SOLID

FP7-248629

SOLID

Solid State Systems for Quantum Information Processing

Integrated Project

Deliverable D8.1.2

Second intermediate report on scientific progress and management
1 February – 31 July 2011

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Start date of project: 2010-02-01 Duration: 3 years
Chalmers University of Technology (Chalmers) Version 1.0

Dissemination Level PU

Table of Contents

Executive summary and recommendations

During the third six-month period February-July 2011, the SOLID partners have been very active, as is evident from the individual partner reports.

It is particulary gratifying that the experimental side shows highly encouraging progress concerning implementation of protocols for superconducting multi-qubit systems, demonstrating for instance the Grover algorithm (CEA), tomography of 3-qubit etangled states (ETHZ), a Toffoli gate (ETHZ), and order-of-magnitude longer T1 and T2 with transmon-qubits in a 3D cavity (TUD, DiCarlo).

Leo Di Carlo from Schoelkopfs group at Yale has taken up an Assistant professorship at TU Delft, and his group is now a highly appreciated member of SOLID with a small support of 50 kEuro.

The review report on the Warsaw Y1 evaluation was SOLIDly positive. The requested improvements have been addressed.

Assessment and recommendations:

SOLID is well on track and following the time plan. A few milestones (M1.2 and M5.1) are delayed, but this has presently no consequences for the progress of the SOLID tasks. Single shot readout of individual qubits (M2.1 has been passed for 2-qubit circuits by CEA, and when CEA soon extends to 3-qubit circuits, single-shot readout will be implemented and deployed. The experimental development of parametric readout for qubits (M5.1) is delayed because Chalmers decided to put highest priority on the more urgent task of demonstrating coupling between spin qubits and photonic states (M4.2), aiming for micowave-optical interfaces.

There is currently no reason for corrective action. The 24-month milstones are expected to be passed.

Status of scientific progress and management

Scientific progress

The progress is demonstrated by the titles of a selection of publications and preprints describing the most recent work, addresing the SOLID tasks and milestones:

Demonstration of a Single-Photon Router in the Microwave Regime
Io-Chun Hoi, C. M. Wilson, G. Johansson, T. Palomaki, B. Peropadre, and P. Delsing , Phys. Rev. Lett. **107**, 073601 (2011). 10.1103/PhysRevLett.107.073601.

Observation of the Dynamical Casimir Effect in a Superconducting Circuit
C.M. Wilson, G. Johansson, A. Pourkabirian, J.R. Johansson, T. Duty, F. Nori, P. Delsing, Nature (2011), in press; arXiv:1105.4714

Characterization of a two-transmon processor with individual single-shot qubit readout
A. Dewes, F. R. Ong, V. Schmitt, R. Lauro, N. Boulant, P. Bertet, D. Vion, D. Esteve arXiv:1109.6735

R*unning Grover search algorithm on a two qubit quantum processor fitted with independent qubit readout*
A. Dewes, F.R. Ong, V. Schmitt, R. Lauro, P. Milman, P. Bertet, D. Vion, and D. Esteve

S*torage and retrieval of a microwave field in a spin ensemble*
Y. Kubo C. Grezes, P. Bertet, D. Vion, and D. Esteve (arXiv:1109.3960v1)

Single-shot correlations and two-qubit gate of solid-state spins
K.C. Nowack, M. Shafiei, M. Laforest, G.E.D.K. Prawiroatmodjo, L.R. Schreiber, C. Reichl, W. Wegscheider and L. M. K. Vandersypen, Science, published online 4 aug 2011

Single-spin magnetometry with multi-pulse dynamical decoupling sequences
G. de Lange, D. Ristè, V. V. Dobrovitski, R. Hanson,
Physical Review Letters106, 080802 (2011)

High-fidelity projective readout of a solid-state spin quantum register
Lucio Robledo, Lilian Childress, Hannes Bernien, Bas Hensen, Paul F. A. Alkemade, Ronald Hanson
Accepted for publication in Nature

Implementation of a Toffoli Gate with Superconducting Circuits,
A. Fedorov, L. Steffen, M. Baur, A. Wallraff, (arXiv:1108.3966)

Benchmarking a Teleportation Protocol realized in Superconducting Circuits,
M. Baur, A. Fedorov, L. Steffen, S. Filipp, M. P. da Silva, A. Wallraff, (arXiv:1107.4774)

Multi-Mode Mediated Qubit-Qubit Coupling and Dark-State Symmetries in Circuit Quantum Electrodynamics,
S. Filipp, M. Göppl, J. M. Fink, M. Baur, R. Bianchetti, L. Steffen, and A. Wallraff, Phys. Rev. A 83, 063827 (2011).

Lasing, trapping states, and multistability in a circuit quantum electrodynamical analog of a single-atom injection maser
M. Marthaler, J. Leppäkangas, and J. H. Cole, Phys. Rev. B 83, 180505(R) (2011)

Rare earth spin ensemble magnetically coupled to a superconducting resonator
P. Bushev, A. K. Feofanov, H. Rotzinger, I. Protopopov, J. H. Cole, C. M. Wilson, G. Fischer, A. Lukashenko, A. V. Ustinov, Phys. Rev. B 84, 060501(R) (2011)

Readout of a Qubit Array via a Single Transmission Line
M. Jerger, S. Poletto, P. Macha, U. Hübner, A. Lukashenko, E. Il'ichev and A. V. Ustinov, Europhys. Lett. (2011), in press

Universal quantum computation with topological spin-chain networks,
Y. Tserkovnyak and D. Loss, arXiv:1104.1210.

Quantum-control approach to realising a Toffoli gate in circuit QED,
V.M. Stojanovic, A. Fedorov, C. Bruder, and A. Wallraff*,* arXiv:1108.3442.

Excited state quantum couplings and optical switching of an artificial molecule
K. Mueller, G. Reithmaier, E. C. Clark, V. Jovanov, M. Bichler, H. J. Krenner, M. Betz, G. Abstreiter and J. J. Finley,. Phys. Rev. B 84, 081302(R) (2011)

Direct observation of a non-catalytic growth regime for GaAs nanowires
D. Rudolph, S. Hertenberger, S. Bolte, W. Paosangthong, D. Spirkoska, M. Doeblinger, M. Bichler, J. Finley, G. Abstreiter, G. Koblmueller. Nano Letters 11, 3848 (2011).

Quantum measurement and orientation tracking of fluorescent nanodiamonds inside living cells
McGuinness, L. P.; Yan, Y.; Stacey, A.; Simpson, D. A.; Hall, L. T.; MacLaurin, D.; Prawer, S.; Mulvaney, P.; Wrachtrup, J.; Caruso, F.; Scholten, R. E.; Hollenberg, L. C. L. Nature Nanotechnology **6**, 358-363 (2011).

Electric-field sensing using single diamond spins
H. Fedder, F. Dolde, M. W. Doherty, T. Nobauer, F. Rempp, G. Balasubramanian, T. Wolf, F. Reinhard, L. C. L. Hollenberg, F. Jelezko, J. Wrachtrup, *Nat Phys* 2011, *7*, 459-463.

Spin-supersolid phase in Heisenberg chains: A characterization via matrix product states with periodic boundary conditions
Davide Rossini, Vittorio Giovannetti, and Rosario Fazio, Phys. Rev. B 83, 140411 (2011)

Quantum simulation of the Klein Paradox,
R. Gerritsma, B. Lanyon, G. Kirchmair, F. Zähringer, C. Hempel, J. Casanova, J. J. García-Ripoll, E. Solano, R. Blatt, and C. F. Roos, Phys. Rev. Lett. **106**, 060503 (2011).

Quantum simulation of the ultrastrong coupling dynamics in circuit QED
D. Ballester, G. Romero, J. J. García-Ripoll, F. Deppe, and E. Solano, submitted to Phys. Rev. Letters (2011).

On Majorana Hamiltonians
I. L. Egusquiza, C. Sabín, L. Lamata, J. J. García-Ripoll, J. León, and E. Solano, submitted to Physical Review Letters (2011).

Management

During February-July 2011, the main management activities involved:

- Preparation of the SOLID Y1 Management report
- Participating in the preparation of all Deliverables
- Managing the Warsaw Y1 review meeting 14-15 April 2011
- Distributing the SOLID Y1 money to the Partners 15 August 2011 (in a request from the coordinator to the Chalmers administration).
- Participating in the SOLID referece group for the SOLID exchange program
- SOLID co-organised (UPV/EHU) and supported (3000 Euro) the Benasque workshop on quantum simulation
- SOLID supported QIPC 2011 (conference and school, Sept 2011, 15 000 Euro), Zürich, organised by the ETH SOLID groups (A. Wallraff et al.)
- Submitting an INCO extension to FET-Open (TUD, Chalmers, UCSB (USA) and JILA-NIST (USA).
- Preparing SOLID Topical workshops (#1 in Jan 2012) and a General meeting (Grenoble, Feb 2012).
- Discussing an amendment of SOLID (UPV/EHU-Ikerbasque)

Recommendations from the SOLID Warsaw Y1 review

On p.3 in the Technical Review Report (Warsaw review), the reviewers recommend (in the coordinator's wording):

(i) More interaction between groups and institutions, specifically in the form of topical workshops.

Action: SOLID is organising a "Topical Workshop on JJ circuits" in Delft on Monday-Tuesday 16-17 January 2012. The workshop is focused on Josephson-junction (JJ) based superconducting qubits, circuits and systems.
Topics for discussion:
1. quantum feedback with superconducting ckts. What can we do today?
2. quantum simulation with superconducting ckts. What can we do today?
3. coherent qubits based on cQ3D (3D architecture)
4. quantum error correction
5. teleportation (coherence+measurement+feedforward)
6. microwave-optical interfaces
7. spin-superconducting hybrids
8. hot topics: among them efficient 3-q gates

(ii) At least one all-SOLID workshop per year

Action: The SOLID workshop in 2012 will be organized in Grenoble.
The program will consist of 3 working days
- half a day for internal SOLID discussions,
- 2 days of seminars, poster session. These sessions will be open to the Grenoble community interested by the topics.
- half a day to visit the Grenoble labs.

The workshop will be localized close to the physics labs (NEEL, LPMMC, INAC, ...).

(iii) The self-assessment WP7 is a good idea but should be more analytical and quantitative. It should aim to make specific recommendations about the feasibility of technological approaches.

Action: The coordinator appreciates that his concept is well received by the reviewers. He will make a special effort to make the Y2 assessment more analytical and quantitative.

(iv) At the next review (Y2, Germany, April 2011), at least all PIs should be present.

Action: The message has been transmited to the SOLID partners.

(v) The coordinator is urged to reduce the size of the reporting by avoiding repetition.

Action: The coordinator agrees – it will be a pleasure to oblige.

Assessment and recommendations:

SOLID is well on track and following the time plan. A few milestones (M1.2 and M5.1) are delayed, but this has presently no consequences for the progress of the SOLID tasks. Single shot readout ov individual qubis (M2.1 is passed for 2-qubit circuits by CEA, and when CEA soon extends to 3-qubit circuits, single-shot readout will be implemented and deployed. The experimental development of parametric readout for qubits (M5.1) is delayed because Chalmers decided to put highest priority on the more urgent task of demonstrating coupling between spin qubits and photonic states (M4.2) aiming for micowave-optical interfaces.

There is currently no reason for corrective action. The 24-month milstones are expected to be passed.

Status reports of individual partners

1. Chalmers

Employment status
Exp: postdoc (Dr. Matthias Staudt, since May 2010)
Theory: postdoc (Dr. Waltraut Wustmann, since 1 April 2011)

Financial situation
There is currently some underspending on the theory side due to the delayed employment of the postdoc.

Ongoing research

- Exp: We are focused on measuring the coherent coupling of spins in rare earth doped crystals to superconducting circuits. We are currently investigating systems doped with Er and Nd. We have developed a test system for performing microwave measurements of these hybrid systems at 1.5 K and 300 mK. The goal of these systems is to provide fast turn around in characterizing candidate materials for more detailed measurements at very low temperatures (~ 20 mK). We have also performed very low temperature measurements in a dilution refrigerator. We are developing tunable superconducting resonators to couple to the ensembles, to allow us to study zero-field hyperfine lines, which will obviate the use of large magnetic fields.

- Theory: Tasks 5.1.1 – 5.1.2. We focused on the development of theory of quantum parametric resonant phenomena in tunable QED cavity. We considered superconducting strip line resonator integrated at each edge with a SQUID, and extended the description of this system to the case of parametric modulation of magnetic flux through the one (or both) SQUID(s).

- Theory: We have participated in the analysis of the experiment on detection of the dynamical Casimir effect in superconducting circuits, performed at Chalmers. In particular, we have extended the theoretical analysis including numerical simulations of the strong driving regime, to be published in Nature 2011 (arXiv:1105.4714). We are working on a longer manuscript on the theory behind the work described in “The Photon Router” PRL (see below). In particular it includes a detailed analysis of the coupling between the transmon qubit and the transmission line. Also, we are continuing the work on feedback-assisted parity measurements in circuit QED. In particular, we have improved the protocol to allow achieve perfect cancellation of measurement induced dephasing, given a quantum limited detector. In addition, we are working on a protocol for a simplified single-qubit demonstration of quantum feedback. This work is in collaboration with Leo di Carlo at TU Delft. Ref: "High-fidelity feedback-assisted parity measurement in circuit QED", L. Tornberg and G. Johansson, Phys. Rev. A 82, 012329 (2010).

Recent results

- Exp: In the last year, we have measured both Er and Nd doped crystals at very low temperatures. In both cases we observed couplings of order 10 MHz between the ensemble and the resonator. In the Er samples, the decoherence rates of the ensembles were significantly larger than expected, ~70 MHz. The results for Nd are preliminary, but the coherence times seem much better, and in fact, we are able to reach the strong coupling regime between the cavity and the Nd ensemble. This is very promising as the Gisin group at Geneva group has moved to using Nd ensembles for their optical quantum memories.

  In a separate experiment, we have demonstrated a single-photon router operating in the microwave regime. The router is made by embedding an artificial atom, a superconducting “transmon" qubit, in an open transmission line. When an input coherent state, with an average photon number N << 1 is on resonance with the artificial atom, we observe extinction of up to 99.6% in the forward propagating field. We then use electromagnetically induced transparancy to make a single-photon router, where we can control to what output port an incoming signal is delivered. The maximum on-off ratio is around 99% with a rise and fall time on the order of nanoseconds, consistent with theoretical expectations. The router can easily be extended to have multiple output ports and it can be viewed as a rudimentary quantum node. This work was recently published in PRL.

- Theory, parametric amplification: We considered first a classical regime, and found instability regions for the degenerate case, when the driving frequency equals twice the frequency of a single cavity mode, and the non-degenerate case, when the driving frequency equals the sum of the frequencies of two cavity modes. When the two SQUIDs are driven, the instability region is found in terms of algebraic sum of (complex) driving amplitudes.
  Next we included the lowest order nonlinearity of the SQUID inductances, and described the secular resonant dynamics in the terms of “metapotential”. The main observation here is that the retardation effects disappear in the secular approximation (in spite of the instability does include the retardation effects), hence the derived metapotential resembles the one of a lump element oscillator. Then we considered the quantum regime, and derived quantum Hamiltonian for the secular dynamics.
  Thus we accomplished a necessary preliminary work to proceed investigating variety of quantum parametric effects in cavities: quantum fluctuation, entangled photon states of different modes, quantum theory of parametric amplification, etc.

Publications 2011

1. Io-Chun Hoi, C. M. Wilson, G. Johansson, T. Palomaki, B. Peropadre, and P. Delsing *Demonstration of a Single-Photon Router in the Microwave Regime*, Phys. Rev. Lett. **107**, 073601 (2011). 10.1103/PhysRevLett.107.073601.
2. T. Greibe, M.P.V. Stenberg, C.M. Wilson, Th. Bauch, V.S. Shumeiko, and P. Delsing, “Are ‘‘pinholes’’ the cause of excess current in superconducting tunnel junctions? A study of Andreev current in highly resistive junctions”, Phys. Rev. Let**t. 106,** 097001 (2011).
3. A. A. Slutskin, K. N. Bratus’, A. Bergvall, and V. S. Shumeiko, Non-Makovian de- coherence of two-level system weakly coupled to bosonic bath, EuroPhys. Lett**. 96**, (2011).
4. C.M. Wilson, G. Johansson, A. Pourkabirian, J.R. Johansson, T. Duty, F. Nori, P. Delsing, Observation of the Dynamical Casimir Effect in a Superconducting Circuit; Nature (2011), in press; arXiv:1105.4714

5. P. Bushev, A. K. Feofanov, H. Rotzinger, I. Protopopov, J. H. Cole, C. M. Wilson, G. Fischer, A. Lukashenko, A. V. Ustinov, *Rare earth spin ensemble magnetically coupled to a superconducting resonator*, Phys. Rev. B 84, 060501(R) (2011); DOI: 10.1103/PhysRevB.84.060501

Other achievments

Vitaly Shumeiko:
Josephson Dynamics in Junctions with in-Gap Quasiparticles, Swiss-Swedish Meeting on Quantum materials and Devices, Les Diablerets, January 2011

Josephson Dynamics in Junctions with in-Gap Quasiparticles,
Workshop of IARPA Consortium “Coherent Superconducting Qubits”, San Diego, January 2011

Non-adiabatic Josephson Dynamics in Junctions with in-Gap Quasiparticles, Moriond Conference, Le Thuile, March 2011

Andreev Spectroscopy of Tunnel Barriers in Superconducting Junctions, Sweden-Japan QNANO Workshop, Visby, June 2011

Quantum Internet: Challenges of Future Information and Communication, MC2 Day at Chalmers, May 2011

Andreev current in highly resistive superconducting tunnel junctions, EUCAS, The Hague, September 2011

Göran Johansson:
"Towards Quantum Feedback in Superconducting Circuits",
Swiss-Swedish Meeting, Stenungsbaden, Sweden, 25-27th of August 2011

"The dynamical Casimir effect and quantum optics in superconducting circuits",
Seminar, TU Delft, Delft, The Netherlands, 14th July 2011.

"Investigating the dynamical Casimir effect in superconducting circuits",
Seminar fuer Neutronen-, Festkoerper- und Quantenphysik, TU Wien, Vienna, Austria, 17th June 2011.

