Materials and Processes for Quantum Information Science Focus Topic

Room On Demand - Session QS-Contributed On Demand

Materials and Processes for Quantum Information Science Contributed On Demand Session

QS-Contributed On Demand-1 Power and Temperature Dependence of High Q Superconducting Resonators*, **Ashish Alexander**, C. Weddle, C. J. Richardson,* Laboratory for Physical Sciences, University of Maryland, College Park, MD

An integrated temperature and power dependent model of a resonator internal quality factor predicts the loss contribution from two-level systems and quasiparticles simultaneously in a superconducting resonator. At millikelvin temperatures, the sub-gap microwave photons due to resonator readout signal drive the quasiparticle number and phonon density far from the thermal equilibrium corresponding to the bath temperature.

Here we propose a two-temperature, power and temperature dependent model to evaluate resonator losses that define the driven quasiparticle density by a distinct effective temperature than the bath temperature. The contribution of the readout power for different power and temperature is also explored. Resonators fabricated from epitaxial molecular beam epitaxy grown aluminum on float-zone refined silicon are evaluated to have quality factors above 1M. These results are analyzed with the proposed model and the contribution of various loss mechanisms is explored.

QS-Contributed On Demand-4 A Density-Functional Theory Study of the Al/AlO_x/Al Tunnel Junction*, **Chang-Eun Kim**, K. Ray, V. Lordi,* Lawrence Livermore National Laboratory

The aluminum oxide tunnel junction is a key component of superconducting quantum devices. The quantum coherence time of the aluminum oxide tunnel junction has seen five orders of magnitude improvement over the last twenty years, however, it is still too short to realize a scalable quantum computer. We asked what may be still limiting its further improvement. We used ab-initio calculations to develop a realistic model of the tunnel junction and compared to experimental observations known to date. The ab-initio electronic structure result shows that under-coordinated Al ion forms conducting channel, effectively rendering the true thickness of the insulating part of tunnel junction significantly thinner than what may be measurable under electron microscopes. The computed properties of amorphous junction are compared to a series of ideal crystalline junction models with variable thickness, highlighting what would be possible if we had better control over the interface microstructure of the tunnel junctions. Electron tunneling of model junction is probed by solving Schrödinger equations (SE) using the potential obtained from ab-initio result, revealing channel formation and inhomogeneous tunneling transport that is correlated to the thickness distribution. The detailed theoretical description of the widely used aluminum oxide tunnel junction, along with the ab-initio-based systematic approach to predict the performance of tunnel junction, will further strengthen our understanding of this critical materials system that is indispensable to realize superconductor-based quantum computing devices. (Prepared by LLNL under Contract DE-AC52-07NA27344)

QS-Contributed On Demand-7 A Cold Atom Interferometry Sensor Platform Based on Diffractive Optics and Integrated Photonics*, J. Lee, R. Ding, H. McGuinness, J. Christensen, R. Rosenthal,* Sandia National Laboratories, USA*; G. Biedermann,* University of Oklahoma*; S. Kemme, D. Gillund, A. Ison, G. Hoth, B. Little, D. De Smet, C. Walker, A. Kodigala, M. Gehl, E. Skogen, M. Eichenfield, A. Lentine,* ***Peter Schwindt****,* Sandia National Laboratories, USA

Keywords—atom interferometer; cold atoms; magneto-optical trap; integrated photonics

We report the current progress in the development of a compact, deployable cold atom interferometry sensor platform, which could be generally applied to cold-atom gravimeters, accelerometers, gyroscopes, and clocks. Our effort targets the miniaturization of key components of the sensor platform and includes significant engineering efforts in the development of grating-mirror magneto-optical traps (G-MOTs), vibration-resistant structural design, custom titanium vacuum package with passive pumping, silicon-photonic multi-channel on-chip single sideband modulators, and a feedforward technique to extend the dynamic range of the atom interferometer inertial sensors.

