Triple to quintuple quantum dots for making multiple qubits

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To date various types of spin qubits have been developed with quantum dots including spin-1/2, singlet-triplet and exchange-only qubits. We have used a micro-magnet technique to make two spin-1/2 qubits and an entangling gate with a double quantum dot. The necessary step for further scaling up the qubit system is to increase the number of quantum dots having a suitable charge state for qubit system and improve the qubit gate fidelity as well. We have optimized the micro-magnet technique to speed up the X and Z-rotation with a high spin-flip fidelity. In addition we have fabricated three to five tunnel coupled quantum dots in series for making multiple spin qubits. For the triple quantum dot we use two plunger gates for the two side dots to establish the most suitable charge state configuration for making three spin qubits: one electron in each dot and spin blockade for the coupled center and right dot as well as for the left and center dot. We use this configuration to demonstrate c.w. electron spin resonance and Rabi oscillation for the three dots. We discuss a possible scheme for conditional teleportation based on Bell measurement using the working three qubits. For the quadruple quantum dot we first reach the single electron regime for each dot and furthermore demonstrate an efficient tunability of the system in this regime, with which we are able to realize the proper charge state configurations for spin blockade readout.

Electrical control of a long-lived spin qubit in a Si/SiGe quantum dot

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Nanofabricated quantum bits permit large-scale integration but usually suffer from short coherence times due to interactions with their solid-state environment [1]. The outstanding challenge is to engineer the environment so that it minimally affects the qubit, but still allows qubit control and scalability. Here we demonstrate a long-lived single-electron spin qubit in a Si/SiGe quantum dot with all-electrical two-axis control. The spin is driven by resonant microwave electric fields in a transverse magnetic field gradient from a local micromagnet [2], and the spin state is read out in single-shot mode [3]. Electron spin resonance occurs at two closely spaced frequencies, which we attribute to two valley states. Thanks to the weak hyperfine coupling in silicon, a Ramsey decay timescale of 1us is observed, almost two orders of magnitude longer than the intrinsic timescales in GaAs quantum dots, while gate operation times are comparable to those reported in GaAs. The spin echo decay time is around 40us both with one and with four echo pulses, possibly limited by intervalley scattering. These advances strongly improve the prospects for quantum information processing based on quantum dots.

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Hole spin dephasing and spin-orbit coupling in Ge/Si nanowires

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Using electrically gated Ge/Si core/shell nanowires at dilution refrigerator temperatures we investigate confined hole states as spin qubits. Compared to electron-based spin qubits, hole states are expected to allow fast electrical spin manipulation due to strong spin-orbit coupling in the valence band. Compared to III-V spin qubits, these devices are expected to be robust against dephasing by random nuclear spins.

By confining holes in a single quantum dot we perform transport measurements in the Coulomb blockade regime as a function of magnetic field. We observe antilocalization of Coulomb blockade peaks, consistent with strong spin-orbit coupling. By comparing the low-field peak height distribution with the symplectic symmetry class of random matrix theory, we are able to place an upper bound of 25 nm on the spin-orbit length.

By tuning the device into a double quantum dot we can manipulate and measure the spin states using fast (sub-nanosecond) gate pulses and dispersive readout using a radio-frequency LC charge sensor. We observe an inhomogeneous spin dephasing time $T_2^*\sim 0.18\,\mu s$ that exceeds corresponding measurements in III-V semiconductors by more than an order of magnitude, as expected for predominantly nuclear-spin-free materials. Unlike the Gaussian dephasing previously seen in nuclear-spin-dominated materials, we observe a loss of coherence that is exponential in time, indicating the presence of a broadband noise source.

Dopant atoms and molecules in a semiconductor vacuum

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Semiconductor nano devices whose operation derives from the bound states of individual dopants have received considerable attention because of the promise for new functionalities in quantum electronics. Silicon offers a particularly interesting platform for single dopants because when isotopically purified, silicon acts as a "semiconductor vacuum" for spin, giving it extraordinary coherence. Towards the goal of realising quantum electronics in silicon, controlled access to electron and nuclear spin states of phosphorous donors has recently been demonstrated. Although more difficult in silicon, optical control of single qubits is very attractive since it allows for precision quantum control with ultrahigh spectral resolution, and could enable long distance communication. Here, we present optical addressing and electrical detection of individual erbium dopants with exceptionally narrow line width. The hyperfine coupling to the *Er* nucleus is clearly resolved, which paves the way to single shot readout of the nuclear spin, and is the first step towards an optical interface to dopants in silicon. Furthermore, spatially resolved tunneling experiments performed by cryogenic scanning tunneling spectroscopy will also be discussed. They reveal the spectrum and wavefunction of both single dopants and exchange-coupled dopant molecules. Donors up to 5nm below a silicon surface are measured, and exhibited quantum interference processes reflecting the valley degrees of freedom inherited from the silicon "semiconductor vacuum". Finally, exchange-coupled solid-state molecules of holes bound to nearby acceptors were studied. The signature of quantum correlations and entanglement were detected by spatially resolved local tunneling spectroscopy experiments in the single-hole tunneling regime. With increasing bond distance, evidence was found for a crossover from an uncorrelated state, to a correlated state.

