Silicon Carbide: Classical and Quantum Technologies

816. WE-Heraeus-Seminar

28 – 31 July 2023

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 816. WE-Heraeus-Seminar:

Silicon carbide (SiC) is today's leading third-generation semiconductor, and the first to demonstrate a light emitting diode. Its extraordinary thermo-electric properties made it the dominating semiconductor for high power electronics, such as electric mobility. Since more than ten years, the SiC industry continues growing at an annual rate of 30%, and more than 70% global market share is held by STMicroelectronics and Infineon. This makes silicon carbide one of the very few semiconductors in which Europe is competitive. The continued research on improving "classical" SiC material production and fabrication has propelled the creation of a new valorisation pathway: The emerging field of SiC "quantum" technologies. Especially in the last 5 - 10 years, colour centres in SiC have shown a disruptive potential across all relevant fields in quantum technologies.

This seminar brings together the leading experts in SiC quantum and classical technologies, including partners from academia, RTOs, and industry. This will improve the general understanding between cross-border fields and develop new synergies and joint efforts to accelerate the development of the SiC quantum-classical technology branch. The seminar also serves as a platform for setting up a white paper to inform policy makers about the unique opportunities offered by the SiC platform. Since this conference unites partners from highly diverse backgrounds, it provides early-stage researchers an ideal platform to obtain a holistic overview on career possibilities.

Scientific Organizer:

Dr. Florian Kaiser	Luxembourg Institute of Science and Technology E-mail: florian.kaiser@list.lu
Dr. Petr Siyushev	Hasselt University, Belgium E-mail: petr.siyushev@uhasselt.be
Dr. Vadim Vorobyov	University of Stuttgart, Germany E-mail: v.vorobyov@pi3.uni-stuttgart.de

Introduction

Administrative Organization:

Dr. Stefan Jorda
Elisabeth Nowotka

Wilhelm und Else Heraeus-Stiftung
Kurt-Blaum-Platz 1
63450 Hanau, Germany

Phone +49 6181 92325-12
Fax +49 6181 92325-15
E-mail nowotka@we-heraeus-stiftung.de
Internet: www.we-heraeus-stiftung.de

Venue:

Physikzentrum
Hauptstrasse 5
53604 Bad Honnef, Germany

Conference Phone +49 2224 9010-120

Phone +49 2224 9010-113 or -114 or -117
Fax +49 2224 9010-130
E-mail gomer@pbh.de
Internetwww.pbh.de

Taxi Phone +49 2224 2222

Registration:

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

Program

Program

Sunday, 28 July 2024

17:00 – 20:00	Registration	
18:00	*BUFFET SUPPER, discussions and informal get-together*	

Monday, 29 July 2024

08:00	*BREAKFAST*	
08:45 – 08:55	Florian Kaiser Petr Siyushev Vadim Vorobyov	**Opening**

SiC seen from various actors

08:55 – 09:15	Oscar Diez	**European commission activities on quantum technologies: The chips act and procurement strategies**
09:15 – 10:00	Heinrich Heiss	**SiC quantum magnetometer from innovation to volume production**
10:00 – 10:30	Anna Pertsova Amos Martinez Garcia	**Inside nature family journals**
10:30 – 11:00	*COFFEE BREAK*	

Program

Monday, 29 July 2024

Potential applications and use cases

11:00 – 11:30	Heiko Weber	**Novel device concepts for the study of charge-photon interaction using epitaxial graphene on 4H-SiC**
11:30 – 12:00	Georgy Astakhov	**High density optical data storage with atomic defects in SiC over million years**
12:00 – 12:30	Matthias Niethammer	**Compact SiC-based quantum computing demonstrator**
12:30	*LUNCH*	

Qubit systems in SiC

14:00 – 14:45	Jörg Wrachtrup	**tba**
14:45 – 15:30	Tim Hugo Taminiau	**Towards quantum networks based on the VSi in SiC**
15:30 – 16:30	**Poster flash session**	
16:30 – 17:00	*COFFEE BREAK*	

Advancing SiC materials I

17:00 – 17:45	Amberly Xie	**Generation, control, and fabrication of defects and devices in 4H-silicon carbide**
17:45 – 18:15	Roland Nagy	**Interaction of Silicon Vacancy Centers in 4H-SiC within electronic devices**
18:15	*DINNER*	
19:45 – 22:00	**Poster session, ctd.**	

Program

Tuesday, 30 July 2024

07:30	*BREAKFAST*	

SiC nanophotonics

08:30 – 09:15	Xiaoke Yi	**Cubic silicon carbide for integrated photonic devices**
09:15 – 10:00	Melissa Guidry	**Quantum spectroscopy of Kerr frequency combs using silicon carbide integrated photonics**
10:00 – 10:30	*COFFEE BREAK*	

SiC colour centres enabling applications

10:30 – 11:00	Andreas Sperlich	**Room-temperature silicon carbide maser: Unveiling quantum amplification and cooling**
11:00 – 11:30	Andrei Anisimov	**Nuclear spin polarization in SiC using spin-3/2 centers at room temperature in the Earth's magnetic field**
11:30 – 12:00	Robert Cernansky	**Quantum sensing of RF fields with 10 Hz spectral resolution using NV centers in Silicon Carbide**
12:00	*LUNCH*	

Program

Tuesday, 30 July 2024

Quantum sensing

13:30 – 14:15	Jin-Shi Xu	**Preparation and manipulation of single divacancy defects near stacking faults in 4H-SiC**
14:15 – 15:00	Naoya Morioka	**Photoelectrical readout of electron and nuclear spins in silicon carbide at ambient conditions**
15:00 – 15:20	Xiaoyi lai	**Single-shot readout of a nuclear spin in silicon carbide**
15:20 – 15:40	Pierre Kuna	**High fidelity optical readout of a nuclear spin qubit in Silicon Carbide**
15:40 – 16:00	Timo Steidl	**Tunability of VSi color centers in 4H-SiC nanostructures**
16:00 – 16:30	*COFFEE BREAK*	

Advancing SiC materials II

16:30 – 17:00	Chis Anderson	**Mitigating electrical and magnetic noise for SiC qubits**
17:00 – 17:30	Marianne E. Bathen	**Doping-induced color centers in silicon carbide**
17:30 – 18:15	Patrick Berwian	**SiC device technology for quantum applications: challenges and prospects**
18:15 – 19:00	Jawad Ul-Hassan	**Epitaxial growth of SiC for quantum applications**
19:00	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Wednesday, 31 July 2024

07:30	*BREAKFAST*	

Computational modelling of SiC colour centres

08:30 – 09:15	Adam Gali	**Theory of SiC defect qubits**
09:15 – 10:00	Benedikt Tissot	**Transition metal defects in silicon carbide as telecom quantum memories**
10:00 – 10:30	*COFFEE BREAK*	

New colour centres in SiC

10:30 – 11:00	Thomas Astner	**Quantum photonics with vanadium in 4H-SiC**
11:00 – 11:30	Joel Davidsson	**Exploration of the ADAQ defect database for quantum applications**
11:30 – 12:00	Timur Biktagirov	**First-principles study of the NV center in 3C-SiC: A promising solid-state qubit**
12:00	*LUNCH*	

Colour centres interacting with their local environment

13:30 – 14:00	Michel Bockstedte	**Understanding the spin-selective transitions of color center for quantum applications by ab initio theory**
14:00 – 14:30	Mauricio Bejarano	**Parametric magnon transduction to spin qubits in silicon carbide**
14:30 – 15:00	*COFFEE BREAK*	

Program

Wednesday, 31 July 2024

Nanophotonics with SiC colour centres

15:00 – 15:45	Daniil Lukin	**How solid-state emitters can help us explore new Hamiltonians in cavity QED**
15:45 – 16:30	Marina Radulaski	**Wafer-scale quantum photonics in silicon carbide**
16:30 – 17:00	Florian Kaiser Petr Siyushev Vadim Vorobyov	**Poster prize** **Closing statement**

End of the seminar

18:00 *DINNER (for participants leaving on Thursday morning)*

Thursday, 01 August 2024

08:00 *BREAKFAST*

Departure

Posters

Posters

Yanis Abdedou	**Photoluminescence of femtosecond laser-irradiated silicon carbide**
Joshua Bader	**4H silicon-carbide on Insulator: Integrated quantum photonics based on telecom-range defects**
Philipp Bredol	**Effect of Helium ion implantation on 3C-SiC nanomechanical string resonators**
Flavie Davidson-Marquis	**Towards the development of a small room-temperature quantum simulator based on modified divacancies in 4H-SiC**
Helton Goncalves de Medeiros	**Charge penetration into 4H-SiC/SiO_2 semiconductor-oxide interfaces in the presence of border traps**
Tom Delord	**Low temperature color centers as atom-like sensors of charges in the solid state**
Adil Han Dogan	**Electrical control for quantum emitters integrated in silicon carbide photonic chips**
Laurens Feije	**Spectral diffusion dynamics of narrow-linewidth emitters in commercially available bulk 4H-silicon carbide**
Julietta Förthner	**Integrating silicon carbide into quantum technology**
Ghulam Abbas Gilani	**Screening of an NV-like defect in 4H-SiC using ADAQ with the SCAN meta-GGA functional**
Zhen-Xuan He	**Maskless generation of single silicon vacancy arrays in silicon carbide by a focused He+ ion beam**
Jonah Heiler	**Developing a high-throughput characterisation setup for colour centres in SiC**
Jannis Hessenauer	**Color centers in silicon carbide integrated into a fiber-based Fabry-Pérot microcavity**

Posters

André Hochreiter	**Monolithically etched 4H-SiC nanomechanical resonators**
Seung-Jae Hwang	**Selective initialization mechanism of silicon vacancy spin qubits with S =3/2 in silicon carbide**
Alexander Jones	**Scalable registration of silicon vacancies in solid immersion lenses by femtosecond laser writing**
Heungjoon Kim	**High-Q SiC 2D photonic crystal nanocavities operating below 1100 nm for quantum applications**
Philipp Koller	**Exploring vanadium in SiC for quantum communication**
Jonathan Körber	**Fluorescence enhancement of single V2 centers in a 4H-SiC cavity antenna**
George Li	**Optical propagation loss extracted via dft analysis of twinning defects in 3C-SiC**
Wu-Xi Lin	**Room temperature coherent control of a single solid-state spin under anti-Stokes excitation**
Sjoerd Loenen	**Quantum-network nodes with real-time noise mitigation using spectator qubits**
Alex Rubin	**Photoluminescence and lifetime measurements of silicon carbide nv centers below 2 K**
Pranta Saha	**Triangular nanodevices: A wafer-scale approach to SiC color center photonics**
Jannik Schwarberg	**Investigation of CMOS single process steps on 4H-SiC a-plane wafers for quantum applications**

Posters

Florian Sledz	**Electrical excitation of color centers in n-type diamond Schottky diodes**
Maximilian Steinhilber Samuel Oliver Ruf	**Characterization of a nuclear spin register in silicon carbide and development of optimal control algorithms**
Gerben Timmer	**Simulation and experimental characterization of alligator cavities in 4H-SiCOI for future quantum networks**
Guido van de Stolpe	**Optimising decoherence-protected radio-frequency quantum gates for sensing and control**
Raphael Wörnle	**PL6 centers in 4H-SiC for spin-based quantum technologies**
Yu Zhou	**Nuclear-electron entanglement and spin integration in a semiconductor photonics platform**

Abstracts of Talks

(in alphabetical order)

Mitigating electrical and magnetic noise for silicon carbide qubits

C. P. Anderson[1]

[1]*University of Illinois Urbana-Champaign, Urbana, IL, USA*

I will overview our past work on the neutral divacancy center in 4H-SiC. First, I highlight the opportunity for semiconductor device integration to enable near-transform limited quantum emission [1]. Enabled by the first single-shot readout in this platform, I will then discuss our demonstration of world-record coherence times exceeding five seconds [2]. Our vision for photonically-enabled SiC quantum technology and a brief comparison between SiC defects will be overviewed [3].

References

[1] C. P. Anderson*, A. Bourassa*, et al., Science 336, 6470, 1225-1230 (2019)
[2] C. P. Anderson*, E. O. Glen*, et al., Science Advances 8, 5 (2022)
[3] C. P. Anderson and D. D. Awschalom. Physics Today 76 (8), 26–33 (2023)

Nuclear spin polarization in SiC using spin-3/2 centers at room temperature in the Earth's magnetic field

A. N. Anisimov[1], A. V. Poshakinskiy[2], and G. V. Astakhov[1]

[1]Helmholtz-Zentrum Dresden-Rossendorf, Institute of Ion Beam Physics and Materials Research, 01328 Dresden, Germany
[2]ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain

Nuclear spins are considered as a very promising quantum system for quantum information processing and sensing. Due to their very long spin coherence time, they are a key component of spin-based quantum registers. Nuclear spin hyperpolarization can enhance the signal intensities in magnetic resonance imaging by several orders of magnitude allowing detection of small chemical shifts and analysis of single cells. Due to the small value of the nuclear magneton, an effective way to initialize nuclear spins is first to polarize electron spins using optical excitation and then to transfer this polarization to the nuclear spin via the hyperfine interaction (HFI). Dynamic nuclear polarization (DNP) has been demonstrated in a variety of materials, including GaAs [1], diamond [2] and silicon carbide (SiC) [3].

Coupled electron-nuclear spins represent a promising quantum system, where the optically induced electron spin polarization can be dynamically transferred to nuclear spins via the hyperfine interaction. Most experiments on DNP are performed at cryogenic temperatures and/or in moderate external magnetic fields, the latter approach being very sensitive to the magnetic field orientation. Here, we demonstrate that the ^{29}Si nuclear spins in SiC can be efficiently polarized at room temperature even in the Earth’s magnetic field. We exploit the asymmetric splitting of the optically detected magnetic resonance (ODMR) lines inherent to half-integer S = 3/2 electron spins, such that certain transitions involving ^{29}Si nuclei can be clearly separated and selectively addressed using two radiofrequency fields. As a model system, we use the V3 silicon vacancy (V_{Si}) in 6H-SiC, which has the zero-filed splitting parameter comparable with the HFI constant. Our theoretical model considers DNP under optical excitation in combination with RF driving and agrees very well with the experimental data. These results provide a straightforward approach for controlling the nuclear spin under ambient conditions, and may be an important step toward realizing nuclear hyperpolarization for bioimaging and long nuclear spin memory for quantum networks.

