	**Electrical control for quantum emitters integrated in silicon carbide nanophotonic devices**
David Fehr	**Theory of Double-Quantum Control of Silicon Vacancies in Isotopically-Purified 4H-SiC for Enhanced Magnetic Field Sensing**
Amit Finkler	**Quantum-enhanced magnetic resonance imaging using spin-3/2 SiC nanoparticles**
Julietta Förthner	**Silicon Carbide Technology for Integrated Quantum Circuits**

Posters

Helton Goncalves De Medeiros	**Towards understanding silicon vacancy formation in silicon carbide via particle irradiation**
Nathan Gonzalez	**Seeing the forbidden: overcoming optical selection rules through nanophotonic integration**
Yihong Hu	**Towards High-Fidelity Quantum Gates for the V2 Defect in 4H-SiC**
Ole Jaeger	**Concepts for microwave-free vector magnetometry with silicon vacancies in 4H-SiC**
Karlo Kriedemann	**Towards a Miniaturized SiC Quantum Sensor in an Advanced Semiconductor Package with Layout-Optimized B0/B1 Coils**
Nien-Hsuan Lee	**High-Efficiency Photonic Interfaces for Optically Active Defects in Silicon Carbide**
Sang-Yun Lee	**Thermal Optimization for Resonant Readout and Multilevel Ramsey Spectroscopy of Spin-3/2 V1 Centers in 4H-SiC**
Alexey Lyasota	**Benchmarking single Er3+ optical coherence time in Silicon Carbide on Insulator-based micropillars**
Fabian Magerl	**High-Temperature Annealing and Cryogenic Characterization of CMOSCompatible 4H-SiC c- and a-plane pin-Diodes for Integrated Quantum Devices**
Stefano Meinardi	**Advancing SiC Quantum Magnetometry: Optimized Divacancies and Single Vacancies PDMR Readout**
Oliver Moen Duran	**Photoluminescence study of SiC-SiO2 interface defects**
Jule Neidhart	**Towards Time-Bin Encoded Photonic Qubit Generation and Readout Using an Unbalanced Mach-Zehnder Interferometer**

Posters

Angeliki Nikolaou	**Electric driving of hyperfine-coupled spin for the V color center in SiC**
Kazuki Okajima	**Ionization-based current spectroscopic characterization of single V1/V2 centers in 4H-SiC**
Jan Riegelmeyer	**Hybrid integration of silicon carbide color centers into photonic integrated circuits**
Zakaria Said	**Solid Immersion Lens–Enhanced Modified Divacancy Arrays for Scalable Spin–Photon Architectures in 4H-SiC**
Michael Seidel	**Dopant-selective photo-electrochemical etching of SiC and SiC-on-Insulator**
Alexander Spyrantis	**Advanced fabrication and characterization of solid immersion lenses in diamond and silicon carbide**
Timo Steidl	**Studying V2 color centers in photonic devices and modify them using Schottky junction technology**
Peter Stuermer	**Scalable Quantum Magnetometer Chip Based on Wafer-4H SiC Technology**
Marie Luise Sturm	**Large-scale characterization of color centers in diamond through automated photoluminescence excitation measurements**
Adalbert Istvan Tibiassy	**Radiofrequency and Microwave Driven Localised Spin Ensembles in Silicon Carbide**
Gerben Timmer	**Simulation and Experimental Characterization of Fishbone PCCs for Future Quantum Networks**
Michael Titze	**Tin–Lead Liquid Metal Alloy Source for Focused Ion Beams**

Posters

Erik Weiss	**Reversible Qudit Entanglement Protocols for Silicon Carbide Defect Centers**
Raphael Woernle	**PL6 centers in SiC for spin-based quantum technologies**
Matteo Ziino	**Direct color center writing in silicon carbide using Liquid Metal Alloy Ion Source Focused Ion Beams**

Abstracts of Talks

(in alphabetical order)

Photonically integrated low-noise SiC qubits

C. P. Anderson[1]

[1]*Department of Materials Science and Engineering, University of Illinois Urbana-Champaign, Urbana, IL USA*

I will highlight recent advances in neutral divacancy color centers in 4H-SiC. This includes the demonstration of the longest Hahn-Echo T_2 time for any qubit in any platform, including atoms and ions, on the scale of minutes [1]. This is enabled by isotopic and electronic device engineering. Prospects and recent results in photonic integration into wafer scale silicon carbide on insulator (SiCOI) and lateral p-i-n diodes will be presented. An outlook for advanced device integration and defect discovery for SiC quantum technology will be overviewed [2].

References

[1] C. Zeledon et al., arXiv 2504.13164 (2025)
[2] C. P. Anderson and D. D. Awschalom. Physics Today **76** (8), 26–33 (2023)

Chlorine defects in silicon carbide: A new platform for telecom quantum memory

G. V. Astakhov

Helmholtz-Zentrum Dresden-Rossendorf,
Institute of Ion Beam Physics and Materials Research, Dresden, Germany

Solid-state quantum emitters operating in the telecommunication bands are a key building block for scalable quantum networks. In this talk, I will present recent progress on chlorine-related defects in silicon carbide (SiC) as a new platform for integrated quantum photonics. These defects are predicted to combine telecom-band optical emission with spin functionality in a technologically mature, wafer-scale material [1]. I will discuss their creation by ion implantation and their optical properties across the telecom O- and C-bands [2]. I will also demonstrate spin-dependent optical readout using optically detected magnetic resonance. The observed spin-photon interface, together with coherent spin control and hyperfine interactions with nuclear spins, highlights their potential for quantum memory applications [3]. I will further address key challenges, including charge-state control, spectral stability and the microscopic understanding of their electronic structure. Finally, I will outline future directions toward single-emitter isolation, integration into nanophotonic devices and the realization of scalable quantum architectures based on telecom spin-photon interfaces in SiC.

References

[1] O. Bulancea-Lindvall, J. Davidsson, R. Armiento, I. A. Abrikosov, Phys. Rev. B **108**, 224106 (2023).
[2] A. N. Anisimov, A. V. Mathews, K. Mavridou, U. Kentsch, M. Helm, G. V. Astakhov, Opt. Express **33**, 54285 (2025)
[3] A. N. Anisimov, K. Mavridou, A. V. Mathews, M. Helm, G. V. Astakhov, arXiv:2605.03717 (2026)

Room temperature Purcell enhanced photon-emission of single erbium defects in silicon-carbide-on-insulator microring resonators

J. Bader[1], A.Lyasota[2], S.Q.Lim[3,4], B.C.Johnson[4], D. Broadway[4], R. Wang[5], Q. Li[5], J.C.McCallum[3], S.Rogge[2] S.-I. Sato[6] and S. Castelletto[1]

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[6]*National Institutes for Quantum Science and Technology, Takasaki, Gunma, 370-1292, Japan*

Optically excited single photon emitting point defects operating at the telecommunication C-band are essential building block qubits in a photonic quantum computer and in quantum communication networks. Especially, the on-chip integration of these emitters via photonic integrated circuits (PICs) hosted in a CMOS compatible material, such as 4H-Silicon carbide-on-Insulator (4H-SiCOI), could enable long-distance, scalable, and secure communication even over existing fiber infrastructure.
For this, Erbium-defects (Er^{3+}) have shown promises due to key properties like photon-emission at 1540nm [1-4] directly in the C-band, removing the need of frequency conversion, and exceptional optical coherence [5], which could be preserved at room temperature (RT).
We present the successful demonstration of a RT single-photon emitting Er^{3+}-defect embedded in a microring resonator hosted in thin-film 4H-SiCOI. The Er^{3+}-defect in the microring is introduced by ion implantation and is resonantly excited using the fundamental mode of a waveguide evanescently coupled to the microring resonator. The single photon emission is collected via another waveguide and subsequently detected by superconducting nanowire single photon detectors. Additionally, Purcell enhancement of ~70 which enhances the photon-emission rate from the defect significantly and narrow emission lines were observed.
This work stems for the first demonstration of Er^{3+} integrated single photon emission at RT and paves the way to advance the current state of the art of single-photon sources, providing solutions compatible with existing PICs to achieve scalable operations within the C-band. This enables additional applications as quantum memory or spin-photon interfaces which are commonly utilized as quantum processors and are under investigation.

[1] A. Gritsch et al., *Physical Review X* 12, 041009 (2022)
[2] S. Wang et al., *Applied Physics Letters* 116, 15 (2020)
[3] A. Dibos et al., *ACS Nano Letters* 22, 16 (2022)
[4] A. Gritsch et al., *Optica* 10, 6 (2023)
[5] S. Ourari, *Nature* 620, 977–981 (2023)

Defect generation, integration and control: Theory and experiment combined

M. E. Bathen[1]

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Defects in silicon carbide (SiC) are being rapidly functionalized for quantum technology applications within sensing, computing and communication devices that utilize their magneto-optical properties. A multitude of different color centers have been discovered in SiC that show potential for distinct application areas. However, integration of these quantum defects into electrical and photonic quantum devices raises a vital question: how does device integration influence the defect's thermodynamic, vibrational and electronic states?

Density functional theory (DFT) in combination with electro-optical measurements and device modeling are essential tools for understanding the interaction between a quantum defect and the device it is introduced into. In this contribution, we explore the interaction between quantum defects in SiC and the surrounding material [1], electrically controlled Schottky-type devices [2-4], nanophotonic structures [5] and strain that can be introduced by material or device processing [6]. Overall, we find that both detrimental and beneficial effects on quantum emission are likely to occur, emphasizing the need for understanding the complex interactions between defect, material and device to drive the color center into its optimal operating regime.

References

[1] A.T. Younesi, et al., arXiv: 2602.14818 (2026).
[2] M.E. Bathen, et al., npj Quantum Information 5, 111 (2019).
[3] M.E. Bathen, et al., Defect and Diffusion Forum 425, 35-42 (2023).
[4] E.L. Ousdal, et al., Materials Science in Semiconductor Processing 201, 110097 (2026).
[5] A.H. Rubin, et al., arXiv:2605.04277 (2026).
[6] V. Žalandauskas, et al., arXiv:2602.19640 (2026).

Developing a pilot line for integrated SiC quantum devices: From process modules to AI-driven color center characterization

P. Berwian[1], C. Gobert[1], M. Scharin-Mehlmann[1], M. Titl[1], M. Hofmann[1], J. Förthner[1,2], F. Magerl[2], M. Seidel[1]

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[2]*Chair of Electron Devices at Friedrich-Alexander-Universität Erlangen-Nürnberg*

Fraunhofer IISB and the Chair of Electron Devices at Friedrich-Alexander-Universität Erlangen-Nürnberg jointly operate a SiC-CMOS pilot line. Over recent years, we have systematically expanded its capabilities to encompass technology modules for integrated SiC quantum and photonic devices.

In this contribution, we present an overview of our progress across key steps of the manufacturing chain — from "quantum-grade" epitaxy and SiC-on-insulator substrate development to the integration of photonic components into our CMOS platform.

Many of these process steps critically influence color center performance and exhibit complex interdependencies, making rapid characterization feedback essential for efficient process development. To address this, we have developed a high-throughput method for V_{Si} color center yield determination, combining low-dose full-area ion irradiation, confocal photoluminescence imaging, and a convolutional neural network (CNN) trained on synthetically generated data [1]. The method completes a full yield evaluation in approximately one hour per sample — a speedup of at least 50× over conventional g^2-based approaches [2] — while delivering superior statistics with well-defined uncertainty estimates and requiring no nanofabrication infrastructure. We demonstrate its practical utility in a surface passivation study.

References

[1] C. Gobert et al., J. Phys. D: Appl. Phys. **58**, 265305 (2025).

[2] . Fuchs et al., Nat. Commun. **6**, 7578 (2015)

Engineering photonic structures in SiC for improved spin-photon interfacing

Cristian Bonato, Alexander Jones, Zakaria Said, Sounak Biswas, Shivani Bisht, Pasquale Cilibrizzi, Muhammad Junaid Arshad, Christiaan Bekker

[1]*Institute of Photonics and Quantum Sciences, Heriot-Watt University, Edinburgh (UK)*

I will present some of our group's working in developing quantum technologies based on single spins in silicon carbide [1], a semiconductor which uniquely combines excellent spin properties with mature microelectronics and promising photonics.
In the first part of my talk, I will present our work on single vanadium centres in SiC, emitting in the telecom O-band [2]. I will discuss the optical selection rules at the basis of spin-photon interfacing, and how material engineering (doping, isotopic composition) can be used to tune the quantum emitters properties, in terms of charge state control and tailoring of optical emission. In particular, we have shown that, by engineering the isotopic composition of the SiC matrix, we reduce the inhomogeneous spectral distribution of different emitters down to 100 MHz, significantly smaller than any other single quantum emitter [2].
In the second part of my talk, I will discuss our progress in fabricating large arrays of photonic microstructures [3] to enhance photon collection efficiency, and in marker-free registration of single quantum emitters aligned to solid immersion lenses by femtosecond laser writing [4].

References

[1] S. Ecker et al, "Quantum communication networks with defects in silicon carbide", arXiv:2403.03284 (2024)
[2] P. Cilibrizzi et al, "Ultra-narrow inhomogeneous spectral distribution of telecom-wavelength vanadium centres in isotopically-enriched silicon carbide", Nature Communications 14, 8448 (2023)
[3] C. Bekker et al, "Scalable fabrication of hemispherical solid immersion lenses in silicon carbide through grayscale hard-mask lithography", Applied Physics Letters 122, 173507 (2023)
[4] A. R. Jones et al, "Scalable registration of single quantum emitters within solid immersion lenses through femtosecond laser writing", Nano Letters 25, 30, 11528 (2025)

Time-domain crosstalk analysis for multilevel control and readout of silicon-vacancy qudits in 4H-SiC

J.-J. Choi,[1] S.-J. Hwang,[1] S. Paik,[1] J. Kim,[1] J. Ul-Hassan,[2] N. T. Son,[2] H. Abe,[3] T. Oshima,[3,4] J. Suk,[5] H.-H. Jeong,[1] D.-H. Kim,[1] S.-Y. Lee,[1]

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[5] *Korea Atomic Energy Research Institute, Gyeongju, Republic of Korea*

Color-center spins in 4H-SiC combine wafer-scale maturity, long spin coherence, and chip-level photonics, making them promising platforms for scalable quantum technologies. The silicon vacancy hosts an S = 3/2 ground state, forming a four-level spin qudit that enables compact encodings and subspace-selective control. In multilevel systems, finite-duration operations probe dynamics beyond an effective two-level approximation. Using broadband Ramsey interferometry, we quantify spectator-transition crosstalk from coherent microwave driving within the ground-state manifold [1]. In isotopically engineered $^{28}Si^{12}C$, T_2^* exceeds 30 μs, enabling high-resolution Ramsey spectroscopy. Because the zero-field splitting of the V1 silicon-vacancy center is small, transition frequencies can lie within the bandwidth of short hard pulses, allowing multiple level pairs to be driven simultaneously. Ramsey Fourier spectra therefore show extra lines beyond the addressed transition. Analytically, each line maps to a pairwise energy difference of the rotating-frame Hamiltonian with amplitudes set by the prepared state and pulse parameters, yielding a deterministic six-branch structure. Numerical propagation reproduces the detuning-dependent branch pattern without frequency fitting, establishing a spectator-aware framework for multilevel coherent control. We further examine how finite detection windows affect resonant optical readout. Population estimation often assumes that detected photons are proportional to initial ground-state populations, yet optical detection couples the spin manifold to metastable states via intersystem crossing, and fluorescence need not scale linearly with time. Incorporating these processes into the multilevel model, we analyze time-dependent fluorescence and compare analytical approximations with simulations. This identifies conditions where population inference remains reliable and regimes where sequential dual-channel readout (O1-O2) may introduce deviations. Together, these results provide a time-domain framework for control and readout engineering in silicon-vacancy spin qudits.

