Engineering a Scalable Quantum Information Processor

695. WE-Heraeus-Seminar

23 – 26 April 2019
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 695. WE-Heraeus-Seminar:

Quantum computers, once available for widespread use, will revolutionize the ways we generate and use new knowledge – of fundamental scientific nature and for a wide range of applications. The quest for a scalable quantum computer is as of yet largely driven by experts in physics and in computer science. The challenges posed by this task, however, will necessarily require in addition dedicated and target-driven efforts in engineering. Vigorous innovative research and development in various fields of engineering will be pivotal for advancing successfully on the route towards a quantum computer, or quantum simulator, that is able of solving problems that, for all practical purposes, are intractable on classical computers. This workshop will bring together researchers already active at the forefront of this rapidly developing field, both from fundamental science and from engineering. It will put emphasis on implementations of quantum computing and quantum simulation using semiconductors, superconducting structures, and trapped atomic ions as physical systems.

Scientific Organizers:

Prof. Christof Wunderlich	Universität Siegen, Germany E-mail: christof.wunderlich@uni-siegen.de
Dr. Carsten Degenhardt	Forschungszentrum Jülich, Germany E-mail: c.degenhardt@fz-juelich.de

Administrative Organization:

Dr. Stefan Jorda Elisabeth Nowotka	Wilhelm und Else Heraeus-Stiftung Postfach 15 53 63405 Hanau, Germany Phone +49 6181 92325-12 Fax +49 6181 92325-15 E-mail nowotka@we-heraeus-stiftung.de Internet: www.we-heraeus-stiftung.de

Program

Program

Tuesday, 23 April 2019

10: 00 – 14:00	Arrival and Registration	
12:00	*LUNCH*	
13:30 – 13:40	Scientific organizers	**Welcome words**
13:40 – 14:40	Andreas Wallraff	**Quantum information processing with superconducting circuits**
14:40 – 15:40	Philipp Schindler	**Quantum information processing in ion traps - an overview**
15:40 – 16:10	*COFFEE BREAK*	
16:10 – 17:10	Hendrik Bluhm	**Semiconductor spin qubits – a scalable platform for quantum computing?**
17:10 – 19:00	**Postersession**	
18:45	*DINNER*	

Program

Wednesday, 24 April 2019

08:00	*BREAKFAST*	
09: 00 – 09:20	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
09:20 – 10:00	Winfried Hensinger	**Engineering challenges to construct a practical trapped ion microwave quantum computer**
10:00 – 10:40	Koen Bertels	**The trend towards quantum accelerators**
10:40 – 11:30	*INFORMAL DISCUSSIONS, COFFEE and POSTERS*	
11:30 – 12:10	Lotte Geck	**Scalable Cryogenic CMOS Electronics for Spin Qubits**
12:10 – 12:20	**Conference Photo** (in the front of the lecture hall)	
12:30	*LUNCH*	
14:00 – 14:40	Silvano de Franceschi	**Leveraging silicon technology for scalable quantum processors**
14:40 – 15:20	Michael Johanning	**Microwaves and trapped ions: A fertile marriage**
15:20 – 15:50	*COFFEE BREAK*	
15:50 – 16:30	Alexey Ustinov	**Locating two-level material defects that limit the coherence of superconducting qubits**
16:30 – 18:30	**Postersession**	
19:00	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Thursday, 25 April 2019

08:00	*BREAKFAST*	
09:20 – 10:00	Markus Müller	**Scalable quantum error correction – concepts and engineering challenges**
10:00 – 10:40	Ferdinand Schmidt-Kaler	**Trapped ion quantum computing**
10:40 – 11:30	*INFORMAL DISCUSSIONS and COFFEE*	
11:30 – 12:10	Peter Maunz	**High-fidelity quantum operations in microfabricated surface ion traps**
12:10 – 12:30	**Topics for Breakout Sessions are chosen**	
12:30	*LUNCH*	
13:30 – 14:10	Fabio Sebastiano	**Cryogenic CMOS interfaces for large-scale quantum computers**
14:10 – 15:00	Christian Ospelkaus	**Microfabricated ion traps for scalable quantum information processing with trapped ions**
15:00 – 15:30	*COFFEE BREAK*	
15:30 – 15:50	Bastian Hiltscher	**BMBF Funding of Quantum Technologies**
15:50 – 17:30	**Break-out sessions**	
18:00	*DINNER*	

Program

Friday, 26 April 2019

08:00	*BREAKFAST*	
09:00 – 09:40	Sven Höfling	**Quantum dots as spin-photon interfaces**
09:40 – 10:25	**Summary of Breakout Sessions (3 x 15 Min)**	
10:25 – 11:00	*INFORMAL DISCUSSIONS and COFFEE*	
11:00 – 11:40	Norbert M. Linke	**A programmable trapped-ion quantum computer**
11:40– 12:20	Jan Benhelm	**Linking analog to digital: scalable instrumentation for quantum computing**
12:20 – 12:30	Scientific organizers	**Closing remarks**
12:30	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Saturday morning

Posters

Posters

Anton Artanov Mina Assarzadeh Dennis Nielinger Patrick Vliex	**Scalable cryogenic CMOS electronics for spin qubit control**
Patrick Barthel	**Robust two-qubit gates generated by pulsed dynamical decoupling**
Amado Bautista-Salvador	**Micro ion traps with 3D microwave conductors for applications in quantum technologies**
Ivan Boldin	**Planar-electrode ion trap for microwave-based quantum information processing**
Jonas Bylander	**Engineering a superconducting quantum computer**
Andreas Conta	**Improving qubit coherence times via adjustable permanent magnets and magnetic field tracking**
António Costa	**Quantum Fredkin gate from a triple quantum dot system**
Max Cykiert	**Robust quantum optimal control with noise**
Pieter Eendebak	**Quantum inspire - QuTech's silicon spin qubit-based full stack quantum computer prototype**
Christian Gogolin	**Sample complexity of device-independently certified "quantum supremacy**
Thomas Harty	**Microwave-driven high-fidelity quantum logic with 43Ca+**
Stefan Heidbrink	**An electric field generator for versatile trapping potentials in the microstructured ion traps**
Patrick Huber	**Parallel adaptive addressing of microwave-driven trapped-ion qubits**

Posters

Wolfgang M. Klesse	**Opportunities and limitation of advanced material science towards the scaling of Si-based quantum computing**
Florian Köppen	**High-fidelity preservation of quantum information during trapped-ion transport**
Malin Kück	**Tailoring the spatial and frequency correlations of entangled biphoton wavefunctions**
Lukas Lackner	**Deterministic alignment of gate-defined nanostructures and self-assembled quantum dots with sub µm accuracy**
Felix Lange	**High-defined crystalline silicon and germanium materials and structures for quantum circuits**
Loïck Le Guevel	**FDSOI technology for circuits at cryogenic temperatures for scalable quantum processors**
Fahd A. Mohiyaddin	**Advanced simulation & design of a spin-photon interface in Silicon**
Jonathan Morgner	**Quantum logic with microwaves in surface-electrode ion traps**
Alexander Müller	**Towards a programmable NISQ quantum processor based on trapped ions**
Matthias Müller	**Optimal control: Scaling of the control complexity with system size**
Yasser Omar	**Quantum link prediction in complex networks**
Armando Perez-Leija	**On-chip laser-written photonic circuits for quantum applications**

Posters

Marco Pezzutto	**An out-of-equilibrium non-Markovian quantum heat engine**
Daniel Pijn	**A shuttling-based trapped ion quantum processing node**
Krzysztof Pomorski	**Towards universal framework for electrostatic-qubit-based semiconductor quantum computer and its integration with CMOS electronics and superconducting quantum circuits**
Hector Jonathan Rojas	**Decoherence dynamics of electron spins in an optically active quantum dot**
Oliver Sanders	**Integrated FPGA-platform as control and readout interface for superconducting qubits**
Lars Schreiber	**Long-range quantum bus for electron spin qubits in silicon**
Hendrik Siebeneich	**Experimental implementation of a device-independent dimension test for quantum systems using genuine temporal correlations**
Theeraphot Sriarunothai	**Quantum-enhanced deliberation with trapped-ion qubits**
Konrad Tschernig	**Adiabatic quantum state preparation in photonic tight-binding lattices**

Abstracts of Talks

(in chronological order)

Quantum Information Processing with Superconducting Circuits

Andreas Wallraff

Department of Physics, ETH Zurich, Switzerland
www.qudev.ethz.ch

Superconducting circuits are a prime contender for realizing universal quantum computation and solving noisy intermediate-scale quantum (NISQ) problems on fault-tolerant or non-error-corrected quantum processors, respectively. In this talk, I will present elements of an architecture, which enables fast, high-fidelity, single shot qubit read-out [1], unconditional reset [2], which can be multiplexed [3]. Integrating multiple qubits in a single device, we evaluate performance metrics such as the single and two-qubit gate fidelity and the qubit readout fidelity. We also test the performance of the architecture in parity measurements with real-time feedback, which is a basic element of error correcting codes [4]. To provide a potential avenue for extending monolithic chip-based architectures for quantum information processing, we employ the circuit elements of our architecture to implement a deterministic state transfer and entanglement generation protocol [5]. Our protocol is based on an all-microwave process, which entangles or transfers the state of a superconducting qubit with a time-symmetric itinerant single photon exchanged between individually packaged chips connected by a transmission line. We transfer qubit states at rates of 50 kHz, absorb photons at the receiving node with near unit probability, and achieve transfer process fidelities and on demand remote entanglement state fidelities of about 80 %. We also show that time bin encoding can be used to further improve these quantum communication metrics [6]. Sharing information coherently between physically separated chips in a network of quantum computing modules may be an essential element for realizing a viable extensible quantum information processing system.

This research was performed in a collaboration between J.-C. Besse, A. Akin, S. Gasparinetti, J. Heinsoo, P. Kurpiers, P. Magnard, M. Pechal, B. Royer, Y. Salathe, S. Storz, T. Walter, A. Blais, C. Eichler, and A. Wallraff.

References

[1] T. Walter et al., Phys. Rev. Applied 7, 054020 (2017)
[2] P. Magnard et al., Phys. Rev. Lett. 121, 060502 (2018)
[3] J. Heinsoo et al., Phys. Rev. Applied 10, 034040 (2018)
[4] C. Kraglund Andersen et al., arXiv:1902.06946 (2019)
[5] P. Kurpiers et al., Nature 558, 264-267 (2018)
[6] P. Kurpiers et al., arXiv:1811.07604 (2018)

Quantum information processing in ion traps - an overview

Philipp Schindler[1]

[1]*Institut für Experimentalphysik, Universität Innsbruck, Austria*

In this talk, I will introduce the concepts of quantum information processing with trapped ions. The working principle of an ion trap will be briefly introduced, followed by a discussion of suitable ion species and their possible qubits. I will briefly discuss the Mølmer-Sørensen type entangling operations and their application in several proof-of-concept experiments [1,2,3]. These experiments will serve as examples to analyze the technical and fundamental limitations of state-of-the-art ion trap quantum information processors [4]. I will then summarize the experimental efforts to realize scalable ion trap systems and the respective technical challenges.

References

[1] E. A. Martinez et al, Nature **534**, 516 (2016)
[2] T. Monz et al, Science **351**, 1068 (2016)
[3] A. Erhard et al, arXiv:1902.08543 (2019)
[4] P. Schindler et al, New. J. Phys. **15**, 123012 (2013)

Semiconductor spin qubits – A scalable platform for quantum computing?

H. Bluhm[1]

[1] *JARA-Institute for Quantum Information, RWTH Aachen University Aachen, Germany and Forschungszentrum Jülich, Jülich, Germany*

For the realization of a quantum computer, a good qubit design as the basic building block is a nontrivial starting point. To fully leverage the potential of quantum computing, quantum processors will likely have to incorporate billions of high-quality qubits. Several approaches are being pursued and exhibit different strength and weaknesses. The device concepts and fabrication procedures for semiconductor based qubits are very similar to those used in the semiconductor industry. Using the spin-degree of freedom, their coherence properties and the quality of single-qubit operations have now reached the required level and are on par with competing approaches. Two-qubit operations will likely follow suit in the near future. With these basic requirements being met, it is now time to think if and how increasingly large multi-qubit systems and eventually functional quantum processor can be realized. This quest raises many pertinent questions, some of which equally apply to other qubit platforms. How reproducibly can the different types of semiconductor qubits be produced? How can their operating point be adjusted efficiently and in an automated way? How can they be connected to form meaningful multi-qubit circuits? How severe are multi-qubit control issues such as crosstalk and frequency crowding, and how can they be avoided? What control system architectures are most suitable for operating large numbers of qubits? What is the limit of cryogenic electronics regarding power consumption and integration density? I will give a (partial) overview of the state of the art in the field and discusses future challenges associated with the realization of large-scale quantum processors, many of which will greatly benefit from input from engineering science. The guiding vision is that of a highly integrated quantum processor with an ultra-low power cryogenic control system.

References

[1] L. M. K. Vandersypen, H. Bluhm, J. S. Clarke, A. S. Dzurak, R. Ishihara, A. Morello, D. J. Reilly, L. R. Schreiber, and M. Veldhorst, "*Interfacing spin qubits in quantum dots and donors—hot, dense, and coherent*" npj Quantum Inf. **3**, 34 (2017).

