Toward robust hybrid quantum bits

Patrice Bertet, Denis Vion, and Daniel ESTEVE
Quantronics, Service de Physique de l'Etat Condensé, CEA-Paris-Saclay,
CEA, CNRS, UPSay,
91191 Gif-sur-Yvette, France

***Abstract*—This paper introduces the architecture challenge for making a quantum processor, and discusses new routes for obtaining robust superconducting quantum bits, in particular the hybrid systems combining superconducting circuits and spins investigated in Quantronics.**

Keywords:quantum computing, superconducting quantum bits, spins, microwave resonators, ESR.

I. QUANTUM COMPUTING

Using a quantum hardware for computing scrambles the complexity classes of numerical problems compared to those for sequential computers manipulating classical bit registers [1]. This discovery made in the early 1980s triggered an intense research of physical systems suitable for making a quantum processor. Implementations in numerous fields of physics where controlling individual quantum systems has been achieved are now aiming at this goal. A blueprint of the standard design considered for making quantum processors is sketched in Fig.1 in the simplest case. A two-quantum bit (qubit) register can perform any unitary evolution using a universal set of gates and be read in the computational basis when needed. The main challenge is to perform the desired unitary evolution with the needed accuracy despite gate errors and decoherence arising from the unavoidable coupling between the qubits and their external environment. Manipulating the qubits and being able to read their quantum state indeed requires to couple them to the external world.

An essential figure of merit of a qubit platform is the number of gate operations that can be performed before a detrimental error occurs. This sets the maximum length of quantum algorithms that can be implemented without performing quantum error correction.

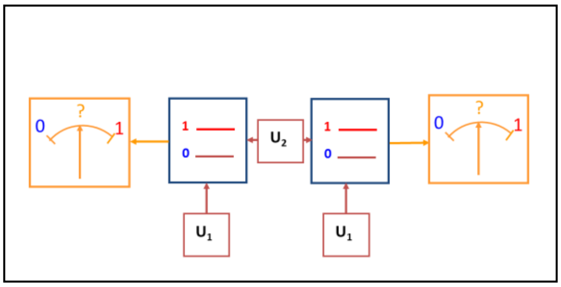

Fig. 1.. Blueprint of a digital quantum processor. Quantum bits (two-level systems) are manipulated using a universal set of qubit gates U_1 and U_2. Each quantum bit can be read and reset.

II. THE SCALABILITY CHALLENGE

A. Resource needs

Any quantum algorithm is characterized by the resources it needs in terms of number of qubits. Whereas simulating the dynamics of N interacting quantum two-level systems does not require more qubits, solving any of the computationally hard tasks of interest often requests a huge number of qubits [1]. For factoring a number N, the celebrated Shor's factorization algorithm requires about $(\ln N)^3$ qubits, which yields to about 10^8 qubits for the largest RSA number already factorized after a few years of collective effort. This explains why computing tasks that would provide a quantum advantage without requiring so huge resources are sought after. Computational quantum chemistry [2] is interesting in this respect since it requires a relatively small number of qubits, about one hundred for providing a quantum advantage over classical computers. Given that present day super-computers are able to simulate a quantum processor with up to 40-50 qubits, the above considerations indicate that the interesting range of qubit resources needed for performing useful tasks is at least of about one hundred logical qubits, but that most of the interesting tasks one would wish to address request a much larger number. Other implementations of quantum computing concepts, such as measurement based quantum computing [3], also request large resources. In the case of quantum assisted annealing, that can be seen as a weak form of adiabatic quantum computing [4], one estimates that about five thousand qubits are requested for providing quantum advantage over classical computers. Note that getting a quantum advantage does not mean delivering the full quantum speed-up expected from quantum computing.

B. Quantum error correction

The qubits mentioned above are ideal logical qubits, i.e. physical qubits corrected by a suitable quantum error correction scheme. The textbook schemes for correcting quantum errors [1] request an error threshold for all qubit operations in the 10^{-5} range, which is considered as too difficult to reach for the large platforms mentionned above. Different approaches are considered for addressing the scalability issue.

The support of the ERC grant CIRQUSS is gratefully acknowledged.

C. *The fault-tolerant surface-code approach*

Fault-tolerant processor architectures compatible with the effective sub 1% error threshold reached by different implementations including superconducting qubits, have been proposed.

