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13. ABSTRACT (Maximum 200 words)

The project concentrates on the design, fabrication, implementation and operation of solids state quantum logical elements and circuits for the realization of quantum computers. It utilizes qubits based on circulating persistent currents in superconducting loops containing (three) Josephson junctions.
This Final Report presents the major achievements obtained during the project, highlighting the progress from the initial spectroscopy and first Rabi results on a single qubit to the most recent finding of controlled quantum dynamics of multi-element circuits, controlled-invasiveness state detection, coupled 2-qubit systems, and large increase of coherence by proper circuit layout and parameter control.
It briefly puts these into perspective with respect to the contribution of Persistent Current Qubits to the development of quantum information processing based on solid state devices.

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(First Sheet)

Tools for Persistent-Current Qubits

(DAAD19-01-1-0548)

1. Foreword.

Project DAAD19-01-1-0548, denoted “Tools for Persistent-Current Qubits”, is part of a broad research activity supported by ARO which concentrates on the development of Quantum Information Processing. The central aim of the effort is to answer the question: “Is it possible to realize a quantum computer; and if so, how can this be accomplished”. It encompasses a wide range of fields. One of these focusses on the use of Solid State devices for this purpose. Within this field the superconducting implementation is a central player.

This Final Report, covering the full running periode of May 2001 until Februari 2004, presents the major achievements obtained during the project on Superconducting Persistent Current qubits, based on the use of multiple Josephson junctions configured in a closed loop topology. It highlights the progress from the initial spectroscopy and first Rabi results on a single qubit to the most recent finding of controlled quantum dynamics of multi-element circuits, controlled-invasiveness state detection, coupled 2-qubit systems, and large increase of coherence by proper circuit layout and parameter control.
It puts these into perspective with respect to the central question of the ARO program, highlighting the contribution of Persisten Current Qubits to the development of quantum information processing based on solid state devices.

2. Table of Contents: ---

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4. Statement of the Problem studied.

The project aims at the design, fabrication, implementation and operation of solids state quantum logical elements and circuits for the realization of quantum computers. It focusses on qubits based on circulating persistent currents in superconducting loops containing three Josephson junctions. It includes key aspects such as the origin of decoherence and its reduction, the role of the measurement on the quantum processes, the definition and manipulation of qubit-qubit coupling, all in view of optimizing solid state elements and circuits for real world applications.
Based on initial realistic estimations and by now strongly endorsed by the results acquired inside (and outside) the project we feel that this superconductive implementation of a solid state qubit has the best potential to lead to real-world quantum computing elementary units, configurable in complex circuits that can be controllably designed and fabricated, thus providing good scalability capability.

5. Scientific Progress and Accomplishments.

The project aim is strongly based on and directed to the well known DiVincenzo criteria list. These requirements have been summarized in the by now rather famous “List of Five Conditions”, comprising: Robust representation; Scalability; Universal set of gates; Well defined initial state; and, hi-fidelity result state measurement. Sometimes this list is augmented with two additional criteria related to the coupling of stationary and flying qubits, ascertaining the ability for quantum computers to communicate over appropriate distances.

Our superconducting qubit implementation is a loop comprising three Josephson junctions, fabricated in Al-AlOx-Al using e-beam lithography and two-angle shadow evaporation. If approximately half a flux quantum is applied to the loop containing the junctions, it acts as a 2-level system. Varying the flux controls the level separation. Given the large ratio between the Josephson coupling energy E_J and the charging energy E_C charge fluctuations will have a neglibable effect on the dynamical properties of our qubit. In this flux-bias region a quantum superposition of the two basic states can be set up, and the states can be distinguished by their associated circulating persistent current. The circulating current generates a flux that can be detected by a nearby DC-SQUID magnetic detector, either in a switching threshold way or using a non-switching dispersive approach. Quantum state manipulation is performed by the application of radiation inducing transitions: in this case we need magnetic microwave fields at a frequency resonant with the level splitting. The precise superposition state is controlled by the microwave amplitude and duration, as applied during the actual quantum manipulation or computation stage.

a. When the project started (May 1, 2001), the Delft group had succeeded in demonstrating the design and fabrication of single superconducting persistent current qubits, showing clear spectrocopic properties well