"Theory for investigating the dynamical Casimir effect in superconducting circuits",
International Workshop on Dynamical Casimir Effect, Padova, Italy, 6-8th June 2011.

"The Dynamical Casimir effect in Superconducting Circuits",
12th International Conference on Squeezed States and Uncertainty Relations, Brazil, 2-6 May 2011.

"Investigating Relativistic Quantum Field Theory in Superconducting Circuits",
Quantum Simulations Workshop, Benasque, Spain 28th February - 5th of March 2011

"Towards Quantum Feedback and Relativistic Quantum Field Theory in Superconducting Circuits",
Swiss-Swedish Meeting, Les Diablerets, Switzerland 7-9 January 2011

Your assessment of your situation relative to tasks and milestones

The experimental work is focused on measuring the coherent coupling of spins in rare earth doped crystals to superconducting circuits, and is basically ahead of time (M4.2).

The experimental development of parametric readout for qubits (M5.1) is delayed because priority as been given to the work for M4.2.
On the theoretical side, we have developed necessary preliminary work to proceed investigating variety of quantum parametric effects in cavities: quantum fluctuation, entangled photon states of different modes, quantum theory of parametric amplification, etc.

2. CEA

Employment status

- 2 Postdocs: Yuimaru Kubo, previously supported by the MIDAS project, has been supported by SOLID since January 2011 for searching on hybrid structures. Romain Lauro was recruited on January 2011 for developing multiqubit circuits.
- A PhD student, Andreas Dewes, working full time for SOLID, is supported by a personal grant and by CEA. His thesis defense is planned around October 2012.
- Small support for permanent researchers P. Bertet, D. Vion, D. Esteve, whole project duration.

Financial situation

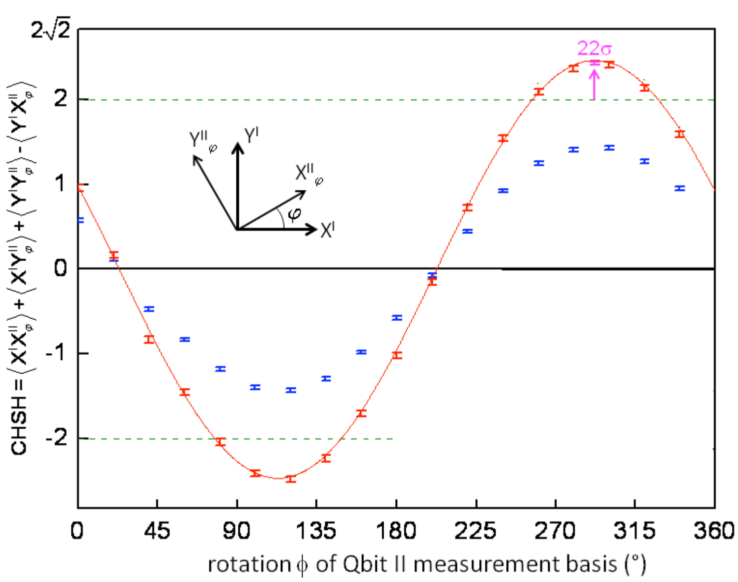
Satisfactory.

Ongoing research

- The team is now designing and fabricating multiqubit circuits (4 to 8 qubits) based either on simple transmons or on Tunable Coupling Qubits following the design recently probed by Srinivasan et al. (Phys. Rev. Lett. **106**, 083601 (2011).
- Hybrid structures combining transmon qubits coupled to spin ensembles (nitrogen-vacancy (NV) centers in a diamond crystal) are further developed and operated.

Recent results

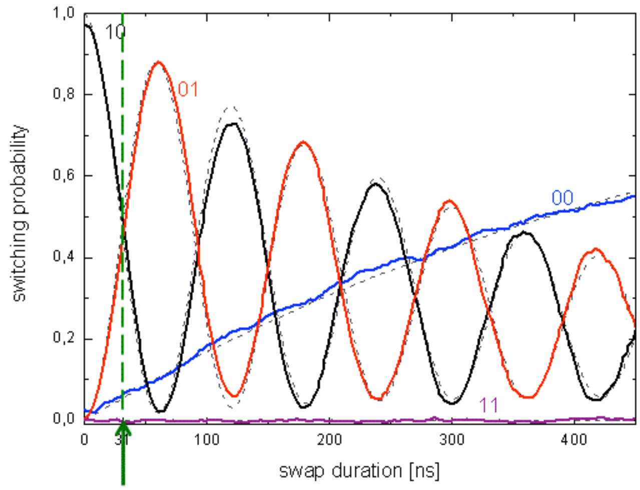
- CEA has operated a two transmon-qubit circuit fitted with individual single shot readout achieving a readout fidelity of ~75% for the two qubits at their measuring working point. The manuscript m1 addresses issues related to the interaction between the qubit and non-linear resonator used to measure it.

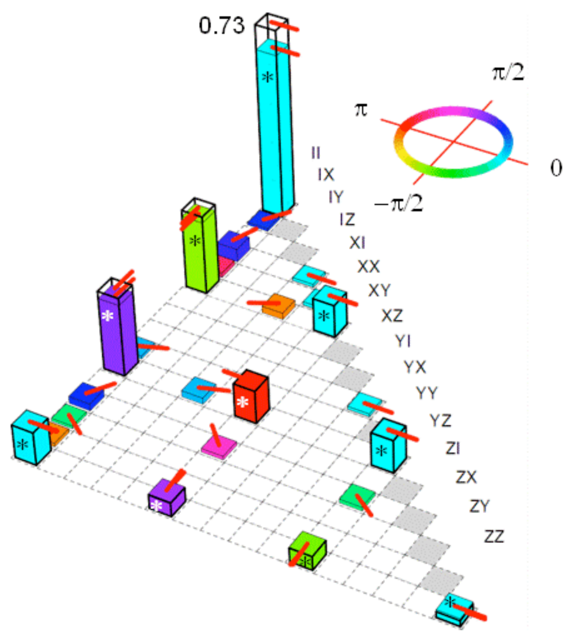


<u>Test of the CHSH Bell inequality on a Bell state.</u> Blue (resp. red) error bars are the experimental CHSH entanglement witness determined from the raw (resp. readout errors corrected) measurements as a function of the angle ϕ between the two measuring bases. The maximum violation demonstrated, well above 2, proves the non classical character of the entangled state prepared.

The two transmons are capacitively coupled, which implements a swapping interaction between them when on resonance. This interaction yields the Sqrt (Iswap) universal gate for a quarter of the swapping period. Entangled states were first prepared and measured. The violation of Bell inequality was demonstrated using the CSHS criterion as shown in the figure above, but without closing the detection loophole (m2).

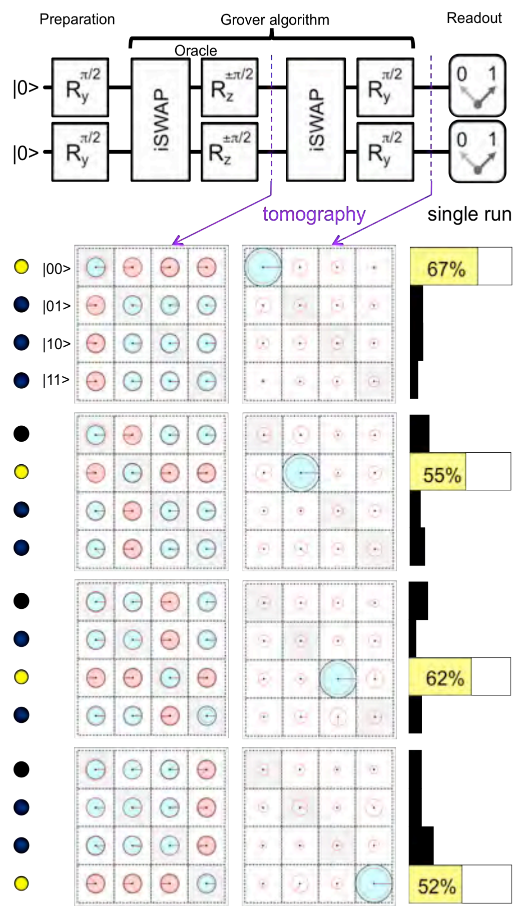
- The superoperator representing the Sqrt(Iswap) gate implemented was determined in the Pauli set basis $\{I, X_1, X_2, \ldots, X_1 X_2, \ldots Z_1 Z_2\}$. An overall gate fidelity of 90% was found, and the residual errors could be analyzed and attributed to small errors in unitary operations and to qubit relaxation (manuscript m2).





<u>Characterization of the Sqrt(i Swap) universal gate.</u>
Top: The similtaneous measurement of the two qubits starting from state I01> *demonstrates the swapping evolution between the two qubits placed on resonance. The evolution corresponds to the universal gate Sqrt(i Swap) at one quarter of the swapping period.*
Bottom: Hermitian process χ matrix of the implemented gate Sqrt(i Swap) in the Pauli operator basis. *Theoretical (empty black thick bars) and experimental (color filled thin bars) lower triangular part of the χ, matrix with residual elements below 1% not shown. Each matrix element is represented by a bar with height proportional to its modulus and a red phase pointer and a filling color in the experimental case) giving its argument (see inset). Expected peaks are marked with a star.*

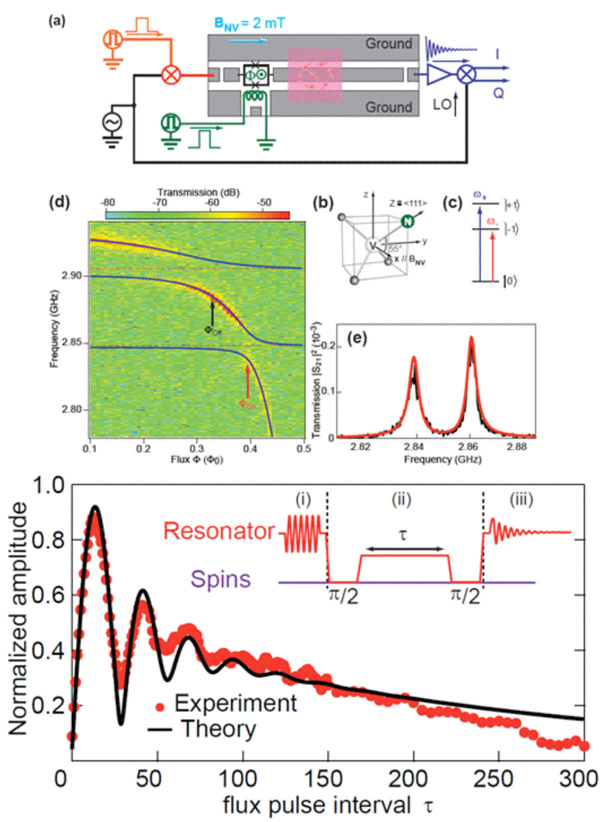
- With this 2 qubit processor, CEA has demonstrated the Grover search algorithm on four objects without resorting to an averaging procedure, as described in the figure below.



<u>Demonstration of the Grover search algorithm on four objects.</u>
The algorithm is described at the top, and the state tomography is shown at two stages of the algorithm. One Oracle operator chosen among four possible ones corresponding to different combinations of Z rotations has to be identified. Each one tags a given basis state (marked in yellow on the left). Starting from state I00>*, a superposition of all basis states is first prepared, and the unknown Oracle operator is applied once, and the retrieved. A the end, the raw success rate of the algorithm is determined (yellow boxes), and the errors indicated (black boxes). The state tomography performed at the end provides the full information on the density matrix obtained at the end of the algorithm. The actual density matrix is compared to the ideal one.*

The unknown operator is retrieved with a probability of about 55-60% in a single run. Although the problem considered here is rather trivial, it provides a benchmark of the overall quantum evolution of the processor. This result first demonstrates quantum speed-up in an electrical quantum circuit (manuscript m3) for a true quantum algorithm.

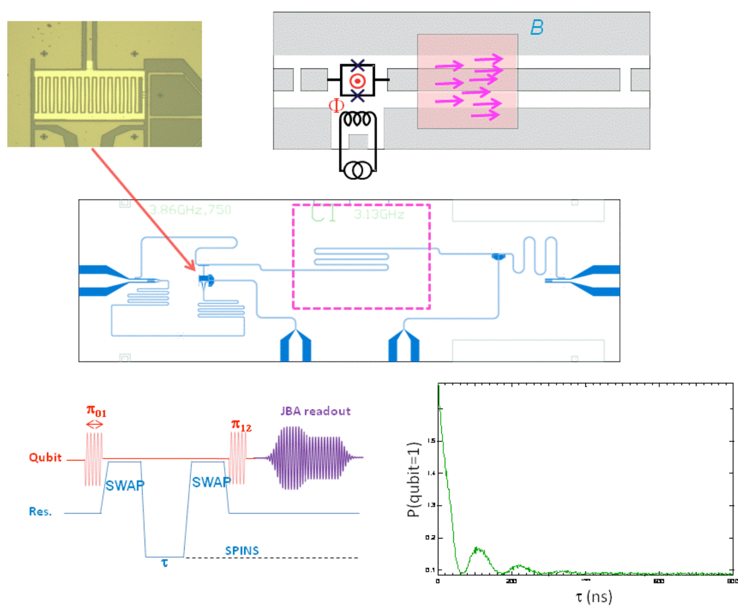
- With the support of the MIDAS project, CEA had demonstrated in 2010 the coherent coupling between an ensemble of nitrogen-vacancy (NV) spins and a microwave resonator. In the new dilution refrigerator installed in 2010 with the support of MIDAS and SOLID, hybrid structures combining an ensemble of NV spins and a transmon qubit coupled to a same microwave resonator have been operated. In order to perform experiments in the time domain, the coherent transfer of between a small field in the resonator and the NV spins was first demonstrated as shown in the figure below. The experimental protocol is detailed in the caption. The Ramsey fringes experiment performed shows oscillations with a rather short decay time of about 30 ns which is well explained by theory for the parameters of the sample used (manuscript m4). Decoherence in this system results from the leakage of the collective spin mode in which the excitation is stored to the numerous other spin modes of the spin ensemble. Decoherence processes, which limit the duration of the field storage in the spins, will be further investigated.



<u>*Coherent transfer of excitations between a spin ensemble and the microwave field in a resonator.*</u>
Top: An ensemble of NV spins is placed on top of a tunable resonator. The resonator frequency is adjusted by applying a flux through a SQUID embedded in its central conductor.
Middle: Right: level scheme of an NV center. Left: the resonator transmission, plotted as a function of the flux threading the SQUID loop, displays the transition frequency of the resonator-NV spins coupled

system in a 1.7 mT magnetic field. The cut shown displays two polaritonic peaks with a vacuum Rabi splitting larger thatn the peak width, which demonstrates the strong coupling regime.
Bottom: A Ramsey fringes experiment determines the coherence of the spin system. The resonator, first loaded with a small coherent field, is moved to the resonance condition for a time corresponding to a π/2 rotation of the coupled system; it is then moved slightly away (30 MHz) *for a duration* τ *, another π/2 pulse is applied, and the outgoing field is measured. The decay of the outgoing field agrees with theory and yields a spin coherence time of about* 30 ns *that determines the field storage time.*

- An hybrid structure that implements a memory in an NV spin ensemble for a transmon-qubit has been operated, as shown in the figure below. In this structure, a transmon-qubit and a NV spin ensemble are coupled to a same tunable resonator. By moving the resonance frequency, a single excitation can be transferred back and forth from the qubit to the spin ensemble through the resonator. Measurements are done at the end of a sequence by performing high fidelity ~70% single-shot of the qubit. One finds that the retrieval of a single excitation after a full transfer is at most 20% due to spin decoherence as measured in the experiment discussed above. Improving the retrieval probability will thus request to reduce the leakage of the storage spin-mode to the other spin modes. These results are described in the manuscript m5.



<u>*Implementation of a memory for a transmon qubit in a NV spin ensemble.*</u>
Top: A transmon qubit (picture) coupled to a non-linear readout resonator used for its single-shot readout, is also capacitively coupled to a tunable microwave resonator sketched in the top right scheme; an ensemble of NV spins embedded in a diamond single crystal is also coupled to this resonator.
Bottom: implementation of a memory element in the spin ensemble for the transmon qubit: A π pulse first excites the qubit; this single excitation is then passed to the coupling resonator by performing a π pulse with the qubit; The excitation is then swapped to the spins for a variable time τ; another π pulse brings back the residual exciation to the qubit which is measured as previoulsy demonstrated by CEA. The minima correspond to the full trasnfer of a single excitation in the spin ensemble. The first maximum corresponds to a single back and forth transfer of a single excitation between the qubit and the spin ensemble. The recobvery height, about 20%, is limited by the short spin coherence time.

Publications January-July 2011: articles in preparation

m1: *Back-action of a driven nonlinear resonator on a many-level superconducting qubit*
Maxime Boissonneault, A. C. Doherty, F. R. Ong, P. Bertet, D. Vion, D. Esteve, and A. Blais.

m2: *Characterization of a two-transmon qubit gate with individual readouts*

A. Dewes, F. R. Ong,V. Schmitt, R. Lauro, N. Boulant, P. Bertet, D. Vion, and D. Esteve.

m3: *Running Grover search algorithm on a two qubit quantum processor fitted with independent qubit readout*
A. Dewes, F.R. Ong, V. Schmitt, R. Lauro, P. Milman, P. Bertet, D. Vion, and D. Esteve

m4: *Storage and retrieval of a microwave field in a spin ensemble*
Y. Kubo C. Grezes, P. Bertet, D. Vion, and D. Esteve (arXiv:1109.3960v1)

m5: *Coherent dynamics of a qubit coupled to a spin ensemble*
Y. Kubo, C. Grezes, A. Auffeves, I. Dinis, J. Isoya, , P. Bertet, D. Vion, and D. Esteve.

Invited Talks at Conference, Workshops and Seminars

A. Dewes, DMQS 2010, University of Tokyo, Japan, 14.02.2011, *Characterization of a two-transmon iSWAP gate*.

Y. Kubo, Hasselt Diamond Workshop 2011 (SBDD XVI), Hasselt, Belgium, Feb 2011, Strong *Coupling of a Spin Ensemble to a Superconducting Resonator: Towards Superconductor - Spin Ensemble Hybrid Quantum Circuits.*

Y. Kubo, Stuttgart University, Stuttgart, Germany, May 2011, *Coupling a Superconducting Qubit to NV Centers*

P. Bertet, DPG conference, Dresden (Germany), 17/03/11, *Strong coupling of a spin ensemble to a superconducting resonator*.