[2] An article with similar content to this talk is expected to appear in the proceedings of the 2019 IEEE International Symposium on Circuits and Systems (ISCAS) at https://ieeexplore.ieee.org/xpl/conhome.jsp?punumber=1000089

Engineering challenges to construct a practical trapped ion microwave quantum computer

Winfried K. Hensinger[1]

[1] Sussex Centre for Quantum Technologies, Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, United Kingdom

Trapped ions are arguably the most mature technology capable of constructing practical large scale quantum computers. We are now moving away from fundamental physics studies towards tackling the required engineering tasks in order build such machines.

By inventing a new method where voltages applied to a quantum computer microchip are used to implement entanglement operations, we have managed to remove one of the biggest barriers traditionally faced to build a large-scale quantum computer using trapped ions, namely having to precisely align billions of lasers to execute quantum gate operations. This new approach, quantum computing with gobal radiation fields, is based on the use of well-developed microwave technology [1].

In order to be able to build large scale device, a quantum computer needs to be modular. One approach features modules that are connected via photonic interconnect, however, only very small connection speeds between modules demonstrated have been demonstrated so far. We have invented an alternative method where modules are connected via electric fields, allowing ions to be transported from one module to another giving rise to much faster connection speeds [2].

We recently unveiled the first industrial blueprint [2] on how to build a large-scale quantum computer which I will discuss in this talk. I will present an overview of some of the practical engineering challenges to build such a device.

References

[1] Trapped-ion quantum logic with global radiation fields, S. Weidt, J. Randall, S. C. Webster, K. Lake, A. E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker, and W. K. Hensinger, Phys. Rev. Lett. **117**, 220501 (2016)

[2] Blueprint for a microwave trapped ion quantum computer, B. Lekitsch, S. Weidt, A.G. Fowler, K. Mølmer, S.J. Devitt, Ch. Wunderlich, and W.K. Hensinger, Science Advances 3, e1601540 (2017)

The trend towards quantum accelerators

Koen Bertels

QuantumForce, Delft University of Technology
Delf, The Netherlandst

This presentation will focus on the development of Quantum Accelerator, which is maybe a subset of a Quantum Computer. It is not clear what should be understood by a Quantum Computer but a Quantum Accelerator is a more specific and clear definition. Modern computers are composed of many co-processor units such as GPU, TPUs and FPGAs. So a logical next step is to include a quantum accelerator. We are currently investing our effort in the development of a Quantum Genome Sequencing accelerator. This talk will describe the full-stack from Quantum application to the simulation on our QX simulator platform.

Reference

Quantum Computer Architecture: Towards Full-Stack Quantum Accelerators, K. Bertels, S. Varsamopoulos, A. Mouedenne, T. Hubregtsen, A. Sarkar,R. Nane, Z. Al-Ars, QCA lab, Delft University of Technology, Netherlands

Scalable Cryogenic CMOS Electronics for Spin Qubits

L. Geck[1], C. Degenhardt[1], P. Vliex[1], D. Nielinger[1], A. Artanov[1], M. Assarzadeh[1], A. Kruth[1], C. Grewing[1] and S. van Waasen[1,2]

[1] ZEA-2 Electronic Systems, Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Straße, 52425 Jülich, Germany

[2] Communication Systems, NTS, University of Duisburg-Essen, Bismarckstr. 81, 47057 Duisburg, Germany

A universal quantum computer including error correction schemes is expected to require at least 10^6 qubits to run quantum algorithms like Shor's Algorithm or to perform molecular simulations [1]. Semiconductor spin qubits are viable candidates for significantly scaling up qubit numbers, especially due to their compatibility with large volume and small feature size lithographic manufacturing processes. These qubits operate at very low temperatures (<100 mK) and require several distinct electrically generated signals per qubit. In current experiments, signals for qubit control are generated at room temperature and fed into a dilution refrigerator. This approach is not suitable for more than a couple of hundred qubits due to the diameter of the cables and the generated heat load. A solution for further scaling would be to locate the electronics in the immediate vicinity of the qubits. Depending on the qubit type electronics could be integrated on the same chip, as proposed in [2], or be placed on an additional chip connected for example by chip-to-chip bonding. Our work investigates the different challenges associated with bringing the electronics next to the qubit at cryogenic temperatures. In addition to the design of an electrical control system and the examination of its practical feasibility, methods to deal with the limited cooling power and the missing valid models for electrical components will be discussed in the talk.

References

[1] N. C. Jones, R. V. Meter, A. G. Fowler, P. L. McMahon, J. Kim, T. D. Ladd, and Y. Yamamoto, Physical Review X **2**, 031007 (2012)

[2] L. M. K. Vandersypen, H. Bluhm, J. S. Clarke, A. S. Dzurak, R. Ishihara, A. Morello, D. J. Reilly, L. R. Schreiber, and M. Veldhorst, npj Quantum Information **3**, 34 (2017)

Leveraging silicon technology for scalable quantum processors

S. De Franceschi

Univ. Grenoble Alpes & CEA, IRIG/PHELIQS, 38000 Grenoble, France
Quantum Silicon Grenoble, *https://www.quantumsilicon-grenoble.eu*

Silicon transistors are the building blocks of modern microprocessors. We carry billions of them in our pockets every day. Following decades of uninterrupted development, transistors have gotten smaller and smaller. Nonetheless, the physics laws governing their operation remain largely classical.

Under extreme conditions such as very low temperatures, however, the switching efficiency of silicon transistors can drastically improve enabling the possibility of realizing electronic circuits with reduced power consumption. At the same time, quantum phenomena become prominent opening the possibility to realize quantum dot devices operating as spin qubits, where the elementary bit of quantum information is encoded in the spin state of an electrostatically confined electronic charge.

The Quantum Silicon Grenoble Group, gathering physicists and engineers from different institutions (UGA, CEA, and CNRS), is exploring these new opportunities. We aim at the development of scalable spin qubit arrays and cryogenic control hardware, all based on silicon-on-insulator technology. I will present our state-of-the-art and outline our research plans for the coming years.

References

[1] Maurand et al., Nature Communications **7**, 13575 (2016).
[2] Corna et al., Nature Quantum Information **4**, 6 (2018)
[3] Crippa et al. Physical review letters 120, 137702 (2018)
[4] Crippa et al., arXiv:1811.04414v1 (2018)
[5] Urdampiilleta et al. arXiv:1809.04584 (2018).
[6] Vinet et al., 2018 IEEE International Electron Devices Meeting (IEDM), 6.5. 1 - 6.5. 4 (2018).

Microwaves and Trapped ions: a fertile marriage

M. Johanning[1]

[1]*Universität Siegen, Experimentelle Quantenoptik, 57072 Siegen, Germany*

Microwave manipulation of atoms is a well-established technology and already finds numerous applications in our everyday life ranging from medical examinations to the availability of precise atomic clocks used for navigation or telecommunication. The combination of microwave control with individual control over quantum systems as provided in modern quantum information experiments using trapped ions paves the way for copious seminal work in quantum information and quantum metrology:

High fidelity single qubit gates have been demonstrated using microwave fields, and I will outline, how NMR schemes can be adopted to create robust pulse sequences, which do not suffer severely from imperfect calibration or experimental drifts [1]. The additional application of static magnetic field gradients allows for individual manipulation and single ion addressing in frequency space with unprecedented low cross-talk [2], and I will discuss, how such field configurations can be obtained using permanent magnets and solenoids. Furthermore, the Zeeman shift creates a state-dependent force which leads to an effective spin-spin coupling, which can be used for conditional gates [3]. I will show, how these couplings can be tailored by shaping the trapping potential and the magnetic field distribution, and how this tailoring can be exploited together with additional microwave pulses to create long distance entanglement [4]. Similarly, the inhomogeneous ac-Zeeman effect can be exploited for conditional gates [5]. The dephasing of Zeeman qubits upon magnetic field fluctuations can be mitigated by the application of dressing fields and a boost of coherence time by three orders of magnitude has been observed [6].

As one application, single atom magnetometers, which greatly benefit from this extended coherence, have been demonstrated to operate with unprecedented precision at the standard quantum limit, and an operation even beyond can be envisaged using entangled atoms. A few other applications of trapped ions spin qubits and microwave manipulation will be briefly reviewed, e.g. the demonstration of almost unit internal state fidelity upon transport and the investigation of temporal correlations of quantum measurements.

References

[1] N. Timoney et al., Phys. Rev. A **77**(5), 052334 (2008)

[2] C. Piltz et al., Nat. Comm. **5**, 4679 (2014)

[3] A. Khromova et al. Phys. Rev. Lett. **108**(22),220502 (2012)

[4] S. Zippilli et al. Phys. Rev. A **89**(4), 042308 (2014)

[5] C. Ospelkaus et al. Nature **476**(7359), 181–184 (2011)

[6] N. Timoney et al. Nature, **476**(7359), 185–188 (2011)

Locating two-level material defects that limit the coherence of superconducting qubits

J. Lisenfeld[1], A. Bilmes[1], G. Weiss[1], and A.V. Ustinov[1,2]

[1] *Karlsruhe Institute of Technology, Physikalisches Institut, Karlsruhe, Germany*
[2] *Russian Quantum Center and National University of Science and Technology MISIS, Moscow, Russia*

Atomic tunneling systems emerge from material defects and have been identified as a major source of decoherence in superconducting quantum circuits. Until now, their microscopic origin and location in a given device remained unknown. We developed a technique to tune the resonance frequencies of defects in superconducting qubits by applying both strain and dc-electric fields which are generated by electrodes surrounding the sample chip. A comparison of the observed response to electric field and strain allows us to distinguish the defects in the tunnel barriers of qubit junctions from those residing on the sample surface. Our statistical analysis indicates that these both defect classes contribute to qubit decoherence. We present a method to obtain information about the locations of individual defects on the sample surface by comparing their coupling strengths to different sample electrodes. This technique can be applied to any ready-made superconducting qubit sample. It helps to identify the critical interfaces where the defects limit the qubit coherence.

Scalable Quantum Error Correction – Concepts and Engineering Challenges

M. Müller[1]

[1]*Department of Physics, Swansea University, Swansea, United Kingdom*

To date, the construction of a fault-tolerant quantum computer remains a fundamental scientific and technological challenge, due the influence of unavoidable noise which affects the fragile quantum states. In our talk, we first introduce basic concepts of quantum error correction and topological quantum error-correcting codes. The latter allow one to protect quantum information during storage and processing by distributing logical quantum information over quantum many-body spin systems. We then discuss experimental prospects and general engineering requirements for practical and scalable experimental quantum error correction. Time permitting, I will also present some recent theory work of our group on resource-efficient and fault-tolerant protocols to control single and coupled logical qubits of increasing size and robustness in scalable trapped-ion architectures.

References

[1] A. Bermudez *et al.*, Assessing the progress of trapped-ion processors towards fault-tolerant, quantum computation, Physical Review X 7, 041061 (2017)

[2] M. Gutiérrez, M. Müller, and A. Bermudez, Transversality and lattice surgery: exploring realistic routes towards coupled logical qubits with trapped-ion quantum processors, Phys. Rev. A. 99, 022330 (2019)

[3] A. Bermudez, X. Xu, M. Gutiérrez, S. C. Benjamin, M. Müller Fault-tolerant protection of near-term trapped-ion topological qubits under realistic noise sources, arXiv:1810.09199

Trapped Ion Quantum Computing

F. Schmidt-Kaler

QUANTUM, Univ. Mainz, Germany
https://www.quantenbit.physik.uni-mainz.de

I describe the approach of trapped ion qubits for scalable quantum computing, This includes a general discussion of architectures, required trap technologies and fabrication methods, control electronics for quantum register reconfigurations [1], the improvements qubit coherence [2,3], and a characterization. We have realized multi-qubit operations [4], eventually leading to quantum error correction algorithms [5]. I report on the setup of a cryogenic trap, expected advantages and challenges

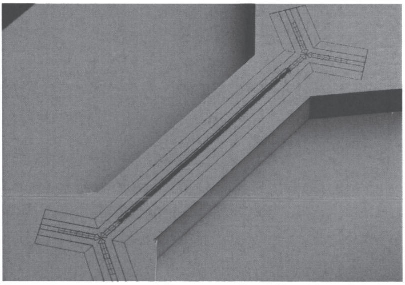
References

[1] Kaufmann, et al, "Fast ion swapping for quantum information processing",Phys. Rev. A 95, 052319 (2017)
[2] Rusteret al "A long-lived Zeeman trapped-ion qubit",Applied Physics B, 122(10), 1
[3] Ruster, et al "Entanglement-Based dc Magnetometry with Separated Ions", Phys. Rev. X 7, 031050
[4] Kaufmann et al "Scalable Creation of Long-Lived Multipartite Entanglement", Phys. Rev. Lett. 119, 150503
[5] A. Bermudez et al, "Assessing the Progress of Trapped-Ion Processors Towards Fault-Tolerant Quantum Computation", Phys. Rev. X 7, 041061

High-fidelity quantum operations in microfabricated surface ion traps

Peter Maunz

Sandia National Laboratories, Albuquerque, NM, USA



Scanning Electron Micrograph of Sandia's High optical access (HOA) surface electrode ion trap.

