Quantum computing with semiconductor spins: the flip-flop qubit universal quantum gates set

Elena Ferraro
CNR-IMM Agrate Unit, Agrate Brianza (MB), Italy

Institute for Microelectronics and Microsystems
Consiglio Nazionale delle Ricerche

SEMICONDUCTOR QUBIT:
AN INTRODUCTION

From the original proposals...

PHYSICAL REVIEW A VOLUME 57, NUMBER 1 JANUARY 1998

Quantum computation with quantum dots

Daniel Loss[1,2,*] and David P. DiVincenzo[1,3,†]
[1]*Institute for Theoretical Physics, University of California, Santa Barbara, Santa Barbara, Ca*
[2]*Department of Physics and Astronomy, University of Basel, Klingelbergstrasse 82, 4056 B*
[3]*IBM Research Division, T.J. Watson Research Center, P.O. Box 218, Yorktown Heights,*
(Received 9 January 1997; revised manuscript received 22 July 1997)

articles

A silicon-based nuclear spin quantum computer

B. E. Kane
Semiconductor Nanofabrication Facility, School of Physics, University of New South Wales, Sydney 2052, Australia

Quantum computers promise to exceed the computational efficiency of ordinary classical machines because quantum algorithms allow the execution of certain tasks in fewer steps. But practical implementation of these machines poses a formidable challenge. Here I present a scheme for implementing a quantum-mechanical computer. Information is encoded onto the nuclear spins of donor atoms in doped silicon electronic devices. Logical operations on individual spins are performed using externally applied electric fields, and spin measurements are made using currents of spin-polarized electrons. The realization of such a computer is dependent on future refinements of conventional silicon electronics.

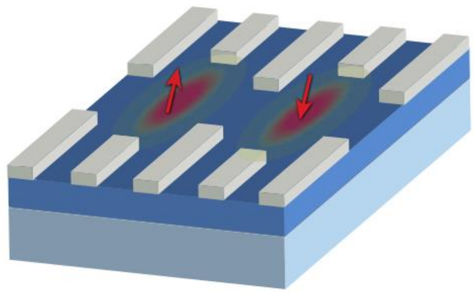
Confinement of spins in semiconductor represents a fruitful platform for UNIVERSAL QUANTUM COMPUTATION

Group III-V (GaAs)

N-V center (point defect in diamond)

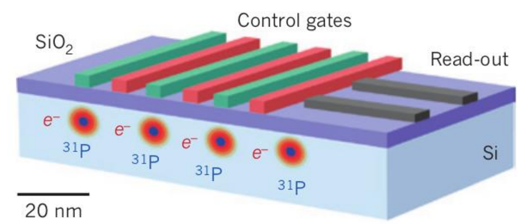
Group IV (Si)

QUANTUM DOT-based qubit



Long coherence time
Fast gate operations
Easy manipulation
Potential for scaling

Group IV seminconductor
Silicon
Nuclear free isotopes
Integrability with CMOS infrastructure



DONOR-based qubit

IMM Consiglio Nazionale delle Ricerche
Institute for Microelectronics and Microsystems

J. J. L. Morton et al., Nature 479, 345–353 (2011)

npj | Quantum Information

www.nature.com/npjqi

ARTICLE OPEN

High-fidelity resonant gating of a silicon-based quantum dot hybrid qubit

Dohun Kim[1,2], Daniel R Ward[1], Christie B Simmons[1], Don E Savage[3], Max G Lagally[3], Mark Friesen[1], Susan N Coppersmith[1] and Mark A Eriksson[1]

