Quantum memories based on arrays of shallow donors in silicon

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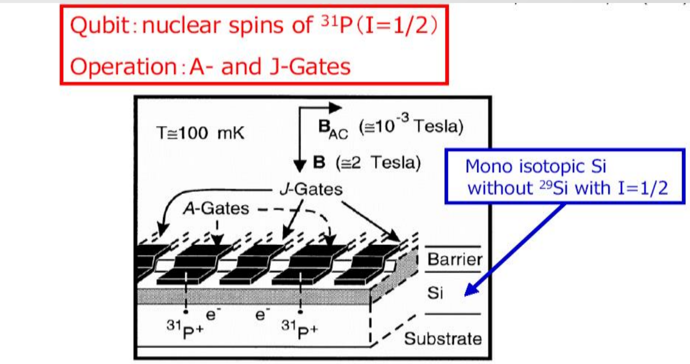
Motivations

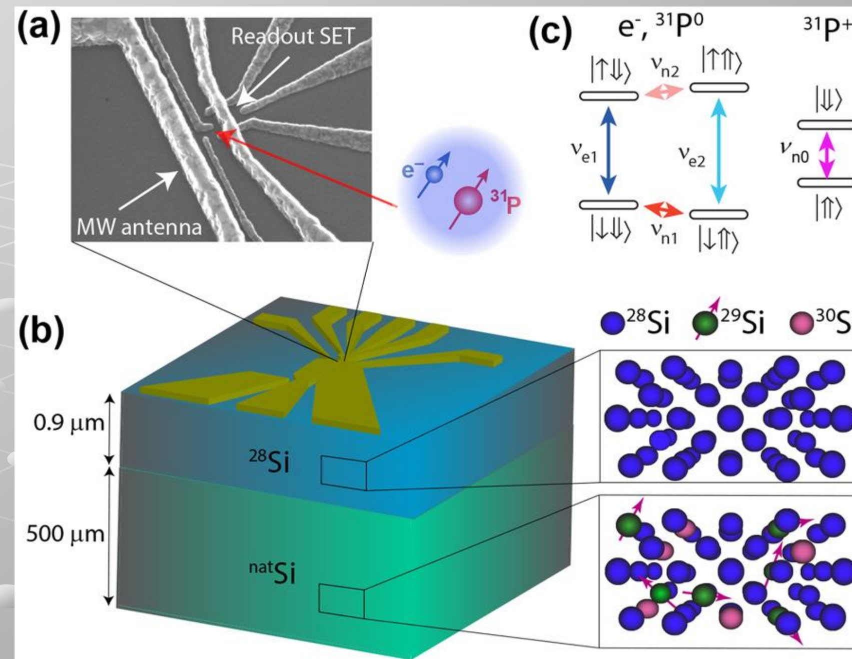
- Quantum memories are indispensable in quantum information applications such as quantum repeaters and hybrid quantum computing architectures.
- Shallow single donors in Si are currently used as qubits: single spin manipulation/readout based on electrical detection of magnetic resonance
- Deep levels could also be used to store information in combination with a semiconductor qubit
- T1 and T2
- Arrays of donors (or other impurities) can be used as quantum memories to be coupled with a superconductor qubit