Trapped ions are uniquely suited to realize scalable quantum information processing as they provide identical qubits that are well isolated from the environment, have near-ideal quantum state preparation and measurement and minimal idle errors. Furthermore, optical addressing of ions can enable low-crosstalk operations between any pairs of qubits in a linear chain of ions [1]. However, realizing these systems and scaling them to the number of qubits required to solve interesting problems using conventional macroscopic traps quickly becomes intractable. To overcome the scalability and repeatability challenge, advanced microfabrication techniques have been adapted and employed to support a variety of complex electrode layouts, allowing for precise control of confining potentials. We use silicon microfabrication techniques developed by the semiconductor industry to fabricate surface electrode ion traps. The use of multi-level metallization enables us to realize any desired electrode configuration and allows for the integration of passive elements integrated with the device. As an example, Sandia's High-Optical-Access trap is shown in the figure above. Using Sandia's microfabricated surface ion traps, which feature low heating rates, high trap frequencies, and long trapping times, we demonstrate novel classical control techniques that employ parametric voltage solutions for elegant composition of shuttling operations and accurate control over the curvature of the confining potential. To demonstrate the viability of Sandia's microfabricated ion traps for quantum information processing, we have realized high-fidelity single-qubit gates below a rigorous fault tolerance threshold for general noise [2,3] and two-qubit Mølmer-Sørensen gates with a process fidelity of 99.58(6)%.

This research was supported, in part, by the Office of the Director of National Intelligence (ODNI), Intelligence Advanced Research Projects Activity (IARPA), the U.S. Department of Energy, Office of Science, Office of Advanced Scientific Computing Research Quantum Testbed Program, and the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multi-program laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

References

[1] N.M. Linke et al. Proc. Natl. Acad. Sci. 114, 13 (2017).

[2] R. Blume-Kohout et al. Nature Communications, 8, 14485 (2017).

[3] P. Aliferis and J. Preskill, Phys. Rev. A 79, 012332 (2009).

Cryogenic CMOS Interfaces for Large-Scale Quantum Computers

F. Sebastiano

[1]*Delft University of Technology, Delft, The Netherlands*

Quantum computers rely on processing the information stored in quantum bits (qubits) that must be typically cooled well below 1 K for proper operation. Performing operations on qubits requires a classical (i.e. non-quantum) electronic interface, which is currently implemented at room temperature for the few qubits available today. However, future quantum processors will comprise thousands or even millions of qubits. To avoid the unpractical requirement of thousands of cables from the cryogenic refrigerator to the room-temperature electronics, the electronic interface must operate at cryogenic temperatures as close as possible to the qubits.

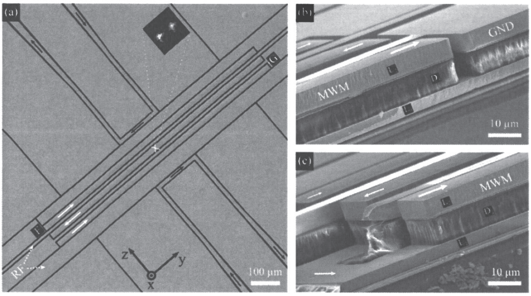
By leveraging the progress of the semiconductor industry, standard CMOS technology is the only electronic technology that demonstrated both operation at temperatures well below 1 K and the capability to integrate the billions of transistors required to interface a large-scale quantum computer. This talk will address the challenges of building such a scalable cryogenic CMOS interface. First, to enable the reliable design of cryogenic circuits, two main ingredients are required: on one hand, compact models for the cryogenic CMOS devices and, on the other hand, a comprehensive methodology to co-design the electronics and the quantum processor. After addressing those aspects, we will focus on implementing the several functionalities required in such complex System-on-a-Chip (SoC), whose complexity is comparable or even higher than room-temperature SoC for state-of-the-art transceivers. We will then demonstrate several complex analog and digital systems operating at 4 K, such as low-noise amplifiers, RF oscillators, voltage references and FPGAs, thus showing that cryogenic CMOS is a viable technology to enable large-scale quantum computing.

Microfabricated ion traps for scalable quantum information processing with trapped ions

A. Bautista-Salvador[2,1], J. Morgner[1,2], M. Wahnschaffe[2,1],
G. Zarantonello[1,2], H. Hahn[2,1], C. Ospelkaus[1,2]

[1]*Institut für Quantenoptik, Leibniz Universität Hannover*
[2]*Physikalisch-Technische Bundesanstalt, Braunschweig*

Surface-electrode ion traps are a scalable platform for quantum information processing with trapped ions. This architecture provides a very versatile marriage of a solid state, micro and mass fabricated control element with the high quality and coherence of atomic quantum systems. In this presentation, we will discuss the requirements and desired properties for a microfabrication process from an ion trapping perspective and in view of integrating as much as possible of the optical and electronic control infrastructure for the ions into the trap array. We discuss different microfabrication approaches that have been pursued so far. We will present a new multilayer microfabrication approach developed at PTB and LUH recently, offering thick electroplated metal electrodes and interconnect layers, with thick dielectric layers sandwiched in between. It is compatible with through-substrate vias to allow optimized laser access. We present results on trapping of ions in a trap with a top electrode structure, a vertical interconnect layer and a lower metal structure for bringing in control signals. We review different elements of a surface-electrode trap component library for scalable quantum logic and present the realization of an integrated microwave entangling gate module which has allowed us to realize entangling operation with a fidelity better than 98.4% and with so far only obvious technical effects affecting the fidelity.



Multilayer ion trap sample with integrated microwave circuitry.
Inset: Ions trapped above the sample surface.
A. Bautista-Salvador et al., arXiv:1812.01829 [quant-ph]

Quantum dots as spin-photon interfaces

**T. Huber[1], J. Quilter[1], A. Pfenning[1], M. Moczała-Dusanowska[1],
Ł. Dusanowski[1], L. Lackner[1], S. Gerhardt[1], J. Jurkat[1], C. Schneider[1],
and S. Höfling[1,2]**

[1] *Lehrstuhl für Technische Physik, Physikalisches Institut und Röntgen Center for Complex Material Systems, Am Hubland, 97070 Würzburg, Germany*
[2] *SUPA, School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, KY16 9SS, UK*

In 1997, Peter Shor presented an algorithm for prime factorization in polynomial time on a quantum computer[1]. Since the security in classical cryptography relies on the mathematical complexity of prime factorization, a possible realization of a quantum computer threatens classical cryptography. To fix this problem there are two possible solutions. One is post-quantum cryptography[2] algorithms, which is still based on mathematical complexity. Here, the encryption is modified such that there is no known attack from a quantum computer. The other solution is quantum key distribution[3], which is solely based on physical principles. The latter solution is preferable, because it is genuinely secure – also in the future.

In order to go away from direct links, one needs a quantum repeater[4] which needs a local memory or a fully connected cluster state[5], which probably needs a local qubit as well to build up the entanglement[6]. Spins in QDs are a promising platform, because their spins can be coherently controlled[7], entangled with emitted photons[8], or entangled with other distant spins[9]. A limiting factor in scalability is their random position, which can be overcome by site controlled growth. Another approach is to combine self-assembled QDs with gate defined quantum dots on high mobility 2D electron gases. This allows for scalability and local spin-spin interaction, as well as an efficient spin-photon interface. We present our recent developments on highly efficient, tunable self-assembled QDs in photonic structures and our latest results on coupling gate defined QDs and self-assembled QDs.

References

[1] P. Shor, SIAM J. Sci. Statist. Comput. **26**,1484 (1997)

[2] Daniel J. Bernstein: *Introduction to post-quantum cryptog*raphy. Springer 2009

[3] C. Bennett and G. Brassard, Proceedings of IEEE International Conference on Computers, Systems and Signal Processing **175**, 8 (1984)

[4] H.-J. Briegel, W. Dür, J. I. Cirac, and P. Zoller, Phys. Rev. Lett. **81**, 5932 (1998)

[5] K. Azuma, K. Tamaki, and H.-K. Lo, Nature Comm. **6**, 6787 (2015)

[6] I. Schwartz *et al.*, Science **354**, 434 (2016)

[7] D. Press D, T.D. Ladd, B. Zhang, Y. Yamamoto, Nature **456**, 218 (2008)

[8] K. De Greve *et al.*, Nature **491**, 421 (2012)

[9] A. Delteil *et al.,* Nature Physics **12**, 218 (2016)

A programmable trapped-ion quantum computer

N.M. Linke[1], N.H. Nguyen[1], C.H. Alderete[1], D. Zhu[1], K.A. Landsman[1], and C. Monroe[1,2]

[1]Joint Quantum Institute, University of Maryland, College Park, MD 20742, USA
[2] IonQ Inc., College Park, MD 20740, USA

Trapped ions are a promising candidate platform to realize a scalable quantum computer. We present a system comprised of a chain of $^{171}Yb^{+}$ ions with individual Raman beam addressing and individual readout [1]. This fully connected processor can be configured to run any sequence of single- and two-qubit gates, making it in effect an arbitrarily programmable quantum computer that does not incur swap-gate overhead [2].

We have been using this system to demonstrate a wide range of quantum algorithms on up to seven qubits [3]. Recently, we have added a classical feedback layer to this computing architecture. Quantum-classical hybrid systems of this kind offer a path towards the use of near-term quantum computers for different optimization tasks. We present several demonstrations relating to machine learning in such a hybrid approach, such as finding the ground state binding energy of the deuteron nucleus, the training of shallow circuits [4], and the preparation of quantum critical states using a quantum approximate optimization algorithm (QAOA) scheme. Recent results from these efforts will be presented.

Additionally, I will discuss ideas and current engineering challenges in boosting the performance of the different quantum operations employed, and for scaling up this machine to larger qubit numbers.

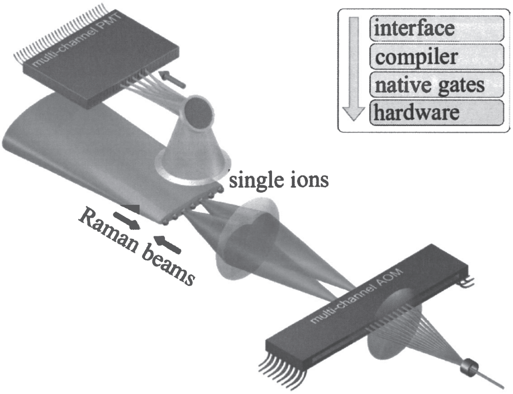


***Fig.:** Hardware: Trapped ions addressed by individual Raman beams, imaged onto a photo-detector array for readout.*
Inset: Programmable quantum computing stack.

References

[1] S. Debnath et al., Nature **563**, 63 (2016)
[2] NML et al., PNAS **114**, 3305 (2017)
[3] K. A. Landsman et al., Nature, in print (2019)
[4] D. Zhu et al., arXiv 1812.08862

Linking analog to digital: scalable instrumentation for quantum computing

Jan Benhelm

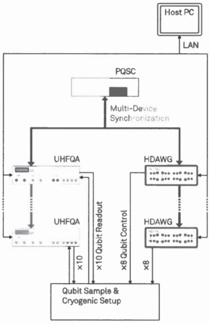
Zurich Instruments AG, Zurich, Switzerland

Zurich Instruments' mission is to support scientists and engineers in building a useful quantum computer by providing the instrumentation to efficiently link their analog quantum bits with the digital domain. We present the first scalable commercial solution for readout and control of up to 100 qubits (see Fig. 1 and [1]).

Qubit control: The HDAWG Arbitrary Waveform Generator generates control pulses for 1-qubit and 2-qubit gates. The high channel density and synchronization ability make the HDAWG an ideal candidate for scaling to large systems. A trigger-to-first-sample-out latency of 50 ns and dynamic sequencing capability are crucial for feedback experiments.

Readout: The HDAWG has 8 photon counters for qubit detection in NV color center and trapped ion experiments. For cavity QED and quantum dots the UHFQA Quantum Analyzer offers the simultaneous measurement of up to 10 readout resonators. Measurement speed and fidelity are optimized with matched filters. Fig. 2 details the implemented functionality. For more details and measurements see [2,3].

System control: The PQSC Programmable Quantum System Controller synchronizes and orchestrates all instruments to form an integrated real-time system. Its reprogrammable FPGA allows for the implementation of user-defined real-time algorithms for quantum processor control.



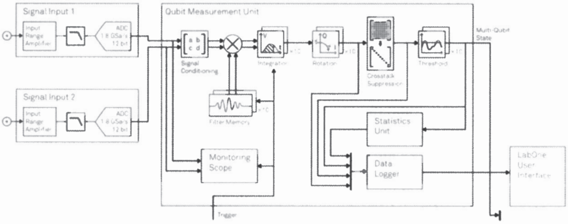


Fig 1. (left) The complete Quantum Computer Control System.