We will highlight the development of a compact cold atom sensor head for measuring acceleration. Laser light is brought to the sensor head via optical fiber to perform the functions of laser cooling and trapping, the atom interferometer three pulse laser sequence, and atomic state sensitive detection. The atoms are contained in a custom Ti vacuum chamber (volume of ~90 cm^3), and we demonstrated a G-MOT where the grating is inside the chamber. Finally, we discuss the results of the atom interferometric acceleration measurements with sensor head.

We have also developed the Ti vacuum chamber that it is only passively pumped; no active pumping is required to maintain the vacuum for a cold-atom trapping. Excluding the grating and using sapphire windows, we have demonstrated a MOT in the passively pumped chamber for nearly one year with no apparent degradation in the vacuum quality.

For extreme system miniaturization, there are significant efforts in the development of heterogeneously integrated photonic integrated circuits (PICs) for the cold atom sensor using silicon photonics, amplification with III-V gain materials, and second harmonic generation. We demonstrated a four-channel optical single sideband (SSB) modulator on a silicon PIC at 1560 nm with a high extinction ratio and a high carrier-injection modulation, which can dynamically control laser frequencies and intensities during the experimental sequence of a cold atom interferometer. We envision a fully integrated system, in which 30 on-chip SSB modulators can be applied to a 6-degree-of-freedom (DOF) matterwave inertial measurement unit (IMU). Such a PIC-based system could shrink the size of the typical laser system for an atom interferometer from the size of an optical table to tens of cm^3.

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QS-Contributed On Demand-10 Observation of the Two-Photon Transition and Bloch-Siegert Shift of the Electrically Detected Magnetic Resonance Spectrum of Interface Defects in 4H-SiC Metal-Oxide-Semiconductor Field-Effect Transistors*, **James P. Ashton**, P. Lenahan,* The Pennsylvania State University

We report on the observation of multiple-photon transitions in the electrically detected magnetic resonance (EDMR) spectrum of interface defects at the 4H-SiC/SiO_2 interface. Multiple-photon transitions are important for quantum engineering as they have been linked to spin-based quantum computation for coherent manipulation of spin-qubits [1]. These observations are made possible with the utilization of a new EDMR scheme that incorporates an RF frequency sweep with the sample held at constant ultra-low magnetic field B_0 instead of a magnetic field sweep at constant RF frequency. The latter is the traditionally utilized EDMR scheme known as continuous wave (cw) EDMR. In the frequency-swept (fs) EDMR spectrum, the two-photon transition emerges because of ultra-strong coupling effects between the spin system and the driving field B_1 which provides the RF radiation. fsEDMR measurements are made in the sub-mT regime, where the Zeeman interaction is weak. Sub-mT EDMR measurements using a cwEDMR approach would be difficult as there is an oftentimes pervasive near-zero field magnetoresistance (NZFMR) effect that occurs in the sub-mT range [2]. Thus, the fsEDMR scheme is useful in such measurements since the NZFMR response can be eliminated by sweeping the RF frequency instead of sweeping the B_0 field. We utilize the fsEDMR scheme to validate that the transitions we observe are caused by multiple-photon transitions. In a fsEDMR spectrum, these transitions occur at integer divisions of the resonant frequency where in a magnetic field sweep scheme, the transitions occur at multiples of the resonant magnetic field. In this way, we rule out the possibility of harmonic detection of the resonant frequency caused by the apparatus. The two-photon line shape is analyzed as a function of the B_1/B_0 and it is found that spectral narrowing occurs as the ratio B_1/B_0 is increased. This observation is consistent with recent theoretical work provided by Mkhitaryan *et al.* [3]. The fsEDMR response is also slightly shifted off resonance due to the Bloch-Siegert shift [4]. We confirm the observation of the Bloch-Siegert shift via an extraction of B_1 and compare it to the value B_1 extracted using a sniffer test coil. Within experimental error, the values of B_1 extracted using both techniques are the same.

This work at Penn State was supported by the U.S. Army Research Laboratory.