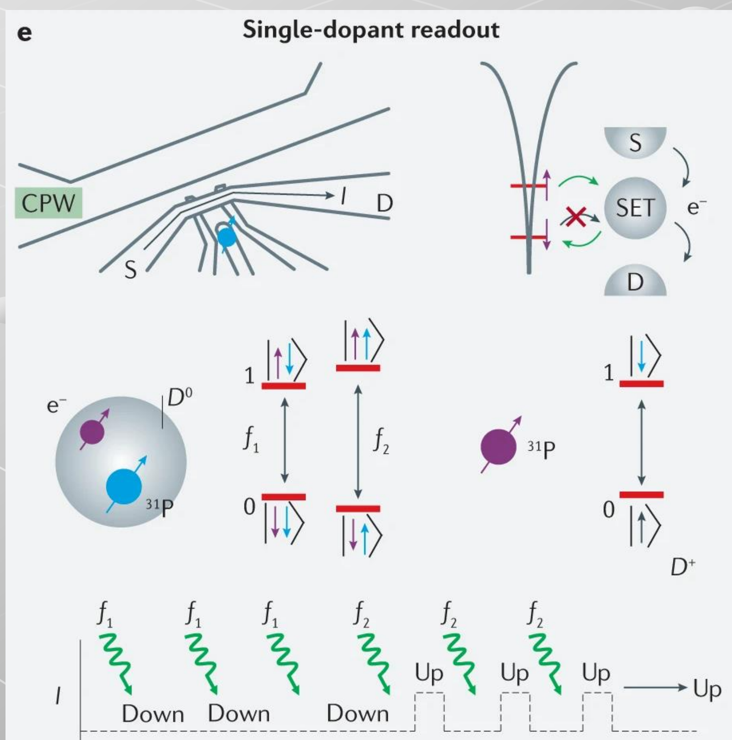
Silicon Based QC: 1998->2023

[B.E. Kane, Nature **393**, 133 (1998)]



[A. Morello et al. Adv. Quantum Technol. 3, 2000005 (2020)]

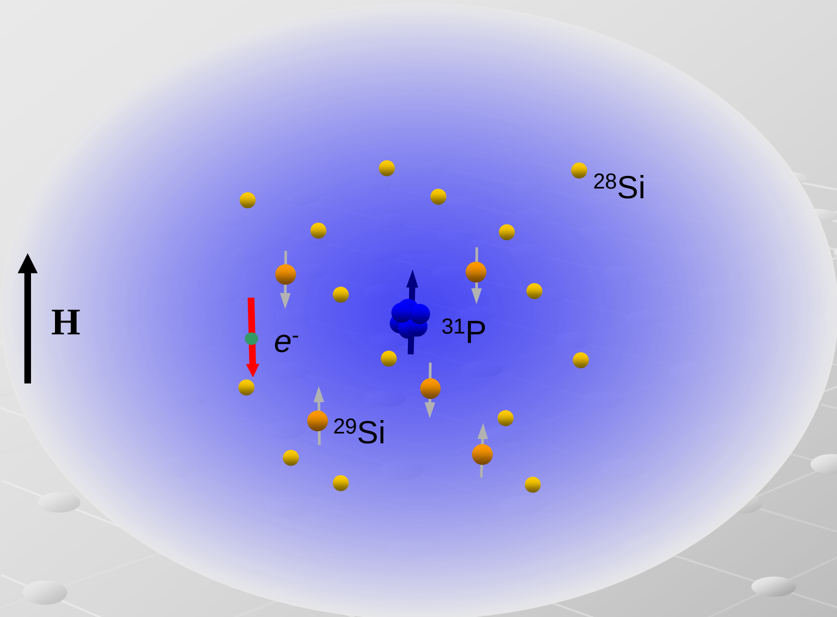




Readout of shallow dopants using the DC current I running through a single-electron transistor (SET) charge sensor. Dopant energy levels (D^+) and (D^0) form the two-level system for the ionized nuclear spin and the electron spin qubit, respectively. Transitions are addressable using distinct frequencies (f_1 and f_2) delivered via a coplanar waveguide (CPW).

A. Chatterjee et al., Nat. Rev. Phys. 3, 157 (2021)

Donor electron spin in Si: P



Effective Bohr radius ~ 20-25 Å
Lattice constant = 5.43 Å

In a natural Si crystal the donor electron interacts with ~ 150 nuclei of ^{29}Si

System of ^{29}Si nuclear spins can be considered as a spin bath

Spin Hamiltonian

$$H_{\text{Spin}} = H_Z^e + \sum_i H_Z^{\text{nucl}}(i) + \sum_i H_{\text{Hf}}(i) + \sum_{i \neq j} H_{\text{Dip}}(i,j)$$

Effect of external field | **Electron-nuclei interaction** | **Nuclei-nuclei interaction**

