## QI 2: Semiconductor Qubits (joint session QI/HL)

Time: Monday 9:30–12:45 Location: HFT-FT 131

**Invited Talk** QI 2.1 Mon 9:30 HFT-FT 131

**Spin circuit-QED in the time-domain** — •Jurgen Dijkema[1], Xiao Xue[1], Patrick Harvey-Collard[1], Maximilian Rimbach-Russ[1], Sander L. de Snoo[1], Guoji Zheng[1], Amir Sammak[2], Giordano Scappucci[1], and Lieven M.K. Vandersypen[1] — [1]QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands — [2]QuTech and Netherlands Organization for Applied Scientific Research, Delft University of Technology, Delft, The Netherlands

Semiconductor spin qubits hold promise for quantum computation due to their long coherence times and potential for scaling. So far, interactions between spin qubits are limited to spins a few hundreds of nanometers apart. A distributed architecture with local registers and long-range couplers will be needed to scale up to millions of qubits. Circuit quantum electrodynamics can provide a pathway to realize interactions between distant spins. Here, we report long-range spin-spin interactions using an on-chip superconducting resonator in two regimes. First with two spins detuned from the resonator frequency, allowing the demonstration of two-qubit iSWAP logic via virtual photons. Next, we tune the two spin frequencies to match the resonator frequency and demonstrate spin state-transfer using real resonator photons.

QI 2.2 Mon 10:00 HFT-FT 131

**Optimal electron trajectories improving the spin-shuttling fidelity beyond the adiabatic limit** — •Alessandro David[1], Lars R. Schreiber[2], Hendrik Bluhm[2], Tommaso Calarco[1], and Felix Motzoi[1] — [1]Institute of Quantum Control (PGI-8), Forschungszentrum Jülich GmbH, Jülich, Germany — [2]JARA-FIT Institute for Quantum Information, Forschungszentrum Jülich GmbH and RWTH Aachen University, Aachen, Germany

Spin-qubit quantum computers are currently limited by a connectivity problem. A promising solution is the use of conveyor-mode shuttling architectures [1] where the qubit encoded in the spin of an electron is reliably transported by a moving quantum dot [2]. During this process the spin experiences decoherence from uncontrollable features of the device heterostructure such as interface roughness, valley degree of freedom and spin-orbit coupling [3]. In this work we compute the energy splitting of the valley with the help of an alloy-disorder model [4] and we focus on the dephasing interaction between spin and valley. Using quantum optimal control techniques we find electron trajectories that improve the spin-shuttling fidelity by reducing the valley excitation even at higher speeds than the adiabatic limit. The experimental adequacy of our results is inspected through statistical sampling of different devices and bandwidth limitation of the electron trajectories.

[1] Künne and Willmes et al., arXiv:2306.16348 (2023) [2] Struck et al., arXiv:2307.04897 (2023) [3] Langrock and Krzywda et al., PRX Quantum 4, 020305 (2023) [4] Wuetz, et al., Nat. Comm. 13, 7730 (2022)

QI 2.3 Mon 10:15 HFT-FT 131

**Counteracting decoherence induced by spin-valley coupling in single-qubit manipulation zones via quantum optimal control** — •Akshay Menon Pazhedath[1], Alessandro David[1], Lars R. Schreiber[2], Tommaso Calarco[1], Matthias M. Müller[1], Hendrik Bluhm[2], and Felix Motzoi[1] — [1]Peter Grünberg Institute-Quantum Control (PGI-8), Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany — [2]JARA-FIT Institute for Quantum Information, Forschungszentrum Jülich GmbH and RWTH Aachen University, Aachen, Germany

Quantum bus architectures based on electron spin shuttling in a Si/SiGe heterostructure are promising candidates for scalable quantum computing. Electrically controlled single qubit gates are achieved with a carefully placed micro-magnet that provides a synthetic spin-orbit coupling in the designated manipulation zones [Künne et al. arXiv:2306.16348 (2023)]. The presence of spin-valley mediated decoherence hotspots at the vicinity of the micro-magnet can cause spin decoherence, limiting the capability to achieve fault tolerant gates. Using quantum optimal control techniques, we obtain new electron trajectories leading to significant improvements to the gate fidelity. The influence of valley splitting and the distance from decoherence hotspots are also investigated, based on statistical sampling of prototypical device configurations. For increasing values of spin-valley coupling, 99.12% of the samples converged below the required fault tolerant gate fidelity threshold, where all of the under- performing samples are due to a high value of spin-valley coupling.