Fig 2. (above) Functional blocks of the UHFQA Quantum Analyzer readout part. Not shown is the integrated AWG that generates the readout pulses

References

[1] Quantum Computing Control System, https://www.zhinst.com/quantum
[2] J. Heinsoo et al, Phys. Rev. Applied **10**, 034040 (2018), arXiv:1801.07904
[3] C. C. Bultink, Appl. Phys. Lett. **112**, 092601 (2018), arXiv:1711.05336

Abstracts of Posters

(in alphabetical order)

Scalable Cryogenic CMOS Electronics for Spin Qubit Control

A. Artanov[1], **D.Nielinger**[1], **P. Vliex**[1], **M. Assarzadeh**[1], **C. Degenhardt**[1], **L.Geck**[1], **C. Grewing**[1], **A. Kruth**[1], **and S. van Waasen**[1,2]

[1] ZEA-2 Electronic Systems, Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Straße, 52425 Jülich, Germany
[2] Communication Systems, NTS, University of Duisburg-Essen, Bismarckstr. 81, 47057 Duisburg, Germany

The Central Institute for Electronic Systems at Forschungszentrum Jülich develops, designs and tests scalable solutions for the control and readout of qubits to be used in future quantum computers. The focus lies on highly integrated system-on-chip (SoC) solutions leveraging state-of-the-art commercial semiconductor technologies.

Qubits work only at very low temperatures (<1K) and one of the main challenges for integrating a high number of qubits is their connection to the room temperature control electronics and their sensitivity to any kind of noise. Therefore the integration of circuits in close vicinity to the qubit promises significant benefits and will be most likely the only way to reach qubit numbers beyond a thousand [1]. The extremely low temperature poses severe challenges to classical circuit design, amongst others the power budget which is limited by the cooling power of the dilution refrigerator.

The operation of a qubit requires fast and precise voltage pulses with a dynamic range of approximately 8 mV as well as multiple DC voltages to form potential wells and tune the qubit into operating region. With these requirements a test chip was designed and layouted in a commercial 65nm CMOS process. The chip employs a pulse-digital-to-analog converter, with a sampling rate of 250 MS per second, to generate pulses with ±4 mV amplitude as gate sequences for operating a qubit. For generation of the DC Voltages a low power multi-output-channel digital-to-analog converter with an output range of -1 to 0 V is incorporated. The chip can be placed in close proximity to the actual qubit at the milli-kelvin temperature stage.

In this presentation, we will describe the chip architecture in detail, show corresponding simulation results and measured chip performance including first results at cryogenic temperature.

References

[1] C. Degenhardt et al., "CMOS based scalable cryogenic Control Electronics for Qubits," International Conference on Rebooting Computing (ICRC), Washington, Dec 2017

Robust two-qubit gates generated by pulsed dynamical decoupling

P. Barthel[1], J. Casanova[2], P. Huber[1], Th. Sriarunothai[1], G. S. Giri[1], M. Plenio[2] and Ch. Wunderlich[1]

[1] *Department Physik, Universität Siegen, 57068 Siegen, Germany*
[2] *Institut für Theoretische Physik, Albert-Einstein-Allee 11, Universität Ulm, 89069 Ulm, Germany*

High-fidelity quantum gates are a key ingredient of any quantum computing architecture. While microwave-driven trapped-ion qubits are a promising system for scalable quantum computing – allowing for individual addressing in frequency space by a global radiation field as well as interaction between internal and motional states of the qubits using magnetic gradient induced coupling [1] – gate operations are often limited by decoherence due to fluctuations of ambient magnetic fields. A common method to overcome this obstacle are pulsed or continuous dynamical decoupling (DD) techniques, which extend the coherence time of magnetically sensitive qubits to allow for multi-qubit gates.

A recently proposed, novel DD sequence is presented that not only extends the coherence time, but should also result in a tunable two-qubit phase gate with high fidelity [2]. By using both motional modes of a two-ion crystal it furthermore allows for higher gate speeds than comparable gates using only a single mode. We report on the implementation of this sequence on a set of two $^{171}Yb^{+}$ ions in a linear Paul trap to realize a π/4 gate using microwave driving fields. We demonstrate the applicability of the sequence for Controlled-NOT operations and the creation of Bell states. While the possible speed-up of the gate cannot yet be exploited in the current experimental setup, we show its robustness to errors in Rabi and trap frequency.

References

[1] T. Sriarunothai et al, Quantum Sci. Technol. **4**, 015014 (2019)
[2] I. Arrazola et al., Phys. Rev. A **97**, 052312 (2018)

Micro ion traps with 3D microwave conductors for applications in quantum technologies

A. Bautista-Salvador[1,2], **G. Zarantonello**[1], **H. Hahn**[1] **and C. Ospelkaus**[2]

[1] Institute for Quantum Optics, Hannover
[2] Physikalisch-Technische Bundesanstalt, Braunschweig

Within the trapped ion approach, one of the essential prerequisites to scale quantum technologies to a larger number of qubits is the realization of microfabricated ion traps that allow the integration of routing signals in a scalable way [1]. We have recently developed and demonstrated a scalable technology capable to fabricate multilayer ion traps to, in principle, an arbitrary number of metal-dielectric layers [2]. Here we present the operation of a novel trap with integrated 3D microwave conductors. The trap not only features the necessary set of conductors to induce single and multi-qubit quantum operations but also generates a low residual field and a high magnetic field gradient at the trap center measured by a single $^9Be^+$ ion [3]. The fabrication method will allow the realization of ion traps with a broad variety of geometries, functionalities and applications.

References

[1] C. Monroe and J. Kim, Science **339**, 1164 (2013)

[2] A.Bautista-Salvador et al New J. Phys. in press (2019)
https://doi.org/10.1088/1367-2630/ab0e46

[3] H. Hahn, G. Zarantonello et. al arXiv:1812.02445 [quant-ph] (2018)

Planar-electrode ion trap for microwave-based quantum information processing

I. A. Boldin, **A. Kraft, M. Porst, E. Esteki, B. Okhrimenko and Ch. Wunderlich**

[1]Department Physik, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, 57068 Siegen, Germany

We present the status of our experiment on the realization of a quantum processor with microwave-driven ions trapped in a novel planar ion trap. This approach uses a static spatially inhomogeneous magnetic field for MAgnetic Gradient Induced Coupling (MAGIC) between qubits and for individual addressing of the qubit states [1]. We present a newly designed trap chip (Fig. 1) that features the possibility to trap parallel strings of ions with variable ion-surface separation and variable separation between the ion strings. The trap chip also has built in resonator structures that enhance the microwave field amplitude and hence the speed of quantum gates. This new experimental setup incorporates an Ar^+-ion gun for in-situ cleaning of the trap surface in order to reduce the electric field noise and thus motional heating of the ions. The trap is enclosed in a custom-designed mu-metal magnetic field shielding in order to reduce magnetic field noise that limits the coherence times of the qubits. The experimental apparatus also includes a novel magnetic system for creating a strongly inhomogeneous static magnetic field required for MAGIC.

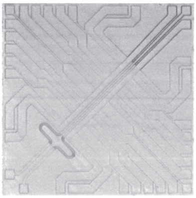


Fig. 1. Photograph of the ion trap chip that includes electrodes for trapping parallel ion Coulomb crystals and for changing their trapping height and mutual separation. The chip is 11x11 mm in size.

References

[1] Ch. Piltz, Th. Sriarunothai, S. Ivanov, S. Wölk, Ch. Wunderlich, Science Advances 2 e1600093 (2016)

Engineering a superconducting quantum computer

Jonas Bylander and Per Delsing

Chalmers University of Technology, Göteborg, Sweden

We are engineering a superconducting quantum processor with up to 100 qubits within the Wallenberg Center for Quantum Technology [1] in Sweden and the collaborative project OpenSuperQ [2] of the EU Flagship on Quantum Technology. We aim to focus on applications within quantum simulation of quantum chemistry and of optimization problems. We collaborate closely with theorists, both in-house and within OpenSuperQ, on modeling as well as quantum algorithms and application use cases. We also have several paying partners from Swedish industry.

We will present our quantum computer *engineering approach* encompassing,

- design, process development, and fabrication of high-coherence superconducting quantum hardware – currently our qubits reproducibly show relaxation times $T_1 > 50$ us and T_1-limited T_2^* decoherence times, and we understand the limiting factors;
- quantum–classical control circuit integration and packaging;
- control and calibration techniques for high-fidelity quantum gate operations; and
- a software stack bridging quantum algorithms and quantum hardware.

References

[1] http://www.wacqt.se
[2] http://opensuperq.eu

Improving qubit coherence times via adjustable permanent magnets and magnetic field tracking

A. Conta, **J. Nicodemus, D. Pijn, B. Lekitsch, F. Schmidt-Kaler and U. Poschinger**

QUANTUM - University of Mainz, Staudingerweg 7, 55128 Mainz, Germany

We perform intermediate scale quantum computation based on magnetic-field dependent $^{40}Ca^{+}$ spin qubits stored in a segmented Paul trap. This trap consists of 32 segments, which can store ions at multiple locations and allows for intermediate scalability via shuttling operations [1]. The homogeneity and stability of the magnetic field are fundamental prerequisites for high-fidelity quantum gates. For generation of the quantizing magnetic field, we employ 134 intrinsically temperature-compensated permanent magnets mounted on six individual rings outside of the vacuum vessel. We show the homogeneity of the magnetic field is significantly improved as compared to previous setups [2], such that the accumulation of spurious shuttling-induced phases is prevented.

Residual field drifts are caused by temperature changes or ambient field drifts. We show that also the temperature-induced field drift is decreased for the current setup. In order to mitigate the impact of the residual drift, we predict the drift using a Kalman-filter based approach. Using Bayesian statistics, this filter allows to compensate for drifts and mitigates the effect of measurement uncertainties.

References

[1] Scalable creation of long-lived multipartite entanglement
H. Kaufmann, T. Ruster, C. Schmiegelow, M. Luda, V. Kaushal, J. Schulz, D. von Lindenfels, F. Schmidt-Kaler, and U. Poschinger,
Physical Review Letters 119, 150503 (2017)

[2] T. Ruster, C. T. Schmiegelow, H. Kaufmann, C. Warschburger,
F. Schmidt- Kaler, U. G. Poschinger, Apllied Physics B (2016), 122:254

Quantum Fredkin gate from a triple quantum dot system

A. T. Costa[1], **J. Moutinho**[1], **M. Pezzutto**[1], **S. Bose**[2], **Y. Omar**[1]

[1]Instituto de Telecomunicações and IST, ULisbon, Portugal
[2] University College London, UK
E-mail: yasser.omar@tecnico.ulisboa.pt

We present a theoretical proposal for the implementation of a quantum Fredkin gate based on the reversible dynamics of a triple quantum dot system. Our proposal does not rely on fine-tuning of parameters and could be implemented on any of the currently existing quantum dot architectures. We show that the gate performance is not critically affected by electrostatic noise, either quasi-static or high frequency.

Robust quantum optimal control with noise

M. Cykiert[1] and E. Ginossar[1]

[1]*Advanced Technology Institute*
University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom

In order to get useful output out of quantum algorithms we need to be able to perform operations on individual qubits. Despite these operations not being achieved perfectly there exists an error rate for which quantum computation will be feasible using some error correcting scheme, with an amount of redundancy in the qubits. This repetition of information can increase the number of qubits by a factor greater than a thousand! By obtaining extremely high fidelity, a measure of the reliability of the execution of said operations, this overhead can be reduced.

The way these reliable operations are achieved is by using microwave pulses. However, in the presence of fluctuations in the parameters of the qubit or when there is noise, the value for the fidelity drops significantly. Gradient based optimisation methods are suited for improving the fidelity, one such strategy, sequential convex programming[2], is used to fight these undesirable effects. SCP finds control pulses that are robust to fluctuations and noise in the parameters of the qubit and control. Due to the sensitivity to the initial condition of the optimisation a large number of starting points are often needed to be used to explore the fidelity landscape this requires code that can be run on multiple computers at once.

References

[1] B. Russell, Journal of Physics A: Mathematical and Theoretical, 50, 205302, (2017).
[2] J. Allen, Phys. Rev. A, 95, 042325, (2017).

Quantum Inspire - QuTech's silicon spin qubit-based full stack Quantum Computer prototype

T. Last {1}, R. Versluis {1}, N. Samkharadze {1}, P. T. Eendebak{1}, L. Blom{2}, K. Martens{2},
J. Winters{1}, G. F. IJ. Kramer{1}, R. Grooters{1}, N. Khammassi{2}, K. Bertels{2},
M. Veldhorst {2}, G. Scappucci{2}, L. M. K. Vandersypen{2} and G. J. N. Alberts{1}

{1}QuTech and Netherlands Organization for Applied Scientific Research (TNO),
Stieltjesweg 1, 2628 CK Delft, The Netherlands

{2}QuTech and Kavli Institute of Nanoscience, Delft University of Technology,
Lorentzweg 1, 2628 CJ Delft, The Netherlands

Quantum computing holds the promise to tackle big problems in energy, health and security. It can impact our daily lives. Therefore, teams of QuTech's Shared Development and Fault-Tolerant Quantum Computing roadmaps are developing Quantum Inspire (QI), a Si spin qubit-based full stack Quantum Computer prototype (www.quantum-inspire.com). This prototype system will offer the public cloud-based access to QuTech technologies such as (i) a programmable Si spin qubit-based quantum information processor, (ii) a programmable quantum computer simulator and (iii) tutorials and user background knowledge on quantum information science.

Quantum Inspire will be rolled out in two phases. Access to QuTech's QX quantum simulator and a collection of quantum information science tutorials is already made available online. In the second phase, we will provide access to programmable Si spin qubit-based quantum processors, starting with a two-qubit device. Our quantum chips are based on accumulation mode Si/SiGe multi-dot arrays [1, 2]. For the most part QI's control and cryogenic hardware had been assembled and initial electrical device characterization is already under way.