P. Bertet, APS meeting, Dallas, TX (USA), 23/03/11, *Probing the quantum fluctuations of a nonlinear resonator with a superconducting qubit*.

P. Bertet, Vienna University for CoQus colloquium, Vienna (Austria), 23/5/11, Colloquium: *Hybrid quantum circuits*.

P. Bertet, 11th Canadian Summer School on Quantum Information, Jouvence (Canada), 6/6/11 , *Lecture on superconducting qubits*.

P. Bertet, Institute for Quantum Computing, Waterloo (Canada), 9/6/11, *Hybrid quantum circuits*.

D. Vion, International Symposium on Nanoscale Transport and Technology 2011, Tokyo, Japan, 11-14 Jan 2011: *Strong Coupling of a Spin Ensemble to a Superconducting Resonator.*

D. Vion, Seminar of the Physics Department of Ulm university, 10 May 2011, Ulm, Germany, "*Strong Coupling of a Spin Ensemble to a Superconducting Resonator*".

D. Vion, Frontiers of Quantum and Mesoscopic Thermodynamics, 25 - 30 July 2011, Prague, Czech Republic: *Towards hybrid Quantum circuits: Strong Coupling of a Spin Ensemble to a Superconducting Resonator.*

D. Esteve, Quantum Mesoscopic Physics, Rencontres de Moriond, La Thuile (Italy), March 2011, keynote speech: *Electrical circuits for quantum physics and quantum information.*

D. Esteve, Les Houches Summer School on Quantum Machines, Les Houches (France), July 2011: *Series of lectures: Readout of superconducting qubits.*

Your assessment of your situation relative to tasks and milestones

M1.2 Multi-qubit platforms: single shot QND readout of individual qubits.

Done on a two transmon-qubit platform.

M1.3 Quantitative determination of readout fidelities for 1- and 2-qubit readout for multi-qubit platforms.

Done on a two transmon-qubit platform with 80% readout fidelity.

M1.7 Experimental implementation of algorithms and protocol on multi-qubit platforms.

Done: demonstration of Bell measurements, of the violation of Bell inequality, of the Grover search algorithm on 4 objects in a single run.

M4.1 Realisation of hybrid systems for quantum information processing on different platforms.
Done for NV spins combined with transmons.

M4.4 Demonstration of reversible information transfer in a hybrid structure. (24,36m)
Done: reversible transfer of quantum information between a Sc qubit and a NV spin ensemble achieved. .

M4.5 Demonstration of a quantum memory in a hybrid structure, evaluation of the storage performance. (36m)
Done but with poor storage performance. Further work will be devoted to this milestone.

Work is in progress on the other milestones of concern to us.

3. TUD

Employment status
The allocated person months has been entirely fulfilled.

- Postdoc: E. Laird (1-2-2010 to present)
- Tim Taminiau (1-3-2011 to present)
- K. Nowach (1-2-2010 to 31-3-2011)

Financial situation
We have spent entire budget except the personnel cost.
In order to carry out further experiments we use some other funding.

Ongoing research

Vandersypen: We have recently integrated electron spin resonance (ESR) in our ongoing quantum dot experiment, in which already were able to achieve independent read-out, coherent exchange. At present, ESR control is demonstrated for adiabatic inversion using fast frequency sweeps. We are working on coherent Rabi oscillations of the spin.
The adiabatic inversion experiments show novel effects of feedback on the nuclear spin bath (in several ways different from those we reported in 2009), that we are currently trying to understand.

We have achieved a fast reset of electron spin qubits in quantum dots by taking advantage of level (anti-)crossings. This reset takes less than 1 microsecond, compared to more than 10 ms previously.

We have been able to reach the few-electron regime in a Si/SiGe quantum dot (fabricated in the group of Mark Eriksson at U Wisconsin) and aim to demonstrate Pauli spin blockade as means for detecting spin states.

Hanson: We have recently achieved the main goal of task 3.3: high-fidelity single-shot readout of a single NV electron spin. Furthermore, we are working on optimizing the single-shot readout of multiple nuclear spins in diamond. First results will be published in Nature.
We have finalized the spin bath control, showing that decoherence can be mitigated through control of the environment. Current efforts are geared at understanding the limits of coherence when dynamical decoupling is applied to NV spin qubits in the presence of the nuclear spin bath.

Zwiller: We have demonstrated an efficient light extraction from our nanowire quantum dots making use of a controlled tapering in their structure.
We have demonstrated large current amplification in a single nanowire pn junction under intense reverse bias, paving the way towards single photon detection with a single nanowire quantum dot.
We have performed a full measurement of the electron and hole g-factor in a quantum dot using a new experimental setup based on a vector magnet.
We are using strain tuning to dynamically tune the emission from a single quantum dot to a rubidium vapor.

DiCarlo: We have reproduced the groundbreaking result from Yale that allows order-of-magnitude improvements in transmon qubit coherence by switching from a planar to a three-dimensional circuit QED architecture.
The best qubit relaxation and dephasing (echo) times achieved to date are 85 and 94 microseconds, respectively. DiCarlo and Wendin have submitted a SOLID INCO extension proposal titled EntangleMe, targeting the realization of entanglement by measurement and feedback through an 18-month international collaboration between JILA-NIST (Lehnert), University of California, Santa Barbara (Martinis), Chalmers (Johansson, Shumeiko, Wendin), and TU Delft (DiCarlo).

Recent results

See the publication list.

Publications 2011

Single-shot correlations and two-qubit gate of solid-state spins
K.C. Nowack, M. Shafiei, M. Laforest, G.E.D.K. Prawiroatmodjo, L.R. chreiber, C. Reichl, W. Wegscheider and L. M. K. Vandersypen
Science, published online 4 aug 2011

Single-spin magnetometry with multi-pulse dynamical decoupling sequences
G. de Lange, D. Ristè, V. V. Dobrovitski, R. Hanson,
Physical Review Letters106, 080802 (2011)

Spin dynamics in the optical cycle of single nitrogen-vacancy centres in diamond
L. Robledo, H. Bernien, T. van der Sar, R. Hanson,
New Journal of Physics13, 025013 (2011).

High-fidelity projective readout of a solid-state spin quantum register
Lucio Robledo, Lilian Childress, Hannes Bernien, Bas Hensen, Paul F. A. Alkemade, Ronald Hanson
Accepted for publication in Nature

Controlling the quantum dynamics of a mesoscopic spin bath in diamond
G. de Lange, T. van der Sar, M.S. Blok, Z. H. Wang, V.V. Dobrovitski, and R. Hanson,
submitted, see http://arxiv.org/ftp/arxiv/papers/1104/1104.4648.pdf

Bright single photon source in bottom-up tailored nanowires
Reimer M. E., Bulgarini G., Akopian N., Hocevar M., Bouwes Bavinck M., Bakkers E. P. A. M., Kouwenhoven L. P., Zwiller V.
Submitted

Measurement of g-factor tensors in a quantum dot and disentanglement of exciton spins
Witek B. J., Heeres R. W., Perinetti U., Bakkers E. P. A. M., Kouwenhoven L. P., Zwiller V.
Submitted

Quantum nature of light measured with a single detector
Steudle G. A., Schietinger S., Höckel D., Dorenbos S. N., Zwiller V., Benson O.
Submitted

Other achievments

Invited talks
Vandersypen

- Nuclear spin squeezing in quantum dots, Workshop on the Quantum Physics of Low Dimensional Systems and Materials, Stellenbosh, South-Africa, 3-7 January 2011
- Spin qubits and quantum magnetism in quantum dots, Workshop on Quantum Simulations, Benasque, Spain, Feb 28 – March 5, 2011
- 26th Low Temperature Conference, Beijing, China, Aug 2011 (talk by K.Nowack)

Hanson:

- Quantum measurement and coherence protection of spins in diamond, The 62nd Diamond Conference, Warwick (UK), July 5, 2011.
- Quantum measurement and coherence protection of single spins in diamond, Seminar at CEA-Saclay, Paris (France), April 27, 2011.
- Advanced quantum control of spins and photons in diamond (invited), 476th WE-Heraeus Seminar: Diamond: spintronics, photonics, bio-Applications, Bad Honnef (Germany), April 5, 2011.
- Control of single-spin decoherence by dynamical decoupling and spin bath manipulation, March meeting of the American Physical Society, Dallas (USA), March 25, 2011.
- Quantum control of single spins and single photons in diamond. Seminar at AMOLF (FOM Institute for Atomic and Molecular Physics), Amsterdam (Netherlands), February 7, 2011.
- Dynamical decoupling of single spins: demonstration and applications, Seminar at California NanoSystems Institute at UCSB, Santa Barbara (USA), January 28, 2011.
- Control and coherence of the optical transition of single defect centers in diamond, SPIE Photonics West, San Francisco (USA), January 26, 2011.

Zwiller:

- SPIE Orlado, May 2011
- IPRM Berlin, May 2011
- Single Photon workshop, Braunschweig Germany
- SPIE August 2011 San Diego (3 invited talks for the Zwiller group)
- Meeting on Hybrid Nanostruvtures, Torun, Poland, August 2011, keynote talk
- Plasmonics conference, October 2011, Bad Honnef, Germany

DiCarlo:

- It needn't be nano to be quantum: Quantum computing with macroscopic circuits, Biannual Casimir Symposium, Delft University of Technology, May 26, 2011

- Engineering multi-particle entanglement in superconducting quantum circuits, Condensed Matter Seminar, University of Basel, May 30, 2011
- Robust superconducting circuits for quantum computing, NanoCTM meeting, Lake Balaton, June 16, 2011
- Superconducting circuits that compute with quantum magic, One-slide presentation of research to the general public, NWO Laureate lunch, Museum of Communication, The Hague, June 24, 2011.

Your assessment of your situation relative to tasks and milestones

Vandersypen: M2.1 was already partly achieved by 12m. We now added what was missing, namely single-qubit manipulation by means of adiabatic inversion through fast frequency sweeps.

Hanson: M3.3 Using dynamical decoupling techniques we have achieved the T1 limit at room temperature in ultrapure (but not isotopically purified) diamond. Interesting next step is to study coherence at lower temperatures where the T1 limit goes from milliseconds to minutes.

Zwiller: The work carried out in the past 6 months in the Zwiller group has demonstrated that high out-coupling efficiency can be achieved for a single quantum dot in a nanowire, an important ingredient for an efficient transfer of information to and from quantum dots with photons.

A new setup with a base temperature of 0.3 K, optical access and vector magnet is now operational enabling the full measurement of electrons and holes g factors. This setup will be essential in future work where the quantum state of a single photon will be mapped on the state of a single electron.

Further work has been carried out on the coupling of single quantum dots to Rubidium vapors through the use of novel tuning mechanisms. This enables further work in the coupling of hybrid quantum systems based on rubidium and quantum dots.

4. ETH Zurich

Employment status

Feb 2011 -July 2011

- Tobias Frey, PhD student of K. Ensslin and A. Wallraff (starting date 02/2011, is expected to complete his PhD thesis 12/12)
- Emre Ilgunsatiroglu, PhD student of A. Imamoglu and A. Wallraff, (starting date 04/2010, is expected to stay on the project until the end)
- Lars Steffen, PhD student of A. Wallraff (starting date 01/2011, is expected to complete his PhD thesis 12/12)

Financial situation

Satisfactory, as planned.

Ongoing research

WP1

We have realized two three-qubit platforms within circuit QED architecture which use resonant and dispersive cavity-qubit interactions for implementation of quantum protocols. The setups have been used for generation of maximally entangled two- and three-qubit states. The fidelities for the resulting states were determined by the state tomography and are between 89% - 93% for Bell states, 83% for CHZ-state and 89% for W-state. We have also implemented a teleportation protocol, up to the single-shot measurement step. Using full quantum state tomography and evaluating an entanglement witness, we show that the protocol generates a genuine tripartite entangled state of all three-qubits. Calculating the projection of the measured density matrix onto the basis states of two qubits allows us to reconstruct the teleported state with an averaged fidelity of 88%. A three-qubit platform has been also used for demonstration of a Toffoli gate. The Toffoli gate can be used for universal reversible classical computation and it is also one of the essential building blocks in quantum error correction schemes. By exploiting the third energy level of the transmon qubit, the number of elementary gates needed for the implementation of the Toffoli gate, as well as the total gate time can be reduced significantly in comparison to theoretical proposals using two-level systems only. We characterize the performance of the gate by full process tomography and Monte Carlo process certification. The gate fidelity is found to be 64.5%.

WP2 + WP4 The focus of the research carried out in collaboration between the groups of A. Imamoglu and A. Wallraff is the coherent manipulation of single quantum dot electron spin using electron spin resonance (ESR).

We are particularly interested in using ESR to assess the degree of Overhauser field narrowing that is achieved using optical manipulation techniques. The PhD student Emre Ilgunsatiroglu has already successfully fabricated microwave cavity and waveguide structures out of gold on GaAs samples containing InGaAs quantum dots (QD). Using these devices Emre, together with postdocs Parisa Fallahi and Martin Kroner (paid from other sources) have observed microwave photon sidebands in optical absorption of neutral and single-electron charged QDs. What is striking about these results is that the microwave coupling is strong enough to completely eliminate the QD response at the zero-photon line. The next step in these experiments is the investigation of nuclear magnetic resonance of a single QD by monitoring the change in the Overhauser field in response to the applied radio-frequency.

WP4 The focus of the research carried out in collaboration between the groups of K. Ensslin and A. Wallraff is the integration of lateral semiconductor quantum dots in superconducting cavities for hybrid quantum information processing.
In this period the PhD student Tobias Frey together with a postdoc Peter Leek (paid from other sources) have managed to develop a scheme, where a split-gate defined double quantum dot on AlGaAs heterostructures is dipole-coupled to a superconducting microwave resonator. A central gate placed on one of the two quantum dots is directly connected to the inner conductor of the microwave resonator. This way the charge stability diagram of the double dot, usually measured with dc techniques, has been investigated by detecting the phase and amplitude of the transmitted microwave signal.

Publications 2011

1. T. Frey, P. J. Leek, M. Beck, K. Ensslin, A. Wallraff, and T. Ihn
"Characterization of a microwave frequency resonator via a nearby quantum dot"
Appl. Phys. Lett. 262105, **98** (2011), arXiv:1104.3535
2. Arkady Fedorov, Lars Steffen, Matthias Baur, Andreas Wallraff, *Implementation of a Toffoli Gate with Superconducting Circuits*, arXiv:1108.3966 (2011).
3. Matthias Baur, Arkady Fedorov, Lars Steffen, Andreas Wallraff, *Benchmarking a Teleportation Protocol realized in Superconducting Circuits*, arXiv:1107.4774 (2011).

Other achievements

Conferences participated in:

„Irreversibility in single-electron tunneling (invited talk)“

B. Küng, C. Rössler, T. Ihn, and K. Ensslin

Workshop on "Nonlinear spin and charge transport through nanoscopic systems", Mallorca, Spain, June 6-9, 2011

Invited talk at Workshop on Quantum Science and Technologies, Trento May 2011 (Imamoglu)

Tutorial at EQEC, Munich May 2011 (Imamoglu)

Lectures at the Quantum Impurity School, MPI Dresden, June 2011 (Imamoglu)

Benchmarking a Teleportation Circuit realized in Circuit QED (invited talk),
A. Fedorov, M. Baur, L. Steffen, M. Baur, A. Fedorov, M.P. da Silva, A. Wallraff
The 1st International Conference on Quantum Technologies, Moscow, July 12 - 17, 2011

Your assessment of your situation relative to tasks and milestones

Projects are progressing as expected.

5. KIT-U

Employment status

- Exp: No one employed during February-July 2011.
- Theory: PhD student Andreas Heimes (1.7.2011 - ...)

Financial situation
Important underspending during the first 18 months.

Ongoing research

KIT-Theory

Circuit QED with Josephson qubits
Motivated by recent ``circuit QED'' experiments we studied the lasing transition and spectral properties of single-qubit lasers. In the strong coupling, low-temperature regime quantum fluctuations dominate over thermal noise and strongly influence the linewidth of the laser. When the qubit and the resonator are detuned, amplitude and phase fluctuations of the radiation field are coupled, and the phase diffusion model, commonly used to describe conventional lasers, fails. We predict pronounced effects near the lasing transition, with an enhanced linewidth and non-exponential decay of the correlation functions [1]. We cover a wide range of parameters by using two complementary approaches, one based on the Liouville equation in a Fock state basis, covering arbitrarily strong coupling but limited to low photon numbers, the other based on the coherent-state representation, covering large photon numbers but restricted to weak or intermediate coupling.

We studied the photon generation in a transmission line oscillator coupled to a driven qubit in the presence of a dissipative electromagnetic environment. It has been demonstrated previously that a population inversion in the qubit may lead to a lasing state of the oscillator. We could show that the circuit can also exhibit the effect of "lasing without inversion" [2,3]. This is possible since the coupling to the dissipative environment enhances photon emission as compared to absorption, similar to the recoil effect which was predicted for atomic systems. While the recoil effect is very weak, and so far elusive, the effect described here should be observable with present circuits. We analyze the requirements for the system parameters and environment.

We studied a superconducting single-electron transistor (SSET) which is coupled to a LC oscillator via the phase difference across one of the Josephson junctions [4]. This leads to a strongly anharmonic coupling between the SSET and the oscillator. The coupling can oscillate with the number of photons, which makes this system very similar to the single-atom injection maser. The advantage of a design based on superconducting circuits is the strong coupling and existence of standard methods to measure the radiation field in the oscillator. This makes it possible to study many effects that have been predicted for the single-atom injection maser in a circuit quantum electrodynamics setup.

In collaboration with experimentalists at NEC, Japan we have investigated charge transport in ultrasmall superconducting single and double Josephson junctions coupled to resonant modes of the electromagnetic environment [5]. We observe pronounced current peaks in the transport characteristics of both types of devices and attribute them to the process involving simultaneous tunneling of Cooper pairs and photon emission into the resonant modes. The experimental data are well reproduced by our theoretical models.