Electron spin Zeeman + S.O term: $H_Z^e = g\beta \mathbf{HS}$

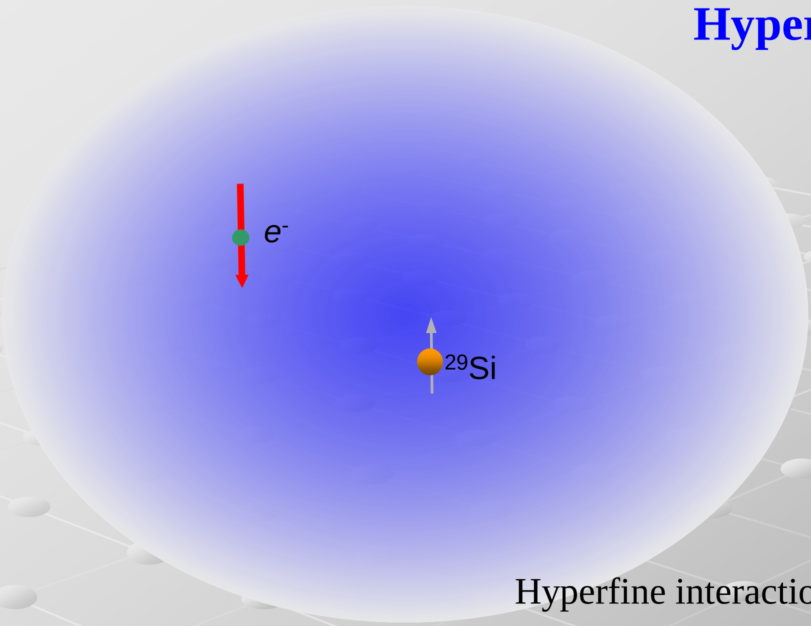
Nuclear spin Zeeman term: $H_Z^{\text{nulc}}(i) = -\gamma_i \hbar \mathbf{HI}$

Hyperfine electron-nuclear spin interaction: $H_{\text{Hf}}(i) = \mathbf{S}\mathbf{A}_i\mathbf{I}^i$

Dipole-dipole nuclear spin interaction: $H_{\text{Dip}}(i,j) = \mathbf{I}^i\mathbf{D}_{ij}\mathbf{I}^j$

Donor electron spin in Si:P

Hyperfine interaction



Contact interaction:

$$H_{\mathrm{Cont}} = A\mathbf{SI}$$

Dipole-dipole interaction:

$$H_{\mathrm{Dip}} = \frac{\boldsymbol{\mu}_e \boldsymbol{\mu}_n}{r^3} - \frac{3(\boldsymbol{\mu}_e \mathbf{r})(\boldsymbol{\mu}_n \mathbf{r})}{r^5}$$

Hyperfine interaction:

$$H_{\mathrm{Hf}} = \begin{pmatrix} S_x & S_y & S_z \end{pmatrix} \begin{pmatrix} A_{xx} & A_{xy} & A_{xz} \\ A_{yx} & A_{yy} & A_{yz} \\ A_{zx} & A_{zy} & A_{zz} \end{pmatrix} \begin{pmatrix} I_x \\ I_y \\ I_z \end{pmatrix}$$

Approximations:

Contact interaction only:

$$\mathbf{A} = \begin{pmatrix} A_{xx} & 0 & 0 \\ 0 & A_{yy} & 0 \\ 0 & 0 & A_{zz} \end{pmatrix}$$

High magnetic field

$$\mathbf{A} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ A_{zx} & A_{zy} & A_{zz} \end{pmatrix}$$

Contact interaction
High magnetic field

$$\mathbf{A} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & A_{zz} \end{pmatrix}$$

If I ≥ 1and EFG EFG ≠ 0 (Symmetry) : quadrupole interaction may also be exploited