References

[1] M. Kotur et al., Communications Physics **4**, 193 (2021).
[2] L. Childress et al., Science **314**, 281 (2006).
[3] E. Hesselmeier et al., Physical Review Letters **132**, 090601 (2024)

High density optical data storage with atomic defects in SiC over million years

G. V. Astakhov[1], M. Hollenbach[1], C. Kasper[2], D. Erb[1], L. Bischoff[1], G. Hlawacek[1], H. Kraus[3], W. Kada[4], T. Ohshima[5,7], M. Helm[1,6], S. Facsko[1] and V. Dyakonov[2]

[1]Institute of Ion Beam Physics and Materials Research, Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany
[2]Experimental Physics 6 and Würzburg-Dresden Cluster of Excellence ct.qmat, Julius-Maximilian University of Würzburg, 97074 Würzburg, Germany
[3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[4]Department of Quantum Science and Energy Engineering Graduate School of Engineering, Tohoku University, 6-6-01-2, Aza-Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan
[5]National Institutes for Quantum Science and Technology, Takasaki, Gunma 370-1292, Japan
[6]Technische Universität Dresden, 01062 Dresden, Germany
[7]Department of Materials Science, Tohoku University, 6-6-02 Aramaki-Aza, Aoba-ku, Sendai 980-8579, Japan

There is an urgent need to increase the global data storage capacity, as current approaches lag behind the exponential growth of data generation driven by the Internet, social media and cloud technologies. In addition to increasing storage density, new solutions should provide long-term data archiving that goes far beyond traditional magnetic memory, optical disks and solid-state drives. We propose a concept of energy-efficient, ultralong, high-density data archiving based on optically active atomic-size defects in a radiation resistance material, silicon carbide (SiC) [1]. The information is written in these defects by focused ion beams and read using photoluminescence or cathodoluminescence. The temperature-dependent deactivation of these defects suggests a retention time minimum over a few generations under ambient conditions. With near-infrared laser excitation, grayscale encoding and multi-layer data storage, the areal density corresponds to that of Blu-ray discs. Furthermore, we demonstrate that the areal density limitation of conventional optical data storage media due to the light diffraction can be overcome by focused electron-beam excitation.

References

[1] M. Hollenbach et al., Adv. Funct. Mater. (2024); doi: 10.1002/adfm.202313413

Quantum photonics with vanadium in 4H-SiC

T. Astner[1], P. Koller[1], B. Tissot[2], G. Burkard[2], M. Trupke[1]

[1]Institute for Quantum Optics and Quantum Information (IQOQI) Vienna, Austrian Academy of Sciences, Boltzmanngasse 3, 1090 Vienna, Austria
[2]Department of Physics, University of Konstanz, D-78457 Konstanz, Germany

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, [1–6]: 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. Our investigations have resulted in significant advances in our understanding of this remarkable system, the control of its electron spin, and the development of photonic interfaces for quantum networks[7].
Spin-dependent optical transitions, which are crucial for quantum communication and computation applications, have now been demonstrated[6]. 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[4,8]. 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 neighboring lattice sites[6].

References

1. L. SPINDLBERGER et al., “Optical Properties of Vanadium in 4 *H* Silicon Carbide for Quantum Technology,” Phys. Rev. Applied **12** 1, 014015 (2019);
2. C. M. GILARDONI et al., “Hyperfine-mediated transitions between electronic spin-1/2 levels of transition metal defects in SiC,” New J. Phys. **23** 8, 083010 (2021);
3. B. TISSOT et al., “Nuclear spin quantum memory in silicon carbide,” Phys. Rev. Research **4** 3, 033107 (2022);
4. T. ASTNER et al., “Vanadium in Silicon Carbide: Telecom-ready spin centres with long relaxation lifetimes and hyperfine-resolved optical transitions,” arXiv (2022);
5. J. HENDRIKS et al., “Coherent spin dynamics of hyperfine-coupled vanadium impurities in silicon carbide,” arXiv (2022);
6. P. CILIBRIZZI et al., “Ultra-narrow inhomogeneous spectral distribution of telecom-wavelength vanadium centres in isotopically-enriched silicon carbide,” Nature Communications **14** 1, 8448 (2023);
7. J. FAIT et al., “High finesse microcavities in the optical telecom O-band,” Appl. Phys. Lett. **119** 22, 221112 (2021);
8. K. NEMOTO et al., “Photonic Architecture for Scalable Quantum Information Processing in Diamond,” Physical Review X **4** 3 (2014);

Doping-induced color centers in silicon carbide

M.E. Bathen[1], B.C. Johnson[2], A. Galeckas[1], M.I.M. Martins[3], P. Kumar[3], L. Razinkovas[4], L. Vines[1], and U. Grossner[3]

[1] *University of Oslo, Oslo, Norway*
[2] *RMIT, Melbourne, Australia*
[3] *ETH Zürich, Zürich, Switzerland*
[4] *FTMC, Vilnius, Lithuania*

Single-photon emitters (SPEs) with emission energies in the near-infrared (NIR) are of particular interest for quantum technology applications because of their compatibility with fiber optic technology. Silicon carbide (SiC) is a promising host platform for SPEs considering its favorable properties and scalable fabrication. SiC hosts a variety of intrinsic and extrinsic SPEs. Perhaps most studied are the silicon vacancy (V_{Si}) [1], the carbon antisite-vacancy pair ($C_{Si}V_C$) [2], the divacancy ($V_{Si}V_C$) [3], and the nitrogen-vacancy or NV center (N_CV_{Si}) in 4H-SiC [4]. The NV center is intriguing because of zero phonon line (ZPL) energies in the NIR and the fact that nitrogen impurities, commonly used as n-type dopants in SiC, are involved.

Dopants in SiC exhibit different lattice site preferences. Nitrogen donors strongly prefer the C site over the Si site [5], while boron acceptors can occupy both atomic sites but act as shallow dopants only in the case of B_{Si} [6]. Phosphorous can occupy either the C or Si site from the energetic point of view, but the Si site is preferred [7].

In this work, we investigate the formation of optically active defects due to n-type doping by ion implantation in 4H-SiC epitaxial layers (N_D~3×10^{15} cm^{-3}). The samples underwent box profile formation by N or P doping to approximately 300 nm depth and N_D~10^{18} cm^{-3} density. The samples were then exposed to activation annealing at 1600 °C, followed by 1.8 MeV He irradiation to different fluences and 1100 °C annealing for 1 h for defect creation. The resulting defects are monitored by photoluminescence (PL) measurements. We observe features that are compared to density functional theory (DFT) calculations of different point defect complexes.

References

[1] M. Widmann, et al., Nature Materials 14, 164–168 (2015).
[2] S. Castelletto, et al., Nature Materials 13, 151–156 (2014).
[3] D.J. Christle, et al., Nature Materials 14, 160–163 (2015).
[4] S.A. Zargaleh, et al., PRB 94, 060102(R) (2016).
[5] S. Greulich-Weber, PSS A 162, 95 (1997).
[6] V.J.B. Torres, et al., PRB 106, 224112 (2022).
[7] M. Bockstedte, et al., APL 85, 58 (2004).

Parametric magnon transduction to spin qubits in silicon carbide

M. Bejarano[1,2], F. J. T. Goncalves[1], T. Hache[1,3], M. Hollenbach[1,2], C. Heins[1], T. Hula[1,4], L. Körber[1,2], J. Heinze[1], Y. Berencén[1], M. Helm[1,2], J. Fassbender[1,2], G. V. Astakhov[1], H. Schultheiss[1]

[1]Helmholtz-Zentrum Dresden Rossendorf, Dresden, Germany
[2]Technical University of Dresden, Dresden, Germany
[3]Max Planck Institute of Solid State Research, Stuttgart, Germany
[4]Technical University of Chemnitz, Chemnitz, Germany

The integration of heterogeneous modular units for building large-scale quantum networks requires engineering mechanisms that allow suitable transduction of quantum information. Magnon-based transducers are especially attractive due to their wide range of interactions and rich nonlinear dynamics, but most of the work to date has focused on linear magnon transduction in the traditional system composed of yttrium iron garnet and diamond, two materials with difficult integrability into wafer-scale quantum circuits. In this work, we present a different approach by using wafer-compatible materials to engineer a hybrid transducer that exploits magnon nonlinearities in a magnetic microdisc to address quantum spin defects in silicon carbide. The resulting interaction scheme points to the unique transduction behavior that can be obtained when complementing quantum systems with nonlinear magnonics.

References

[1] M. Bejarano et al., Parametric magnon transduction to spin qubits. Sci. Adv.**10**, eadi2042 (2024). DOI:10.1126/sciadv.adi2042

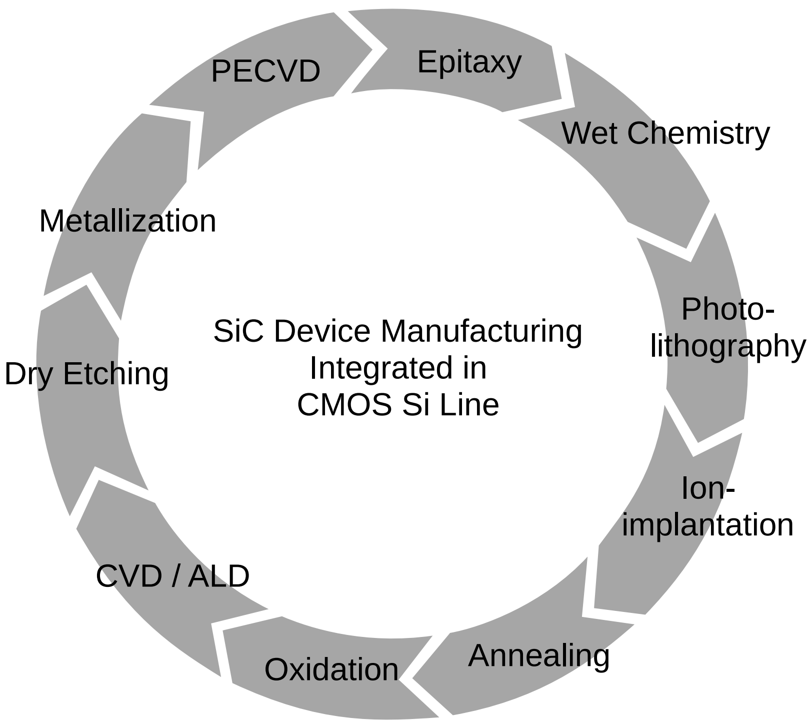
SiC device technology for quantum applications: challenges and prospects

P. Berwian[1]

[1]*Fraunhofer Institute for Integrated Systems and Device Technology, Erlangen, Germany*

SiC is one of the four most important semiconductor materials. Its main applications are in the field of power electronics, where SiC impresses with high efficiencies, power densities and low system (e.g. inverter) weights. Further applications are made possible by SiC CMOS circuits for harsh environments or high temperatures, as well as SiC sensor components.

This mature material and technology platform is an excellent prerequisite for the realization of quantum and photonic applications of SiC. However, these new SiC applications also place significantly different demands on materials and device technology than most electronic SiC applications.



In this contribution, we look at SiC quantum technology from the perspective of a SiC-CMOS technology line. We present classical SiC electronics applications, which devices are used for these applications, and the processes that are typically performed in such a SiC CMOS line. From this, we conclude which challenges and prospects arise when integrating quantum photonic device fabrication into such a line.

First-Principles Study of the NV Center in 3*C*-SiC: A Promising Solid-State Qubit

T. Biktagirov[1], H. J. von Bardeleben[2], U. Gerstmann[1], W. G. Schmidt[1]

[1]Paderborn University, Paderborn, Germany
[2] Sorbonne Université, Institut des Nanosciences de Paris, Paris, France

The nitrogen-vacancy (NV) center in cubic silicon carbide (3*C*-SiC) has emerged as a promising solid-state qubit, analogous to the NV center in diamond, but with significant technological advantages [1, 2]. Using density functional theory (DFT) calculations, we provide detailed insights into the magneto-optical properties of this spin center. Our results identify that the NV center in 3*C*-SiC emits at 1289 nm, within the telecom O-band, which is highly advantageous for device applications due to low transmission losses in optical waveguides. The phonon sideband analysis reveals a Huang-Rhys factor of 2.85 and a Debye-Waller factor of 5.8%. Combined with long low-temperature coherence times, these characteristics position the NV center in 3*C*-SiC as a formidable candidate for quantum technological applications.

References

[1] S. A. Zargaleh, et al, Physical Review B **98**, 165203 (2018).
[2] H. J. Von Bardeleben, et al, Nano Letters **21**, 8119-8125 (2021).

Abstract title (sample)

F. Author[1] and <u>S. Author</u>[2]

[1]Institute, Town, Country
[2] another Institute, another town, another country

The abstract should be headed by a **title**, **name(s) and complete address(es) of the author(s).** Please <u>underline the name</u> of the author who will present the paper and leave a 3.0 cm margin on top and 2.5 cm margin on all other sides. As font you should use Arial or Helvetica, 12pt with a line spacing of 16pt. The abstract can contain Figures, Tables and References, but the length of the abstract should not exceed **one** DIN A4 page. Please note that coloured abstracts will be converted to black-and-white.

References

[3] F. Author, Journal **volume**, page (year)
[4] S. Author, Journal **100**, 101101 (2009)

Understanding the spin-selective transitions of color center for quantum applications by ab initio theory

M. Neubauer[1], M. Schober[1], W. Dobersberger[1], and M. Bockstedte[1]

[1]Institute, Town, Country
[2] another Institute, another town, another country

Color centers in semiconductors, such as the NV-center in diamond, the silicon vacancy (V_{Si}^-), and the di-vacancy ($V_C V_{Si}$) in 4H-silicon carbide (4H-SiC), are potential candidates for quantum bits (qubits). Manipulating the spin optically involves exciting the fundamental high-spin multiplets and intersystem crossing (ISC), mediated by spin-orbit, spin-spin, and spin-phonon couplings. These interactions, together with the zero-field splitting of ground and excited states, enable various spin-photon protocols. For optimal engineering of such interfaces, a comprehensive understanding of spin-selective interactions and resulting spin-relaxation pathways is pivotal. Recent experiments regarding the V_{Si}^- in 4H-SiC have revealed spin-dependent lifetimes and intercrossing rates using an effective model that considers only one or two instead of the five predicted intermediate doublet states [1]. Here we address this issue. We employ our extended CI-cRPA embedding approach for correlated defect states [2] to calculate the relevant spin-coupling parameters. We present a fine structure of the quartet states of V_{Si}^- consistent with existing literature. Based on our calculations, we discuss the ISC and spin-relaxation paths. In particular, we calculate ISC-rates for the two spin components that are in agreement with the experimental findings [1]. The calculated rates provide insight into the underlying role of the different intermediate states and indicate handles for engineering approaches.

References

[1] N. Morioka, et al., Phys. Rev. Appl. **17,** 054005 (2022).
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Quantum sensing of RF fields with 10 Hz spectral resolution using NV centers in Silicon Carbide

Z. Jiang[1,2], H. Cai[3,4], R. Cernansky[5], X. Liu[1,2,6], Weibo Gao[3,4,7]

[1,2] Joint School of NUS and Tianjin University, International Campus of Tianjin University, Binhai New City, Fuzhou 350207, P. R. China.
[2] Department of Chemistry, NUS, Singapore 117543, Singapore.
[3] Division of Physics and Applied Physics, SPMS, NTU, Singapore 637371, Singapore.
[4] The Photonics Institute and Centre for Disruptive Photonic Technologies, NTU, Singapore 637371, Singapore.
[5] Institute for Quantum Optics, Ulm University, Albert-Einstein-Allee 11, D-89081 Ulm, Germany
[6] Institute of Materials Research and Engineering, Agency for Science, Technology and Research, Singapore 138634, Singapore
[7] Centre for Quantum Technologies, NUS, 117543 Singapore, Singapore.