Circuit QED with quantum dots

We studied a double quantum-dot system coherently coupled to an electromagnetic resonator [6,7]. A current through the dot system can create a population inversion in the dot levels and, within a narrow resonance window, a lasing state in the resonator. The lasing state correlates with the transport properties. On one hand, this allows probing the lasing state via a current measurement. On the other hand, the resulting narrow current peak allows resolving small differences in the dot properties, e.g., a small difference in the Zeeman splittings of the two dots.

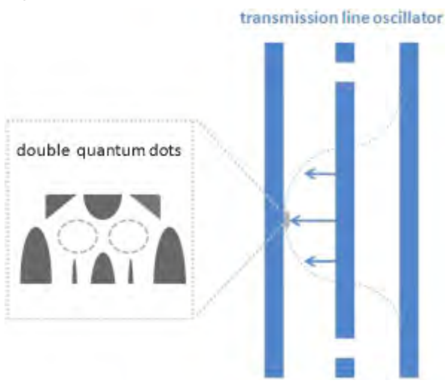


FIG. 1. Illustration of a double quantum-dot resonator circuit. The dot is placed at a maximum of the electric field of the transmission line to maximize the dipole interaction with the resonator. For gate-defined quantum dots most parameters can be tuned by the applied voltages.

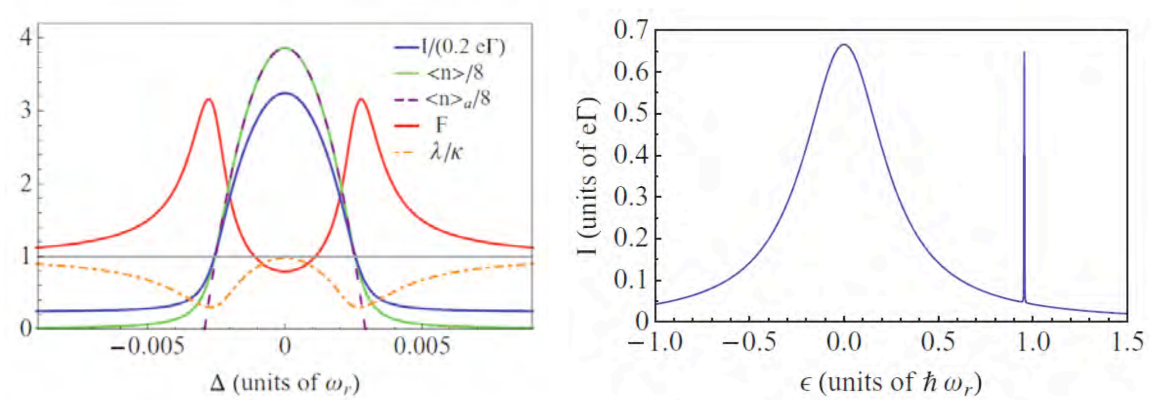


FIG. 2. Lasing in the quantum-dot resonator circuit. The left panel shows properties of the radiation field in the resonator in the lasing state, the right panel the transport current through the double dot system. The lasing state leads to the sharp resonance at ε near 1.

We consider a laser-driven and dissipative system of two coupled cavities with Jaynes-Cummings nonlinearity. In particular, we investigate both incoherent and coherent laser driving, corresponding to different experimental situations. We evaluate the fluorescence spectrum and the spectrum of the second-order correlation function of the emitted light field [8]. Finally, we relate the measured spectra of the dissipative quantum system to excitations of the corresponding nondissipative quantum system. Our results demonstrate how to interpret spectra obtained from dissipative quantum systems and specify what information is contained therein.

Parametrically modulated oscillator

We showed that the noise spectrum of a parametrically excited nonlinear oscillator can display a fine structure [9,10]. It emerges from the interplay of the nonequidistance of the oscillator quasienergy levels and quantum heating that accompanies relaxation. The heating leads to a finite-width distribution over the quasienergy, or Floquet states, even for zero temperature of the thermal reservoir coupled to the oscillator. The fine structure is due to transitions from different quasienergy levels, and thus it provides a sensitive tool for studying the distribution. For larger damping, where the fine structure is smeared out, quantum heating can be detected from the characteristic double-peak structure of the spectrum, which results from transitions accompanied by the increase or decrease of the quasienergy.

Microscopic origin of TLS

In [16] we have conducted a comprehensive fitting of the spectroscopy data to the possible microscopic models of the TLS. The possible parameter space of the Andreev TLS model was severely restricted, whereas the charge TLS model remained unrestricted and thus preferable.

Entanglement

The KIT experimentalists demonstrated induced coherent interaction between two intrinsic two-level states (TLSs) formed by atomic-scale defects in a solid via a superconducting phase qubit. The tunable superconducting circuit serves as a shuttle communicating quantum information between the two microscopic TLSs. In collaboration with them we performed a detailed comparison between experiment and theory and find excellent agreement over a wide range of parameters [11]. We then use the theoretical model to study the creation and movement of entanglement between the three components of the quantum system.

Dissipation in superconducting qubits

In high quality Josephson qubits quasiparticle tunneling may lead to a significant amount of decoherence. We investigated quasiparticle tunneling in a Cooper-pair box which is embedded in a superconducting ring to allow control of the total phase difference across the island [12]. The phase affects the transition rate between different electron number parity states of the island, which can be observed in experiment by established means. The phase dependence also leads to what is known as the $\cos\phi$ term in the tunneling characteristics of classical Josephson junctions. This effect has remained controversial for decades; the proposed scheme opens an independent way to probe it.

Hybrid devices

Interfacing superconducting quantum processors, working in the GHz frequency range, with optical quantum networks and atomic qubits is a challenging task for the implementation of distributed quantum information processing as well as for quantum communication. Using spin ensembles of rare earth ions provide an excellent opportunity to bridge microwave and optical domains at the quantum level. The KIT experimentalists demonstrated magnetic coupling of Er^{3+} spins doped in Y$_{2}$SiO$_{5}$ crystal to a high-Q coplanar superconducting resonator. We could add some theoretical considerations [13].

Publications 2011
(incl. updates published after submission of previous report)

1. S. André, P. Q. Jin, V. Brosco, J. H. Cole, A. Romito, A. Shnirman, and G. Schön, *Single-qubit lasing in the strong-coupling regime*, Phys. Rev. A 82, 053802 (2010); doi: 10.1103/PhysRevA.82.053802
2. M. Marthaler, Y. Utsumi, D. S. Golubev, A. Shnirman, and G. Schön, *Lasing without Inversion in Circuit Quantum Electrodynamics*, arXiv:1012.3557, accepted for publication in Phys. Rev. Lett.
3. M. Marthaler, P. Q. Jin, J. Leppäkangas, and G. Schön, *Sub-Poissonian photon statistics in a strongly coupled single-qubit laser*, to be published in Journal of Physics: Conference Series, Proceeding LT26, Beijing 2011
4. M. Marthaler, J. Leppäkangas, and J. H. Cole, *Lasing, trapping states, and multistability in a circuit quantum electrodynamical analog of a single-atom injection maser*, Phys. Rev. B 83, 180505(R) (2011); DOI: 10.1103/PhysRevB.83.180505
5. Yu. A. Pashkin, H. Im, J. Leppäkangas, T. F. Li, O. Astafiev, A. A. Abdumalikov, E. Thuneberg, and J. S. Tsai, *Charge transport through ultrasmall single and double Josephson junctions coupled to resonant modes of the electromagnetic environment,* Phys. Rev. B 83, 020502(R) (2011); DOI: 10.1103/PhysRevB.83.020502
6. P. Q. Jin, M. Marthaler, J. H. Cole, A. Shnirman, G. Schön, *Lasing and transport in a quantum-dot resonator circuit*, Phys. Rev. B 84, 035322 (2011); DOI: 10.1103/PhysRevB.84.035322
7. P. Q. Jin, M. Marthaler, J. H. Cole, M. Köpke, J. Weis, A. Shnirman, and G. Schön, *Correlation between lasing and transport properties in a quantum dot-resonator system*, to be published in Journal of Physics: Conference Series, Proceeding LT26, Beijing 2011
8. M. Knap, E. Arrigoni, W. von der Linden, J. H. Cole, *Emission characteristics of laser-driven dissipative coupled-cavity systems,* Phys. Rev. A 83, 023821 (2011); DOI: 10.1103/PhysRevA.83.023821
9. M. I. Dykman, M. Marthaler, V. Peano, *Quantum heating of a parametrically modulated oscillator: Spectral signatures*, Phys. Rev. A 83, 052115 (2011); DOI: 10.1103/PhysRevA.83.052115
10. L. Guo, M. Marthaler, S. André, and G. Schön, *The role of damping for the driven anharmonic quantum oscillator*, to be published in Journal of Physics: Conference Series, Proceeding LT26, Beijing 2011
11. G. J. Grabovskij, P. Bushev, J. H. Cole, C. Müller, J. Lisenfeld, A. Lukashenko, A. V. Ustinov, *Entangling microscopic defects via a macroscopic quantum shuttle*, New J. Phys. 13, 063015 (2011); DOI: 10.1088/1367-2630/13/6/063015
12. J. Leppäkangas, M. Marthaler, and G. Schön, *Phase-dependent quasiparticle tunneling in Josephson junctions: Measuring the cos ϕ term with a superconducting charge qubit*, Phys.

Rev. B 84, 060505(R) (2011); DOI: 10.1103/PhysRevB.84.060505
13. P. Bushev, A. K. Feofanov, H. Rotzinger, I. Protopopov, J. H. Cole, C. M. Wilson, G. Fischer, A. Lukashenko, A. V. Ustinov, *Rare earth spin ensemble magnetically coupled to a superconducting resonator*, Phys. Rev. B 84, 060501(R) (2011); DOI: 10.1103/PhysRevB.84.060501

Other achievments

- N. Vogt, Master Thesis "Three level systems and decoherence" (February, 2011
- J. Jeske, Master Thesis "Two qubits as a decoherence probe of the environment" (April, 2011)

Invited Talks at Conference, Workshops and Seminars

- G. Schön, *Quantum State Engineering with Josephson Junctions*, Plenary talk at 26th Int. Conference on Low Temperature Physics, Beijing, China, August 10-17, 2011
- G. Schön, *Lasing and Transport in a Quantum Dot - Resonator Circuit,* Conference on Frontiers of Quantum and Mesoscopic Thermodynamics, Prague, Czech Republic, July 25-30, 2011
- G. Schön, *Lasing and Transport in Circuit QED,* Int. Conference on Quantum Technologies, Moscow, Russia, July 13-17, 2011
- P.-Q. Jin, *Lasing and Transport in a Quantum Dot-Resonator System*, Talk at 26th Int. Conference on Low Temperature Physics, Beijing, China, August 10-17, 2011
- G. Schön, Program chairman of the Spring meeting of the Section Condensed Matter of the German Physical Society, Dresden, Germany, 13-18 March 2011

Your assessment of your situation relative to tasks and milestones

2011 text from GS

Our theoretical work represents contributions to

Milestone M 5.4
Single-qubit lasing in the strong-coupling regime, Superconducting micromasers

Milestone M 5.13
Understanding entanglement sudden death through multipartite entanglement and quantum correlations

Milestone M 3.? / WP3
Ultrasensitive diamond magnetometry using optimal dynamic decoupling

Milestone M 5.1
Our work on parametrically modulated oscillators is important for the use of such systems for the read-out process

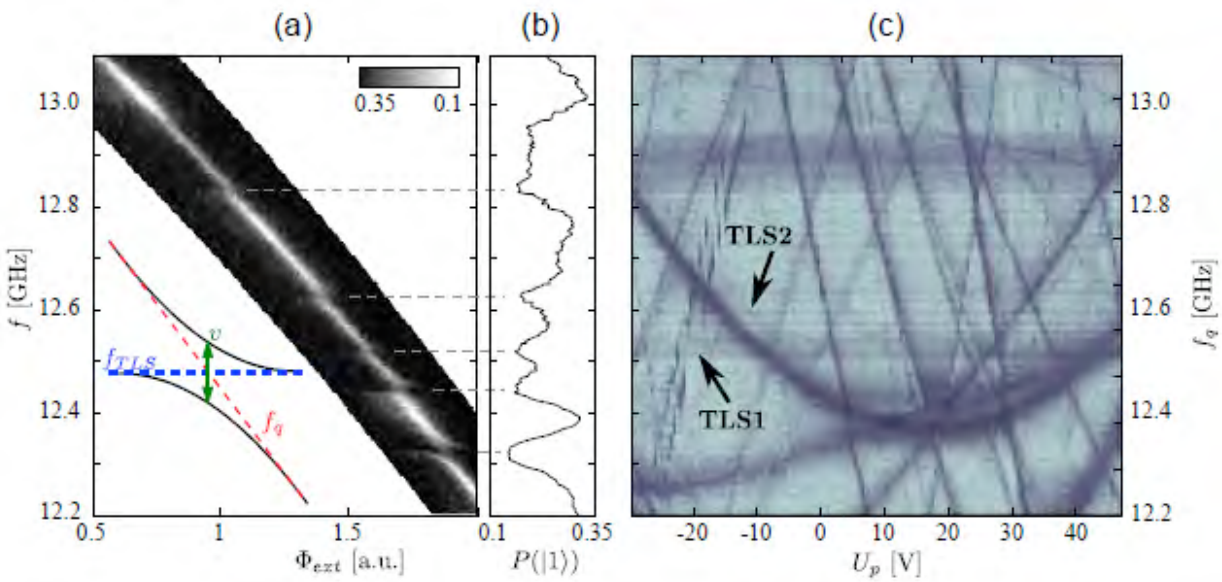
In addition work is in progress concerning
Milestone M2.4
Quantum protocols on two spin qubits in quantum dots.

KIT-Experiment

Tuning TLSs by mechanical strain

Whether two-level systems are indeed individual atoms tunneling between two positions in the dielectric's amorphous matrix is still under debate. We could show for the first time [1] that the properties of TLSs depend sensitively on the mechanical strain which is applied *in situ* to the material, which is indicative for the correctness of the tunneling atom model.

We apply a strain to the thin-film Josephson junction by a mechanical deformation of the chip. This is realized by a piezo actuator, whose length is controlled by an applied voltage U_p. The piezo applies pressure to the middle of the qubit chip's backside, by which it bends the qubit chip which is mounted in a special sample holder. From measurements, we estimate the elongation of the piezo actuator to about 11 nm per volt U_p below a temperature of 4 K.



In order to detect the resonance frequencies of the TLS, we perform spectroscopy on the qubit as shown in above Fig. (a). Figure (b) shows that TLS–induced avoided level crossings generate dips in the qubit population at the TLS resonance frequency. These dips appear as dark lines in Fig. (c), which plots the TLSs resonance frequencies versus the applied piezo voltage Up.

We find that most TLS change their resonance frequency linearily with the applied mechanical strain, while some of them show a hyberbolic dependence. This can be readiliy explained within the tunneling atom model by assuming that the minimum frequency of any hyperbola is associated with a symmetric double-well potential for the tunneling atom, i.e. its two metastable states have equal energy, while a linear dependence indicates a strongly asymmetric double-well potential.

This new technique provides a handle to tune the resonance frequency of TLSs at will and therefore renders TLSs interesting candidates for being used as active qubits or quantum memories. It can also be used to shift TLS away from a desired qubit working point, which is especially useful in multi-qubit platforms. Moreover, by measuring the TLS coherence times vs. mechanical strain we hope to identify the microscopic mechanism by which TLS couple to the environment, shedding more light on to their nature.

Frequency-Division Multiplexing Readout

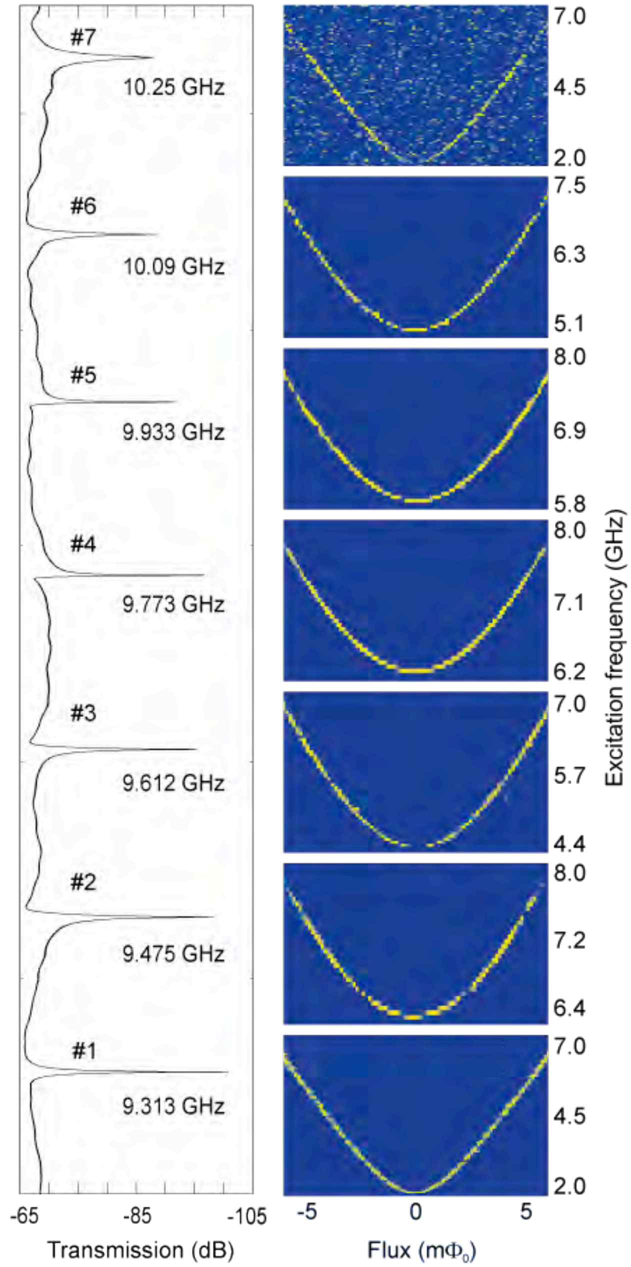
It is well know that the resonance frequency of a resonator coupled to a qubit depends on the state of the qubit. Although the quantum dispersive measurement of one, two and three qubits with coplanar microwave resonators has already been achieved, the scalability to a register of an arbitrary number of qubits remains an open problem.