References

[1] J.-J. Choi, arXiv:2601.15559 (2026)

Shaping Europe's Quantum Future: Policy Support for Industrial Leadership

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Europe has established a strong position in quantum science and now faces the strategic challenge of converting scientific excellence into industrial leadership. This contribution will present the European policy perspective on how public action can support the development, scale-up and uptake of quantum technologies across the Union.

The talk will place quantum technologies within Europe's broader objectives of competitiveness, resilience and technological capacity. It will discuss how policy support can strengthen the full innovation chain, from research and enabling technologies to startups, scale-ups and industrial deployment. In this context, particular attention will be given to the importance of reinforcing European value chains in quantum computing, communication and sensing, while also supporting the materials, components and device integration capabilities that underpin future quantum systems.

Against this background, the presentation will highlight the role of European instruments in reducing fragmentation, mobilizing investment, fostering collaboration and creating the conditions for companies to grow in Europe. It will also address the importance of linking excellent research communities with industrial actors, investors and public authorities in order to build a more coherent and globally competitive ecosystem.

For fields such as silicon carbide and related enabling technologies, this broader policy perspective is especially relevant. Progress in quantum is not only determined by advances at system level, but also by continued innovation in materials, fabrication, integration and manufacturing. Europe's ability to lead in quantum will therefore depend on connecting frontier research with industrial capabilities and market creation.

The overall message is that Europe's quantum future will rely not only on scientific breakthroughs, but also on sustained policy support for industrialization, scale-up and ecosystem building.

References

[1] European Commission, Quantum Europe Strategy (2025)
[2] European Commission, Proposal for a Quantum Act (2025)

Deterministic Placement of Silicon-Vacancy Centers and High-Q Photonic Crystal Cavities in Thin-Film Silicon Carbide

Roman Dimov, Guido van de Stolpe, Dominic Catanzaro, Gerald Xu, Trung Kien Le, Giovanni Scuri, Souvik Biswas, Shei Sia Su, Michael Titze, Jawad Ul Hassan, Jelena Vuckovic

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Silicon carbide (SiC) is an emerging platform for solid-state quantum technologies, combining optically addressable spin defects with mature nanofabrication and electrical control. Achieving scalable device architectures requires deterministic emitter placement alongside high-Q/V optical cavities.

We report progress toward deterministic integration of silicon-vacancy (V2) centers with photonic crystal cavities in SiC. Deterministic lithium focused-ion-beam (Li-FIB) implantation generates V2 centers with ~ 50 nm placement precision in bulk material [1], enabling controlled positioning relative to nanophotonic structures. Optical characterization via resonant photoluminescence excitation reveals inhomogeneous linewidths of a few gigahertz and sub-gigahertz upper bounds on the homogeneous linewidth, currently limited by photon collection efficiency from bulk material.

In parallel, we fabricate modulated-waveguide photonic crystal cavities [2] in thin-film SiC. Cavity spectroscopy confirms high-yield fabrication of resonators with modes near the V2 zero-phonon line and measured quality factors exceeding 5×10^4.

Together, these results establish the key components required for deterministic integration of V2 centers with photonic crystal cavities in SiC. Ongoing efforts focus on integrating on-chip electrodes for charge stabilization and DC Stark tuning. This approach aims to enable spatially and spectrally controlled color centers in SiC toward scalable multi-emitter cavity quantum electrodynamics.

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Hybrid integration of quantum building blocks onto photonic integrated circuits

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Integrated quantum photonic circuits based on solid-state emitters are a promising platform for scalable quantum information processing, but their realization requires the combination of quantum-grade materials with large-scale photonic circuitry and control hardware. In this talk, we present a transfer-printing-based heterogeneous integration approach that enables the assembly of complex quantum photonic systems by combining foundry-fabricated photonic integrated circuits with superconducting detectors and quantum emitters from disparate material platforms. We begin with the hybrid integration of superconducting nanowire single-photon detectors (SNSPDs) onto foundry silicon photonics and lithium-niobate-on-insulator circuits via transfer printing [1], including recent advances enabling SNSPD operation under magnetic fields relevant for spin-active color centers [2], as well as integrated cryogenic CMOS control [3]. We then discuss transfer-printed quantum dots integrated into foundry silicon photonic chips, including electric-field-induced spectral tuning for improved emitter control and scalability [4]. Building on previous work with diamond color centers [5], we introduce new device designs and fabrication methods specifically developed for the transfer printing of diamond color center chiplets onto foundry photonic integrated circuits. Finally, we present recent results on the transfer printing of SiC chiplets onto in-house silicon nitride photonic circuits designed for the V2 defect and quasi-TM mode operation. Together, these results outline a pathway toward scalable quantum photonic processors combining quantum emitters, photonics, detectors, and electronics on a single platform.

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Laser-induced creation of coherent V2 centers in bulk-grown silicon carbide

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The ability to create defect centers with high accuracy and high yield in nanophotonic devices is an important challenge for scaling up solid-state defects for quantum technologies. Recently, pulsed lasers have emerged as a promising approach for creating defects in both diamond and silicon carbide [1,2]. However, the optical and spin properties of single laser written defects in SiC have not yet been investigated.

In this work, I will present our experiments on above-bandgap laser writing of V2 centers in HPSI 4H-SIC. We developed a systematic method to create V2 centers in nanopillars fabricated in HPSI 4H-SIC without inducing damage to the material. Using check-probe methodology [3] we find that laser-induced V2 centers exhibit optical coherence comparable to naturally occurring V2 centers in the same material, with linewidths approaching the lifetime limit. Furthermore, we measure electron coherence times T_2^* ~0.9(1) us and Hahn-echo T_2 ~0.49(2) ms, similar to values reported in epitaxial grown material with natural abundance of nuclear isotopes [4].

Beyond HPSI SiC, I will also present our ongoing efforts to extend laser-induced defect creation in epitaxially grown material and suspended nanophotonic structures such as photonic crystal cavities and waveguides. Together, these results represent an important step toward using laser writing to place V2 centers with preserved optical and spin coherence within prefabricated SiC nanophotonic structures.

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Electrical Spin State Readout in Thin Film Silicon Carbide on Insulator

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Photoelectrical detection of magnetic resonance (PDMR)[1] is a promising technique for the construction of magnetic field sensors based on spin defects, and for readout in quantum spin-photonic networks. We report photoelectrical detection of magnetic resonance in a thin film of silicon carbide suitable for photonic integration. These advances merge a readout technique suitable for massively parallel sensing with an integrated photonics capable [2] silicon carbide on insulator (SiCOI) platform, suitable for massively parallel spin sensor control. The platform is suitable for scale up to CMOS compatible wafer scale production. We demonstrate a comparison of optical and electrical readout techniques on an ensemble of silicon vacancies in bulk and thin film 4H silicon carbide, showing our thin-film processing does not significantly impact spin coherence.

Furthermore, we demonstrate that electrical readout is possible with excitation wavelength well beyond the zero-phonon line; up to 990nm, offering potential for lower noise readout with improved bio-compatibility.

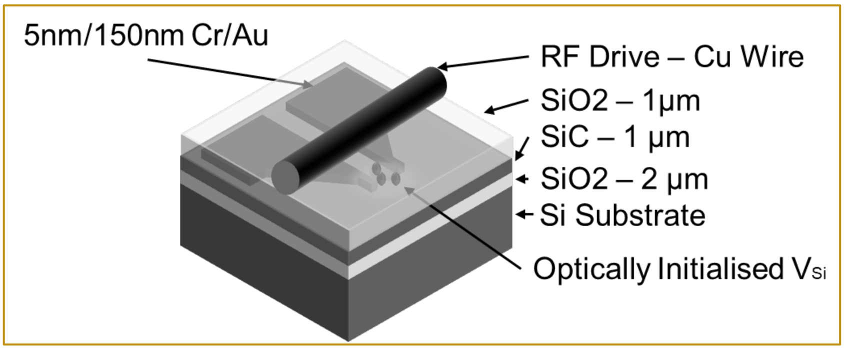

Figure 1 Schematic of photoelectrical readout device in 4H-silicon carbide on insulator

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Spectrally stable near-surface silicon vacancies in silicon carbide through surface passivation

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Silicon carbide (SiC) with quantum-grade quality has recently become available due to materials advances in SiC high-power electronics. It can host optically active spins, so called color centers, that are promising for quantum communication applications, as shown in a series of landmark proof-of-concept experiments.
The widespread deployment of this technology, however, requires a more efficient interface and a scalable fabrication. Both can be achieved by integrating the color centers into electro-optic SiC chips. Yet, all previous efforts toward the necessary nano-integration resulted in a strongly degraded optical performance, linked to electromagnetic noise from surfaces in sub-micron proximity to the color centers [1]. To overcome this challenge, we can be benefit from approaches that have been developed in power electronics and passivate our SiC surfaces [2, 3].
Here, we investigate several surface passivation techniques for stabilizing the spectral properties of near-surface silicon vacancy (VSi) color centers in SiC toward obtaining the well-known spectral stabilities of deep-bulk color centers [4]. To do so, we first create near-surface (70-180 nm) VSi's via focused helium ion beam implantation. Subsequently, we passivate multiple SiC surfaces using different cleaning procedures and dielectric layer deposition methods. To benchmark these different passivation methods, we measure the spectral stability of a statistical relevant number of single VSi color centers using low-temperature resonant photoluminescence excitation spectroscopy (PLE).
We will report on at least one recipe that shows bulk-like spectral stabilities of color centers with sub-micron proximity to the surface. Moreover, we report on stable spectral lines even under high laser powers far beyond the saturation intensity, making our method compatible with efficient spin-photon entanglement generation schemes. As an outlook, we will give our next steps toward applying and verifying surface passivation methods on our in-house fabricated nanocones and waveguides.

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Highly Integrated Quantum Sensors: From Quantum Physics to System-in-Package Solutions

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Silicon carbide (SiC) is emerging as a compelling technology platform for next-generation quantum devices. With appropriate pre-treatment, SiC exhibits quantum properties approaching those of diamond, while offering a far more mature and scalable semiconductor technology base. Although diamond-based magnetometers have demonstrated pT/√Hz sensitivities under laboratory conditions[1], SiC-based quantum magnetometers — currently operating in the nT/√Hz regime[2] — hold significant untapped potential for performance breakthroughs. Leveraging decades of innovation driven by power electronics, SiC enables unprecedented levels of integration, paving the way toward system-on-chip quantum sensors with transformative miniaturization potential. This talk explores the vision and current progress toward fully integrated SiC quantum sensors, including on-chip PDMR read-out and the co-integration of photonics and laser sources at the package level, highlighting both the opportunities and the challenges on the path to scalable quantum sensing systems.

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Direct is beautiful:
Exploiting the full potential of focused electron and ion beams

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Future breakthroughs in nanotechnology will depend on the ability to produce materials and devices by design, i.e. to shape both the material properties and the geometry of the devices according to a sophisticated blueprint. In this regard, direct writing techniques that combine great flexibility and ease of implementation with the highest possible spatial resolution are of particular interest. Focused ion or electron beams not only enable the rapid prototyping of novel components in a maskless process, but also the local modification of materials and components with maximum spatial resolution.

The structuring with charged particle beams is based on a digital process in which the beam dwells in one position for a certain time and is then moved again to dwell again. The sum of these beam positions constitutes the beam path and, depending on the mass of the primary particles, along this path either the substrate is sputtered and/or modified or new material is deposited. While these processes are conceptually very simple, the physical and chemical processes that take place locally are highly complex [1]. In my presentation, I will give an overview of the fundamentals and various possibilities of direct structuring with particle beams. Using examples, particularly for nano-photonic [2] and quantum applications [3,4], I will then explain the specific advantages and disadvantages of these techniques in more detail.

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Impact of Strain on the Spin Dynamics of Silicon Vacancy Centers in 4H Silicon Carbide

Maximilian Hollendonner

Currently color centers in semiconductors are among the most promising platforms for quantum technology. Especially the negatively charged cubic silicon vacancy center (V_{Si}) in 4H silicon carbide (SiC) stands out due to its exceptional spin and optical properties [1], as well as the ability to be integrated into semiconductor structures [2]. For this reason, the V_{Si} is an ideal candidate for the realization of quantum memory nodes [3,4].

It was observed in previous studies [5] that the V_{Si} center can exhibit significant strain when integrated into nanophotonic structures. How strain affects the spin properties of V_{Si} centers is currently not fully understood. As the latter is dictated by the transition rates in and out of the metastable states [6], we developed purely optical pulse sequences which allow the measurement of these rates. In particular, we find that the transition rates are significantly altered in the presence of only moderate strain. My poster will not only show the changed rates but also present the underlying mechanisms which cause these changes.

