International Workshop on Solid-State Qubits

22 April 2019 (Tutorial)
23-24 April 2019 (Main Workshop)

Daejeon Convention Center, Korea

BRL SOLID STATE QUBITS LAB

NRF

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KOREA UNIVERSITY 고려대학교 기초과학연구원 THE INSTITUTE OF BASIC SCIENCE

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http://qubits.korea.ac.kr/index.php/Qubits2019

The field of quantum computation and information has grown rapidly through intensive theoretical and experimental studies. Recent developments lead by industrial institutes including Google, IBM and Microsoft are attracting even more public interests, especially, in quantum computation schemes based on solid-state circuits and devices. The workshop aims to review the recent developments of solid-state qubits and promote further theoretical and technical advances in the field.

The topics include

- Qubits based on superconducting circuits
- Qubits based on semiconductor quantum dots
- Qubits based on quantum defects in solids
- And other novel qubits based on nano-scale devices

Program

Monday, April 22

13:00 – 14:00	Registration
14:00 – 18:00	**Paul Nation** (IBM) Hands-On Tutorial on IBM Qiskit with **Ha-Eum Kim** (KU) and **Hoang-Anh Le** (KU) as assistants
18:30 – 20:00	Reception

Tuesday, April 23

09:00 – 09:40	**Aharonovich, Igor** (*University of Technology Sydney*) Nanophotonics With Hexagonal Boron Nitride
09:40 – 10:00	**Kim, Je-Hyung** (*UNIST*) Integration of solid-state quantum emitters with dissimilar platforms
10:00 – 10:40	**Dehollain, Juan Pablo (***University of Technology Sydney***)** Analogue simulations and digital processing with spins in quantum dots
10:40 – 11:00	Break
11:00 – 11:20	**Kim, Dohun** (*Seoul National University*) Electron and nuclear spin control in semiconductors: progress towards robust environment Hamiltonian engineering
11:20 – 11:40	**Kim, Jaewan** (*KIAS*) Coherent State Qudits for Quantum Information Processing
11:40 – 12:00	**Suh, Junho** (*KRISS*) Aharonov-Bohm oscillation in nanomechanical measurements of topological insulator nanowire
12:00 – 14:00	Lunch
14:00 – 14:40	**Chong, Yonuk** (*KRISS*) Superconducting qubit entanglement with all microwave control
14:40 – 15:00	**Moon, Kyungsun** (*Yonsei University*) Circuit QED system using Triple-Leg Stripline Resonator
15:00 – 15:40	**Kono, Shingo** (*University of Tokyo*) Quantum measurement of itinerant microwave photons using superconducting circuits
15:40 – 16:00	Break
16:00 – 16:40	**Paik, Hanhee** (*IBM*) IBM Q Experience: Cloud-based superconducting quantum computer for the NISQ-era
16:40 – 17:00	**Choi, Manh-Soo** (*Korea University*) Superconducting Circuit QED System Interacting with Quantum Spins
17:00 – 17:40	**Peronnin, Théau** (*ENS de Lyon*) Realizing a Catch-Disperse-Release read-out of a qubit
17:40 – 18:00	**Choi, Jae-Hyuk** (*KRISS*) Control and measurement of magnetic fluxoid quanta for small force standard

Wednesday, April 24

09:00 – 09:20	**Kim, Jae Hoon** (*Yonsei University*) Conductance Quantization and Magnetic Control of Topological Insulators
09:20 – 09:40	**Doh, Yong-Joo** (*GIST*) Fractional Josephson Effect in Topological Insulator Nanoribbons
09:40 – 10:00	**Lee, Minchul** (*Kyunghee University*) Quantum resistor-capacitor circuit with Majorana fermion modes in a chiral topological superconductor
10:00 – 10:20	**Jung, Minkyung** (*DGIST*) Shot noise measurements with an impedance matching circuit at GHz frequencies
10:20 – 10:40	**Seo, Hosung** (*Ajou Uciversity*) First-principles theory of spin defects in 2D crystals for quantum applications
10:40 – 11:00	Break
11:00 – 11:40	**Taminiau, Tim** (*QuTech, Delft University*) Diamond quantum networks for distributed quantum computation
11:40 – 12:00	**Lee, Sang-Yun** (*KIST*) Scalable defect-based solid-state quantum devices
12:00 – 14:00	Lunch
14:00 – 14:40	**Doherty, Marcus** (*Australian National University*) New understanding and engineering of defect qubits in diamond
14:40 – 15:00	**Choi, Soonwon** (*UC Berkeley*) Discrete time-crystalline order in black diamond: realization and probe of quantum many-body dynamics
15:00 – 15:40	**Heinrich, Andreas J.** (IBS QNS, Ewha Womans University) Quantum Nanoscience: Atoms on Surfaces
15:40 – 16:00	Break
16:00 – 16:40	**Zhou, Brian** (*Boston College*) Using Optical Pulses for Quantum Control and Sensing
16:40 – 17:00	**Kim, Chulki** (*KIST*) Nanoscale magnetic resonance detection towards nano MRI
17:00 – 17:40	**Yang, Sen** (*Chinese University of Hong Kong*) Towards measurement induced quantum state engineering
17:40 – 18:00	**Lee, Donghun** (*Korea University*) Quantum control of a single-spin quantum emitter in diamond via coupling with a mechanical oscillator
18:30 – 20:00	Banquet