In collaboration with IPHT Jena, we are currently investigating a frequency multiplexing readout scheme that allows overcoming the problem of scalability. The system we designed consists of several coplanar waveguide resonators with distinct resonance frequencies. All resonators are capacitively coupled to a common transmission line, and every resonator is coupled to an individual qubit. The states of the qubits can be determined by measuring the dispersive shift of each resonator. The qubits can be read out simultaneously by applying a multitone signal to the transmission line that probes all resonators.

We have demonstrated the readout system for seven qubits located on the same chip, being read out through a single transmission line. We sequentially measured the spectra of the qubits and their coherent properties in a single measurement run [2].

We also implemented simultaneous readout and manipulation of the qubits with the same chip layout with a detection bandwidth of 1 GHz [3].

Measurements on a quantum register with coupled qubits and a multiplexed readout in contrast to an array of uncoupled qubits are planned later in 2011.



(left) Transmission spectrum of the sample at zero flux bias.
(right) Spectra of the seven qubits close to their respective symmetry points.

Calculations of the expected crosstalk of this readout system show that it should be scalable to up to 100 qubits per GHz of detection bandwidth with the resonator parameters used in the current implementation. It could also be combined with the microwave readout of phase qubits [4] to achieve their multiplexed single-shot readout.

Publications 2011 (incl. updates published after submission of previous report)

14. G. Grabovskij, T. Peichl, J. Lisenfeld, G. Weiss, and A. V. Ustinov, in preparation (2011).
15. M. Jerger, S. Poletto, P. Macha, U. Hübner, A. Lukashenko, E. Il'ichev and A. V. Ustinov, Readout of a Qubit Array via a Single Transmission Line, accepted for publication in Europhys. Lett. (2011)
16. M. Jerger, S. Poletto, P. Macha, U. Hübner, A. Lukashenko, E. Il'ichev and A. V. Ustinov, in preparation (2011)
17. T. Wirth, J. Lisenfeld, A. Lukashenko, and A. V. Ustinov, Microwave Readout Scheme for a Josephson phase qubit, Appl. Phys. Lett. **97**, 262508 (2010). DOI:10.1063/1.3533805

Assessment of situation relative to tasks and milestones

Our experimental work represents contributions to

Milestone M 1.1
The readout of 7 qubits (uncoupled) on one chip using a single measurement line is experimentally demonstrated (joint work of KIT-exp + Jena)

Milestone M 4.1
The hybrid TLS-JJ qubit experiments performed.

Milestone M 4.3 Both 2-partite and 3-partite entanglement demonstrated in the hybrid TLS-JJ qubit system.

Milestone M 4.4
Reversible information transfer in a hybrid structure has been demonstrated for a hybrid TLS-JJ qubit system.

Milestone M 4.5
TLS quantum memory for superconducting qubits has been demonstrated with TLS coherence time 10 times longer than qubits

Milestone M 5.1
Our work on parametrically modulated oscillators is important for the use of such systems for the read-out process

In addition work is in progress concerning
Milestone M2.4
Quantum protocols on two spin qubits in quantum dots.

6. IPHT

Employment status

- Exp: PhD P. Macha, April 2010 -

Financial situation

Satisfactory: spending February-August 2011, 34.200 Euro

Ongoing research

1. SQUID amplifier.

We designed and fabricated SQUID amplifier for qubit readout. First devices have a relatively narrow bandwidth - from dc up to several megahertz. Nevertheless they can be used for impedance measurements of the low-frequency tank circuits, which, in turns, coupled to qubit of interest. Measurements, at the beginning at liquid helium temperatures, are in progress

2. Multiqubit structures

Together with KIT we continue investigation of multiqubit structures. Measurements are in progress.

3. M5.11 Experimental demonstration of lasing with a single flux qubit

Lasing at the Rabi frequency with flux qubit (we believe) has been observed. Paper is in progress – we have already fitted data. In order to demonstrate consistency between theory and experiment we perform mow additional test measurements which are in progress.

Recent results

1. Material science

Detailed study of the microstructure of submicron Al/Al-O/Al Josephson junction fabricated by the conventional shadow evaporation technique has been performed. We demonstrated that Al-O barrier layer for the single-grain contact has relatively flat interfaces with the thickness $d = 2.0 \pm 0.2$ nm, comparing with multi-grain contact where $d = 2.0 \pm 0.6$ nm (Fig. 1). The most pronounced thickness deviations are observed in the vicinity of so-called "triple points", where the grain boundary crosses interlayer, forming two-grain contact (Fig. 1). Therefore, taking into account the exponential dependence of the critical current on the interlayer thickness, we conclude that a reproducible technology requires a single-grain contact. However, as it was also shown, even for the single-grain contacts the Al-AlO interface is not atomically flat. Recently it was argued that this disorder can be an origin of the low temperature flux noise [S.K. Choi, D-H. Lee, S. G. Louie, J. Clarke Phys. Rev. Lett. 103, 197001 (2009)]. Therefore to improve the performance of superconducting circuits it is necessary to realize the better quality of the metal-insulator interfaces. One of the possible solutions could be an epitaxial growing of the Josephson junctions. The paper has been recently submitted.

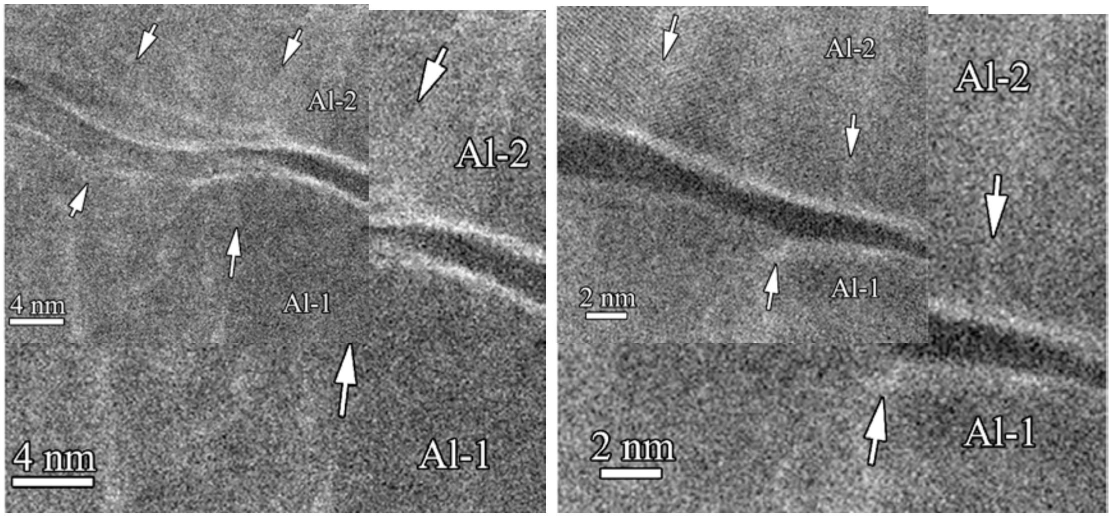


Fig. 1TEM images of barrier layer area. The grain boundaries in Al-1 and Al-2 contacts are shown by arrows. (left) – The Al GBs in Al-1 contact are inherited by GBs in Al-2 contact and (right) - the triple junction area.

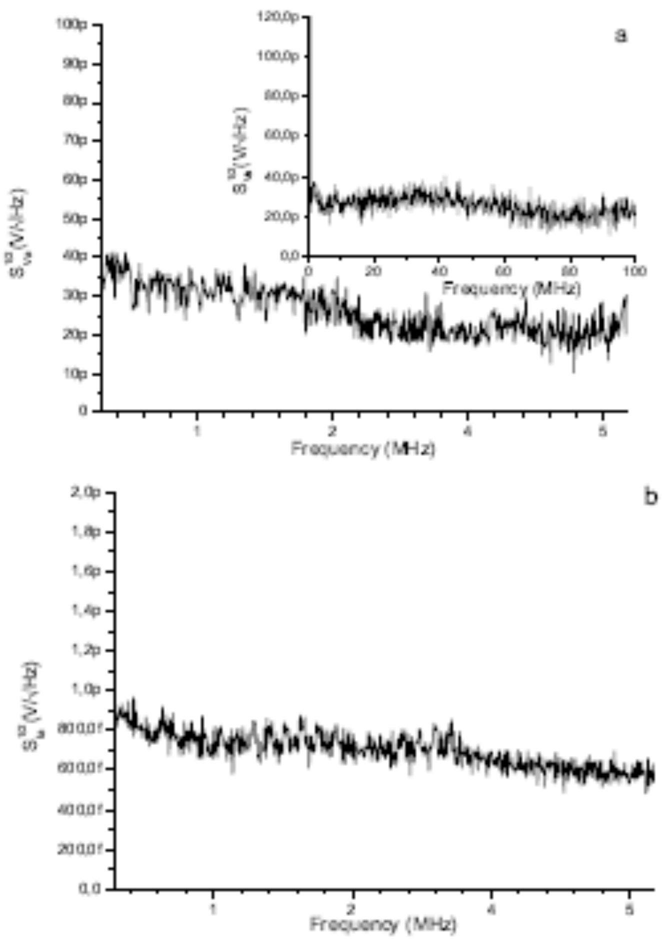


Fig. 2. (a) Measured input voltage noise spectral density in 100 kHz - 5 MHz and 5 - 100 MHz (upper plot) frequency ranges. (b) Corresponding current noise spectral density of the amplifier.

2. Low noise amplifier.
An ultra-low-noise one-stage SiGe heterojunction bipolar transistor amplifier was designed for cryogenic temperatures and a frequency range of 10 kHz-100 MHz. A noise temperature $T_N \approx$ 1.4 K was measured at an ambient temperature of 4.2 K at frequencies between 100 kHz and 100 MHz for a source resistance of $\approx$ 50 Ω. The voltage gain of the amplifier was 25 dB at a power consumption of 720 μW. The input voltage noise spectral density of the amplifier is about 35pV/(Hz)$^{1/2}$ (Fig. 2). The low noise resistance and power consumption makes the amplifier suitable for readout of resistively shunted DC SQUID magnetometers and amplifiers.

Publications 2011

1. B. I. Ivanov, M. Trgala, M. Grajcar, E. Il'ichev, and H.-G. Meyer, *Cryogenic ultra-low-noise SiGe transistor amplifier,* Rev. Sci. Instr., accepted
2. V. V. Roddatis, U. H¨ubner, B. I. Ivanov, E. Il'ichev, H.-G. Meyer, M. V. Koval'chuk, and A. L. Vasiliev, *The morphology of Al-based submicron Josephson junction*, submitted

Other achievments

Invited talks
E. Il'ichev
- 14-18.03.2011 Symposium "Nanophysics and Nanoelectronics" Nizhnii Novgorod, Russia
- July 13-17.06, 2011 INTERNATIONAL CONFERENCE ON QUANTUM TECHNOLOGIES, Moscow Russia
- 20-25.08 Moscow International Symposium on Magnetism, Moscow Russia

PhD
- Simon van der Ploeg "Characterization of Multiqubit Systems" May 2011; Univ. of Twente

Your assessment of your situation relative to tasks and milestones

We are almost ready with task 5.4, Milestone M5.11.

7. CNRS-University Joseph Fourier

Employment status

- Alexey Feofanov, Post-doc, starting date: March 1st 2011.
- Gianluca Rastelli, post-doc
- Florent Lecocq (PhD: 7 months from November 2010 to May 2011)

Financial situation

The main costs are related to personnel cost.
A new UHV sample holder has been purchased (25 k€ with 10 k€ from SOLID contract).

Ongoing research

Non-dispersive read-out of a phase-slip qubit
We theoretically study a circuit in which a phase-slip (PS) qubit is coupled to a resonator. The PS-qubit can be a superconducting nanowire, a single Josephson junction in a highly inductive environment, or a chain of Josephson junctions. The aim of this analysis is to characterize the circuit through the relevant parameters of the individual elements. Special attention will be paid to the strength of the coupling between the PS element and the resonator. The results of this study will be used to design an experimental set-up for dispersive read-out.
Artificial atom with a V-shape energy spectrum
The non linear coupling term inside the inductive Camelback phase qubit creates an atomic-like structure for the combined two mode states with a V-like scheme. We are planning new experiments using this property.
Growth of Al layers and Re layers
The growth of Al layers has been investigated. It has been found that a rather good epitaxial growth may be achieved on a sapphire substrate if the substrate is kept in a narrow range of temperature during the growth (around 150 °C). A full trilayer Josephson junction has been also realized. Measurements of the current transport properties are in progress.
The new UHV sample holder which includes a furnace will be able to reach 1000 °C during the deposition of the Re layers. Indeed, it has been found that the crystallographic quality of the Re increases with the growth temperature, but so far we have been limited to 600 °C due to the limited range of our present furnace.

Recent results

Superconducting artificial atom with two internal degrees of freedom
We realized a theoretical and experimental study on a superconducting artificial atom with two-degrees of freedom. The circuit is realized by an inductive Camelback phase qubit, i.e. a dcSQUID with a loop inductance larger than the Josephson inductance and operated at zero-current bias. In addition to the usual symmetric plasma mode (s-mode), an anti-symmetric mode appears (a-mode) because of the large inductance inserted between the two Josephson junctions.

These two modes can be described by two anharmonic oscillators with eigenstates $|n_s>$ and $|n_a>$ for s and a-mode, respectively. Spectroscopy measurements show that a strong non-linear coupling between the modes leads to a large energy splitting between states $|0_s,1_a>$ and $|2_s,0_a>$. Coherent free oscillations between states $|0_s,1_a>$ and $|2_s,0_a>$ are observed, demonstrating a time resolved up and down frequency conversion.

Macroscopic quantum tunneling rate in a general quartic potential

Calculation of the macroscopic quantum tunneling rate in a general quartic potential with two escape paths, generalizing the well known result for a cubic potential. A specific limiting case of this result was used to describe a recent experiment, where the so-called Camelback potential was studied.

Driven three-level Josephson-atom maser

We also analyzed the quantum dynamics of a three-level atom coupled to a quantum-mechanical resonator in the presence of a driving on the cavity within the framework of the Lindblad master equation. Our results of our quantum approach agree with the experimental findings by Nakamura at NEC-Japan.

Junction fabrication by shadow evaporation without a suspended bridge

We developped a novel shadow evaporation technique for the realization of junctions and capacitors. The design by e-beam lithography of strongly asymmetric undercuts on a bilayer resist enables *in situ* fabrication of junctions and capacitors without the use of the well-known suspended bridge. The absence of bridges increases the mechanical robustness of the resist mask as well as the accessible range of the junction size. These recent results on inductive Camelback phase qubit demonstrate the high quality of the junction obtained by this bridge-free technique.

Training activity

The Grenoble Physics Graduate School, in collaboration with the Grenoble SOLID node organized a series of three lectures *Quantum superconducting circuits*, given by M. Devoret (Yale University). The lectures were held December 16-17, 2010 and were attended by about 70 participants: Master students, Ph-D students, post-docs and scientists.

Publications

Asymmetric Cooper pair transistor in parallel to a dc SQUID: Two coupled quantum systems, A. Fay, W. Guichard, O. Buisson, and F. W. J. Hekking, Phys. Rev. B 83, 184510 (2011)

Junction fabrication by shadow evaporation without a suspended bridge, F. Lecocq, I. M Pop, Z. Peng, I. Matei, T. Crozes, T. Fournier, C. Naud, W. Guichard and O. Buisson, Nanotechnology **22** (2011) 315302.

Non-linear coupling between the two oscillation modes of a dc-SQUID, F. Lecocq, O. Buisson, and P. Milman, submitted for publication.

Superconducting artificial atom with two internal degrees of freedom, F. Lecocq, I. M. Pop, I. Matei, E. Dumur, A. Feofanov, C. Naud, W. Guichard, O. Buisson, in preparation.

Other achievments

Florent Lecocq, PhD Thesis, 11 May 2011.
Quantum dynamics in a dc SQUID: From phase qubit to a two-dimensional quantum oscillator.

Etienne Dumur, Master Report, June 2011.
Studies of a two dimensional artificial atom

Invited Talks at Conference, Workshops and Seminars

O. Buisson, May 2011, Taiwan-France joint school on Quantum Information Science & Workshop on Quantum Measurement, Taiwan: *Superconducting quantum circuit with multidegrees of freedom*.
O. Buisson, July 2011, école de Physique des Houches on Quantum Machines: *Artificial atom with two internal degrees of freedom*.

Your assessment of your situation relative to tasks and milestones

An artificial atom with V-shape energy spectrum can be very useful to develop new read-out scheme. We plan to couple this artificial atom to a cavity and develop a QND one shot measurements. These studies are relevant for milestones M1.2 and M1.9.

8. UNIBAS

Employment status

- Exp: no funding for exp. position
- Theory: postdoc: Dr. Diego Rainis, starting date: Dec. 1, 2010.

Financial situation

Important underspending during the first 18 months.

Ongoing research

D. Loss: We have theoretically studied the low-energy hole states of Ge/Si core/shell nanowires and the properties we found make this system a promising candidate for applications, particularly via EDSR. The system allows for quantum dots and spin-qubits with energy levels that can vary from nearly zero to several meV, depending on the relative shell thickness. Moreover, Ge and Si can be grown nuclear-spin free, avoiding completely nuclear-spin-induced decoherence [1].

We have also shown that anisotropic spin chains with gapped bulk excitations and magnetically-ordered topological ground states offer a promising platform for quantum computation, which bridges the conventional single-spin based qubit concept with recently developed topological Majorana-based proposals [2].

In Ref. [4], in order to analyze electron-nuclear spin hyperfine interaction theoretically, we have diagonalized the central spin Hamiltonian in the high magnetic B-field limit. The level spacing of the nuclear sublevels is exponentially small in the middle of each of the two electron Zeeman levels but increases super-exponentially away from the center. This suggests to select states from the wings of the distribution when the system is projected on a single eigenstate by a measurement to reduce the noise of the nuclear spin bath.

Inspired by spin-electric couplings in molecular magnets, in Ref. [5] we have introduced in the Kitaev honeycomb model a linear modification of the Ising interactions due to the presence of quantized cavity fields. This allows to control the properties of the low-energy toric code Hamiltonian, which can serve as a quantum memory, by tuning the physical parameters of the cavity modes, like frequencies, photon occupations, and coupling strengths. We have shown that, depending on the specific setup, the cavity modes can allow to detect the presence of anyons through frequency shifts and to prolong the lifetime of the memory by enhancing the anyon excitation energy or mediating long-range anyon-anyon interactions with tunable sign.

