International Workshop on Recent Experimental Progress in Semiconductor Qubits

---

Programme , Map, and Book of Abstract

University of Science and Technology of China, Hefei, China

13th – 15th September 2017

Background

The International Workshop on Recent Experimental Progress in Semiconductor Qubits is principally an international forum in the discussion about the semiconductor physics enabled quantum science and technology. The research on semiconductor qubit has emerged as one of the leading approaches for the implementation of quantum computing: it promises much faster solutions for array of complex problems.

The first part of the challenges for quantum computing is on the coherent control, which is being attacked in many ways as atomic states, nuclear spins, electron spins, and superconducting loops (to mention just a few) have all been used as candidate qubits. The second part of the challenges on the integration of quantum bits into conventional electronic circuitry, is just starting to be addressed. One of the most promising approach involves qubits in semiconductor hosts, since semiconductors are the materials platform for present-day computing technologies.

The main objective of this workshop is to provide a comprehensive review of the current status and future directions of research on semiconductor qubits for quantum computing. The setup of the workshop should allow free interactions among experts from different fields, and exchanges between experimentalists and theorists.

This workshop includes five main sessions:

1. Multi-qubits logic operation.
2. Silicon based qubits.
3. Spin qubits coherent control.
4. Quantum dot/Microwave resonator hybrid system.
5. Spin/Charge hybrid qubits

This workshop is not only open to experts in the fields related to semiconductor qubits, but to scientists and graduate students who are interested in this general direction of research. Please apply to the workshop by completing the registration. You may contact the workshop secretary, Dr. Hao Tan, at tanhao@ustc.edu.cn for further information.

Organizing Committee of the Workshop
Guoping Guo (USTC)
Hongwen Jiang (UCLA)
Guangcan Guo (USTC)

Workshop Schedule

Wednesday 13th of September 2017

8:30 – 9:00 **Opening remarks and welcome by sponsors**
9:00 – 9:30 **Introduction of conference and QT by Prof. Guo**
Session 1: Multi qubit logical gates
9:30 – 10:30 **Menno Veldhorst (UNSW, Austria, and Delft University of Technology, Netherlands)**
10:30 – 10:45 **Coffee break**
10:45 – 11:45 **Ming Xiao (University of Science and Technology of China, China)**
11:45 – 13:00 **Lunch and rest**
Session 2: Silicon Based Qubits
13:00 – 14:00 **Seigo Tarucha (The University of Tokyo, Japan)**
14:00 – 14:15 **Coffee break**
14:15 – 15:15 **Silvano De Franceschi (Université Grenoble Alpes, France)**
15:15 – 16:15 **Poster pitches**
16:15 – 17:00 **Coffee break and poster viewing**
18:30 – **Dinner**

Workshop Schedule (cont'd)

Thursday 14th of September 2017

Session 3: Spin Qubits Coherent Control
8:30 – 9:30 **Lieven Vandersypen (Delft University of Technology, Netherlands)**
9:30 – 9:45 **Coffee break**
9:45 – 10:45 **Ferdinand Kuemmeth (University of Copenhagen, Denmark)**
10:45 – 11:45 **Laboratory visit**
11:45 – 13:00 **Lunch and rest**
Session 4: Quantum Dot/Microwave Resonator Hybrid System
13:00 – 14:00 **Jason Petta (Princeton University, USA)**
14:00 – 15:00 **Klaus Ensslin (ETH, Switzerland)**
15:00 – 15:15 **Coffee break**
15:15 – 16:15 **Guangwei Deng (University of Science and Technology of China, China)**
16:15 – 17:15 **Francois Mallet (PSL Research University, France)**
18:30 – **Dinner**

Workshop Schedule (cont'd)

Friday 15th of September 2017

Session 5: Spin/Charge Hybrid Qubits
8:30 – 9:30 **Mark A. Eriksson (University of Wisconsin-Madison, USA)**
9:30 – 9:45 **Coffee break**
9:45 – 10:45 **Gang Cao (University of Science and Technology of China, China)**
10:45 – 11:15 **Closing remarks by sponsors**
12:00 – **Lunch and campus walking**

Route of USTC

There are five gates around this campus (USTC east campus):
The workshop location is close to the north gate, the upside one (along the Huangshan Road) in the following map.

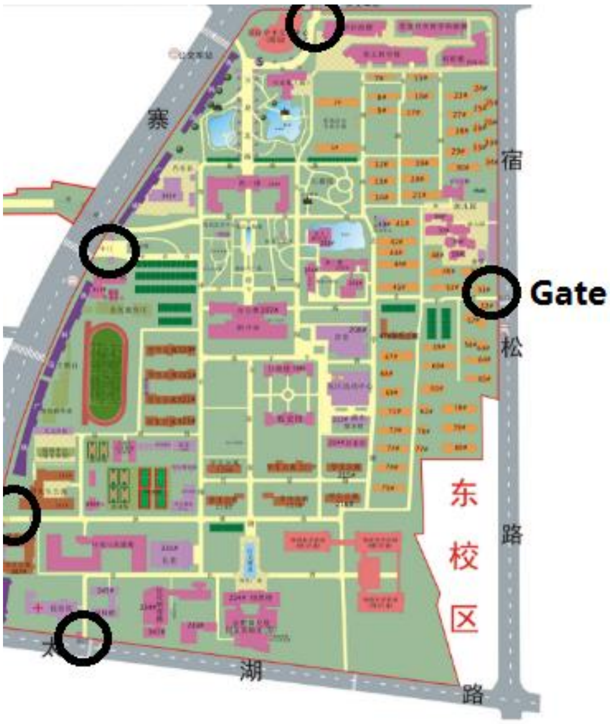


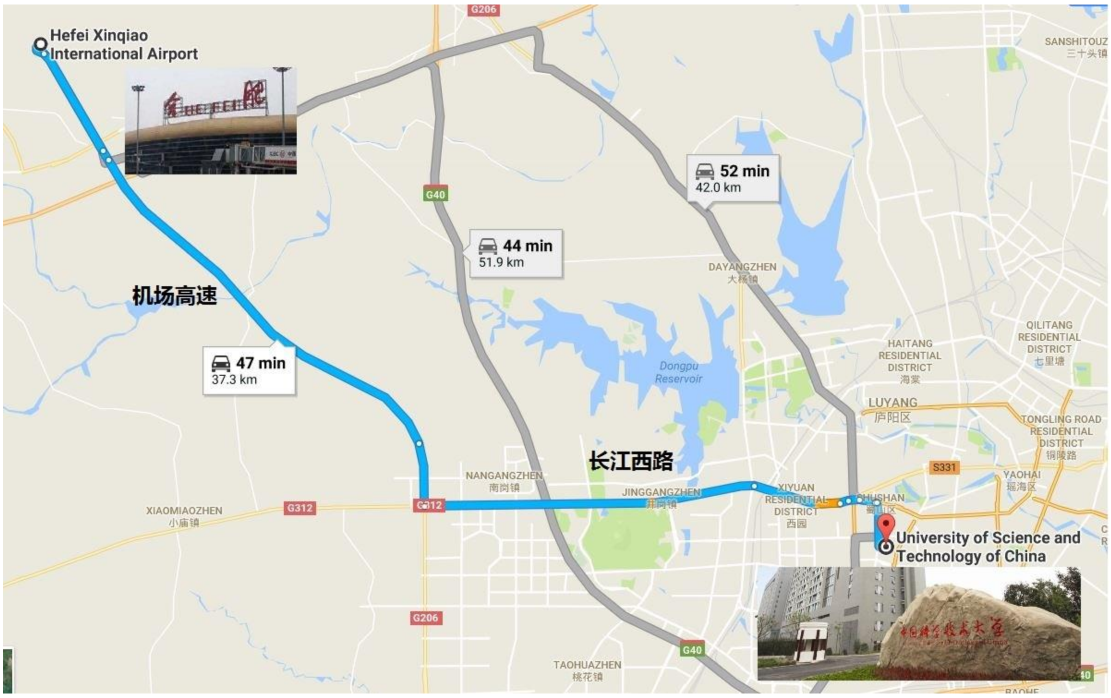
Fig 1. Five gates around east campus

Fig 2. Workshop and our lab location.

Taking a taxi is advised, if you have any trouble when English communication or something else, please let the driver contact **<u>18225881725</u>** **or show the following Chinese sentences. (如需帮助，请拨打此号码)**

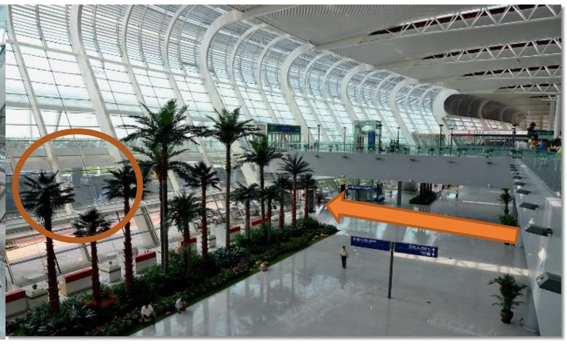
From Hefei Xinqiao International Airport:

It takes nearly 1 hour and about 110 RMB by taxi.