Hands-On Tutorial on IBM Qiskit

Nation, Paul

IBM Thomas J. Watson Research Center, USA

As widely known by now, IBM Qiskit is "an open-source quantum computing framework for leveraging today's quantum processors in research, education, and business." In shor, you can have a hand-on experience, remotely, with real quantum computers, or do some research experiments on the machines.

Paul Nation, a member of the Qiskit core development team, will guide you through all the steps from installing the Qiskit package to mastering the technical programming in Qiskit. To help those who are less experienced in (classical) computing environment, two assistants, Ha-Eum Kim and Hoang-Anh Le, are ready at your service.

Nanophotonics With Hexagonal Boron Nitride

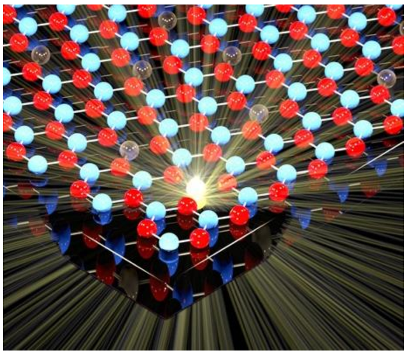
Aharonovich, Igor

University of Technology Sydney, Australia

Engineering solid state quantum systems is amongst grand challenges in realizing integrated quantum photonic circuitry. While several 3D systems (such as diamond, silicon carbide, zinc oxide) have been thoroughly studied, solid state emitters in two dimensional (2D) materials are still in their infancy.

In this talk I will introduce hexagonal boron nitride (hBN) as a promising layered material that hosts ultra bright quantum emitters. I will present several avenues to engineer these emitters in large exfoliated sheets, multilayers and 2D monolayers using top down and bottom up approaches. I will also discuss potential atomistic structures of the defects supported by density functional theory.

I will then highlight promising avenues to integrate the emitters with plasmonic and photonic cavities to achieve improved collection efficiency and Purcell enhancement. These are fundamental experiments to realize integrated quantum photonics with 2D materials. I will summarize by outlning challenges and promising directions in the field of quantum emitters and nanophotonics with 2D materials and other wide band gap materials.



Integration of solid-state quantum emitters with dissimilar platforms

Kim, Je-Hyung

Ulsan National Institute of Science and Technology, Korea

Scalable photonic quantum information processors require methods to integrate single photon sources with compact photonic devices that can manipulate the quantum light on-a-chip. Simple monolithic integration of quantum emitters and photonic structures such as waveguides and beam splitters has shown possible potentials of on-chip quantum photonic devices. However, as the complexity of the quantum system grows fast, integrating multiple quantum emitters with more functional and integrated photonic components are becoming more important. Hybrid integration allows us to perform post selection of the quantum emitters and to employ advanced photonic circuits such as Si photonic chips for these emitters. Therefore, such integration could enable complex quantum information processors in a compact solid-state material. Here, we will present the recent progress on the hybrid integration of solid-state quantum emitters with various dissimilar platforms. This integration opens up the possibility to leverage the highly-advanced photonic capabilities developed in photonic chips to control and route non-classical light from on-demand single photon sources. Also, we will discuss the quantum emitters at telecom wavelengths and their integration with fiber platforms, which are useful for fiber-based quantum communication. Our technique could solve one of the main challenges for a scalable quantum system.

Analogue simulations and digital processing with spins in quantum dots

Dehollain, Juan Pablo

University of Technology Sydney, Australia

Electrostatically defined quantum dots in semiconductors are one of the leading platforms for the development of quantum technologies, owing to their fast and efficient control and measurement, as well as their compatibility of fabrication with commercial semiconductor industry processes. At the Vandersypen Lab, we focus on using the spin and charge degrees of freedom of electrons confined in quantum dots, to explore physics through analogue quantum simulations and digital quantum information processing.

In this talk I will delve into some of our latest and most exciting experiments. I will begin with a description of the types of quantum dot arrays that we operate, highlighting the techniques that we have developed recently to overcome the problem of disorder and efficient control, which is crucial to the operation and scale-up of these systems as quantum simulators and processors. I will then describe our latest quantum simulator device—a 2x2 plaquette of quantum dots in a GaAs heterostructure—which we use to demonstrate Nagaoka ferromagnetism, one of the well-known theories of ferromagnetism based on the Hubbard model, which had yet to be demonstrated experimentally. Finally, I will present the capabilities of our silicon-based 2-qubit quantum information processor, with an outlook on how this technology can be further developed towards a large-scale universal quantum computer.