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QS-Contributed On Demand-13 Tunable Filters and Parametric Amplifiers from NbTiN Transmission Line Resonators*, R.M. Lewis*, *W. Kindel, L. Tracy, C. Harris, T. Lu, D. Luhman,* Sandia National Laboratories, USA

Quantum computing applications require that control signals be carefully filtered to minimize noise reaching the qubits. Quantum limited amplification of output signals is also used to reduce readout time. We present measurements of non-linear NbTiN resonators which are useful as both tunable bandpass filters and as parametric amplifiers.

Transmission line resonators make excellent bandpass filters. Here we demonstrate that such filters made from NbTiN are tunable by pumping a higher or lower harmonic of the resonator. We present data for a resonator with a full line width of ~ 150 kHz which is tunable by several MHz. We demonstrate a tuning of many linewidths and achieve an on/off ratio of ~ 30 dB. Further exploiting the nonlinearity of the NbTiN, this resonator exhibits gain of nearly 15 dB when pumped near the critical power at which bifurcation occurs.

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QS-Contributed On Demand-16 Nv Center Generation by Electron Beam Excited Plasma*, Akihito Saeki*, *A. Chikamoto,* Meijo University Graduate School, Japan*; P. Abraha,* Meijo University, Japan

The nitrogen-vacancy (NV) centers, point defects in diamond, have a property of photoluminescence useful for sensors in the field of quantum life science. The NV centers must be highly sensitive for use in the measurements of exothermic energy of proteins such as enzymes in cells. The sensitivity of NV centers can be increased through the near-surface formation of NV centers and increased number density. This research details the simultaneous formation of the vacancy and annealing processes performed by electron irradiation.

Currently, NV centers have been created by annealing after electron irradiation of 200 keV to 10 MeV onto the synthetic diamond surface. However, the energy of the irradiated electron is excessively large, which severely damages the surface.

In this research, experiments were conducted by irradiating the diamond surface with accelerated electrons using an electron beam excited plasma system. The system allows for controllable delivery of energy and density of the accelerated electrons. Here, NV centers are formed by electron irradiation while simultaneously annealing the diamond surface through electron collision that heats the surface. Photoluminescence using a Raman spectrometer confirms the formation of NV centers. The treated diamond showed peaks of NV center emission at around 637 nm. The peak intensities increased gradually with the applied energy and density of the irradiated beam. In this presentation, the gradual increase in the fluorescence intensity at 637 nm for the varying electron energy and electron density of the electron beam excited plasma will be shown.

QS-Contributed On Demand-19 Strain-Induced Interdiffusion in III-V Compound Semiconductors for Quantum Structure Formation*, Leonid Miroshnik*, Chemical & Biological Engineering, University of New Mexico*; B. Rummel,* Nanoscience & Microsystems Engineering, University of New Mexico*; A. Li,* Chemical & Biomolecular Engineering, University of Pennsylvania*; G. Balakrishnan,* Center for High Technology Materials, University of New Mexico*; T. Sinno,* Chemical & Biomolecular Engineering, University of Pennsylvania*; S. Han,* Nanoscience & Microsystems Engineering, University of New Mexico

We demonstrated stress-directed compositional patterning in compound semiconductors as a novel method to form quantum structures[1-4]. This is a significant departure from the traditional methods of forming quantum structures, such as strain-driven Stranski-Krastanov growth or solvothermal synthesis. In this work by applying a thermo-mechanical stress field, we are expanding the idea to III-V compound semiconductors, where InGaAs on GaAs is our model system. The approach allows for 3D quantum structures to be scalably manufactured. We characterized the atomic interdiffusion in the InGaAs/GaAs model system. Understanding the behavior of non-Fickian diffusion as a function of strain provides a pathway to design systems where patterned stress fields under thermally activated conditions can be used to produce 3D spatially ordered quantum structures. Previous studies provided a large uncertainty in calculated Arrhenius diffusion coefficients, and there is a disagreement on the effects of strain in diffusion.Measuring the interdiffusion parameter is extremely sensitive to the processing and characterization conditions. Molecular beam epitaxy (MBE) was used to grow high-quality quantum wells with well-defined concentration profiles. The structures were annealed in a rapid thermal annealer (RTA) and analyzed using Secondary Ion Mass Spectroscopy (SIMS). This characterization technique provides precise information on the composition on the angstrom scale. In this presentation, we show our processing, annealing and characterization technique provides a high accuracy repeatable compositional profile. In addition, we have developed a multiscale computational model that couples continuum methods with coarse-grained lattice kinetic Monte-Carlo to extract stress mediated diffusion parameters and to predict the time evolution of technologically relevant compositions.