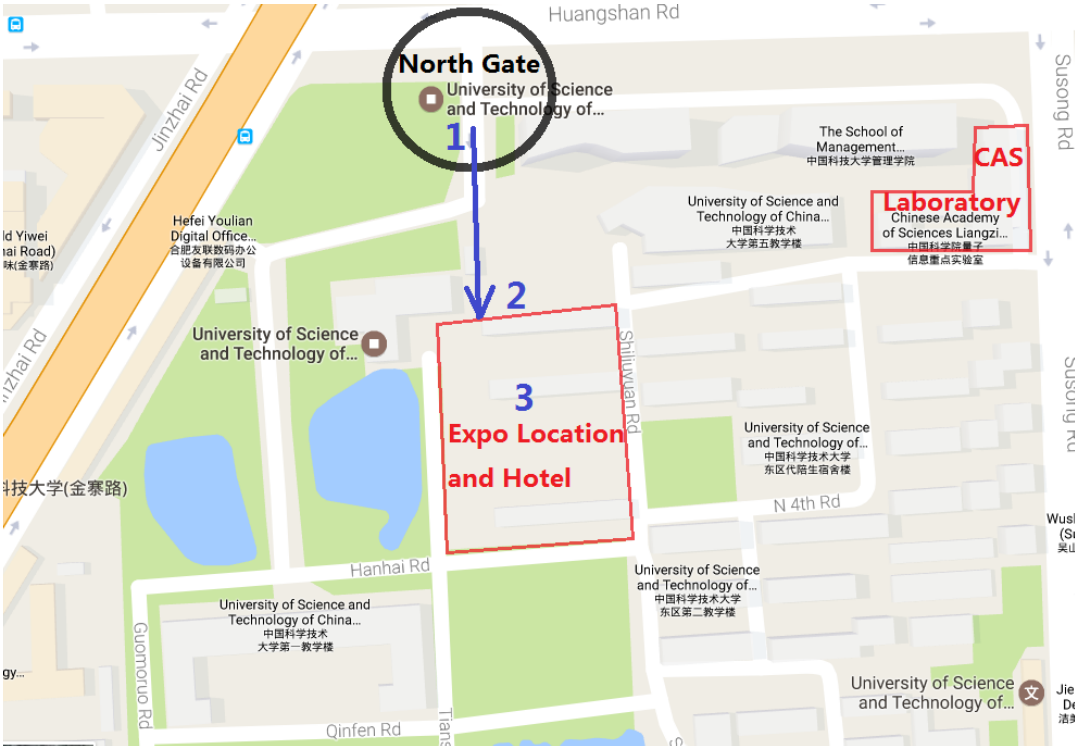


-- Where is the taxi area at the airport ?

-- Just outside the exit as following (orange circle).



At the USTC gate, where to get to the hotel ?



1: Entrance gate image

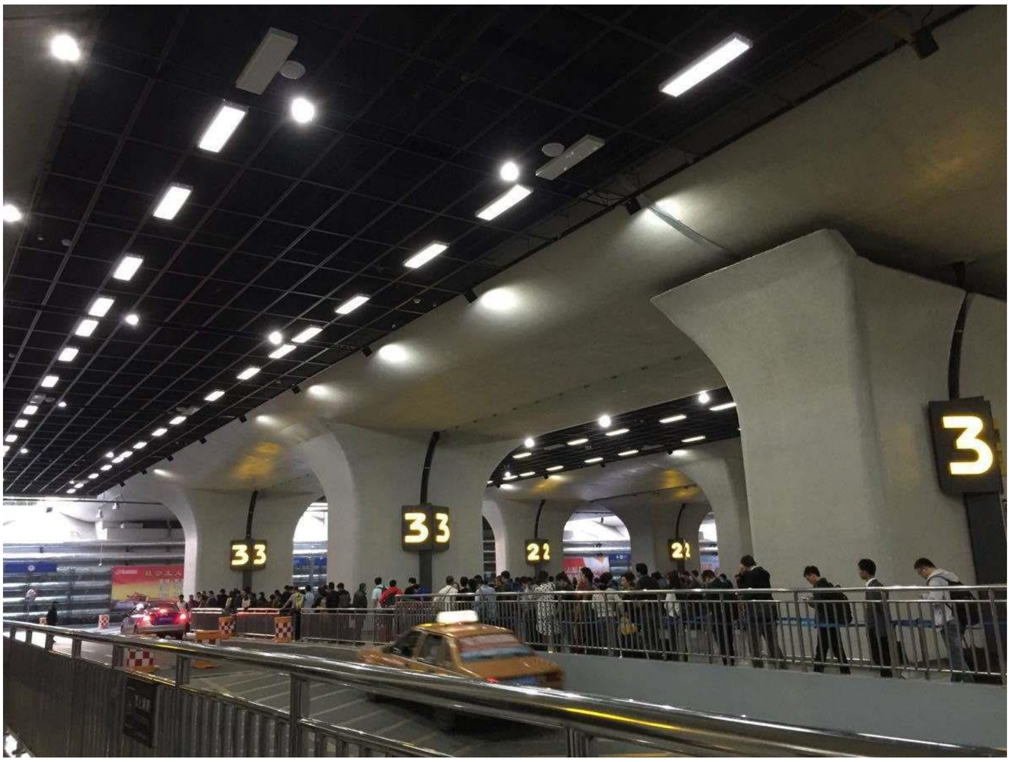
2: Turning location

3: Entrance of the hotel

***From Hefei South Station (Railway)**:*

It takes 15 mins and about 18 RMB by taxi.

There is some indicators for the taxi area, if you have trouble to recognize, please show this sentence to any passerby “**请问，出租车在哪里？如果您不会英语，请指给我方向，谢谢**”。



Abstracts

A Crossbar Network for Silicon Spin Qubits

M. Veldhorst

QuTech and Kavli Institute of Nanoscience, TU Delft, The Netherlands

The spin states of single electrons in gate-defined quantum dots satisfy crucial requirements for a quantum computer. These include extremely long coherence times, high-fidelity quantum operation, and the ability to shuttle electrons as a mechanism for on-chip flying qubits. In order to increase the number of qubits to the thousands or millions of qubits needed for practical quantum information we introduce an efficient architecture based on crossbar control, where only a limited number of control lines is needed. The qubit grid design enables flexible qubit arrangement and crucially provides a mechanism for creating long-range entanglement, opening a path towards non-planar quantum error correction protocols. The qubit grid is based on a three-layer design to define plunger and tunnel gates. We show that a double strip line on top of the structure can drive high-fidelity single-qubit rotations without excessive heating. Direct currents through the superconducting lines that define the barrier gates provide a self-aligned magnetic field distribution and enable qubit addressability and readout. Qubit coupling is based on the exchange interaction, and we show that parallel two-qubit gates can be performed at the detuning noise insensitive point. While the architecture requires a high level of uniformity, it stands out for its simplicity and provides prospects to be realized in the near future, such that large-scale quantum computation becomes within sight.

Multiple Semiconductor Charge Qubits

Ming Xiao

Key Laboratory of Quantum Information, Chinese Academy of Sciences
Synergetic Innovation Center of Quantum Information & Quantum Physics
University of Science and Technology of China, Hefei 230026, China

Semiconductor quantum dots (QD) are a leading approach for the physical implementation of quantum computation, mainly due to their potential for large-scale integration. Here we report our progress on making single and multiple qubits in semiconductor quantum dots, by taking advantage of their easiness to electrically define, manipulate, and measure two-level quantum systems.

Our particular proposal makes use of the charge degree of freedom of a GaAs/AlGaAs double quantum dot where the logical basis is defined by whether an electron is localized to one dot or the other. We developed a way to rotate both the amplitude and phase of the electron wavefunction with adiabatic electric voltage pulses, and therefore to realize a universal set of single qubit logic gates with ultrafast speed.

Through their electrostatic interactions readily controlled by electric gate voltages, double and triple qubits composed of neighboring double quantum dots can be strongly coupled. Based on this, one qubit's coherent rotation is conditioned on another qubit's state, and on both of other two qubits' states. This enables us to perform a two-qubit controlled-NOT (CNOT) gate. By integrating two control qubits and one target qubit in a combination of a linear array and a T-gate architectures, we also demonstrated the functionality of a three-qubit Toffoli gate.