Electron and nuclear spin control in semiconductors: progress towards robust environment Hamiltonian engineering

Kim, Dohun

Department of Physics and Astronomy, and Institute of Applied Physics,
Seoul National University, Korea

The electron and nuclear spin degrees of freedom in solids form natural bases for constructing quantum two level systems, or qubits. The electron spin qubit offers a route for fast manipulation of spins using magnetic resonance, but generally suffers from fast dephasing due to strong coupling to the environment, especially nuclear spin bath, where decoherence dynamics is often non-Markovian. On the other hand, nuclear spins in semiconductors are attracting great interest due to their extremely long coherence time, but generally requires interaction to electron spins to achieve quantum control. In this talk I will discuss experimental progresses, with examples in GaAs 2-dimensional electron gas – based quantum dots and nitrogen-vacancy (NV) centers in diamond, towards controlling nuclear spins via hyperfine interaction with electron spins. In quantum dot system, spatially distributed electron wavefunctions sees millions of nuclear spins, where controlling spin bath polarization is achieved using electrical pulse-based dynamic nuclear polarization scheme. In diamond NV center, hyperfine interaction in combination with optical illumination is used to polarize individual nuclear spins around electron spin. Introducing these concepts, I will further discuss implication of these experiments toward efficient environment Hamiltonian engineering.

Coherent State Qudits for Quantum Information Processing

Kim, Jaewan

Korea Institute for Advanced Study, Korea

A coherent state could be interpreted as an evenly weighted superposition of pseudo-number states which are the partial sums of a coherent state represented in number states with spacings of an integer 'd'. Pseudo-number states forms a basis of qudit system of dimension d, and their conjugates, pseudo-phase states are coherent states with equal phase spacing on a circle in the quadrature space. Small Cross-Kerr nonlinear interaction can entangle two coherent states into a maximal entanglement of pseudo-number states and pseudo-phase states. This can be extended into a graph state or cluster state of qudits.

Aharonov-Bohm oscillation in nanomechanical measurements of topological insulator nanowire

Suh, Junho

Korea Research Institute of Standards and Science, Korea

In topological insulator nanowires, gapless surface states exhibit Aharonov–Bohm (AB) oscillations in conductance with this quantum interference effect accompanying a change in the number of transverse one-dimensional (1D) modes in transport. Thus the density of states (DOS) of such nanowires is expected to show AB oscillations, however this effect has yet to be observed. Here, we adopt nanomechanical measurements that reveal AB oscillations in the DOS of a topological insulator. The TI nanowire under study is an electromechanical resonator embedded in an electrical circuit, and quantum capacitance effects from DOS oscillation modulate the circuit capacitance thereby altering the spring constant to generate mechanical resonant frequency shifts. Detection of the quantum capacitance effects from surface-state DOS is facilitated by the small effective capacitances and high quality factors of nanomechanical resonators, and as such the present technique could be extended to study diverse quantum materials at nanoscale.

Superconducting qubit entanglement with all microwave control

Chong, Yonuk

Korea Research Institute of Standards and Science, Korea

Here we introduce our recent work on the all-microwave scheme for the controlled-NOT (cNOT) gate between two superconducting transmon qubits.
We constructed cNOT gate based on the microwave-activated phase (MAP) gate, with phase compensation by Z-axis phase gates using microwave hyperbolic secant pulses.
We present advantages and limitations of this method, together with the brief analysis of sources of errors.

Circuit QED system using Triple-Leg Stripline Resonator

Moon, Kyungsun

Department of Physics and IPAP, Yonsei university, Korea

In circuit QED system, strong coupling between superconducting qubit and intra-cavity microwave photon can make the unexplored regime of quantum optics readily accessible. We have theoretically shown that the coherent coupling of two cavity photon modes by a qubit can generate a squeezed state of light [1,2]. Recently we have theoretically proposed a new circuit QED system implemented with a triple-leg stripline resonator (TSR). Unlikely from the LSR, the fundamental intra-cavity microwave modes of the TSR are two-fold degenerate. When a superconducting qubit is placed near one of the TSR legs, one fundamental mode is directly coupled to the qubit, while the other one remains uncoupled. Using our circuit QED system, we have theoretically studied a two-qubit quantum gate operation in a hybrid qubit composed of a flying microwave qubit and a superconducting qubit [3].

Conventional linear stripline resonators (LSR) have been used to build several interesting lattice structures including 2D Kagome and Lieb lattice. However, due to its structural limitations, it is hard to fabricate honeycomb lattice structures using the LSR. In contrast, our TSR can form an optical honeycomb lattice, since each resonator can be symmetrically connected to the three adjacent ones. We have obtained Dirac dispersion produced by photonic orbitals in our optical lattice structure and have shown the distinct features from that of graphene.