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Materials and Processes for Quantum Information Science Invited On Demand Session

QS-Invited on Demand-1 Quantum Matter, Simulation, and Clock*, Jun Ye*, JILA and University of Colorado Boulder **INVITED**

Precise engineering of quantum states of matter and major advances in optical coherence and laser technology are elevating the performance of optical atomic clocks to new levels. A low-entropy Fermi gas of Sr atoms loaded into a three-dimensional optical lattice represents a powerful platform to discover, understand, and utilize many-body quantum systems that are metrologically powerful and lay the foundation for the connection between quantum simulation and quantum sensing. These increasingly powerful measurement capabilities are promising greater opportunities for probing fundamental and emerging phenomena.

QS-Invited on Demand-7 Photonic Interfaces for Ion-trap Quantum Computers*, Tracy Northup*, University of Innsbruck, Austria **INVITED**

Trapped ions are among the most promising quantum computing platforms, but there are technical limits to the number of ions, and thus the number of quantum bits (qubits), that can be stored in a single trap. One approach to scale up the number of qubits beyond these limits is to link together multiple ion-based processors in a network via photonic quantum interfaces. I will describe how optical cavities provide efficient quantum interfaces between ions and photons and how we integrate these cavities with ion traps. An important materials question is whether the presence of dielectric cavity mirrors compromises the computing performance of nearby ions. To address this question, I will present recent work in which we model and experimentally measure the heating rate of a trapped ion placed in the vicinity of a cavity mirror. This work not only has implications for ion-based quantum networks but also may provide new insight into the heating mechanisms in microfabricated ion traps.

QS-Invited on Demand-13 Empowering Quantum Photonics with Nanoplasmonics and Machine Learning*, Vladimir Shalaev*, *A. Boltasseva,* Purdue University **INVITED**

New approaches to address major challenges in quantum photonics by employing plasmonic metamaterials and machine learning will be discussed.

QS-Invited on Demand-19 Engineering Silicon Qubits at the Atomic Scale*, Sven Rogge,* University of New South Wales, Australia **INVITED**

Spins in silicon are attractive candidates for scalable quantum information devices, because of their long coherence times and potential for high-density integration. This talk focuses on challenges in scaling from the device to the circuit level. While quantum information devices in spin based systems have been shown to be promising, the small dipole moment of spins make interaction of multiple qubits challenging to implement. Recently, artificial spin-orbit coupling induced by micro-magnets in double quantum dot devices has been successfully implemented to couple spin qubits in silicon to a microwave cavity on the single photon level. The presence of intrinsic spin-orbit coupling in acceptors however, could allow for fast quantum-gate manipulations and effective long-range inter-qubit coupling with a simple device layout. Recent acceptor qubit proposals suggest the possibility of maintaining the dipole moment between the spin-orbit states, without suffering from short coherence times. By coupling a bulk 28Si crystal to a superconducting coplanar waveguide resonator, we measured a coherence time (T2) of 0.7 ms for an acceptor spin ensemble in bulk 28Si crystal under strain. This value for this coherence time is over 4 orders of magnitude higher than previously found in boron-doped silicon devices, and demonstrates the potential of boron-based acceptor spins in silicon as a candidate for scalable, electrically-driven qubits with long coherence times. The second part of the talk focuses on single dopant atom placement. Atomic-scale engineering reached a level of control where single-atom devices can be reproducibly fabricated. The indirect band gap of silicon and the resulting valley degree of freedom has been considered to be challenging for donor qubit architectures. This is due to the fast oscillations of the valley component of the donor wave function that is incommensurate with the silicon lattice. Single-electron spectroscopy maps obtained on fully integrated donor devices in ultra-high vacuum allow a direct measurement of the valley phase difference between two donors. Such quantum-state images of two-donor devices led to a donor based two qubit gate design that is robust in regard to variability in dopant placement.