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Hong-Ou-Mandel Interference of Spatially Separated Silicon Vacancy Centers in 4H-SiC

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Color centers in semiconductors are among the most promising platforms for quantum networks, with the V2 silicon vacancy center (k-V_{Si}) in 4H-SiC standing out for its favorable electron spin and optical properties [1]. Preceding work has already demonstrated a key building block for V_{Si}-based quantum networking, namely spin-controlled generation of indistinguishable photons from a single h-V_{Si} center via Hong-Ou-Mandel (HOM) interference [2]. Scaling to functional, multi-node quantum networks requires spatially separated, independently operated color centers to maintain mutual spectral indistinguishability. Whether and for how long k-V_{Si} centers meet this requirement has remained unexamined, as previous demonstrations were performed with a single emitter probed over short measurement windows [2].
To address this, we independently tuned two k-V_{Si} centers into a common spectral regime and interfered their cavity-filtered zero-phonon-line emissions in a free-space HOM setup. Both centers are embedded in separate p-i-n diode structures within their own cryostats, physically separated by two meters.
Realizing quantum networks requires not only remote interference, but sustained node stability: current photonic entangling protocols typically demand 10^3–10^5 physical attempts per successful, usable distributed state [3], while even state-of-the-art solid-state network nodes report duty cycles of 20–34%, with a substantial fraction of data discarded due to charge-environment-induced spectral diffusion [4].
We use two-photon interference between two independently operated k-V_{Si} centers as a direct probe of their joint long-term spectral stability, demonstrating a coincidence dip clearly beyond the classical limit while being sustained over several days of continuous operation. Altogether, we establish a viable route towards long-term-stable quantum interference between remote silicon vacancy emitters in 4H-SiC.

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Long-lived 13-carbon and 29-silicon quantum memories close to silicon vacancy and dicavancy centers

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Silicon carbide (SiC) has emerged as a highly promising platform for solid-state quantum technologies owing to its long spin coherence times, mature crystal growth and post-processing techniques, low-noise surfaces, and well-established nanofabrication methods. A wide variety of optically addressable defect qubits have been identified in SiC, including silicon vacancies, divacancies, SiC NV centers, chlorine-vacancy complexes, and the yet unassigned PL5-PL7 emitters, all of which occur in multiple configurations in 4H-SiC and across other polytypes. This rich defect landscape provides a wealth of opportunities for engineering defect-based quantum functionalities. Recent experiments have demonstrated coherent control of nuclear spins coupled to silicon vacancy centers, highlighting their potential as long-lived quantum memories. In this work, we employ large-scale, high-accuracy density functional theory calculations to systematically investigate the hyperfine interactions between defect electron spins and nearby ^{13}C and ^{29}Si nuclear spins at all lattice sites surrounding silicon vacancy and divacancy centers. By analyzing the complete hyperfine tensors, we identify non-precessing nuclear spin configurations with exceptionally long coherence lifetimes in the vicinity of these defects. In addition to symmetry-protected lattice sites, we uncover a substantially larger set of sites that can also host long-lived nuclear spin memories. We further provide a quantitative comparison of the density and distribution of such candidate memory sites across different defect types and configurations, thereby identifying the most promising defect-nuclear-spin combinations for scalable quantum information and quantum network applications.

Integrated Photonic Components and Single-Photon Detection in Silicon Carbide for Scalable Quantum Information Processing

Lin Jin

Silicon carbide (SiC) is increasingly recognized as a leading platform for integrated quantum photonics, driven by its exceptional optical and spin properties. Optically addressable color centers in SiC exhibit stable single-photon fluorescence and controllable coherent spins [1], providing a robust photonic interface for quantum applications. Furthermore, as an established semiconductor material, SiC benefits from mature industrial fabrication infrastructure and demonstrates strong compatibility with CMOS technology. However, realizing scalable SiC-based quantum information processing will require advances in photonic and electronic device integration.

Here, we present key building blocks for integrated SiC circuits that combine photonic architecture with detection systems. First, we fabricated SiC waveguides utilizing 3D couplers [2] to enable optical access via fiber arrays. A coupling efficiency of 30% was achieved at 917 nm, enabling the transmission of quantum information encoded in ZPL emission of V2 centers. Additionally, we integrated superconducting nanowire single-photon detectors (SNSPDs) directly on SiC, demonstrating high critical currents and unity internal detection efficiency over a wide wavelength range [3]. Beyond material-specific developments, we also advanced detection control and readout techniques designed to be platform-agnostic and adaptable to SiC. Given the magnetic fields are essential for spin initialization and control, we evaluated the performance of SNSPDs in their presence and investigated strategies to minimize performance degradation. Furthermore, we implemented a cryo-CMOS readout to facilitate high-fidelity detection within a compact footprint. This readout showcased low power consumption and tunable recover time, achieving a time jitter as low as 40 ps [4].

Collectively, these advancements provide a robust and scalable toolkit for integrated quantum photonics in SiC, paving the way for efficient encoding of spin states into photons.

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Quantum photonics for colour centres in silicon carbide

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I will provide a review on the latest advances using nanophotonic engineering of silicon carbide to improve the performance of colour centres in view of quantum technologies and applications.

Key building blocks for a quantum repeater node based on silicon carbide

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Quantum networks promise fundamentally new capabilities in secure communication, distributed quantum computing, and quantum- enhanced sensing, while their realization requires scalable architectures that enable long-distance entanglement distribution together with local quantum processing and storage. Solid-state systems offer intrinsic advantages in robustness and integrability. Among them, silicon carbide (SiC) stands out by combining wafer-scale photonic integration with color centers that offer highly coherent optical transitions together with long-lived spin-based quantum memories, even when embedded in nanophotonic structures. Here we propose a SiC–based quantum repeater architecture and experimentally demonstrate its essential building blocks: metropolitan-scale spin–photon entanglement distribution, long-lived quantum memory, and on-chip spin-spin entanglement. We achieved spin-photon entanglement distribution over a 22 km fiber link with record-high link efficiency of 2. Furthermore, we successfully generated entanglement between two spin clusters on the same chip—each comprising a k-site silicon vacancy (V2) center communication qubit and a strongly coupled 29Si nuclear spin memory qubit. Crucially, by leveraging the communication qubits, we mediated and verified entanglement between the two nuclear spin memory qubits. These results establish SiC color centers as a scalable plat- form for quantum repeaters and represent a significant step towards integrated quantum networks operating at metropolitan distances.

Engineering vacancy defects in SiC for precision timing and sensing

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Interest in resilient UK and European sovereign position navigation and timing (PNT) systems has increased significantly recently due to its economic and strategic implications. The ability to demonstrate high precision, low drift RF signals in a low power, compact footprint is a key enabling technology. The development of Microwave Amplification by Stimulated Emission of Radiation (MASER) technology has demonstrated high accuracy timing systems that can be found in a range of applications. However, these systems are physically large and require highly protected, stable environments to operate precisely, making them unsuitable for use in a wide range of applications, from industrial settings through to transport. Atomic defects in wide band gap semiconductors, such as diamond and silicon carbide (SiC) [1] offer a unique opportunity to realise a robust, all solid-state quantum system as the basis to a MASER. This work describes the technological developments and challenges in building a silicon carbide based solid state MASER amplifier suitable for deployment outside of a laboratory setting and the requirements of ensuring a stable RF performance [2]. This demands RF cavity parameter design optimisation, enhancing spin-cavity coupling and careful thermal management. By design, it leads the way to improved sensitivity towards external perturbations particularly DC and RF magnetic fields [3]. To illustrate the sensitivity of these spin defects, the work demonstrates how an optical setup running in continuous wave operation can be modified for polarisation control which can be leveraged for optical detection and control of multi-RF photon magnetic resonances. The dependence of the zero field Optically Detected Magnetic Resonance contrast relating to these resonances on the RF polarization indicates strong correlation between them.

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Photoelectrical probing of spin defects in SiC

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Silicon carbide (SiC) is a promising platform for solid-state quantum technologies, as it hosts diverse promising spin-active defects while offering excellent semiconductor properties and compatibility with electronic device integration. In SiC devices, carriers generated by defect photoionization can be collected as electrical signals, enabling photocurrent-based defect-spin detection. [1] This electrical access is attractive not only for integrated spin readout but also for probing spin–charge properties of defects from a perspective distinct from optical detection. This talk will present our recent progress in photoelectrical spin readout and characterization of spin defects in SiC.

Single-defect detection is essential for quantum technologies, but the photocurrent from a single defect is extremely small. Therefore, sensitive readout requires suppressing leakage currents while efficiently collecting photoionized carriers. We address this challenge by using blocking-contact SiC devices with optimized design and biasing conditions, enabling sensitive detection of spin-dependent photocurrent from single defects. [2] This single-defect photoelectrical access also enables wavelength-dependent photocurrent spectroscopy, relevant to both photoelectrical readout performance and charge-state stabilization of spin–photon interfaces. [3]

Photoelectrical detection can also provide defect selectivity based on differences in defect ionization responses. We demonstrate selective photoelectrical detection of PL5, PL6, and PL7 defects in a 4H-SiC sample whose optical spin-readout spectrum contains overlapping resonances from NV centers and unidentified defects, facilitating analysis of previously unknown spin parameters of these important spin defects. [4]

Together, these results highlight photoelectrical detection as an effective approach for sensitive, device-integrated spin detection and defect characterization.

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Local area sensing in silicon carbide devices using silicon vacancy introduced by particle beam writing

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Negatively charged silicon vacancy (V_{Si}) in silicon carbide (SiC) is known as a spin defect acting as quantum sensor and quantum bit at room temperature [1]. This means that the important parameters such as temperature, magnetic field induced by current, and electric field in SiC devices can be monitored using V_{Si} [2,3]. For this purpose, particle beam writing (PBW) technique is a powerful tool because V_{Si}s can be created in certain locations [4]. In our previous studies [2], we demonstrated temperature sensing in a local area in a SiC pn diode using V_{Si}s introduced by PBW.

In this study, we create ensemble V_{Si} in SiC devices using PBW and measure electric field in the devices. Figure 1 shows room temperature photoluminescence (PL) map for a planar pn SiC diode. Ensemble V_{Si} were introduced by PBW (He ion microbeams with 5×10^3 He ions/1μmΦ). Array of bright PL spots from V_{Si}s are observed in Fig. 1. Next, we measure optically detected magnetic resonance (ODRM) for V_{Si}s in the SiC pn diode with and without the reverse bias. Figure 2 shows ODMR signals for V_{Si}s in the SiC pn diode applied at 0 V and 1500 V (2.3 MV/cm). The peak of ODMR signal is obtained at 70 MHz from the diode without electric field. On the other hand, the ODMR peak linearly decreases with increasing electric field and the ODMR peak is 8 MHz at 1500V. In the presentation, the details of electric field dependence of ODMR signals will be discussed.

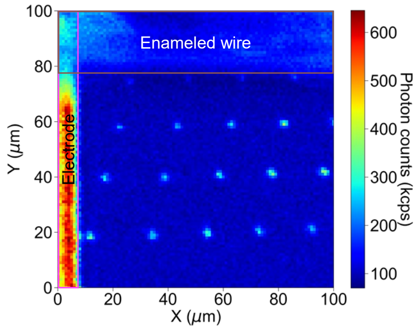

Fig. 1 room temperature PL map

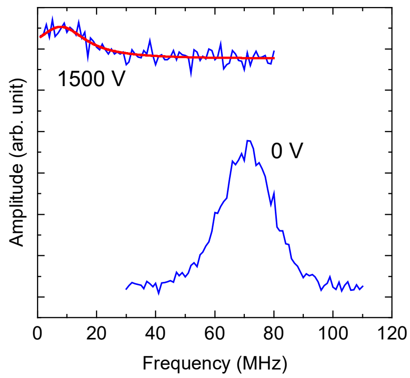

Fig. 2 ODMR signals for SiC pn diode

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Color center integration with photonic devices for quantum networking and analog simulation

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We integrate near infrared color centers in silicon carbide (SiC) with photonic devices for applications in quantum light sources, quantum repeaters and analog quantum simulation at scale. Our angle-etching method produces close-to-uniform triangular cross-section devices across a 5-inch SiC wafer while maintaining the spectral properties of color centers [1, 2]. Furthermore, we utilize nanopillars to enhance excitation and light collection in a polarization-sensitive manner in nitrogen-vacancy (NV) and divacancy (VV) centers in 4H-SiC [3, 4] and expand on the optical cryogenic characterization and utility of these promising quantum emitters with near-telecom emission. Finally, we propose a photonic scheme for the analog quantum simulation of the Lattice Gauge Theories on the Jaynes-Cummings-Hubbard (JCH) model of a coupled cavity array with integrated quantum emitters.

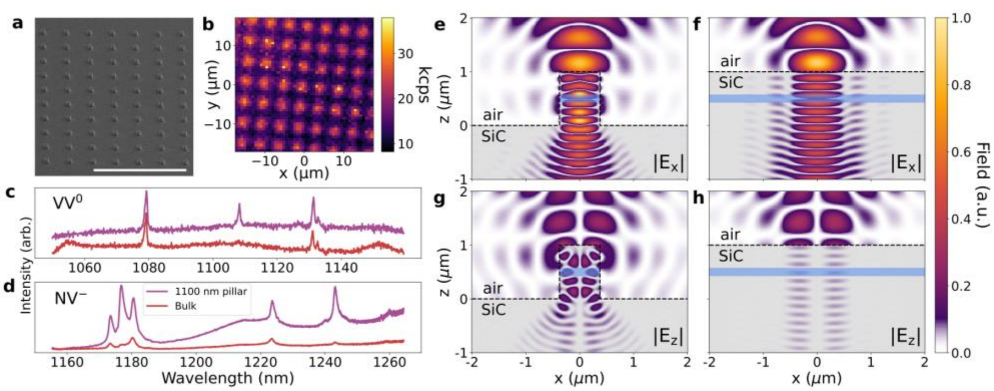

Fig. 1. *The nanopillar enables prohibited and enhances allowed optical transitions of VV and NV defects in 4H-SiC, compared to the bulk, by altering the polarization of the excitation laser [4].*

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Nanophotonic Solid-State Spin-Photon Interfaces

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Optically active spin defects in diamond have proven to be a promising resource for quantum communication and recently enabled the first demonstration of a 3-node network. In this presentation I bridge ongoing work and proposed concepts in the control [1], analysis and engineering of single spin defects for applications in quantum communication [2]. I introduce a recent proposal demonstrating theoretically that error-corrected quantum communication over 1000 km becomes achievable with solid-state spin qubits efficiently coupled to optical nanostructures [3]. These coupled spin defects and their coherent control, however, have complex requirements beyond current state-of-the-art. In our work, we focus on understanding the spin qubits' nano- and microscopic noise environment [4], coupling to nanostructures, and system control schemes [5]. To illustrate these efforts, I outline how we coherently control single diamond spin qubits with optical SUPER pulses [6], enhance qubit-to-waveguide coupling with the adiabatic Sawfish cavity with efficiencies up to 99% [7, 8], and mitigate noise in such nanostructures to maintain high photon coherence. Finally, I look ahead and lay out how we plan [9] to generate multi-qubit entangled states with integrated photonics [10] and hetero-integrated diamond nanophotonics [11].