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[1] K. Moon and S. M. Girvin, Phys. Rev. Lett. **95** 140504 (2005).
[2] K. Moon, Phys. Rev. A **88** 043830 (2013).

Quantum measurement of itinerant microwave photons using superconducting circuits

Kono, Shingo

University of Tokyo, Japan

Itinerant microwave photons are indispensable for realizing a quantum network between localized superconducting qubits. However, it remains challenging to measure itinerant microwave photons due to the lack of high-efficiency photodetectors in the microwave domain, in contrast to the optical frequency domain.

In this talk, we show the results on quantum measurements of itinerant microwave photons by using a circuit quantum electrodynamical system, where a microwave cavity plays a crucial role in facilitating the interaction between itinerant photons and a superconducting qubit. First, we characterize the photon-number distribution of a microwave squeezed vacuum by measuring the photon-number-resolved excitation spectrum of the qubit in a cavity that is driven externally and continuously with the squeezed vacuum. We confirm that the photon-number distribution reveals an even-odd photon number oscillation and quantitatively constitutes the nonclassicality. Second, we implement a deterministic entangling gate between a superconducting qubit and an itinerant microwave photon reflected by a cavity containing the qubit. Using entanglement and high-fidelity qubit readout, we demonstrate a quantum non-demolition detection of a single photon. The existence of the detected microwave photon is confirmed by using Wigner quantum state tomography.

These results on the fundamental characterizations of itinerant microwave photons have promising applications for quantum sensing and metrology in the microwave regime. Furthermore, the efficient entangling gate between itinerant photons and a superconducting qubit can be a building block for quantum networks connecting distant qubit modules.

IBM Q Experience: Cloud-based superconducting quantum computer for the NISQ-era

Paik, Hanhee

IBM Thomas J. Watson Research Center, USA

Since its launch in 2016, the IBM Q Experience, a cloud-based superconducting quantum processor for research and education, has been fostering the quantum computing community by attracting more than 100,000 users worldwide, producing more than 130 research papers on quantum information. I will discuss the future challenges in advancing quantum hardware and how IBM quantum processors can benchmark the noisy intermediate-scale quantum (NISQ)-era quantum computing systems.

Superconducting Circuit QED System Interacting with Quantum Spins

Choi, Manh-soo

Korea University, Korea

Superconducting circuit QED systems provides a wide range of scientific platforms from quantum computer to accurate quantum sensing of elementary charge or spin. In this talk, we first examine the exotic quantum states of the circuit QED systems in the ultra-strong coupling limit. They can simulate the Majorana bound state and exhibit photon localization-delocalization double transitions [1,2]. Next, we demonstrate how the frozen charge state at the Kondo resonance can be directly probed using the circuit QED architecture [3]. A quantum dot is coupled to a high finesse microwave cavity to measure, with an unprecedented sensitivity, the dot electronic compressibility. It is illustrated that the Kondo resonance, visible in transport measurements, is ‘transparent’ to microwave photons trapped in the high finesse cavity. Finally, we discuss unusual physical properties of a circuit QED system in which the Transmon qubit involves a quantum spin. The 0-π transition resulting from the competition of superconductivity and Kondo effect [4] gives rise to rich characteristics of the circuit QED systems from negative supercurrent to anharmonic-doubling effect [5].

[1] M.-J. Hwang and Mahn-Soo Choi, Phys. Rev. B 87, 125404 (2013).
[2] M.-J. Hwang, M. Kim, and Mahn-Soo Choi, Phys. Rev. Lett. 116, 153601 (2016).
[3] M. M. Desjardins et al., Nature 545, 71 (2017).
[4] Mahn-Soo Choi, M. Lee, K. Kang, W. Belzig, Phys. Rev. B 70, 020502 (2004); Phys. Rev. Lett. 94, 229701 (2005).
[5] A recent experiment by P. J. Leek (private conversation).

Realizing a Catch-Disperse-Release read-out of a qubit

Peronnin, Théau

Ecole Normale Superieure de Lyon, France

Fast read-out is an essential piece of measurement based error correction codes and is often limited by its reset time but the usual technique of driving a dispersively coupled resonator presents some limitations. To overcome those limits Sete and al. [1] proposed a catch, disperse and release scheme that we recently realized. It uses a resonator with a tunable coupling to the transmission line. That resonator is coupled to the qubit in the dispersive coupling limit. First, we do brief unconditional coherent displacement of the resonator. Then the phase of the stored coherent state grows linearly in time at a rate depending on the state of the qubit. Finally, we release the resonator's state into the transmission line and measure the phase of the out-coming signal. Our experiment implements that scheme by using a Josephson Parametric Converter as a tunable coupler between a low and a high Q factor resonator [2] to measure a transmon qubit in CPW geometry. We demonstrate a state-of-the-art read-out with a fidelity of 97.5% in a total of 240 ns. The fidelity is limited by the 6us qubit's lifetime. We demonstrate the quantum non-demolition, reset, and Purcell protection granted by this scheme.

