SQUBIT-2/RSFQubit/EuroSQIP Workshop
12-14 October 2005, Karlsruhe

Abstracts

Wednesday 09:00, Shinichi Yorozu, ISTEC-SRL, JST, and NEC Corporation:

Progress of RSFQ circuits and packaging technology for supporting superconducting qubit in Japan

In this talk, I would like to show recent Japanese activities of RSFQ circuits and packaging technology for qubits.

Qubit control circuits divide into following four functions; driver, read-out, coupler, and control processing. A microwave chopper and a voltage converter were proposed for driver, and a time-to-digital converter was proposed for read-out circuit. Low power consumption circuits have also been investigated for control processing. I would like to discuss them.

It is difficult to integrate both SFQ circuits and qubits into a single-chip, because of the dissipative characteristics of SFQ circuits. Therefore, a multi-chip packaging technology for a qubit control module has been developed. The module consists of SFQ circuit chips, qubit chips, and a substrate all of which are fabricated with Nb and Al technology. The chips are flip-chip bonded with superconducting solder bumps. Characteristics of wiring with bumps were tested by using ring shape circuit. Maximum SFQ pulse throughput is over 100Gbps, which is enough to use.

Wednesday 10:00, Quentin Herr, Northrop Grumman Corp.:

Qubits and RSFQ

The idea of using RSFQ control is as old as the idea of the Josephson-based Qubit. However, present qubit demonstrations are not at the level where RSFQ control is used or required. I will compare the fundamentals of room temperature electronics vs. RSFQ control in terms of noise, heat load, latency, and interconnect density. I then consider the merits RSFQ Delta Sigma ADC technology for state readout. I present two approaches to overcome the extreme low heat load requirements for RSFQ at milliKelvin temperatures: First, packaging that allows the RSFQ circuit to be located at the 1 K temperature stage. Second, unconventional RSFQ circuits that have zero static power dissipation.

Wednesday 11:10, Alexander Zorin and Marat Khabipov, PTB:

Progress report of PTB on SIN junctions and RSFQ circuits

M. Khabipov, D. Balashov, S. Lotkhov, F.-I. Buchholz and A. Zorin

Recently we have proposed the using of Superconductor-Insulator-Normal metal (S-I-N) tunnel junctions as frequency-dependent shunts for S-I-S junctions in RSFQ-qubit circuits. The advantage of these shunts consists in their small zero-voltage-bias damping and, therefore, small noise generated at the characteristic frequencies of a qubit. However, in order to ensure sufficiently large total damping in “S-I-S + S-I-N” system, the damping of S-I-N junction at larger (Josephson) frequencies should be very large, i.e. this junction should have very transparent barrier. We report our experiments on S-I-N junctions made by different methods (multilayer technique and shadow evaporation) from different materials (Nb, Al, AuPd and Cu) with different transparency of tunnel barrier. We show, in particular, that sufficiently transparent barriers (with specific resistance of unit area of 10-30 $\Omega\cdot\mu m^2$) can exhibit at small voltage bias the enhancement of their asymptotic resistance by 1-2 orders of magnitude. This should result in corresponding reduction of noise acting on the qubit.

We also report the development of RSFQ circuit controlling the two-loop flux qubit proposed by CNR group. The core element of this circuit is the T-flip-flop (TFF) cell. A sequence of SFQ pulses arrives at the TFF and causes its switching. The rectangular output current pulses produced in the saving inductance of TFF are converted into flux and applied to both “barrier-height-control” and “asymmetry-control” loops of the qubit with corresponding attenuation. The design of the circuit is optimized for both VTT technology (critical current density j_c = 30 A/cm^2) and PTB technology (critical current density j_c = 100 A/cm^2) and put into production. The operating ranges obtained by this optimization are larger than ± 20% for the current density, ± 25% for bias currents and ± 30% for inductances. The circuits include the test RSFQ circuits coupled to dummy qubit circuits with the aim of conducting a trial of its operation and specifying the strength of inductive coupling both without and with flux transformer. The transformation factors of the coupling transformers will also be measured experimentally. Some possible improvements towards reduction of the output noise of TFFs are discussed. The TFF circuit based on junctions with high-ohmic shunt resistors (giving value of McCumber parameter β_c up to 5) and single low-ohmic resistor connected symmetrically such that it does not contribute to the output noise is optimized and put into production at PTB.

Wednesday 11:35, Anna Kidiyarova-Shevchenko, Chalmers:

Towards development of the RSFQ microwave generator for charge qubit control and digital squid for flux qubit readout.