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Silicon Carbide Waveguides for Augmented Reality and Beyond

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Augmented Reality (AR) is poised to revolutionize human-computer interaction by seamlessly integrating digital elements onto our physical world. To realize this vision, it is crucial to develop displays that blend effortlessly with reality, maintaining a compact form factor without obstructing the user with artifacts or perceptual mismatch. Although progress has been made, further breakthroughs in Optics, Optoelectronics, and Photonics are essential to meet the rigorous requirements for size, quality, efficiency, and cost. Silicon Carbide emerges as a lightweight and durable material with a high refractive index, enabling a wide field of view with minimal artifacts. This talk will explore SiC as a waveguide platform and its potential as an integral component in the journey toward a new era of human-computer interfaces. We will examine recent material development and improvements in SiC crystal quality, and discuss its broader potential as a photonic platform - where advances in growth, processing, and optical performance may also benefit applications beyond AR, including quantum technologies.

Towards distributed quantum computation with SiC color centers

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Optically active spin defects in silicon-carbide are a promising platform for investigating quantum networks and distributed quantum computation. In this talk, I will discuss our recent progress on creating integrated silicon-carbide quantum devices with controlled spin qubits based on the VSi (silicon-vacancy center, V2), including nanophotonic device fabrication, laser-induced VSi creation, and spin qubit control [1,2]. The results will be put in the context of the requirements of large-scale distributed quantum computation [3].

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Cathodoluminescene mapping of band bending effects from different 4H-SiC Schottky diodes for defect spin control

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Optically controllable defect spins in wide band gap semiconductors are promising systems for scalable quantum technology (QT). SiC is a wide band gap material with mature fabrication methods and several promising defects for QT. The silicon vacancy, for example, is an intrinsic defect in 4H-SiC with room temperature single-photon emission and millisecond spin coherence times [1, 2]. Furthermore, the Si vacancy has demonstrated favorable effects of device integration with e.g Schottky diodes, attributed to band bending and subsequent preferred occupation of the bright charge state [3]. However, different Schottky device constructions have not been evaluated.

In this work, differences between band bending effects of different contact materials used for defect charge state manipulation are investigated by spatially mapping the emission from the silicon vacancy with cross-sectional cathodoluminescence (CL). Al, Ti, Ni, Au, and Pd are used as contact materials, that are PVD deposited on a 4H-SiC surface in five parallel stripes. The 4H-SiC is He-irradiated to create a high concentration silicon vacancy box profile in the top 1.2 um of the epitaxial layer. The CL measurements reveal the evolution of the defect luminescence deeper into the sample.

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Spin centres in Silicon Carbide for Scalable Spin-Photon Interfaces

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Spin centres in crystals, particularly in diamond and silicon carbide (SiC), are a key platform for the development of quantum technology. Among these, vanadium in SiC has recently emerged as a strong candidate for quantum photonics, (1–5): It has an optical transition at 1.3 µm, compatible with optical fiber networks, a long-lived electron spin, and is hosted in a material that is available with high quality at an industrial scale. Recent investigations have resulted in significant advances for our understanding of this remarkable system, the control of its electron-nuclear spin qudit, and the development of photonic interfaces for quantum networks(6).

Spin-dependent optical transitions, which are crucial for quantum communication and computation applications, have now been demonstrated(3,5). Furthermore, we have shown that vanadium can be used as an extremely sensitive probe for the crystalline structure and electronic properties of the silicon carbide host: Its charge state stability depends strongly on the electronic environment in the SiC crystal, and its zero-phonon line resonance frequency is dependent on the isotope composition of the neighbouring lattice sites(3). Together with its long spin lifetime of over 20 s at cryogenic temperatures, this defect holds promise for a spin-based quantum technology platform with photon-mediated entanglement operations(7,8).

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Building a nuclear spin register with V2 center in SiC

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Nuclear spins in solids present valuable resource for quantum information. Moreover their precise spectroscopy is important for material characterization and benchmarking with Ab-initio studies. In this presentation we report detailed characterization of a 25 nuclear spin cluster around a single V2 center in 4H silicon carbide, having implications on realization of a nuclear spin based quantum register for quantum memory applications [1].

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In-situ magnetic sensing based on silicon carbide color centers

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In recent years, quantum precision measurement using the silicon carbide solid-state spin system has become a leading research hotspot in quantum sensing. For magnetic field detection specifically, this system has already realized nanotesla-level high-sensitivity magnetic field sensing, building up the core performance required for real-world implementation in a wide range of scenarios. In this talk, I will give a systematic overview of our team’ s body of research in this field. I will start with a brief review of the research progress in SiC-based quantum precision measurement. Then, I will focus on our team’ s original findings in SiC-enabled high-pressure in-situ quantum magnetic detection, including our work using this technique to achieve in-situ quantitative characterization of the magnetic evolution of two-dimensional (2D) magnetic materials under high pressure. I will also cover our team’ s other related work, including in-situ magnetic detection of 2D magnetic materials under ambient pressure, and our development of a fiber-integrated SiC magnetometer tailored for practical applications. To conclude, I will summarize and share our outlook on the potential application directions for SiC-based high-pressure quantum precision measurement.

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Tuning of on-chip mechanical resonators by bending-induced stress

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Silicon carbide (SiC) is a material that could advance the field of nanomechanics thanks to its exceptional low internal damping. Even more exciting is the prospect of hybridising mechanics with the spin degrees of freedom of colour centres such as V_{SI}, which opens up additional possibilities for quantum sensing and quantum communication.

However, the challenge lies in matching the frequency of a nanomechanical resonator with that of a spin when the resonance is as narrow as a single Hertz. We present recent experiments and results in continuation of high-quality-factor resonator studies [1][2] where the frequency of a monolithically fabricated single-crystal resonator is continuously tuned from approximately zero stress to more than 200 MPa. This analysis became possible by a thorough validation between simulation and experiment. The result of the first experiments is a 250% increase of the fundamental eigenfrequency and, simultaneously, a five-fold boost of the mechanical quality factor.

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Towards spin-based quantum technologies in hybrid nanomechanical systems based on silicon carbide

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Silicon carbide (SiC) has extraordinary material properties, combining some of the most favorable properties of diamond and silicon. It hosts spin-carrying color centers and exhibits high mechanical quality factors. It is thus ideally suited for the realization of advanced hybrid nano-mechanical devices incorporating atomic-scale defects. In addition, SiC crystallizes in a variety of polytypes. This entails different routes towards realizing high Q mechanical resonators. Cubic 3C-SiC enables thin-film epitaxial growth on silicon. Strong tensile pre-stress is incorporated when grown on a silicon substrate oriented along the (111) direction, leading to high Q from dissipation dilution. On the other hand, hexagonal 4H-SiC is a well-established material in nanophotonics and known for its highly coherent color centers. Recently, high intrinsic Q factors exceeding 10^5 have been demonstrated in monolithic 4H-SiC nanoresonators [1]. Here, I will compare nanomechanical resonators made of both 3C-SiC and 4H-SiC and explore their use for optomechanical crystal devices. I will discuss how to generate color centers by means of He-ion implantation [2], and outline the prospects of both materials for spin-mechanical and spin-optomechanical quantum technologies.

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High-yield engineering and identification of oxygen-related modified divacancies in 4H-SiC

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Modified divacancies in 4H-SiC are promising spin color centers for room-temperature quantum technologies because of their improved charge stability and spin addressability. However, their practical application has been limited by two major challenges: low formation yield and the lack of direct microscopic structural identification. In this talk, I will present a controllable oxygen-ion-implantation approach for the high-yield generation of oxygen-related modified divacancies in 4H-SiC, together with direct identification of their atomic structure. Based on their optical and spin-resonance signatures, we experimentally resolve four types of modified divacancies. By further measuring isotope-resolved hyperfine interactions with 17O nuclei, we identify these four defect types as the four crystallographic configurations of oxygen-vacancy (OV) complexes. Remarkably, single OV centers account for more than 90% of the total defect population and exhibit superior optical properties and spin coherence compared with defects created by conventional carbon- or nitrogen-ion implantation. I will also discuss the zero-phonon-line spectroscopy, the distinct temperature-dependent spin-readout behavior of these centers, and the realization of high-density ensembles through optimization of implantation dose and annealing temperature, where clear Rabi-beating patterns are observed for basal-type defects. These results establish both a scalable route to engineer oxygen-related modified divacancies in 4H-SiC and direct microscopic evidence of their structure, opening new opportunities for SiC-based quantum information and sensing applications.

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Wafer-scale monolithic integration of coherent spins in semiconductor photonics

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Silicon carbide (SiC) is a promising material for quantum technologies, yet the development of large-scale quantum integrated circuits (QICs) faces significant challenges such as emitter generation, ambient readout, and multi-qubit integration. This study presents a scalable strategy for monolithic quantum photonic hardware on a 4H-silicon-carbide-on-insulator (4H-SiCOI) platform, addressing these challenges through three principal advancements.

First, scalable fabrication is achieved using a wafer-scale device-first approach. Automated focused-ion-beam (FIB) registration enables site-controlled implantation of single divacancy spins into pre-fabricated resonator arrays. Second, strain engineering in the SiC membrane enhances the off-resonant spin readout contrast, exceeding 60% at room temperature while preserving intrinsic coherence[1]. Third, for multi-qubit architectures, controlled integration of electron-nuclear spin registers into waveguides is demonstrated, achieving maximally entangled states with a room-temperature fidelity of 0.89[2].

Together, these independent advancements in site-controlled manufacturing, intrinsically enhanced readout, and multi-qubit register integration establish a robust foundation for scaling monolithic quantum photonic networks.

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Abstracts of Posters

(in alphabetical order)

Optically addressable spin centers in the telecom window based on chlorine defects in SiC

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Optically and spin-active point defects in solids, known as color centers, provide a versatile platform for exploring light–matter interactions and enabling quantum technologies. Silicon carbide (SiC) is particularly attractive due to its favorable optical and spin properties combined with mature semiconductor fabrication capabilities. Although multiple color centers in SiC have been investigated, emitters operating directly within the telecommunication wavelength bands remain exceptionally rare.

We report the first experimental observation and characterization of the spin and optical properties of chlorine vacancies (ClV) in SiC. Following the recent discovery and optical identification of these defects, their spin properties had not previously been explored. Using ODMR, we demonstrate spin polarization and reveal the spin resonance signatures of this previously unstudied defect system.

A detailed analysis of the ODMR spectra, supported by calculations of possible spin configurations and their magnetic-field dependence, enables us to find the zero-field splitting parameters and estimate the hyperfine interaction constants with the 35Cl nuclear isotope. Furthermore, we measure the excited-state lifetime and establish a direct correspondence between the observed ODMR resonances and the zero-phonon optical transitions through microwave-assisted spectroscopy.

This first demonstration of coherent spin properties in ClV in SiC identifies them as a promising new class of telecom-band quantum emitters and opens a pathway toward their application in quantum technologies.

Diamond membrane platform for scalable photonic crystal cavities

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Quantum memories are a key building block for long-distance quantum communication networks, where they serve as essential components of quantum repeaters. Beyond this central role, they enable enhanced quantum key distribution, scalable photonic quantum computing, and distributed quantum sensing. Color centers in wide-bandgap materials, such as silicon carbide or diamond, have shown to be particularly promising candidates due to their long spin coherence times, optical addressability, and compatibility with integrated photonics.

In recent years, substantial effort was invested into coupling single atomic defects to suspended one-dimensional photonic crystal cavities to enhance light-matter interaction and enable efficient spin-photon interfaces. However, the fabrication of these structures relies on a complex process: quasi-isotropic under-etching, which limits thickness control, complicates post-fabrication characterization, and reduces reproducibility. Such constraints hinder deterministic cavity design and fabrication yield.

In this work, we pursue an alternative approach based on single-crystal diamond membranes fabricated using Smart-Cut technology. This method enables large-scale production with precise and repeatable thickness control, which is crucial for scalable quantum photonic platforms. The planar geometry also simplifies thickness metrology and systematic optimization of cavity parameters. Moreover, the significantly reduced bottom surface roughness is expected to minimize discrepancies between simulated and measured quality factors.

This robust membrane platform enables the exploration of optimized cavity geometries in a two-dimensional photonic crystal architecture. Such an approach is expected to offer enhanced confinement and greater flexibility in mode engineering compared to one-dimensional cavities.

We report on recent developments in membrane-based fabrication strategies and photonic crystal cavity design in diamond, aimed at scalable quantum photonic device integration.

Quantum Photonics with Vanadium in Silicon Carbide

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Silicon Carbide (SiC) has emerged as a premier CMOS-compatible platform for scalable quantum technologies, offering a large variety of optically active color centers for high-performance photonic integration. Among these, the Vanadium defect stands out as it features native emission in the telecom O-band. This intrinsic compatibility with fiber-optic infrastructure enables long-distance quantum communication while bypassing the efficiency bottlenecks associated with frequency conversion.

We demonstrate the coherent control of the 16-level Vanadium hyperfine manifold, reporting a longitudinal relaxation T1 of 25 seconds and a Hahn echo coherence T2 of 1.5 ms. To translate these spin properties into scalable quantum nodes, we integrate these defects into high-finesse photonic micro-cavities designed for the high-cooperativity regime.

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Silicon Carbide Nanocrystals for Quantum Sensing

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Quantum sensing based on spins can be used to study cellular mechanisms with extremely high sensitivity. Nano-diamonds containing NV centers are a popular platform for these studies, as they are non-toxic and allow monitoring properties such as temperature, pH, nanoscale forces, and chemical reactions [1, 2, 3]. Furthermore, nanodiamonds have also been used to improve sensitivity in quantum-enhanced lateral flow tests [4]. However, under green excitation, they luminesce around 700nm where cells also show bright fluorescence, resulting in a lower signal-to-noise ratio [5].

Here we discuss the possibility to use SiC nanocrystals with PL6 divacancies. These defects are excited at ∼900nm, with much less background fluorescence, while maintaining ∼30% ODMR contrast [6, 7, 8]. SiC nanocrystals have been fabricated by ball milling and implanted with oxygen to create divacancies. We expect these nanocrystals to reduce background fluorescence in intra-cellular environments and lateral flow tests, resulting in larger sensitivity in monitoring processes relevant for biology and healthcare.