[1] Sete and al., Phys. Rev. Lett. 110, 210501 (2013).

[2] Flurin and al., Phys. Rev. Lett. 114, 090503 (2015)

Control and measurement of magnetic fluxoid quanta for s mall force standard

Choi, Jae-Hyuk

Division of Physical Metrology, Korea Research Institute of Standards and Science, Korea

In absence of force standard established in the range below a micro-newton, our research driven toward a quantum-based force standard is introduced. Exploring candidates which provide force units identical and stable intrinsically, and useful in applications, we suggested a hybrid system of a superconducting micro-annulus with multiple-quantum states and a mechanical spring in classical regime combined: the magnetic moment of the annulus proportional to the quantum number generates force in magnetic-field gradient. With an ultrathin silicon nitride cantilever with an 8 μm-diameter Nb annulus on, the magnetic moment due to a single fluxoid quantum was precisely determined using a lab-built attonewton-sensitivity cantilever magnetometer. In this talk, we present a scheme to control the number of fluxoid quanta by designed magnetic and thermal cycles, and preliminary results in small-force realization in a sub-piconewton range as well as the construction of a low-temperature realization setup.

Conductance Quantization and Magnetic Control of Topological Insulators

Kim, Jae Hoon

Department of Physics, Yonsei University, Korea

Topological insulators as well as related topological materials are likely to provide us with an ideal materials base for fault-tolerant topological quantum computing in the near future.

In this talk, I will review current research on the detection, manipulation, and hybridization of topological surfaces states in topological insulators. Conductance quantization in the ambient in units of the fundamental conductance quantum has been established in ultrathin films in which the top and bottom surface states are strongly hybridized. External magnetic fields and exchange interaction further modify these quantum states. We employ various experimental techniques including MBE film synthesis, terahertz time domain spectroscopy, and magnetooptical polarimetry for our investigation.

Fractional Josephson Effect in Topological Insulator Nanoribbons

Doh, Yong-Joo

Department of Physics and Photon Science,
Gwangju Institute of Science and Technology, Korea

Topological insulator (TI) nanowire combined with conventional s-wave superconductor is expected to provide the topological superconducting state for hosting the Majorana fermion, which is essential for the topological quantum computation. Here, we report the experimental evidences of the topological supercurrent through surface states in (Bi0.81Sb0.19)2Se3 TI nanowire-PbIn superconductor Josephson junctions. When an axial magnetic filed is applied, the Josephson supercurrent oscillates, and their period is consistent with the Aharonov-Bohm (AB) oscillations of normal conductance, indicate that the supercurrent is caused by the topological surface states. Furthermore, when we applied microwaves to the junctions, anomalous Shapiro steps with the first step missing are observed at around 300 mK. In the topological superconducting state, the supercurrent has a 4 -period and is expected to show doubled Shapiro steps, so called the factional Josephson effect. Therefore, our anomalous Shapiro steps can be caused from the topological supercurrent, and it is also verified by numerical calculations. To the best of our knowledge, our experimental results are for the first time in the world to simultaneously demonstrate the surface supercurrent AB oscillations and fractional Josephson effect in a topological nanowire.

Quantum resistor-capacitor circuit with Majorana fermion modes in a chiral topological superconductor

Lee, Minchul

Kyunghee University, Korea

We investigate the mesoscopic resistor-capacitor circuit consisting of a quantum dot coupled to spatially separated Majorana fermion modes in a chiral topological superconductor. We find substantially enhanced relaxation resistance due to the nature of Majorana fermions, which are their own antiparticles and are composed of particle and hole excitations in the same abundance. Furthermore, the zero-frequency relaxation resistance is completely suppressed due to a destructive interference. As a result, the Majorana mode opens an exotic dissipative channel on a superconductor which is typically regarded as dissipationless due to its finite superconducting gap. We also discuss the dissipation via the Majorana mode beyond the linear-response regime, establishing the Joule law for the Majorana mode.

Shot noise measurements with an impedance matching circuit at GHz frequencies

Jung, Minkyung

Daegu Gyeongbuk Institute of Science & Technology Research Institute, Korea

In this work, we present carbon nanotube (CNT) single and double quantum dots coupled to a GHz superconducting impedance matching circuit using a CNT stamping technique. The device shows a tunable bipolar double dot behavior, reaching the few-electron/hole regime. The resonance response reflected by the matching circuit is a sensitive probe of the charge state of the device, allowing a determination of the absolute charge number. The impedance matching circuit allows excellent shot noise measurement performance in a carbon nanotube single quantum dot regime. The signal to noise ratio at a device resistance of 100 kΩ is enhanced by a factor of 3.5 compared to a wide-band detection without impedance matching. We also perform shot noise measurements in ultra-clean graphene p-n junctions with an impedance matching circuit.