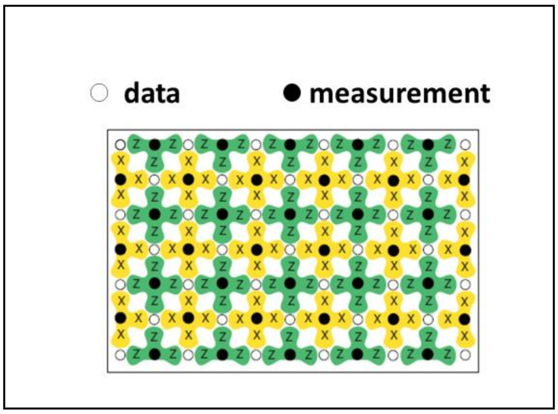

Fig. 2. Sketch of a surface-code array. Data and measurement qubits are coupled by CNOT and SWAP gates. Measurement qubits have two flavors: green and yellow, for measuring to two different error syndromes of thie neighboring qubits without projecting them. The error syndrome measurement outcomes are used for modifying the subsequent execution of the quantum algorithm with no need to correct the qubits. Figure taken for ref. [5].

The surface-code architecture [5] sketched in Fig. 2 consists of a fabric made of data and measurement qubits coupled in two different ways. A logical qubit is obtained by removing some qubits from an array in order to keep two unconstrained degrees of freedom equivalent to a single logical qubit. Surface-codes or their variants based on the same concept of topological robustness request a huge resource overhead, 10^3 to 10^4 physical qubits for each logical qubit according to ref. [5]. A processor architecture compatible with the surface-code approach was recently proposed in [6] for qubits based on CMOS transistors such as those demonstrated in [7], a route compatible with microelectronics fabrication.

D. *Back to square one ?*

Given quantum error correction is a formidable roadblock and fault-tolerant architectures extremely demanding in terms of resources, mitigating the detrimental effects of decoherence is a route worth being investigated, even if it does not solve the whole problem. This means exploring new routes for making more robust qubits.

III. ALTERNATIVE QUBIT DESIGNS

A. *Dissipation engineered cat-qubits in a high Q microwave resonator*

A rather surprising route for making robust qubits is based on dissipation engineering. By imposing a dominant dissipation process felt by a quantum system, one can maintain it inside a given computational subspace of its Hilbert space, record the other uncontrolled dissipation processes that may occur, and correct them as needed. Schrödinger cat states made of coherent states of a high quality factor microwave resonator have been proposed in [8] for making robust logical qubits. The multiphoton dissipation imposed by a suitable pumping scheme does not affect the qubit states, and the detrimental single photon decay events that occur can then be detected using photon number parity measurements in the resonator. Preliminary results have reached the breakeven point and improved the coherence time of the resonator, which demonstrates the potential of this route [9].

B. *Hybrid systems*

Among the degrees of freedom considered for making qubits, nuclear spins with long coherence times are appealing. Although NMR based quantum computing has been abandoned because of its lack of flexibility, the progress achieved in circuit quantum electrodynamics for manipulating superconducting qubits has open the new route of hybrid systems that combine spins and superconducting circuits.

IV. HYBRID SPIN SUPERCONDUCTING QUBIT CIRCUITS

Although the scheme we propose is rather general, we only discuss here the ^{28}Si:^{209}Bi system [10], see Fig.3, of Bi impurities implanted in nuclear spin-less silicon 28. Here, a pair of hyperfine levels $|F,m_F>$ could define a two-level system, possibly suitable for making a qubit.

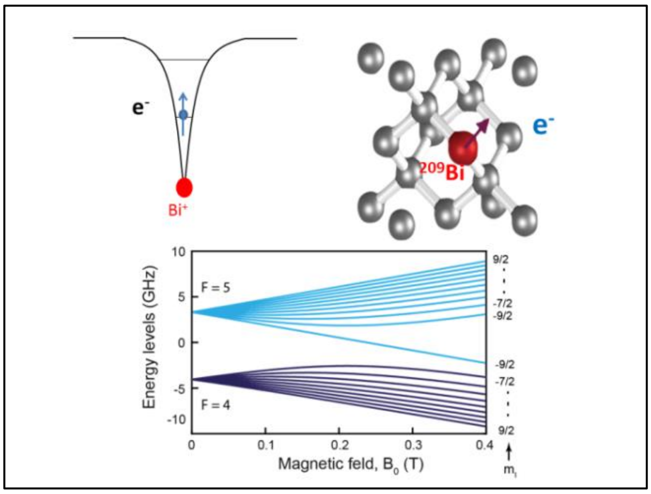

Fig. 3. Level scheme of a Bi impurity in nuclear spin-less silicon 28. The hyperfine levels of the electronic states coupled to the I=9/2 Bi nucleus have a 7.35 GHz zero-field splitting.

A. *An electronic-nuclear spin system coupled to a Flux qubit*

We have already demonstrated that an ensemble of electronic spins coupled to a microwave resonator can provide a quantum memory for a superconducting transmon qubit [11].

We now consider a hybrid system consisting of a single electronic-nuclear spin system magnetically coupled to the loop of a flux qubit embedded in a LC resonator, as sketched in Fig. 4. This coupling scheme has the potential to reach the large coupling regime between the spin system and the Flux-qubit [12-13]. The LC resonator is itself placed inside a microwave cavity for probing it by transmission or reflection measurements.