Nuclear Magnetic Resonance (NMR) spectroscopy is an important analytical tool commonly used in life sciences. Its advantages come from its nature to be a non-invasive method to detect molecular structure of biological samples required for applications in diagnostics and fundamental science. However, the limited magnetic sensitivity restricts its utility to study only macroscopic sample sizes on the order of few hundred μm^3. Diamond has shown to be very promising candidate to overcome the current limitations of bulky NMR machines by using Nitrogen Vacancy (NV^-) defects that are able to reach comparable sub-Hz spectral resolution while reaching nano and few micrometer[1] spatial resolution. However, diamond is an expensive material that is not compatible with standard CMOS fabrication which makes developing scalable and low-cost magnetometers difficult to achieve. On the other hand, Silicon Carbide (SiC) is a technology friendly material with large scale production of high-temperature electronics that host high quality defects useful for quantum sensing applications, like ones present in diamond. Here we present our results to detect a 900 kHz radio-frequency field generated via a test coil. By utilizing the advantages of "Synchronized readout" technique[1] we were able to reach a 10 Hz spectral resolution using ensemble of NV^- centers in SiC[2] while simultaneously achieving the record room temperature coherence time of 28.1 μs. These results pave a way of using SiC defects for future practical sensing applications.

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Exploration of the ADAQ Defect Database for Quantum Applications

Joel Davidsson[1], Rickard Armiento[1], and Igor A. Abrikosov[1]

[1]*Department of Physics, Chemistry and Biology (IFM), Linköping, Sweden*

A handful of point defects in a few materials are being studied for quantum applications. Could there be undiscovered defects with better properties? To address this, we have developed an online database[1] built using ADAQ[2], which holds the high-throughput results of over 30 000 processed defects. Among the hosts are well-studied quantum materials like 4H-SiC, where we found the modified silicon vacancy that was experimentally confirmed.[3] We also predict chlorine vacancy with a ZPL emission in the telecom range.[4] These discoveries are due to the high-throughput database ADAQ, and in this presentation, we explore it to highlight some promising systems.

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European Commission activities on Quantum Technologies: The Chips Act and Procurement Strategies

Oscar Diez

Head of Quantum Technologies, European Commission

The rapid advancement of quantum technologies, including quantum computing, sensing, and communication, represents a critical frontier in global technological competition and innovation. The European Commission, recognizing the strategic importance of these technologies, has been at the forefront of fostering an environment conducive to their development and deployment. This presentation will provide an insightful overview of the European Chips Act and its implications for the quantum sector, focusing on the quantum part of the Act that aims to bolster Europe's technological sovereignty and competitiveness on the global stage.

Moreover, we will delve into the procurement activities related to quantum technologies, shedding light on the requirements and preparatory steps necessary for research groups and entities looking to engage with these initiatives.

This discussion aims to illuminate the path forward for researchers, startups, and established companies within the EU, emphasizing the need for a well-coordinated approach that aligns technological innovation with policy frameworks and procurement strategies. By examining these aspects, we seek to foster a more inclusive and prepared ecosystem that can fully leverage the potential of quantum technologies, ensuring Europe remains at the cutting edge of this transformative field.

References

Theory of SiC defect qubits

Bian Guodong[1], Gergő Thiering, and Ádám Gali[1,2,3]

[1]Wigner Research Centre for Physics, Budapest, Hungary
[2]Budapest University of Technology and Economics, Budapest, Hungary
[3]MTA-WFK Lendület "Momentum" Semiconductor Nanostructures Research Group, Budapest, Hungary

We reported a theoretical study and analysis on divacancy defects in silicon carbide (SiC) in 2009 that showed that its electronic structure is akin to that of the nitrogen-vacancy center in diamond, and they can be applied as solid state defect qubits. The theoretical proposal was then confirmed in experiments, and the SiC based defect qubit research has been flourished.
The success of the host material relied on their favorable intrinsic properties: relatively long spin relaxation times up to room temperature and the long spin coherence times of the defects' S>1/2 spins. We will present theoretical analysis on the temperature dependent electron spin relaxation times of divacancy spins and compare those with that of the nitrogen-vacancy spins to explain this behavior.
Furthermore, we show some major theoretical results on selected SiC defects such as silicon-vacancies and vanadium centers from recent years that shaped the field, e.g., for selecting the favorable configuration in the 4H polytype for quantum optics experiments that might be applicable for entangled based quantum communication applications.

This work was supported by the National Research, Development, and Innovation Office of Hungary (NKFIH) for the Quantum Information National Laboratory (Grant No. 2022-2.1.1-NL-2022-00004) and the European Commission for the project SPINUS (Grant No. 101135699).

Quantum spectroscopy of Kerr frequency combs using silicon carbide integrated photonics

Melissa A. Guidry[1]

[1]E. L. Ginzton Laboratory, Stanford University, Stanford, CA, USA
E-mail: mguidry@stanford.edu

Dissipative Kerr solitons (DKS) are self-assembled optical pulses in Kerr resonators driven by a continuous-wave laser source [1]. In this work, we use silicon carbide-on-insulator integrated photonics [2] to study the squeezing structure of these nonlinear states of light for the first time: the high third-order optical nonlinearity of silicon carbide and low propagation loss of the integrated photonics allow for milliwatt-level operation powers [3], in addition to freedom from parasitic processes.

The Kerr nonlinearity is the third-order optical nonlinearity of the material, which mediates a four-photon process: two photons are destroyed to create a pair of photons. To generate a coherent comb from a monochromatic source, the system undergoes spontaneous symmetry breaking via an optical parametric oscillation threshold, with features analogous to lasing such as coherence broadening and asymptotic growth in count rate [3]. The field which undergoes this threshold exhibits an extreme degree of quadrature squeezing, an important resource for precision measurement and continuous-variable quantum information.

As the state self assembles from a monochromatic pump into pulses, it must transition through multiple optical parametric oscillation thresholds, where the squeezing structure is distributed across the full spectral comb. Numerical studies of the DKS predict that the pulses themselves are squeezed, with a detuned spectral structure with respect to the frame of the equidistant comb [4].

In this work, we perform "quantum spectroscopy" on Kerr frequency comb states to map out the spectral structure of their quantum fluctuations and intermode connectivity, as well as their coherence properties through soliton transitions and soliton states of formation. We perform this measurement using balanced homodyne and heterodyne detection with a reconfigurable multimode local oscillator [5].

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SiC Quantum Magnetometer
from Innovation to Volume Production

P. Stürmer[1], Y. Huck[1], S. Krainer[1], H. Heiss[2] and J. Wrachtrup[3]

[1] *Infineon Technologies Austria AG, Villach, Austria*
[2] *Infineon Technologies AG, Munich, Germany*
[3] 3rd Physical Institute of the University of Stuttgart*, Stuttgart, Germany*

Spin-based quantum sensing based on NV-centers in diamond has been under development for quite some time and already found its way into commercialization in niche segments like biotech or material analysis [1]. However, there are major process obstacles for diamond-based quantum technologies to achieve the required scalability for higher volume production. Silicon carbide, which also has a wide bandgap and hosts stable crystal defects that give rise to solid-state spin quantum systems [2], is already a proven material system and has been in volume production for DC power and RF devices for many years. SiC also has favorable quantum properties due to low spin-orbit interaction [3]. Novel di-vacancies in 4H SiC materials demonstrate quantum properties on par with diamond and, thus, makes SiC a promising candidate for high-volume production of quantum devices [4] like Quantum magnetometers.

To achieve a high sensitivity for quantum magnetometers, a high resonance signal contrast, narrow linewidth and a high number of signal-counts are mandatory besides other system requirements, like temperature drift compensation methods. In our investigations we focus on 4H-SiC silicon-vacancy ensemble-based quantum magnetometers where we investigated different methods to increase signal-counts through an increase in ensemble density. This is only possible up to a certain point, as higher ensemble densities lead to higher crystal damage, in turn causing severe deterioration of quantum properties as well as sharp decrease in signal-to-noise contrast. Another option which we investigated is to increase the active volume by keeping the ensemble density constant. This, however, requires an optical waveguide in order to efficiently excite the color centers and extract their signal. We will present the progress made and remaining challenges on monolithic SiC optical waveguide integration for silicon vacancy ensemble-based quantum magnetometers based on Infineon's productive SiC technology platform.

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High fidelity optical readout of a nuclear spin qubit in Silicon Carbide

Authors:

Erik Hesselmeier,[1], Pierre Kuna, [1], Wolfgang Knolle, [2] Florian Kaiser, [3], [4] Nguyen

Tien Son, [5] Misagh Ghezellou, [5] Jawad Ul-Hassan, [5] Vadim Vorobyov, [1], and Jörg Wrachtrup[1],[6]

[1] 3rd Institute of Physics, IQST, and Research Center SCoPE, University of Stuttgart, Stuttgart, Germany

[2] Department of Sensoric Surfaces and Functional Interfaces,

Leibniz-Institute of Surface Engineering (IOM), Leipzig, Germany

[3] Materials Research and Technology (MRT) Department,

Luxembourg Institute of Science and Technology (LIST), 4422 Belvaux, Luxembourg

[4] University of Luxembourg, 41 rue du Brill, L-4422 Belvaux, Luxembourg

[5] Department of Physics, Chemistry and Biology, Linköping University, Linköping, Sweden

[6] Max Planck Institute for solid state physics, Stuttgart, Germany

Abstract:

Quantum state readout is a key requirement for a successful qubit platform. In this work, we demonstrate a high-fidelity quantum state readout of a V2 center nuclear spin based on a repetitive readout technique. We demonstrate up to 99.5% readout fidelity and 99% for state preparation. Using this efficient readout, we initialize the nuclear spin by measurement and demonstrate its Rabi and Ramsey nutation. Finally, we use the nuclear spin as a long-lived memory for quantum sensing application of a weakly coupled diatomic nuclear-spin bath.

Single-Shot Readout of a Nuclear Spin in Silicon Carbide

Xiaoyi Lai[1] , Renzhou Fang[1], Xiaoyihui Bao[1], Jianwei Pan[1]

[1]*University of Science and Technology of China*

Solid-state qubits with a photonic interface is very promising for quantum networks. Color centers in silicon carbide have shown excellent optical and spin coherence, even when integrated with membranes and nano-structures. Additionally, nuclear spins coupled with electron spins can serve as long-lived quantum memories. Pioneering work in previous has realized the initialization of a single nuclear spin and demonstrated its entanglement with an electron spin. In this paper, we report the first realization of single-shot readout for a nuclear spin in SiC. We obtain a deterministic nuclear spin initialization and readout fidelity of 94.95% with a measurement duration of 1ms. With a dual-step readout scheme, we obtain a readout fidelity as high as 99.03% within 0.28ms by sacrificing the success efficiency. Our work complements the experimental toolbox of harnessing both electron and nuclear spins in SiC for future quantum networks.

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How solid-state emitters can help us explore new Hamiltonians in cavity QED

Daniil M. Lukin

Ginzton Laboratory, Stanford University, Stanford, CA, 94305, USA

Photon-mediated interaction of multiple integrated quantum emitters is a prerequisite for many quantum applications envisioned for optically-addressable solid-state defects. Their narrow, atom-like optical transitions are possible because of the concept of the "semiconductor vacuum" – that in a perfect semiconductor, atom-like electron states can exist by virtue of the Bloch theorem.

But the semiconductor vacuum is not perfect in many ways: it is a wonderous environment full of crystal defects, strain, and phonons. Optically-addressable defects have brought tremendous advances to spin physics as the sensors and manipulators of this environment [1]. An unfortunate side effect of the imperfect semiconductor vacuum for cavity QED is that the optical transitions of defects are quite sensitive to the imperfections: The otherwise atom-like transitions broaden, jitter, or go entirely dark. This makes it challenging pursue multi-emitter cavity QED experiments of complexity on par with what is done with atoms trapped in true vacuum [2]. However, by leveraging their unique, *solid-state* features, defects in resonators are now beginning to make contributions to cavity QED physics [3].

I will discuss our effort toward the study of multi-emitter cavity QED Hamiltonians using silicon vacancy color centers integrated into high-Q whispering gallery mode resonators fabricated in the 4H-SiC-on-Insulator photonics platform [4]. The talk will include observations of indistinguishable emission from a small ensemble of ~10 emitters; descriptions of the multi-mode phase-sensitive Hamiltonians that the system realizes; the effects of disorder on photon correlations, which reveal under certain conditions the emergence of steady-state chirality in the otherwise achiral system; and the first realization of a cavity QED system in a parametrically driven optical resonator, using the strong Kerr nonlinearity of silicon carbide.

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Inside Nature family journals

Amos Martinez[1] **and Anna Pertsova**[2]

[1]*Nature Materials, 4 Crinan Street, London N1 9XW, UK*
[2] *Nature Communications, Heidelberger Platz 3, 14197, Berlin, Germany*

In this talk, Amos Martinez from Nature Materials and Anna Pertsova from Nature Communications will introduce the editorial and peer-review process within Nature journals, and discuss the synergies between journals, journal scopes, as well as the various outcomes and options during manuscript submissions. Finally, they will discuss the responsibilities and challenges of being an editor in scientific publishing and present recent initiatives within the portfolio aimed at supporting early career researchers.

Amos Martinez is a senior editor at Nature Materials. He handles manuscripts in the areas of photonics, plasmonics and metamaterials. His research background is in nonlinear optics and photonics.

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Photoelectrical readout of electron and nuclear spins in silicon carbide at ambient conditions

Naoya Morioka[1,2]

[1] *Institute for Chemical Research, Kyoto University, Uji, 611-0011 Japan*
[2] *Center for Spintronics Research Network, Kyoto University, Uji, 611-0011 Japan*

Silicon carbide (SiC) hosts electronic spins of atomic-scale point defects with long coherence time even at ambient conditions [1]. These spins couple to nuclear spins with extremely long coherence time, which can play an important role as a quantum memory [2] and a resource to enhance the sensitivity of quantum sensors [3]. The spin of defects in SiC is usually detected optically. However, the electrical spin readout utilizing excellent semiconductor properties of SiC is highly advantageous for practical applications and will enable on-chip integration and the miniaturization of the system. Also, the electrical readout is expected to achieve superior detection sensitivity to the optical readout [4] thanks to the controllability of the charge collection by the electric field, whereas optical detection suffers from inefficient photon collection due to the total internal reflectance. Photoelectrical detection of magnetic resonance (PDMR) is a technique that provides coherent electrical spin detection by measuring spin-dependent photocurrent generated from defects [5]. Room-temperature coherent electrical spin detection of the spin ensemble of silicon vacancies in 4H-SiC [6] by PDMR. However, achieving high spectral resolution and access to nuclear spins have remained challenging with PDMR in SiC. In this talk, we present our recent results on high-resolution and efficient electronic spin detection of silicon vacancies and surrounding nuclear spins in SiC by photocurrent detection technique.