Topological insulators, helical liquids, and Rashba interactions

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Topological insulators are new phases of quantum matter characterized by an insulating gap in the bulk and gapless edge or surface states. In the case of an ideal 2D topological insulator, the edge states form a 1D helical liquid, with electrons of opposite spins propagating in opposite directions, Given the right conditions, these spin-filtered states may serve as ballistic conduction channels, holding promise for future applications in spintronics and quantum information processing, including "on-demand" production of entangled electron spin qubits [1]. Unfortunately, the reactivity and "softness" of present experimental realizations of 2D topological insulators make them unsuitable for applications. Alternative realizations of 1D helical liquids are therefore in high demand.

In this talk I will begin by giving an elementary introduction to the subject of 2D topological insulators and their helical edge states. I will then discuss a new idea how to "do away with" the topological insulator, and instead produce a helical liquid in a quantum wire by performing a trick with a modulated Rashba interaction [2].

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Electron Spin Qubits in Silicon Quantum Dots

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Spin qubits in silicon are excellent candidates for scalable quantum information processing [1] due to their long coherence times and the enormous investment in silicon MOS technology. Our effort in Australia on Si QC has to date largely focused on spin qubits based upon the donor electron [2] or nucleus [3] of phosphorus dopant atoms implanted in Si. By using enriched ^{28}Si substrates, such qubits can have exceptionally long coherence times and very high gate fidelities [4]. In parallel, we have begun exploring spin qubits based on single electrons confined in Si-MOS quantum dots [5]. Such qubits can have long spin lifetimes $T_1 \sim 2$ s, while the Si-MOS device architecture allows for electric field tuning of the conduction band valley splitting, thus avoiding problems associated with spin and valley mixing [6]. Most recently, we have demonstrated a quantum dot qubit in ^{28}Si with a control fidelity of 99.6% [7], consistent with that required for fault-tolerant QC. By gate-voltage tuning of the electron g*-factor, we can Stark shift the ESR frequency by > 10 MHz [7], providing a direct path to large-scale arrays of addressable high-fidelity qubits.

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Soft decoding of a quantum measurement apparatus

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Quantum measurements are commonly performed by thresholding a collection of analog detector-output signals to obtain a sequence of single-shot bit values. The intrinsic irreversibility of the mapping from analog to digital signals discards soft information associated with an `a posteriori' confidence that can be assigned to each bit value when a detector is well-characterized. Accounting for soft information, we show significant improvements in enhanced state detection with the quantum repetition code as well as quantum state/parameter estimation. These advantages persist in spite of non-Gaussian features of realistic readout models, experimentally relevant small numbers of qubits, and finite encoding errors. These results show useful and achievable advantages for a wide range of current experiments on quantum state tomography, parameter estimation, and qubit readout.

Storing quantum information for 35 seconds on a single spin in silicon

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A phosphorus (^{31}P) donor in silicon is, almost literally, the equivalent of a hydrogen atom in vacuum. It possesses electron and nuclear spins1/2 which act as natural qubits, and the host material can be isotopically purified to be almost perfectly free of other spin species, ensuring extraordinary coherence times.

I will present the current state-of-the-art in silicon quantum information technologies. Both the electron and the nuclear spin of a single ^{31}P atom can be read out in single-shot with high fidelity, through a nanoelectronic device compatible with standard semiconductor fabrication. High-frequency microwave pulses can be used to prepare arbitrary quantum states of the spin qubits, with fidelity in excess of 99%. Our latest experiment on the ^{31}P nucleus has established the record coherence time (35 seconds) for any single qubit in solid state [1].

Finally, I will discuss current efforts to scale up the system to multi-qubit quantum logic operations. We have proposed a new scheme for entangling two-qubit logic gates that does not require atomically precise placement of the ^{31}P donors [2], and we have demonstrated the real-time observation of singlet-triplet states of an exchange-coupled donor pair [3].

These results show that silicon – the material underpinning the whole modern computing era – can be successfully adapted to host quantum information hardware.

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Quantum Computation and Quantum Metrology based on Single Electron Spin in Diamond

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One of the key issues in quantum computation is to realize precise control over quantum qubits in the realistic system. The electron spin suffers the noise resulted by the around nuclear spin bath. This noise will not only destroy the quantum states of the electron spin, but also will deteriorate the quality of the quantum gates. It is of great challenge to perform the accurate controlling the electron spin qubits, due to the noises aroused from the nuclear spin bath and the driving field.

