

Implementing a quantum memory at microwave frequencies with Bismuth donors in silicon

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Superconducting circuits: how to implement qubits and gates ?







Quantum superconducting circuits

Quantum mechanics with microwave circuits

First brick: microwave harmonic oscillator

100 pH - 15 nH 50 fF - 2pF $\omega_0/2\pi = 3-10 \text{ GHz}$





Reaching the quantum regime ?



Dilution refrigerator

Different flavors of oscillators : bulk type

We need long-lived states

⇒ use superconducting materials
⇒ low temperature for best quality factor

Aluminum 3D cavity (T_c = 1K) 99.999% purity



 $T_{decay} = 1.6 \text{ ms}$ $Q = 5 \times 10^7$

Niobium half elliptical cavity ($T_c = 9.2K$)



O. Milul et al., *arxiv* 2302.06442

Different flavors of oscillators : planar type

Tantalum distributed planar resonators ($T_c = 4.4 \text{ K}$)



$$T_{decay} = 19 \ \mu s$$

 $Q = 1.1 \ 10^{6}$

NbTiN lumped resonators ($T_c = 13 \text{ K}, B_0 = 1 \text{ T}$)



 $T_{decay} = 16 \ \mu s$ $Q = 6 \ 10^5$

Superconducting qubit



Non-linear LC oscillator





transitions observed in 1980's [Berkeley & Saclay] strong coupling regime of CQED in 2004 [Yale]

 $\hbar\omega_0$

Superconducting qubit



strong coupling regime of CQED in 2004 [Yale]





Superconducting qubit: control



Superconducting qubit: control



Superconducting qubit: coherence

Energy relaxation (T₁)



Superconducting qubit: coherence



Typical setup





Zoology and lifetimes



E. Hyyppä et al., *Nat. Comm.*, 2022

Kjaergaard et al., Ann Rev Cond Matt Phys, 2020

Examples of two qubit gates : SWAP gate



Conner et al., Appl. Phys. Lett. (2021)



Conner et al., Appl. Phys. Lett. (2021)

Only hope for viability : quantum error correction



Google Quantum Al

1 cycle = $1.1 \, \mu s$

Bosonic codes



Redundancy given by usage of multiple Fock states



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Storing qubits' quantum states

Reduce the number of processing qubits in a quantum computer



Factoring 2048-bit RSA Integers in 177 Days with 13 436 Qubits and a Multimode Memory, Gouzien & Sangouard, *PRL* (2021)

Quantum memory hierarchies: Efficient designs to match available parallelism in quantum computing, Thaker et al., Symposium on Computer Architecture (2006).

Enable long-distance communication



The quantum internet, H.J. Kimble, Nature (2008)

Ideal candidate : Bismuth donors in silicon



Nuclear spin I = 9/2

Ideal candidate: Bismuth donors in silicon



Ideal candidate: Bismuth donors in silicon

Energy levels at 65.6 mT



Bismuth donors in silicon













Regime of interaction given by cooperativity

$$C = \frac{4 g_{\rm ens}^2}{\kappa_{\rm a} \Gamma} = \frac{4 N g_0^2}{\kappa_{\rm a} \Gamma}$$







Spin ensemble as a memory: protocol

How to store an incoming arbitrary wave packet and retrieve it?



Julsgaard, et al. (2012), Yin et al. (2013), Ranjan et al. (2020), phase encoding: O'Sullivan et al. (2022)

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Multimode?

Random access to multiple stored states by echo silencing... except on retrieval !



Spin-ensemble as a memory : requirements & state of the art

- Long spin coherence
 - \checkmark Aim for clock transitions
- ✓ Tunable resonator frequency

 \checkmark For echo silencing

- \checkmark For aiming for clock transitions
- X Tunable linewidth
- X Reach unit cooperativity

NV centers in diamond



Grezes et al., PRA (2015)

Efficiency 0.3 % C = 0.22 $T_2 = 84$ us

Bismuth donors in silicon



Perspective

Running a protocol maximizing efficiency for classical pulses



Building a bidirectional link between qubit and processor





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