CEMS Topical Meeting Online

Recent advances in semiconductor qubits

Japan standard time (UTC+9)

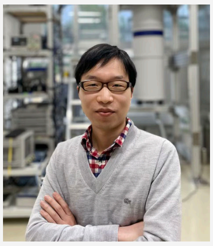
Tuesday, 9 March 2021, 13:00 – 18:00

13:00- Opening

13:10-13:40

Kenta Takeda (RIKEN)

“Manipulation of three-spin states in a silicon triple quantum dot”



13:40-14:10

William Coish (McGill)

"First-principles hyperfine and spin-electric coupling for electron-spin and hole-spin qubits”

14:10-14:40

Stephano Chesi (CSRC)

"Superradiant-like dynamics of nuclear spins by non-adiabatic electron shuttling”

14:40-15:10

Takafumi Fujita (Osaka)

"Accelerated electric-dipole spin resonance in a quantum dot array”

15:10-15:30 Break

15:30-16:00

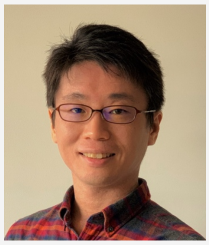
Peter Stano (RIKEN)

"Optimal frequency estimation and its application to quantum dots”

16:00-16:30

Jun Yoneda (Tokyo Tech)

"Single electron spin tunneling in silicon quantum dots”



16:30-17:00

Pasquale Scarlino (EPFL)

"Hybrid cQED with semiconductor QDs and high impedance superconducting resonators”

17:00-17:30

Matthiew Delbecq (LPENS)

“Hyperfine coupling of ultra-clean carbon nanotube spin qubits in cQED architecture”

17:30-18:00

Ferdinand Kuemmeth (NBI)

"Navigating high-dimensional gate-voltage spaces of multi-dot spin qubits”

https://cems.riken.jp/topicalmeeting/009_spinqubits/

RIKEN CEMS

Manipulation of three-spin states in a silicon triple quantum dot

Kenta Takeda[1]

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Semiconductor quantum dots are one of the most promising platforms for quantum computing due to their nanofabrication capability for scaling-up. Recent technical advances have enabled high-fidelity one- [1,2] and two-qubit [3] gates for spins in quantum dots. The next crucial step toward scaling up is the demonstration of genuinely multipartite entanglement, an essential resource for quantum error correction. This requires at least three qubits with full capabilities of control and measurement, a lot further than individual qubit manipulation. In this talk, we first show individual initialization, measurement, and universal manipulation of three electron spins in a silicon triple quantum dot. Second, we show generation and characterization of a three-qubit Greenberger–Horne–Zeilinger state, a type of maximally entangled state that is usable to implement a bit-flip or phase-flip quantum error correcting code. We obtain a state fidelity of 88.0 % by quantum state tomography, which witnesses a genuine three-qubit entanglement. We anticipate that our results will enable exploration of multi-spin correlations and demonstration of multi-qubit algorithms in scalable silicon-based quantum computing devices.

[1] J. Yoneda et al., Nat. Nanotechnol. 13, 102–106 (2018).
[2] C. H. Yang et al., Nat. Electron. 2, 151–158 (2019).
[3] W. Huang et al., Nature 569, 532–536 (2019).

First-principles hyperfine and spin-electric coupling for electron-spin and hole-spin qubits

W. A. Coish

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Abstract

Through a combination of first-principles density-functional theory (DFT) and k.p theory, we have calculated hyperfine tensors for electrons and holes in GaAs and crystalline silicon [1], and also in germanium [2]. Our results for electrons are consistent with existing experimental measurements. For GaAs, we theoretically predict that the heavy-hole hyperfine coupling to the As nuclear spins is stronger and almost purely Ising, while the (weaker) coupling to the Ga nuclear spins has significant non-Ising corrections. In the case of hole spins in silicon, we find (surprisingly) that the strength of the hyperfine interaction in the valence band is comparable to that in the conduction band and that the hyperfine tensors are highly anisotropic (Ising) in the heavy-hole subspace. These results suggest that the hyperfine coupling cannot be ruled out as a limiting mechanism for coherence (T_2^*) times recently measured for heavy holes in silicon quantum dots.