Shallow donors in silicon

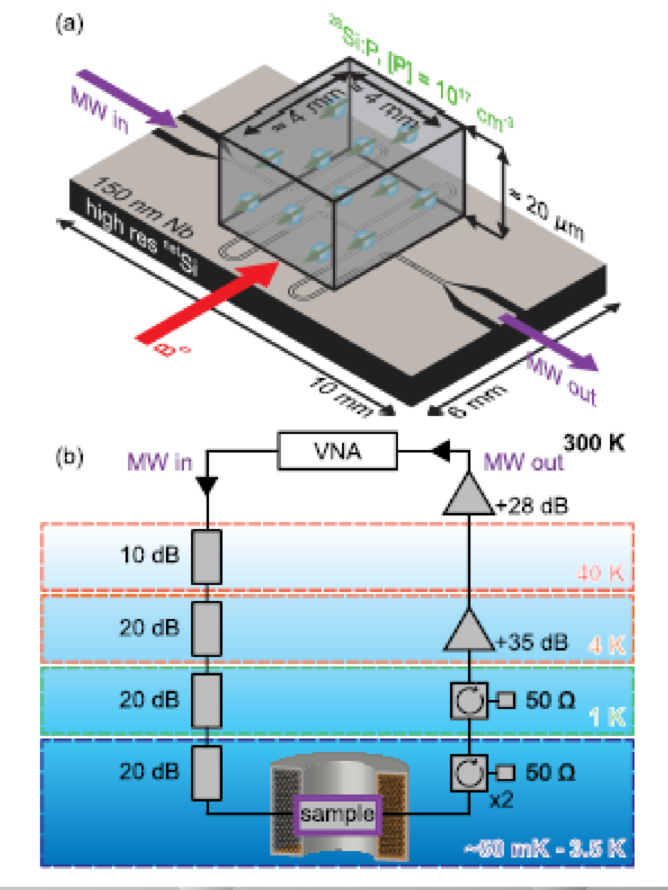
Nucleus	E_c-E_d [meV]	Nat. Abund. (%)	gN	I	ENDOR Freq. @0,350 T [MHz]	EZn @0,350 T [eV]	ge	EZe @0,350 T [eV]	EHI [eV]	EHI [MHz]	Zero Field Splitting [MHz]
P31	45,59	100	2,2632	0,5	6,03801	2,50E-08	1,9985	4,04883E-05	4,86E-07	117,53	117,53
As75	53,76	100	0,959647	1,5	2,56025	1,06E-08	1,99837	4,04856E-05	8,20E-07	198,35	396,7
Sb121	42,74	57,21	1,34536	2,5	3,5893	1,48E-08	1,99858	4,04899E-05	7,73E-07	186,802	560,406
Sb123		42,79	0,72851	3,5	1,9436	8,04E-09	1,99858	4,04899E-05	4,20E-07	101,516	406,064
Bi209	70,98	100	0,9134	4,5	2,437	1,01E-08	2,0003	4,05248E-05	6,10E-06	1475,4	7377
Se77(+)	306,5	7,63	1,070149	0,5	2,855058	1,18E-08	2,0057	4,06342E-05	6,87E-06	1660,4	1660,4
Te125(+)	196	7,07	4,740899	0,5	4,740899	5,23E-08	2,0023	4,05653E-05	1,44E-05	3491,65	3491,65

Current state of the art for silicon donor spin qubit

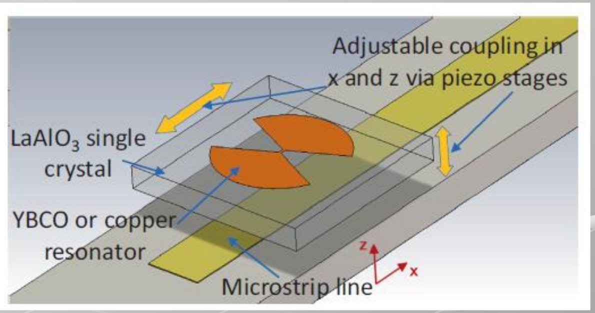
	Time scales		Quantum Computing		Quantum Sensing	
	T1	T2DD	Single qubit gate time	Single qubit fidelity	Quantity	Sensitivity
Electron	>1 h (ref.1) (ens), 10 s (ref.2)	10 s (ref.3)) (ens), 0.56 s (ref.4)	~100 ns (ref.5)	99.94%*(ref.6)	Magnetic field (AC)	18 pT/ Hz (ref.4)
Nuclear	>days (ref.7)	3 h (ref.8) (ens), 35.6 s (ref.4)	~20 μs (ref.7)	99.98%*(ref.9)	Magnetic field (AC)	2 nT/ Hz (ref.10)