In this talk, I will briefly introduce our new researches in the robust quantum control and metrology. Firstly, we adopted a type of dynamically corrected gats to realize robust and high-fidelity quantum gates in the presence of fluctuation of static magnetic field. The results show that the noise was suppressed to 6th order and the quantum gate's performance was pushed to T1rho limit [Phys. Rev. Lett. 112, 050503 (2014)]. On the other hand, we experimentally observed a new Rabi Oscillations (ROs) resulting from more than 100 Landau-Zener (LZ) transitions. The fluctuations of the driving field can be suppressed in the new ROs relative to common ROs under the same driving microwave power [Phys. Rev. Lett. 112, 010503 (2014)]. Besides, cooperating with German research group, we have experimentally realized the quantum error correction in diamonds, which is another effective method to overcome the noise effect [Nature 506, 204 (2014)]. Precise quantum control and effectivly supressing noise of the environment are also of great importance for quantum metrology. Cooperating with theory group, we recently succeeded in sensing and atomic-scale analysis of single nuclear spin clusters in diamond at room temperature via quantum interferometer [Nature Physics 10, 21 (2014)]. Besides, we have succeed to detect few nuclear spins with single spin sensitity [Nature Commu., accepted (2014)].

Nuclear spin correlations detected by central spin decoherence

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Decoherence of a central spin in solids is not only an ideal model problem for understanding the foundation of quantum physics but also a critical issue in quantum information technologies. Studying central spin decoherence caused by environmental fluctuations may yield key insights into the nature of many-body interactions in the environment. Furthermore, dynamical control over the central spin can affect the dynamics of the environment in a detectable manner. In the light of these ideas, exploiting central spin decoherence for sensing single nuclear spins has been demonstrated. Recently, this idea has been pushed to new depths: theoretical studies show that the central spin decoherence can be a novel probe to many-body physics, in particular, phase transitions in spin baths. Multiple-spin correlations are one of the essential characteristics in spin baths, but detection of such correlations is a long-standing challenge in many-body physics. Taking a phosphorus donor electron spin in a natural-abundance ^{29}Si nuclear spin bath as our model system, we discover both theoretically and experimentally that many-body correlations in nanoscale nuclear spin baths produce identifiable signatures in the decoherence of the central spin under multiple-pulse dynamical decoupling control. We find that when the number of decoupling π-pulses is odd, central spin decoherence is primarily driven by second-order nuclear spin correlations (pairwise flip-flop processes). In contrast, when the number of π-pulses is even, fourth-order nuclear spin correlations (diagonal interaction renormalized pairwise flip-flop processes) are principally responsible for the central spin decoherence. Many-body correlations of different orders can thus be selectively detected by central spin decoherence under different dynamical decoupling controls, providing a useful approach to probing many-body processes in nanoscale nuclear spin baths.

I acknowledge support by Hong Kong RGC/GRF Project 401413 and collaboration with Wen-Long Ma, Gary Wolfowicz, Nan Zhao, Shu-Shen Li, and John J. L. Morton.

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Circuit QED with a graphene double quantum dot and a reflection-line resonator

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Circuit quantum electrodynamics (cQED) has drawn considerable recent attention due to its potential to mediate entanglement between distant solid-state qubits. Meanwhile, graphene has also become a hot electronic material due to its unique physical properties and potential applications. Here we demonstrate for the first time a successful coupling between two distant graphene double quantum dots through a superconductor reflection-line resonator (RLR). The dephasing rate of graphene qubit is measured for the first time. Several hints to the four-fold filling feature of graphene quantum dot are also observed. The coupling strength of the resonator to the graphene quantum dot, made of a single atomic layer, is determined to be just as good as that for semiconductor and superconductor counterparts.

Exploration of Si MOS Based Spin Qubits

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Silicon MOS technology, developed over decades, has been a cornerstone of mainstream microelectronics. Common wisdom tends to say that quantum information processing based on individual electron spins in semiconductors will require new materials and new technology. However, recently several groups around the world have demonstrated both unprecedented device stability and the abilities to control and to measure single spins on electrostatic quantum dots made out of conventional Si MOS materials. In this talk, I would like to describe our experimental activities at UCLA to develop this type of qubits. A measurement of spin-lattice relaxation time of individual spins in the presence of a magnetic field, using a pump-and-probe technique, will be presented. Our detection of electron spin resonance and measurement of inhomogenous phase decoherence time of a single spin, that reveal novel spin-valley physics, will be reported. Preliminary results of an exchange-only spin qubit will also be discussed.

Entangled states with spin-orbit coupling: spin measurement and spin driving

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Spin-orbit coupling (SOC) leads to a spin-coordinate entanglement producing mixed states in reduced spin subspace. We study two consequences of this entanglement for free and driven spin dynamics.