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The spin- & photo physics of prototypical color centers in SiC using quantum embedding methods

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Prototypical color centers in silicon carbide, were identified as promising candidates for the implementation of quantum applications such as quantum sensing or quantum networks. Their coupled electron spins feature correlated high/low-spin states and an optical cycle with a spin-selective relaxation path [1] that enable spin-selective manipulation e.g., via photo excitation, magnetic fields or mechanics. Advanced quantum embedding of a color center via a hamiltonian with an effective screened Coulomb interaction and a solver based on configuration interaction has provided access to a quantitative understanding of the involved physics and opens access to theory-based qubit engineering [2]. The modelling capabilities are not restricted to just the defect high and low spin states but also include correlated defect resonances. Our insight into the spin-selective optical cycle and photo ionization of the silicon vacancy in SiC demonstrates this. Our recent development enables the calculation of orbit-strain/spin-strain coupling as well as hyperfine coupling parameters. We will address implication for the optical cycle.

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The best of two worlds: hexagonal boron nitride exfoliated on stressed silicon carbide string resonators

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The boron vacancy (VB) of hexagonal boron nitride (h-BN) is a promising single photon emitter for applications in quantum technologies. Nanomechanical control of the VB would greatly enhance its versatility in such applications, therefore nanomechanical h-BN resonators are of great interest. Exfoliating h-BN on substrates with holes was shown to create mechanical drum resonators, however it is difficult to leverage dissipation dilution effects in such drums.

Here we demonstrate that h-BN can be exfoliated on a chip with a pre-stressed silicon carbide thin-film heteroepitaxially grown on silicon and subsequently patterned into nanomechanical string resonators with high tensile stress. The resulting h-BN covered string resonators have high mechanical quality factors due to dissipation dilution and show the optically detected magnetic resonance signature of the VB of h-BN. The higher order mechanical modes of the string resonators match the expectations for such a two layered beam from room temperature down to 4K, which suggests that no harmful defects or disorder were introduced by the exfoliation and that the mechanical connection between SiC and h-BN is firm. Our fabrication approach allows to decouple the choice of the defect hosting 2D-material from the engineering of the mechanical mode and opens up routes to acoustic control of single photon emitters in h-BN and other 2D materials.

Towards Spin-Resolved Electrical Detection

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Silicon carbide's (SiC's) unique ability to form epitaxial graphene on its top surface via sublimation of silicon [1] and its technological maturity brings along a huge potential for the on-chip integration of quantum technology. We work towards utilizing epitaxial graphene in device designs, with which we will perform electrical measurements of the defect's spin of silicon vacancies (V_{Si}).
Graphene brings in many advantages: Its optical transparency allows for efficient optical pumping of spin distributions underneath electrical contacts. Moreover, it passivates the surface to provide longer spin coherence times and less spin noise. Finally, the interaction of graphene with the electromagnetic environment is negligible, giving a more defined mode structure of the radio waves used to excite spin transitions. Electrically, graphene can form Ohmic and Schottky contacts to p- and n-type 4H-SiC depending on the SiC/graphene interface [2] [3].
We propose device and measurement concepts that exploit these characteristics and employ the spin dependent capture of charge carriers into defects as a result of the Pauli principle. Here we present SiC p-n diodes with transparent graphene contacts that will be used to measure the defect spin via the recombination current within the depletion region. Furthermore, a novel approach using a deep level transient spectroscopy (DLTS)-like measurement schema will be explored. We strive for detecting spin signals (i) via capacitance transients within a graphene Schottky diode and (ii) via current transients within a graphene MeSFET-like structure [3]. These transients are dependent on the emission of charge carriers, which were subject to the Pauli principle during carrier capture.

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Electro-Optic Tunability of 4H Silicon Carbide Photonics for Quantum Applications

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Containing vacancy centers, electro-optic tunability, low optical loss, and bulk non-linearity, 4H silicon carbide has emerged as an exciting new material for developing integrated quantum photonic devices. The silicon vacancy in 4H silicon carbide is particularly attractive because of its well-studied spin-3/2 level structure, long spin coherence, and convenient optical transition wave-length (916 nm) [1,2]. A core challenge in building complex spin-photon entan-gled states with the silicon vacancy is the spectral diffusion and inhomogeneous distribution of individual defect optical frequencies, caused by charged carriers within the surrounding silicon carbide material. The usage of carrier depletion utilizing PIN diodes [6] and Schottky diodes [4] have demonstrated a reduction in spectral diffusion within silicon vacancies. Additional electrical control of sili-con vacancy centers has enabled the tuning of individual defect centers utilizing the Stark effect [5]. To date, the silicon vacancy has been integrated within primarily passive photonics, or electrically active bulk devices.

Here we demonstrate progress towards the integration of silicon vacancy cen-ters into electrically active photonic cavities. Utilizing whispering gallery mode photonic resonators with complex geometry, we demonstrate electro-optic tun-ability of cavities compatible with silicon vacancies, and extract the r_{13} and r_{33} Pockels coefficients for 4H silicon carbide. These coefficients have been previ-ously measured by [3], but our resonator geometry also enables extraction of the previously unmeasured r_{51} Pockels coefficient for 4H silicon carbide. We additionally demonstrate progress towards utilizing electrical control schemes demonstrated in bulk silicon carbide to precisely tune interactions between sil-icon carbide vacancies and the optical whispering gallery modes within high quality factor microresonators.

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Atomic-Scale Characterization of Silicon Carbide Interfaces: Key Step for Device Integration in Quantum Technologies.

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Silicon carbide is gaining traction as a platform for quantum technologies because it combines mature semiconductor processing with optically active defects that can be used as quantum emitters and spin systems. Its wide bandgap, thermal stability, and compatibility with standard fabrication processes make it suitable for integrating photonic and electronic functionalities on the same platform (Castelletto & Boretti, 2020).

Recent work on 4H-SiC-on-insulator demonstrates that low-loss photonic structures can be fabricated while preserving high-quality color centers, together with nonlinear optical functionality within CMOS-compatible processing (Lukin et al., 2020). These results position SiC as a viable material system for integrated quantum photonic devices.

Despite this progress, the SiO_2/SiC interface remains a limiting factor for device performance. Electrical measurements show a high density of near-interface traps that degrade carrier transport and stability. Detailed microscopy and spectroscopy studies indicate that these traps are not associated with graphitic carbon accumulation, but instead originate from intrinsic defects formed within the transition region at the interface (Pippel et al., 2005).

This makes interface control a central challenge for SiC-based quantum devices. Achieving reliable performance requires understanding how processing conditions translate into atomic-scale structure and defect formation at the interface. Techniques such as STEM and EELS provide direct access to local chemistry and bonding, enabling correlations between interface structure and electronic behavior.

In this context, this work presents atomic-scale characterization of the SiO_2/SiC fabricated under different environments, and its connection with device performance, guiding improvements in interface quality for scalable SiC quantum technologies.

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Electrical control for quantum emitters integrated in silicon carbide nanophotonic devices

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Color centers in silicon carbide are promising candidates for chip-scale quantum information processing. They combine atom-like optical transitions and long-lived electron and nuclear spin qubit clusters in a nanofabrication-friendly host material. Their integration in nanophotonic structures provides enhanced spin-photon interaction and increases photon collection efficiency. However, this necessitates an efficient integration of the spin defects in the hosting photonic structure. Requirements therefore are spectral tunability of the quantum emitter and its environment as well as absence or minimal spectral diffusion. We develop electrical control of spin defects to achieve emitter stabilization and environment compatibility. Charge depletion around the spin defects enables a modulation of the local electrical environment for a deterministic charge-state control [1]. Additionally, the Stark effect and the strong optical nonlinearities in silicon carbide allow for defect tuning in the nanophotonic environment. Thus, we project a possible path towards on-chip quantum photonic information processing through key advances in nanofabrication and electrical control in silicon carbide.

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Theory of Double-Quantum Control of Silicon Vacancies in Isotopically-Purified 4H-SiC for Enhanced Magnetic Field Sensing

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Recent studies of silicon vacancies in isotopically-purified silicon carbide (SiC) reported significantly prolonged coherence times and the emergence of new spectral features [1-3]. In this work, optically detected magnetic resonance (ODMR) simulations of silicon vacancies in isotopically-purified 4H-SiC using Lindblad equations are presented and validated with corresponding measurements. At low magnetic field, a rich ODMR spectrum is revealed: multi-photon and multi-quantum transitions, vertical ODMR transition lines, and anticrossings of transition lines. These features were fully characterized, and a Floquet-Schrieffer-Wolff transformation was used to derive effective Hamiltonians, microwave couplings, and AC Stark shifts of multi-photon features. The interplay between inhomogeneous noise, microwave magnetic field strength, and double-quantum sensing enhancement was also explored; which concluded that magnetic noise is the primary mechanism limiting double-quantum-enhanced sensing.

This material is based upon work supported by the U.S. Department of Energy Office of Science National Quantum Information Science Research Centers as part of the Q-NEXT center, which supported the full characterization of spectral lines with derivations of effective Hamiltonians. In addition, ODMR simulations were supported by the U. S. Air Force Office of Scientific Research under Award number FA9550-24-1-0355. Research at the U.S. Naval Research Laboratory is supported by the Office of Naval Research.

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Quantum-enhanced magnetic resonance imaging using spin-3/2 defects in SiC nanoparticles

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Conventional magnetic resonance imaging (MRI) relies on the difference in polarization between the two spin states of hydrogen nuclei at a given magnetic field. This is impeded by the minute Boltzmann distribution, especially at room temperature. Different approaches for hyperpolarizing nuclear spins have been proposed and used over the years, the most notable of which are dynamical nuclear polarization processes such as the solid effect and the cross effect or using parahydrogen as a polarizing agent.

With the introduction of color centers (or defects) in solids as novel agents for hyperpolarization, the expectation is to transfer the high degree of optical polarization of the defect's electron spin to the surrounding nuclei around it. While polarization transfer has been demonstrated from nitrogen-vacancy centers to the proximal ^{13}C nuclei, a subsequent transfer to hydrogen (say in water) is challenging.

In this poster we outline our approach to hyperpolarization with spin-3/2 defects, namely the SiV in SiC. We explain our reasoning for using solid state qubits with low zero-field splitting and discuss the possible applications in MRI that may come out of this research direction.

Silicon Carbide Technology for Integrated Quantum Circuits

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This contribution gives an overview about the current quantum research at the Chair of Electron Devices at the FAU in Erlangen and beyond about our objectives in the project SiCqurTech of the QuantERA program [1] as a follow-up to our last presentation at this conference. In our research, we focus on up-grading our SiC semiconductor device fabrication line for quantum technologies and on the investigation of the SiC material itself as well as of SiC devices under ambient parameters for quantum applications, e.g. a cryogenic temperature.
Typically, SiC is promoted for its reliable functionality even at high temperatures and at high voltages. In contrast, for quantum applications SiC devices are operated below 10 K leading to a more insulating semiconductor and thus a restricted conductivity. For a better understanding we investigated SiC contact and sheet resistances of highly doped n- and p-regions using test structures such as VdP or TLM. Electrical parameters of n-regions remain well defined at cryogenic temperatures whereas the behavior of p-regions turned out to be more complex, probably due to dopant freeze-out and contact degradation. [2]
Furthermore, we researched various electrical device types for tuning and controlling color centers. Not every device is automatically suitable for every type of color center. It is important to consider the electrical field strength and energy required for tuning and charging of color centers. As an example, a vertical SiC pin diode fabricated on c-plane material can be operated at voltages below 20 V for Stark shift tuning. In contrast, a less suitable capacitive SiC structure barely reaches the required field strength at operating voltages above 100 V. [3]
The presentation will show our suggestions and future solutions for the above-mentioned challenges.

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Towards understanding silicon vacancy formation in silicon carbide via particle irradiation

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The silicon vacancy (V_{Si}) in silicon carbide (SiC) is one of the most promising color centers for SiC based quantum technologies due to long coherence times, stable optical emission, and charge state control [1, 2]. Several methods to integrate V_{Si} into nano-fabricated devices have been reported in literature, including fs-LASER irradiation or particle irradiation (electron, proton, neutron, ions) [3,4]. Heavy-ion irradiation allows controlling the depth where V_{Si} are formed by selecting the particle electronic stopping power (S_e) and nuclear stopping power (S_n), hence, the mass and the energy of the incoming ion [5]. The sum of Se and Sn defines the total stopping power (S). In this work, we study the influence of S and the ion fluence on the V_{Si} formation, and compare those results to neutron and proton irradiation. To understand the V_{Si} creation via particle irradiation, we have performed optical measurements such as zero phonon line (ZPL) measurements, to identify the V_{Si}, and Raman Spectroscopy to study the damage. Depth dependent measurements on the presence of point defects were performed with low-energy muon spin spectroscopy (LE-µSR) [6]. Our results show the dependence on the S parameter and fluence for the V_{Si} creation. Furthermore, we discuss the signatures of the heavy-ion created V_{Si} dependent on the excitation wavelength. ZPL and Raman results on MeV irradiation also show a dependency on the fluence and S parameter. In addition, carbon vacancies (V_C) are formed in the near-surface region, as shown by LE-µSR results, extending more than two times the heavy-ion penetration depth. Further, the V_C density and overall surface damage increase with fluence. In summary, this work presents the creation of V_{Si} via ion irradiation, and the damage associated, with a clear emphasis on the interaction of incoming ion and the local SiC host crystal environment at nuclear level. The V_{Si} created by various heavy ions show distinct features at different excitation wavelengths

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Seeing the forbidden: overcoming optical selection rules through nanophotonic integration

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Optically addressable spin defects in silicon carbide, including the neutral divacancy (VV^0) and the negative nitrogen-vacancy (NV^-), are among leading building blocks of solid-state quantum technologies. Integrating these defects into photonic structures such as nanopillars improves photon collection efficiency, but the consequences extend further. We show that the sub-wavelength geometry of nanopillars drastically modifies the local electromagnetic environment, providing optical access to defect transitions that are otherwise suppressed by selection rules in bulk material. Using low-temperature photoluminescence spectroscopy, we observe that emission from the PL3 divacancy, which is nearly absent in planar devices, becomes pronounced in nanopillars owing to a polarization transformation of the excitation field within the pillar. We further leverage the orientation-dependent collection of nanopillars to resolve the origin of previously ambiguous spectral lines. In particular, the NV4′ feature displays the signal enhancement expected for axially oriented NV^- centres, consistent with assignment to a higher excited state of the *kh* defect configuration. Our results establish nanophotonic integration as a symmetry-sensitive probe that can both activate nominally dark transitions and identify the dipole character of poorly understood defect states.