Finally, in Ref. [6], we have presented a technique for manipulating the nuclear spins and the emission polarization from a single optically active quantum dot. When the quantum dot is tunnel coupled to a Fermi sea, we have discovered a natural cycle in which an electron spin is repeatedly created with resonant optical excitation. The spontaneous emission polarization and the nuclear spin polarization exhibit a bistability. Away from such bistability, the nuclear spin polarization can be changed continuously from negative to positive, allowing precise control via the laser wavelength.

C. Bruder: We theoretically investigate local quantum control of interacting qubit systems. Recently, we have investigated the robustness of control of an array by a single qubit to random noise fields and looked at ways to generate GHZ states and perform 3 qubit gates.

D. Zumbühl: We are working on cooling GaAs samples to temperatures below 1 mK in order to be able to thermodynamically polarize the nuclear spins at magnetic fields ~ 10 T. Towards this goal, we have recently made further progress by cooling the Cu nuclear refrigerators to ~ 0.3 mK on a new, improved, 2nd generation nuclear stage setup (previously cooled to 1 mK). Work on demonstrating mK and sub-mK temperatures in the GaAs samples is under way.

Recent results
See above, Ongoing research.

Publications 2011
D. Loss:

1. C. Kloeffel, M. Trif, and D. Loss, *Strong Spin-Orbit Interaction and Helical Hole States in Ge/Si Nanowires,* arXiv:1107.4870.
2. Y. Tserkovnyak and D. Loss, *Universal quantum computation with topological spin-chain networks,* arXiv:1104.1210.
3. K.A. van Hoogdalem and D. Loss, *Rectification of spin currents in spin chains,* Phys. Rev. B **84**, 024402 (2011).
4. O. Tsyplyatyev and D. Loss, *Spectrum of an Electron Spin Coupled to an Unpolarized Bath of Nuclear Spins,* Phys. Rev. Lett. **106**, 106803 (2011).
5. F.L. Pedrocchi, S. Chesi, and D. Loss, *Quantum memory coupled to cavity modes,* Phys. Rev. B **83**, 115415 (2011).
6. C. Kloeffel, P.A. Dalgarno, B. Urbaszek, B.D. Gerardot, D. Brunner, P.M. Petroff, D. Loss, and R.J. Warburton, *Controlling the Interaction of Electron and Nuclear Spins in a Tunnel-Coupled Quantum Dot,* Phys. Rev. Lett. **106**, 046802 (2011).

C. Bruder:

7. V.M. Stojanovic, A. Fedorov, C. Bruder, and A. Wallraff*, Quantum-control approach to realising a Toffoli gate in circuit QED,* arXiv:1108.3442.
8. S. Aldana, Ying-Dan Wang, and C. Bruder, *Greenberger-Horne-Zeilinger generation protocol for N superconducting charge qubits capacitively coupled to a quantum bus,* arXiv:1104.1022, submitted to Phys. Rev. B.
9. Ying-Dan Wang, Xiaobo Zhu, and C. Bruder *, Ideal quantum non-demolition measurement of a flux qubit at variable bias,* Phys. Rev. B **83**, 134504 (2011).
10. R. Heule, C. Bruder, D. Burgarth, and V.M. Stojanovic*, Controlling qubit arrays with anisotropic XXZ Heisenberg interaction by acting on a single qubit,* Eur. Phys. J. D **63**, 41 (2011).

Other achievements
PhD thesis: 19. 05. 2011, Dr. Kai Schwarzwaelder: *Towards Cooling Nanoelectronic Devices to Microkelvin Temperatures*

Invited Talks at Conference, Workshops and Seminars 2011:
Loss group:

- *Helical modes and Majorana edge states in interacting nanowires,* D. Loss, Invited lecturer, Frontiers in Nanoscale Science and Technology Workshop 2011 January 5-7, 2011, RIKEN Wako Campus (Tokyo), Japan.

- *Mesoscopic Quantum Coherence: Quantum Measurement Frontiers,* D. Loss, Invited talk, Kavli Futures Symposium Plenty of Room in the Middle: Nanoscience The Next 50 Years, Caltech, Pasadena, USA.
- *Quantum information in solid-state systems* (U55.00002), D. Loss, Invited talk, Session U55: “Trends” in the APS Publication Physics. APS March Meeting 2011, March 2125, 2011; Dallas, Texas, USA.
- *Helical modes and Majorana edge states in interacting nanowires,* D. Loss, Invited talk, CIFAR Quantum Physics Discussion and WinterSchool April 03- 07, 2011, Fairmont Chateau Whister, Whistler, Canada.
- *Quantum information in solid-state systems: spin qubits in quantum dots,* D. Loss, Invited talk, Colloquium Celebrating the Foundation of the Peter Grünberg Institute, April 7-8, 2011, Forschungszentrum Jülich, Germany.
- *Helical modes and Majorana edge states in interacting nanowires,* D. Loss, Invited talk. 15th Brazilian Workshop on Semiconductor Physics (BWSP-15), April 10 15, 2011, Juiz de Fora, Minas Gerais, Brazil.

Bruder group:

- ”Quantum control of interacting qubits”, Swiss-Swedish Meeting on *Quantum Materials and Devices*, 9.1.11, Les Diablerets, Switzerland
- ”Cavity optomechanics - quantum measurement and backaction”, 1st General Meeting NCCR Quantum Science and Technology, 12.1.11 Arosa, Switzerland
- ”Quantum control of interacting qubits”, KITPC Workshop on Atomic physics using superconducting quantum circuits, 8.6.11 Kavli Institute Beijing, China
- ”Quantum control of interacting qubits”, Workshop on *Quantum Information and Quantum Control*, 11.6.11 Tsinghua University, Beijing, China
- ”Quantum control of interacting qubits”, Conference on *Frontiers of Quantum and Mesoscopic Thermodynamics* (FQMT 11), 26.7.11Prague, Czech Republic
- ”Quantum control of interacting qubits”, Workshop on *Electronic Correlations in Models and Material*s ECMM2011, 14.9.11Augsburg, Germany

Zumbühl group:

- "Quantum Transport Experiments in Nanostructures", D. Zumbuhl, Invited speaker, First General Meeting of the NCCR Quantum Science and Technology, January 2011, Arosa, Switzerland
- "Approaching Microkelvin Temperatures in Nanosamples", Invited speaker, February 2011, Max Planck Institute Stuttgart, Germany
- “Towards Microkelvin Temperatures in Nanosamples”, Invited speaker, European Microkelvin Meeting, March 2011, Smolenice, Slovakia
- "Approaching Microkelvin Temperatures in Nanosamples", Invited speaker, June 2011, University of Stuttgart, Germany

Outreach / Talk for Highschool students

D. Zumbuhl: "Nanotechnologie für den Quantenrechner der Zukunft", presentation at the Leonhard Gymnasium, March 2011, Basel, Switzerland

Your assessment of your situation relative to tasks and milestones

Progress according to plans.
Theory-Loss: there is no clear connection to any milestone, which are mostly related to experimental demonstrations. Some major contributions to Task 2.3.2 and 2.3.3 have been made in Refs. [1], [4] and [6]. The work [1] has some relevance also for Task 2.3.4, even if Basel was not officially involved in that specific Task. On the other side, the works [2] and [5] contain recent proposals for new quantum computation platforms and improvements for quantum memory operation, significant for WP5.

9. TUM

Employment status: As in the first 12 months of SOLID, Dipl. Phys. Daniel Rudolph continues to be employed as a PhD student at TUM.

Financial situation: Compared to the first 12 months of SOLID, spending has increased significantly and is now in line with our projections at the outset (including the underspend from 2010)

Ongoing research:
WP2: The TUM group continued to work on optical initialization and control of spin in individual self-assembled QDs and **extended it to double dots**. Specifically, we successfully applied the scheme to probe the relaxation of the spin of an individual electron spin qubit [D. Heiss *et al.* Phys. Rev. B 82, 245316 (2010)] (for **M2.3**) and are currently performing microwave driven electron spin resonance (ESR). Using quantum dot molecules we made surprisingly good progress. In particular, we were successful to optically measure the excited state structure of a single QD-molecule and use it to demonstrate a conditional optical response. The study showed that excited state transitions occur between hybridized electronic states and different hole states in the upper dot. By simultaneously pumping two different excited states with independent laser fields a strong (88% on-off contrast) laser-induced switching of the optical response was identified. The results obtained represent an electrically tunable, discrete coupled quantum system with a *conditional* optical response.

K. Mueller, G. Reithmaier, E. C. Clark, V. Jovanov, M. Bichler, H. J. Krenner, M. Betz, G. Abstreiter and J. J. Finley, Excited state quantum couplings and optical switching of an artificial molecule. Phys. Rev. B 84, 081302(R) (2011)

Most recently, the TUM group applied these techniques to probe the inter- and intra-molecular dynamics of charge carriers in the QD-molecule. Ultrafast pump probe measurements have been used to probe few Fermion spectra of the molecule and the dynamics of the charge carriers. Besides tunneling out of the molecule we observe a strongly reduced tunneling time of the coupled states (< 5ps) and phonon-assisted non-resonant tunneling which is most efficient at energy detunings of $\approx$ 3meV. Temperature dependent measurements are performed to support these findings. Based on these results, we have very recently extended our work to perform ultrafast preparation of a hole spin qubit in a single QD-molecule (preparation fidelity >95%, timescale 3ps) and achieved a breakthrough insofar as we are now able to monitor the coherent spin precession of a single hole, optically prepared in a QD-molecule, over ultrafast timescales. The figure below shows examples of these (still unpublished) results.

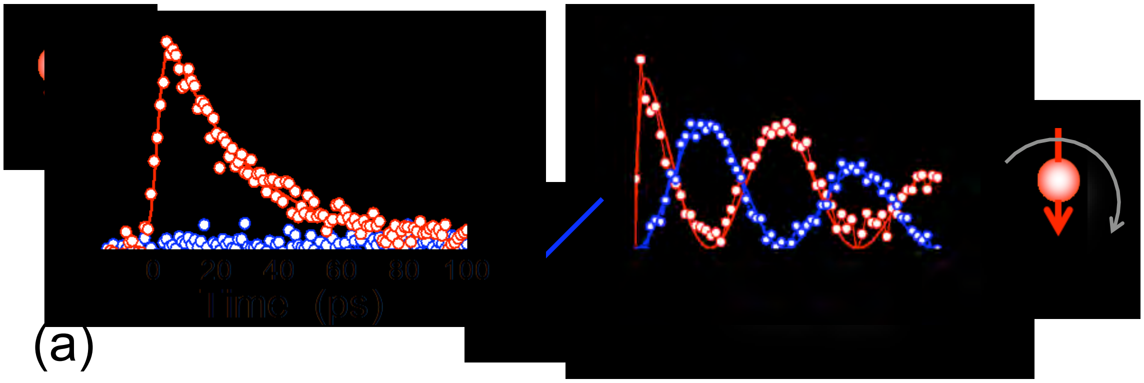


Figure TUM-1: *(a) Demonstration of Pronounced Pauli blocking arising from the optical creation of a single hole spin qubit in a quantum dot molecule and subsequent readout via a second, time delayed probe laser pulse. The hole spin initialization time is limited only by the laser pulse duration (here 3ps) and the state preparation fidelity is >95% limited by the noise in the measurement. (b) Direct observation of single free hole precession in a single QD molecule.*

Our work on electrically tunable g-factors in single QDs has now been published and is in the process of being extended to magnetic g-factor tunability. One manuscript is published and a second is in course of preparation.

V. Jovanov, T. Eissfeller, S. Kapfinger, E. C. Clark, F. Klotz, Daniel Rudolph, Gerhard Abstreiter and Jonathan J. Finley, Strong electrically tunable exciton g-factors in an individual quantum dots due to hole orbital angular momentum quenching, Phys. Rev. B 83, 161303(R) (2011))

Our work on the design, fabrication and testing of co-planar stripline (CPS) antennas to allow coherent spin manipulation was published.

F. Klotz, H. Huebl, D. Heiss, K. Klein, J. J. Finley, M. S. Brandt. Coplanar stripline antenna design for optically detected magnetic resonance on semiconductor quantum dots. Rev. Sci. Instrum. 82, 074707 (2011)

WP2 /WP4: We also continued our work on site selective growth of GaAs-InGaAs nanowire (NW) heterostructures by ultra–high purity solid source MBE. This study is key to the development of optically active “few-QD” nanostructures for the spin and photonic goals in **WP-2** (Task **2.2, M2.1),** and **WP-4** (M4.2), respectively. Here, GaAs and InAs nanowires were grown without external catalyst using molecular beam epitaxy (MBE) on nano-patterned SiO_2/Si templates. Site-selective growth of nanowires from pre-defined nucleation holes was achieved with an areal density as low as ~$10^7 cm^{-2}$. This facilitates optical measurements on individual NW- heterostructures with optical addressing along the NW growth axis - vital for utilizing the optical selection rules for spin-photon conversion in WP-2. From M6 onwards efforts focussed specifically on the incorporation of $In_xGa_{(1-x)}As$ segments into GaAs nanowires to form quantum dots and optical passivation of the NW surface by growing an $Al_{0.3}Ga_{0.7}As$ shell. A series of *core-shell* GaAs-AlGaAs NW samples [see e.g. A. Fontcuberta i Morral et al., Appl. Phys. Lett. 92, 063112 (2008), C. Colombo et al., Phys. Rev. B 77, 155326 (2008)] were grown with shell thicknesses in the range of 8-100nm. Comparison of the luminescence efficiency of these samples and an uncapped reference sample revealed enhancements in excess of $>10^3$ with respect to the uncapped NWs – essentially independent of the shell thickness. The TUM group thoroughly investigated the effect of growth temperature and III/V ratio on the nanowire growth and identified a growth regime that does not involve a catalyst particle in the formation of GaAs NWs on Si. This was confirmed using electron microscopy and in-situ nucleation studies using reflection-high-energy-electron-diffraction. Our findings are expected to provide a route toward abrupt axial nanowire heterostructures that are typically prevented by a catalyst particle during growth. Results of the nanowire growth studies performed during M1-M8 were presented at the 5th annual Nanowire Growth Workshop (Rome, 4-5th Nov 2010 - www.nwg2010.artov.imm.cnr.it/index.html), at the EP2DS19/MSS15 (Tallahassee, 25-29th Jul 2011 - http://www.magnet.fsu.edu/mediacenter/seminars/ep2dsmss/), at SemiconNano2011 (Traunkirchen, 11-16th Sep 2011 - http://www.hlphys.jku.at/SemiconNano2011/) and contribute specifically towards deliverable **D2.1.**

D. Rudolph, S. Hertenberger, S. Bolte, W. Paosangthong, D. Spirkoska, M. Doeblinger, M. Bichler, J. Finley, G. Abstreiter, G. Koblmueller. Nano Letters 11, 3848 (2011).

S. Hertenberger, D. Rudolph, S. Bolte, M. Döblinger, M. Bichler, D. Spirkoska, J. J. Finley, G. Abstreiter, G. Koblmueller. Appl. Phys. Lett. 98, 123114 (2011).

S. Hertenberger, D. Rudolph, M. Bichler, J. J. Finley, G. Abstreiter, and G. Koblmüller. J. Appl. Phys. 108, 114316 (2010).

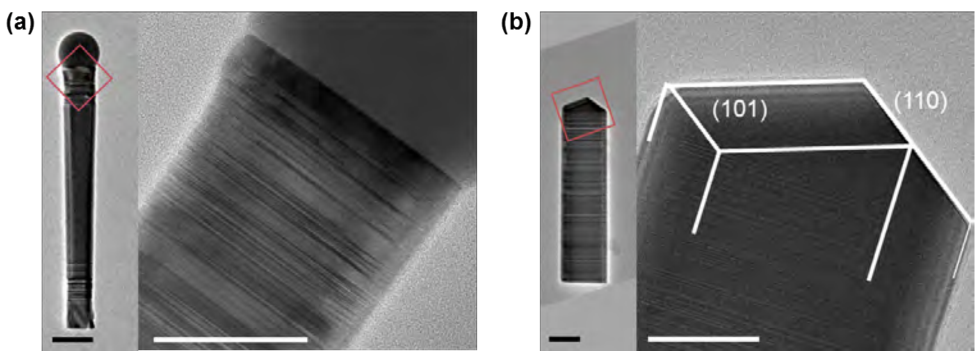


Figure TUM-2: *Transmission electron micrograph of (a) a autocatalytic GaAs nanowire (under low As/Ga ratio) and (b) a catalyst-free GaAs nanowire (under high As/Ga ratio). White bars are 50nm, black scale bars are 100nm.*

WP5: Here, the TUM group continued the work on few dot photonic crystal defect nanocavities QDs strongly coupled to the same cavity mode. Since experiments have slowed due to the transition to a new etching system in Munich that prevented fabrication of new samples, we explored our existing results theoretically. The results of these studies have been summarized in a submitted manuscript that is now close to acceptance.

F.P. Laussy, A. Laucht, E. del Valle, J.J. Finley, J.M. Villas-Bôas. Cavity versus dot emission in strongly coupled quantum dots-cavity systems, arXiv:1102.3874 (2011)

WP6: TUM also continued to maintain the SOLID website and supported training activities via a number of new measures: (1) Over 100 publications are now listed and weblinked on the website, (2) SOLID provided financial support to several international workshops (2) Leo Di Carlo has taken up an Assistant professorship at TU Delft, and his group is now a member of SOLID and received financial support of 50 kEuro, (3) We introduced the SOLID training activity to facilitate short scientific visits (max 14 day duration) to, or from a participating institution within SOLID. Such visits are possible both inside the SOLID consortium and with collaborators not directly working within SOLID. To date, **four such visits** have been supported and a further one has been approved. Short reports on the visits have now been requested and will be included in the 24-month report.

10. USTUTT

Employment status

- Exp: Postdoc, Boris Naydenov, 2010-03-01

Financial situation

Satisfactory.

Ongoing research

The immediate goal of our SOLID-related research is the measurement of the ultimate limits of the coherence time in isotopically engineered diamond. We have constructed and are currently operating a dedicated setup, which enables measurements in a magnetically ultraquiet environment. Here we have measured T_2 times which are up to 6ms in isotope depleted crystals. Lowest ^{13}C concentration so far is 0.0007%. By optimizing our defect production procedure we were able to observe coherent strong coupling between defect pairs separated by 20nm. We are currently characterizing these pairs which completes accomplishment of M3.1, M3.2 and M3.3.

