# US-Korea Workshop on Quantum Information Abstracts

## Progress in development of the quantum repeater based on ion trap technology at SK Telecom

**Taehyun Kim**
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To implement complex and practical quantum network, qubit exchange between arbitrary nodes without measurement is the most difficult technical challenge. Quantum repeater is an ideal solution for this problem with the help of entanglement. At SK telecom, we are developing quantum repeater based on ion trap technology. Trapped ions have several advantages as an ideal platform for quantum repeater, such as long trapping time by the electrical confinement, long coherence time from the perfect isolation in ultra high-vacuum (UHV) environment, and relatively easy interface with photonic qubit due to optical transition in atomic structure.

To develop a scalable platform for ion trap, we developed our own micro-fabrication process for ion trap chips based on micro-electro-mechanical system (MEMS) technology. As the initial development, we used electrode layout similar to the trap chip fabricated by Sandia National Laboratory [1]. Figure 1 (a) shows an SEM image of the fabricated chip, and Figure 1 (b) shows the image of six trapped $^{174}Yb^{+}$ ions.

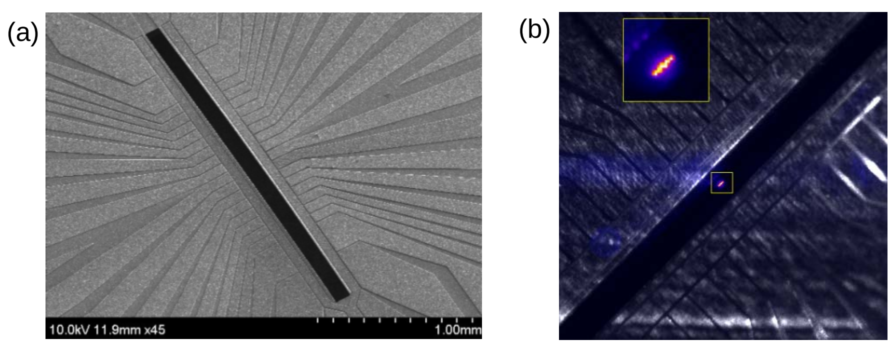


**Figure 1**: *(a) SEM image of the fabricated MEMS chip. (b) Six* $^{174}Yb^{+}$ *ions trapped on the micro-fabricated MEMS chip. Buckling of the ion chain starts from six ions. The image of the surface trap electrode structure was taken separately and overlaid for clarity.*

To confirm that we can manipulate ionic qubit, we trapped one $^{171}Yb^{+}$ ion and applied microwave around the frequency of the hyperfine splitting [2]. Figure 2 (a) shows the Rabi flopping result as we vary the detuning of the microwave and Figure 2 (b) shows that the coherence time is at least more than 50 msec. In this talk, I'm going to present with our recent progress towards quantum repeater development.

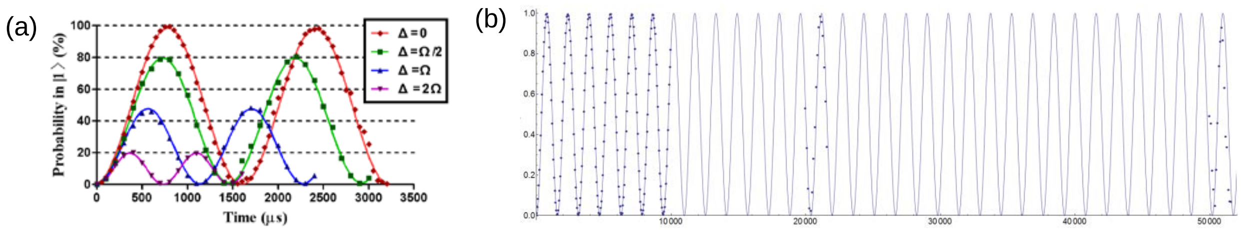


**Figure 2**: *Rabi oscillation measurement. (a) Comparison of theoretical calculation and the measured data as we increase the detuning of the microwave frequency. (b) Data for coherence time measurement. Up to 50 msec, visibility of Rabi oscillation is above 90%.*

**REFERENCES**


1. E. Mount *et al.*, “Single qubit manipulation in a microfabricated surface electrode ion trap,” New J. Phys. Vol. 15, 093018 (2013).
2. S. Olmschenk *et al.*, “Manipulation and Detection of a Trapped Yb+ Hyperfine Qubit ,” Phys. Rev. A Vol. 76, 052314 (2007).