This work was partly supported by JSPS KAKENHI (JP20H00355, JP21H04553, JP21K20502, JP22H01526, and JP23K19120), JST SPRING (JPMJSP2110), MEXT Q-LEAP (JPMXS0118067395), and Kyoto University Nanotechnology Hub in ARIM Project sponsored by MEXT, Japan.

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Interaction of Silicon Vacancy Centers in 4H-SiC within Electronic Devices

Fedor Hrunski[1], Daniel Scheller[1], Maximilian Hollendonner[1], and Roland Nagy[1]

[1] Institute of Applied Quantum Technologies (AQuT.), Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Konrad-Zuse-Str. 3-5, 91052 Erlangen, Germany

Optically active solid-state spin systems have demonstrated their unique potential in quantum computing, communication, and sensing technologies. Achieving scalability and increasing application complexity requires entangling multiple individual systems, for example, via photon interference in an optical network. A significant challenge in this regard is the broad emission spectra and inhomogeneous linewidth broadening of most solid-state emitters, which hinder the realization of quantum technologies.

This is where silicon carbide (SiC) comes into play. As a host material for the silicon vacancy center (VSi center) in 4H-SiC, it offers the possibility to manipulate both the emission spectrum and linewidth simultaneously with integrated electronic devices. This capability gives spin systems in SiC a unique advantage over other host materials, such as diamond, in overcoming the aforementioned challenges.

In my presentation, I will show you our recent progress in coupling a VSi center in 4H-SiC to an integrated PIN diode structure. This coupling allows for the manipulation of the optical emission linewidth and the performance of a Stark shift.

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Compact SiC-based Quantum Computing Demonstrator

R. Wörnle[1,2], J.Körber[2] , M. Högen[3], K. Kafenda[3], J. Wrachtrup[1,2] and M. Niethammer[3]

[1] TTI GmbH/TGZ Squtec, Stuttgart, Germany
[2] 3rd Institute of Physics & Center for Applied Quantum Technology, University of Stuttgart, Germany
[3]Advanced Quantum GmbH, Allmersbach im Tal, Germany

As with the introduction of quantum mechanics, at the heart of quantum technologies lie the people that scrutinize, innovate and in the process push the boundaries of feasibility and understanding. While many promises are made for the short- and long-term impact of quantum sensing and especially quantum computing, in order to deliver on these, next to intrinsic physical feasibility, market demand and economical value generation, many physics and engineering problems need to be overcome. This requires a motivated, well-trained and broadly skilled work-force, which is scarce and one of the limiting factors within the quantum technology industry.

While training from a software and algorithm point of view is easily available thanks to python frameworks and online services, it is the underlying hardware and availability that is the limiting factor.

In the project “KompaQD” within the DLR Quantum Computing Initiative we develop a compact and portable demonstrator, showcasing the potential of SiC based quantum technology and bring the technology out of the lab into public space.

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Inside Nature family journals

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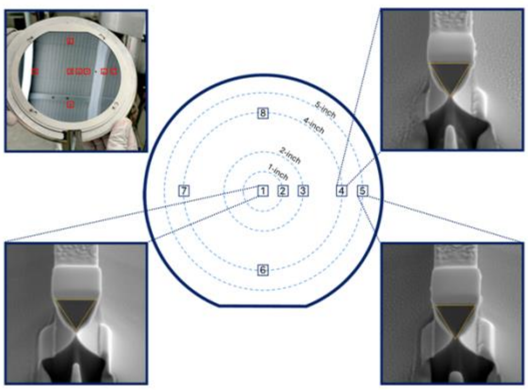
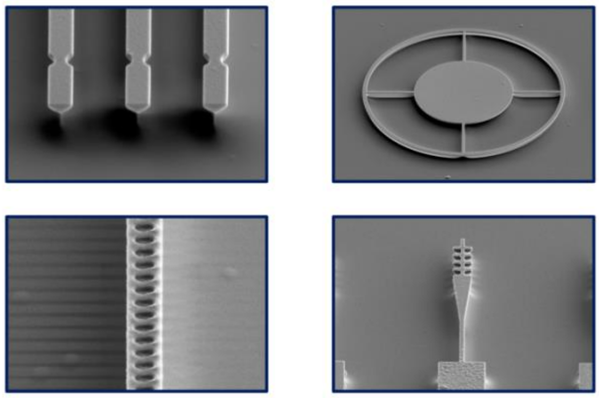
Wafer-scale quantum photonics in silicon carbide

M. Radulaski[1]

[1]University of California, Davis, USA

Integration of color centers with photonic in silicon carbide is a key approach to scalability and efficient utility of these systems in wide range of quantum technologies, from quantum communication and sensing to all-photonic quantum simulation [1,2]. Various approaches to fabricating photonic devices that do not compromise optical and spin properties of color centers have been explored yielding successes up to chip-scale dimensions. By focusing on triangular device geometry and angle-etch processes based on ion beam etching [3-7], we develop a wafer-scale process that preserve optical properties of integrated near infrared color centers such as the divacancy and the NV center in 4H-SiC. We also address the scalability of instrumentation for cryogenic characterization of devices by incorporating superconducting nanowire single photon detectors directly into a 1.56 K optical cryostat, significantly reducing the instrumentation footprint and cost. We use this system to optically characterize color centers Integrated in SiC photonic devices, including the first lifetime measurements of NV centers in nanopillars below 2 K with increased collection efficiency [8].





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Room-Temperature Silicon Carbide Maser: Unveiling Quantum Amplification and Cooling

Andreas Gottscholl[1,2], Maximilian Wagenhöfer[1], Valentin Baianov[1], Vladimir Dyakonov[1] and Andreas Sperlich[1]

[1]Experimental Physics 6 and Würzburg-Dresden Cluster of Excellence ct.qmat, Julius-Maximilians-Universität Würzburg, 97074 Würzburg, Germany
[2]NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

We present the very first demonstration of a maser utilizing silicon vacancies (V_{Si}) within 4H silicon carbide (SiC). Leveraging an innovative feedback-loop technique, we elevate the resonator's quality factor, enabling maser operation even above room temperature. The SiC maser's broad linewidth showcases its potential as an exceptional preamplifier, displaying measured gain surpassing 10dB and simulations indicating potential amplification exceeding 30dB. By exploiting the relatively small zero-field splitting (ZFS) of V_{Si} in SiC, the amplifier can be switched into an optically-pumped microwave photon absorber, reducing the resonator's mode temperature by 35 K below operating conditions. This breakthrough holds promise for quantum computing advancements and fundamental studies in cavity quantum electrodynamics. Our findings highlight SiC's transformative potential in revolutionizing contemporary microwave technologies.

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Tunability of VSi color centers in 4H-SiC nanostructures

Timo Steidl1 , Marcel Krumrein1 , Nils Gross2 , Di Liu1 , Erik Hesselmeier1 , Jurgen Smet2 , Vadim Vorobyov1 and Jörg Wrachtrup1

1 3rd Institute of Physics, IQST, and Research Centre SCoPE, University of Stuttgart, ZAQ, Stuttgart, Germany

2 Solid State Nanophysics, Max Planck Institute for Solid State Research, Stuttgart, Germany

Solid state color centers have been intensively studied for last two decades. A huge zoo of defects in a large varity of host materials have shown great results and useful advantages, enabling their justified contributions in quantum sensing, quantum communication and quantum computation. A common drawback of many of these quantum platforms is a rather low photon rate, which claims mandatory integration into nano-photonic devices [1]. Additionally photonic interference is a proven pathway to scale up quantum systems [2], but requires indistinguishable photon emission of multiple emitters. Both, interference and matching resonances of emitter and photonic cavities, can be accomplished e.g. using Stark shift tuning. As such solid state color centers are not only sensitive to electric fields, but also to strain, temperature and magnetic environment, we want to demonstrate different approaches to manipulate our color centers.
Here, we show our work on shifting the resonant wavelength of silicon vacancy centers in designed silicon carbide structures. In particular, we apply external strain and extensively manipulate charge environment in the surrounding of single VSi.

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Towards quantum networks based on the V_{Si} in SiC

T.H.Taminiau

QuTech, Delft University of Technology

Solid-state color centers provide a path towards realizing quantum networks for communication and distributed quantum computation. The silicon vacancy (V_{si}) defect in 4H-silicon carbide is a promising candidate due to good spin-optical properties [1,2], the potential for integration in nanophotonic structures [3,4,5] and scalable fabrication methods. In this talk, I will present our recent process towards harnessing such defects for quantum networks. In particular, I will discuss progress towards characterizing spectral diffusion and towards integrating V_{Si} centers in nanophotonic “alligator” cavities based on a 4H-silicon-carbide-on-insulator platform [4].

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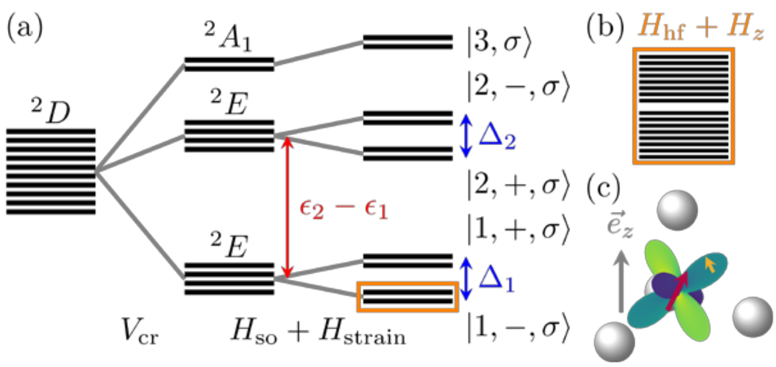
Transition metal defects in silicon carbide as telecom quantum memories

B. Tissot[1] **and G. Burkard**[1]

[1]*Universität Konstanz, Konstanz, Germany*



Transition metal defects in silicon carbide are a promising platform for quantum memories. These defects are a potentially viable alternative to the well-established nitrogen vacancy in diamond for certain applications as they feature a distinct set of beneficial properties. Two beneficial properties are due to the host material silicon carbide, which can be used to create and interface with photonic structures and - due to its use by the semiconductor industry - is available on a waver scale. Finally, some defects, e.g., vanadium, possess optically addressable electron and nuclear spins, as well as optical transitions in one of the telecom bands rendering them compatible with telecom fiber optics. Combined, this makes transition metal defects in silicon carbide a leading candidate as a quantum memory for network applications. In this talk, we overview key quantum mechanical properties of these defects that can be theoretically derived based on their electronic configuration and the symmetry imposed by the surrounding crystal. In particular, we discuss an effective model to describe these defects and use it to study application ranging from a deeper understanding of the energy levels and selection rules to state preparation and strain engineering.

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Epitaxial growth of SiC for quantum applications

M.Ghezellou[1] and Jawad Ul-Hassan[1]

[1]*Linköping University, Sweden*

Silicon Carbide (SiC) is an increasingly important wide bandgap material in quantum technologies due to its unique properties and commercial availability in the form of high-quality large diameter wafers, which make it suitable for a variety of quantum applications. SiC hosts several types of defect centers such as silicon vacancies, carbon vacancies, divacancies and other complex centers that can act as qubits. Long spin coherence times, which are crucial for maintaining quantum information over longer periods, makes such defects suitable for applications in quantum communication and quantum computing [1]. These defects can also be initialized and read out optically/electrically, which is essential for many quantum technologies [2-4]. Material development is an essential part of developing new technologies. Long spin-coherence time of a defect and charge state stability, for example, would require ultra-high purity of the host material both in terms of charge and spin. Linköping university has been at the forefront of developing high purity natural SiC (with natural abundance of Si and C isotopes) and isotopically enriched $^{28}Si^{12}C$ epilayers for fundamental studies of quantum properties and their applications. We will present some fundamental aspects and limitations of SiC growth following the requirements of different quantum applications, for instance, integrated SiC photonics platform [5]. Continued research and development are likely to further enhance its applications in quantum computing, sensing, communication, and hybrid systems, making SiC a key material in the evolving quantum technology landscape.

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Novel device concepts for the study of charge-photon interaction using epitaxial graphene on 4H-SiC

Heiko B. Weber[1]

[1]*Chair for Applied Physics*

Epitaxial graphene on SiC is a transparent metal-semiconductor system that is suited to perform otherwise barely achievable experiments in the realm of light-matter interaction.

This will be demonstrated along three examples. A first example is the creation of light with graphene tunnel currents. Due to their extreme robustness, graphene electrode pairs on SiC can be DC biased to several volts, where they emit visible light. Not only the commonly told narrative of light excitation during tunneling is questioned [1], but it could also be demonstrated how Planck spectra in patterned electromagnetic environments differ significantly from the usual Planck spectra [2]. In a second example, electronic currents are generated in a graphene/SiC Schottky diode with the light field. While the diode can be accurately described with a consistent parameter set from DC to the THz region, the so far inaccessible region at even higher frequencies indicates first oscillatory tunneling currents in the MIR [3] and subsequently in the NIR spectral range, where the Schottky description suddenly becomes invalid. A third line of devices are graphene electrodes that exert fields to color centers in SiC, like the V_{Si}. Here, the interplay of optical signatures and electrical fields and potentials can be controlled [4-6]. Altogether, epitaxial graphene devices offer a rich toolbox for both classical and quantum devices in SiC.

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Generation, Control, and Fabrication of Defects and Devices in 4H-Silicon Carbide

J. Dietz[1], A. Day[1], A. Xie[1], E. Hu[1]

[1]Harvard University, Cambridge, MA. 02138, USA
E-mail: axie@g.harvard.edu

4H-Silicon Carbide (4H-SiC) is a wide bandgap semiconductor hosting native point defects which have been widely studied for applications in quantum sensing and quantum networking. Controlling the material qualities of 4H-SiC, such as through doping and thermal processing, is crucial to achieve optimal defect performance in terms of high intensity photoluminescence and long coherence times. Integration of defects into nanophotonic structures, such as photonic crystal cavities, has already been demonstrated to enhance defect emission through the Purcell effect.[1] However, challenges still remain in effectively controlling the spin states and in optimizing the spatial placement of defects. To address these issues, we show that acoustic control of spin-active point defects[2] introduces a new avenue in coherent population control and have established an above bandgap laser writing protocol[3] to deterministically embed defects into photonic crystal cavities. These efforts, however, employed thick bulk resonators and highly doped cavities, respectively, which are ultimately detrimental to device performance. Because of this, we have developed a new technique to fabricate large area (100um x 100um) suspended thin-film membranes of unintentionally doped 4H-SiC utilizing a modified photoelectrochemical (PEC) etching process.[4] While traditional PEC etching processes rely solely on high doping contrast to achieve suspended devices, highly doped material is unsuitable for low optical losses and introduces unwanted decoherence pathways for defects. Through the application of an additional junction bias, we demonstrate independent control of the etching potentials of differently doped layers without the need for a large difference in doping concentration. We apply this technique to demonstrate a 3-fold enhancement in spin lifetime of emitters integrated in undoped versus highly doped membranes and for use in bottom-up fabrication of nanodevices.