An essential requirement with respect to choices within our hardware layer is the scaling of the number of controllable spin qubits. Scaling requires a drive to lower the cost per qubit, system engineering approaches and novel (quantum-centric) supply chains. We will discuss our perspective on qubit scaling by presenting our hardware architecture. It is comprised of (i) in-house DACs and voltage sources to define the qubit plane and energy landscape and (ii) commercially available vector sources for qubit control will be replaced by custom-made microwave sources and upconverters.

[1] N. Samkharadze, G. Zheng, N. Kalhor, D. Brousse, A. Sammak, U. C. Mendes, A. Blais, G. Scappucci, L. M. K. Vandersypen, "Strong spin-photon coupling in silicon", Science 359, 6380, 1123 (2018).

[2] T. F. Watson, S. G. J. Phillips, E. Kawakami, D. R. Ward, P. Scarlino, M. Veldhorst, D. E. Savage, M. G. Lagally, M. Friesen, S. N. Coppersmith, M. A. Eriksson, L. M. K. Vandersypen, "A programmable two-qubit quantum processor in silicon", Nature 555, 633 (2018).

Sample complexity of device-independently certified "quantum supremacy"

Dominik Hangleiter, Martin Kliesch, Jens Eisert, Christian Gogolin (1)

(1) Covestro, Leverkusen, Germany

Results on the hardness of approximate sampling are seen as important stepping stones towards a convincing demonstration of the superior computational power of quantum devices. The most prominent suggestions for such experiments include boson sampling, IQP circuit sampling, and universal random circuit sampling. A key challenge for any such demonstration is to certify the correct implementation. For all these examples, and in fact for all sufficiently flat distributions, we show that any non-interactive certification from classical samples and a description of the target distribution requires exponentially many uses of the device. Our proofs rely on the same property that is a central ingredient for the approximate hardness results: namely, that the sampling distributions, as random variables depending on the random unitaries defining the problem instances, have small second moments.

Microwave-driven high-fidelity quantum logic with 43Ca+

T P Harty[1]

[1]Department of Physics, University of Oxford, UK

Magnetic field gradients in the proximity of a conductor carrying microwave current can be used to couple the internal and motional states of atoms and thus implement two-qubit gates [1, 2]. Driving logic operations with microwaves as opposed to lasers offers several advantages such as simpler phase control, lower cost, elimination of photon scattering errors and improved scalability. Two-qubit gate fidelities of 99.7(1) % have been achieved with this method in a room-temperature surface trap [3].

Here we present the design and initial characterisation of a next-generation surface electrode ion trap operated at cryogenic temperatures that will aim to improve both the fidelity and gate speed achieved in microwave-driven quantum gates. Notable features include passive field nulling via the geometry of the microwave conductor, a reduction in distance from ion to trap surface and segmented electrodes to confine qubits in different zones. Additionally, we switch to a different "clock" qubit in 43Ca+ to increase gate speed and reduce errors due to off-resonant excitations. Combined with lower heating rates and increased ion lifetime at cryogenic temperatures, this will enable further progress towards microwave-driven quantum algorithms.

References

[1] C. Ospelkaus et al., Phys. Rev. Lett. 101, 090502 (2008)
[2] C. Ospelkaus et al., Nature 476, 181 (2011)
[3] T. P. Harty et al., Phys. Rev. Lett. 117, 140501 (2016)

An Electric Field Generator for Versatile Trapping Potentials in the Microstructured Ion Traps

M. T. Baig, M. Johanning, A. Wiese, S. Heidbrink,*
M. Ziolkowski and C. Wunderlich

Faculty of Science and Technology, Department of Physics,
University of Siegen, D-57068 Siegen

Abstract

We present a multichannel arbitrary waveform generator that simultaneously generates arbitrary voltage waveforms on 24 independent channels with a dynamic update rate of up to 12.5 Msps. A real-time execution of a single waveform and/or sequence of multiple waveforms in succession, with a user programmable arbitrary sequence order is provided under the control of a stand-alone sequencer circuit implemented using a field programmable gate array. The device is operated using an internal clock and can be synced to other devices by means of transistor-transistor logic (TTL) pulses. The device can provide up to 24 independent voltages in the range of up to ± 13 V with a dynamic update-rate of up to 12.5 Msps and a power consumption of less than 35W. Every channel can be programmed for 16 independent arbitrary waveforms that can be accessed during run time with a minimum switching delay of 160 ns. The device has a low-noise of 250 μVrms and provides a stable long-term operation with a drift rate below 10 μV/min and a maximum deviation less than ± 300 μVpp over a period of 2 h.

Parallel adaptive addressing of microwave-driven trapped-ion qubits

P. Huber[1], P.Barthel[1], T. Sriarunothai[1], S. Wölk[2], G.S. Giri[3], Ch. Wunderlich[1]

[1]Department Physik, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex- 4 5 Str. 3, 57072 Siegen, Germany
[2]Institute for Theoretical Physics, University of Innsbruck, Technikerstraße 21a, 6020 Innsbruck, 6 7 Austria
[3] Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf Germany

Coulomb crystals of laser cooled ions stored in Paul traps are a promising candidate for scalable quantum information processing. A spatially varying magnetic field applied to such a crystal couples the ions' internal and motional states (MAgnetic Gradient Induced Coupling scheme (MAGIC) [1]), thus enabling multi-qubit gates. In addition, qubit resonances can be individually shifted and become position-dependent, thereby making them distinguishable and addressable in frequency space [2].

Individual addressing in a string of $^{171}Yb^{+}$ trapped-ion qubits in the RF regime allows for selective manipulation as part of single- or multi-qubit gates. This relies on the exact knowledge of an ion's qubit resonance frequency, v, here of ground state hyperfine transitions. Due to uncontrolled magnetic fields, v may drift and fluctuate in time. The fidelity of quantum gates can be enhanced by tracking v and correcting for its variations. To efficiently carry out this tracking and adaption of v in parallel for N qubits, we sample the qubit's resonance curve only at two points [3] to deduce v. We demonstrate this adaptive addressing scheme for eight qubits (a Qubyte) in parallel, and characterize its impact on single- and multi-qubit gate fidelities.

References

[1] Th. Sriarunothai, S. Wölk, G.S. Giri, N. Friis, V. Dunjko, H.J. Briegel, Ch. Wunderlich, Quantum Sci. Technol. **4** 015014 (2019).

[2] C. Piltz, Th. Sriarunothai, A.F. Varón, Ch. Wunderlich, Nat. Commun. **5** 4679 (2014).

[3] Andrew D. Ludlow, Martin M. Boyd, Jun Ye, E. Peik, and P.O. Schmidt, Rev. Mod. Phys. **87**, 637 (2015).

Opportunities and Limitation of Advanced Material Science towards the Scaling of Si-based Quantum Computing

Wolfgang M. Klesse[1] and Giovanni Capellini[1,2]

[1] IHP – Leibniz-Institut für innovative Mikroelektronik, 15236 Frankfurt (Oder), Germany
[2] Dipartimento di Scienze, Università Roma Tre, Viale Marconi 446, 00146 Rome, Italy

Recent literature on semiconductor spin-qubits highlights their high potential for scalability by referring to their compatibility with Si-based mainstream technology. It is true that leveraging the manufacturing capabilities of modern CMOS fabrication facilities opens a path to integrated and miniaturized quantum computing architectures. However, this aspect is only one side of the medal towards the realization of quantum circuits comprising $>10^3$ physical qubits. In particular, it is appearing more and more clear that the real bottleneck is represented by the actual material properties of the host material, typically SiGe/Si heterostructures or Si:P, limiting the fabrication yield of useable spin-qubits. In fact, it is still unclear whether the extremely demanding material quality requested is achievable on the wafer scale, when transferring the qubit fabrication form the lab to real state-of-the-art CMOS processes.

In this framework, we discuss different advanced characterization techniques to probe the structural properties which highly affect the quantum properties of spin-qubits at the nm-scale, e.g. the defect density, the strain distribution, and the interface quality. For example, by combing the state-of-the-art characterization techniques scanning-x-ray diffraction-microscopy and transmission-electron microscopy through suitable modeling, it is possible to correlate how the plastic strain relaxation processes occurring in Si/SiGe heterostructures can affect the strain distribution within the active layer and, ultimately, the electron band energy dispersion. Additionally, we shall discuss the use of atomic probe tomography (ATP) for the characterization of the heterostructures with particular focus on the quality of the heterointerfaces. As a matter of fact, APT is the sole technique allowing for the 3D analysis of the interface roughness, enabling the extraction of both the RMS roughness value and its correlation length, which are the two key parameters controlling the scattering of electron and holes localized in quantum wells with the interface.

Overall, these latest advances in the field of group IV material research will trigger a fruitful debate on the material aspects and their optimization critical to the scaling of Si-based quantum computing.

High-Fidelity Preservation of Quantum Information During Trapped-Ion Transport

Peter Kaufmann, Timm F. Gloger, Delia Kaufmann, Florian Köppen, Michael Johanning, and Christof Wunderlich[1]

[1]Department Physik, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, 57068 Siegen, Germany

In order to design and build a scalable quantum information processor using trapped atomic ions it will be important to connect different registers each containing a limited number of ions. Exchanging quantum information, encoded in the internal states of ions, between such registers can then be achieved by physical transport of ions.

Quantum error correction schemes are an essential element of a scalable universal quantum computer. These schemes typically require the execution of single-qubit rotations, entangling gates, individual measurements, and transport of ions. Each of these computational building blocks needs to be implemented with sufficiently high fidelity. Fidelities beyond 99.99% – often considered as a threshold for the implementation of effective error correction schemes – have been demonstrated for some of these individual computational steps.

The transport of ions in segmented Paul traps is an approach already demonstrated experimentally and optimized with respect to the preservation of the *motional* state [1-2]. Conserving the *internal* state of ions during transport is equally important for the transport of quantum information between the registers. To reach an effective implementation of error correction, the constraints on the fidelity of each individual operation is more stringent than the above mentioned threshold, since in particular transport-based error correction schemes require a number of transport operations, N>>1 [3].Therefore, the infidelity of a single transport operation should be an order of magnitude smaller than the desired infidelity of the entire error correction sequence.

In this experiment we use Ramsey spectroscopy and a novel method for data analysis to deduce the internal state fidelity of a single $^{171}\mathrm{Yb}^{+}$ ion upon transport in a segmented micro-structured Paul trap. We obtain a state fidelity per ion transport of 99.9994(+6 -7)% and perform a total of $2.2 \cdot 10^{7}$ transport operations over a distance of 280 µm without ion loss [4].

[1] R. B Blakestad et. al., Phys. Rev. A **84**, 032314 (2011)

[2] A. Walther et. al., Phys.Rev. Lett. **109**, 080501 (2012)

[3] A. Bermudez et. al., Phys. Rev. X **7**, 041061 (2017)

[4] P. Kaufmann et. al., Phys. Rev. Lett. **120**, 010501 (2018)

Tailoring the spatial and frequency correlations of entangled biphoton wavefunctions

Malin Kück, Kurt Busch, and Armando Perez-Leija

Max-Born-Institut, Max-Born-Straße 2A, 12489 Berlin, Germany
Humboldt-Universität zu Berlin, Institut für Physik, AG Theoritische Optik & Photonik,
Newtonstraße 15, 12489, Berlin, Germany

In the processes of spontaneous parametric down conversion (SPDC), photon pairs are generated through the interaction of a strong optical beam with the atoms or molecules of some special types of nonlinear crystals [1]. Nowadays, SPDC is the most accessible generator of photonic correlations and entanglement [2]. The main reason is because there exist many different types of nonlinear crystals that can be customized to achieve diverse applications. Moreover, there exist many different types of pump sources, ranging from low-cost CW diode lasers to expensive femtosecond pulsed lasers. In general, photon correlations and entanglement are not generated directly in the SPDC process [3]. Instead, the creation of entanglement requires the judicious tailoring of the biphoton wavefunctions [4].

In this contribution we describe a theoretical proposal for engineering the spatial and frequency correlations and anti-correlations of two-photon light by means of the spatial and frequency continuous fractional Fourier transform [5].

Altogether, the versatility offered by the nonlinear crystals, the optical pump sources, and the proper manipulation of the biphoton wavefunctions will allow us to create almost any type of two-photon entangled states.