Recent results

Our recent results comprise measurement of long T_2 times of up to 6ms in isotopically pure diamond. We have improved our coherent control and readout technology and used this to demonstrate violation of Legget-Garg inequality as well as adaptive phase estimation which enables sub standard quantum limited scaling of magnetic field measurements. Further on we have used precise control of spin Hamiltonian to measure electric field induced shifts in the ground state of diamond defects. In cooperation with partners from Australia we do have measure quantum properties of spin defects in diamond nanocrystals in living cells which might find useful application in cellular biophysics.

Publications 2011

[1] G. Waldherr, J. Beck, M. Steiner, P. Neumann, A. Gali, T. Frauenheim, F. Jelezko, J. Wrachtrup, *Phys Rev Lett* **2011**, *106*;
[2] B. Naydenov, F. Dolde, L. T. Hall, C. Shin, H. Fedder, L. C. L. Hollenberg, F. Jelezko, J. Wrachtrup, *Phys Rev B* **2011**, *83*;
[3] T. Muller, I. Aharonovich, L. Lombez, Y. Alaverdyan, A. N. Vamivakas, S. Castelletto, F. Jelezko, J. Wrachtrup, S. Prawer, M. Atature, *New J Phys* **2011**, *13*;
[4] L. C. L. Hollenberg, L. P. McGuinness, Y. Yan, A. Stacey, D. A. Simpson, L. T. Hall, D. Maclaurin, S. Prawer, P. Mulvaney, J. Wrachtrup, F. Caruso, R. E. Scholten, *Nat Nanotechnol* **2011**, *6*, 358-363;
[5] P. Hemmer, B. Grotz, J. Beck, P. Neumann, B. Naydenov, R. Reuter, F. Reinhard, F. Jelezko, J. Wrachtrup, D. Schweinfurth, B. Sarkar, *New J Phys* **2011**, *13*;
[6] H. Fedder, F. Dolde, M. W. Doherty, T. Nobauer, F. Rempp, G. Balasubramanian, T. Wolf, F. Reinhard, L. C. L. Hollenberg, F. Jelezko, J. Wrachtrup, *Nat Phys* **2011**, *7*, 459-463.

Other achievements

~10 invited talks in the current funding period.

Your assessment of your situation relative to tasks and milestones

So far, we are clearly on schedule. We have passed milestone M3.1 (creation of single centers in isotopically pure material) with results which we will report on by the end of the 18m period. A dedicated setup has been constructed and allowed significant progress towards M3.3 within the next months. Samples for the achievement of M3.2 and M3.4 have been prepared. Suitable pairs to demonstrate coherent coupling have been found.

11. SNS

Employment status

- One postdoc, dr. Davide Rossini, has been hired: his research contract has started in October 2010 and will last till the end of the project. He will be working on WP1 and WP5.

Financial situation

Satisfactory, slight underspending.
Up to now, costs have been born for participating in conferences to present results of SOLID, for the salary of the postdoc and for prof. Fazio's hours worked on the project.

Ongoing research

The research of the SNS team has concentrated in the last year on the following three main activities: 1) Quantum optimal control 2) Topological and geometric computation with superconducting qubits 3) Efficient codes to simulate the dynamics of many-qubit systems.

In addition we continued to work on some aspects related on circuit-QED systems (in particular on phase transition the ultra-strong regime) and the manipulation of quantum information using the edge states in the quantum Hall regime. A list of the main results obtained in this area will be included in the publications of the SNS team.

Recent results

1) Quantum optimal control

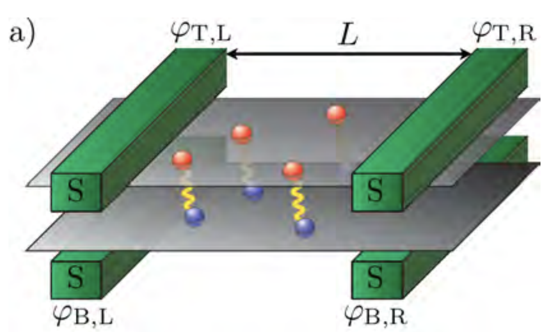
1.1 We introduced a new approach to assess the error of control problems we aim to optimize. The method offers a strategy to define new control pulses that are not necessarily optimal but still able to yield an error not larger than some fixed a priori threshold, and therefore provide control pulses that might be more amenable for an experimental implementation. We applied this formalism to an exactly solvable model and to the Landau-Zener model, whose optimal control problem is solvable only numerically. The developed method may be of importance for applications, as solid state qubits, where a high degree of controllability of the dynamics of quantum systems is required. At the same time distortions on the applied pulses are unavoidable and therefore one is interested in estimated to which extent it is possible to tolerate such distortions without large deviations from the optimal fidelity.

1.2 We continued our work on exploring the ultimate limits of optimal control. The ability to accurately control a quantum system is a fundamental requirement in many areas of modern sciencesuch as quantum information processing. It is usually necessary to realize these quantum manipulations in the shortest possible time in order to minimize decoherence, and with a large stability against fluctuations of the control parameters. While optimizing a protocol for speed leads to a natural lower bound in the form of the quantum speed limit rooted in the Heisenberg uncertainty principle on the other side stability against parameter variations typically requires adiabatic following of the system. The SNS analyzed theoretically the optimal pulses at the quantum speed limit and collaborated with their experimental implementation with the group of Prof. Arimondo (Pisa). The experimental implementation of these optimal control schemes that achieve nearly perfect fidelity for a two-level quantum system realized with Bose-Einstein condensates in optical lattices. By suitably tailoring the time-dependence of the system's parameters, we transformed an initial quantum state into a desired final state through a short-cut protocol reaching the maximum speed compatible with the laws of quantum mechanics. We implement the recently proposed transitionless superadiabatic protocols, in which the system perfectly follows the instantaneous adiabatic ground state. We demonstrated that superadiabatic protocols are extremely robust against parameter variations, making them useful for practical applications

1.3 We studied optimized protocols for adiabatic quantum computation. We analyzed several situations including the adiabatic Grover's search algorithm. We discussed under which conditions the fidelity at the end of the computation is arbitrary close to one. Furthermore we showed that the minimum time required to enter this regime is $T \sim \pi/\Delta$, where Δ is the minimum spectral gap, unveiling an intimate connection between an optimized unitary dynamics and the intrinsic measure of the Hilbert space for pure states. Surprisingly, the dynamics is non-adiabatic, this result can be understood by assuming a simple two-level dynamics for the many-body system. Furthermore we introduced an algorithm to perform an optimal adiabatic evolution that operates without an a priori knowledge of the system spectrum. By probing the system gap locally, the algorithm maximizes the evolution speed, thus minimizing the total evolution time. We tested the algorithm on the Landau-Zener transition and then apply it on the quantum adiabatic computation of 3-SAT: The result is compatible with an exponential speed-up for up to twenty qubits with respect to classical algorithms.

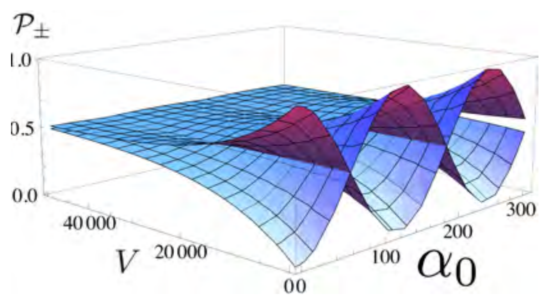
2) Topological and geometric computation with superconducting qubits

2.1 We investigated the transport properties of a bilayer exciton condensate that is contacted by four superconducting leads. We focused on the equilibrium regime and investigate how the Josephson currents induced in the bilayer by phase biases applied to the superconducting electrodes are affected by the presence of an exciton condensate in the bulk of the system. *The system we investigate provides an implementation of the supercurrent mirror proposed by Kitaev as a viable way to realize topologically protected qubits.*



As long as the distance between the superconducting electrodes is much larger than the exciton coherence length, the Josephson current depends only on the difference between the phase biases in the two layers. This result holds true in both short- and long-junction limits. We relate it to a novel correlated four-particle Andreev process which occurs at the superconductor - exciton condensate interface.

2.2 We proposed a method to generate environment induced geometric phase in qubit-oscillator system. In general, the problem of enforcing quantumness under unfavorable conditions, such as increasingly higher temperatures, have received great attention in the last years, being the topic of great interest both from a technological and from a fundamental point of view. In this line of thoughts, we considered a system in which genuine non-classical features not only survive to temperature and dissipation, but they are indeed induced by these environmental influences. In the spirit of previous works we considered the famous model called *Von Neumann measurement scheme*, which models the measurement process as a coupling between a large measurement apparatus, used as a probe, and the microscopic system on which the measurement is performed. This scheme is studied under a new prospective, using the microscopic system (a qubit) to measure a dissipation-induced geometric phase attached to the macroscopic system (an harmonic oscillator), with the roles of the two systems somehow inverted respect to Von Neumann original model. We showed how such a phase, generated by a cyclic evolution in the phase space of the harmonic oscillator, can be kicked back on the qubit, which plays the role of a quantum interferometer. The environment induced geometric phase can then be measured through an interference scheme on the qubit. In the figure below the interference fringes as detected using the qubit as a function of the displacement and the variance of an initially prepared thermal gaussian state.



We further extended our study to finite-temperature dissipative Markovian dynamics. Potential implementations of the proposed scheme are circuit-QED systems or micro nano-mechanical devices coupled to an effective two-level system.

2.3 So far, nano-scale pumps have been realised only in Coulomb blockade systems, whereas evidence for pumping in the absence of Coulomb-blockade has been elusive. It was proposed that a potentially interesting setup to experimentally detect the effect would be to use the ac Josephson effect to induce periodically time-dependent Andreev-reflection amplitudes in a hybrid normal-superconducting system. Very recently the experimental detection of charge flow in an unbiased InAs nanowire (NW) embedded in a superconducting quantum interference device (SQUID) was achieved in the NEST laboratories in Pisa. The SNS team contributed to the theoretical analysis of the experiment. In this system, pumping may occur via the cyclic modulation of the phase of the order parameter of different superconducting electrodes. The understanding and measurement of the symmetry of the current with respect to the enclosed magnetic flux and bias SQUID current was a crucial signature of pumping. Currents exceeding 20 pA were measured at 250 mK.

3) Efficient codes to simulate the dynamics of many-qubit systems.

A very important problem towards the understanding of many-qubit system is the ability to efficiently simulate its quantum dynamics. In recent years, starting from the celebrated density matri renormalization group algorithm, a number of methods have been propsed. We recently developed a number of codes that allow to study the low lying spectrum and the quantum dynamics of interacting qubits and we applied to several models in one-dimension with periodic boundary conditions.

Publications 2011

1) Amit Agarwal, Marco Polini, Rosario Fazio, and G. Vignale, Phys. Rev. Lett. **107**, 077004 (2011)

2) F. Giazotto, P. Spathis, S. Roddaro, S. Biswas, F. Taddei, M. Governale and L. Sorba, Nature Physics (2011) doi:10.1038/nphys2053

3) Nicolas Didier, Stefano Pugnetti, Yaroslav M. Blanter, and Rosario Fazio, Phys. Rev. B **84**, 054503 (2011)

4) Tommaso Caneva, Tommaso Calarco, Rosario Fazio, Giuseppe E. Santoro, and Simone Montangero, Phys. Rev. A **84**, 012312 (2011)

5) Angelo Russomanno, Stefano Pugnetti, Valentina Brosco, and Rosario Fazio, Phys. Rev. B **83**, 214508 (2011)

6) Davide Rossini, Vittorio Giovannetti, and Rosario Fazio, Phys. Rev. B **83**, 140411 (2011)

7) Nicola Paradiso, Stefan Heun, Stefano Roddaro, Davide Venturelli, Fabio Taddei, Vittorio Giovannetti, Rosario Fazio, Giorgio Biasiol, Lucia Sorba, and Fabio Beltram, Phys. Rev. B **83**, 155305 (2011)

8) D. Venturelli, V. Giovannetti, F. Taddei, R. Fazio, D. Feinberg, G. Usaj, and C. A. Balseiro, Phys. Rev. B **83**, 075315 (2011)

9) Pietro Silvi, Fabio Taddei, Rosario Fazio, Vittorio Giovannetti, J. Phys. A: Math. Theor. **44** 145303 (2011)

10) Davide Rossini, Vittorio Giovannetti, Rosario Fazio, J. Stat. Mech. (2011) P05021

11) Antonio Negretti, Rosario Fazio, Tommaso Calarco, J. Phys. B: At. Mol. Opt. Phys. **44,** 154012 (2011)

12) Biswajit Karmakar, Davide Venturelli, Luca Chirolli, Fabio Taddei, Vittorio Giovannetti, Rosario Fazio, Stefano Roddaro, Giorgio Biasiol, Lucia Sorba, Vittorio Pellegrini, and Fabio Beltram, " Controlled coupling of spin-resolved quantum Hall edge states", arXiv: 1106:3965

13) J. Nehrkorn, S. Montangero, A. Ekert, A. Smerzi, R. Fazio, T. Calarco, "Staying adiabatic with an unknown energy gap", arXiv:1105:1707

14) Giovanni Vacanti, Stefano Pugnetti, Nicolas Didier, Mauro Paternostro, G. Massimo Palma, Rosario Fazio, Vlatko Vedral, " Photon production from the vacuum close to the super-radiant transition: When Casimir meets Kibble-Zurek", arXiv:1107:0178

15) G. Vacanti, R. Fazio, M. S. Kim, G. M. Palma, M. Paternostro, V. Vedral, " Geometric phase kickback in a mesoscopic qubit-oscillator system" arXiv:1108:0701

16) Luca Chirolli, Vittorio Giovannetti, Rosario Fazio, Valerio Scarani, "Time-bin entanglement of quasi-particles in semiconductor devices" arXiv:1101.4767

Other achievements

Master thesis: G. Micchi "Circuit-QED in the ultra-strong regime", expected to finish in september 2011
PhD thesis: Diego Rainis, expected to discuss in october 2011
Stefano Pugnetti " Quantum Transport in Wires and Nanoelectromechanical Systems", january 2011

Invited Talks at Conference, Workshops and Seminars

1) Workshop on New Trends in Quantum Dynamics and Quantum Entanglement - ICTP Trieste, Feb 2011 (Rosario Fazio - invited)
2) Quantum Information Processing and Applications - HRI- Allahabad, India, Feb 2011 (Rosario Fazio - invited)
3) Quantum science and technologies - Rovereto, May 2011 (Rosario Fazio - invited)
4) Entanglement, Quantum information and the Quantum to classical transition - Rome May 2011 (Rosario Fazio - invited)
5) ICSSUR2011 - Foz de Iguazu Brazil, May 2011 (Rosario Fazio - invited but had to cancel)
6) FEYNMANN FEST - Foz de Iguazu Brazil, May 2011 (Rosario Fazio - invited but had to cancel)
7) CFN Summer School 2011 on NANO-ELECTRONICS - Bad Herrenalb, Sept 2011 (Rosario Fazio - invited)
8) Quantum to Classical Crossover in Mechanical Systems - Leiden Oct 2011 (Rosario Fazio - invited)
9) Engineering and Control of Quantum System - Dresden Oct 2011 (Rosario Fazio - invited)
10) “Nonlinear spin and charge transport through nanoscopic systems", IFISC, Palma di Maiorca (Spain), June 2011 (Fabio Taddei - invited)
11) “Frontiers of quantum and mesoscopic thermodynamics, FQMT'11", Prague, July 2011 (Fabio Taddei - invited)
12) Quantum simulations, Benasque , March 2011 (Davide Rossini - contributed talk)
13) Many-Body Quantum Dynamics in Closed Systems: challenges and applications, Barcelona, sept 2011 (Davide Rossini - invited talk)

Your assessment of your situation relative to tasks and milestones
The work proceeds as expected

12. UPV/EHU

Employment status

Theory: Postdoctoral position continues with Dr. Daniel Ballester (from October 2010)

Financial situation

Satisfactory. The reported underspending is due to a late employment of a postdoctoral researcher during Y1. It is expected that this issue is balanced without major problems during Y2 an Y3.

Ongoing research

We have achieved most of our current milestones. However, we are delaying or postponing some of them due to novel and timely other research projects, as described below.

Milestones current status at 18m

M1.8: Design of a toolbox of resonant two-qubit gates (18m)
M1.9: Design of high-fidelity qubit readout techniques inspired in quantum-optical concepts (18m)

Both passed at 12m

M5.3: Design of metamaterial, in the context of circuit QED, for implementing realistic microwave photon detectors and photon counters with propagating quantum microwave fields acting on qubit/clusters inside waveguides (18m)

Done: see B. Peropadre, G. Romero, G. Johansson, C. M. Wilson, E. Solano, and J. J. García-Ripoll, ”Perfect microwave photodetection in circuit QED”, arXiv:1101.0016

M5.4: Development of a theory for propagating quantum microwaves interacting with one qubit or more qubits inside waveguides in circuit QED (18m)

Ongoing research: soon (24m), we will submit a manuscript dealing with the theory of circuit quantum photonics, where quantized microwaves interact with linear and nonlinear quantum circuits.

M5.14: Design of protocols for generating and reconstructing the state or phase-space representation (e.g., Wigner function) of propagating quantum microwaves (18m)

Done (however, further work is currently being developed for 30m): see E. P. Menzel, F. Deppe, M. Mariantoni, M. Á. Araque Caballero, A. Baust, T. Niemczyk, E. Hoffman, A. Marx, E. Solano, and R. Gross, ”Dual-path state reconstruction scheme for propagating quantum microwaves and detector noise tomography”, Phys. Rev. Lett. 105, 100401 (2010).