**DATE:** **MONDAY, NOVEMBER 17, 2014**
**TIME:** **5:15 PM – 5:50 PM**

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**Quantum bit based on inter-valley splitting and quantum gate model in Si quantum dot structures**


**Doyeol Ah_n**
Center for Quantum Information processing, University of Seoul


Quantum bit based on the inter-valley state splitting of Si quantum dot is studied. Multi-valley effective mass theory for silicon quantum devices is developed taking into account the external fields and the quantum interfaces. Theoretical predictions were in a reasonably good agreement with the experimental observation of valley splitting in a quantum well, which proves the validity of our approach. An explicit scheme for the implementation of controlled-NOT (CNOT) gate with all electrical control based on the polarized inter-valley states of silicon quantum dots is studied. This new feature of the valley splitting would give an additional degree of freedom in the design of quantum gate based on Si quantum dot structures.

**DATE: TUESDAY, NOVEMBER 18**
**TIME: 9:40 AM – 10:15 AM**

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**Plug and play measurement-device-independent quantum key distribution (P&P MDI-QKD)**

**Sang-wook Han**
Nano & Quantum Information Research Center, KIST

Nano & Quantum Information Research Center at Korea Institute of Science and Technology (KIST), established in 2012, is the leading research facility in South Korea, focusing on the research and development of practical implementation of quantum cryptographic system. Our project portfolio includes design and fabrication of avalanche photodiode, implementation of single photon detection unit, and development of plug and play BB84 system. Moreover, we also study single photon sources based on SPDC, theoretical research on quantum discord, *etc*. Recently, we have demonstrated a proof-of-principle experiment of two-photon interference using only one laser source. Based on this result, we propose a scheme for plug and play measurement-device-independent quantum key distribution (P&P MDI-QKD). In summary, this protocol is described as follows. Strong light is prepared by Charlie and sent to Alice and Bob. Alice and Bob encode key bits by modulating the polarization of the beam and return them to Charlie. Then, Charlie does interferometric measurement of the returned beam and announces the results to Alice and Bob. Because our scheme only requires one laser, the indistinguishability between the modes from Alice and Bob can be guaranteed without any active control units that are costly and cumbersome to install. As the originally proposed scheme for MDI-QKD by Lo *et al.* suggested, our scheme also ensures the security proof against any quantum hacking on detectors and the doubled maximum communication distance between Alice and Bob.

**DATE: TUESDAY, NOVEMBER 18**
**TIME: 11:55 AM – 12:30 PM**

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**Quantum MEM's: Micro-Mechanical Devices for Sensing, Amplification and Thermometry**

**John Teufel**
NIST

While micromechanical resonators are a ubiquitous technology in applications such as sensing and telecommunications, only recently are these engineered mechanical devices encountering the fundamental limitations and opportunities afforded by their true quantum mechanical nature. By incorporating microfabricated mechanical resonators into superconducting microwave circuits, we achieve the unprecedented ability to use microwave photons to cool and to probe motion near the quantum limit. At NIST, we are developing this emergent technology toward an array of applications including: force sensing, quantum-limited microwave amplification, frequency conversion, primary thermometry, and processing of quantum information. I will discuss recent progress toward each of these goals as well as recent experiments which merge these mechanical circuits with other existing quantum systems.

**DATE:** **TUESDAY, NOVEMBER 18**
**TIME:** **2:00 PM – 2:35 PM**

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**Precision Measurement using ultracold fermi gases**

**Jongchul MUN**
KRISS

Atom interferometer is one of key parts in precision measurement experiment field due to its high sensitivity and precision. The basic concept is coherently manipulating the matter wave of atoms and making them interfere. For example, the matter wave of atoms is coherently split into two states, and they experience different phase accumulation. The two states are coherently recombined leading to interference pattern, and the resulting interference pattern includes the phase difference information. Such atom interferometers offer valuable opportunities for studying fundamental quantum mechanical phenomena, probing atomic and material properties, measuring inertial motion, etc.