References

[1] D. N. Klyshko, Photons and Nonlinear Optics (Nauka, Moscow, 1980)
[2] A. F. Abouraddy, *et al,* Phys. Rev. Lett. **87**, 123602 (2001)
[3] A. Joobeur, *et al*, Phys. Rev. A 50, 3349 (1994)
[4] M. H. Rubin, Phys. Rev. A 54, 5349 (1996)
[5] V. Namias, J. Inst. Maths. Applics. 25, 241-265 (1980)

Deterministic alignment of gate-defined nanostructures and self-assembled quantum dots with sub µm accuracy

L. Lackner[1], J. H. Quilter[1], Ł. Dusanowski[1], M. Moczała[1],
M. Emmerling[1], S. Brodbeck[1], F. Hartmann[1] and S. Höfling[1,2]

[1] *Technische Physik, Universität Würzburg, Am Hubland, 97074, Würzburg, Germany*
[2] *SUPA, School of Physics and Astronomy, University of St Andrews, St Andrews, KY16 9SS, United Kingdom*

This system is an approach towards a full semiconductor quantum optical interface based on a GaAs/AlGaAs heterostructure with a single InAs self-assembled quantum dot (SAQD) [1] or dot molecule [2] in close proximity (<100 nm) to a two-dimensional electron gas (2DEG). The 2DEG can be depleted by electrostatic surface gates forming gate-defined quantum dots (GDQD's), which provide a scalable platform for high-fidelity coherent control of single electrons [3]. Figure 1 shows a schematic of the proposed quantum optical interface. The InAs dots are grown above an inverted heterointerface to minimize the loss of mobility due to strain and scattering if they were grown underneath a standard 2DEG. To laterally align the gated structure with the SAQD, the position of the SAQD relative to alignment markers is determined using scanning micro-photoluminescence spectroscopy with an accuracy below a few hundred nanometers. Nanoscale electrostatic gates are fabricated on the sample surface afterwards, patterned with e-beam lithography with an alignment accuracy of ~25 nm. Therefore, we hope to apply this technique to align a fully functional GDQD and an energetically and spatially isolated SAQD with high accuracy to provide coupling between them, making a hybrid device. This would function as a quantum optical interface, combining the scalability of GDQD's, which can be built into an array for a quantum processor, and the opportunity for long-distance communication due to the optical properties of the SAQD.

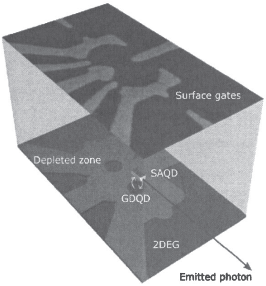


Figure 1: Schematic of the quantum optical interface.

References

[1] H. A. Engel *et al.*, ArXiv cond-mat/0612700, (2006)
[2] D. Kim *et al.*, Phys. Rev. Applied **5**, 024014 (2016)
[3] K. C. Nowack *et al.*, Science **318**, 1430–1433 (2007)

High-defined crystalline silicon and germanium materials and structures for quantum circuits

F. Lange[1,2], **N. Abrosimov**[2], **Th. Teubner**[2], **and T. Boeck**[2]

[1]Brandenburgische Technische Universität (BTU) Cottbus-Senftenberg,
Universitätsplatz 1, 01968 Senftenberg , Germany
[2] Leibniz-Institut für Kristallzüchtung (IKZ), Max-Born-Str. 2, 12489 Berlin, Germany

Among solid-state approaches for emerging quantum technologies, particularly quantum computing, gate-defined electron spin qubits within silicon are very promising since they potentially enable an upscaling to a large number of qubits realized with the highly sophisticated Si-CMOS fabrication technology [1]. A two-dimensional electron gas confined in a thin potential well of a tensile strained SiGe/^{28}Si/SiGe heterostructure serves as the host for electrons for qubits, which are formed by top gates due to electrostatic confinement. The ^{28}Si layer has to exhibit well defined interfaces to the surrounding layers, monoisotopic ^{28}Si material, no dislocations, and a low content of structurally and electrically disastrous impurities. A charged impurity density $< 1 \times 10^{14}$ cm^{-3} is requested.

Two approaches will be pursued to limit the density of dislocations permeating the active region. The first approach consists of a graded SiGe virtual substrate to induce the plastic relaxation of the lattice mismatch existing between Si and $Si_{0.7}Ge_{0.3}$ in a controlled way while enabling the realization of a fully strained thin ^{28}Si layer. For the second approach, we will realize $Si_{0.7}Ge_{0.3}$ cladding layers in form of short period Si/Ge superlattices that nominally provide the desired Si/Ge content [2].

We perform low temperature molecular beam epitaxy (MBE) to grow the Si/Ge layers. High purity monoisotopic ^{28}Si single-crystalline material that is prepared by floating zone (FZ) technique at IKZ [3] serves as evaporation source. MBE competes with the chemical vapor deposition (CVD) technique in the field of Si/Ge epitaxy. Recent improvements of $^{28}SiH_4$ raw material purity [4] promotes the applicability of CVD. Therefore, we will demonstrate the inherent advantages of MBE, i.e. the purity of the growth ambient and the precise control of the growth process.

Reducing the growth temperature is an essential way to reduce thermodynamically determined point defects, to enable flat interfaces, and to preserve strain for structural perfection. The aim of this work is to find the optimum of lowest impurity content at highest structural perfection.

References

[1] M. Veldhorst *et al.*, Nature Nanotechnology **9**, 981 (2014)
[2] G. Abstreiter *et al.*, Journal of Crystal Growth **95**, 431 (1989)
[3] N.V. Abrosimov *et al.*, Metrologia **54**, 599 (2017)
[4] V. Mazzocchi et al., Journal of Crystal Growth **509**, 1 (2019)

FDSOI Technology for Circuits at Cryogenic Temperatures for Scalable Quantum Processors

L. Le Guevel[a*], G. Billiot[a], M. Zurita[a], S. Barraud[a], L. Hutin[a], B. Bertrand, M. Vinet[a], S. De Franceschi[b], M. Sanquer[b], X. Jehl[b], A.G.M. Jansen[b], and G. Pillonnet[a]

a. Univ. Grenoble Alpes, CEA, LETI, Minatec Campus, F-38000 Grenoble, France
b. Univ. Grenoble Alpes, CEA, INAC, PHELIQS, F-38000 Grenoble, France

∗ loick.leguevel@cea.fr

In quantum computers, superposition and entanglement between quantum two-level systems, named qubits, are used to speed-up important algorithms such as prime number factorization and database queries. In the last two decades, few qubits system have been made out of various technologies, most of them operating at deep-cryogenic temperatures (10-100 mK).

Current realizations of quantum bits are operating in a cryogenic environnement where addressing from room-temperature electronics is achieved with meter-scale wiring. Except for some amplifiers or filters placed at 4 K, general state-of-the-art electronics is used at room temperature. In actual setups, scaling up the number of qubits increases the number of addressing lines and the heat load from room temperature will become a showstopper. Interface electronics[1] using multiplexers, microcontrollers, amplifiers, and local oscillators, as in microprocessors but now placed at low temperature, is the option to reduce the number of addressing lines coming from room temperature.

Most technologies used for cryogenic electronics such as BiCMOS or bulk CMOS suffer from substrate carrier freeze-out at 4 K and below that deteriorates the functioning of transistors and leads to specific design with poor analog performances. The industrial-ready Fully Depleted Silicon On Insulator (FDSOI) technology based on extremely thin MOSFET channel-structure has promising applications at low temperature with less sensitivity to carier freeze-out, low dissipation, and faster operation. The control of the threshold voltage via back gating has been reported to decrease the consumption of a ring oscillator by 40%[2] allowing low power cryogenic electronics to be made.

Using preliminary FDSOI 28nm characterizations, we designed building blocks of electrical circuits (multiplexers, transimpedance amplifiers, ring oscillators,...) for low temperature operation. Examples of designs using FDSOI's body biasing as a tool to achieve low power tunable performances will be shown together with early electrical measurements at cryogenic temperatures.

[1] E. Charbon et al., Cryo-CMOS for quantum computing, in *Electron Devices Meeting*, 2016

[2] H. Bohuslavskyi et al., Cryogenic Characterization of 28-nm FD-SOI Ring Oscillators with Energy Efficiency Optimization, in *IEEE Transactions on Electron Devices*, 2018

Advanced Simulation & Design of a Spin-Photon Interface in Silicon

F. A. Mohiyaddin[1], N. I. Dumoulin Stuyck[1,2], B. Govoreanu[1], R. Li[1], A. Potočnik[1], J. Verjauw[1,2], F. Ciubotaru[1], S. Brebels[1], B. T. Chan[1], J. Jussot[1], S. Kubicek[1], A. Spessot[1], and I. P. Radu[1]

[1] *Imec, Kapeldreef 75, Leuven, B-3001, Belgium*
[2] *Department of Materials Engineering (MTM), KU Leuven, Leuven, B-3000, Belgium*

Silicon qubits have gained great attention with recent demonstrations of high-fidelity qubit gates [1] along with long coherence times, compactness and compatibility with semiconductor fabrication methods. A large-scale silicon quantum computer benefits from a modular architecture, with qubits in each module connected with short-range (< 100 nm) interactions, and modules connected by long-range (~ mm) couplers [2]. Superconducting resonators are a strong candidate for mediating long-range interactions between qubits in such architectures. Here, we show the detailed design of a long-range quantum interconnect between electron spins confined in MOS silicon quantum dots, with superconducting resonators [3, 4]. The design, based on well-calibrated multi-physics models, encapsulate several aspects of quantum dots and resonators - including electrostatics, capacitances, band-structure, superconductivity, high-frequency electromagnetics, micromagnetics and spin dynamics. By simulating these aspects with appropriate techniques, we detail the physical mechanism of the interconnect, device geometry, desired materials, expected coupling rates between the qubits, and sources of qubit dephasing. Our design and choice of methods imply that several existing semiconductor modeling methods can be extended to engineer a scalable silicon quantum processor.

References

[1] M. A. Fogarty et al., Nature communications **9**, 4370 (2018)
[2] L. M. K Vandersypen et al., npj Quantum Information **3**, 34 (2017)
[3] X. Mi et al., Nature **555**, 599 (2018)
[4] N. Samkharadze et al., Science **359**, 6380 (2018).

Quantum logic with microwaves in surface-electrode ion traps

Jonathan Morgner[1,2], Giorgio Zarantonello[1,2],
Henning Hahn[1,2], Amado Bautista-Salvador[1,2], Christian Ospelkaus[1,2]
[1]*Leibniz Universität Hannover, Germany.*
[2]*Physikalisch-Technische Bundesanstalt, Braunschweig Germany.*

To successfully scale up quantum information processing, a universal set of high-fidelity gate operations is needed. For trapped ions, single and multi-qubit gates driven by microwave near-fields have shown to be a possible technique to achieve this [1,2].

In this poster we will present a microwave entangling gate module embedded into a microfabricated surface-electrode trap, used to perform entangling gates on $^9Be^+$ hyperfine qubits. The two-qubit entangling gate fidelity of 98.2(1.2)% is not limited by any technical effects intrinsic to the method [3]. We discuss steps to address the biggest present source of infidelities, radial mode frequency fluctuations. The design can also be realized in a scalable multilayer fabrication process which we have developed in our group [4-5].

Finally, we present an evolved experimental setup in which an Ar^+ gun will be implemented to clean the trap surface from contaminants [6] and reduce the motional mode heating, which can be relevant for the gate fidelity in the future.

References

[1] C. Ospelkaus *et al.,* Nature **476**, 181 (2011)
[2] T. P. Harty *et al.,* Phys. Rev. Lett. **117**, 140501 (2016)
[3] H. Hahn *et al.,* arXiv:1902.07028 (2019)
[4] H. Hahn, G. Zarantonello *et al.,* arXiv 1812.02445 (2018)
[5] A. Bautista-Salvador *et al.,* arXiv:1812.01829 (2018)
[6] D. A. Hite *et al.,* Phys. Rev. Lett. **109**, 103001 (2012)

Towards a programmable NISQ Quantum Processor based on trapped ions

A. Müller, V. Kaushal, D. Pijn, J. Hilder, A. Stahl, O. Gräb,
B. Lekitsch, F. Schmidt-Kaler and U. Poschinger
JGU Mainz, Institute for Physics, Staudingerweg 7, 55128 Mainz, Germany
E-mail: mueller_unimainz@web.de

Reaching scalability remains the biggest challenge to overcome for realizing useful quantum computers. For trapped ion quantum computing, a possible solution is to store atomic qubits in segmented radio-frequency traps and move these within the trap array by changing the control voltages applied to the segments [1]. This shuttling circumvents the problems of storage and addressing of ions occurring for large Coulomb crystals.

In this contribution, we present our work towards of a shuttling-based quantum processor capable of NISQ with up to 20 qubits. We present previous and ongoing work on the required technological and methodological components, including the micro-structured ion traps, trap control hardware and the components of the QC software stack.

Furthermore, we present previous results on scalable entanglement generation [2] and ongoing work towards fault-tolerant syndrome readout for enabling quantum error correction [3].

References

[1] D. Kielpinski et al., Nature **417**, 709 (2002)
[2] Scalable creation of long-lived multipartite entanglement, H. Kaufmann et al., Physical Review Letters 119, 150503 (2017)
[3] A. Bermudez et al., Phys. Rev. X 7, 041061 (2017)

Optimal Control: Scaling of the Control Complexity with System Size

M.M.Müller[1]

[1]FZ Jülich, Jülich, Germany

Driving a quantum system with control pulses designed by Optimal Control Theory can considerably speed up desired operations like state transfer or gates and enhance the fidelity of the operations [1]. As the system size scales up, however, more resources (e.g. bandwidth, number of control parameters) are needed to control the system and the complexity of the control task grows [2]. In my contribution I will present the DCRAB algorithm [3] as an optimal control tool that allows to engineer such complex control pulses also under the action of constraints [3]. A proper choice of the control objective can decrease the effective number of parameters needed to achieve the control task [4,5]. A similar effect can be achieved by dynamically tailoring the system into subsystems relevant to the control task, e.g. by Quantum Zeno Interactions.