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Towards High-Fidelity Quantum Gates for the V2 Defect in 4H-SiC

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Point defects in silicon carbide are emerging as promising candidates for scalable quantum applications. Among them, the k-site silicon vacancy (V2) in 4H-SiC has been used to demonstrate several key steps towards quantum computing, quantum sensing and quantum network applications, including single-shot readout of a coupled ^{29}Si spin [1,2], mapping and control of 25 coupled ^{13}C and ^{29}Si spins [3] and spin-photon entanglement generation [4].

Here, we present our progress in designing, characterizing and optimizing high-fidelity quantum gates on the V2 center electron spin in nanopillar devices [5]. For this, we build on our experience with gate-set tomography (GST) on NV centers in diamond [6]. Precisely characterized high-fidelity gates would form an important step towards potential quantum internet technologies based on qubits in SiC.

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Concepts for Microwave-Free Vector Magnetometry with Silicon Vacancies in 4H-SiC

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Spin-3/2 silicon vacancies (VSi) in 4H-SiC enable room-temperature, all-optical magnetic sensing via a pronounced photoluminescence (PL) response at ground-state level anticrossings (GSLACs), avoiding microwave drive fields [1]. Exploiting fine and ^{29}Si hyperfine structure near the GSLAC enables full vector reconstruction by comparing level-anticrossing spectra to reference spectra and applying calibrated “modifying” fields, recently demonstrated in a 3-axis Helmholtz-coil scheme [2]. We present concepts toward wafer-integrated microwave-free vector magnetometers based on VSi ensembles in 4H-SiC, leveraging mature SiC processing and progress in photonic and electrical integration. We focus on two integration bottlenecks: (i) PL signal-to-noise, limited by modest LAC contrast and photon collection in planar chips, and (ii) generation of stable, low-noise bias/compensation fields (up to mT-scale) with on-chip conducting leads without excessive Joule heating, drift, or electromigration. We discuss design trade-offs and integration strategies, including light-trapping/waveguide geometries and current-loop layouts that use SiC’s high thermal conductivity to maintain field stability [3][4].

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Towards a Miniaturized SiC Quantum Sensor in an Advanced Semiconductor Package with Layout-Optimized B0/B1 Coils

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Silicon carbide (SiC) defect-based quantum sensors are a promising platform for compact magnetic field sensing due to their potential for integration into scalable microsystems. A key challenge is the realization of a package-level solution that combines electrical interconnect and local magnetic field generation with low power consumption. This project targets the integration of a SiC quantum sensing chip into an advanced semiconductor package, enabling a miniaturized and manufacturable sensor module. The system requires two different B fields. First, an adjustable DC offset field B0 to set the sensor's operating point, and second, an RF field B1 to drive spin transitions. The target spin-resonance drive frequency is 70 MHz, while the experimental platform is intended to support broadband excitation from 1 MHz up to 1 GHz to cover a large magnetic-field dynamic range. Achieving these targets in a module solution introduces parasitic coupling and layout constraints, including limited routing layers, maximum current load capacity and RF losses like parasitic coupling.
To find a suitable trade-off between B-field homogeneity, power consumption, design constraints and resonance frequency simulations were performed. The B0 and B1 structures are realized as separate inductors distributed across multiple RDL layers, providing additional degrees of freedom for homogeneity in the region of interest (ROI) and impedance control. Magnetic field strength and homogeneity are evaluated using Ansys Maxwell. The sensing ROI is modeled as the VSi-implanted active area of the 1 mm × 1 mm SiC chip including an additional 9 µm-thick waveguide [1]. Homogeneity evaluation is set up to report peak-to-peak metric. The RF structure is analyzed in Ansys HFSS to capture resonance behavior and impedance characteristics in the presence of package parasitics. Current results demonstrate a feasible RF coil concept compatible with package routing boundary conditions. Initial HFSS simulations indicate a resonance near 250 MHz for the present RF inductor design, which provides design margin for impedance tuning and matching toward efficient operation at 70 MHz, as well as flexibility for broadband sweep experiments.
Next steps include extracting quantitative field efficiency (field-per-current) and homogeneity metrics over the defined ROI, followed by experimental verification through S-parameter measurements.

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High-Efficiency Photonic Interfaces for Optically Active Defects in Silicon Carbide

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Colour centres offer great potential for scalable quantum communication networks, providing robust spin and optical properties. Among these, optically active defects in silicon carbide (SiC), such as the silicon-, di-, and oxygen-vacancies, are particularly promising due to their long coherence times and CMOS-compatibility [1]. However, a major challenge for solid-state quantum systems remains the limited optical efficiency, mainly concerning photon coupling into optical fibres, e.g., for long-distance communication.

Various approaches have been proposed to enhance the emitted light coupling efficiency, including pillars, solid immersion lenses, waveguides, and cavities. Common fabrication challenges for these photonic enhancement techniques include unintended scattering due to surface and sidewall roughness [2], background fluorescence, as well as reproducibility and scalability [3].

Here, we present a systematic investigation into fabrication-related surface roughness and the origins of surface fluorescence in the framework of optimising SiC photonic structures. We explore a wide range of parameters, including the use of different etch masks, plasma chemistries, etching strategies, as well as reproducibility. Structural and optical characterisation of the resulting waveguides allowed us to identify key loss mechanisms and critical parameters for high-efficiency photon transmission.

Based on these process developments, we demonstrate a new method for producing free-standing SiC waveguides with high reproducibility and uniformity across the wafer. Furthermore, we introduce a new design of inverted nanocone structure in SiC, which can provide up to 10x enhanced photon collection efficiency compared to bulk SiC. These results provide a reproducible toolset for the wafer-scale (quantum) photonic platform in SiC, including integrated colour centres. We anticipate strong potential in the field of quantum communication based on solid-state quantum repeaters.

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Thermal Optimization for Resonant Readout and Multilevel Ramsey Spectroscopy of Spin-3/2 V1 Centers in 4H-SiC

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Color-center spin-photon interfaces generally require cryogenic operation to suppress phonon broadening and spectral diffusion and thus preserve narrow optical linewidths and high photon indistinguishability. This requirement is especially stringent for silicon vacancies in 4H-SiC: the O1 and O2 zero-phonon-line transitions are separated by only about 1 GHz, so inadequate thermal optimization readily causes strong spectral overlap. Moreover, while V2 remains relatively insensitive over a broader cryogenic range, V1 becomes highly temperature sensitive already near 5 K. We therefore investigate single V1 centers in 4H-SiC using a compact closed-cycle confocal cryostat with an in-vacuum objective. By varying the sample mounting and optical geometry, we find that the thermal margin at the emitter changes strongly even when cryostat thermometers remain near 5 K. Pulsed resonant photoluminescence-excitation measurements reveal linewidth variations of more than an order of magnitude between configurations, indicating substantial differences in local thermal loading. After optimizing the thermal interface and optical configuration, linewidth broadening is strongly suppressed and the spin-selective O1/O2 transitions are cleanly resolved for resonant initialization and readout [1]. On this optimized platform, we perform coherent microwave control and high-resolution Ramsey spectroscopy of the spin-3/2 manifold. Because the zero-field splitting of V1 is relatively small, short pulses can coherently excite spectator transitions in addition to the addressed transition, producing multiple Ramsey components beyond the two-level expectation. These features are explained by a four-level rotating-frame model and reproduced numerically as a deterministic six-branch structure [2]. Taken together, these results show that thermal optimization is a practical prerequisite for quantitative studies of multilevel coherent dynamics and resonant readout engineering in V1-based spin-photon interface experiments.

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Benchmarking single Er^{3+} optical coherence time in Silicon Carbide on Insulator-based micropillars

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Developing quantum emitters with long spin and optical time coherence in complementary metal-oxide-semiconductor (CMOS) platforms is a promising pathway towards optical quantum applications. Recently, excellent optical and spin coherence of trivalent Er ions was demonstrated in isotopically purified Silicon (Si) [1] and Silicon on Insulator (Si) [2, 3]. Here, we show the coherent optical control of single Er^{3+} ions in SiC micropillar arrays. These micropillars were fabricated in Silicon Carbide on Insulator (SiCOI), CMOS-compatible quantum material, implanted with 10^{16} Er/cm^3. Single Er^{3+} ions in micropillar arrays were measured using sample-on-superconductor single photon detector (SSPD) method [1]. Micropillar arrays enabled ~0.1 collection efficiency of Er^{3+} optical signal when corrected for the SSPD detection efficiency. The measured linewidth of single Er^{3+} ions varied from ~1 MHz (limited by the wavemeter resolution and laser frequency stability) to ~10 MHz. The larger linewidth ions exhibited the top-hat line shape suggesting unresolved internal structure due to interactions with nearby Si and C nuclear, and Er electron spins. Optical Hahn coherence time measured for an ion with sub-MHz linewidth was ~30 μs. The observed narrowest Er^{3+} linewidth and optical coherence are superior to values measured in both Si^{28}, and SOI-based photonic cavities at similar implantation densities [4]. These results position Er^{3+} in SiCOI as a promising candidate for scalable and fully integrated on-chip quantum photonic systems.

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High-Temperature Annealing and Cryogenic Characterization of CMOS-Compatible 4H-SiC c- and a-plane pin-Diodes for Integrated Quantum Devices

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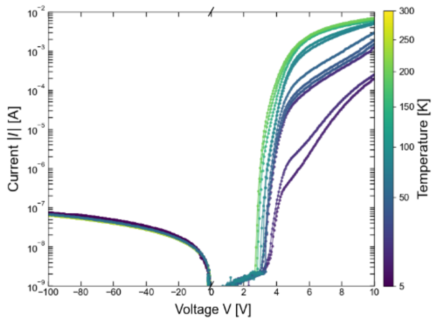
Integrated silicon carbide (SiC) pin-diodes enable local charge depletion and Stark tuning for various types of color centers while leveraging CMOS compatibility [1]. In the present study, we set forth three significant advancements that have been made towards the development of a fully integrated 4H-SiC quantum device.

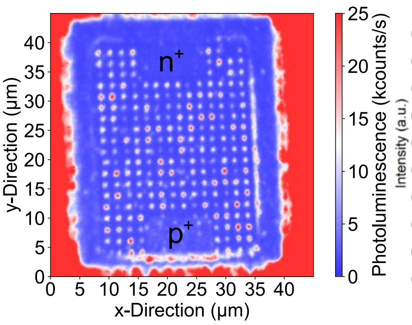
First, we show wafer scale fabrication and cryogenic characterization of CMOS-compatible c- and a-plane pin-diodes. Both crystal orientations show comparable electrical properties with a more pronounced knee voltage shift observed in a-plane devices below 90 K. Notably, the freeze-out effect yields lower reverse leakage currents at cryogenic temperatures, allowing large spectral shifts at low noise.

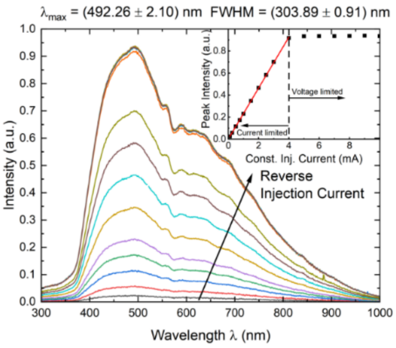
Second, we present the implantation of a silicon vacancy array into a pin-diode and demonstrate the resilience of these diodes against the thermal annealing up to 900 °C. Above 850 °C, significant degradation in ideality and on-current occurs alongside a knee voltage reduction, though leakage current remains below detection limits up to −200 V reverse bias.

Third, we show a p-channel MOSFET and a white light emitting tunneling diode on c- and a-plane showcasing the superiority of SiC over other materials. The a-plane nMOS shows comparable characteristics to conventional c-plane devices while the tunneling diode shows still 43% of maximum intensity at 730 nm, giving rise to on-chip excitation of color centres. Both devices remain functional at cryogenic temperatures.

Our results demonstrate the thermal stability of integrated pin-diodes as charge depletion and Stark tuning devices for various defects paving the way for the full integration of electronic control structures for color centers in SiC-based quantum applications.







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Advancing SiC Quantum Magnetometry: Optimized Divacancies and Single Vacancies PDMR Readout

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We present experiments towards a magnetometer based on modified divacancy spins in 4H-SiC. This work follows our previous demonstration of single-vacancy ensembles, which are limited by intrinsically low ODMR contrast. Divacancies provide superior performance, featuring high photon count rates and ODMR contrast. Moreover, the near-infrared excitation and emission are promising for biological sensing applications. A range of nitrogen implantation and annealing protocols were investigated to optimize divacancy creation and background suppression. Even if they still lack the same scalability ease, photoluminescence and optically detected magnetic resonance (ODMR) measurements reveal improved metrics compared to single-vacancy systems. Additionally, we present initial results on structures engineered for PDMR (photoelectrically detected magnetic resonance) of single vacancies. PDMR enables readout via direct measurement of spin-dependent photocurrent, eliminating the need for an external photodetector. This approach promises more compact, scalable, and integrated sensor design, eventually opening a pathway toward fully electrical quantum magnetometers in SiC.

Photoluminescence study of SiC-SiO_2 interface defects

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As a potential future quantum technology platform, point defects in wide band gap materials provide a promising opportunity for scalability and potential room temperature operations for emerging quantum technologies (QT). The interface between silicon carbide (SiC) and thermally grown silicon dioxide (SiO_2) has emerged as an interesting host for defects that could be suitable for QT [1]. This heterostructure is also widely used in power electronics, where SiO_2 serves as the gate insulator in metal-oxide-semiconductor field-effect transistor (MOSFET) devices [2]. Although the thermal oxidation process creates interface defects that degrade electronic performance, these same defects have demonstrated single-photon emission with brightness exceeding that of NV-centers in diamond [3], which as of today is the benchmark for quantum defects. However, realizing their potential as single-photon sources remains challenging due to limited control over defect formation and a lack of structural identification. This project addresses the microscopic characterization of these emitters, aiming to establish the SiC-SiO_2 interface as a controllable source of quantum light.

Experimentally, (0001) n-type ($n = 1 \times 10^{15}$ cm^{-3}) 4H-SiC samples having 10 µm epitaxial layers purchased from Wolfspeed have been used. The samples were thermally oxidized in an open tube furnace for 15 min at temperatures (°C) of 400 and 1300. Time-of-Flight Elastic Recoil Detection Analysis (ToF-ERDA) was carried out to map the elemental distribution in the interface, see Figure 1a) for measurement of sample annealed at 1300 °C.