Spin Dephasing and its Suppression in GaAs and Si Quantum Dots

Seigo Tarucha

Department of Applied Physics, The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan
Center for Emergent Matter Science, RIKEN, Wako-shi, Saitama, 361-0198, Japan

Quantum dephasing is yet a critical problem in implementing fault tolerant solid-state quantum computing. Quality factor as defined by the dephasing time divided by qubit gating time is a measure of gate fidelity. To date various kinds of techniques have been developed to improve the quality factor by fast gating of qubit states and reduction of influences from the noise environment, magnetic or electrical. I will discuss spin dephasing measured for quantum dots (QDs) made out of GaAs, natural Si/SiGe and isotopically purified Si/SiGe and how to suppress the dephasing and increase the gate fidelity well exceeding the threshold of fault tolerant qubit gates. In GaAs QDs the dephasing arises from the fluctuating nuclear spin bath. This noise is time-correlated and the variance increases with increasing correlation time from msec to 100 sec (Non-ergodic) and then becomes saturated (Ergodic). We employ a micro-magnet technique for making fast the qubit gates and a fast measurement under the non-ergodic condition as well as a fast feedback control to compensate for the magnetic noise. The highest gate fidelity of spin-1/2 qubits achieved is 97 %. On the other hand, in Si QDs the magnetic noise is significantly reduced but electrical noise can be crucial instead. We apply the micro-magnet technique for natural Si/SiGe QDs and isotopically purified Si/SiGe QDs, and obtain the fidelity of 99.6%, and 99.9 %, respectively. Particularly for the isotopically purified Si/SiGe QDs, we find the fidelity is limited by charge noise. Finally, I will discuss influences of strong microwave drive of Rabi oscillations to lower the quality factor.

Intrinsic Mechanisms for Electrically Driven Spin Qubits in Silicon

Alessandro Crippa[1,4], Andrea Corna[1,4], Leo Bourdet[2,4], Romain Maurand[1,4], Dharmraj Kotekar-Patil[1,4], Heorhii Bohuslavskyi[1,2,4], Romain Lavieville[1,2,4], Louis Hutin[3,4], Benoit Bertrand[3,4], Sylvain Barraud[3,4], Xavier Jehl[1,4], Yann-Michel Niquet[2,4], Marc Sanquer[1,4], Maud Vinet[3,4], Silvano De Franceschi[1,4]

[1] *CEA, INAC-PHELIQS, Grenoble, France*
[2] *CEA, INAC-MEM, Grenoble, France*
[3] *CEA, LETI-MINATEC, Grenoble, France*
[4] *University Grenoble Alpes, Grenoble, France*

The use of electric-dipole spin resonance (EDSR) for spin-qubit manipulation, as opposed to the more conventional magnetic-field control, may facilitate the scalability of semiconductor spin qubits by reducing the overhead for their control hardware and by allowing for faster manipulation. The spin-orbit (SO) interaction provides a natural mechanism for coupling an electronic spin degree of freedom to a gate-voltage driven electric-field modulation.
In the conduction band of silicon, the SO interaction is known to be very weak though. Here we demonstrate that in a silicon-on-insulator nanowire quantum dot, relatively fast EDSR can still be achieved through a special interplay of the weak SO interaction and the multi-valley structure of the silicon conduction band[1]. We present a simple model capturing the essential physics and use tight-binding simulations to support our analysis.
An alternative route consists in using holes instead of electrons. The valance-band states of silicon are in fact characterized by a sizeable SO interaction. Following our proof-of-concept demonstration of a hole-spin qubit in a silicon-on-insulator device[2], we have recently carried out a systematic study of the underlying EDSR mechanism[3]. The main results will be presented in the second part of the talk.

This work was supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 688539 MOSQUITO. Part of the calculations were run on the TGCC/Curie and CINECA/Marconi machines using allocations from GENCI and PRACE.

References:

[1] A. Corna et al., arXiv:1708.02903.
[2] R. Maurand et al., Nature Communications 7, 13575 (2016).
[3] A. Crippa et al., in preparation.

A “Spins-inside” Quantum Processor

L.M.K. Vandersypen

QuTech and Kavli Institute of Nanoscience, TU Delft, Lorentzweg 1, 2628 CJ Delft, Netherlands

Quantum computation has captivated the minds of many for almost two decades. For most of that time, it was seen mostly as an extremely interesting scientific problem. In the last few years, we have entered a new phase as the belief has grown that a large-scale quantum computer may actually be built. Quantum bits encoded in the spin state of individual electrons in silicon quantum dot arrays, have emerged as a highly promising direction. In this talk, I will present progress in our group along three fronts.

First, we have achieved universal all-electrical control of two spin qubits in a double quantum dot, in combination with individual single-shot read-out of each qubit [unpublished]. We have begun to test quantum algorithms and other protocols to test and demonstrate integrated device operation. This work builds on our earlier work on all-electrical single-spin manipulation in a Si/SiGe quantum dot [1].

Second, we have explored coherent coupling of spin qubits at a distance via two routes. In the first approach, the electron spins remain in place and our coupled via an intermediary degree of freedom [2]. In the second approach, spins are shuttled along a quantum dot array, preserving both the spin projection [3] and spin phase [4].

Third, we have developed new concepts and techniques that make quantum dot arrays a credible platform for quantum simulation of the Mott-Hubbard model. As a first demonstration, we map out the transition from Coulomb blockade to collective Coulomb blockade, the finite-size analogue of the Mott insulator transition [unpublished].

When combined, the progress along these various fronts can lead the way to scalable networks of high-fidelity spin qubit registers for computation and simulation.

References:

[1] E. Kawakami, T. Jullien, P. Scarlino, D.R. Ward, D.E. Savage, M.G. Lagaly, V.V. Dobrovitski, Mark Friesen, S.N. Coppersmith, M.A. Eriksson and L.M.K. Vandersypen, Gate fidelity and coherence of an electron spin in a Si/SiGe quantum dot with magnet, Proceedings of the National Academy of Science, 113, 11738–11743 (2016)

[2] T.A. Baart, T. Fujita, C. Reichl, W. Wegscheider, L.M.K. Vandersypen, Coherent spin-exchange via a quantum mediator, Nature Nanotechnology, 12, 26–30 (2017)

[3] T. A. Baart, M. Shafiei, T. Fujita, C. Reichl, W. Wegscheider, L. M. K. Vandersypen, Single-Spin CCD, Nature Nanotechnology 11, 330-334 (2016)

[4] T. Fujita, T. A. Baart, C. Reichl, W. Wegscheider, L. M. K. Vandersypen, Coherent shuttle of electron-spin states, njp Q Info, in print, see arXiv:1701.00815
[5] T. Hensgens, T. Fujita, L. Janssen, Xiao Li, C. J. Van Diepen, C. Reichl, W. Wegscheider, S. Das Sarma, L. M. K. Vandersypen, Quantum simulation of a Fermi-Hubbard model using a semiconductor quantum dot array, Nature, in print, see arXiv:1702.07511

Gate Control of Spin Exchange Processes in GaAs Multidot Devices

Ferdinand Kuemmeth

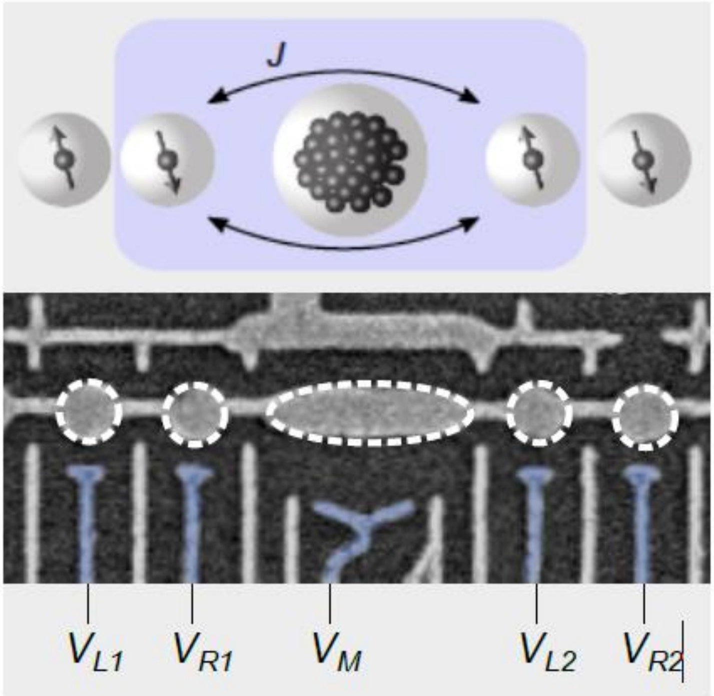
Center for Quantum Devices, Niels Bohr Institute
University of Copenhagen, Denmark

I will present recent results on how to control the spin exchange dynamics between neighboring GaAs quantum dots in order to implement coherent operations in multidot devices.