References

[1] C. Brif, R. Chakrabarti, and H. Rabitz, N. J. Phys. 12, 075008 (2010)
[2] S. Lloyd, S. Montangero, PRL 113, 010502 (2014)
[3] N. Rach, MMM, T. Calarco, S. Montangero, PRA 92, 052343 (2015) (ES)
[4] MMM, T. Pichler, S. Montangero, T. Calarco, Appl. Phys. B, 122:104 (2016)
[5] MMM, D.M. Reich, M. Murphy, H. Yuan, J. Vala, K.B. Whaley, T. Calarco, C.P. Koch, Phys. Rev. A 84, 042315 (2011)

Quantum Link Prediction in Complex Networks

João P. Moutinho[1], André Melo[1,2], Bruno Coutinho[1],
István A. Kóvacs[3], Albert-László Barabási[3], Yasser Omar[1,4]
[1]Physics of Information and Quantum Technologies Group,
Instituto de Telecomunicações, Portugal
[2]Delft University of Technology, Delft, The Netherlands
[3]Network Science Institute, Northeastern University, USA
[4]Instituto Superior Técnico, Universidade de Lisboa, Portugal

Predicting the existence of a link in a complex network is a non-trivial task, namely for large social and biological networks, with important applications. Experiments to map the full structure of biological networks (e.g. protein-protein interactions) are very challenging, costly and time consuming, and large amounts of data is still missing [1]. Link prediction methods are not only a key computational tool to aid these efforts in understanding complex biological systems, but also very useful for other studies of time-varying complex networks, as for example social networks.

In this work we present a novel method for link prediction in complex networks based on continuous-time quantum walks. The control of a relative phase allows our method to be used in different types of networks (physical, biological, social, etc.). By exploiting quantum coherence we are able to outperform the state of the art classical methods [2, 3], indicating that our method is also able to capture complex local patterns (such as local communities around paths of length 3) without the need to impose a specific pattern structure, as done in [3]. Our results indicate there is a strong potential for combining quantum algorithms with complex network research to produce tools with direct and immediate experimental relevance.

References

[1] T. Rolland, et al., Cell **159**, 1212 (2014).
[2] Kovács, István A., et al., Nature communications 10.1 (2019): 1240.
[3] A. Muscoloni, et al., bioRxiv (2018), https://doi.org/10.1101/346916

On-chip Laser-written Photonic Circuits for Quantum Applications

A. Perez-Leija,[1,2] M. Gräfe,[3] S. Weimann,[4] A. Szameit,[4] and K. Busch,[1,2]

[1]Max-Born-Institut, Max-Born-Straße 2A, 12489 Berlin, Germany
[2]Humboldt-Universität zu Berlin, Institut für Physik, AG Theoritische Optik & Photonik, Newtonstraße 15, 12489, Berlin, Germany

[3]Institute of Applied Physics, Friedrich-Schiller Universität, Max-Wien-Platz 1, 07743 Jena, Germany

[4]Institute für Physics, Universität Rostock, D-18051 Rostock, Germany

Quantum computing and information science is a recent and rapidly developing interdisciplinary research field. In this context, one of the most ambitious goals is to realize scalable quantum information processing and computing based on only linear optical configurations and photon-counting devices [1, 2]. In that vein, a promising approach for miniaturizing and scaling optical quantum circuits is to use on-chip laser written waveguides, which promises strong improvements in performance due to high stability, low noise and therefore almost negligible decoherence. In addition, this particular fabrication method allows creating complex three-dimensional waveguide architectures with multiple degrees of freedom, such as diffraction control and birefringence. In this contribution, we report on our recent progress in integrating laser-written photonic quantum circuits. Essentially we provide a closer look at several particular examples regarding the experimental realization of quantum circuits to achieve particular tasks: an integrated quantum random number generator [3], the implementation of discrete Fractional Fourier transforms of classical and quantum wave functions [4, 5], and a quantum simulator of dephasing processes [6].

References

[1] P. Kok, W. J. Munro, K. Nemoto, T. C. Ralph, J. P. Dowling, and G. J. Milburn, Rev. Mod. Phys., **79**, 135, (2007)
[2] E. Knill, R. Laflamme, and G. J. Milburn, Nature **409**, 46-52 (2000)
[3] M. Gräfe, *et al*, Nat. Photonics 8, 791 (2014)
[4] S. Weimann, *et al*, Nature Communications **7**, 11027 (2016)
[5] K. Tschernig, R. León-Montiel, O. S. Magaña-Loaiza, A. Szameit, K. Busch, A. Perez-Leija, JOSA B, **35** 1985 (2018)
[6] A. Perez-Leija, *et al*, “Endurance of quantum coherence due to particle indistinguishability in noisy quantum networks” npj Quantum Information, 4, 45 (2018)

An out-of-equilibrium non-Markovian Quantum Heat Engine

M. Pezzutto[1], **M. Paternostro**[2] **and Y. Omar**[1,3]

[1]Instituto de Telecomunicações, Physics of Information
and Quantum Technologies Group, Lisbon, Portugal
[2]Centre for Theoretical Atomic, Molecular and Optical Physics, School of
Mathematics and Physics, Queen's University Belfast BT7 1NN, United Kingdom
[3]Instituto Superior Técnico, Universidade de Lisboa, Portugal

We study the finite-time thermodynamics of a heat engine operating an Otto cycle whose working medium is a quantum harmonic oscillator. Hot and cold environments are modelled via a collections of spin-1/2 particles. The work strokes of the cycle are implemented via parametric changes of the frequency of the harmonic oscillator, while heat exchanges result from collisional dynamics with the environments that may allow for memory effects.

The scope of our study is twofold: on the one hand, we investigate work transformations of controlled yet variable duration, spanning the whole range from an infinitely slow (and thus adiabatic) transformations, to the opposite extreme of a sudden quench. On the other hand, by including intra-environment interactions, we allow for the emergence of memory effects and thus non-Markovianity in the dynamics of the engine. We investigate numerically the behaviour of the engine and its performance in the two cross-overs from adiabaticity to sudden quench, and from Markovianity to non-Markovianity.

We find that the efficiency of the device always decreases as we approach the sudden-quench regime, and the quantification of an optimal time at which the power output is maximum. Intra-environment interactions, in turn, seem to have no effect on the long-time engine performance. However, they affect the transient of the evolution of the engine by seemingly lowering the efficiency of the heat-transfer process – at least in the case when the both the engine and the environment particles are initialized in a thermal state. In no case we observe a performance exceeding the classical bounds. We do observe however a strong connection between non-Markovianity and the coherences in the initial engine state. Finally, the analysis of the behaviour of the machine at different temperatures allowed us to single out the parameter regime in which it behaves as a refrigerator rather then a thermal engine.

References

M. Pezzutto, M. Paternostro and Y. Omar, *Quant. Sci. and Tech.* **4**, 2 (2018)

A Shuttling-Based Trapped Ion Quantum Processing Node

D. Pijn, J. Hilder, A. Stahl, B. Lekitsch,
F. Schmidt-Kaler and U. Poschinger
JGU Mainz, Institut of Physics, Staudingerweg 7, 55128 Mainz, Germany
E-mail: dpijn@uni-mainz.de

We present our work towards the implementation of a complete error correction algorithm in a shuttling-based trapped ion quantum system. Ions are stored in a segmented linear Paul trap with a designated laser interaction zone (LIZ). Addressed single- and two-qubit gate operations are performed by selectively transporting ions into the LIZ. A multi-channel waveform generator based on a system-on-chip device (SoC) controls the movement of ions, including shuttling, crystal separation/merging and swapping, and all laser-driven qubit operations.

Making use of this setup, four-qubit GHZ states using sequential entangling gates [1] and a dc magnetometer with quantum enhanced performance [2] have been successfully demonstrated. We will present results of ongoing work on a fault-tolerant error syndrome measurement scheme based on six fully controlled trapped-ion qubits: four data qubits, one flag and one syndrome qubit. Furthermore, we will discuss current work on extending the technical capabilities of our setup towards the implementation of a complete topological quantum error correction algorithm using up to 10 qubits.

In addition, we will describe how the current setup can be modified to include optical interconnects making it a good candidate for use as an elementary logic unit (ELU). ELUs were first proposed as a critical building block for a large-scale trapped ion quantum computer by Monroe et al. [3]. We will present a concept on how such an ELU can be realized using a linear Paul trap and selective shuttling of ions without the use of optical cavities.

References

[1] H. Kaufmann et al., Phys. Rev. Lett. 119, 150503 (2017)
[2] T. Ruster et al., Phys. Rev. X 7, 031050 (2017)
[3] C. Monroe et al., Science. 339, 6124 (2013)

Towards Universal Framework for Electrostatic-Qubit-Based Semiconductor Quantum Computer and its Integration with CMOS Electronics and Superconducting Quantum Circuits

Krzysztof Pomorski[1], *Panagiotis Giounanlis*[1], *Elena Blokhina*[1], *Dirk Leipold*[2], *Robert Staszewski*[1,2]

1: University College Dublin, School of Electrical and Electronic Engineering, Dublin 4, Ireland
2: Equal1 Labs, Fremont, CA 94536, USA

We are presenting a universal simulation framework describing semiconductor position-based electrostatic qubits [1], [4], [5], [7], eigenenergy-based electrostatic qubits, hybrid electrostatic/spin-based qubits [2], [3], [6], and an interface between semiconductor and superconducting quantum circuits. The presented algorithms are able to model the quantum neural networks with the use of semiconductor position-dependent qubits and their transition to classical semiconductor single-electron neural networks.

The implementation of 2- and 3-dimensional quantum programmable matter is indicated. The reference to CMOS cryogenic based electronics is specified [8]. Particular attention is paid to the case of two interacting electrons placed at two interacting single-electron lines and the quantum phase transitions that can be induced by electrostatic qubit tuning. The decoherence processes are treated in phenomenological way. The numerical scheme for massive coupling of many qubits in operational modes is provided. The teleportation of quantum state from position-based qubit across waveguide is described.

References

[1]. *T.Fujisawa, T. Hayashi, Y. Hirayama*, "Controlled decoherence of a charge qubit in a double quantum dot", Journal of vacuum science and technology B, Vol. 22, No 4, 2004.

[2]. *D.Loss and D.P. DiVincenzo*, "Quantum computation with quantum dots", Physical Review A, Vol.57, No.1, 1998.

[3]. *J.A.Schreier, A.A.Houck, J.Koch, D.I.Schuster, B.R.Johnson, J.M.Chow, J.M.Gambetta, J.M.Majer, L.Frunzio, M.H.Devoret, S.M.Girvin, R.J.Schoelkopf*, "Suppressing charge noise decoherence in superconducting charge qubits", Physical Review B, Vol. 77, No 180502, 2008.

[4]. *K. D. Petersson, C.G. Smith, D.Anderson, P. Atkinson, G.A.C. Jones, D.A.Ritchie,* "Spin State Readout of a Double Quantum Dot Coupled to a Resonator", Nano Lett., Vol.10, No.8, 2010.

[5]. K.D.Petersson, J.R.Petta, H.Lu, A.C.Gossard, "Quantum Coherence in a One-Electron Semiconductor Charge Qubit", Physical Review Letters, Vol.105, No 246804, 2010

[6]. *M.Veldhorst, H.G. J.Eenink, C.H.Yang, A.S.Dzurak*, "Silicon CMOS architecture for a spin-based quantum computer", Nature Communications, Vol.8, No 1766, 2017.

[7]. *P. Giounanlis, E. Blokhina, D. Leipold, and R. B. Staszewski*, "Occupancy oscillations and electron transfer in multiple–quantum–dot qubits and their circuit representation," in Proc. of 25th IEEE International Conf. On Electronics Circuits and Systems (ICECS). IEEE, 2018.

[8]. *B. Patra, R. M. Incandela, J. P. Van Dijk, H. A. Homulle, L. Song, M. Shahmohammadi, R.B. Staszewski, A.Vladimirescu, M.Babaie, F. Sebastiano et al.*, "Cryo-cmos circuits and systems for quantum computing applications," IEEE Journal of Solid-State Circuits, Vol. 53, No. 1, 2018.

Decoherence Dynamics of Electron Spins in an Optically Active Quantum Dot

H. J. Rojas[1], C. Dangel[1], A. Bechtold[1], T. Simmet[1], P. L. Ardelt[1], D. Rauch[1], F. Li[2], N. A. Sinitsyn[2], K. Müller[1] and J. J. Finley[1]
[1] *Walter Schottky Institut, am Coulombwall 4, 85748 Garching, Germany*
[2] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

Semiconductor self-assembled quantum dots (QDs) offer a manifold of possibilities to realize interacting quantum systems for quantum information elements such as qubits, gates and spin-photon interfaces. However, assessing the suitability for applications requires a detailed understanding of the decoherence dynamics and exploring ways to extend the obtainable coherence times.

For electron spin in QDs two basic types of spin relaxation are recognized in phenomenological models of decoherence: fast ensemble dephasing due to the coherent precession of spin qubits around nearly static but randomly distributed hyperfine fields (~2ns) and a much slower process (>1µs) of irreversible monotonic relaxation of the spin qubit polarization due to nuclear spin co-flips with the central spin or due to other complex many-body interaction effects [1]. Here, we demonstrate experimentally and theoretically that not only two but three distinct stages of decoherence can be identified in the relaxation of a QD electron spin qubit. Measurements and simulations of the spin projection without an external field clearly reveal an additional decoherence stage at intermediate timescales [2]. The additional stage corresponds to the effect of coherent dephasing processes that occur in the nuclear spin bath itself induced by quadrupolar coupling of nuclear spins to strain-driven electric field gradients, leading to a relatively fast but incomplete non-monotonic relaxation of the central spin polarization at intermediate (~750ns) timescales.