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Preparation and manipulation of single divacancy defects near stacking faults in 4H-SiC

Jin-Shi Xu and Chuan-Feng Li

CAS Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei, Anhui, 230026, China

Color centers in silicon carbide (SiC) have shown significant promise for quantum information processing. Various polytypes of divacancies have been identified in SiC. In addition to the usual lattice-vacancy-related defects (PL1-PL4), PL5-PL7 have been associated with divacancy configurations near stacking faults, which possess unique optical and spin properties.

In this report, we discuss our recent experimental results on the preparation and manipulation of single divacancy defects using carbon-ion implantation and focused helium ion beams. We successfully achieved coherent manipulation of single PL6 centers in 4H-SiC, with high readout contrast and a high photon count rate under ambient conditions, comparable to NV centers in diamond.

Furthermore, we demonstrated long-term emission stability with minimal linewidth shift for the single PL6 defects through low-temperature photoluminescence excitation (PLE) experiments. By measuring the ionization rate for different polytypes of divacancies, we found that the divacancies within stacking faults are more robust against resonant excitation. Moreover, the PLE linewidths are narrower and the spin-coherence times are longer for defects prepared by focused helium ion beams compared to those implanted by carbon ions at the same depth. These findings open new opportunities for SiC-based quantum devices and the development of efficient spin-to-photon interfaces.

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Cubic silicon carbide for integrated photonic devices

Xiaoke Yi[1] and Marko Loncar[2]

[1]School of Electrical and Computer Engineering, the University of Sydney, NSW 2006, Australia
[2]John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, 02138, USA

Silicon carbide (SiC) has been gaining momentum as a platform to realize many optical functionalities due to its diverse properties, such as a wide band-gap, absence of two photon absorption at telecom wavelengths, low thermo-optic coefficient and high thermal conductivity. Cubic SiC (3C-SiC) can be grown on a host substrate (Si) with the option to grow SiC to a desired thickness required for the targeted application, which features the advantage of scalability and compatibility with electronic devices. The isotropic crystal structure and symmetric electro-optic (EO) tensor make 3C-SiC attractive for birefringent free EO devices and allow for novel quasi-phase matching schemes for efficient second order non-linear processes. Moreover, 3C-SiC are efficient quantum emitters both optically pumped and electrically driven in visible and telecom wavelengths, making it promising for applications in quantum optics.
Integrated photonic devices on 3C-SiC are often fabricated on suspended films [1,2] and on the SiC on insulator (SiCOI) platforms. Conventional suspended 3C-SiC ring resonators feature optical quality (Q) factors in the range of 11,000 to 24,000. Annealed optical resonators yield quality factors of over 41,000, which corresponds to a propagation loss of 7dB/cm, and is a significant improvement over the 24dB/cm in the case of the non-annealed chip [1]. This improvement is attributed to the enhancement of SiC crystallinity and a significant reduction of waveguide surface roughness. In 3C-SiCOI a flip, bond, etch and polish method is developed to remove the stacking faults and anti-phase boundaries at the SiC-Si interface [3,4]. Leveraging the low propagation loss of the SiCOI platform, we recently designed, fabricated, and demonstrated a SiC EO modulator. Optical modulation is achieved by electrically driving a microring resonator based on sub-micron-wide 3C-SiCOI waveguides via the Pockels effect. The microring modulator is fabricated with a CMOS foundry compatible process and is able to operate continuously at high optical intensities of up to 913 kW/mm^2 without signal degradation.

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Abstracts of Posters

(in alphabetical order)

Photoluminescence of Femtosecond Laser-irradiated Silicon Carbide

Y. Abdedou[1], A. Fuchs[2], P. Fuchs[2], D. Herrmann[2], S. Weber[3], M. Schäfer[3], J. L'huillier[3], C. Becher[2] and E. Neu[1]

[1]RPTU Kaiserslautern-Landau, 67663 Kaiserslautern, Germany
[2] Saarland University, 66123 Saarbrücken, Germany
[3]Institut für Oberflächen- und Schichttechnik GmbH, Research Center OPTIMAS, RPTU Kaiserslautern-Landau, 67663 Kaiserslautern, Germany

Silicon carbide (SiC) is the leading wide-bandgap semiconductor material, providing mature doping and device fabrication. Additionally, SiC hosts a multitude of optically active point defects (color centers), it is an excellent material for optical resonators due to its high refractive index and an outstanding material for mechanical resonators due to its high Q/f product. Moreover, epitaxial graphene layers can be grown as ultrathin electrodes and provide the potential to fine-tune color center resonances. These characteristics render SiC an ideal platform for experiments with single color centers towards quantum technologies including coupling color centers towards cooperative effects.
A crucial step towards harnessing the full potential of the SiC platform includes technologies to create color centers with defined localization and density, e.g. to facilitate their coupling to nano-photonic structures and to observe cooperative effects. Here, silicon vacancy centers (V_{Si}) stand out as no impurity atom is needed and high-thermal budget annealing steps can be avoided. We characterize the effect of localized, femtosecond laser irradiation of SiC, investigating surface modifications and photoluminescence including Raman spectroscopy and optical lifetime measurements.

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4H Silicon-carbide on Insulator: Integrated quantum photonics based on telecom-range defects

J. Bader[1,2], H. Arianfard[1], J.McCallum[3], S.Lim[3], Q. Li[4], A.Peruzzo[1,5] and S. Castelletto[2]

[1]Quantum Photonics Laboratory and Centre for Quantum Computation and Communication Technology, School of Engineering, RMIT University, Melbourne, VIC 3000, Australia

[2] School of Engineering, RMIT University, Melbourne, VIC 3000, Australia

[3] Centre for Quantum Computation and Communication Technology, School of Physics, University of Melbourne, Melbourne, VIC 3000, Australia

[4] Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA

[5] Qubit pharmaceuticals, Advanced Research Department, Paris, France

Optically addressable single photon emitting color centre's hosted in 4H-Silicon carbide on Insulator (4H-SiCOI) are one encouraging contender to be utilized as qubits in defect-based integrated quantum photonics. Erbium-defects (Er^{3+}) have been demonstrated in other platforms previously, like Silicon (Si) [1], titanium oxide [2], lithium niobate on Insulator (LNoI) [3] as well as bulk SiC [4], however a demonstration in thin film 4H-SiCOI is lacking which could provide an increased understanding of the feasibility of utilizing this particular emitter in combination with integrated quantum photonics.

Here, we present the successful demonstration of Er^{3+}-defects embedded in thin-film 4H-SiCOI utilizing ion implantation. Ideal implantation parameters as well as thermal annealing procedures will be reported. With the ZPL-line determined near 1540nm, this defect has ideal prerequisites to be utilized in a spin-photon interface (SPI) operating at telecommunication wavelength which could enable long distance transmission of quantum information embedded in a CMOS-compatible material.

Furthermore, we report a photonic device which is engineered to achieve a spectral response from optical analogues of Fano resonances [5] that yield ultrahigh spectral extinction ratios (ERs) and slope rates (SRs) by tailoring the coherent mode interference. Integrating these Fano-like resonances with defect-induced quantum emitters in 4H-SiCOI could result into precise control over emission properties, facilitate high-purity single-photon generation and enhance light-matter interaction.

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Effect of Helium Ion Implantation on 3C-SiC Nanomechanical String Resonators

P. Bredol[1], F. David[1], N. S. Jagtap[2], Y. S. Klaß[1], G. V. Astakhov[2], A. Erbe[2] and E. M. Weig[1]

[1]Department of Electrical Engineering, School of Computation, Information and Technology, Technical University of Munich, 85748 Garching, Germany
[2]Institute of Ion Beam Physics and Materials Research, Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany

Hybrid quantum devices enable novel functionalities by combining the benefits of different subsystems. Particularly, point defects in nanomechanical resonators made of diamond or silicon carbide (SiC) have been proposed for precise magnetic field sensing and as versatile quantum transducers. However, the realization of a hybrid system may involve tradeoffs in the performance of the constituent subsystems. In a spin-mechanical system, the mechanical properties of the resonator may suffer from the presence of engineered defects in the crystal lattice. This may severely restrict the performance of the resulting device and needs to be carefully explored. Here, we focus on the impact of defects on high Q nanomechanical string resonators made of pre-stressed 3C-SiC grown on Si(111). We use helium ion implantation to create point defects and study their accumulated effect on the mechanical performance. Using Euler-Bernoulli beam theory, we present a method to determine Young's modulus and the pre-stress of the strings. We find that Young's modulus is not modified by implantation. Under implantation doses relevant for single defect or defect ensemble generation, both tensile stress and damping rate also remain unaltered. For higher implantation dose, both exhibit a characteristic change [1].

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Towards the development of a small Room-Temperature Quantum Simulator based on Modified Divacancies in 4H-SiC

F. D. Marquis[1], J. Heiler[1], S. Kucera[1], F. Kaiser[1]

[1]*MRT Department, Luxembourg Institute of Science and Technology (LIST), Belvaux, Luxembourg*

Recent studies on the nature of modified divacancies (VVs) in 4H silicon carbide have shown their remarkable stability under ambient conditions [1] as well as readout contrast and count rates comparable to the nitrogen vacancy in diamond [2]. In this poster, newly obtained results pertaining to the spin properties of a single PL6 are presented. Coherent control of the spin defect is supported by run-of-the-mills Rabi oscillation measurements. Moreover, coupling to a nearby nuclear spin qubit is observed though the acquisition of continuous-wave excitation optically detected magnetic resonance spectra. Initialisation of said nuclear spin's quantum state is further demonstrated via polarisation studies. In the scope of developing a room-temperature quantum simulator unit, outlook discussion of higher-level nuclear spin control within the di-atomic lattice.

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Charge penetration into 4H-SiC/SiO_2 semiconductor-oxide interfaces in the presence of border traps

<u>H. G. de Medeiros</u>[1], C. Kalin[2], P. Kumar[1], L. Deuschle[2], M. E. Bathen[3], M. Luisier[2], U. Grossner[1]

[1]Advanced Power Semiconductor Laboratory, ETH Zurich, Zurich, Switzerland
[2] Integrated Systems Laboratory, ETH Zurich, Zurich, Switzerland
[3] Department of Physics/Centre for Materials Science and Nanotechnology, University of Oslo, Oslo, Norway

The on-state resistance of SiC metal-oxide-semiconductor field effect transistors (MOSFETs) rated for blocking voltages below ~1.7 kV is mostly limited by their channel resistance [1]. Thus, reducing this parameter is important to produce devices with lower on-state losses. Both interface defects and border traps induced by thermal oxidation processes have been identified as the origin of channel resistance increases and reduced channel mobility [2,3]. Different thermal oxidation and post-oxidation annealing (POA) treatments have been proposed to reduce the density of interface traps (D_{it}) and boost the SiC mobility. However, POA treatments have been shown to create border traps, in addition to those existing from the thermal oxidation process [4]. Since border traps are near-interface defects in the oxide, there is a barrier for the charge carrier exchange with the channel. Due to the inherent difficulty to measure at which distance the border traps are located from the interface, the tunneling barrier is usually used as fitting parameter, both in experimental and theoretical works [4,5]. This study aims to present values for the tunneling distance between the border traps and the channel by using quantum transport simulations.
Our approach consists of simulating border traps as a quantum well (QW) within the silicon dioxide (SiO_2) insulating layer in the metal-semiconductor-oxide capacitor (MOSCAP). By varying the width of the QW we can modulate how many states are allowed inside of it, which affects the amount of charge penetration inside the SiO_2. By varying the distance from the QW to the interface, simulating different QW widths, testing different effective mass directions, and applying different gate voltages we can probe several parameters that affect the charge penetration into the oxide. In particular, we will present how does the charge penetration into the oxide varies within the parameter space.

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Low Temperature Color Centers as atom-like sensors of charges in the solid state

T. Delord[1], R. Monge[1], C.A. Meriles[1]

[1]*Department. of Physics, CUNY-City College of New York, NY 10031, USA*

Color centers are widely used for quantum sensing, mostly for their ease of use. Under cryogenic conditions, their optical transitions typically sharpen and become highly sensitive to their electric environment. While this sensitivity can present an obstacle to the creation of indistinguishable photon sources, it can also be leveraged to study -and mitigate- electric noise sources. Here, we study how resonant excitation of narrow optical lines can be exploited for sensing in the specific case of the NV- center in diamond. We first show that closely packed sensors can be optically addressed independently below the diffraction limit, thanks to local heterogeneities [1]. This enables new sensing modalities [2] that use correlation across sensors to gain spatial information. We demonstrate this principle by elucidating the source of spectral diffusion, a common phenomenon where slow electric noise affects optical lines via the Stark effect. We use cross-sensor measurements to precisely determine the position and sign of multiple charge traps surrounding our sensors [3]. Similarly, we observe strong (classical) Coulomb interactions between sensors, which we use to map their respective position beyond common super-resolution techniques. These methods [3,4] can be applied widely to study charge dynamics in diamond and other semiconductors. Finally, we expose the effect of electric permanent and transition dipoles on the NV- optical spectrum [5], which may be used to study electric-active defect in the AC regime.

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Electrical control for quantum emitters integrated in silicon carbide photonic chips

Adil Han Dogan[1,2]

[1]ETH Zürich, Zürich, Zürich, Switzerland
[2] University of Stuttgart, Stuttgart, Baden-Württemberg, Germany

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 involves 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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Spectral diffusion dynamics of narrow-linewidth emitters in commercially available bulk 4H-silicon carbide

L.J. Feije[1,2], G.L. van de Stolpe[1,2], S.J.H. Loenen[1,2], G.M. Timmer[1,2], A. Das[1,2], D. Bedialauneta[1,2], T.W. de Jong[1,2], B. Pingault[1,2] and T.H. Taminiau[1,2]

[1]Qutech, Delft University of Technology, Delft, The Netherlands
[2]Kavli institute of Nanoscience Delft, The Netherlands
E-mail: l.j.feije@tudelft.nl

Point defects in 4H-silicon carbide have shown themselves to be an interesting candidate for scalable quantum applications, thanks to their outstanding spin-optical properties [1,2] and the successful integration of defects in nanophotonic structures [3,4,5]. An interesting question is if coherent optical transitions can be accessed in widely available commercially available silicon carbide wafers. I will present our recent results on studying the optical coherence and spectral stability of V_{Si} centres in samples diced from a bulk commercially available, c-plane silicon carbide wafer. We fabricate light guiding nanopillars to enhance the limited collection efficiency. Moreover, we show orders of magnitude difference in spectral diffusion rates under the influence of resonant and offresonant laser illumination. We then apply methods to prepare the charge environment and demonstrate that close to lifetime limited linewidths in nanopillars in commercially available bulk c-plane silicon carbide can be obtained.