Photoluminescence (PL) studies were carried out at 325, 532 and 633 nm excitation and in the 380-1050 nm wavelength range, revealing the appearance of multiple sharp peaks after thermal oxidation. In Figure 1b), a sharp feature is visible at 764 nm in the PL spectrum of the sample that was thermally oxidized at 1300 °C. The feature does not appear in the native oxide or 400 °C annealed sample, suggesting a defect related origin.

Further experiments are in progress to investigate defect formation as a function of a wider range of oxidation temperatures, Fermi level position (i.e. doping), and pre- and post-treatment of the samples such as etching of the epitaxial layer and post growth annealing with the use of different ambient gases.

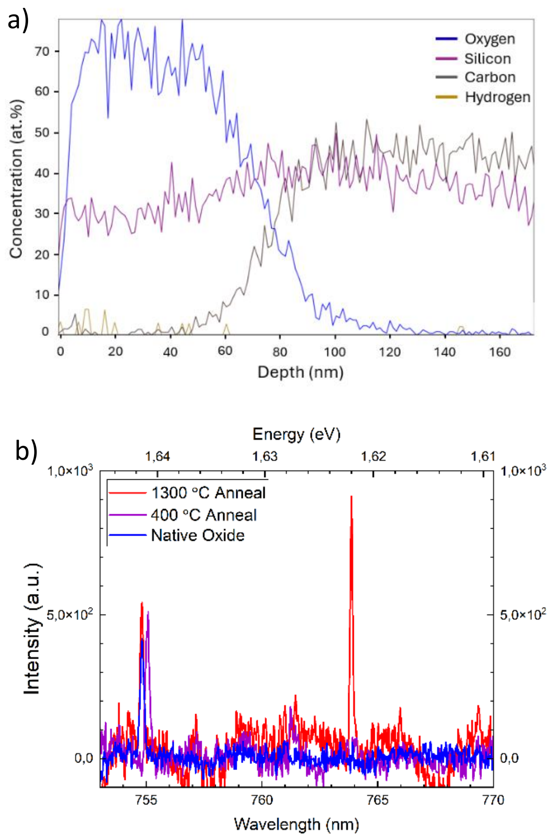

Figure 1: (a) ToF-ERDA profile of sample oxidized at 1300 °C, and (b) Photoluminescence spectra of samples annealed at 400 and 1300 °C in addition to a reference sample with only native oxide. Here an excitation source consisting of photons with wavelength of 633 nm was used.

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Towards Time-Bin Encoded Photonic Qubit Generation and Readout Using an Unbalanced Mach-Zehnder Interferometer

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Solid-state quantum emitters are a resource for single-photon generation, relevant for integrated quantum photonics and quantum communication networks. In this work, we implement time-bin encoded photon generation and analysis in combination with a tin-vacancy (SnV) center in diamond. Our approach uses an actively stabilized unbalanced Mach-Zehnder interferometer (UMZI) for both state preparation and phase-sensitive projective measurements of time-bin encoded photons [1]. Weak coherent laser pulses ($\mu \ll 1$) pass through the interferometer, erasing time information and non-deterministically creating single photons in a superposition state of $|early\rangle$ and $|late\rangle$ [2]. During projective measurement, this temporal information is converted to phase-dependent interference. Phase stabilization of the UMZI is achieved via periodic recalibration using a reference laser signal to control an integrated fiber stretcher, effectively compensating for thermal drift, mechanical vibrations, and environmental perturbations. This enables stable and precise control of the interferometer phase on timescales relevant to photon coherence. By combining the SnV center's optical properties with precise interferometric control, this work contributes to the development of scalable quantum photonic platforms, including applications in quantum repeater nodes and quantum key distribution.

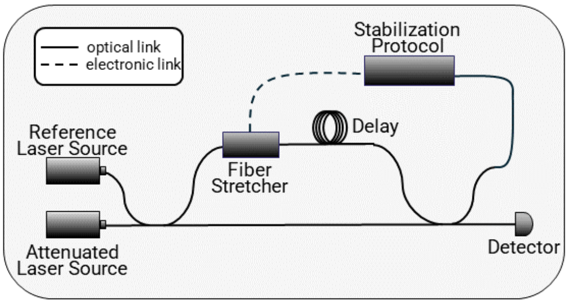

Figure 1 **Experimental setup of the UMZI.** The setup includes an attenuated laser source for generating weak coherent pulses and a reference laser for phase monitoring. A phase shifter (integrated fiber stretcher) is controlled by a stabilization protocol to compensate for environmental drift, ensuring long-term interference stability. The output is monitored by a single-photon detector to perform projective measurements.

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Electric driving of hyperfine-coupled spin for the V color center in SiC

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Vanadium defects in 4H-SiC are a promising system for quantum technologies due to their optical transitions in the telecom wavelength range, and their hyperfine-coupled spin system [1]. However, scaling up such systems is quite challenging, as it requires controlling individual spins for coherent operation. The need to address the spin system via oscillating magnetic fields intricates their implementation in multi-spin nanodevices, because the field is hard to localize or screen [2]. Electric driving of the spin system would solve that problem. Electric fields can be effectively routed and confined in a complex nanoscale device, offering a new approach to manipulate localized spins in electronic devices [3]. To investigate this phenomenon, a SiC layer (that can host the spin-active vanadium defects) was prepared by coating both sides with thin gold layers, forming a parallel-plate capacitor. These gold films are thin and semi-transparent, and allow for optical readout while maintaining homogeneous conductivity. Their reflective properties create a Fabry Pérot cavity, which can be harnessed for optimal performance.

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Ionization-based current spectroscopic characterization of single V1/V2 centers in 4H-SiC

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Understanding the defect charge state is critical to both spin–photon interfaces and photoelectrical spin readout[1,2], but the ionization rate of silicon vacancies (V1/V2) in silicon carbide (4H-SiC) has remained unclear[3]. Here, we employ photocurrent spectroscopy of individual defects to evaluate the wavelength dependence of their ionization cross-sections (σ_i) at room temperature. We reveal that σ_i of both V1 and V2 increases as the wavelength shortens (FIG. 1(a)) and also observe the steep increase of the background photocurrent below 830 nm (FIG. 1(b)), which is attributed to photoionization of carbon vacancies. From these results, we can discuss the charge stability of V1 and V2 under resonant excitation and the wavelength regime to optimize V2-photocurrent generation relative to background contributions (FIG. 1(c)). Our work demonstrates that photocurrent spectroscopy is a critical tool to complement optical characterization methods toward defect-based advanced quantum technologies[4].

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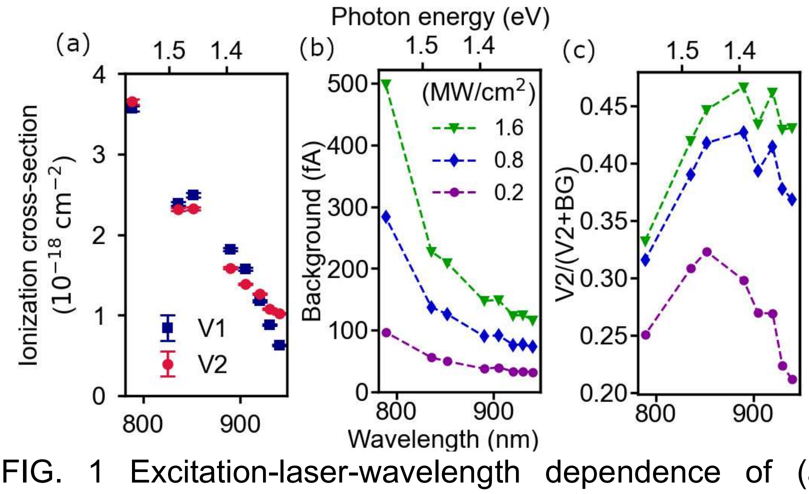

FIG. 1 Excitation-laser-wavelength dependence of (a) photoionization cross-sections of V1 and V2, (b) background photocurrent (BG), and (c) the V2 photocurrent fraction as V2/(V2+BG).

Hybrid integration of silicon carbide color centers into photonic integrated circuits

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Color centers in the silicon carbide (SiC) are promising qubit candidates for quantum information processing, but scaling to practical systems requires significantly increasing the number of qubits within a single processing unit [1]. A solution to this challenge is integrating color centers into photonic integrated circuits (PICs) for efficient and miniaturized photon collection, routing, and detection [2]. However, even though SiC wafers are commercially available, SiC lacks well-established PIC technology, thereby limiting scalability. In contrast, silicon nitride (SiN) is a widely used and foundry compatible platform for PICs.

Here, we address this limitation of SiC via the hybrid integration of SiC chiplets into SiN PICs using micro transfer printing [3]. The chiplets are suspended structures fabricated from 4H-SiC-on-insulator containing photonic waveguides and cavities designed for the V2 color center. We optimized the geometry of chiplet and PIC to ensure reliable transfer printing and efficient optical transmission, and we demonstrate successful hybrid integration. Looking ahead, hybrid integration of SiC not only enables scaling of the number of addressable color centers, but also their control, as the heterogeneous platform allows for routing of metal layers beneath the SiC chiplets for efficient frequency and spin control via Stark tuning and microwave driving.

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Solid Immersion Lens–Enhanced Modified Divacancy Arrays for Scalable Spin–Photon Architectures in 4H-SiC

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Modified divacancy centres in 4H-SiC, notably the PL6 line, combine strong spin–optical performance at room temperature with CMOS-compatible fabrication, positioning them as promising spin–photon platforms [1]. Progress toward scalable quantum technologies requires improved photon collection while preserving coherent spin control within large, device-compatible array architectures.

We investigate a 4H-SiC sample comprising a spatially ordered array of modified divacancy centres generated through ion implantation, forming a scalable platform of quantum emitters. On this platform, we implement a patterned array of solid immersion lenses (SILs) to enhance photon extraction using a nanofabrication-compatible approach scalable to the wafer level [2].

The optical and spin properties of the emitters are probed through photoluminescence and coherent spin spectroscopy, including optically detected magnetic resonance and time-domain control protocols. This provides an integrated framework for photon extraction and coherent spin control.

The SIL-based strategy remains compatible with Schottky diode integration, enabling electrostatic control of the defect charge environment, including charge-state stabilization and zero-phonon-line tuning toward electrically controlled and highly efficient spin–photon interfaces and quantum memory architectures in SiC.

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Dopant-selective photo-electrochemical etching of SiC and SiC-on-Insulator

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SiCOI (SiC-on-Insulator) heterosubstrates are fundamental to realize active and passive (quantum) photonic elements on 4H-SiC, e.g. waveguides, microresonators or electro-optic modulators, and to combine them with electronic components, e.g. diodes for charge-state control of color centers. For such applications, quantum-grade SiCOI is required, comprising thin (< 500 nm), homogeneous and intrinsic epilayers of low surface roughness. While low-defect intrinsic epilayers are grown routinely on 4H-SiC, it is more difficult to achieve comparable quality for SiCOI thin films. So far, bond-grind-polish SiCOI have shown the highest quality [1], but suffer from large inhomogeneity due to mechanical grinding, e.g. [2]. Dopant-selective photo-electrochemical etching offers the capability to reduce the thickness variation via pre-defined doping contrasts, as shown for multiple etch stop layers on bulk SiC [3], and, more recently, for a single stop layer with weaker contrast, on SiCOI [4]. In this contribution, we demonstrate a photo-electrochemical etch stop on bulk SiC through the selective removal of a p-doped epilayer (see Figure 1), verified by the match between etch depth and epilayer thickness, while preserving a low surface roughness. In the next step, we will leverage this dopant selectivity to electrochemically planarize SiCOI substrates.

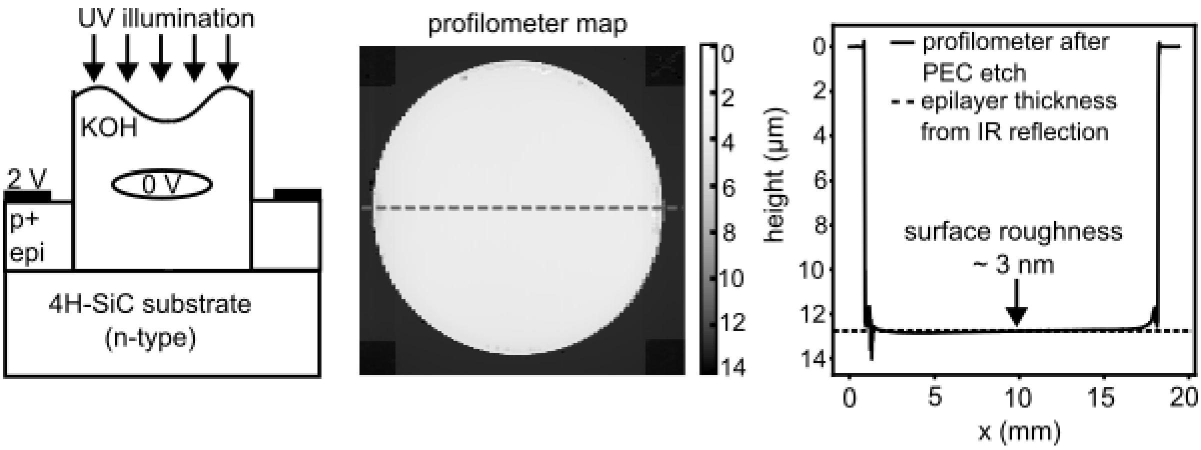

Figure 1: Left: Schematic of the photo-electrochemical (PEC) etching method to selectively remove a 4H-SiC p-type epilayer as a model system. Middle: Profilometry height map demonstrating a homogeneous etch stop at the epilayer/substrate interface. Right: Profilometry line-scan confirming that the etch depth equals the epilayer thickness determined by infrared reflectometry.

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Advanced fabrication and characterization of solid immersion lenses in diamond and silicon carbide

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Solid immersion lenses (SILs) are hemispherical microstructures that significantly increase the light collection efficiency of defect-based quantum emitters in high refractive index materials like silicon carbide and diamond. They can be created using a deterministic and mask-less approach by utilizing focused ion beam (FIB) milling. Although previous attempts improved the collection efficiency, they required post-processing and lacked reproducibility due to beam damage and redeposited material at the side walls. We implemented a new milling process resolving those issues [1].
Using a continuous spiral pattern, we have achieved SILs with optimal curvature, yielding a 6-fold enhancement in light collection efficiency in combination with reduced background noise. Interestingly, depending on the ion beam energy, step edges of different sizes form at the side walls of the lens. This is studied using continuum and binary collision modeling. In-line with the predictions from modeling, microstructural characterization indicates the presence of only a very thin amorphization layer on the intact crystalline material due to the efficiently suppressed redeposition.
The milling process is currently being adapted for SiC-based SILs and further expanded to realistically account for angle-dependent local sputtering rates. Those lenses will be used for the optimized characterization of silicon carbide quantum emitters, like silicon vacancies or vanadium impurity defects, that range from the near infrared to telecom wavelengths [2] with the goal to implement the emitters into photonic structures based on a silicon carbide on insulator (SiCOI) platform [3].