Since the realization of Bose-Einstein Condensate(BEC) in 1995, there have been many efforts to apply BEC to atom interferometry leading to a number of successful results. However, one of the big problems still need to be overcome: interaction effect. For example, clock shift in BEC spectroscopy is induced due to the interaction resulting in the measurement error. Another example is Bloch oscillation. Bloch oscillation of BEC could not be performed over many cycles since the interaction induces the decoherence in BEC. However, for fermi gas Bloch oscillation could be achieved over very long cycle, since the interaction in fermi gas is suppressed at very low temperature due to Pauli exclusion principle. The period of Bloch oscillation is linearly related to the applied force, and such long Bloch oscillation could be applied to the precision measurement of the force or acceleration. This is our basic experimental motivation to achieve using ultracold $^{40}K$ atomic gas, which is fermionic species.

In this talk, we report our current status of experimental setup which is being built at KRISS for the realization ultracold mixture of $^{87}Rb$ and $^{40}K$, and its future application to the precision measurement using Bloch oscillation.

**DATE: TUESDAY, NOVEMBER 18**
**TIME: 3:10 PM – 3:45 PM**

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**TQuantum state measurement and spectroscopy in superconducting 3D transmon qubit**

**Yonuk Chong**
Korea Research Institute of Standards and Science (KRISS)

I will introduce our efforts during last couple of years on the development of superconducting qubit(=quantum bit) system in KRISS. A Josephson junction embedded in a machined high-Q superconducting aluminum resonator constitutes the unit of quantum information processing, a 3D transmon qubit in circuit QED structure. The qubit operation is performed in a cryogen-free dilution refrigerator with the base temperature of 7 mK. I will present basic qubit coherence measurements by standard Rabi oscillations and Ramsey fringes measurements. Several further results on ac Stark shift measurement and multi-photon processes will also be presented. Basic spectroscopy results on the qubit dressed states will be also briefly discussed. We hope our superconducting qubit research will contribute to broaden our knowledge on quantum state measurement and manipulation in a metrology laboratory.

**DATE: TUESDAY, NOVEMBER 18**
**TIME: 3:45 PM – 4:20 PM**

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**Measurement of High-Dimensional Quantum State Utilizing Photonic Path Qubits**

**Hee Soo Park**, Ph. D.,
KRISS

Single photons are a useful quantum information carrier that has intrinsically infinite degrees of freedom (DOFs) over polarization, paths, spatial modes, and time bins. The purity or indistinguishability of photons with respect to all of the DOFs, used or unused, is essential for quantum information processing that requires more than one photons. This work, after introducing a few multiphoton experiments in KRISS, describes a method to efficiently characterize the purity of photonic quantum state by a controlled-swap operation with two photonic paths being a control qubit. This work also describes measurement of arbitrary superposition states of fiber spatial modes, which require experimental techniques different from free space implementation, unlike the other DOFs.

**DATE: TUESDAY, NOVEMBER 18**
**TIME: 5:25 PM – 6:00 PM**

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**Silicon-based quantum devices**

**M. D. Stewart, Jr.**
NIST

Silicon-based approaches to quantum devices have several advantages: the ability to leverage industrial fabrication techniques, easy integration with CMOS control electronics, excellent coherence times, and the luxury of working in an extremely clean, stable, and well-studied material system. While silicon is well established as a material system for quantum devices, individual implementations have their own advantages and disadvantages. Thus, exploring different architectures and materials is vital for the future of quantum information in the silicon platform. In this talk, I will give an overview of the efforts of several collaborations at NIST in silicon-based quantum devices and materials. These include top-down fabricated quantum dot devices, bottom-up, single-atom devices, and isotopically enriched 28Si for both device lines.

**DATE: WEDNESDAY, NOVEMBER 19**
**TIME: 8:30 AM – 9:05 AM**

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**Observation of quantum states of P nuclear spins in Si:P by double resonance**

**Soonchil Lee**
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KAIST

The working principle of the silicon-based nuclear spin quantum computer proposed by Kane is the electric control of the hyperfine interaction of a phosphorous ion doped in silicon and the indirect interaction between nuclear spins of Phosphorous ions mediated by electron spins. We plan to observe the mechanism by magnetic resonance of ensemble of spins in electric field, because the technique of single nuclear spin detection is not applicable to general structures yet. The first step is to measure the NMR spectrum for phosphorous doped silicon accurately but it is well known that NMR spectrum is unobservable for P concentration as low as the Kane's model. Therefore, we use double resonance techniques to get necessary information indirectly. Dynamic Nuclear Polarization (DNP) experiment detects the influence of $^{29}$Si, which exists inevitably even in purified silicon, on the electron spins of P ions. DNP reveals the existence of $^{29}$Si ions and makes it possible to control a nuclear spin state of a single $^{29}$Si ion near a phosphorous donor. We set and observed quantum states of P nuclear spins through Electron Nuclear DOuble Resonance (ENDOR). Rabi oscillation lasts for several periods.