Combined with our progress towards integrating V_{Si} centers in nanophotonic “alligator” cavities fabricated with the 4H-silicon-carbide-on-insulator platform [4], these results open new opportunities for large-scale quantum technologies based on qubits in silicon carbide.

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Integrating Silicon Carbide into Quantum Technology

J. Foerthner[1]

[1]*Chair of Electron Devices, Friedrich-Alexander-University Erlangen-Nuremberg, Germany*

E-mail: julietta.foerthner@fau.de

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]. Our main subject areas relate to 'Integrating Silicon Carbide into Quantum Technology', as SiC has shown excellent optical, electrical and spin properties of color centers [2].

In doing so, we focus on re-using our well established (CMOS-) fabrication line for 6-inch SiC wafers for quantum applications and investigate their specific boundary conditions. Therefore, we are currently upgrading and expanding our fabrication processes, e.g., concerning lithography methods for nano structures or implantation techniques for the generation of color centers. For photonic quantum applications an optical readout of color centers is of high importance, which is much easier to access perpendicular to the a-plane of SiC (in contrast to the c-plane) [3]. Thus, we no longer specialize exclusively in processing c-plane SiC, but also in a-plane SiC. Processing on a-plane requires an adjustment of several parameters (e.g., thermal oxidation, implantation angle or consideration of a small wafer size of 3-inch), on which we are already working. Furthermore, we prepare an in-line generation of color centers, which will be realized by an He implantation using low doses and high energies. For a more direct access to the optical and electrical properties of color centers and surrounding deep defects than the usual quantum PL and ODMR experiments can provide, we use DLTS (on vertical Schottky diodes). Due to the surface proximity of the color centers as well as their very deep energy level in the band gap, DLTS is not trivial, and we are working on evaluating optimal parameters (e.g., for the Schottky metallization - relating to the work function - and in combination with the implantation dose of He ions). The presentation will show our suggestions and future solutions for the above-mentioned challenges.

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Screening of an NV-like defect in 4H-SiC using ADAQ with the SCAN meta-GGA functional

Ghulam Abbas Gilani, Oscar Bulancea-Lindvall, Joel Davidsson, Rickard Armiento, Igor A. Abrikosov

Department of Physics, Chemistry and Biology, Linköping University, SE-581 83 Linköping, Sweden

Email: ghulam.abbas@liu.se

Abstract

Kohn-Sham density functional theory is widely used for high-throughput screening of atomic and electronic structure of deep color centers. For almost a decade, the hybrid exchange-correlation functional, developed by Heyd, Scuseria, and Ernzerhof (HSE), has remained a standard reliable tool for characterization of defect formation energies and magneto-optical properties such as zero-phonon lines, zero-field splitting, and hyperfine coupling parameters. Automatic Defect Analysis and Qualification (ADAQ)[1] is our in house framework of automatic workflows for high-throughput simulations of magneto-optical properties of point defects in semiconductors. For large-scale screening, it relies on imprecise quantitative description of defects based on exchange-correlation effects described by the Perdew-Burke-Ernzerhof (PBE) generalized gradient approximation (GGA), as HSE remains unpractical in high-throughput screening automatic workflows, mainly due to its high computational demands. Motivated by the Strongly Constrained and Appropriately Normed (SCAN)[2] meta-GGA functional performance for nitrogen-, silicon-, germanium-, and tin-vacancy centers in diamond[3]. We evaluate the performance of the SCAN meta-GGA functional of DFT on well-known NV-like color centers in 4H-SiC using ADAQ. In particular, we study nitrogen, oxygen, fluorine, sulfur, and chlorine vacancy centers in 4H-SiC for their use in quantum technological applications[4]. For this small sample set of defects it is found that calculations using SCAN achieves an overall better quantitative precision of magneto-optical parameters closer to HSE, at a fraction of the computational cost. Based on our preliminary findings, SCAN may be a computationally inexpensive alternative for studying color centers in solids.

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Maskless Generation of Single Silicon Vacancy Arrays in Silicon Carbide by a Focused He+ Ion Beam

Zhen-Xuan He[1,2] and Jin-Shi Xu[1,2]

[1]CAS Key lab of quantum information, Hefei Anhui 230026, China
[2] University of science and technology of China, Hefei Anhui 230026, China

Precise generation of spin defects in solid-state systems is essential for nanostructure fluorescence enhancement. We investigated a method for creating single silicon vacancy defect arrays in silicon carbide using a helium-ion microscope. Maskless and targeted generation can be realized by precisely controlling the focused He+ ion beam with an implantation uncertainty of 60 nm. The generated silicon vacancies were identified by measuring the optically detected magnetic resonance spectrum and room temperature photoluminescence spectrum. We systematically studied the effects of the implantation ion dose on the generated silicon vacancies. After optimization, a conversion yield of ∼6.95% and a generation rate for a single silicon vacancy of ∼35% were realized. This work paves the way for the integration and engineering of color centers to photonic structures and the application of quantum sensing based on spin defects in silicon carbide.

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Developing a high-throughput characterisation setup for colour centres in SiC

J. Heiler[1,2], L. Zimmermann[1,2], F. Davidson-Marquis[1,2], S. Kucera[2], and F. Kaiser[1,2]

[1]Luxembourg Institute of Science and Technology (LIST), 4422 Belvaux, Luxembourg
[2] University of Luxembourg, 4365 Esch-sur-Alzette, Luxembourg

The favourable properties of silicon carbide (SiC) for high-power electronics raised the interest of the semiconductor industry especially in the context of the green energy transition. [1] This interest resulted in the development of mature (micro-)manufacturing processes and wafer-scale availability of the material.

We want to take advantage of this progress and use SiC in the context of distributed quantum technologies in fields like sensing, communication, and computation. SiC presents itself as a promising candidate in these fields since it hosts optically active spins, so-called colour centres which inherently provide a spin-photon interface. The high refractive index of SiC, however, limits the efficiency of this interface and nanophotonic structuring is required to overcome this limitation. Material removal for nanophotonic structuring decreases the distance from colour centres to the surface, which makes them more susceptible to surface charge noise and causes undesired spectral instabilities. [2]

The conventional method to investigate these effects is confocal microscopy. However, it allows by design only for a small number of colour centres in the confocal volume to be investigated which makes obtaining conclusive statistics on the influence of processing on the emitters a time consuming and tedious task. We want to accelerate this process by building a cryo-optic wide-field setup that is able to investigate spectral properties on a statistically relevant number of 100-1000 near-surface colour centres simultaneously. [3]

This novel setup subsequently allows us to conduct a large-scale investigation of different ideas on improving the spin-optical robustness of SiC colour centres, e.g., via surface passivation, annealing, or crystal doping. Here, we present our latest results on the realisation of this setup together with processes to be studied.

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Color centers in silicon carbide integrated into a fiber-based Fabry-Pérot microcavity

Jannis Hessenauer[1], Jonathan Körber[2], Jawad Ul-Hassan[3], Georgy Astakhov[4], Wolfgang Knolle[5], Florian Kaiser[6,7], Jörg Wrachtrup[2], David Hunger[1]

[1]Karlsruhe Institute for Technology, Karlsruhe, Germany
[2] University of Stuttgart, Stuttgart, Germany
[3]Linköping University, Linköping, Sweden
[4]Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany
[5]Leibniz-Institute of Surface Engineering, Leipzig, Germany
[6]Luxembourg Institute of Science and Technology (LIST),Belvaux, Luxembourg
[7]University of Luxembourg, Belvaux, Luxembourg

Color centers in silicon carbide (SiC) have recently emerged as promising solid-state spin-photon interfaces. Among those, the two negatively charged silicon vacancy centers in 4H-SiC have been studied extensively, and showed narrow optical linewidths close to the lifetime limit.
Despite first promising results, the integration of optically-coherent defect centers in optical cavities has remained challenging [1,2]. In this work, we integrate a few micron-thick SiC membrane with color centers into a cryogenic fiber-based Fabry-Pérot-resonator. We characterize the cavity performance and observe a high finesse exceeding 40000, indicating low losses introduced by the membrane. We study the complex mode dispersion stemming from the hybridization of the membrane with the empty cavity and the strong birefringence of the material.
Finally, we observe cavity-coupled emission of color centers by tuning the cavity resonance over a spectral region while monitoring the fluorescence. We measure the optical lifetime and the second order autocorrelation function of the detected photons, indicating predominant single photon emission and moderate Purcell enhancement.

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Monolithically etched 4H-SiC nanomechanical resonators

André Hochreiter[1], Philipp Bredol[2], Felix David[2], Heiko B. Weber[1], Eva M. Weig[2]

[1] Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen, Germany.
[2]Department of Electrical & Computer Engineering, Technical University of Munich, 85748 Garching, Germany

We present results of 4H-SiC singly and doubly clamped nanomechanical cantilevers, monolithically etched via electrochemical etching (ECE) [1]. Here, we remove dopant-selective p-SiC volumina to release the n-SiC cantilevers. The doping contrast is provided by ion implantation of Aluminium for p-type and Nitrogen for n-type.
The following methods are employed in the mechanical investigation of our structures: Laser Doppler Vibrometer (LDV) for mode-matching, and a Fabry-Pérot interferometer setup to ascertain quality factors.
We report high intrinsic mechanical Qs for unstressed, singly clamped cantilevers up to 150k, slightly exceeding those recently reported for SiC-on-insulator [2] and close to those observed in diamond (~400k) [3]. Here, we investigate the influence of fabrication techniques and surface modifications on the quality factor of 4H-SiC resonators. One challenge in device fabrication is the production of cantilevers with precise customized eigenfrequencies. First, we investigate thinning of the cantilever with atomic layer precision. Eigenfrequencies were tuned by 20% by atomic layer etching (ALE). The cantilever thickness is thinned from 570 nm down to 426 nm. However, quality factors decrease by a factor of two.
Typical device fabrication steps involve standard dry etching techniques, which includes the novel approach of ALE. Dry etching processes are known to deteriorate the crystal and induce damage [4]. Because of the unique monolithic fabrication process, post-annealing steps at high temperatures are available. Such high temperature protocols also allow for epitaxial graphene growth and the creation, conversion and annealing of spin-carrying color centers. Annealing the cantilevers at 1200°C partially recovers the mechanical properties, with increasing quality factors.

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Selective Initialization Mechanism of Silicon Vacancy
Spin Qubits with S =3/2 in Silicon Carbide

Jeongeun Park[1], Seoyoung Paik[1], Seung-Jae Hwang[1], Di Liu[2], Öney O. Soykal[3], Joerg Wrachtrup[2], Sang-Yun Lee[1]

[1]Gwangju Institute of Science and Technology, Cheomdan-gwagiro123, Gwangju, Republic of Korea
[2] University of Stuttgart, Pfaffenwandring 57, Stuttgart, Germany
[3] Photonic Inc., Vancouver, Canada
E-mail: sangyunlee@gist.ac.kr

Silicon vacancies in silicon carbide (SiC) are emerging as promising candidates for quantum repeater applications due to their efficient spin-photon interfaces and long-lived spin qubits[1]. However, the challenge of achieving high-fidelity deterministic initialization of these qubits has not been fully addressed.
This research focuses on the photodynamic properties of the V1 center in SiC, analyzed using a 9-state rate model. This model effectively captures the complex dynamics of population distribution caused by static rate transitions, selective optical transitions, and electron spin resonance (ESR). Through detailed analysis, we elucidate the mechanisms driving population redistribution among the spin sublevels.
We systematically explored the parameter space within this rate model through simulations, investigating key factors like optical Rabi frequency, spin Rabi frequency, and laser excitation time. Our extensive simulations enabled us to identify optimal parameter configurations that lead to population condensation into specific ground states. These optimized parameters are crucial for achieving selective pure state initialization.
Our study demonstrates possible improvements in qubit initialization fidelity, higher than the previous benchmarks of 97% [2], that can reach up to 99% for the $|+3/2\rangle_{gs}$ or $|-3/2\rangle_{gs}$ ground state within a 1 ms time scale.
In conclusion, this study makes a certain contribution to the development of silicon vacancy qubits, moving them closer to practical applications in quantum communication and computing.

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Scalable Registration of Silicon Vacancies in Solid Immersion Lenses by Femtosecond Laser Writing

Alexander Jones[1], Xingrui Cheng[2], Patrick Salter[2], Jason Smith[2], Cristian Bonato[1] and Christiaan Bekker[1]

[1]Institute of Photonics and Quantum Science, Heriot-Watt University, Edinburgh , UK

[2] Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK

Optically active Silicon atom vacancies (V_Si) in Silicon Carbide (SiC) can act as qubits, interfacing with their spins using photons. This allows it to encode photonics information within its spin state and readout on demand, making it promising for applications as quantum memories. Defects generated within SiC are crucial for these applications [1] and often exhibit low brightness due to SiC's high refractive index, limiting their utility. This work demonstrates an approach that builds on our earlier work to fabricate solid immersion lenses (SILs) using a scalable greyscale hard-mask lithography technique. By reducing reflections back into the SiC crystal, these lenses show that transmission out of the SIL achieves a factor of 4.4 +/- 1 increase in collected photons from a single emitter [2]. Quantum emitters can be fabricated in SiC using electron irradiation, however, the VSi's are randomly generated across the sample, reducing the spatial selectivity, resulting in a loss of scalability in the fabrication process [2]. Here, we demonstrate a method based on femtosecond laser writing that is spatially selective and can scalably yield single defects [3]. We utilise this method to align the location of defects more precisely to SILs after their fabrication, which requires aberration correction to account for lens profiles, but generates VSi's at lower laser writing powers due the focusing effect of the SIL. We have determined an optimal set of laser writing parameters for single V_Si generation. We also present a set of preliminary results from an ongoing study at 4K temperatures of spectral emission lines that have yet to be identified in the literature.

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High-Q SiC 2D photonic crystal nanocavities operating below 1100 nm for quantum applications

Heungjoon Kim[1], **Bong-Shik Song**[2], **Takashi Asano**[1], **Susumu Noda**[1]

[1]*Kyoto University, Katsura, Kyoto 615-8150, Japan*
[2]*Sungkyunkwan University, Jangan-gu, Suwon, 16419, Korea*

Photonic nanocavities are the key components for various quantum applications. In particular, SiC photonic crystal (PC) nanocavities have attracted much attention because their high quality (Q) factor and small mode volume (V) enable to greatly enhance the spontaneous emission (SE) of various SiC color centers. So far, the nanocavities operating near SE wavelengths, which are usually shorter than 1100 nm, have been mainly formed of 1D PC nanobeams [1,2]. Although 1D PC nanobeams have an advantage of compactness, they are somewhat difficult to achieve high-density and large-scale photonic integration with various devices.