Using a linear array of quantum dots in a GaAs heterostructures, defined and controlled by top gates, I will explore different configurations and choices of inducing coherent spin exchange processes. I will explain the use of pulsed barriers to implement symmetric exchange pulses, resulting in an enhancement of two-electron coherence at electrical sweet spots. I will then show the symmetric tuning of triple-dot qubits, yielding multi-dimensional electrical sweet spots in the three-electron spin spectrum, and demonstrate coherent control using an IQ-modulated resonant control tone.

As an application of high-quality exchange pulses (employing more than a a thousand control π pulses), I will demonstrate notch filtering of the nuclear spin noise present in these samples. In fact, at high magnetic fields we find that qubit depasing originates from nuclear Larmor precessions, occurring at well-defined discrete frequencies associated with ^{69}Ga, ^{71}Ga, and ^{75}As nuclear spins. By applying pulse sequences that implement notch filters at exactly these discrete frequencies we extend qubit coherence times to 0.87 ms, i.e. more than five orders of magnitude longer than the duration of a π exchange gate in the same device.

Finally, I will show coherent spin exchange processes that involve a large multielectron dot (occupied by approximately 100 electrons). We find that the resulting spin-exchange coupling can have opposite sign compared to exchange between singly-occupied dots, indicating the presence of non-trivial electron correlations. By coupling two singlet-triplet qubit to a multielectron dot, we map out different configurations useful for long-distance spin exchange, including superexchange, direct spin exchange, and on-site exchange mediated by the multielectron dot. Our results show a pathway to implementing fast, non-nearest neighbor two-qubit gates in semiconducting spin qubits.



Top panel:
A central multielectron dot is used to mediate exchange coupling J between two double dots, each operated as a singlet-triplet qubit.

Bottom panel:
Fast electrical control of non-nearest neighbor spin exchange is accomplished by pulsing five gate electrodes simultaneously (shaded in blue) on top of a GaAs heterostructure.

A Coherent Spin-Photon Interface in Silicon

Jason Petta

Princeton University, Department of Physics

Electron spins in silicon quantum dots are attractive quantum bits (qubits) due to their long coherence times and the promise of rapid scaling using semiconductor fabrication techniques. While nearest neighbor exchange coupling has been demonstrated, the interaction of spins via microwave frequency photons could enable long distance spin-spin coupling and “all-to-all” qubit connectivity. Here we couple a single spin in silicon to a microwave frequency photon using a coupling mechanism that is based on spin-charge hybridization in the presence of a strong magnetic field gradient. Spin-cavity coupling rates $g_s/2 > 10$ MHz are achieved and vacuum Rabi splitting is observed in the cavity transmission, indicating strong spin-photon coupling. These results open a direct path toward entangling single spins using microwave frequency photons.

Strong Coupling of a Superconducting Resonator to a Charge Qubit

A. Stockklauser, P. Scarlino, A. Landig, J. Koski, S. Gasparinetti, C. Kraglund Andersen, C. Reichl, W. Wegscheider, T. Ihn, A. Wallraff and K. Ensslin

Solid State Physics, ETH Zurich, Switzerland

We demonstrate the strong coupling limit with individual electronic charges in GaAs double quantum dots by using the enhancement of the electric component of the vacuum fluctuations by increasing the resonator impedance Z_r beyond the typical 50 Ω of a standard coplanar waveguide. We have realized a frequency-tunable microwave resonator with impedance $Z_r \sim 1.8$ kΩ using the large inductance $L_r \sim 50$ nH of a SQUID array combined with a small stray capacitance $C_r \sim 15$ fF. Its resonance frequency, and thus also its impedance, is tunable by applying a small magnetic field using a mm-sized coil mounted on the sample holder. The frequency tunability of the resonator is particularly useful in this context, as it allows for the systematic study of its interaction with semiconductor nanostructures without changing their electrical bias conditions. In the resonant regime, we resolve the vacuum Rabi mode splitting of 238 MHz at a resonator linewidth 12 MHz and a charge qubit decoherence rate of 40 MHz extracted independently from microwave spectroscopy in the dispersive regime. In addition we demonstrate a semiconductor charge qubit coupled to a TiNbN superconducting resonator operated at magnetic fields up to 5T. This way spin effects such as spin blockade in the double quantum dot can be investigated using microwave resonators.

Coupling Quantum Dots with Microwave and Nano-electromechanical Resonators

Guang-Wei Deng

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China.
Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China.

In this talk, I will introduce our recent works on quantum dots based hybrid systems, including microwave and nano-electromechanical resonators. First, I will show how graphene-based double quantum dots can be coupled with a microwave resonator. Here the resonator can not only be treated as a measurement tool but can also operate as a quantum bus to connect distant quantum dots. Four-fold periodicity of the dephasing rates in graphene quantum dots and non-classical current cross-correlations between two quantum dots are observed. Second, I will show the potential using nano-electromechanical resonators as phonon buses in quantum dot chips. I will introduce some works about strongly coupled nano-mechanical resonators based on carbon materials, such as carbon nanotube and graphene. These resonators have very high resonance frequencies and are highly tunable. We have experimentally realized the strong coupling between charge transport and mechancial motions, and we have also observed the strong coupling between different modes of one mechanical resonator. Moreover, we have realized the coherent phonon Rabi operation using the strong coupling and we further implement the distant strong coupling between two mechaical resonators. These results have shown that the strongly coupled nano-mechanical resonators can provide a platform for the coherent electron-phonon interactions, the long distance phonon (electron) interactions and entanglement state generation, and we can exploit them as future quantum buses.

Hybrid Quantum Circuits with Carbon Nanotubes

François Mallet

PSL Research University, France

Carbon nanotubes are low dimensional conductors which can be used to implement various types of model system. They can be used to investigate various aspects of condensed matter system ranging from atomic like systems (i.e. quantum dots) to strongly correlated electron systems. In the first part of my talk, I will present our recent work in which we combine superconducting contacts with a magnetic texture proximal to a carbon nanotube. We demonstrate a large synthetic spin orbit interaction which deeply modifies the induced superconducting correlations in the carbon nanotube. We also observe a zero bias conductance peak which is the hallmark of Majorana zero modes.

The Quantum Dot Hybrid Qubit in Silicon

Mark A. Eriksson

Wisconsin Institute for Quantum Information and Department of Physics
University of Wisconsin-Madison

One of the remarkable features of spins in the solid state is the enormous range of time-scales over which coherent manipulation is possible. If one considers gate-controlled manipulation of nuclear spins at one extreme [1], and strongly-interacting multi-electron qubits at the other extreme [2-4], coherent control of spins in semiconductors has been demonstrated with over 9 orders of magnitude variation in the manipulation time. Remarkably, confining three electrons in two neighboring quantum dots – the quantum dot hybrid qubit (QDHQ) – enables all electrical control and measurement of spin dynamics on time scales less than one nanosecond [5]. In this talk I will describe implementations of this qubit in Si, describing two different manipulation modes, dc and ac, and I will discuss the important role that valley splitting has played in early implementations of this qubit.

[1] J. T. Muhonen, et al., *Nat. Nanotechn.* **9**, 986 (2014).
[2] D. P. Divincenzo, et al., *Nature* **408**, 339 (2000).
[3] J. Levy, *Phys. Rev. Lett.* **89**, 147902 (2002).
[4] Z. Shi, et al., *Phys. Rev. Lett.* **108**, 140503 (2012).
[5] D. Kim, et al., *Nature* **511**, 70 (2014).

This work sponsored in part by the Army Research Office (ARO) under Grant Numbers W911NF-17-1-0274 and W911NF-12-1-0607, by NSF (DMR-1206915, PHY-1104660, DGE-1256259) and by the Vannevar Bush Faculty Fellowship program sponsored by the Basic Research Office of the Assistant Secretary of Defense for Research and Engineering and funded by ONR through grant N00014-15-1-0029. Development and maintenance of the growth facilities used for fabricating samples is supported by DOE (DE-FG02-03ER46028). The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Office (ARO), or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein. This research used facilities supported by NSF through DMR-1121288.

Tunable Hybrid Qubit in GaAs Quantum Dot System

Gang Cao

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

Synergetic Innovation Center of Quantum Information & Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China

Finding a balance between coherence and maneuverability is an open problem in the pursuit of a scalable solid state quantum computer. A hybrid qubit is one of the proposals that attempt to address this issue.

We firstly demonstrate the tunable hybrid qubit in a five-electron GaAs double quantum dot. The qubit is encoded in the (1,4) charge regime of the double dot, and can be manipulated completely electrically. More importantly, dot anharmonicity leads to quasi-parallel energy levels and a new anti-crossing, which help preserve quantum coherence of the qubit and yield a useful working point. We have performed experiments near the new working point, and find that the qubit decoherence time is significantly improved over a charge qubit.

