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Cécile Grèzes

Towards a Spin-Ensemble Quantum Memory for Superconducting Qubits

Design and Implementation of the Write, Read and Reset Steps

Doctoral Thesis accepted by
the University of Paris VI, France

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Supervisor's Foreword

The research project described in Cécile Grezes's Ph.D. thesis takes place within a large effort worldwide to build a new type of machine called a quantum computer. A quantum computer relies on registers of quantum two-level systems called qubits, which obey the laws of quantum physics. By placing the qubit registers in complex superpositions of quantum states according to the rules of a quantum algorithm, a quantum computer can implement certain tasks more efficiently than a classical machine, such as factorizing large numbers or simulating interacting quantum systems. Because of their coupling to a fluctuating environment, qubits placed in superpositions of states retain their quantum coherence only during a finite time; this coherence time defines the longest calculation that can be performed with the computer. Electrical circuits made in superconducting metallic electrodes and incorporating tunnel junctions, cooled at millikelvin temperatures in a dilution refrigerator, are among the most promising qubit candidates nowadays, with demonstrations of elementary processors including up to 10 qubits. However, the coherence time of superconducting qubits is presently too short (few tens of microseconds) to hope building a truly operational large-scale quantum computer.

A new research direction emerged in 2008 to solve this issue, when several theorists proposed to combine superconducting qubits with other quantum systems having much longer coherence times which would serve as quantum memory and could thus extend the time allowed for a quantum computation. It rapidly appeared that ensembles of electronic spins in a solid could be well suited for this idea. When embedded in ultra-pure crystals, spins can have coherence times reaching seconds or hours. In our group, we started an experimental effort to build a quantum memory using an ensemble of nitrogen-vacancy (NV) centers in diamond. NV centers consist of a substitutional nitrogen atom sitting next to a vacancy of the diamond lattice; their ground state has a spin degree of freedom with a demonstrated coherence time up to 1 second, which is thus promising to store quantum information.

When Cécile arrived in the group to work on this project for her Ph.D., early initial steps had been taken by postdoc Yuimaru Kubo, who had demonstrated spectroscopically the coherent coupling of an ensemble of NV centers to microwave photons in a superconducting resonator. However, the design and realization of an operational quantum memory remained very far from reach, and this was precisely the Ph.D. subject of Cécile. As a first step of her thesis work, Cécile was involved in a collaboration with theorists from Aarhus University in Danemark. This made possible to devise a complete quantum memory protocol and to calculate its fidelity for realistic parameters. The protocol includes a "write" step during which the quantum state is transferred from a superconducting qubit into the spin-ensemble memory, and a subsequent "read" step triggered by complex sequences of microwave pulses to recover the state after storage.

The first experiment demonstrating the "write" step was a success, in which Cécile was actively involved at the beginning of her Ph.D. But the most experimentally challenging part was the implementation of the "read" step of the protocol. Indeed, it required the combination of spin-echo techniques borrowed from magnetic resonance, with optical irradiation to actively reset the spins in their ground state between experimental sequences, all the experiment being cooled at millikelvin temperatures. Cécile took the lead in this experimental effort. Thanks to her dedicated work, insight, and talent, she obtained several remarkable results, which culminated with the first demonstration of the storage of a microwave pulse at the single-photon level into the NV ensemble memory, and its retrieval 100 microseconds later by a spin-echo sequence. This is a landmark result for this field, which opens the way to realistic quantum memory implementations in a near future. As a recognition of the significance of her work, Cécile was asked to give an invited talk at the Americal Physical Society 2015 March meeting, and she received the Madeleine Lecoq prize from the French Academy of Sciences.

Cécile's Ph.D. manuscript contains a detailed account of this work, from the description of the quantum memory protocol up to the experimental implementation of most of its building blocks. It also includes a chapter which summarizes all the theoretical aspects needed to understand this complex system involving superconducting qubits, resonators, ensembles of spins, microwave and optical photons. I believe this manuscript will constitute a reference for people interested in the field, and I am very glad to see it published.

Paris, France
May 2015

Prof. Patrice Bertet

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First of all, I would like to thank my supervisor Patrice Bertet without whom none of the work presented here would have been possible. I am very grateful for the opportunity he gave me to be involved in his research, as well as for his invaluable scientific advice and availability for discussions. Thanks also to:

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This work is the result of many theory-experiment collaborations, and my thanks intrinsically go well beyond the Quantronics group to all who contributed to this project.

Last, thank you to my father Yannick for encouraging me through all of my studies, Nabiha—although constantly travelling through the most remote parts of the planet—and Parichat for your unconditional support during the writing of this thesis.

Abstract

Processing quantum information requires quantum-mechanical systems with long coherence times and that can be easily coupled together to perform logic operations. Superconducting qubits are well suited to perform the rapid logic gates since they couple very strongly to microwave fields, but have coherence times limited so far to tens of microseconds. This limitation has motivated proposals to combine them to a physical system better protected against decoherence. In this hybrid architecture, a memory provides the long-lived register of N quantum states and a few-superconducting qubit processor performs qubit gates to create multi-qubit entanglement. The implementation comes however with new challenges. The multi-qubit register must be able to store N quantum states (*write*), retrieve each of them on-demand (*read*), and be re-initialized between successive experimental sequences (*reset*).

This thesis work discusses the development of these three memory operations in a hybrid quantum circuit, in which collective degrees of freedom of an ensemble of NV center spins in diamond are used as a multimode quantum memory for superconducting qubits. In the first part of the thesis, I present the details of our quantum memory protocol. It relies on the coupling of the NV ensemble to a resonator with tunable frequency and quality factor. Incoming quantum states are written by resonant absorption of a microwave photon in the spin ensemble, and then read out of the memory by applying a sequence of control pulses to the spins and to the resonator. The second part of the thesis reports our experimental efforts towards the implementation of this protocol, which requires a combination of the most advanced techniques of superconducting quantum circuits and pulsed electron spin resonance.

The *write step* of the protocol is demonstrated in a first experiment by integrating on the same chip a superconducting qubit, a resonator with tunable frequency, and the NV ensemble. Arbitrary qubit states are stored into the spin ensemble via the resonator. After storage, the resulting collective quantum state is rapidly dephased due to inhomogeneous broadening of the ensemble and a refocusing sequence must be applied on the spins to bring them to return in phase and to re-emit collectively the quantum state initially absorbed as an echo. In a second experiment, we demonstrate an important building block of this read-out operation, which consists in retrieving multiple classical microwave pulses down to the single photon level using Hahn echo refocusing techniques. Finally, optical repumping of the spin ensemble is implemented in order to reset the memory in-between two successive sequences.

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