In addition, we have used similar techniques [3] to find the electric-dipole (pseudospin-electric) coupling between heavy and light holes in GaAs, giving rise to a distinct E-field controllable Dresselhaus-like spin-orbit coupling for heavy holes in a triangular quantum well, with consequences on spin splitting, spin coherence/relaxation (T2*/T1) times, spin-electric coupling for cavity-QED, electric-dipole spin resonance, and spin non-conserving tunneling in double quantum dot systems.

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[2] P. Philippopoulos, *Hyperfine and spin-orbit interactions in semiconductor nanostructures*, Ph.D. thesis, McGill University (2020), https://escholarship.mcgill.ca/concern/theses/tx31qp42d.

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Superradiant-like dynamics of nuclear spins by non-adiabatic electron shuttling

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Superradiant emission of light occurs when, due to quantum coherence, an ensemble of atoms decays collectively at an enhanced rate. Over the years, several schemes were proposed to realize a superradiant-like dynamics in quantum dots, with the role of atoms played by nuclear spins and the emitted light by the transport current through the dot [1-4]. Motivated by experimental progress on electron shuttling through quantum dot arrays, as well as the typical operation of single-electron pumps, we propose here a scheme to achieve superradiant-like dynamics through a single-electron quantum dot, whose position is cyclically shuttled between two external reservoirs. Under suitable conditions, tunneling events are associated with electron-nuclear flip-flops and drive the superradiant-like dynamics. Our proposal has the advantage of avoiding optical excitation [3] as well as ferromagnetic contacts [4]. We first discuss in detail the shuttling process within the approximation of a uniform hyperfine coupling, which allows us to rely on the exact eigenstates and reveal certain subtleties in the treatment of the superradiant-like dynamics, missed by previous literature. We then assess the effect of various imperfections and derive the minimum shuttling time which allows to escape the adiabatic spin evolution. A related discussion of slow/fast shuttling under the inhomogeneous field of a nearby micromagnet is also provided.

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Accelerated electric-dipole spin resonance in a quantum dot array

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Single spin manipulation using the intrinsic spin-orbit interaction is a technique to rotate spins without artificial magnetic structures [1], which has been crucial in semiconductor transport experiments and in the earlier period of quantum information technology. In this talk, we present results on the accelerated electric-dipole spin resonance utilizing a spin-flip tunneling term that appears in a coupled multiple quantum dot. First, we introduce the single spin tunneling associated with a spin flip in a double quantum dot [2]. Next, we discuss measurements to utilize this effect in a spin coherent manner. By setting the microwave frequency on resonance to the magnetic spin splitting after sufficiently increasing the inter-dot tunnel coupling, the acquired Rabi oscillations show enhanced speed, which is dependent on microwave amplitude and energy detuning between the dots. Such concept of spin rotation in a double dot is extended to a triple quantum dot and we observed a larger speed-up owing to the extended charge oscillation distance across the three dots.

Since precise spin rotation using this technique relies on a perfect adiabatic charge shuttling [3], we observed impacts of excited charge states and its decoherence effect that affected the spin coherence in experiment. We will further discuss the results in detail and possible paths for utilizing the large tuning variations in a multiple dot for applying to spin rotations in integrated architectures.

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Optimal frequency estimation and its application to quantum dots

Peter Stano

RIKEN Center for Emergent Matter Science, Japan

I present results on optimal phase estimation of a qubit [1]. I use them to show how to extend the coherence of the current spin-qubit devices against slow noise (nuclear spin-noise in GaAs or quasi-static charge-noise in Si).