In this work, we demonstrate high-Q SiC 2D PC nanocavities operating below 1100 nm. To achieve a resonance near SE wavelengths (λ = 900 – 1000 nm) of SiC color centres, we used a very thin SiC slab with thickness of 150 nm and fabricated 2D PC structures with a lattice constant of a_1 = 350 nm in the slab. Moreover, we formed a heterostructure nanocavity (a_2 = 351.5 nm, a_3 = 353 nm) with a Gaussian-enveloped mode distribution to suppress radiation loss. An input waveguide was placed near the nanocavity for excitation. The SEM image of the fabricated sample is shown in Fig. 1. Then, we utilized a tunable CW laser and measured a resonant spectrum, as shown in Fig. 2. A resonant wavelength of 960 nm and narrow linewidth of 24 pm were obtained. The corresponding Q factor is 4×10^4, which is the highest result among the previously reported values for the SiC photonic nanocavities. Moreover, a radiation pattern with a single spot at the cavity was clearly observed, as shown in the inset. We believe that our nanocavity can greatly improve the SE of SiC color centres for quantum applications. Details will be presented at the seminar.

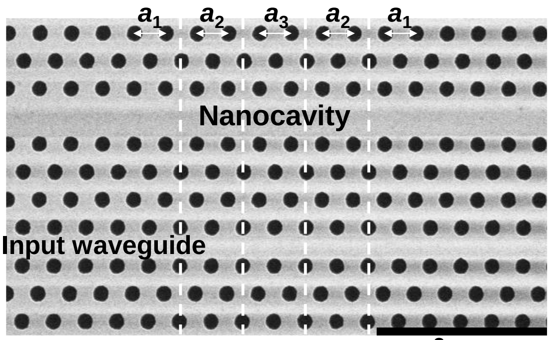

Fig. 1: Surface SEM image of a fabricated SiC photonic crystal nanocavity

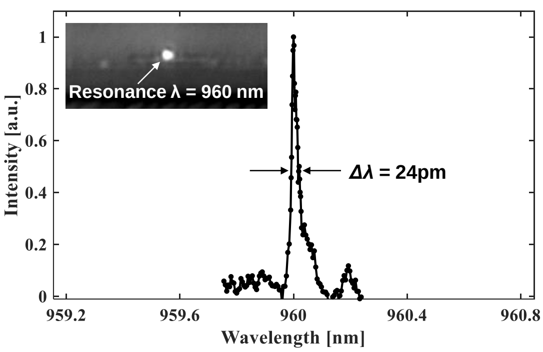

Fig. 2: A measured resonant spectrum of a fabricated nanocavity. The inset shows a radiation pattern.

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Exploring vanadium in SiC for quantum communication

P. Koller[1,2], T. Astner[1], D. Wirtitsch[1], S. Putz[1] and M. Trupke[1]

[1]Institute for Quantum Optics and Quantum Information (IQOQI) Vienna, Austrian Academy of Sciences, Vienna, Austria
[2] University of Vienna, Faculty of Physics & Vienna Doctoral School in Physics, Vienna, Austria

Quantum communication holds the promise of revolutionizing communication capabilities by leveraging the transmission of quantum states of light. However, existing implementations are held back by limitations in communication distance attributed to photon loss in fiber when utilizing photons in the visible range. Silicon carbide (SiC) defects have emerged as a highly promising platform for quantum devices, offering robust optical transitions, sufficiently long spin coherence and lifetimes. Particularly, vanadium exhibits optical transitions within the telecom range and therefore enables seamless integration with fiber networks, removing the need for wavelength conversion. These distinctive attributes position SiC as an attractive platform for quantum nodes in quantum communication networks.
This poster presents explorations of the spin lattice relaxation behavior, coherence time and coherent control of vanadium defects using optically detected magnetic resonance (ODMR) spectroscopy techniques, particularly focusing on their dynamics at mK temperatures. Our findings reveal a significant extension in the spin lattice relaxation time (T1) of vanadium of up to 25s at 100mK, challenging conventional notions about the limitations of vanadium for quantum information tasks.
Additionally, we discuss a memory-enhanced quantum communication protocol, providing insights into the parameters necessary to surpass the performance of direct point-to-point links. These findings outline the essential steps toward the integration of SiC devices into large-scale quantum communication networks, offering a roadmap for future advancements in this domain. By elucidating the spin dynamics of vanadium and exploring the capabilities of SiC defects, this research contributes to the broader quest for practical quantum information and communication technologies.

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Fluorescence enhancement of single V2 centers in a 4H-SiC cavity antenna

J. Körber[1], J. Heiler[1-3], P. Fuchs[4], P.Flad[5], E. Hesselmeier[1], P. Kuna[1], J. Ul-Hassan[6], W. Knolle[7], C. Becher[4], F.Kaiser[1-3] and J. Wrachtrup[1,8]

[1]3rd Institute of Physics, University of Stuttgart, Allmandring 13, 70569 Stuttgart, Germany
[2]Materials Research and Technology (MRT) Department, Luxembourg Institute of Science and Technology (LIST), 4422 Belvaux, Luxembourg.
[3]Department of Physics and Materials Science, University of Luxembourg, 4422 Belvaux, Luxembourg
[4]Universität des Saarlandes, Fachrichtung Physik, Campus E2.6, 66123 Saarbrücken, Germany.
[5]4th Physics Institute and Research Centre SCoPE, University of Stuttgart, Pfaffenwaldring 57, 70569, Stuttgart, Germany.
[6]Department of Physics, Chemistry and Biology, Linköping University, 581 83 Linköping, Sweden.
[7]Leibniz-Institute of Surface Engineering (IOM), Permoserstraße 15, 04318 Leipzig, Germany.
[8]Max Planck Institute for Solid State Research, Heisenbersgtraße 1, 70569 Stuttgart, Germany.

Colour centres in silicon carbide promise various applications for quantum technologies, especially with the latest landmark demonstrations of spin-photon entanglement [1] and nuclear assisted single-shot readout (SSR) of the spin state [2,3]. However, due to the typically large refractive indices of the host materials, photons are extracted inefficiently from such colour centres, while high photon count rates are a key requirement for many applications.
Widely established solutions to collect more photons are solid immersion lenses (SILs), directly carved in the host material [4], or nanopillars, that yield a small waveguiding effect of the embedded colour centres. More advanced fabrication of photonic cavities [5,6] allows for structures that harness the Purcell effect to selectively boost the optical transitions, i.e. enhancing the rate of emitted photons in the zero-phonon-line (ZPL). However, such structures involve tight stability re-strictions under operation, i.e. staying on resonance with the emitter.
Here, we present the fabrication of a planar, cavity-based antenna based on silver-coated, sub-micron-thin silicon carbide membranes to increase the photon extraction from integrated silicon-vacancy colour centres. Our structure lies in the intermediate regime of offering a small Purcell enhancement over a broad spectral range, thus relaxing the necessary fabrication accuracy, while still offering a significant enhancement in the photon count rate over the phonon side band (PSB).
With our structure, we report an average count rate enhancement of a factor of 9 and a maximum enhancement of 15 for single, cavity-integrated colour centres compared to bulk. At cryogenic temperatures, half of the investigated V2 centres show two clearly distinguished PLE lines with a mean linewidth below 80 MHz.
Our results show a promising way of increasing the photon counts from V2 centres that is very robust against emitter displacement from the optimum working point.

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Optical Propagation Loss Extracted via DFT Analysis of Twinning Defects in 3C-SiC

G. Li[1] , O. J. Conquest[2*], B. Liao[1*], C. Stampfl[2,3], X. Yi[1,4]

[1]School of Electrical and Computer Engineering, The University of Sydney, NSW, Australia
[2]School of Physics, The University of Sydney, NSW, Australia
**Authors with equal contributions.*
[3]catherine.stampfl@sydney.edu.au
[4]xiaoke.yi@sydney.edu.au

Silicon carbide (SiC) is an emerging semiconductor material with the potential to fulfill various applications in integrated photonics, where the wide bandgap of SiC allows broadband optical transparency from ultraviolet to infrared. Cubic SiC (3C-SiC) offers desired properties such as zero birefringence and the electro-optic effect [1], while its symmetrical electro-optic index is ellipsoid, with elements of the electro-optic tensor equal in magnitude, which reduces complexities in optoelectronic integration. 3C-SiC has a high thermal conductivity [2] and can be grown on a host substrate (Si) with the option to grow SiC to an exact thickness required for the targeted application. Due to the lattice mismatch between SiC and silicon, stacking faults occur at the growth interface. Therefore it is necesary to analyse the impact of the defects in 3C-SiC for the optical scattering and absorption loss.

We have performed density functional theory calculations using the Vienna Ab initio Simulation Package to evaluate the optical propogation loss induced by twining defects in 3C-SiC. Our investigation specifically focuses on the Silicon-Silicon twin boundary which we simulate based on recreated models from observed fault boundaries from high-resolution transmission electron microscopy. We simulate the defect for a range of super cell sizes going from 1x1x2 to 1x1x6 – 58 atoms up to a maximum of 194 atoms. This approach enables us to determine the stability and optical properties over a range of theoretical defect densities, facilitating the derivation of a worst-case scenario defect-induced absorption-loss estimate by solving for the complex frequency-dependent dielectric function.

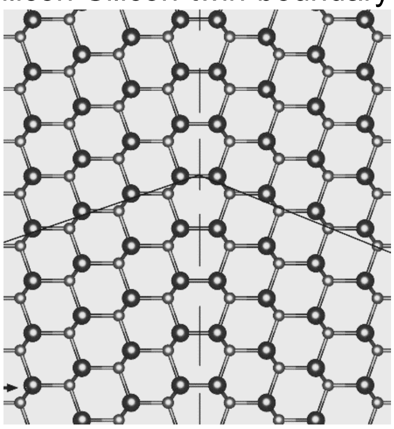

Fig 1: Diagram depicting the Si-Si Bond Twin Boundary in 3C-SiC

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Room temperature coherent control of a single solid-state spin under anti-Stokes excitation

Wu-Xi Lin[1,3,4] , Jun-Feng Wang[2], Qiang Li[1,3,5], Ji-Yang Zhou[1,3], Zhen-Xuan He[1,3], Zhi-He Hao[1,3], Hao Li[6], Li-Xing You[6], Jin-Shi Xu[1,3,4], Chuan-Feng Li[1,3,4], and Guang-Can Guo[1,3,4]

[1]CAS Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei 230026, China
[2] College of Physics, Sichuan University, Chengdu, Sichuan 610065, China
[3] CAS Center for Excellence in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei 230026, China
[4] Hefei National Laboratory, University of Science and Technology of China, Hefei 230088, China
[5] Institute of Advanced Semiconductors and Zhejiang Provincial Key Laboratory of Power Semiconductor Materials and Devices, ZJU-Hangzhou Global Scientific and Technological Innovation Center, Hangzhou, Zhejiang 311200, China
[6] State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China

Single-spin qubits in solid-state materials are important fundamental platforms for quantum information applications. Traditionally, coherent control of solid-state defects is realized under Stokes excitation. Little is known about the coherent control of a single defect spin under anti-Stokes excitation. In this work, we experimentally verify that the mechanism of anti-Stokes excitation of the divacancy in silicon carbide is a phonon-assisted single-photon absorption process and provide the confocal microscopy anti-Stokes photoluminescence scanning image of an isolated single divacancy. Moreover, the optically detected magnetic resonance measurement and coherent control of the single divacancy spin under anti-Stokes excitation are realized at room temperature. We further reveal that the spin readout contrast under anti-Stokes excitation is more robust than that under Stokes excitation at elevated temperatures. Our work establishes a nontraditional protocol for the optical addressing and coherent control of single-spin qubits and expands the boundary of quantum information technology.

Quantum-network nodes with real-time noise mitigation using spectator qubits

S.J.H. Loenen[1,2], Y. Wang[1,3], N. Demetriou[1,2], C.E. Bradley[1,2], M. Markham[4], D.J. Twitchen[4], B.M. Terhal[1,5], T.H. Taminiau[1,2]

[1] QuTech, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands

[2] Kavli Institute of Nanoscience Delft, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands

[3]3. Physikalisches Institut, ZAQuant, University of Stuttgart, Allmandring 13, 70569 Stuttgart, Germany

[4] Element Six, Fermi Avenue, Harwell Oxford, Didcot, Oxfordshire, OX11 0QR, United Kingdom

[5] JARA Institute for Quantum Information, Forschungszentrum Juelich, D-52425 Juelich, Germany

Quantum networks have the potential to unlock advanced quantum communication and modular quantum computing protocols. Solid-state defects are promising platforms because they simultaneously provide an efficient optical interface for entanglement distribution and a nuclear-spin register to store and process quantum information. The capability to generate quantum states faster than they are lost, would enable efficient scaling of quantum networks. Here, as a testbed, we employ additional nuclear spins associated to a nitrogen-vacancy (NV) center as spectator qubits to mitigate correlated noise induced while running entanglement generation protocols. This spectator-qubit approach can likewise be applied to nuclear spins associated with defects in silicon carbide. Upon completion of the protocol, measurements on the spectator qubits reveal information about the phase of the memory qubit. We correct for dephasing in real time. Additional dephasing due to imperfections of the spectator measurements limits the effectiveness of the spectator approach. We bypass this limitation by introducing a gate-based scheme that avoids measurements. Finally, we analyse the impact of spectator qubits for different entanglement generation success probabilities and identify spectator qubits as a promising approach for near-term solid-state testbeds for quantum networks.

Photoluminescence and Lifetime Measurements of Silicon Carbide NV Centers Below 2 K

Alex H. Rubin[1,2], Victoria A. Norman[1,2], Pranta Saha[2], Sridhar Majety[2], Marina Radulaski[2]

[1]*Department of Physics, University of California, Davis, CA 95616, USA*
[2]*Department of Electrical and Computer Engineering, University of California, Davis, CA 95616, USA*

Silicon carbide (SiC) is known to host many color centers, which, due to their exceptional coherence times and single-photon brightness, are leading candidates for the building blocks of optical quantum communication, networking, and sensing [1, 2, 3]. Among these, nitrogen-vacancy (NV) centers in 4H-SiC are an underexplored defect family with great potential for applications in optical quantum technology. In the last four years, research has established NV centers as stable and bright single-photon emitters featuring spin coherence times rivaling those of similar centers in diamond and spin-selective optical transitions that enable it to operate as a spin-photon interface [4, 5, 6]. We leverage a novel optical cryostat design to report the first measurements of NV center photoluminescence spectra and excited state lifetimes at temperatures below 2 K [7]. The cryostat incorporates superconducting nanowire single-photon detectors (SNSPDs) directly in the sample chamber, as well as an integrated room-temperature long-working distance microscope objective, enabling sample cooling plus single-photon collection and detection in one economical package. Our NV centers are fabricated into nanopillars for enhanced collection efficiency and represent the first measurements of SiC NV centers in a photonic device.