First-principles theory of spin defects in 2D crystals for quantum applications

Seo, Hosung

Ajou Uciversity, Korea

Deep-level spin defects in wide-gap semiconductors are promising platforms for applications in quantum information processing, quantum sensing, and quantum photonics [1]. In particular, several point defects in two-dimensional materials such as h-BN have recently emerged as room-temperature single photon emitters (SPEs) with excellent optical stability and brightness [2] and potentially spin qubits [3]. In this study, we use first-principles theory to investigate the optical and spin properties of deep-level defects in two-dimensional crystals including h-BN and MoS2. First, we discuss our recent combined experimental and theoretical study of Stark tuning of SPE's in h-BN [4,5]. We show that it is possible to control the SPEs' optical energy by applying an out-of-plane electric field and we suggested that the presence of the out-of-plane dipole of the SPEs may be originated from spontaneous symmetry breaking of the SPEs' defect structure [4]. We consider diverse defect candidates for SPEs in h-BN such as VNCB, VNNB and we discuss the potential mechanism of the symmetry lowering process of the defect models and its physical implications for their application as single photon emitters [5]. In the second part of the talk, we describe spin decoherence in two-dimensional materials, using spin Hamiltonian and a cluster expansion method [6]. We show that isotopic purification could be much more effective in 2D than in 3D materials. We also discuss additional factors influencing the optimization of spin qubit hosts.

[1] W. F. Koehl, H. Seo, G. Galli, and D. A. Awschalom, MRS Bulletin 40, 1146-1153 (2015).
[2] M. Toth and I. Aharonovich, Annu. Rev. Phys. Chem. 70, 123 (2019)
[3] A. L. Exarhos, D. A. Hopper, R. N. Patel, M. W. Doherty, and L. C. Bassett, Nat. Comm. 10, 222 (2019).
[4] G. Noh, D. Choi, J. Kim, D. Im, Y. Kim, H. Seo, and J. Lee, Nano Lett. 18, 4710 (2018).
[5] J. Bhang, D. Yim, and H. Seo, in preparation (2019).
[6] M. Ye, H. Seo, and G. Galli, under review (2019).

Diamond quantum networks for distributed quantum computation

Taminiau, Tim

QuTech & Kavli Institute of Nanoscience, Delft University of Technology, The Netherlands

Quantum networks provide a promising way to realize quantum computations and simulations. Such networks consist of nodes that contain multiple qubits to store and process quantum states, and that are connected together by distributing entangled states through optical links using photons. Crucially, imperfections and errors can be overcome by distributing logical qubits, computations and error correction over the network [1]. This approach is naturally scalable to large sizes by connecting many independent modules, thus avoiding the challenges of a single large structure of ever increasing complexity.

The nitrogen vacancy (NV) center in diamond is a promising candidate to realize such quantum networks, as it combines optical entanglement links [2] with long-lived multi-qubit nodes that can store and process quantum information [3-5]. In this talk I will discuss the recent progress of my group towards quantum networks for distributed quantum computations.

[1] N. H. Nickerson, Y. Li, S. C. Benjamin, Nature Commun. 4, 1756 (2013)
[2] B. Hensen et al., Nature 526, 682 (2015)
[3] J. Cramer et al., Nature Commun. 7:11526 (2016)
[4] M. H. Abobeih et al., Nature Commun. 9: 2552 (2018)

Scalable defect-based solid-state quantum devices

Lee, Sang-Yun

Center for Quantum Information, Korea Institute of Science and Technology, Korea

Electronic and nuclear spins in solids can form hybrid quantum registers in which electronic spins are ancillary qubits for initialization and readout of nuclear spins that are physical qubits. Their long lifetime and coherence time, exceeding 1 second, and efficient coherent control by magnetic resonance techniques allow for realizing small scale quantum registers [1,2]. In some crystalline solids, the fluorescence properties of point defects can be correlated with electronic spins with high fidelity, thus “artificial atoms” provide quantum links via photonic quantum networks among quantum nodes [2,3]. Such a photonic network may open a pathway towards modular structured quantum information processing devices. However, there exist bottlenecks such as better control of spin-spin interaction and improving spin-to-photon interface efficiency. In this talk, I’ll introduce our progress towards small-scale quantum nodes consisting of coupled electron spin pairs and nuclear spins in diamond, and efficient photonic control using photonic structures such as cone-shaped diamond nano-antenna. Also, recent results from new candidates in wide-bandgap semiconductors will be introduced [1,4,5].

[1] M. Atatüre, D. Englund, N. Vamivakas, S.-Y. Lee, and J. Wrachtrup, Nat. Rev. Mater. 3, 38 (2018).

[2] D. D. Awschalom, R. Hanson, J. Wrachtrup, and B. B. Zhou, Nat. Photonics 12, 516 (2018).