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Studying V2 color centers in photonic devices and modify them using Schottky junction technology

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Solid-state platforms have long been pursued for quantum technologies. Over recent decades, color centers have emerged as powerful resources for quantum sensing, communication, and computation. However, when embedded in solids, their quantum properties are strongly affected by fluctuations in the local charge environment [1]. Suppressing charge noise in the host material is therefore a key requirement for the fundamental scalability of these platforms, making nanoelectrical and photonic integration of quantum optical components essential for scalable solid-state quantum technologies.
Silicon carbide is particularly well suited for this purpose, combining mature high-power semiconductor fabrication with convenient electrical engineering capabilities. Already, SiC color centers have been successfully integrated into PIN diodes and spectrally manipulated [2,3].
Here, we study the behavior of single silicon vacancy (V2) color centers in nanostructures such as waveguides and nanopillars, as well as emitters located close to the sample surface. In these environments, the defects exhibit unusual behavior due to additional charge carriers associated with surface traps. We investigate their response to laser illumination and the controlled electrical modification of the host environment using Schottky diode structures [4]. Our results reveal depletion of charge traps near the electrodes, as well as irregularities leading to asymmetric Stark tuning, spectral hopping, and delayed responses to externally applied fields.
Furthermore, we explore the charge–photon dynamics of the V2 center and its environment in more detail, and additionally we give some insights our deterministically strained experiments. Our work addresses key limitations of semiconductor-based quantum emitters and paves the way toward fundamentally scalable and reproducible optical spin defect platforms in solid-state systems, with broad relevance for the quantum technology community.

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Scalable Quantum Magnetometer Chip Based on Wafer-4H SiC Technology

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We present an industrially scalable, power-efficient, and high-performance quantum magnetometer chip built on proprietary 4H-silicon carbide (SiC) technology. Leveraging wafer-scale fabrication, we optimize V2 silicon vacancy color centers with precise control over depth and density, enabling highly reproducible, industry-grade devices. The color center ensembles are integrated into a planar SiC waveguide, which provides efficient excitation of large active volumes and simplifies fluorescence collection compared to conventional confocal architectures. We demonstrate continuous-wave optically detected magnetic resonance (CW-ODMR) alongside pulsed control sequences (Rabi, Ramsey, and Hahn-echo), establishing coherent manipulation and readout of the embedded V2 ensembles. From these measurements, the device achieves shot-noise-limited magnetic sensitivities that are 2–3 orders of magnitude lower than those attainable with more complex confocal techniques. This integrated approach reduces optical complexity, lowers power requirements, and improves signal throughput, collectively advancing the architecture and performance of SiC-based quantum sensors. These results establish a viable path toward next-generation, chip-scale quantum magnetometers with manufacturable precision and robustness, suitable for deployment in demanding industrial and field applications.

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Large-scale characterization of color centers in diamond through automated photoluminescence excitation measurements

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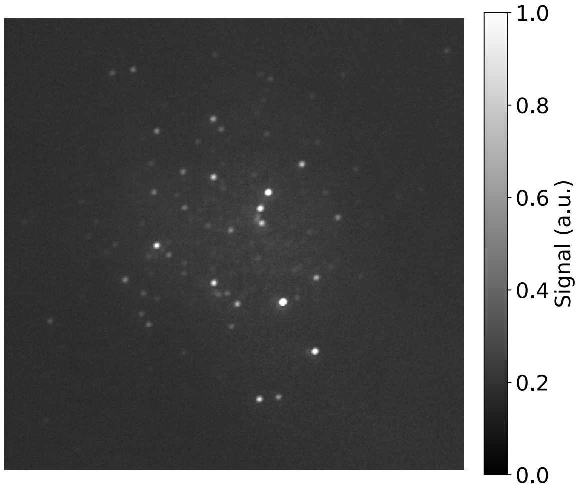

Fluorescing color centers during widefield photoluminescence excitation

In the quantum technology community, various physical platforms, including superconducting qubits, trapped ions, and photonic systems, are being explored, each offering distinct advantages for targeted use cases such as quantum communication and computation. Scaling up quantum devices remains a fundamental challenge across all platforms, limiting progress in the field. This encompasses scalable characterization and integration into quantum circuits.
Spectrally indistinguishable single-photon emitters are a fundamental requirement for generating entanglement in photonic quantum networks. Identifying spectrally indistinguishable color centers demands precise knowledge of their optical transition frequencies and linewidths. We demonstrate a scalable characterization approach for color centers in diamond based on automated photoluminescence-excitation (PLE) spectroscopy. A large-scale characterization capability is enabled by full automation of the experimental control, including tuning of a continuous-wave laser with MHz frequency precision and data acquisition. By exciting a large field of view rather than addressing individual emitters, the overall characterization throughput is significantly enhanced.
Using this technique, we investigate the spectral homogeneity of color centers in diamond. This method enables identification of spectrally indistinguishable emitters for deterministic integration into quantum devices and is applicable to various solid-state platforms including silicon-carbide, paving the way for scalable on-chip quantum-photonic architectures.

Radiofrequency and Microwave Driven Localised Spin Ensembles in Silicon Carbide

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Keywords: silicon carbide, silicon vacancy center, spin dynamics, quantum control, hyperfine interaction, multiphoton transitions

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Solid-state spin qubits in wide-bandgap semiconductors offer a compelling platform for quantum information processing, combining long coherence times, optical addressability, and compatibility with existing semiconductor technologies. In this work, I present a comprehensive numerical investigation of the microwave and radiofrequency driven spin dynamics of silicon vacancy (V_{Si}) centers in 4H-SiC, with particular focus on the V2 center.

Under coherent electromagnetic driving, the V2 center exhibits rich multiphoton dynamics. Linear Zeeman interaction gives rise to first-order transitions ($\Delta m_s = \pm 1$), while non-linear Zeeman terms activate second-order transitions ($\Delta m_s = \pm 2$) with characteristically doubled slopes in frequency–field spectroscopy. At high driving amplitudes, two- and three-photon absorption processes emerge. The system further displays two distinct ground state level anticrossings (GSLAC-1 and GSLAC-2) at specific external magnetic field values, corresponding to crossings between the $m_s = +1/2$ and $m_s = -3/2$ states, and between the $m_s = -1/2$ and $m_s = -3/2$ states, respectively.

Extending the model to multispin configurations by incorporating nearby ^{29}Si and ^{13}C nuclear spins reveals hyperfine-induced splitting of electronic transitions. Carbon nuclear spins couple approximately one order of magnitude more strongly than silicon nuclear spins, leading to more pronounced spectral splitting. The simulations further demonstrate power broadening effects and coherent population trapping in both V-scheme and Λ-scheme configurations.

These findings illustrate the rich and controllable spin dynamics accessible in silicon carbide defect centers, establishing their potential as a versatile platform for advanced quantum control, spin state manipulation, and quantum sensing applications.

Simulation and Experimental Characterization of Fishbone PCCs in 4H-SiCOI for Future Quantum Networks

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The V2 defect (k-site silicon vacancy) in 4H-SiC is a promising platform for future quantum networks, owing to its favorable spin and optical properties [1,2], and its compatibility with nanophotonic integration [3–5]. A key challenge, however, is to enhance the emission and collection of zero-phonon-line (ZPL) photons to increase the rate of remote entanglement generation between two V2 defects. Fishbone photonic crystal cavities (PCCs) offer a viable route toward this goal. Their small mode volume and low-loss TM-like optical modes enable efficient coupling to V2 defects in c-plane 4H-SiC.

To optimize the performance of these fishbone PCCs, we calculate the optimal cavity-to-waveguide coupling Q_{out} required to maximize the entanglement generation rate for different intrinsic loss values Q_{loss}. If time-filtering is considered, we find the highest entanglement rates require that Q_{out} must be drastically smaller than Q_{loss}.

Using temporal coupled-mode theory, we experimentally extract both Q_{out} and Q_{loss} through cavity reflection measurements. We find that the experimentally obtained Q_{out} agree well with the simulated values, demonstrating that we can reliably control the external coupling of our cavities and match the values required for efficient entanglement generation with emission-based schemes. Additionally, Q_{loss} is sufficiently high that entanglement rates are not limited by fabrication. These results pave the way towards high-rate entanglement generation in future quantum networks.

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Tin–Lead Liquid Metal Alloy Source for Focused Ion Beams

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Focused Ion Beams (FIB) have potential use for quantum applications due to their nanoscale spot size, required for precise positioning of quantum emitters inside optical nanostructures. In addition, direct-write capability and the potential for in situ single ion implantation, crucial for fabricating single photon emitters, are benefits of using FIB for quantum applications. Color centers in diamond can function as qubits and are of particular interest due to their capacity to store and transmit quantum information. While Group-IV color centers exhibit high brightness, they require low temperatures to retain coherence. However, lead-vacancy in diamond (PbV) operates at the higher end (4 K) of this temperature spectrum due to larger ground-state splitting, making them particularly interesting. Here, we present results for lead (Pb)-containing alloys with eutectic points below 600 °C and results on using tantalum (Ta) and titanium (Ti) as emitter materials for a Pb liquid metal alloy ion source. We show that a standard FIB system can resolve the different Pb isotopes, showin in Figure 1(a) and achieve nanoscale spot sizes, shown in Figure 1(b). Comparison with commercially available filaments, shown in Figure 1(c) reveals that the spot size achieved with our filament significantly deviates from the expected spot size on the machine. We present development of a fixture for improved performance of the Ta and Ti filaments, shown in Figure 1(d).

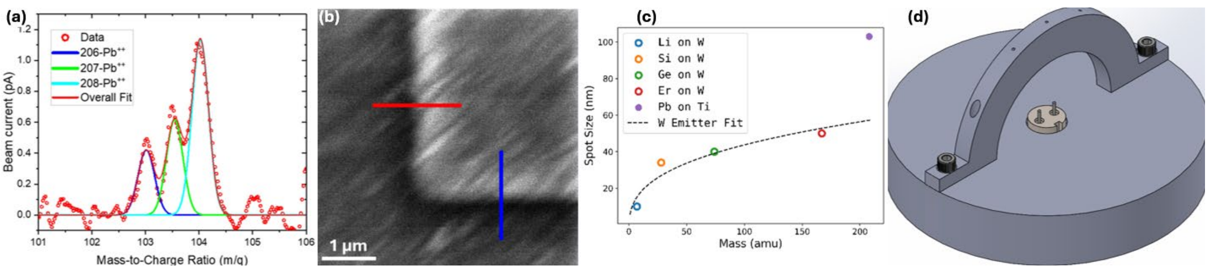

Figure 1(a) Pb mass spectrum showing isotopic resolution. (b) High-resolution secondary electron image using the Pb source. (c) Comparison of the Pb source spot size to sources built on a commercially available emitter. (d) Filament holder design for improving alignment and repeatability of filament during spot welding.

Reversible Qudit Entanglement Protocols for Silicon Carbide Defect Centers

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High-spin nuclear qudits in silicon carbide (SiC) defect centers provide a robust, long-lived platform for quantum memory nodes. Building upon existing iterative schemes for entanglement transfer via hyperfine interactions and projective measurements, we propose a protocol for establishing high-dimensional entanglement between distant nuclear qudits with Hilbert space dimension $d = 2^n$, where n is an integer. By replacing the projective measurements of the communication electron spin with a sequence of local unitary operations, we establish a reversible accumulation process. This approach allows for the creation of high-dimensional entangled states that serve as a versatile resource for a broad range of quantum information tasks, ranging from distributed quantum computing to scalable communication networks.

PL6 centers in 4H-SiC for spin-based quantum sensing

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4H-silicon carbide (SiC) has recently emerged as a promising platform to host point defects with possible applications in quantum technologies, such as distributed quantum computing or sensing.
Recently, modified color centers (PL5-7 centers) have drawn considerable attention with a high spin readout contrast of about 30 % and a high photon count rate at room temperature [1], making them competitive with the nitrogen-vacancy centers in diamond [2] and suitable for applications in magnetic field sensing at room temperature, but in the industry compatible platform SiC.

Here, using a single PL6 center in silicon carbide, we show that coherent control of a coupled nuclear spin is possible without any RF fields [3]. Instead, MW pulses driving the electron spin also manipulate the nuclear spin through hyperfine-enhanced effects, activated by a precisely tilted external magnetic field. We demonstrate high-fidelity nuclear-spin control, achieving 89% two-qubit tomography fidelity and nearly T1-limited nuclear coherence times. This approach offers a simplified and scalable route for future quantum applications.

Further, we demonstrate the integration of those individual color centers in nanophotonic structures like nanopillars and thin membrane pillars to enhance the photon collection efficiency while still containing similar spin properties compared to color centers in bulk SiC [4].

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Direct color center writing in silicon carbide using Liquid Metal Alloy Ion Source Focused Ion Beams

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Deterministic fabrication of single-color centers could be described as the holy grail of semiconductor defect-center-based single photon emitters research. While such an ambitious goal remains still unachieved, several approaches have shown significant potential and are currently under active development [1].

One of such avenues employs Focused Ion Beams (FIBs), a mature technology which boasts some truly enviable advantages. Firstly, the achievable beam diameter at the crystal surface can be as small as a few nanometers. Next, detection of the secondary electrons released as the ion impinges on the target makes it possible to measure doses down to one ion per implanted area [2].

Unfortunately, the choice of implanted species in most FIBs can be lackluster, as such extreme performance relies on an ion source that is as point-like as practically achievable, imposing strict requirements on its materials choice. Unless a desirable color center forms with the limited selection of elements available [3], FIBs are limited to circuitous fabrication schemes. Silicon carbide, however, appears highly suited for FIB implantation, since both silicon vacancies and divacancies – two promising defect centers for spin-photon quantum technologies – can be fabricated through implantation-induced lattice damage [4].

In recent years, Liquid Metal Alloys Ion Sources have seen higher commercial diffusion, as the choice between different ion masses in a single machine allows for highly flexible ion beam lithography. As of yet, however, there has not been a comparison between light and heavy ions in terms of performance in direct color center writing. The author proposes a slice of his work on the matter.

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