Moreover, a triple-dot-based hybrid qubit is demonstrated. The coherent oscillation experiment shows that the present triplet-dot hybrid qubit is comparable to the double-dot hybrid qubit in terms of the coherence time and completely electrical manipulation. More importantly, the operation frequency of the hybrid qubit can be conveniently tuned from 2 to about 15 GHz.

Posters

Josephson Traveling-wave Parametric Amplifier and Purcell Filter Design

Guangming Xue, Guoping Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

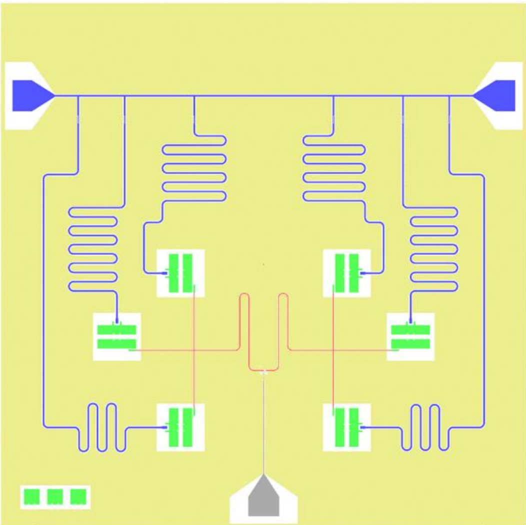
Coupling between qubit and environment is a key factor resulting in qubit relaxation. Low noise amplifier and filter can reduce the influence of environment noise. Here we design and fabricate Josephson traveling-wave parametric amplifier and stepped impedance Purcell filter. Both devices could be used to enhance the performance of qubit.

A six-qubit circuit design using tunable quantum bus

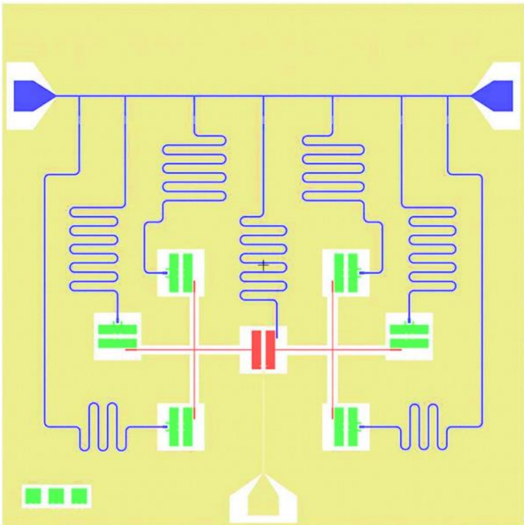
Weicheng Kong, Guangming Xue, Zhilong Jia, Peng Duan and Guoping Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

Superconducting qubits are one promising platform for implementing fault-tolerant quantum computing. As qubit number increasing, an optimal circuit design is especially important, which can reduce the impact on qubit dephasing, and achieve more efficient qubit manipulation. One natural choice is the use of quantum bus. In this poster, we propose a six-qubit circuit design using tunable quantum bus. Via modulating a tunable quantum bus, XX+YY interaction can be activated between any pair of qubits, which can act as natural iSWAP two-qubit gate. The architecture enables the combination of inputs and outputs, results in easier qubit control and readout.



6-qubit structure with bus resonator



6-qubit structure with bus qubit

A six-qubit circuit design using tunable quantum bus

Peng Duan, Guangming Xue, and Guoping Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

Superconducting circuits and semiconductor quantum dot are very suitable hybridization because of the similar fabrication process, like lithography and film deposition.

This poster focus on the fabrication and characterization of superconducting quantum devices such as superconducting resonators with internal quality above one million and superconducting qubits based on superconducting Josephson junctions with lifetime approaching 15 microsecond. Further demonstration of the swap between two qubits imply the capability of multiqubit entanglement and realizing universal two qubit gates in this circuits.

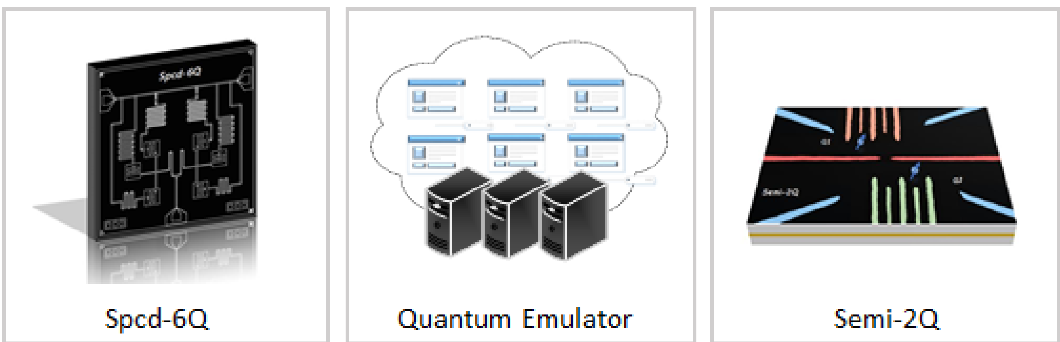
Quantum computing platform

Zhilong Jia, Guangming Xue, and Guoping Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

Some companies or groups in the world have their online quantum computing platform or quantum system.

This poster is a brief introduction of our quantum computing platform which will be accessed online in some days. The first thing is to create quantum program code. Both graphical and text programming interface are provided in our webpage. And then, we have three ways to execute the quantum code. They are quantum emulator, Two-Qubits semiconductor quantum processor and Six-Qubits superconducting quantum processor. In the end, the poster has a brief introduction of our quantum control system, which is a bridge between classical world and quantum world.

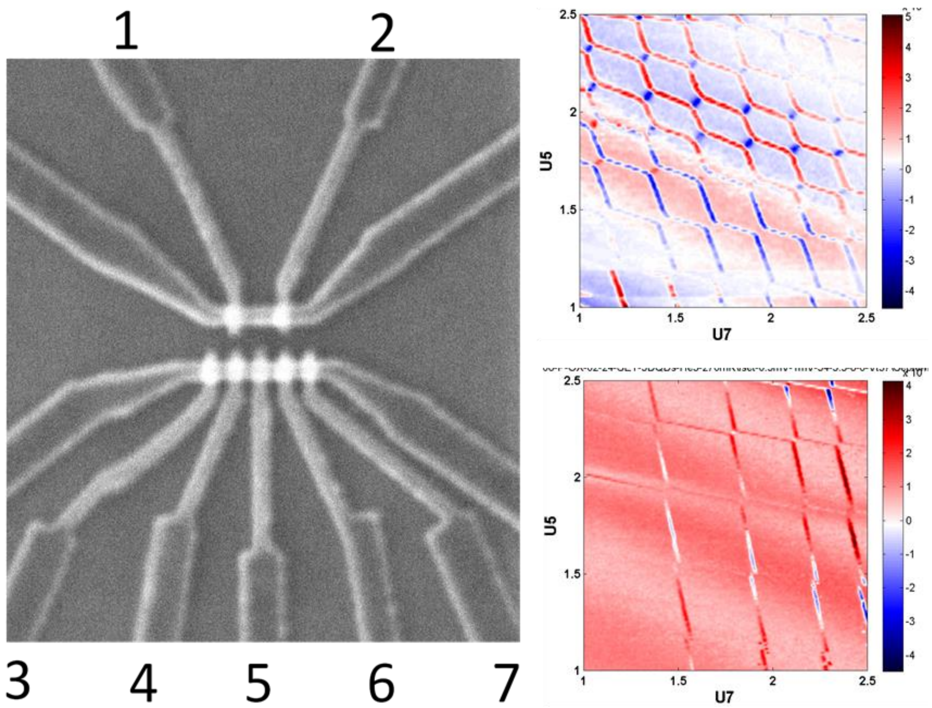


Charge sensing and controllable coupling in a Si-nMOS double quantum dot

Hai-Ou Li, Xin Zhang, Fang-Ming Jing, Ming Xiao, and Guo-Ping Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

Silicon is an attractive candidate for quantum information processing due to the long spin coherence times. We demonstrate the development of a double quantum dot with an integrated charge sensor fabricated in SiO2/Si wafer using overlaping-gated design. Based on the evaluation of the integrated charge sensor, the double quantum dot can be tuned to a few-electron region. Additionally, the inter-dot coupling of the double quantum dot can be tuned to a large extent according to the voltage on the middle gate.