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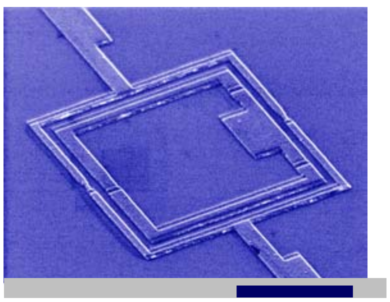

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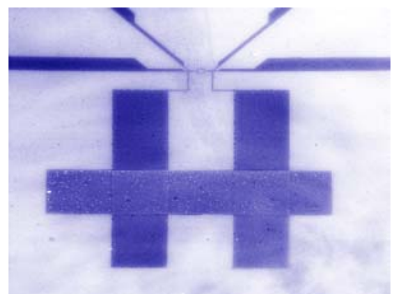
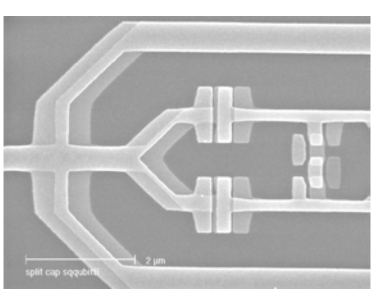


in agreement with theory (1.). Detection was performed by a DC SQUID switching threshold detector of very limited discriminating power. The spectroscopic peaks and dips were very broad, indicating significant decohering influences and rather short dephasing times.

Based on these findings, during the first year of the project (mid 2001 until mid 2002) we initiated efforts to ***structure the local electromagnetic environment***, in order to enhance the coherence. For that purpose on-chip capacitors were implemented (2.). Using a simple pulsed excitation and detection scheme, we demonstrated fairly long relaxation times ***T_1, up to ~ 2 μs***. This was presented at the QCPR in 2001.

During 2002 developments started to accelerate. Based on a different design with enhanced qubit-SQUID coupling (3.) we demonstrated coherent dynamics, showing ***Rabi and Ramsey*** results (4.). Typical time scales amounted ***T_{Rabi} ~ 200 ns and T_2 ~ 20 ns.*** In addition we succeeded to fabricate a ***coupled 2-qubit circuit*** (6.) and ***spectroscopic*** experiments (7.) on this system clearly showed ***qubit-qubit coupling.*** Some of these results have been presented at the August 2002 QCPR review meeting held in Nashville.



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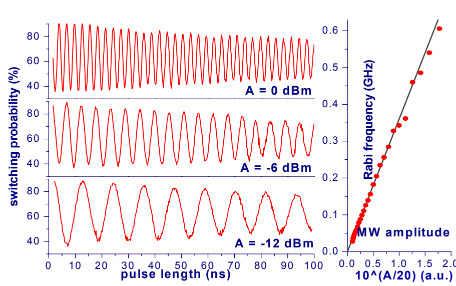

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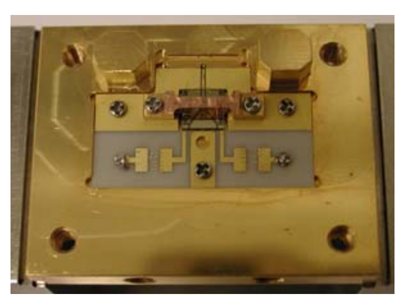

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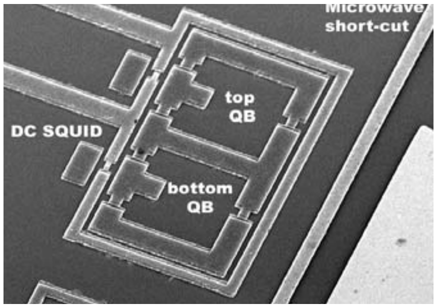

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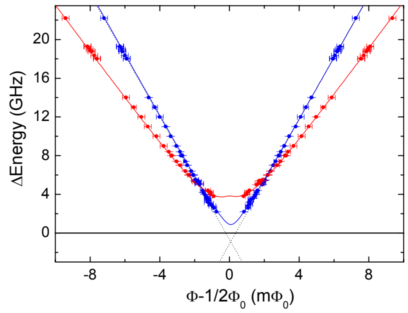