LETTER

doi:10.1038/nature12011

High-fidelity readout and control of a nuclear spin qubit in silicon

Jarryd J. Pla[1], Kuan Y. Tan[1]†, Juan P. Dehollain[1], Wee H. Lim[1]†, John J. L. Morton[2], Floris A. Zwanenburg[1]†, David N. Jamieson[3], Andrew S. Dzurak[1] & Andrea Morello[1]

npj | Quantum Information

Review Article | OPEN | Published: 06 September 2017

Interfacing spin qubits in quantum dots and donors—hot, dense, and coherent

L. M. K. Vandersypen, H. Bluhm, J. S. Clarke, A. S. Dzurak, R. Ishihara, A. Morello, D. J. Reilly, L. R. Schreiber & M. Veldhorst

npj Quantum Information **3**, Article number: 34 (2017) | Download Citation

npj | Quantum Information

Review Article | OPEN | Published: 26 June 2017

Quantum information density scaling and qubit operation time constraints of CMOS silicon-based quantum computer architectures

Davide Rotta, Fabio Sebastiano, Edoardo Charbon & Enrico Prati

npj Quantum Information **3**, Article number: 26 (2017) | Download Citation

nature
International journal of science

Letter | Published: 14 February 2018

A programmable two-qubit quantum processor in silicon

T. F. Watson, S. G. J. Philips, E. Kawakami, D. R. Ward, P. Scarlino, M. Veldhorst, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, M. A. Eriksson & L. M. K. Vandersypen

Nature **555**, 633–637 (29 March 2018) | Download Citation

nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-017-01113-2 OPEN

Coherent coupling between a quantum dot and a donor in silicon

Patrick Harvey-Collard[1,2], N. Tobias Jacobson[3], Martin Rudolph[2], Jason Dominguez[2], Gregory A. Ten Eyck[2], Joel R. Wendt[2], Tammy Pluym[2], John King Gamble[3], Michael P. Lilly[4], Michel Pioro-Ladrière[1,5] & Malcolm S. Carroll[2]

nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-017-01905-6 OPEN

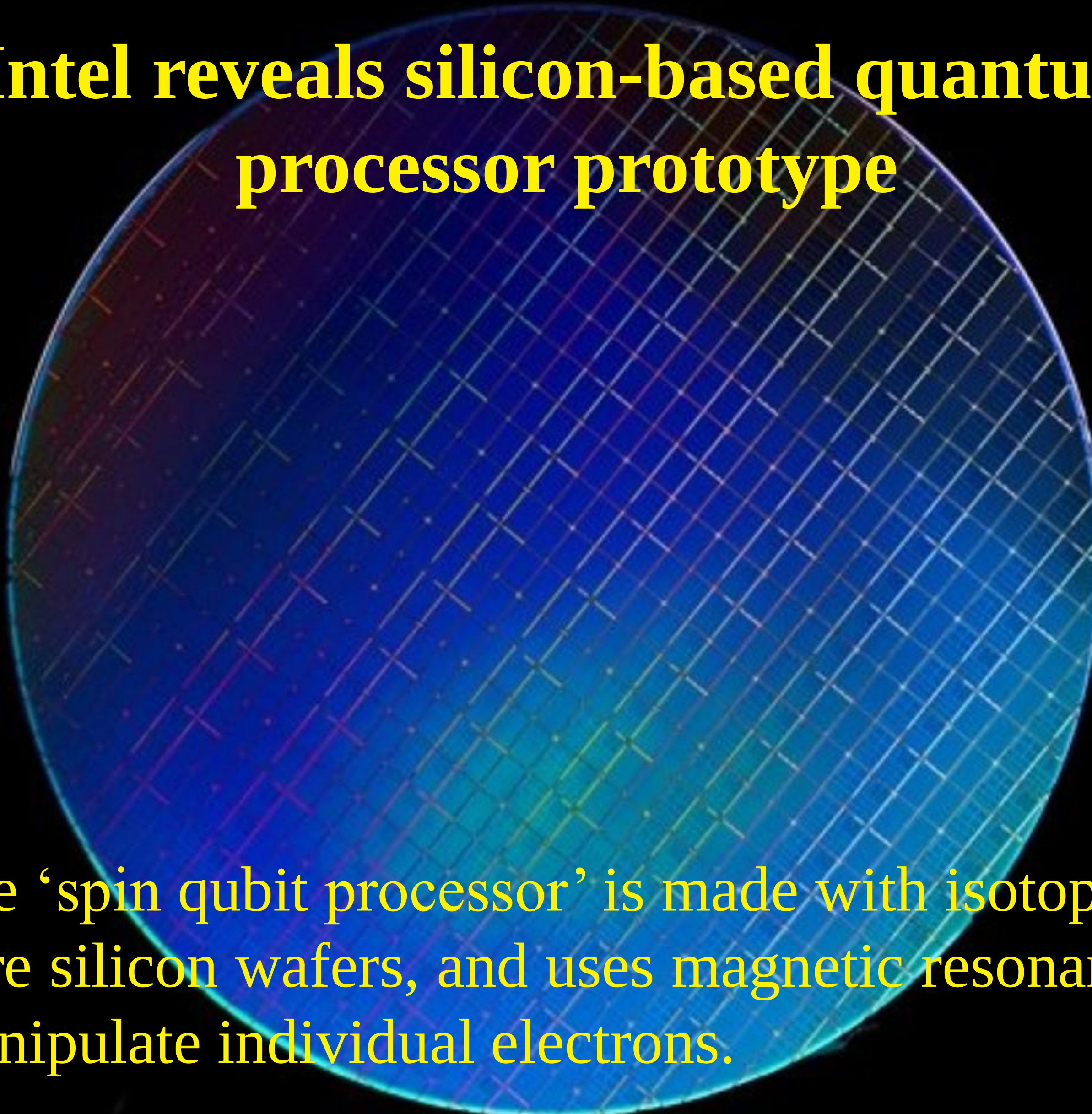
Silicon CMOS architecture for a spin-based quantum computer