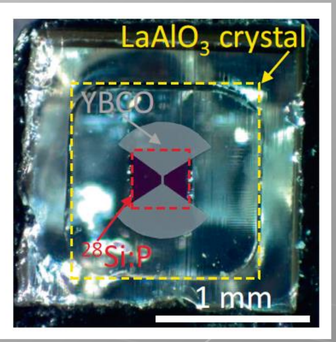
1. [1] G. Feher & E. Gere, *Phys. Rev.* **114**, 1245 (1959)
2. [120] S.B. Tenberg et al., *Phys. Rev. B* **99**, 205306 (2019)
3. [104] A.M. Tyryshkin et al., *Nat. Mater.* **11**, 143 (2012)
4. [124] J.P. Dehollain et al., *Nat. Nanotechnol.* **11**, 242 (2016)
5. [82] J.J. Pla et al., *Nature* **489**, 541 (2012)
6. [127] J.P. Dehollain et al., *New J. Phys.* **18**, 103018 (2016)
7. [66] J.J. Pla et al., *Nature* **496**, 334–338 (2013)
8. [111] K. Saeedi et al., *Science* **342**, 830–833 (2013)
9. [126] J. Muhonen et al., *J. Phys. Condens. Matter* **27**, 154205 (2015)
10. [131] A. Morello et al., *Adv. Quantum Technol.* **3**, 2000005 (2020).

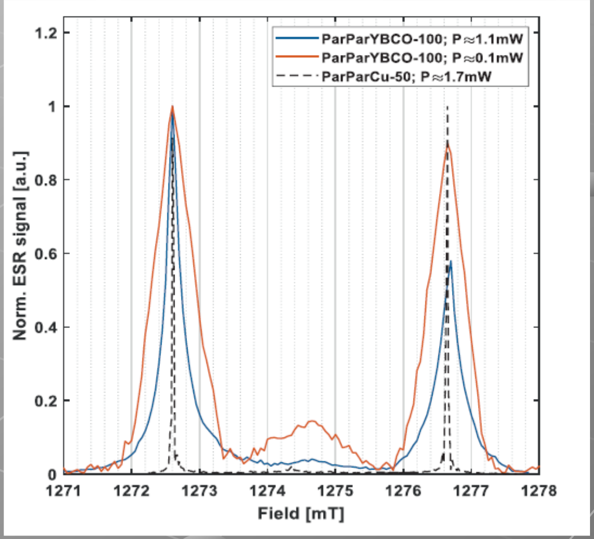
ESR detection with superconducting microwave resonator