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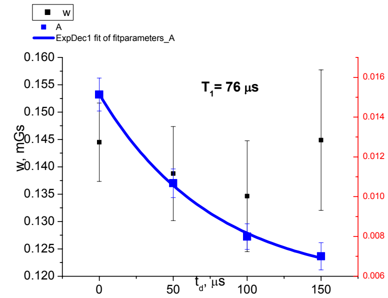
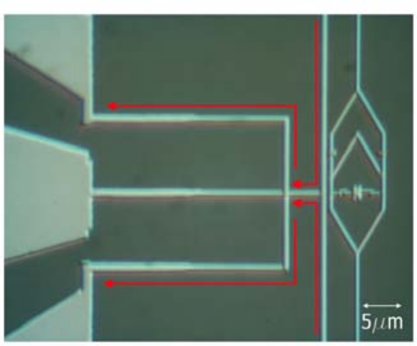


8.

In the next period (mid 2002 to mid 2003) progress persisted. Qubit state detection being a central tool in a QCPU, we investigated a ***new approach of qubit state detection.*** Using the DC SQUID as a flux-sensitive inductor, we could employ non-switching detection. We demonstrated a ***very large relaxation time $T_1 \sim 70\ \mu s$*** for a small tunnelgap qubit (8.). The method bears great potential for low-backaction (and so small excess decohering) state detection. The work on the single qubit evolved, by adding echo results. A ***two-fold increase from T_2 to T_2^**** was found. This limited improvement for some time remained a puzzle. In an additional effort to reduce decoherence we obtainded the first results on a ***gradiometer-type 3-junction qubit*** (9.). Being an implementation of a decoherence free subspace (DFS), we obtained the first spectroscopic data, although rather weak. These and other results have been presented at the August 2003 QCPR review meeting held in Nashville.

The continuation period (mid 2003 - beginning 2004) led to at least three key results. First, an addional detection method was tested based on ***resonantly enhanced tunneling*** of the DC SQUID, using selective excitation of the SQUID at the moment of detection. A clear ***increase of the fidelity*** was obtained. Also during this period we succeeded in taking a leapfrog step in ***coupling a 3-junction flux qubit*** to a ***DC-SQUID based harmonic oscillator***; demonstrating ***controlled conditional quantum dynamics*** of this composite multi-element system from Rabi and Ramsey (10.). The short dephasing time of ~ 5 ns was fully attributable to the low-Q SQUID harmonic oscillator. This approach is felt to be an ***extremely attractive and versatile***, as also multiple qubits can easily be coupled to the harmonic oscillator, despite its very limited size and consequential strong protection towards external decoherence. Selective temporal qubit tuning relative to the oscillator provides the essential ingredient for ***controllable coupling***. Next, in an effort to suppress intrinsic fluctuators in the Al-AlOx junction system, we in the same period had some first results on tri-layer grown materials using etching (11.) and (12.).



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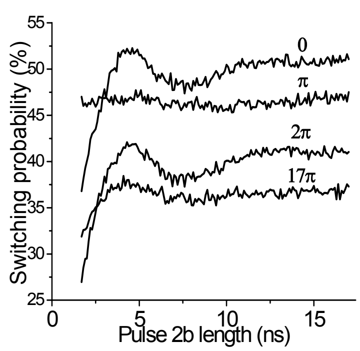

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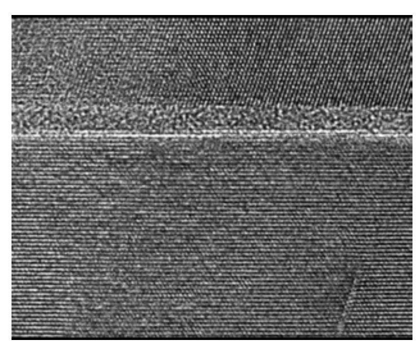

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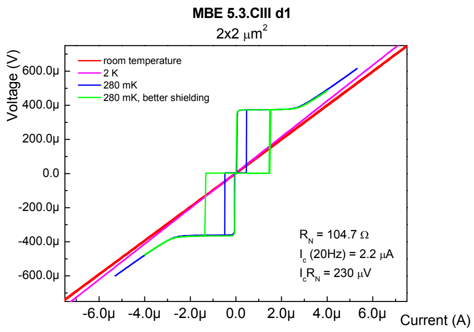