I start with the broad appeal of phase estimation, as the essence of all known quantum algorithms. I explain the relation and point out differences of the estimation of a parameter of a solid-state qubit and the existing phase estimation protocols which had been developed in optics, as a homodyne-with-feedback detection. I formulate optimal estimation as a minimization problem and discuss the figures of merit. I discuss the pros and cons of minimizing the entropy versus the variance of the estimated quantity distribution and the relation to the maximum-likelihood estimation. I then describe the classes of minimization strategies: local versus global and online versus offline. I finally present our algorithm which generates the optimal solution within the local(greedy)+offline class and I prove its uniqueness. I illustrate the construction and behavior of the optimal strategy with numerical examples applied to singlet-triplet qubit in GaAs. I point out how some estimation patterns, usually adopted ad-hoc, naturally emerge in our construction. I show that our method can be used to refine any given class of estimation strategies, for example, the (Kitaev) Quantum Phase Estimation Algorithm (QPEA). I conclude by illustrating the power of noise estimation in boosting the coherence of spin qubits as seen in recent experiments [2-5].

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[3] T. Nakajima, et al., Quantum non-demolition measurement of an electron spin qubit, Nat. Nanotech. **14** 555, (2019).
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Single electron spin tunneling in silicon quantum dots

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The ability to faithfully transfer a quantum bit of information (or qubit) in the quantum computing architecture offers viable routes for scalability and fault tolerance with increased connectivity. Conversely, qubit transfer may introduce dephasing, loss, and state leakage which stationary qubits are meticulously engineered against. Silicon-based quantum dot qubits have demonstrated immense promise in terms of coherence, high control fidelity, and large-scale fabrication. However, it has remained to be seen whether one can transport the qubit with fidelities at the fault-tolerant level in this structure. In this presentation, we show that single electron tunneling can implement highly coherent spin qubit transport in an isotopically-enriched silicon quantum-dot array. Using Ramsey interferometry and quantum state tomography techniques, we assess the impact of tunneling on the spin qubit coherence in detail and report a polarization transfer fidelity of 99.97% and an average coherent transfer fidelity of 99.4%. This transfer method can be extended to longer quantum-dot chains by sequencing it from one site to the next in a bucket-brigade manner, offering micron-scale on-chip quantum links for silicon spin-qubit architectures.

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Hybrid Circuit Quantum Electrodynamics with Semiconductor QDs and Superconducting Resonators

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Semiconductor qubits rely on the control of charge and spin degrees of freedom of electrons or holes confined in quantum dots (QDs). Typically, semiconductor qubit-qubit coupling is short range, effectively limiting qubit distance to the spatial extent of the wavefunction of the confined particle (a few hundred nanometers). This is a significant constraint towards scaling of the QD-based architectures to reach dense 1D or 2D arrays of QDs.

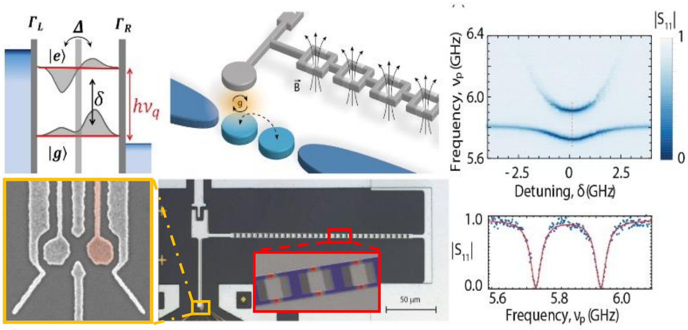

Figure1: a DQD charge system strongly coupled to a SQUID array resonator [1].

Inspired by techniques originally developed for circuit QED, we recently demonstrated the strong coupling limit of individual electron charges [1,2] confined in GaAs quantum dots, by using the enhancement of the electric component of the vacuum fluctuations of a resonator with impedance beyond the typical 50 Ohm of standard coplanar waveguide technology (Fig.1). By making use of this hybrid technology, we recently realized a proof of concept experiment, where the coupling between a transmon and a double QD (DQD) is mediated by virtual microwave photon excitations in a high impedance SQUID array resonator, which acts as a quantum bus enabling long-range coupling between dissimilar qubits [3]. Similarly, we achieved coherent coupling between two DQD charge qubits separated by approximately ~50 um [4]. In the dispersive regime, we spectroscopically observed qubit-qubit coupling as an avoided-crossing in the energy spectrum of the DQD charge qubits. The methods and techniques developed in these works are transferable to QD devices based on other material systems and will be beneficial for spin based hybrid systems [5] (see Fig.2).