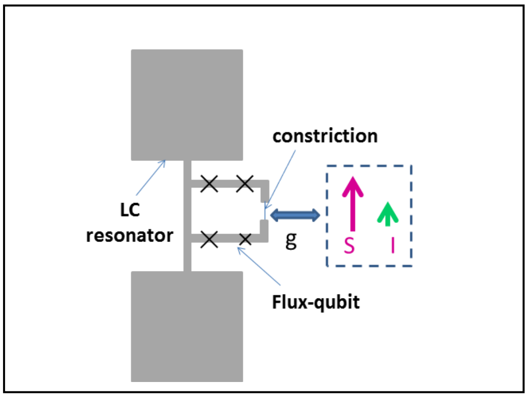

Fig. 4. A combined electronic-nuclear spin system is magnetically coupled to the loop of a Flux qubit embedded in a LC microwave resonator. The strong coupling regime is obtained by placing the spin system very close to the flux qubit loop (15 nm).

B. *A flexible quantum system*

Is such a system well suited for making a qubit ?

Coherence and relaxation. The coherence properties of an electronic-nuclear spin system in a nuclear spin-less material can be excellent, but the spin relaxation time may become excessively long at low temperature. Controlling spin relaxation is thus a critical issue. We have recently demonstrated on the Bi:Si system that coupling strongly electronic spins to a resonator can make electromagnetic spin relaxation by photon emission in the external circuit, namely the Purcell effect, the dominant and furthermore controllable relaxation mechanism [14].

Qubit manipulation. Spin state preparation can be performed by first resetting the Flux-qubit, preparing it in the desired state, and swapping this state with the Bi:Si spin system. Single qubit operations can be performed by driving the spin system through the Flux qubit as discussed in [13].

Entangling spin systems. Different schemes are possible for entangling spins, which would provide the basis for spin-spin gate operation. When two spin systems are in strong coupling regime with the same flux-qubit, spin-spin entanglement can be obtained through the Flux qubit.

Qubit readout. Assuming the hyperfine qubit transition is tuned in resonance with the flux qubit prepared in its ground state for the duration of a SWAP operation, measuring the flux qubit state afterwards by probing the LC resonator implements qubit readout. This has not yet been achieved, but we have already investigated Flux qubits coupled to a LC resonator placed inside a microwave cavity [15].

V. A SPIN-OFF TECHNOLOGY: ULTIMATE ESR

A direct spin-off technology of this research is ultrasensitive ESR. Preliminary results on the ^{28}Si:^{209}Bi system in which a small electronic spin ensemble is coupled to the nanowire forming the inductor of a superconducting resonator have already yielded an improvement by more than four orders of magnitude of ESR sensitivity [16]. This gain can be attributed to the use of high Q and low mode volume superconducting resonators fabricated just on top of the electronic spins implanted in silicon, and of a home-made Josephson parametric amplifier [17] that adds the minimum noise to the signal authorized by the the laws of quantum physics, a nowadays ubiquitous device in superconducting qubit research.

ACKNOWLEDGMENT

Contributions of the past and present Quantronics group members are gratefully acknowledged.

REFERENCES

[1] M. A. Nielsen and I. L. Chuang, Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information* (Cambridge University Press, Cambridge,(UK, 2000).

[2] A. Asparu-Guzik *et al*., Science **309**, 1704 (2005).

[3] R. Raussendorf; D. E. Browne and H. J. Briegel, Phys. Rev. A. **68** 022312 (2003).

[4] E. Fahri *et al*., Science **292**, 472 (2001).

[5] Austin G. Fowler *et al*., PRA **86**, 032324 (2012).

[6] M. Veldhorst *et al*.,.,, ArXiv 1609.09700.

[7] R. Maurand *et al*., Nature Communications, **7**, 13575 (2016).

[8] M. Mirrahimi *et al*. NEW JOURNAL OF PHYSICS, 16, 045014 (2014).

[9] L. Sun *et al*., Nature **511**, 444 (2014).

[10] R.E. George *et al.*, Phys. Rev.Lett. **105**, 087601 (2010).

[11] Y. Kubo *et al.*, Phys. Rev.Lett. **107**, 220501 (2011).

[12] D. Marcos *et al.*, Phys. Rev. Lett. **105**, 210501 (2010).

[13] T. Douce *et al.*, Phys. Rev. A. **92**, 052335 (2015).

[14] A. Bienfait *et al*., Nature **531**, 74 (2016).

[15] M. Stern *et al*., Phys. Rev. Lett. **113**, 123601 (2014).

[16] A. Bienfait *et al*., Nature Nanotechnology **11**, 253 (2016).

[17] X Zhou *et al*., Phys. Rev B, 89, 214517 (2014) and refs. Therein.