[3] P. C. Humphreys, N. Kalb, J. P. J. Morits, R. N. Schouten, R. F. L. Vermeulen, D. J. Twitchen, M. Markham, and R. Hanson, Nature 558, 268 (2018).

[4] R. Nagy, M. Niethammer, M. Widmann, Y.-C. Chen, P. Udvarhelyi, C. Bonato, J. Hassan, R. Karhu, I. Ivanov, N. T. Son, J. Maze, O. Taekshi, Ö. Soykal, A. Gali, S.-Y. Lee, F. Kaiser, and J. Wrachtrup, ArXiv:1810.10296 (2018).

[5] P. Udvarhelyi, R. Nagy, F. Kaiser, S.-Y. Lee, J. Wrachtrup, and A. Gali, ArXiv Prepr. ArXiv1811.02037 (2018).

New understanding and engineering of defect qubits in diamond

Doherty, Marcus

Laser Physics Centre, Research School of Physics and Engineering,
Australian National University, Australia.

Defects in diamond and other wide bandgap semiconductors with electronic spins that may be optically initialised and readout are promising qubit systems for a great diversity of quantum technologies. The negatively-charged nitrogen-vacancy (NV) centre in diamond is the best understood of these defects. It has driven major advances across quantum technology, including quantum computing, nanosensing and microscopy, and communications. However, there still remain unanswered questions about how best to employ it to initialise and read out clusters of coupled nuclear spin qubits. Recently, the negatively-charged silicon-vacancy (SiV-) and germanium-vacancy (GeV-) centres in diamond have come to prominence as possible alternatives to the NV centre in quantum computing and communications due to their superior optical properties. However, they currently suffer from poorer spin properties. Although not prominent, the ST1 centre in diamond promises superior performance as a bus for quantum registers formed from clusters of nuclear spin impurities. Progression towards using the ST1 centre has been hampered because its structure remains a mystery as well as difficulties in its reproduction. In the meantime, the search for new defects for quantum technologies is increasing in breadth and speed.

In this presentation, I will report the discovery of a new defect with an optically-addressable electronic spin: the neutral silicon-vacancy (SiV^0) centre in diamond; as well as new knowledge of the ST1 centre’s structure, methods to enhance the spin properties of SiV- centres, and new insight into the NV centre’s mechanism of single-shot readout/ projective initialisation of nuclear spin qubits.

Discrete time-crystalline order in black diamond: realization and probe of quantum many-body dynamics

Choi, Soonwon

University of California Berkeley, USA

Strongly interacting solid-state spin ensembles provide a promising platform to explore quantum many-body physics. In particular, Nitrogen-Vacancy (NV) centers in diamond are appealing as they exhibit excellent spin properties even at room temperature. In this talk, I will present how a high-density NV ensemble can be used to investigate out-of-equilibrium quantum many-body phenomena. In particular, I will discuss the recent experimental observation of discrete time-crystalline (DTC) order: a nonequilibrium order characterized by a spontaneous breaking of time-translational symmetry and manifested in robust, long-lived subharmonic responses of a periodically driven system [1]. By engineering different types of effective interactions, we find that the spin ensemble can exhibit a long-lived robust subharmonic response over a wide range of parameters. Additional systematic investigation of the lifetime of the DTC response reveals three different regimes of relaxation dynamics, that can be continuously varied from disorder-induced slow thermalization, to driving assisted relaxation, and ultimately to universal Markovian dynamics [2]. These results highlight the utility of high-density NV ensembles as a probe of many-body dynamics and thermalization, an important aspect in the quest for the understanding and control of quantum matter, and may enable novel applications in quantum simulation and metrology with strongly correlated quantum matter [3].

[1] S. Choi et al, Nature 543, 221–225 (2017)
[2] J. Choi et al, Phys. Rev. Lett. 122, 043603 (2019)
[3] S. Choi et al, arXiv:1801.00042 (2018)

Quantum Nanoscience: Atoms on Surfaces

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The scanning tunneling microscope is an amazing tool because of its atomic-scale spatial resolution. This can be combined with the use of low temperatures, culminating in precise atom manipulation and spectroscopy with microvolt energy resolution. In this talk we will apply these techniques to the investigation of the quantum spin properties of magnetic atoms sitting on thin insulating films.

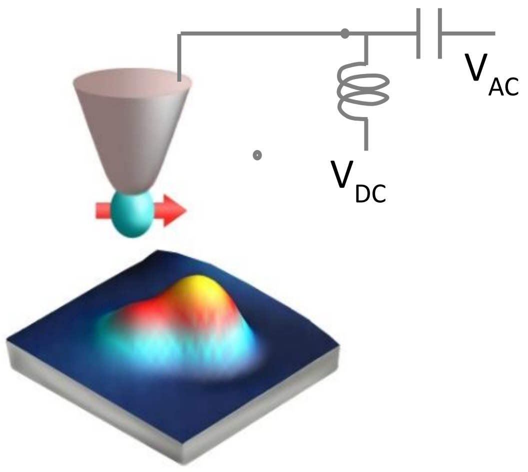

Fig 1. STM image of two Ti atoms on thin MgO film. Superimposed is a model of a spin-polarized STM tip

We will start our exploration with the understanding of the quantum spin states (also called the magnetic states) of these adsorbates. To measure these states, we combined scanning tunneling with x-ray absorption spectroscopy and found amazing agreement of those vastly different techniques (*Science* 2014, *PRL* 2015).