**Invited Talk** QI 2.4 Mon 10:30 HFT-FT 131

**Gate defined electron and hole quantum dots in bilayer graphene** — •Luca Banszerus — Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark — JARA-FIT and 2nd Institute of Physics A, RWTH Aachen University, Aachen, Germany

Bilayer graphene (BLG) quantum dots (QDs) have long been regarded as an attractive platform for hosting spin qubits since the low nuclear spin densities and weak spin-orbit interaction in BLG promise long spin coherence times. In addition to the spin, BLG exhibits a tunable valley degree of freedom, which is associated with a strong out-of-plane magnetic moment with opposite signs for the K- and K'-valley. This allows controlling the valley splitting in BLG and to use valley space as an additional qubit platform.

In contrast to conventional semiconductors, the band structure of BLG is (almost) perfectly electron/hole symmetric and exhibits an electrically tuneable band gap, which we use to form ambipolar electron/hole double QDs. We observe the creation of single electron-hole pairs with opposite quantum numbers and use the electron-hole symmetry to achieve a protected spin-valley blockade in electron-hole double quantum dots. The latter allows for spin-to-charge conversion and valley-to-charge conversion, which is essential for the operation of spin and valley qubits.

QI 2.5 Mon 11:00 HFT-FT 131

**Spin and valley relaxation in a single-electron bilayer graphene quantum dot** — •Lin Wang and Guido Burkard — Department of Physics, University of Konstanz, D-78457, Germany

Bernal-stacked bilayer graphene (BLG) has a tunable gap controlled by an out-of-plane electric field. This makes BLG a possible candidate to form quantum dots (QDs). Spin-based qubits in BLG QDs have received great attention due to the low spin-orbit interaction and low hyperfine coupling. Long spin relaxation times of a single-electron state in BLG QDs was recently reported [1,2]. In addition to spin, valley pseudospin is another degree of freedom in BLG. The two valleys experience opposite Berry curvatures and associated magnetic moments via an out-of-plane electric field. This provides a promising way towards controlling valleys and further establish valley-based electronics and qubits. The valley relaxation time between triplets and singlets was reported to be remarkably long in BLG double QDs [3]. To assess the potential of spin/valley qubits, the spin/valley relaxation time is a crucial parameter since it directly limits the lifetime of encoded information. Here, we theoretically investigate the spin/valley relaxation in a single-electron BLG QD due to spin-orbit/intervalley coupling assisted by (i) 1/f charge noise and (ii) electron-phonon couplings arising from the deformation potential and the bond-length change. Detailed comparisons with the existing experiments on both spin and valley relaxation times are shown. [1]L. Banszerus et al., Nat. Commun. 13, 3637 (2022). [2]L. M. Gächter et al., PRX Quantum 3, 020343 (2022). [3]R. Garreis et al., arXiv:2304.00980.

**15 min. break**

QI 2.6 Mon 11:30 HFT-FT 131

**Classification and magic magnetic field directions for spin-orbit-coupled double quantum dots** — •Aritra Sen[1], Gyorgy Frank[1], Baksa Kolok[1], Jeroen Danon[2], and Andras Palyi[1] — [1]Budapest University of Technology and Economics, Budapest, Hungary — [2]Norwegian University of Science and Technology, Trondheim, Norway

Fundamental building blocks of spin-based quantum computing have been demonstrated in semiconductor double quantum dots with significant spin-orbit coupling. Here, we show that spin-orbit-coupled double quantum dots can be categorized in six classes, according to a partitioning of the multidimensional space of their $g$ tensors. The class determines physical characteristics of the double dot, i.e., features in transport, spectroscopy, and coherence measurements, as well as qubit control, shuttling, and readout experiments. In particular, we predict that the spin physics is highly simplified due to pseudospin conservation, whenever the external magnetic field is pointing to special directions ('magic directions'), where the number of special directions is determined by the class. We also analyze the existence and relevance of magic loops in the space of magnetic-field directions, corresponding to equal local Zeeman splittings. These results present an important step toward precise interpretation and efficient design of spin-based quantum computing experiments in materials with strong spin-orbit coupling.

QI 2.7 Mon 11:45 HFT-FT 131

**Dynamical sweetspots in driven germanium double quantum dot spin qubits** — •Yaser Hajati and Guido Burkard — Konstanz University, Konstanz, Germany