A. Kidiyarova-Shevchenko, P. Delsing, S. Intiso

Precise control and preparation of the qubit state requires exacting tolerances on the timing and shaping of microwave control pulses. These tolerances, at levels below 100 ps, are at or beyond the limits of commercial technology. Moreover, even if these tolerances are met at room temperature, propagating these pulse through meters of cables, connectors, filters, and

attenuators to the qubit is, at best, extremely difficult. The ultra-high speed of RSFQ offers a potential solution.
Main requirements for RSFQ microwave pulse generator for controlling charge qubit have been evaluated: carrier frequency 2 GHz tunable within ± 200 MHz; linewidth < 2 MHz; output impedance < 50 Ohm; noise temperature 50 mK; amplitude more than 1 mV. In order to meet these requirements we have proposed a circuit consisting of single tone generator, Josephson junction imbedded into RSFQ control gate, latch amplifier and high Q superconducting filter. The critical point is reduction of the linewidth of the Josephson oscillation that can be done with careful thermal design of the RSFQ circuits operated at mK temperature range.
Second part of the talk covers aspects related to sensitivity of the digital SQUID in general and application of this technique for readout of the flux qubit using tunable coupling. Such a scheme allows to decouple RSFQ readout from the qubit in "off" state and to perform very fast measurements by controlling coupling with SFQ pulses.

Wednesday 13.00, Alexander Savin, Helsinki University of Technology:

Thermal budget of superconducting digital circuits at sub-kelvin temperatures

A.M. Savin and J.P. Pekola

Superconducting single-flux-quantum (SFQ) circuits have so far been developed and optimized for operation at or above helium temperatures. The SFQ approach, however, should also provide potentially viable and scalable control and read-out circuits for Josephson-junction qubits and other applications with much lower, milli-kelvin, operating temperatures. The overheating problem becomes important in this new temperature range. We suggest a thermal model of the SFQ circuits at sub-kelvin temperatures and present experimental results on overheating of electrons and silicon substrate which support this model [1]. The model establishes quantitative limitations on the dissipated power both for "local" electron overheating in resistors and "global" overheating due to ballistic phonon propagation along the substrate. Possible changes in the thermal design of SFQ circuits in view of the overheating problem are also discussed.

1. A.M. Savin, J.P. Pekola, D.V. Averin, V.K. Semenov, cond-mat/0509318.

Wednesday 13.50, Alexander Kemp, Universität Erlangen-Nürnberg:

Vortex qubits using microshorts

Alexander Kemp, Astria Price and Alexey V. Ustinov

Physikalisches Institut III, Universität Erlangen-Nürnberg, Erlangen, Germany

We demonstrate classical state preparation and readout using a novel type of vortex qubit implementation, in which a very short section of the insulating barrier of a long annular Josephson junction is made slightly wider. The broader tunnel barrier acts like a microshort, width and length of this

region predetermine the strength of the potential barrier. The height of the potential barrier so created can be tuned during experiments by varying the strength of an applied in-plane magnetic field. We develop a model for the double well potential, based on the one-dimensional sine-Gordon equation, in which the change in vortex rest mass energy due to the wider tunnel barrier is explicitly included.

Wednesday 14.15, Daniel Esteve, CEA Saclay:

Is RSFQ readout of the quantronium possible ?

D. Vion and D. Esteve, Quantronics, CEA Saclay

We have evaluated the requirements and the constraints for the readout of a quantronium qubit using a SFQ comparator. First, the critical current of the SFQ junctions should be comparable to that of the quantronium readout junction, i.e. below one μA, which requires a significant downsizing of the present SFQ. Is it then possible to get sufficient readout sensitivity in order to perform the readout in a measuring time short compared to the qubit relaxation time? And is the induced decoherence in the OFF state small enough? Present estimates show that such a readout based on downsized RSFQ logic would at best be marginal. The new SFQ logic concept recently proposed by A. Zorin, and based on SIN ac shunts in place of R shunts might provide a solution with a better safety margin, but no comparator has yet been operated and tested to provide a clear answer. Alternative strategies have also been considered.