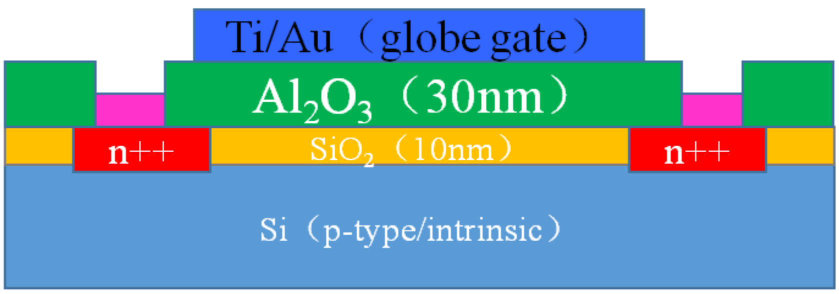


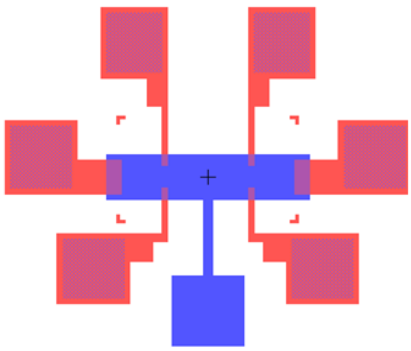
Magnetotransport Studies of Density and Mobility on Si-nMOS Structure

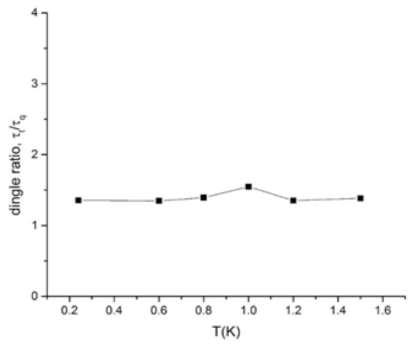
Ke Wang, Hai-Ou Li, Gang Luo, and Guo-Ping Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

In order to get good wafers for quantum dots structure, we have fabricated and characterized scores of Silicon nMOS and pMOS wafers. Finally we can get a mobility of 15000 m^2 / (V s) with Nc almost equal to $2*10^{11}$ cm^{-2} of nMOS wafers. During these tests, we find that the improving quality of nMOS wafer is highly related to the annealing process which can double the mobility compared to non-annealed one.(from 4000 to 9000 cm^2/(V s)) Then we identify the magnetotransport of this type wafer and get the dingle ratio which closes to unity. In this way, we can identify the large angle scattering affect the quality more, such as interface roughness scattering and background impurity scattering.





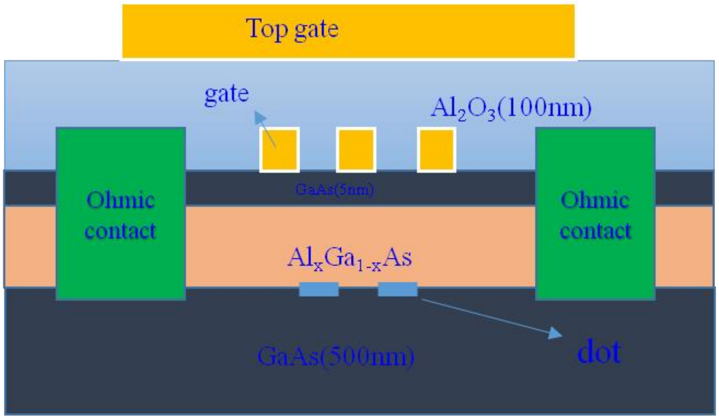


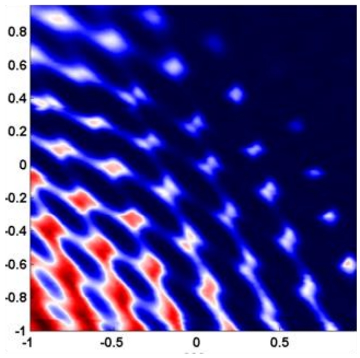
Hole Structure of GaAs & Silicon Quantum Dots

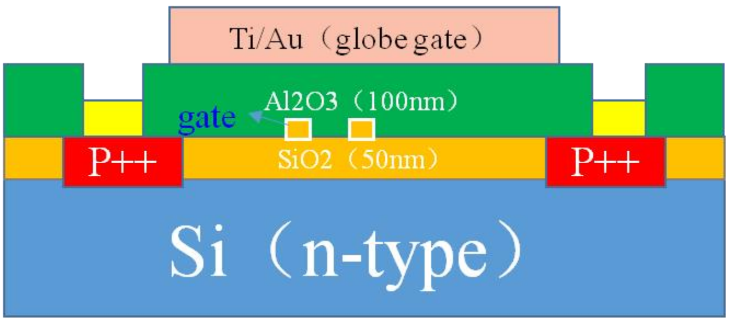
Ke Wang, Hai-Ou Li, Long Yuan, and Guo-Ping Guo

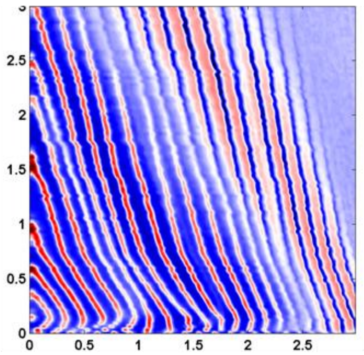
Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

The heavy-holes in both Si and GaAs are promising candidates for all-electrical spin manipulation, owing to the weak hyperfine interaction and strong spin-orbit interaction. We fabricated several structures of double quantum dot, which can define dots and adjust charge stability diagram differently. In order to get few regime, we have to shrink the size of dots compared to electron system of GaAs. Besides, we also defined single dot on Silicon-pMOS wafer with a QPC, in that way we can demonstrate the quality of wafers for the further design.







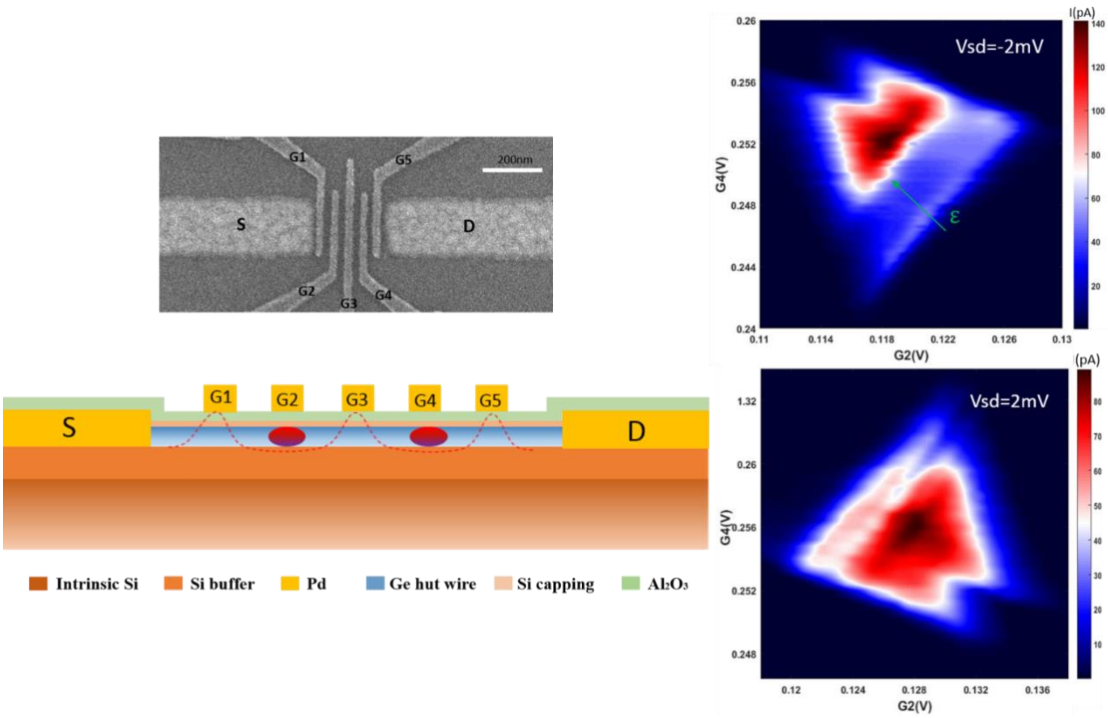


Spin Blockade of Holes in a Germanium Hut Nanowire Double Quantum Dot

Gang Xu, Hai-Ou Li, Jiang-Jun Zhang, and Guo-Ping Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

Holes in Germanium (Ge) have stronger spin-orbit coupling, and longer spin lifetime which provides a fast electrical controllability of the spin state. Ge quantum dots as a promising platform for the realization of high fidelity spin qubits. Therefore, we fabricated Germanium hut nanowire double quantum dot defined by top gates. Creating electrostatically defined, tunability from strong to weak coupling between the dots and demonstrate the Pauli spin blockade at different charge transitions. By analyzing the magnetic field evolution of the leakage current in the blockade regime, we found some blockade regime is dominated by the SOI which is an important step towards a robust hole spin-orbit qubit.