M5.15: Design of protocols for the simulation of useful many-body Hamiltonians in circuit QED (18m)

Postponed research (other topics in quantum simulations are more timely and relevant): requested corrective action: 18m --> 36m

M5.16: Design of protocols for the simulation of quantum relativistic dynamics in circuit QED (18m)

Partially achieved (in the following paper, where the quantum simulation of the full quantum Rabi model is proposed, the Dirac equation in 1+1 dimensions is a particular case included in the model. Further work might arrive for 30m, see below new projects): D. Ballester, G. Romero, J. J. García-Ripoll, F. Deppe, and E. Solano, "Quantum simulation of the ultrastrong coupling dynamics in circuit QED", arXiv:1107.5748

Milestones expected status for 24m

M4.8: Design of sequential protocols for generating multipartite entangled qubits (24m)
M5.13: Design of protocols for generating and measuring multipartite entangled qubit states inside waveguides (24m)

Both delayed and related: very likely a corrective action will be requested 24m --> 36m

New emerging and ongoing research projects

Ultrafast quantum gates in circuit QED: We are currently considering the design of ultrafast quantum gates in circuit QED by means of the access and suitable manipulation of the ultrastrong coupling regime in the qubit-cavity system (24m).

Fast quantum control with integrable quantum Rabi model: We are considering the use of the analytical solutions of the quantum Rabi model, recently proposed by Daniel Braak in Phys. Rev. Letters, to improve our understanding and physical intuition on the ultrastrong and deep strong coupling regime in circuit QED. This will help us to propose and describe different quantum information protocols at higher operation speed (30-36m).

Quantum simulation of Dicke and spin-boson models: We are considering further quantum simulations in relativistic quantum systems and variants of Dicke/spin-boson models in circuit QED (30-36m).

Recent results

See SOLID related publications below for the 18m period

1) F. Zähringer, G. Kirchmair, R. Gerritsma, E. Solano, R. Blatt, and C. F. Roos, "Realization of a quantum walk with one and two trapped ions", Phys. Rev. Lett. **104**, 100503 (2010).

2) N. Kiesel, W. Wieczorek, S. Krins, T. Bastin, H. Weinfurter, and E. Solano, "Operational multipartite entanglement classes for symmetric photonic qubit states", Phys. Rev. A **81**, 032316 (2010).

3) B. G. U. Englert, G. Mangano, M. Mariantoni, R. Gross, J. Siewert, and E. Solano, "Mesoscopic Shelving Qubit Readout in Circuit QED", Physical Review B **81**, 134514 (2010).

4) G. M. Reuther, D. Zueco, F. Deppe, E. Hoffmann, E. P. Menzel, T. Weißl, M. Mariantoni, S. Kohler, A. Marx, E. Solano, R. Gross, P. Hänggi, "Two-resonator circuit QED: Dissipative Theory", Physical Review B **81**, 144510 (2010).

5) C. Sabín, J. J. García-Ripoll, E. Solano, and J. León, "Causality in quantum field theory with quantum circuits", Physical Review B **81**, 184501 (2010).

6) P. Mathonet, S. Krins, M. Godefroid, L. Lamata, E. Solano, and T. Bastin, "Entanglement Equivalence of N-qubit Symmetric States", Phys. Rev. A **81**, 052315 (2010).

7) G. Haack, F. Helmer, M. Mariantoni, F. Marquardt, and E. Solano, "Resonant quantum gates in circuit quantum electrodynamics", Phys. Rev. B **82**, 024514 (2010).

8) J. Casanova, G. Romero, I. Lizuain, J. C. Retamal, C. Roos, J. G. Muga, and E. Solano, "Short-time-interaction quantum measurement through an incoherent mediator", Phys. Rev. A **81**, 062126 (2010).

9) B. Peropadre, P. Forn-Díaz, J. J. García-Ripoll, and E. Solano, "Switchable ultrastrong coupling in circuit QED", Phys. Rev. Lett. **105**, 023601 (2010).

10) I. Lizuain, J. Casanova, J. J. García-Ripoll, J. G. Muga, and E. Solano, "Zeno physics in ultrastrong circuit QED", Phys. Rev. A **81**, 062131 (2010).

11) E. P. Menzel, M. Mariantoni, F. Deppe, M. A. Araque-Caballero, A. Baust, T. Niemzcyk, E. Hoffmann, A. Marx, E. Solano, and R. Gross, "Dual-Path State Reconstruction Scheme for Propagating Quantum Microwaves and Detector Noise Tomography", Phys. Rev. Lett. **105**, 100401 (2010).

12) M. Mariantoni, E. P. Menzel, F. Deppe, M. A. Araque-Caballero, A. Baust, T. Niemczyk, E. Hoffmann, E. Solano, A. Marx, and R. Gross, "Planck Spectroscopy and the Quantum Noise of Microwave Beam Splitters", Phys. Rev. Lett. **105**, 133601 (2010).

13) J. Casanova, J. J. García-Ripoll, R. Gerritsma, C. F. Roos, and E. Solano, "Klein tunneling and Dirac potentials in trapped ions", Phys. Rev. A **82**, 020101(R) (2010).

14) T. Niemczyk, F. Deppe, H. Huebl, E. P. Menzel, F. Hocke, M. J. Schwarz, J. J. García-Ripoll, D. Zueco, T. Hümmer, E. Solano, A. Marx, and R. Gross, "Circuit quantum electrodynamics in the ultrastrong coupling regime", Nature Phys. **6**, 772 (2010).

15) N. Zagury, A. Aragão, J. Casanova, and E. Solano, "Unitary expansion of the time evolution operator", Phys. Rev. A **82**, 042110 (2010).

16) P. Forn-Díaz, J. Lisenfeld, D. Marcos, J. J. García-Ripoll, E. Solano, C. J. P. M. Harmans, and J. E. Mooij, "Observation of the Bloch-Siegert Shift in a Qubit-Oscillator System in the Ultrastrong Coupling Regime", Phys. Rev. Lett. **105**, 237001 (2010).

17) J. Casanova, G. Romero, I. Lizuain, J. J. García-Ripoll, and E. Solano, "Deep Strong Coupling Regime of the Jaynes-Cummings Model", Phys. Rev. Lett. **105**, 263603 (2010).

18) R. Gerritsma, B. Lanyon, G. Kirchmair, F. Zähringer, C. Hempel, J. Casanova, J. J. García-Ripoll, E. Solano, R. Blatt, and C. F. Roos, "Quantum simulation of the Klein Paradox", Phys. Rev. Lett. **106**, 060503 (2011).

19) L. Lamata, J. Casanova, R. Gerritsma, C. F. Roos, J. J. García-Ripoll, and E. Solano, "Relativistic quantum mechanics with trapped ions", to be published in New Journal of Physics (2011).

20) T. Niemczyk, F. Deppe, E. P. Menzel, M. J. Schwarz, H. Huebl, F. Hocke, M. Häberlein, M. Danner, E. Hoffmann, A. Baust, E. Solano, J. J. García-Ripoll, A. Marx, and R. Gross, "Selection rules in a strongly coupled qubit-resonat system", to be published in Phys. Rev. B (2011).

21) B. Peropadre, G. Romero, G. Johansson, C. Wilson, E. Solano, and J. J. García-Ripoll, "Perfect Microwave Photodetection in Circuit QED", submitted to Physical Review A (2011).

22) J. Casanova, C. Sabín, J. León, I. L. Egusquiza, R. Gerritsma, C. Roos, J. J. García-Ripoll, and E. Solano, "Quantum Simulation of the Majorana Equation and Unphysical Operations", submitted to Physical Review Letters (2011).

23) J. Casanova, C. E. López, J. J. García-Ripoll, C. F. Roos, and E. Solano, "Quantum tomography in position and momentum space", submitted to Physical Review A (2011).

24) M. Bina, G. Romero, J. Casanova, J. J. García-Ripoll, A. Lulli, F. Casagrande, and E. Solano, "Solvable model of dissipative dynamics in the deep strong coupling regime", submitted to Phys. Rev. A (2011).

25) J. Casanova, L. Lamata, I. L. Egusquiza, R. Gerritsma, C. F. Roos, J. J. García-Ripoll, and E. Solano, "Quantum simulation of quantum field theories in trapped ions", submitted to Phys. Rev. Letters (2011).

26) D. Ballester, G. Romero, J. J. García-Ripoll, F. Deppe, and E. Solano, "Quantum simulation of the ultrastrong coupling dynamics in circuit QED", submitted to Phys. Rev. Letters (2011).

27) L. Lamata, J. Casanova, I. L. Egusquiza, and E. Solano, "Nonrelativistic limit of the Majorana equation and its quantum simulation in trapped ions", submitted to Physica Scripta (2011).

28) I. L. Egusquiza, C. Sabín, L. Lamata, J. J. García-Ripoll, J. León, and E. Solano, "On Majorana Hamiltonians", submitted to Physical Review Letters (2011).

Other achievements

Invited Viewpoint in online journal APS Physics

E. Solano, "The dialogue between quantum light and matter", Physics **4,** 68 (2011).

Invited Talks and research visits

1) Invited talk at Innsbruck University, Innsbruck, Austria (March 2010)
2) Invited talk at University Paul Sabatier, Toulouse, France (March 2010)
3) Invited talk at CSIC, Madrid, Spain (April 2010)
4) Invited talk at DIPC, San Sebastián, Spain (April 2010)
5) Research visit to Harvard University, Cambridge, MA, USA (June 2010)
6) Research visit to CEA-Saclay, Paris, France (September 2010)
7) Research visit to Walther-Meissner Institut, Garching, Germany (October 2010)
8) Research visit to Innsbruck University, Innsbruck, Austria (October 2010)
9) Invited talk and research visit to Pontificia Universidad Católica del Perú, Lima, Perú (Dec 2010)
10) Invited talk and research visit to University of Zaragoza, Zaragoza, Spain (January 2011)
11) Invited talk and research visit to University "Johannes Gutenberg", Mainz, Germany (March 2011)
12) Research visit to Harvard University, Cambridge, MA, USA (April 2011)
13) Research visit to Oxford University, Oxford, UK (August 2011)
14) Research visit to Bristol University, Bristol, UK (August 2011)
15) Research visit to Imperial College, London, UK (August 2011)

Conference participation and organization

1) Organizer of SOLID Workshop, Bilbao, Spain (February 2010)
2) Workshop “Quantum Effects in Biological Systems”, Harvard University, Cambridge, MA, USA (June 2010).
3) Workshop "Social impact of science, the role of the media", Universidad del País Vasco, San Sebastián, Spain (August 2010).
4) SOLID 2nd Workshop "Interfacing solid-state quantum information systems", invited talk, Munich, Germany (October 2010).
5) Organizer of Workshop "Circuit QED for Quantum Information", Bilbao, Spain (November 2010).
6) Organizer of Workshop "Quantum simulations", sponsored by SOLID, Benasque, Spain (March 2011).
7) Workshop “Quantum Science and Technology”, sponsored by SOLID, member of the Scientific Committee, Rovereto, Italy (May 2011).
8) Central European Workshop on Quantum Optics (CEWQO), invited talk and member of the Advisory Board, Madrid, Spain (June 2011).
9) Workshop "Social responsability of science", Universidad del País Vasco, San Sebastián, Spain (August 2011).

Your assessment of your situation relative to tasks and milestones

The UPV-EHU team is satisfied with the advances in milestones and tasks. Delays and postponed work have to do with new research projects that we have started in three cutting-edge frontlines: quantum propagating microwaves, ultrastrong coupling regime, and quantum simulations in circuit QED. We expect these novel fields to become the dominant ones in the context of quantum information and circuit QED technologies in the very near future.

Table of SOLID Deliverables

Deliverable N°	Deliverable title	WP N°	Nature	Dissemina -tion level	Delivery Date month
D1	Report on Josephson-junction based qubit circuits.	WP1	Report	PU	12,24,36
D2	Report spin-based qubit circuits.	WP2	Report	PU	12,24,36
D3	Report on spin-based qubits in NV-centers.	WP3	Report	PU	12,24,36
D4	Report on hybrid systems and interfaces.	WP4	Report	PU	12,24,36
D5	Report on solid-state quantum technologies.	WP5	Report	PU	12,24,36
D6.1	SOLID kick-off workshop	WP6	Report	PU	3
D6.2	First version of a public and internal SOLID website	WP6	Report	PU	3
D6.3	First technique-orientated summer school	WP6	Report	PU	12
D6.4	Direct training activities available to the consortium	WP6	Report	PU	18
D6.5	Report from SOLID workshop with participation of AQUTE and Q-Essense	WP6	Report	PU	24
D6.6	Report from international conference and SOLID workshop	WP6	Report	PU	36
D7	In-depth critical evaluation of the SOLID progress, in particular concerning systems integration and operation, measured against objectives, milestones, and state of the art.	WP7	Report	PU	12,24,36
D8.1	Intermediate report on scientific progress and management	WP8	Report	PU	6,18,30
D8.2	Annual report on scientific progress and management	WP8	Report	PU	12,24
D8.3	Final report	WP8	Report	PU	36

Table of SOLID Milestones

Milestones Y2 (18-24 months)	18m	24m	36m
WP1			
M1.1 Characterisation and operation of multi-qubit registers (3-6 qubits) with readout of individual qubits coupled through a common oscillator bus. (3 qubits by 18m; 6 qubits by 36m)	M1.1√	M1.1	M1.1
M1.2 Multi-qubit platforms: singleshot QND readout of individual qubits. (18m)	M1.2		
M1.3 Quantitative determination of readout fidelities for 1- and 2-qubit readout for multi-qubit platforms. (24m)		M1.3	M1.3
M1.4 Several platforms will achieve readout fidelity of >> 90% for a single qubit. (18m)		M1.4	M1.4
M1.5 Preparation, readout and tomography of states with 2-4 entangled qubits. (18m)	M1.5		
M1.6 Demonstration and tomographic characterization of universal gate operation on multi-qubit platforms. (24,36m)		M1.6	M1.6
M1.7 Experimental implementationof algorithms and protocols on multi-qubit platforms (Bell mesurements; teleportation; coding; Grover; Deutsch-Jozsa; Iterative Phase Estimation). (24,36m)		M1.7	M1.7
M1.8 Design of a toolbox of resonant two-qubit gates. (18m).	(12m)		
M1.9 Design of high-fidelity qubit readout techniques inspired in quantum-optical concepts. (18m)	(12m)		
WP2			
M2.1 Demonstration of integrated spin qubit functionality in a two-qubit device. (12m)	M2.1√		
M2.2 Decision on whether to use geometric gates in experiments. (12m)			
M2.3 Demonstration of 1 μs single-electron spin dephasing time. (18m)	M2.3		
M2.4 Demonstration of a simple quantum protocol on two spin qubits in quantum dots. (18m)	M2.4		
M2.5 Demonstration of universal spin qubit functionality in a scalable, three-qubit system. (36m)			M2.5
M2.6 Demonstration of electron spin state teleportation between quantum dots. (36m)			M2.6
WP3			
M3.1 Create single color centers in diamond with depleted ^{13}C concentration.	M3.1		
M3.2 Demonstrate coherent coupling between two defects separated by more than 20 nm. (24,36m)		M3.2	M3.2
M3.3 Evaluate coherence time and possibility to reach T1 limit for single spins in isotopically engineered diamond. (24,36m)		M3.3	M3.3
M3.4 Robust deterministic entanglement for small quantum register consisting of 4-8 spins in diamond. (24,36m)		M3.4	M3.4
WP4			
M4.1 Realisation of hybrid systems for quantum information processing on different platforms. (12,24,36m)		M4.1	M4.1
M4.2 Demonstration of the coupling between spin qubits and photonic states (microwave or optical). (24,36m)		M4.2	M4.2
M4.3 Demonstration of the coupling between different types of qubits in hybrid structures. (24,36m)		M4.3	M4.3
M4.4 Demonstration of reversible information transfer in a hybrid structure. (24,36m)		M4.4	M4.4
M4.5 Demonstration of a quantum memory in a hybrid structure, evaluation of the storage performance. (36m)			M4.5
M4.6 Achieve coherent coupling between single NV defect and optical microresonator. (36m)			M4.6
M4.7 Design of multiqubit-multicavity coupling to achieve quantum information tasks. (12m)			
M4.8 Design of sequential protocols for generating multipartite entangled qubits. (24m)		M4.8	
WP5			

M5.1 Development of parametric readout for qubits. (18m) **M5.2** Determination of the dephasing and relaxation rates for the solid-state quantum system with a meta-materials engineered dielectric environment. (24m) **M5.3** Design of metamaterials, in the context of Circuit QED, for implementing realistic microwave photon detectors and photon counters with propagating quantum microwave fields acting on qubit/clusters inside waveguides. (18m) **M5.4** Development of a theory for propagating quantum microwaves interacting with one qubit or more qubits inside waveguides in Circuit QED. (18m) **M5.5** Development of an operational multipartite entanglement characterization and classification for circuit QED. (36m) **M5.6** Spin-photon inter-conversion using solid state nanocavities. (36m) **M5.7** Electrically tunable single dot Nanocavities. (18m) **M5.8** Coherent preparation of hole spin state. **Terminated (Y1 review)** **M5.9** Coupling of NV centers to solid-state photonic structures. (18m) **M510** etermination of the dephasing and relaxation rates for the solid-state quantum system with improved dielectric environment. (18m) **M5.11** Experimental demonstration of lasing with a single flux qubit. (18m) **M5.12** Experimental demonstration of lasing with two qubits coupled to a cavity and/or two cavities coupled to qubit. (36m) **M5.13** Design of protocols for generating and measuring multipartite entangled qubit states inside waveguides. (24m) **M5.14** Design of protocols for generating and reconstructing the state or phase-space representation (e.g., Wigner function) of propagating quantum microwaves. (18m) **M5.15** Design of protocols for the simulation of useful many-body Hamiltonians in circuit QED. (18m) **M5.16** Design of protocols for the simulation of quantum relativistic dynamics in circuit QED. (18m)	**M5.1** **M5.3** **M5.4** **M5.7** **M5.9** **M5.10** **M5.11** **M5.14** **M5.15** **M5.16**	**M5.2** **M5.13**	**M5.5** **M5.6** **M5.12**
WP6			
M6.1 SOLID kick-off workshop. (2m) **M6.2** First version of a public and internal web page. (3m) **M6.3** Technique-orientated summer school (Munich, Oct 2010). (12m) **M6.4** SOLID workshop with participation of AQUTE and Q-Essense (Sept. 2011). (24m) **M6.5** International conference and SOLID workshop (Sept. 2012). (36m)		**M6.4**	**M6.5**
WP7			
M7 Analysis of SOLID progress and formulation of specific recommendations every 6 months.	**M7** D8.1.2	**M7** D8.2.2	**M7** D8.2.3