C. W. Zollitsch et al., Appl. Phys. Lett. 107, 142105 (2015)



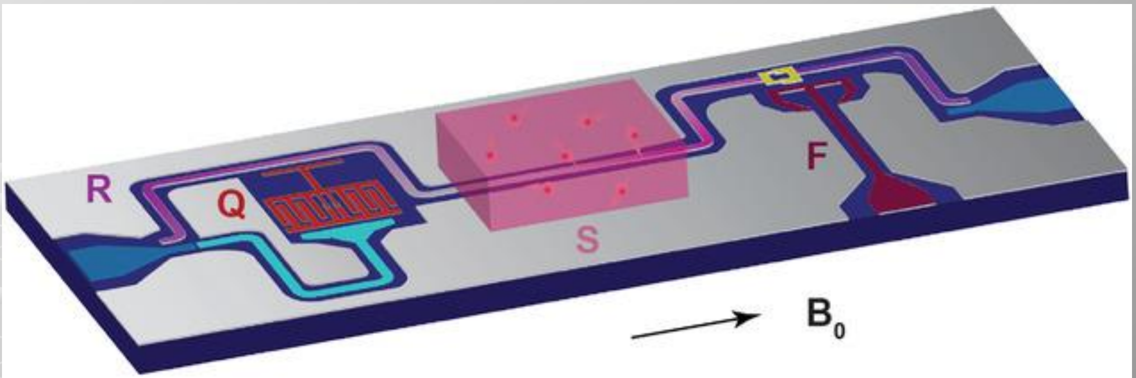




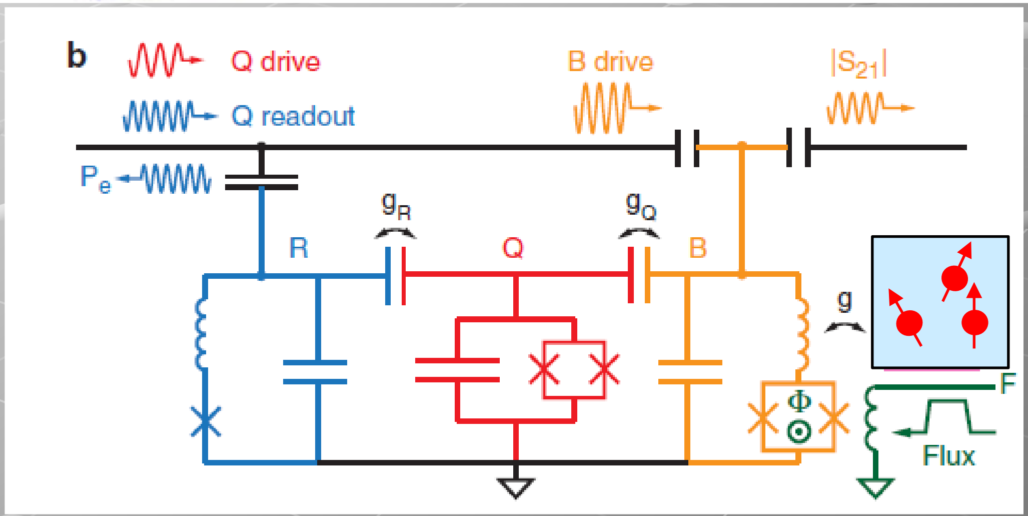
Y. Artzi et al., Journal of Magnetic Resonance 334, 107102 (2022)

Hybrid device (SU/SE)

R: superonducting resonator
S: ensemble of donors in silicon
Q: Transmon qubit



Proof of concept of a spin-based quantum memory for superconducting qubits.



The resonator has an embedded superconducting quantum interference device (SQUID) and flux line (F) to allow for frequency tunability. This particular device implements a quantum memory, where quantum states from Q are transferred to S via R. [Y. Kubo et al. Phys. Rev. Lett.107, 220501 (2011)]

Research Outline

Materials Science

- Disordered arrays of donors (P, Bi) in nat Si and Isotopicaly purified ^{28}Si
- Novel technology for the realisation of ^{28}Si enriched areas (M. Fanciulli, HZDR 2022 and 2023)
- Ordered arrays of donors (Bi) in natSi and ^{28}Si enriched areas: deterministic doping (HZDR) and other techniques (M. Perego, CNR-Agrate)

Experimental Set-up

- CW-EPR (X-band and Q band, ENDOR, **DNP**). T=3-300 K
- Pulse EPR (X-band, Q-band, ENDOR). T=3-300 K (upgrade or collaoration)
- **Pulse EPR broad band, 1-10 GHz, T=10 mK**

Quantum Physics

- T1, T2, Hyperpolarization, DNP
- Transfer of quantum information from electronic spin systems to superconducting qubits (protocols: collaboration with E. Ferraro and with Spoke 1 under discussion)
- Transfer of quantum information between electron and nuclear spins

Conclusions

- For additional information and to discuss a collaboration please contact me: marco.fanciulli@unimib.it