In recent years, significant strides have been made in advancing hole-spin qubits based on semiconductor quantum dots, particularly in germanium (Ge). Hole spins in Ge quantum dots can leverage the strong spin-orbit coupling compared to silicon, potentially enabling fast and reliable qubit operations. Our study focuses on exploring the use of a periodic drive field to engineer the properties of Ge quantum-dot based qubits amidst charge noise. Specifically, we investigated the Rabi frequency of a hole qubit experiencing detuning driving in a planar Ge double quantum dot, focusing on the single-hole flopping mode with spin-orbit interaction. Our findings indicate that the Rabi frequency linked to a hole within a planar double quantum dot, driven on resonance, exhibits an inverse correlation with detuning energy while demonstrating a positive correlation with driving frequency, Zeeman field strength, and spin-orbit coupling. Furthermore, through strategic modulation of the drive frequencies slightly off resonance, we effectively mitigated the impact of charge noise. This modulation significantly boosted the fidelity of quantum gates when manipulating the qubit within specific ranges of drive frequencies and detuning. Importantly, our study shows that fidelity improvements at dynamic sweet spots exceed those achievable by solely adjusting drive frequency and detuning. Discovering these spots holds potential for enhancing quantum gate reliability in Ge quantum dot-based computing.

QI 2.8 Mon 12:00 HFT-FT 131

**Floquet Quantum Processors** — •Giovanni Francesco Diotallevi and Monica Benito — Universität Augsburg, Augsburg, Germany

Quantum dot confined hole spin qubits posses a variety of properties that render them highly attractive candidates for the development of quantum computing platforms [1]. However, using these to construct functioning large quantum processors still faces major challenges. Among these, being able to simultaneously control distant qubits with minimal cross-talk between untargetted qubits remains a goal to be achieved in the field. In this direction recent studies proposed to mediate the coupling between two distant qubits by means of superconducting quantum resonators [2].

In this research we intend to explore techniques involving external periodic drives to better control the coupling of these hole spin qubits to the interaction-mediating resonators. In particular, we envision an ensemble of periodic fields used to control the individual coupling of a series of hole spin qubits to a single resonator. Using Floquet-based theory it is indeed possible to tune the spin-orbit interaction of these qubit systems [3], thus allowing us to selectively choose which qubits to couple in order to perform desired quantum gates.

References: [1] Y. Fang et Al., *Recent advances in hole-spin qubits,* Materials for Quantum Technology, vol. 3, no. 1, p. 012003, 2023. [2] J. Dijkema et Al., *Two-qubit logic between distant spins in silicon,* 2023. [3] O. V. Kibis et Al., *Floquet engineering of the luttinger hamiltonian,* Phys. Rev. B, vol. 102, p. 035301, Jul 2020.

QI 2.9 Mon 12:15 HFT-FT 131

**Quantum Gates with Oscillating Exchange Interaction** — •Daniel Nguyen, Irina Heinz, and Guido Burkard — Department of Physics, University of Konstanz, D-78457 Konstanz, Germany

Two-qubit gates between spin qubits are often performed using a rectangular or an adiabatic exchange interaction pulse resulting in a CZ gate. An oscillating exchange pulse not only performs a CZ gate, but also enables the iSWAP gate, which offers more flexibility to perform quantum algorithms. We provide a detailed description for two-qubit gates using resonant and off-resonant exchange pulses, give conditions for performing the respective gates, and compare their performance to the state-of-the-art static counterpart. We find that for relatively low charge noise the gates still perform reliably and compare to the conventional CZ gate.

D. Q. L. Nguyen, I. Heinz, and G. Burkard, Quantum gates with oscillating exchange interaction (2023), arXiv:2303.18015 [quant-ph].

QI 2.10 Mon 12:30 HFT-FT 131

**Gate operations on Exchange-Only spin qubits with oscillating drive** — •Tobias Heinz, Stephen R. McMillan, and Guido Burkard — Department of Physics, University of Konstanz, D-78457 Konstanz, Germany

A major obstacle on the path towards large-scale quantum computing lies in achieving high fidelities for gate operations. Spin qubits using exchange interaction alone have emerged as promising candidates [1] due to their resistance to certain types of decoherence [2]. Motivated by the proposed gate of Doherty and Wardrop [3], this work focuses on the application of an oscillating drive field to facilitate an entangling two qubit operation between two local Resonant-Exchange qubits. By driving the exchange interaction belonging to one qubit, we propose a CNOT gate for universal quantum computing, with gate times in the range of a hundred nanoseconds. We analyze the impact of the drive amplitude on gate fidelity and gate time, providing insights into the optimal parameter regimes. Through numerical simulations, we determine the impacts of leakage and off-resonant processes on the fidelity. For context, we compare our results to a static gate obtained through a dc pulse of the interqubit exchange coupling. Our proposal contributes to the understanding of the implementation of spin qubits and paves the way for the development of robust and scalable quantum computers. [1] G. Burkard et al. Rev. Mod. Phys. 95, 025003 (2023). [2] J. M. Taylor et al. Phys. Rev. Lett. 111, 050502 (2013). [3] A. C. Doherty et al. Phys. Rev. Lett. 111, 050503 (2013).