Wednesday 15:05, Carsten Hutter, Universität Karlsruhe:

Inductive coupling in different qubit regimes

Carsten Hutter, Alexander Shnirman, Yuriy Makhlin, and Gerd Schön

We investigate inductive coupling of Josephson qubits. Using a systematic method, we derive an effective Hamiltonian of the system and find its range of validity.
As a first example, we study double junction charge qubits coupled via an oscillator. While for qubits with identical junctions the coupling term commutes with the single qubit terms (at the degeneracy point), this is in general not the case when the qubit is asymmetric. We show however, that for a certain range of parameters commutation can be achieved in a more advanced design by tuning experimentally controllable parameters to special points.
As a second system we consider a flux qubit coupled to a SQUID device, which is included in an LC-circuit. This setup was recently used for non-destructive readout of the flux qubit by the Delft group, and is also planned to be investigated experimentally in the group of M. Siegel in Karlsruhe.

Wednesday 17:10, Olivier Buisson, CNRS Grenoble:

Decoherence processes in a current biased dc SQUID

CRTBT-LPM2C-LCMI, C.N.R.S.- Universit\'e
Joseph Fourier, BP 166, 38042 Grenoble-cedex 9, France

A current bias dc SQUID behaves as an anharmonic quantum oscillator controlled by a bias current and an applied magnetic flux. We consider here its two level limit consisting of the two lower energy states $\left| 0 \right>$ and $ \left| 1 \right> $. We have measured energy relaxation times and microwave absorption for different bias currents and fluxes in the low microwave power limit. Decoherence times are extracted. The low frequency flux and current noise have been measured independently by analyzing the probability of current switching from the superconducting to the finite voltage state, as a function of applied flux. The high frequency part of the current noise is derived from the electromagnetic environment of the circuit. The decoherence of this quantum circuit can be fully accounted by these current and flux noise sources.

Wednesday 17:35, Bertrand Georgeot, CNRS Toulouse:

Realisatic quantum computations

Dima Shepelyansky

(CNRS, Toulouse, France)

http://www.quantware.ups-tlse.fr

Abstract

The results obtained recently in Toulouse node are presented. The effects of static interqubit interactions on the accuracy of various quantum algorithms are analyzed. Extensive numerical simulations show that their effect is stronger compared to external decoherence. Analytical approach based on the Random Matrix Theory is developed. It gives a universal law for fidelity decay induced by interqubit static interactions. This determines the time scale for a reliable quantum computation in presence of realistic static imperfections and external decoherence. A generic quantum error correction method is developed, it allows to eliminate coherent effect of static errors and gives significant increase of fidelity. Dissipative effects for quantum evolution are also discussed.

Thursday 09.00, Daniel Esteve, CEA Saclay :

Towards multiququbit circuits based on the quantronium

F. Nguyen, G. Ithier, N. Boulant, P. Bertet, D. Vion and D. Esteve,
Quantronics, CEA Saclay

The successfull operation of multiqubit circuits faces a series of difficult challenges: the coupling between qubits must be controllable, ideally fully switchable, should not hinder individual addressing of qubits, and should induce the least possible decoherence. Furthermore, the duration of two qubit gate operations should be comparable with that of single qubit operations, and logic gates involving all possible qubit pairs in a circuit are desired. We examine these issues for circuits based on the quantronium qubit, and discuss the implementation of some coupling schemes

Thursday 10:00, Jens Könemann, PTB:

Radio-frequency measurements of Nb charge-phase qubits

J. Könemann, H. Zangerle, R. Dolata, B. Mackrodt, S.A. Bogoslovsky, M. Götz and A.B. Zorin

We have fabricated all-Nb charge-phase qubits by the chemical-mechanical polishing technique and characterised them at temperatures T = 4.2 K and 20 mK. So far the quality of small Nb junctions manufactured by this method (area varies from 60 nm by 60 nm to 100 nm by 100 nm) was evaluated from their dc I-V characteristics which showed rather small subgap leakage current and the characteristic gap voltage close to the nominal value for bulk Nb, i.e. about 1.3 mV. The reliable measurement of Josephson characteristics, in particular, the strength of critical current I_c had been the issue. Inserting of such junctions and transistors into superconducting loop coupled to on-chip Nb tank circuit coil, i.e. the qubit configuration, made it possible to characterise these tunnel structures. To improve the S/N ratio in these measurements the structures were realised in a gradiometer configuration, i.e. both the qubit ring and the coil consisted of two loops connected accordingly. The nominal critical current of individual junctions was about 50 nA that was estimated from the Ambegaokar-Baratoff relation for zero temperature. Due to high critical temperature of Nb the measurements were possible at temperature of 4.2 K. These measurements gave the values of I_c about 20 nA for individual junctions. The observable critical current of Bloch transistors was, as expected, dramatically suppressed (down to 1-2 nA), but still measurable. The radio-frequency measurements of our Nb qubit circuits were also carried out at 20 mK. The ratio of Josephson and charging energies E_J/E_C was found in these measurements to be between 1 and 2. We investigated the ground state of the Bloch transistors with different E_J/E_C ratio value by measuring both the flux and gate-modulation curves (see Fig.1). Our experimental results demonstrate the high quality of our small Nb Josephson junctions: the evaluated critical currents agree within less than 50 % to the theoretical Ambegaokar-Baratoff values. The problem of e-2e behaviour of Nb qubits needs further investigation.