First, SOC simulates a von Neumann measurement of a spin1/2 since spatial separation of spin-up and spin-down states decoheres the spin density matrix and allows one reading the spin with the particle coordinate. For a simultaneous measurement of spin projections at orthogonal axes, which cannot be accurately done due to the uncertainty ratio, we find that such a procedure yields measurement-time averages of these projections, which can be precisely known [1]. Second, we consider driving of electron spin by a periodic electric field in a double quantum dot. The interdot tunnelling favours a spin-coordinate entanglement and makes the driving much less efficient than expected. This is, essentially, the Zeno effect of the measurement induced by the spin-orbit coupling, that is slowing of the dynamics of a systems under a permanent observation [2,3]. In addition, this Zeno effect decreases the efficiency of the spin driving with the increase in the spin-orbit coupling strength as found theoretically in [4].

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High fidelity quantum dot hybrid qubit

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This talk will discuss our experimental program for implementing a quantum dot hybrid qubit formed by placing three electrons into an electrostatically gated semiconductor double quantum dot [1, 2]. We have used dc pulsed voltages to manipulate the states of three electrons in a double quantum dot [3], and have performed quantum process tomography measurements demonstrating that dc gating enables initialization, readout, and full manipulation over the entire Bloch sphere, with process fidelities of 85% and higher [4], consistent with expectations from theory [5]. I also will discuss new experiments demonstrating that ac-gating enables hybrid qubit rotations over the entire Bloch sphere with process fidelities exceeding 90%. We describe the experimental approach and report process tomography measurements, and we discuss a proposed path to even higher gate fidelities, with the potential to exceed the threshold for quantum error correction. The work discussed was supported in part by ARO (W911NF-12-0607). Development and maintenance of the growth facilities used for fabricating samples is supported by DOE (DE-FG02-03ER46028). This research utilized NSF-supported shared facilities at the University of Wisconsin-Madison. Work performed in collaboration with Dohun Kim, D. R. Ward, C. B. Simmons, D. E. Savage, M. G. Lagally, Mark Friesen, and S. N. Coppersmith.

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Theory of semiconductor quantum dot hybrid qubits: towards large-scale fault-tolerant operation

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The quantum dot hybrid qubit, which can be viewed as a hybrid of spin and charge, has an attractive combination of speed and fabrication simplicity. The Eriksson group has implemented initialization, full control of a quantum dot hybrid qubit on the Bloch sphere, and readout, and demonstrated process fidelities of 93% and 96% for π rotations about the X- and Z-axes of the Bloch sphere. This talk will discuss theoretical work at Wisconsin characterizing the fundamental factors limiting the gate fidelity of the quantum dot hybrid qubit, which demonstrates that process fidelities exceeding the fault-tolerance threshold using surface codes should be achievable without use of dynamical decoupling techniques. A theoretical framework for optimizing controllability and scalability of device designs for multiple qubits will also be presented.

TBA

Joerg Wrachtrup

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Quantum networks and quantum information with spins in diamond

Tim Hugo Taminiau

Delft University, Kavli Institute of Nanoscience, Delft, Netherlands

The nitrogen vacancy (NV) center in diamond is a promising candidate to realize quantum networks consisting of multi-qubit nodes optically linked over large distances. In this talk, I will outline our recent progress towards this goal. First, I will present how multi-qubit nodes can be formed using the NV electron spin to control and entangle nuclear spins in its environment. As a demonstration I will present the realization of a basic quantum error correction protocol [1]. Second, we will discuss the unconditional quantum teleportation of a nuclear spin to an electron spin in another diamond 3 meters away [2, 3]. Together these results provide the basis for establishing quantum networks based on spins in diamond.

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Spin relaxation in coupled quantum dots: spin hot spots and anisotropies

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The ultimate spin relaxation channel for spin qubits in quantum dots involves spin-orbit coupling and phonons. I will review our theoretical realistic comprehensive modeling [1] of the phonon-induced spin relaxation in GaAs and Si coupled quantum dots, exploring a wide regime of the parameter space comprising interdot tunneling, magnetic field magnitude and orientation, and the crystallographic orientation of the coupled dots. I will discuss the special role of spin hot spots-anticrossing regions in the parameter space in which the spin relaxation rate is enhanced by orders of magnitude, and show how they imprint a unique signature of the crystal and structure anisotropy in the spin relaxation parametric landscape. Both single-electron and two electron (singlet-triplet) spin relaxation is affected by the spin hot spots. I will also briefly discuss complications in the tunneling and interdot-coupling in topological insulator [2] and graphene [3] quantum dots, due to the Dirac band structure. Supported by DFG SPP 1285 and SFB 689.

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Spin Quantum Computation and Topological Quantum Computation

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