Next, we will investigate the lifetimes of excited states. Surprisingly, we find lifetimes that vary from nanoseconds to hours, a truly amazing consequence of the quantum states of different adsorbates.

Finally, we will explore the superposition of quantum states which is inherent to spin resonance techniques. We recently demonstrated the use of electron spin resonance on single Fe atoms on MgO (Science 2015). This technique combines the power of STM of atomic-scale spectroscopy with the unprecedented energy resolution of spin resonance techniques, which is about 10,000 times better than normal spectroscopy.

Using Optical Pulses for Quantum Control and Sensing

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Nitrogen-vacancy (NV) centers in diamond represent a forefront platform for secure quantum networks and high-precision sensing. In this talk, I will discuss novel techniques using controlled optical excitation to implement high-speed quantum control and high resolution quantum sensing. Going beyond conventional microwave control of NV center spins, we utilize resonant and near-resonant optical transitions to achieve robust single-qubit operations. We leverage three-level energy structures in the NV spin-orbit optical manifold for holonomic quantum gates and ‘superadiabatic’ state transfer. Finally, I will introduce a new synchronized optical pulse sequence for using the NV center to probe the transport properties of low-dimensional materials. Optical control improves sensitivity and provides high spatiotemporal resolution. These methods are broadly generalizable to other quantum and material systems and highlight the potential of spin-light interactions for emerging applications.

Nanoscale magnetic resonance detection towards nano MRI

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Magnetic resonance imaging (MRI) with its ability to provide three dimensional, elementally selective imaging has had a revolutionary impact in research fields including medicine and the neurosciences. In the sense that its extension to the nanometer scale could provide a powerful tool for non-destructively visualizing the three dimensional morphology of nanoscale structures, another impact is naturally expected with the development of nano MRI. Recently, negatively charged nitrogen-vacancy (NV) color centers in diamond have been proposed as a promising system for nanoscale magnetic field sensing. NV centers are atomic-sized point defects and can be brought to within a few nanometers of magnetic samples, allowing for nanometric spatial resolution. Over the past few years, these properties have led to rapid progress in developing NV-based magnetometers and magnetic resonance spectroscopy. Here, we introduce some of recent demonstrations of proton magnetic resonance imaging using a NV spin sensor and discuss its limitations and research directions to overcome them.

Towards measurement induced quantum state engineering

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Quantum theory predicts that a quantum system will collapse from superposition of several possible states, to just one, in the moment it is measured. As quantum systems are never isolated from their surrounding environment (quantum bath), its measurement and the associated collapse should also affect the environment coupled to it. The affected spin bath will then effect the trajectory of the quantum system. We demonstrate the role of measurement back-action of a coherent spin environment on the dynamics of a spin (qubit) coupled to it, by inducing non-classical (Quantum Random Walk like) statistics on its measurement trajectory. We show how the long-life time of the spin-bath allows it to correlate measurements of the qubit over many repetitions. We have used Nitrogen Vacancy centers in diamond as a model system, and the projective single-shot readout of the electron spin at low temperatures to simulate these effects. We show that the proposed theoretical model, explains the experimentally observed statistics and their application for quantum state engineering of spin ensembles towards desired states.

Quantum control of a single-spin quantum emitter in diamond via coupling with a mechanical oscillator

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There has been rapidly growing interest in hybrid quantum devices involving a solid-state spin and a macroscopic mechanical oscillator. Such hybrid devices create exciting opportunities to mediate interactions between disparate qubits and to explore the quantum regime of macroscopic mechanical objects. In particular, a system consisting of the nitrogen-vacancy defect center in diamond embedded inside a high quality factor diamond mechanical oscillator is an appealing candidate for such a hybrid quantum device, as it combines the highly coherent and versatile spin properties of the defect center with the excellent mechanical properties of diamond resonators. In this talk, we will present recent experimental progress on diamond-based hybrid quantum devices in which the defect's spin and orbital dynamics are mechanically driven by the motion of a mechanical oscillator. We will discuss the potential usage of multiple mechanical modes to fully engineer the strain environment of the defect center. For instance, simultaneous motion of flexural and torsional modes in T-shaped diamond cantilever can provide selective controls of linear and shear strain terms. We will also discuss future prospective applications, including strain-assisted indistinguishable photon generation, long range, phonon-mediated spin-spin interactions and phonon cooling and lasing in the quantum regime.