The results of the measurements of the Nb charge-phase qubits will be reported by Jens Könemann.

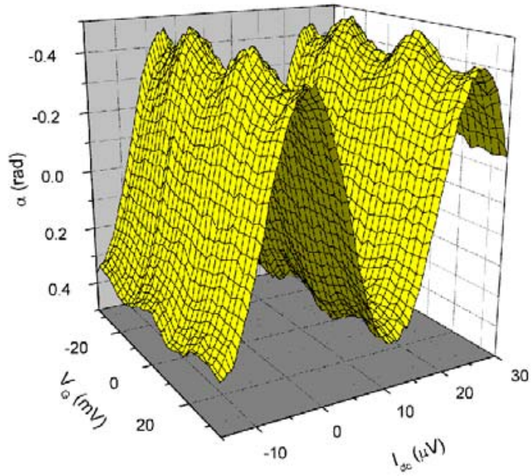

Fig.1. Dependence of the phase shift between the driving signal and oscillations in the tank circuit as a function of flux and gate control signals.

Project status:

The situation in the first part of 2005 was seriously affected by the problem with the dilution refrigerator KelvinOx-400 which is using for the qubit measurements. To conduct the measurements was only possible after repair of the fridge by Oxford, that took significant time and efforts.

The dilution refrigerator (including its malfunctioning parts: root pump, valves and IGH) has been finally repaired by March 2005.
The setup for qubit measurements has been improved by installing new sample box, wiring, cabling, filtering etc. and tested.
The regular measurements were restarted in June 2005. In the meantime, for evaluation of the coherence properties of Nb junctions fabricated at PTB the phase qubit of SQUID configuration were fabricated for measurements in the setup of CNRS (Grenoble).

Technology:
The technology for fabricating the qubits from Nb trilayer sandwich by CMP method was further improved. Structures of gradiometer configuration including single qubits and coupled qubits were fabricated. Generally, Nb qubits are currently fabricated with rather high yield.

Extra: Phase qubits of SQUID configuration were fabricated at PTB and characterized at CNRS (Grenoble).

Measurements:
The Josephson properties of Nb qubits were analyzed at 4.2 K and mK temperatures.
The main parameters of the qubit (E_J and E_c) were derived from measured data and found to be in a good agreement with expected values.

Presentations:
Presentation at “Kryoelektronische Bauelemente 2005, Bad Herrenalb, 9-11 October 2005”, H. Zangerle, R. Dolata, B. Mackrodt, S.A. Bogoslovsky, M. Götz, J. Könemann and

A.B. Zorin, “Characterisation of Nb charge-phase qubit circuits at 4.2 K by radio-frequency method”.
A journal paper describing this experiment is in preparation.

Personnel: Change in staff involved in the project
M. Götz entirely left the laboratory in July 2005,
S. Bogoslovsky who was hired on SQUBIT-2 has finished on August 20, 2005 because of expenditure of the SQUBIT-2 project budget allocated for man-power.
New members – postdoc Jens Könemann, hired on PTB budget from July 2005 and
PhD student Hermann Zangerle, hired on RSFQubit project with deep involvement in qubit measurements.

Thursday 11 :30, Sorin Paraoanu, JyU:

Toward flying qubits in superconducting quantum circuits

Abstract:

I will start by briefly describing our progress in setting up the clean room and the measurement laboratories in the new NanoScience Centre at JyU, which happened during 2005.

A crucial ingredient in future quantum computers are the circuit elements that connect the quantum bits. Recently, there has been a lot of interest in the use of superconducting CPWs (coplanar waveguides) for such purposes. We have started by fabricating a system of coupled Josephson junctions (Fig.1). The circuit can be operated in two ways: we use one junction as an ac-Josephson effect oscillator and excite the other junction (the qubit), or as a system of coupled phase qubits. Our preliminary measurements show that there is indeed an influence in the IV of one junction due to the Josephson radiation emitted by the other junction.