**DATE: WEDNESDAY, NOVEMBER 19**
**TIME: 9:05 AM – 9:40 AM**

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**High performance single photon detectors using superconductors**

**Sae Woo Nam**
National Institute of Standards and Technology, Boulder, CO

There is increasing interest in using superconducting optical photon detectors in quantum information experiments and applications. These applications often require detectors that have extremely low dark count rates, high count rates, and high quantum efficiency. I will briefly review our work on two types of superconducting detectors, the Superconducting Nanowire Single Photon Detector (SNSPD or nSSPD) and superconducting Transition-Edge Sensor (TES). An SNSPD is an ultra-thin, ultra-narrow (nm scale) superconducting meander that is current biased just below its critical current density. When one or more photon is absorbed, a hot spot is formed that causes the superconductor to develop a resistance and consequently a voltage pulse. For applications requiring photon number resolution, we have been using superconducting transistion-edge sensors (TES). By exploiting the sharp superconducting-to-normal resistive transition of tungsten at 100mK, TES detectors give an output signal that is proportional to the cumulative energy in an absorption event. This proportional pulse-height enables the determination of the energy absorbed by the TES and the direct conversion of sensor pulse-height into photon number. In addition to describing our work to develop these detectors, I will discuss a few applications where use of these detectors is essential to the success of the application.

**DATE:** **WEDNESDAY, NOVEMBER 19**
**TIME:** **9:40 AM – 10:15 AM**

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**Fabrication of InGaAs/InP avalanche photodiode and application to single photon detection**

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We fabricated and characterized InP/InGaAs avalanche photodiode(APD) for the use of single photon detection. The APD device has been designed to have moderate internal electric field in the multiplication layer to suppress dark count rate(DCR) and back-illumination structure to increase detection efficiency(DE). The device has been mounted on TO-46 package and pigtailed using SC/PC connector. For measurement, it has been cooled down -40°C to suppress DCR using TEC cooling technique. The gate was operated to have 10MHz of repetition, 2ns FWHM, and 6V of amplitude. The optical input pulse was applied to be 100kHz of repetition, 500ps of FWHM, and 0.1 photon/pulse on average. Using this condition DCR probability/pulse of $2.4\times10^{-6}$ and $5.2\times10^{-6}$ has been observed at 10.4% and 15.2% of DE, respectively. Afterpulse has been measured by 2.7% and 7.5% at 10.4% and 15.2% of DE, respectively. We think that this device can be successfully used for quantum key distribution network.

**DATE: WEDNESDAY, NOVEMBER 19**
**TIME: 10:15 AM – 10:50 AM**

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**ATCA platform based Quantum Cryptography System Prototype for Commercialization**

**Jeong-sik Cho, Jeong woon Choi, Minhyung Kim, Chul woo Park, Seok-beom Cho, Jangmyun Kim, and Seung Hwan Kwak**
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Over the recent years, quantum cryptography systems have begun to be really deployed to optical communication networks in world-wide. The Switzerland company, ID Quantique, has supplied quantum cryptography systems to several banks in Europe for protection of their disaster recovery lines and to even a cloud backup line. Also, it has been known that China is building 2,000 km distance and 32 trusted-relay nodes quantum backbone networks from Beijing to Shanghai. It was reported that NASA and Quintessence Labs join to protect 560 km NASA research lines from Silicon Valley to Pasadena using quantum cryptography technology. It has been well-known that Toshiba Europe Research Labs and Japanese companies such as NEC, Mitsubishi, NTT have been developing quantum technologies so long time and they are almost ready to commercialize. Thus, these reports have to be accepted as a proof for that we are in the totally new phase compared with the years that systems just have been applied for academic researches or demonstrations.

SK Telecom has also developed key technologies and a quantum cryptography system based on ATCA (Advanced Telecommunications and Computing Architecture) platform over three years. We have strategically adopted the ATCA standard platform to supply commercial systems to network carriers and to offer them high level of benefit, that is, carrier-grade manageability such as credibility, operation performance, modularity, configurability and scalability. The system was also designed to be able to provide perfect legacy network compatibility.

We have designed the system in three major modules, optic module, signal processing module and encryptor module.