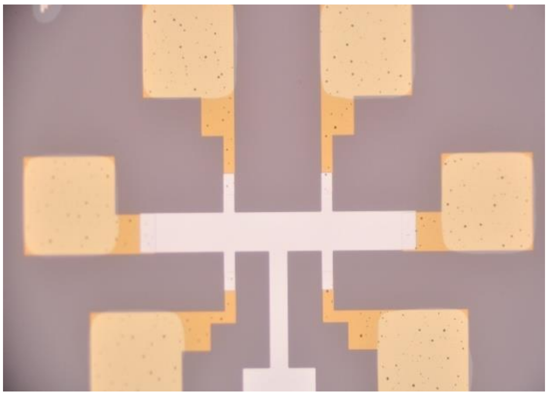


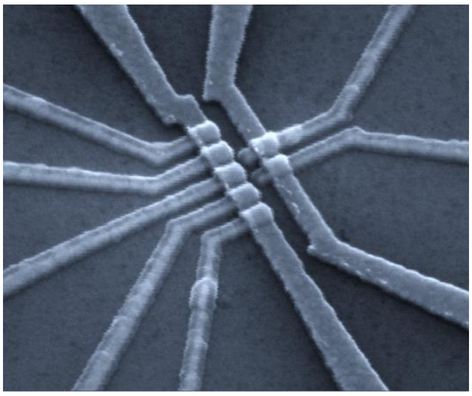
Exploration of the hole system of the quantum dot on undoped GaAs

Long Yuan, Ke Wang, Hai-Ou Li, and Guo-Ping Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

The coupling between hole and nuclear spin is less than that of electron and nuclear spin, leading to longer coherence time. The spin-orbit coupling of hole on undoped GaAs is strong, making EDSR easier to control spin all-electrically. Since there is no intentional doping, GaAs/AlGaAs heterostructures are considered to be much more stable owing to the absence of ionized impurities. In order to get good wafer for quantum dots structure, we have fabricated and characterized scores of undoped GaAs/AlGaAs wafer and quantum dot structures. An important work is to explore the annealing conditions to obtain a flat surface of ohmic contact. We also fabricated a double quantum dot based on the nanoribbon structure.





Coupling a Germanium Hut Wire Hole Quantum Dot to a Superconducting Microwave Resonator

Yan Li, Hai-Ou Li, and Guo-Ping Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

Realization strong coupling between spin and resonator is an important issue for scalable quantum computation in semiconductor system. Benefited from dual advantages of strong spin-orbit coupling strength and long coherence time, Ge hut wire, which is proposed to be site-controlled grown for scalability, is considered as a promising candidate to achieve this goal. Here we present a hybrid architecture in which an on-chip superconducting microwave resonator is coupled to the holes in Ge quantum dot. The charge stability diagram can be obtained from the amplitude and phase response of the resonator independently from the dc transport measurement. Furthermore, we determine the hole-resonator coupling rate of $g_c/2\pi$=70 MHz, and estimate the spin-resonator coupling rate $g_s/2\pi$ to be in the range of 1.13~2.25 MHz, demonstrating that it is feasible to realize strong coupling between hole spins and microwave photons on Ge hut wire with the optimized schemes in the prospective investigation.

Measuring hole spin states of single quantum dot in germanium hut wire

Yan Li, Hai-Ou Li, and Guo-Ping Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

As a group IV material with confined holes, the germanium hut wire is considered a promising candidate for achieving fast electrically controlled spin qubits. Here we fabricated a single quantum dot device on a germanium hut wire and a standard charge stability diagram with excited states was observed by DC transport measurements. By analyzing the Zeeman splitting behaviors of each state, we chose a window for distinguishing different hole parities and spin states, launching the first step towards a useful spin qubit. Effective g-factors around 4.3 for both even and odd hole number states were also extracted.

Kondo effect in quantum dots

Runan Shang, and Guo-Ping Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

The Kondo effect is an essential many-body physics theory that is actively researched in condensed matter physics. Quantum dots (QDs) are an excellent platform to study the Kondo effect because of their precise parameters controllability. In QD an electron spin-flip process under Kondo effect induces a transport resonance through a Coulomb blockade region. Besides spin, the pseudospin Kondo effect might occur in QDs under pseudospin-flip process. However, in gallium arsenide (GaAs) QDs corresponding experimental studies are few as natural pseudospin is absent. Here we show the following results in a series GaAs double quantum dots (DQDs) devices with artificial orbital pseudospin: 1). In a region of one electron, complete spectra with three resonance peaks are observed corresponding to an orbital-spin Kondo effect. 2). Pseudospin degeneracy can be tuned under an electric field and the four-fold degeneracy point is realized at a specific value, indicating a transition from the SU(2) to the SU(4) Kondo effect.

Kondo effect in silicon quantum dots

Ting Zhang, Runan Shang, and Guo-Ping Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

Kondo effect as one of hotspots in condensed matter always draws physicist's attention. With the rapid development of nanometer-scale electronic devices, the tunability of semiconductor quantum dots (QDs) systems via electrostatic gates make them ideal platforms to research the Kondo effect in different regimes. Similar with spin impurity, other degree of freedom can be screened by surrounding electrons as well. This induces pseudospin-flip Kondo process. We know that the conduction-band minimum is twofold degenerate in the strained Si used for QDs as compared to the nondegenerate minimum in GaAs. This valley degeneracy make it possible to observe the valley Kondo effect and SU(4) Kondo effect which is different with GaAs dots. In addition, we may have a chance to observe the transition between spin 1/2 Kondo effect, valley Kondo effect and SU(4) Kondo effect by changing the magnetic field B and voltage on electronic gates.

Synthesis of h-BN/Graphene/h-BN heterostructure

Hui Yang, Guoping Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

Atomically thin two-dimensional materials including graphene and hexagonal-boron nitride are attracting significant interest in the research community due to their intrinsic optical and electronic properties. However, the lack of a significant band gap and electron scattering in the surface of substrate limits graphene for use in transistor applications. The stacked heterostructue has been proved as a promising techniques to engineer and control the band structure without significantly altering the mobility. Unfortunately, up to now, there are no effective method to synthesize the heterostructure.

CVD is a very cheap and convenient method to grow large area graphene which was realize by many lab all of the world [1, 2]. So it's very naturally to get the idea that we use CVD tube furnace to deposit h-BN firstly and then deposit graphene on h-BN repeatedly to get sandwich structure. And we did get monolayer graphene and h-BN respectively by CVD (Figure 1, 2). In our recipe, we used Cu as substrate. But when we move toward to synthesize heterostructure, some obstacles come for us. Low vaccum in tube furnace results in oxidation of h-BN so that h-BN layer disappear after we shut down the supply. Even if we can get stable h-BN layer, methane can't fully decompose into carbon because lake of catalyst. So what we need is a new system which can provide high vaccum and continuous catalyst.

During the process of growing larger h-BN domain, we found some new morphography of h-BN. The normal h-BN is triangle, but we can see we got star like patterns. We call it needle because it's very sharp. To investigate the crystal property of the material, TEM was employed (Figure 3). The electron diffraction patterns are coherent with a single orientation, so we can say it's a single crystal rather than polycrystal. We also studied the types of the edge so that we can find out the reason why this happen.

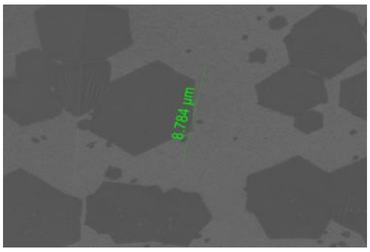


Figure 1. SEM image of graphene

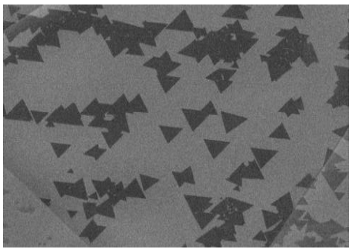


Figure 2. SEM image of h-BN

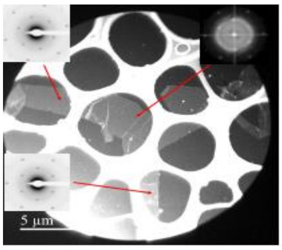


Figure 3. TEM image of h-BN

References

[1] Xuesong Li *et. al*, Nano lett. **10**, 4328–4334, 2010.
[2] Yufeng Hao *et. al*, Science **8** Vol. 342, 2013.