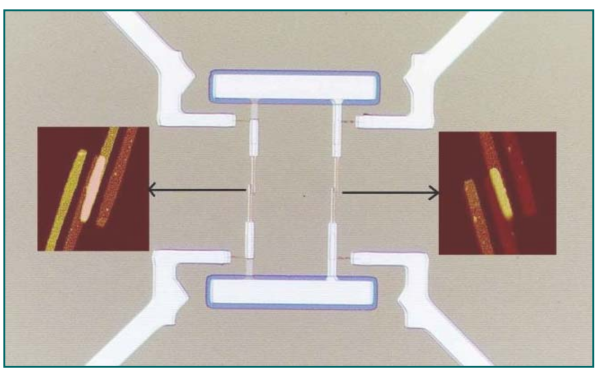

Figure 1. SEM picture of two Josephson junctions coupled through on-chip capacitors and isolated from the external leads by Pt resistors evaporated onto the same chip.

I will also describe the analytical and numerical calculations we are currently doing to understand this circuit.

The next step is to couple the junctions through a CPW resonator instead of the two capacitors. This circuit is in the design stage, and we have tested the fabrication only of the individual components. The junctions are replaced with dcSQUID configuration, so that the qubit energy level separation could be put in resonance or off resonance with the fixed CPW line.

This device could be called a “quantum xylophone”, due to its resemblance with the real musical instrument. A first experiment would be to put one junction in a superposition of the two lowest states and attempting to transmit this state to the other junction (phase qubit).

On the theoretical side, I will describe our progress in understanding the running-wave state of a switching junction used for qubit read-out.

Thursday 15:00, Margareta Wallquist and Göran Johansson, Chalmers theory

Controlled coupling of charge-phase qubits

We have recently presented a circuit for current controlled interaction of loop-shaped SCB-qubits (M. Wallquist *et al*, New J. Phys. 7 (2005) 178, J. Lantz *et al*, Phys. Rev. B 70, 140507(R) (2004)). Lately the charge-phase regime, which is experimentally more tempting, was explored for the SCBs. We found that the entangling qubit operation in principle is unchanged, and qubit read-out by means of current measurement is still possible. We have also looked further into the effects of time-dependent gate voltages on the circuit. Fast changes of the gate voltage may cause MQT in the large JJ which mediates the qubit interaction. For small-amplitude microwave pulses this is not an issue, whereas it puts constraints on the use of trapezoidal gate voltage pulses.

Qubit read-out using the quantum capacitance

In two recent preprints T. Duty *et al* (cond-mat/ 0503531) and M. A. Sillanpaa *et al* (cond-mat/ 0504517) the reactive response of a single Cooper-pair box/transistor is discussed. When inserting the device in a resonant circuit the reactive response shifts the resonance frequency. This shift was detected in the phase-shift of a reflected rf-signal.
Operating the Cooper-pair box as a qubit the sign of the phase shift depends on the qubit state, as also discussed by A. Blais *et al* (PRA **69**, 062320 (2004)). We are analyzing this read-out using the quantum network theory described by Yurke and Denker (PRA 29, 1419 (1984)) and M. Devoret (Les Houches (1995)). This is a work-in-progress report.

Thursday 16:00, Uri Gavish, Innsbruck:

Abstract:

We shall present three on-going projects in cavity-QED based superconducting qubits [Wallraff et al. {\em Nature} {\bf 431}, 162 (2004)] where Cooper-pair boxes are strongly coupled to the quantized field of a transmission line.

1. A coherent control project is aimed at achieving reliable fast state manipulation of the two-qubit system by applying a speed-optimization procedure [Garcia-Ripoll et al., Phys. Rev. Lett. \textbf{91}, 1579011 (2003)] which makes use of the properties of the phase acquired by a coherent state in response to the application of a state-dependent force.

2. The state-transfer project is aimed at achieving ideal

state-transfer by following the proposal of [Cirac et al. Phys. Rev. Lett., {\bf 78}, 3221 (1996)] which enables such a transfer between qubits located inside separate cavities.

3. In a third project we investigate the coupling between rotational states of polar molecules and the electric field in the microwave cavity. The coupling can be used to transfer the quantum state of a charge qubit to the cavity mode and finally to a collective excitation of a molecular ensemble. The molecular ensemble serves as a long-lived quantum memory for the charge qubit state and provides a coherent interface between microwave and optical photons.