QS-Invited on Demand-25 Reproducible Superconducting Circuits for Quantum Information Processors*, Eric Zhang,* IBM T. J. Watson Research Center **INVITED**

Superconducting quantum processors based on fixed-frequency transmon architectures are attractive for their simplicity of fabrication and long coherence times. However, the frequency precision of as-fabricated transmon qubits range from 1 - 2%, which results in significant frequency crowding and reduced two-qubit gate-fidelity. In this talk, we describe selective laser annealing to assign transmon frequencies into desired frequency patterns and describe both the practical (~18 MHz) and fundamental (~5 MHz) precision of the laser annealing process. We combine precision studies with Monte-Carlo yield modeling to ascertain the desired tuning performance metrics required for high-yield of collision-free chips. We will present laser-annealing on our largest multi-qubit processor to date, our 65-qubit Hummingbird processor, with a post-annealed median two-qubit gate fidelity of 98.7%. As a scalable post-fabrication frequency trimming technique, we anticipate laser-annealing to play a central role in the production and scaling of high-fidelity superconducting quantum processors up to and beyond 1000-qubit levels.

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QS-Invited on Demand-31 Materials Loss Measurements Using Superconducting Microwave Resonators*, Corey Rae McRae,* NIST Boulder / CU Boulder **INVITED**

Two level system (TLS) loss in dielectric materials and interfaces remains at the forefront of materials research in quantum information science. The identification of low loss fabrication techniques, materials, and thin film dielectrics is critical to achieving scalable architectures for superconducting quantum computing. Superconducting microwave resonators provide a convenient qubit proxy for assessing loss performance and studying loss mechanisms such as TLS loss, non-equilibrium quasiparticles, and magnetic flux vortices. In this talk, an overview of design considerations for accurate resonator loss measurements will be given, summarizing techniques that have been evolving for over two decades, and will conclude with recommendations for future measurements in this field.

QS-Invited on Demand-37 Organic Color Center: A New Class of Quantum Materials*, Han Htoon,* Los Alamos National Laboratory **INVITED**

Color centers in diamond and SiC are now standing as a key material system for realization of quantum information technologies ranging from ultrasensitive sensing of electric/magnetic fields to eavesdropping-proof communication and quantum computing.Recent studies have shown that defects capable of mimicking some of the key quantum mechanical properties of these color centers can also be created via covalent bonding of organic functional groups onto the side-wall ofSWCNTs.Here in this talk I will provide a brief over view on our recent accomplishments in understanding and controlling quantum optical properties of these covalent defects, which are often referred to as “organic color centers.”[1] Firstly, I will describe our low temperature single defect PL and magneto PL spectroscopies revealing a molecularly tunable electronic structure of these defects[2] and magnetic brightening of spin-sensitive optical transitions. Secondly, Hanbury-Brown-Twiss quantum optic experiment demonstrating the first room temperature single photon generation in O- to C- telecom optical wavelength bands with 99% single photon purity will be presented.[3,4]I will then provide an update on integration of these quantum defects into photonic, plasmonic and electronic nano devices.[5,6] Finally, I will report our most recent Hong-Ou-Mandel quantum optic experiment performed on quantum defects coupled to plasmonic cavities.We were able to realize indistinguishable single photon generation by exploiting the Purcell enhancement of the radiative decay rate of individual defects.[7]

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