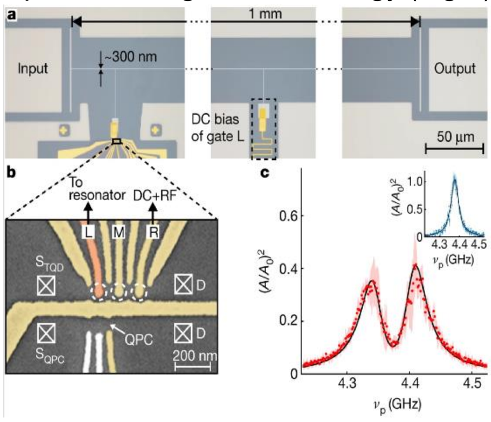

Figure2: a Triple QD resonant exchange spin qubit strongly coupled to a NbTiN resonator [5].

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Hyperfine coupling of ultra-clean carbon nanotube spin qubits in cQED architecture

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[1]Laboratoire de Physique de l'Ecole normale supérieure, ENS, Université PSL, CNRS, Sorbonne Université, Université Paris-Diderot, Sorbonne Paris Cité, Paris, France

Semiconducting spin qubits are promising candidates for manipulating quantum information because of their long coherence times and potential for scalability. For years, the development of semiconducting spin qubits was hindered by a large dephasing due to the hyperfine coupling of the electron spin to surrounding nuclear spins of the host material. Impressive improvements of the dephasing time were recently achieved by switching to materials with less (natural silicon Si) to almost no (isotopically purified ^{28}Si) nuclear spins, compared to GaAs which has a 100% concentration. Interestingly, carbon nanotubes (CNT) have a lower concentration of nuclear spins than natural silicon and can also be isotopically purified. In addition they should theoretically present a hyperfine coupling smaller than in Si by a factor 5 to 20, which would boost the dephasing by this amount compared to Si. However, since the first realization of a CNT spin qubit in 2013, the hyperfine coupling was found to be 10^3 to 10^4 times larger than theoretically predicted. We developed a high vacuum stapling technique that allows for the realization of ultra-clean CNT devices in microwave cavities. Similarly to previous implementations, the spin qubit is realized in a double quantum dot with non-collinear ferromagnetic contacts [1]. The CNT stapling technique results in a much cleaner spectrum as well as a much higher tunability of the device thanks to the clean environment. We observe the largest dephasing time reported in CNT spin qubits (T_2^*~600 ns), reducing the discrepancy with the theoretical value of the hyperfine coupling to a factor ~50 [2]. Possible explanations for the remaining discrepancy comprise Luttinger liquid interactions, effects of the cavity field and a remaining large charge noise, all of which can be investigated and dealt with in future devices.

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Navigating high-dimensional gate-voltage spaces of multidot spin qubits

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The voltage tuning of few-qubit devices is traditionally done by hand by human experts, using low-dimensional charge stability maps as visual aids for navigating in control-voltage space. Large arrays of spin qubits will require automatic tune-up by computers. For gate-voltage tuning, the traditional dense raster scans of charge stability diagrams cannot be scaled to larger arrays with many gate electrodes, due to the prohibitively large number of pixels contained in naive high-dimensional gate-voltage cubes.

To mitigate this challenge we are developing autonomous sparse acquisition methods in which the boundaries of Coulomb-blockade polytopes are reconstructed by suitable algorithms from a discrete set measurements. We test our approach on simulated convex charge stability diagrams as well as actual multi-dot arrays implemented in fully-depleted silicon-on-insulator devices. The charge state boundaries learned by our algorithm for a 2x2 array of quantum dots is in good agreement with two-dimensional diagnostic raster scans measured by traditional methods on the same device.