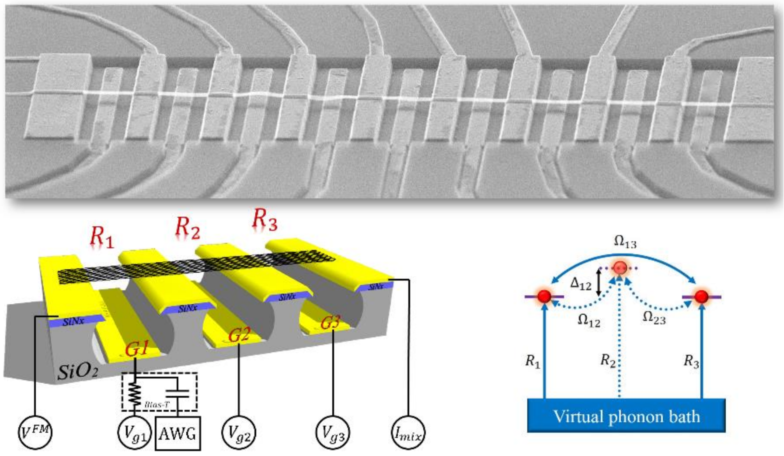
Implementing Phonon Cavity as Quantum Bus

Gang Luo,† Zhuo-Zhi Zhang,† Kai-Long Wang, Guang-Wei Deng* and Guo-Ping Guo*

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

in collaboration with Lin Tian from UC Merced, Xin-He Wang and Kai-Li Jiang from Tsinghua University

Mechanical resonators are promising systems for storing and manipulating information. To transfer information between mechanical modes, either direct coupling or an interface between these modes is needed. In previous works, strong coupling between different modes in a single mechanical resonator and direct interaction between neighboring mechanical resonators have been demonstrated. However, coupling between distant mechanical resonators remains an experimental challenge in this field. In this poster, we review and report our efforts in implementing phonon cavity as quantum bus via experimental observation of strong indirect coupling between separated mechanical resonators in a graphene-based electromechanical system. The coupling is mediated by a far-off-resonant phonon cavity through virtual excitations via a Raman-like process. By controlling the resonant frequency of the phonon cavity, the indirect coupling can be tuned in a wide range. Via the distant coupling, Rabi oscillation is demonstrated between distant phonon states. Because of the coupling between single-electron tunneling and nanomechanical motion, distant phonon mode and single-electron tunneling event can be coupled in this system. Our results may lead to the development of gate-controlled all-mechanical devices and open up the possibility of long-distance mechanical experiments in the quantum regime.



The posted work was partially presented in:

Gang Luo, *et al.*, Nanoscale, 9, 5608-5614 (2017).

Gang Luo, Zhuo-Zhi Zhang *et al.*, submitted to *Nature Nanotechnology*

†These authors contributed equally to this work.

*Correspondence to: gwdeng@ustc.edu.cn or gpguo@ustc.edu.cn

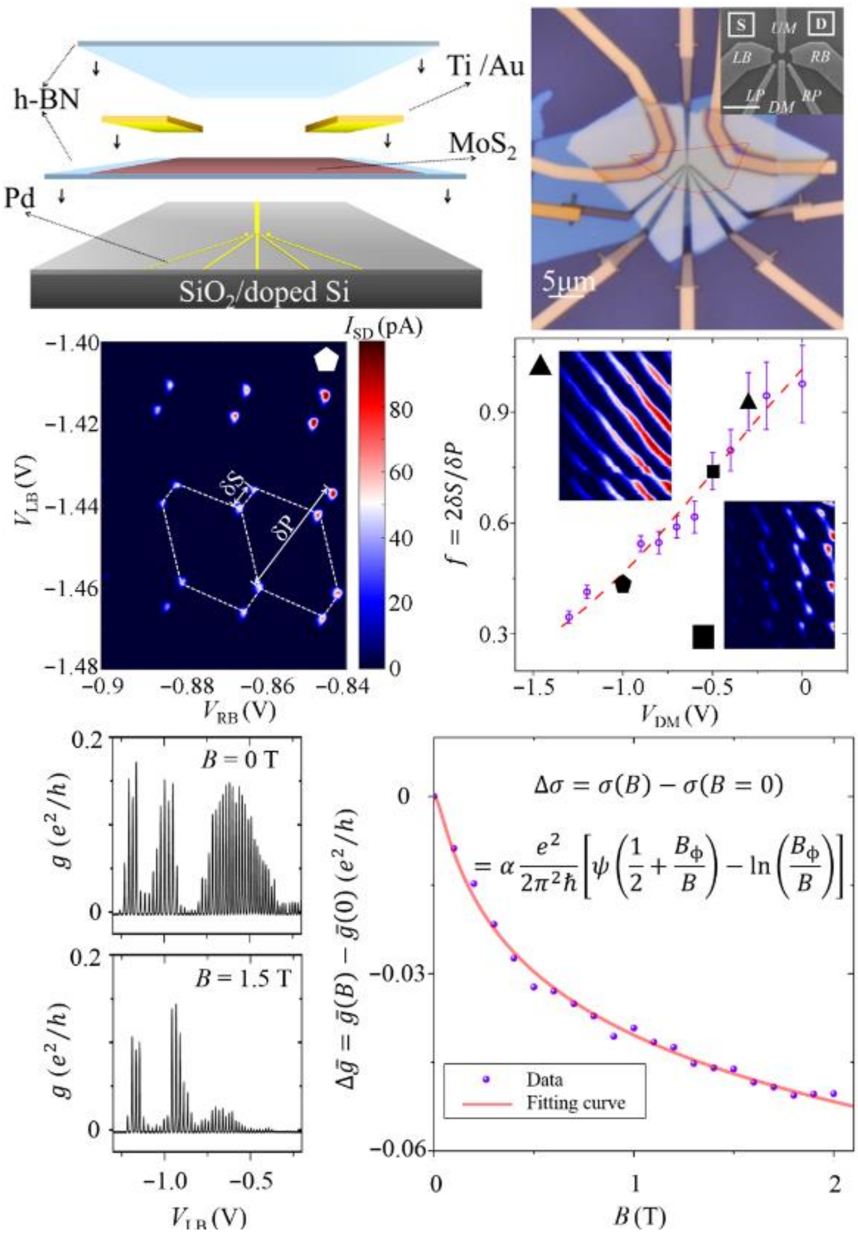
Exploring quantum dot behavior in transition metal dichalcogenides (TMDCs)

Zhuo-Zhi Zhang,† Xiang-Xiang Song,† Gang Luo, Di Liu, Vahid Mosallanejad, Guang-Wei Deng*, and Guo-Ping Guo*

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

in collaboration with T. Taniguchi, K. Watanabe from NIMS and F. Nori from RIKEN

Quantum confinement has made it possible to detect and manipulate single-electron charge and spin states. The recent focus on transition metal dichalcogenides (TMDCs) has attracted significant interests on possible applications to quantum devices, including detecting and manipulating either single-electron charging behavior or spin and valley degrees of freedom. However, most of the experiments studying valley-spin physics in these materials are based on optical methods. The electrical readout and manipulation of valley states in TMDCs, especially down to few-carrier level, remains a tough challenge. In this poster, we review our work in semiconducting TMDCs on 1) achieving single-electron tunneling by forming a single quantum dot (QD); 2) investigation of Coulomb oscillations single QD (especially in temperature dependent behaviors); and 3) realization of gate-controllable double QD. Also, we observed Coulomb blockade weak anti-localization in the low-density regime in MoS_2. Our experiments demonstrate the realization of gate-controllable QDs in TMDCs, and using QD as a tool to study the properties of the material itself. QD in TMDC could be used as a platform for investigating spin-valley physics in these materials. The compatibility with large-scale production, gate controllability, electron-hole bipolarity, as well as new quantum degrees of freedom in the family of 2D materials opens new possibilities for quantum electronics and its applications.



The posted work was presented in:

Xiang-Xiang Song *et al.*, Nanoscale 7, 16867-16873 (2015).

Xiang-Xiang Song *et al.*, Sci. Rep. 5, 16113 (2015).

Gang Luo *et al.*, Front. Phys. 12, 128502 (2017).

Zhuo-Zhi Zhang *et al.*, arXiv: 1704.06871v1

†These authors contributed equally to this work.

*Correspondence to: gwdeng@ustc.edu.cn or gpguo@ustc.edu.cn

A tunable hybrid qubit in a triple quantum dot

Bao-Chuan Wang, Gang Cao, Hai-Ou Li, Ming Xiao, Guang-Can Guo, Xuedong Hu, Hong-Wen Jiang, and Guo-Ping Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, China

We experimentally demonstrate quantum coherent dynamics of a triple-dot-based multi-electron hybrid qubit. Pulsed experiments show that this system can be conveniently initialized, controlled, and measured electrically, and has good coherence time as compared to gate time. Furthermore, the current multi-electron hybrid qubit has an operation frequency that is tunable in a wide range, from 2 to about 15 GHz. We provide qualitative understandings of the experimental observations by mapping it onto a three-electron system, and compare it with the double dot hybrid qubit and the all-exchange triple-dot qubit.