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Triangular Nanodevices: A Wafer-Scale Approach to SiC Color Center Photonics

P. Saha[1], S. Majety[1], V. A. Norman[1,2], A. Rubin[1,2] and M. Radulaski[1]

[1]*Electrical and Computer Engineering, University of California, Davis, CA, USA*
[2] *Department of Physics and Astronomy, University of California, Davis, CA, USA*

Quantum networking hardware requires a medium that will store quantum information for a long time as well as provide an optical interface ideal for integration with the existing optical fiber infrastructure. Color centers in silicon carbide (SiC) are a front-running platform for such hardware because the associated spins can store quantum information for up to seconds long time and their states can be optically read out and could be entangled with near-infrared photons [1]. Integration of color centers with photonic devices is necessary to elevate their performance to an optimum level. Vertical nanopillars can enhance the outcoupling efficiency whereas photonic integrated circuits require in-plane coupling with nanoscale active and passive photonic devices. However, nanofabrication challenges arise from the trade-off between the quality of the lattice and the undercutting techniques. A leading approach to maintaining the color center quality and creating suspended devices uses angle-etching methods which result in triangular cross-section devices. Chip-scale experiments have shown that the optical and spin properties of color centers in silicon carbide remain intact upon integration with triangular waveguides [2]. In this work, we take a different approach to demonstrate wafer-scale angle-etching on an arbitrary SiC substrate via the Reactive Ion Beam Etching (RIBE) process with a rotating tilted wafer [3]. Our finite element modeling results show that the triangular geometry in SiC supports single-mode waveguide propagation [2], high quality factor optical resonances [4], photonic band gap formation [5], mesh photonics [6], and highly efficient integration with superconducting nanowire single photon detectors (SNSPDs) [7]. Hence, color center integrated SiC triangular nanodevices have the potential to realize complex on-chip quantum optical circuitry for large-scale quantum information hardware.

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Investigation of CMOS Single Process Steps on 4H-SiC a-Plane Wafers for Quantum Applications

J. H. Schwarberg[1], R. Karhu[2], B. Kallinger[2], M. Rommel[2], R. Schmidt[1] and J. Schulze[1,2]

[1]Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany
[2] Fraunhofer Institut für Integrierte Systeme und Bauelementetechnologie IISB, Erlangen, Germany

The crystal orientation of 4H-SiC a-plane wafers allows direct optical readout of silicon vacancies across the surface of the wafer. [1] This sparks significant interest in utilizing a-plane (11-20) wafers for quantum applications. To harness the scalability and exploit quantum properties of these silicon vacancies, various semiconductor devices, including pin-diodes, transistors, and other CMOS test devices, are to be implemented on these a-plane wafers. [2]

Given the distinct properties of a-plane wafers compared to conventional c-plane (0001) wafers, well-established CMOS process steps require re-evaluation to ensure a fully functional CMOS process and comparable electrical properties. This contribution addresses process steps on a-plane and c-plane wafers, that show substantial differences, including epitaxial growth [3], ion implantation [4], and thermal oxidation [5].

In epitaxial growth, the layer-by-layer growth on a-plane substrates leads to a smooth surface with a roughness of 0.08 nm. The incorporation of dopants is sevenfold increased, compared to c-plane substrates. For ion implantation on a-plane wafers, the 30° periodicity of (11-20) and (1-100) directions induces extended channeling, creating a 2D ion implantation profile with flanks in the ±30° directions from the intended doping profile. For thermal oxidation a sixfold increased linear rate constant on a-plane wafers led to increased oxide growth rate in the reaction-limited regime.

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Electrical excitation of color centers in n-type diamond Schottky diodes

Florian Sledz[1], Igor A. Khramtsov[2], Assegid M. Flatae[1], Stefano Lagomarsino[3], Shannon S. Nicley[4], Rozita Rouzbahani[4], Paulius Pobedinskas[4], Tianxiao Guo[6], Xin Jiang[6], Paul Kienitz[7], Peter Haring Bolivar[7], Ken Haenen[4] Dmitry Yu. Fedyanin[1,2] and Mario Agio[1,8]

[1]Laboratory of Nano-Optics, University of Siegen, Germany
[2]Laboratory of Nanooptics and Plasmonics, Moscow Institute of Physics and Technology, Russian Federation
[3]Istituto Nazionale di Fisica Nucleare, Sezione di Firenze, Italy
[4]Institure for Material Research (IMO) & IMOMEC, Hasselt University & IMEC vzw, Belgium
[5]Department of Electrical and Computer Engineering, Michigan State University, USA
[6]Lehrstuhl für Oberflächen- und Werkstofftechnologien, University of Siegen, Germany
[7]Group of Graphene-based Nanotechnology, University of Siegen, Germany
[8]National Institute of Optics (INO), National Research Council (CNR), Italy

A robust single-photon source operating upon electrical injection at ambient condition is desirable for quantum technologies, such as quantum key distribution or linear optical quantum computation. Color centers in diamond are promising candidates as they are photostable emitters at room and elevated temperatures[1].
Traditionally, p-i-n or p-n diodes are used for the electrical excitation of color centers[2]. However, their fabrication requires complex growth of diamond heterostructures, which are sensitive to the formation of crystalline defects and deteriorates the quality of the single-photon source.
In contrast to these conventional approaches, we demonstrate the emission of color centers under electrical pumping in a novel Schottky diode configuration based on hydrogen passivated n-type diamond. Selective optical excitation allows the addressing of single color centers in phosphorus-doped diamond[3], while electrical pumping addresses additional active defects at the same time. These are mainly created by the recombination of nitrogen impurities incorporated during the growth and vacancies created by ion implantation.
The electroluminescence processes have been studied in dependence of the applied bias voltages, sample temperature, and ion fluence. Our findings facilitate the realization of the predicted bright electroluminescence of color centers[4].

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Characterization of a nuclear spin register in silicon carbide and development of optimal control algorithms

Maximilian Steinhilber [1], Samuel Ruf[1], Pierre Kuna[1], Erik Hesselmeier-Hüttmann [1], Vadim Vorobyov [1], Jörg Wrachtrup [1,2]

[1]3rd Institute of Physics, University of Stuttgart, Stuttgart, Germany
[2]Max Planck Institute for solid state physics, Stuttgart, Germany
E-mail: maximilian.steinhilber@pi3.uni-stuttgart.de, samuel-oliver.ruf@pi3.uni-stuttgart.de

The control of multiple qubits is the essence of quantum information technologies. Here we begin to build up a qubit register consisting of strongly and weakly coupled nuclear spins coupled to the electron spin of a V2 center in 4H-SiC. We investigate the nuclear spin environment of the V2 center using electron-nuclear double resonance (ENDOR) spectroscopy[1]. Control over the qubit register and the gate fidelities could be improved by quantum optimal control algorithms.

To explain and understand experimental results, a simulation of the quantum system was used which includes the Hamiltonian of the Zero-Field-Splitting, the Zeeman-Shift, the applied microwave and the Hyperfine-Coupling between the electron as well as the silicon and carbon nuclei. To decrease simulation time the Rotating-Wave-Approximation can be used[2]. Optimal control algorithms like GRAPE and dCRAB are being used from the QuOCS[3] python library in a QuTip[4] based python framework to optimize a microwave pulse for a CNOT gate.

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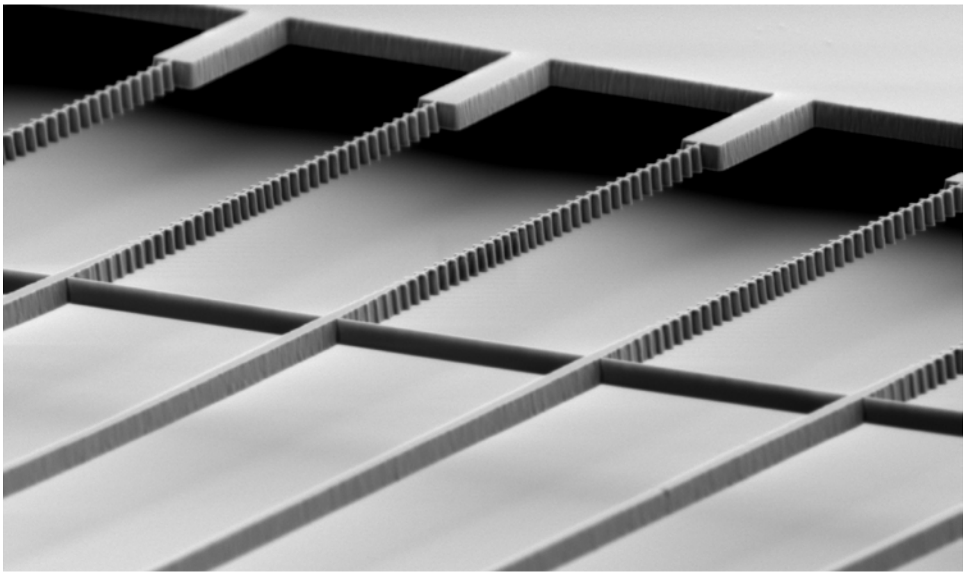
Simulation and Experimental Characterization of Alligator Cavities in 4H-SiCOI for Future Quantum Networks

G.M.Timmer[1] , L.J. Feije[1], G.L. van de Stolpe[1], S.J.H. Loenen[1], A. Das[1], J. Riegelmeyer[1], M.C. van der Maas[1], D. Bedialauneta[1], T. Martens[1], T.W. de Jong[1], C. Errando-Herranz[1] and T.H. Taminiau[1]

[1]QuTech and Kavli Institute of Nanoscience, Delft University of Technology
E-mail: G.M.Timmer@tudelft.nl

The silicon vacancy in 4H-SiC is a promising candidate as a platform for future quantum networks, mainly due to their favourable spin and optical properties [1,2], and compatibility with integration in nanophotonic structures [3,4,5]. However, an open challenge is to enhance the emission of zero phonon line (ZPL) photons to increase the rate of entanglement generation between two separated V2 defects. A viable method to enhance the optical properties of the V2 defect are 1d-nanobeam photonic crystal cavity (PCC). We optimize the 'alligator' PCC design, specifically designed for TM modes because of the vertical electrical dipole orientation of the V2 defect in c-plane 4H-SiC. In order to efficiently couple to the cavity, we simulate a cavity-waveguide interface and collection efficiency through a tapered optical fiber. Together with the simulations, we show the fabrication process and experimental characterization of our PCCs in 4H-silicon-carbide-on-insulator [4], with quality factors up to ~10.000. High quality factor photonic crystal cavities in 4H-SiC will open new opportunities for quantum networks and distributed quantum computation.



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Optimising decoherence-protected radio-frequency quantum gates for sensing and control

H.B. van Ommen[1,2], G.L. van de Stolpe[1,2], N. Demetriou[1,2],

R. Hanson[1,2] and T.H. Taminiau[1,2]

[1]QuTech, Delft University of Technology, Delft, The Netherlands
[2] Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands

The ability to sense and control nuclear spins near solid-state defects, in diamond and silicon carbide, has enabled a wide range of spin-based quantum technologies. In particular, Dynamically Decoupled Radio Frequency (DDRF) control unlocks access to an extended number of nuclear spins, while retaining long electron spin coherence times [1]. In this work, we develop a generalised DDRF framework, that offers greater flexibility in gate design and allows for targeted optimisation of the parameters. These results might inspire new opportunities for nuclear-spin control in materials like diamond and silicon carbide.

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

R. Wörnle[1], J. Körber[1], T. Steidl[1], G. Astakhov[2], F. Kaiser[3] and J. Wrachtrup[1]

[1]3rd Institute of Physics, IQST and Research Centre SCoPE, University of Stuttgart, ZAQ, Stuttgart, Germany

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

[3] MRT Department, Luxembourg Institute of Science and Technology & Department of Physics and Materials Science, University of Luxembourg, Belvaux, Luxembourg

4H-silicon carbide (SiC) has emerged as a promising platform to host point defects with possible applications in quantum technologies, such as distributed quantum computing or sensing. However, the typically detected spin signal contrast of color centers is less than 4 % [1] while the count rates are quite low [2].

Recently, divacancies located near stacking faults in 4H-SiC (PL5-7 centers) have drawn considerable attention. They impress with a high readout contrast of about 30 % and a high photon count rate at room temperature, making them competitive with the nitrogen vacancy centers in diamond [3]. Further, their properties make them suitable for applications in magnetic field sensing at room temperature. However, as the defects are relatively new, their theoretical properties are unexplored and their creation is not yet deterministically possible.

Here, we present the generation of PL5-7 centers through ion irradiation and subsequent annealing. Measurements to characterize those color centers and the investigation of their spin properties via optically detected magnetic resonance (ODMR) and pulsed measurements at room temperature are carried out using a home-built confocal microscope setup. Additionally, the coupling to a nearby nuclear spin is shown and investigated.

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Nuclear-electron Entanglement and Spin Integration in a Semiconductor Photonics Platform

Yu Zhou[1], Xin Ou[2] and Qinghai Song[1]

[1] Harbin Institute of Technology, Shenzhen, 518055, China
Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China

Quantum photonic integrated circuits are reshaping quantum networks and sensing by providing compact, efficient platforms for practical quantum applications. Despite the continuous breakthroughs, significant challenges remain in establishing entangled registers and integrating single spins into photonic devices on a CMOS-compatible platform. Herein, we report single nuclear-electron spin entanglement and spin integration on a silicon-carbide-on-insulator (SiCOI) platform [1]. We present the successful generation of single divacancy electron spins and near-unity spin initialization of single ^{13}C nuclear spins in the SiC membrane. Corresponding coherent manipulation of single nuclear spins and a maximally entangled state with a fidelity of 0.89 are also achieved under ambient conditions. With the assistance of the nanoscale positioning technique, single divacancy spins have been further deterministically integrated into SiC photonic devices for the first time without compromising their optical and spin properties. Our findings highlight the potential of the SiCOI platform as a compelling candidate for future scalable quantum photonic applications.

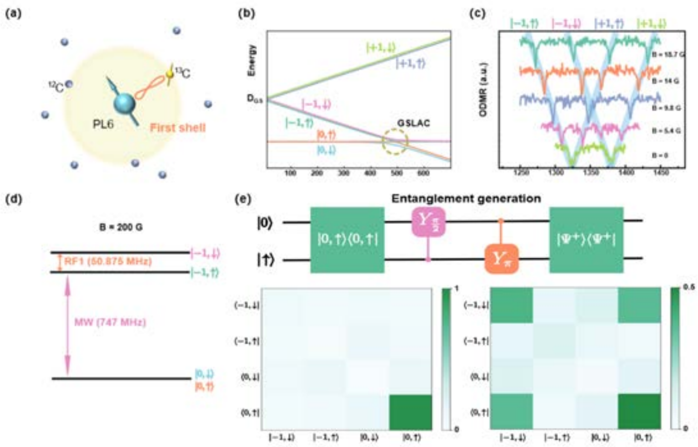

Figure 1 Nuclear-electron entanglement on SiCOI.

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