A system which promises significantly longer T2* times consists of logic singlet-triplet qubits formed in vertically stacked pairs of QDs, so called QD-molecules. Here, a specific "sweet spot" in the applied gate voltage can be realized in which the singlet-triplet energy splitting is in first order independent to electric and magnetic field fluctuations [3]. To these ends, we present our results towards realizing a structure where the two-electron spin states will be all-optically prepared such that the electric control of the electric field applied along the growth direction can be independently used to tune the system to the "sweet spot". Realizing such a promising system requires a systematic engineering of the growth process in order to precisely control parameters such as transition energies of the two QDs and tunneling rates.

References

[1] I. Merkulov et al. Phys. Rev. B 65, 205309 (2002)
[2] A. Bechtold et al., Nature Physics 11, 1005–1008 (2015)
[3] K. M. Weiss et al., Phys. Rev. Lett. 109, 107401 (2012)

Integrated FPGA-Platform as Control and Readout Interface for Superconducting Qubits

O. Sander[1], R. Gebauer[1], N. Karcher[1], M. Weides[2], A. V. Ustinov[3,4] and M. Weber[1]

[1]Institute for Data Processing and Electronics, KIT, Karlsruhe, Germany
[2] School of Engineering, University of Glasgow, Glasgow, United Kingdom
[3] Physikalisches Institut, KIT, Karlsruhe, Germany
[4] Russian Quantum Center, National University of Science and Technology MISIS, Moscow, Russia
E-mail: oliver.sander@kit.edu

The functionality of conventional lab electronics used for quantum computing experiments is limited while the costs are relatively high. Although sufficient for simple experiments, its applicability is limited due to long data communication delays, poor scalability, and static pulse sequences. A faster, more integrated and more flexible solution for qubit readout and control is FPGA-based custom hardware. It not only reduces costs and space requirements but also simplifies measurements and enables customized control schemes like quantum feedback where a low response time is critical.

We will present a flexible FPGA-based integrated control and readout platform for experiments with superconducting qubits which also enables fast feedback loops to control qubits depending on their measured state. Thus, it provides the basis for experiments and algorithms relevant for quantum computation, like quantum error correction or active reset. The platform can perform all standard measurements for qubit characterization. Furthermore, we present experimental results on quantum feedback and extended experimental flows which are supported by the platform. Eventually, we will discuss first concepts on scaling up the system.

Long-range quantum bus for electron spin qubits in silicon

Lars Schreiber[1], Veit Langrock[1], Inga Seidler[1], Arne Hollmann[1], Tom Struck[1], Hendrik Bluhm[1], Lieven Vandersypen[2], Tristan Meunier[3], Sylvain Barraud[4], Lukas Cywinski[5], David DiVincenzo[6]

[1]JARA-Institute for Quantum Information, RWTH Aachen University, Germany
[2]QuTech and the Kavli Institute of Nanoscience, TU Delft, The Netherlands
[3]CNRS, Institut NEEL, France
[4]CEA/LETI-MINATEC, CEA-Grenoble, France
[5]Institute of Physics, Polish Academy of Sciences, Poland
[6]Peter Grünberg Institute: Theoretical Nanoelectronics, Germany

Silicon spin qubits stand out due to their long coherence times, compatibility with reliable and reproducible industrial fabrication techniques and the feasibility to integrate classical electronics. Universal electron spin manipulation with excellent fidelities was demonstrated in this system. However, a key challenge for true scalability of silicon quantum computer architectures remains the realization of a coherent link between separated quantum registers on a chip. Such a link would serve two important functions. First, it enables a modular structure that allows expanding the number of qubits beyond the limits of local registers. Second, coherent links between registers create space for classical control circuits to be integrated with the qubits on-chip.

We present the concept and challenges of a fault-tolerant quantum bus (QuBus) that coherently transfers a single electron with an arbitrary spin qubit state between quantum dots separated by 1 to 10 microns. We are going to shuttle the electron using an array of electrostatic gates, the fabrication of which is fully compatible with gated quantum dot technology. We follow two strategies: (I) An electron spin conveyer i.e. a potential minimum that smoothly moves laterally. (II) An electron spin bucket brigade, i.e. the electron is passed through a series of QDs via adiabatic passage [1]. In both cases and in contrast to Ref. [1], the final goal is a 1 to 10 micron long QuBus, which is controlled by a maximum of four time-dependent voltage inputs.

The project Si-QuBus has received funding from the QuantERA-NET Cofund in Quantum Technologies implemented within the European Union’s Horizon 2020 Programme.

References

[1] A. R. Mills *et al.*, Shuttling a single charge across a one-dimensional array of silicon quantum dots, arXiv:1809.03976 (2018).

Experimental implementation of a device-independent dimension test for quantum systems using genuine temporal correlations

C. Spee, H. Siebeneich, T. F. Gloger, P. Kaufmann, M. Johanning, M. Kleinmann, Ch. Wunderlich and O. Gühne

Department Physik, Universität Siegen, 57072 Siegen, Germany

Spatial correlations between quantum systems are a thoroughly investigated topic and a growing number of applications of spatial entanglement in quantum information science and quantum metrology has been conceived. In comparison to spatial correlations, temporal correlations that appear in sequential measurements of a quantum system are still largely unexplored terrain with only few applications to date. As these correlations depend on the quantum system's dimension, a device-independent measurement scheme has been devised that witnesses the dimension of the system through the violation of temporal inequalities [1]. Using the hyperfine manifold of a single $^{171}Yb^{+}$ ion stored in a micro-structured 3D linear Paul trap [2], we observe temporal correlations between two consecutive measurements of hyperfine states and the violation of the abovementioned inequalities. This serves to certify a lower bound for the dimension of the quantum system used in these experiments [3]. Extending measurement sequences to length three, we demonstrate an even stronger violation and show that the genuine temporal correlation scheme goes beyond the prepare-and-measure schemes.

References

[1] J. Hoffmann, C. Spee, O. Gühne and C. Budroni New J. Phys. 20, 102001 (2018).

[2] P. Kaufmann, T.F. Gloger, D. Kaufmann, M. Johanning and Ch. Wunderlich Phys. Rev. Lett, 120, 010501 (2018).

[3] C. Spee, H. Siebeneich, T. F. Gloger, P. Kaufmann, M. Johanning, Ch. Wunderlich, M. Kleinmann and O. Gühne, arXiv:1811.12259v1 [quant-ph].

Quantum-enhanced deliberation with trapped-ion qubits

T. Sriarunothai[1], S. Wölk[2,1], G. S. Giri[3,1], N. Friis[4,2], V. Dunjko[5,2,6], H. J. Briegel[2,7] and Ch. Wunderlich[1]

[1] Experimental Quantum Optics, University of Siegen, Siegen, Germany
[2] Institute for Theoretical Physics, University of Innsbruck, Innsbruck, Austria
[3] Institute for Experimental Physics, Heinrich-Heine-University Düsseldorf, Düsseldorf, Germany
[4] Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Vienna, Austria
[5] LIACS, Leiden University, Leiden, The Netherlands
[6] Max Planck Institute of Quantum Optics, Garching, Germany
[7] Department of Philosophy, University of Konstanz, Konstanz, Germany
E-mail: sriarunothai@physik.uni-siegen.de

Quantum information technologies and intelligent learning systems are presumably to transform our society in the future. These two fields of study can benefit from each other, applying techniques from one field to solve the problems of the other. In this work, we report a realization of the quantum- 'upgraded' deliberation in the aspect of reinforcement learning, which could be equipped in an autonomous machine. The implementation is in the projective simulation paradigm for machine learning [1,3]. The proof-of-principle experiment is demonstrated on a trapped-ion quantum processor controlled by radio-frequency radiation. A system of two hyperfine-state qubits representing as the processor shows a quadratic speed-up of the deliberation time. Furthermore, an error model successfully describes the deviation of the measured results from the theoretical estimation. This proof-of-principle experiment highlights an application of quantum information processing in the field of artificial intelligence.

References

[1] T. Sriarunothai, *et al.*, Quan. Sci. Tech. **4**, 015014 (2019)
[2] Ch. Piltz, *et al.*, Sci. Adv. **2**, e1600093 (2016)
[3] G. D. Paparo, *et al.*, Phys. Rev. X **4**, 031002 (2014)
[4] V. Dunjko, *et al.*, New J. Phys. **17**, 023006 (2015)

Adiabatic quantum state preparation in photonic tight-binding lattices

Konrad Tschernig[2], **Armando-Pérez Leija**[2], **Kurt Busch**[1,2]
[1]*Theoretische Optik und Photonik, Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, 12489 Berlin, Germany* [2]*Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie im Forschungsverbund Berlin e. V., Max-Born-Str. 2A, 12489 Berlin, Germany*
konrad.tschernig@mbi-berlin.de

In this work we apply the principles of adiabatic quantum computation (AQC) in order to define an efficient quantum state preparation scheme in the realm of integrated linear optics. This is achieved by performing an adiabatic coupling of the waveguides and the waveguide propagation constants. The transition is defined in such a way that the eigenvalues of the initial and final hamiltonian of the system coincide. The resulting device then maps any input Fock-state to an eigenstate of the final system for an arbitrary number of photons. Our protocol can also be viewed as an analog quantum eigenstate solver for bosonic particles in tight-binding lattices.

The essential idea of AQC is to initialize the system in an easy-to-prepare eigenstate of some initial hamiltonian and to slowly (adiabatically) change the hamiltonian until a desired hamiltonian is achieved. In our context we assume that it is easy to prepare non-superpositions of Fock-States $|n_1,\ldots,n_M\rangle$, where n_m is the number of photons occupying the m'th waveguide, M is the number of waveguides and $N=\sum_{m=1}^{M} n_m$ is the total number of photons. The initial hamiltonian $\hat{H}_i=\sum_{m=1}^{M}\beta_m\hat{n}_m$ is that of completely uncoupled waveguides with propagation constants β_m and photon number operators $\hat{n}_m$. The final hamiltonian $\hat{H}_f=\sum_{m=1}^{M-1}\kappa_m\left(\hat{a}_m^\dagger\hat{a}_{m+1}+\hat{a}_{m+1}^\dagger\hat{a}_m\right)$ describes evanescently, nearest-neighbor coupled waveguides with the desired coupling coefficients κ_m and the creation (annihilation) operators $\hat{a}_m^\dagger(\hat{a}_m)$. The adiabatic transition is then described by

$$\hat{H}(z)=\sum_{m=1}^{M}\left(1-\frac{z}{z_f}\right)\beta_m\hat{n}_m+\sum_{m=1}^{M-1}\frac{z}{z_f}\kappa_m\left(\hat{a}_m^\dagger\hat{a}_{m+1}+\hat{a}_{m+1}^\dagger\hat{a}_m\right), \tag{1}$$

where the propagation constants tend to 0 and the coupling coefficients to their desired values in a linear fashion until a final propagation distance z_f is reached. To ensure that the eigenvalues $\lambda_m^{(f)}$ of the final hamiltonian coincide with those of the initial hamiltonian we choose the initial propagation constants to be

$$\beta_m=\lambda_m^{(f)}. \tag{2}$$

Thus our protocol requires the a priori knowledge of the single-photon eigenvalues of the final hamiltonian. Equation 2 guarantees the eigenvalue-matching even in the case of arbitrary photon numbers N, since for $N>1$ the N-photon eigenvalues are each just sums of the single-photon eigenvalues.

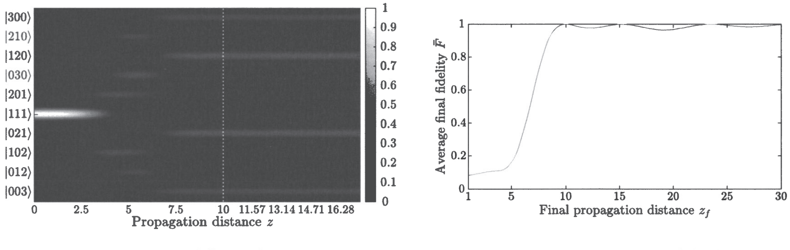


Fig. 1. Left panel: Plot of the evolution of the probability distribution during the adiabatic state preparation. The final hamiltonian is the balanced 3-waveguide beamsplitter with $\kappa_1=\kappa_2=1/\sqrt{2}$. The 3-photon Fock-state $|1,1,1\rangle$ evolves into a 3-photon eigenstate with $\lambda_{1,1,1}^{(f)}=1+0-1=0$ at $z_f=10$ with (numerically) perfect fidelity. Right panel: Plot of the average final fidelity $\bar{F}=\frac{1}{N_F}\sum_{n=1}^{N_F}|\langle\psi_n(z_f)|\phi_n\rangle|^2$ for different "transition-speeds". $N_F=\binom{N+M-1}{N}$ is the number of N-photon-M-waveguide Fock-states, $|\psi_n(z_f)\rangle$ the final state after the adiabatic transition and $|\phi_n\rangle$ the known analytical expression of the corresponding 3-photon eigenstate.