The optic module is composed of a quasi-single-photon signal generator, phase and intensity modulators, PLC (Planar Lightwave Circuit) interferometers and an 125 MHz single photon detector. We use QPSK (Quadrature Phase Shift Keying) modulation in the transmitter side and two-level PSK in the receiver side and modulate split pulses in a differential manner. The intensity of pulses is also modulated in three levels to represent decoy states. The phase modulation information is converted to the intensity information by using the temperature-stabilized Michelson-type PLC interferometer. The single photon detector with two channels working complementarily shows the dark count probability of the order of $10^{-6}$ per gate and after-pulsing less than 5 % with 3 μs dead-time at 10 % detection efficiency. The optic part totally shows the quantum bit-error-rate of around 5 %.

In the signal processing module, we use high speed quantum random number generators to generate bit, basis and decoy signals and for the randomness of signal processing. Singe photon detection events are delivered to the transmitter side through a synchronous 5-Gbps open channel designed to cover the 120 km distance and stored in memories in a dual banking manner. For stored data blocks, modified Winnow error correction, privacy amplification using the Toeplitz matrix, and double-authentication such as quantum channel authentication and final key authentication are conducted and more than 10 kbps secure key are distributed at 50 km distance. Final keys are stored in a key bank with a specified key format and are supplied to over 80 encryptors without any update processing time.

Layer-2 encryptors can process 10 Gbps Ethernet traffics in the latency time less than 10 microseconds. One encryptor card has two 10-Gbps channels and occupies one 1.2 inch ATCA slot. The encryption algorithm is proven AES (Advanced Encryption Standard) and GMAC (Galois Message Authentication Code) secures the integrity of messages.

**DATE: WEDNESDAY, NOVEMBER 18**
**TIME: 11:55 AM – 12:30 PM**

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**Quantum Information and Statistics at NIST Boulder**

**Scott Glancy**
NIST

The quantum information theory group at NIST Boulder has been studying problems related to the statistical analysis of measurements on quantum systems. These have included randomized benchmarking of quantum logic operations, optimization of quantum clocks, quantum state tomography, and quantifying evidence against local realism. This talk will briefly mention each of these topics and give a more detailed discussion of methods that we have developed to compute bounds on p-values for the hypothesis "Local realism is true.", which bounds are close the memory and coincidence-time loopholes.

**DATE: WEDNESDAY, NOVEMBER 19**
**TIME: 2:00 PM – 2:35 PM**

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## QKD for point to multipoint networks

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It is well accepted that quantum key distribution (QKD) provides unconditionally secure communication. Some commercial systems were deployed and in service for some critical applications. However, most activities have been focused on the point-to-point optical communication network, as an initial application. Recently, optical communications, especially optical access networks, has penetrated to business premises and to homes to support bandwidth demands originated from explosion of video services. Thus QKD in point-to-multipoint optical networks became essential for end-to-end secure communications.

Some technical issues in QKD for point-to-multipoint optical networks are a) coexistence of existing classical communication channels and a QKD channel, b) low secure key rate due to high splitting loss due to a large number of optical branching, and c) multiple user interference including synchronization between Alice and multiple users (Bobs).

Most point-to-multipoint optical networks use a single-fiber transceiver for the communication (i.e., bidirectional communication with a single fiber). Thus the QKD channel should use the existing fiber with classical communication channels. Then, optical nonlinearities, especially, the spontaneous Raman scattering, generate background photons that become noise photons to the very weak QKD channels. It limits the performance of the system and useable wavelength windows for the QKD channel.

The losses of optical branching devices are dependent on employed devices. For optical power splitter case, the power loss is inversely proportional to number of users. However, it is about 3 – 5 dB for wavelength router cases. These losses limit either transmission length or the key rate. If the time division multiple access are used for the QKD, the user key rate is less than the aggregated key rate/number of users.

There exists crosstalk induced by QKD signals from multiple users when QKD is integrated in the uplink direction, since users share a single fiber. It also brings about synchronization problems for time division multiple access case. Since the fiber lengths between the branching-point to users are different and received photon arrival rate is very small compared with the transmission rate, synchronization of all users becomes very hard.

Beside of these technical issues, the cost of a QKD system will be very critical to use it for a point-to-multipoint network, since this is the most cost sensitive part of the network. In this presentation, these issues will be addressed with some suggested solutions.

**DATE:** **WEDNESDAY, NOVEMBER 19**
**TIME:** **2:35 PM – 3:10 PM**