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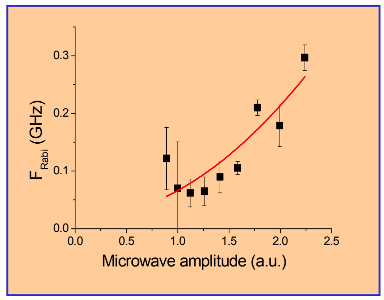

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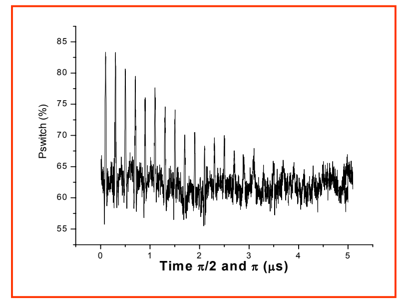

14.

During the final period (untill mid 2004) two important steps were taken. First, we succeeded in showing ***Rabi dynamics using the dispersive detection*** method (13.); the non-linear behaviour is presently not understood. Secondly, we found a method to dramatically enhance the coherence by introducing a ***2-parameter qubit tuning scheme***, with the aim of optimally decouple the qubit from all environmenatl fluctuations. Its effect was vividly demonstrated by the ***very strong (> 10x) enhancement of the echo coherence time*** T_2^* compared to the Ramsey free evolution decay time T_2. The ***crucial conclusion*** that could be drawn from this result is that the majority of the current dephasing originates from external instrumental noise and ***not from an (material/system) intrinsic source***. This conclusion, if confirmed by additional experiments, holds, it is ***one of the most important results*** obtained during the runtime of the project! Part of this work was presented at the QCPR meeting held in August 2004 in Orlando.

b. Based on the progress reported above, the status of the work on superconducting persistent-current qubits (PCQBs) can be summarized as follows.

1. Strong evidence that the major source of decohering fluctuations is ***extrinsic***.

2. ***High frequency fluctuations*** yield a ***small*** contribution in the current level of dephasing.

3. Intial characteric time scale values, at the beginning of the project

   $T_1 \sim 2$ μs $T_{\text{Rabi}} \sim$ -- $T_2 \sim$ -- $T_2^* \sim$ --

   Present characteristic time scale record values

   $T_1 \sim 70$ μs $T_{\text{Rabi}} \sim 500$ ns $T_2 \sim 400$ ns $T_2^* \sim 4$ μs

4. 2-qubit circuit spectroscopy, in very good agreement with calculations.

5. ***Qubit-harmonic oscillator coupled conditional*** quantum dynamics demonstrated.

6. ***Dispersive qubit state detection*** demonstrated.

Taking these results, it seems evident that superconducting persisten current qubits are among the leading ones in solid state, in (multiply) demonstrated operation at or close to the DiVincenzo criteria. More importantly, the recent findings stress the great addional potential for still further large progress in terms of coherence, flexibility and complexity.

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6. List of all Publications and technical Reports

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Nondestructive readout for a superconducting flux qubit, A. Lupascu, C.J.M. Verwijs, R.N. Schouten, C.J.P.M. Harmans and J.E. Mooij, accepted by PRL.
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Detection of a persistent current qubit by resonant activation, P. Bertet, I. Chiorescu, C.J.P.M. Harmans and J.E. Mooij, submitted to PRB-RC
Spectroscopy on two coupled flux qubits
J.B. Majer, F.G. Paauw, A.C.J ter Haar, C.J.P.M. Harmans and J.E. Mooij, submitted to PRL.

Theses:
Caspar van der Wal, Quantum Superpositions of Persistent Josephson Currents, Ph.D. thesis, Delft University of Technology, 2001.
J. B. Majer, Superconducting Quantum Circuits, Ph. D. Thesis, TU Delft, (2002).

7. Participating scientific Pesonnel

Dr. J. Erroms

8. Reports of Inventions

No such reports

9. Bibliography: ---

10. Appendixes: ---