M. Veldhorst[1,2], H.G.J. Eenink[1,2], C.H. Yang[2] & A.S. Dzurak[2]

SOME RECENT RESULTS...

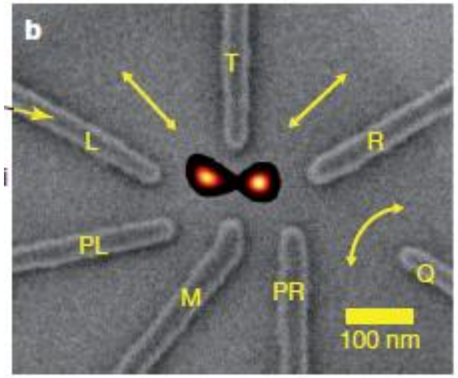
IMM Consiglio Nazionale delle Ricerche
Institute for Microelectronics and Microsystems

Intel reveals silicon-based quantum processor prototype



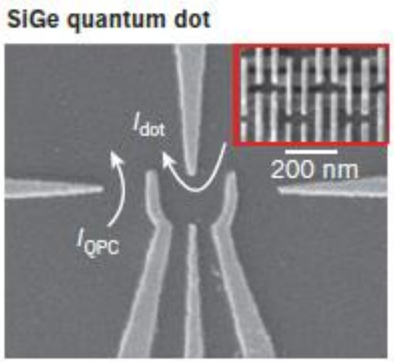
The ‘spin qubit processor’ is made with isotopically pure silicon wafers, and uses magnetic resonance to manipulate individual electrons.

DOUBLE QD SINGLET-TRIPLET QUBIT



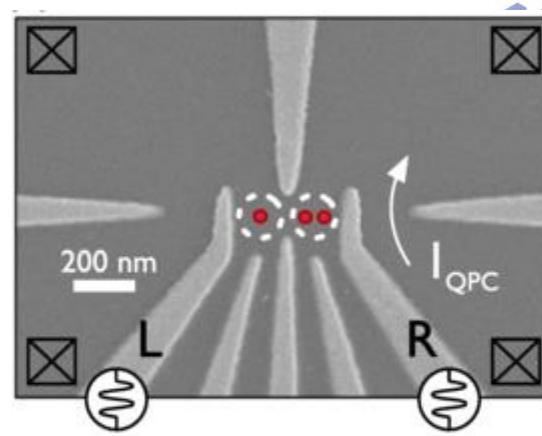
B. M. Maune et al., Nature 481, 344 (2012)

QD SINGLE SPIN QUBIT



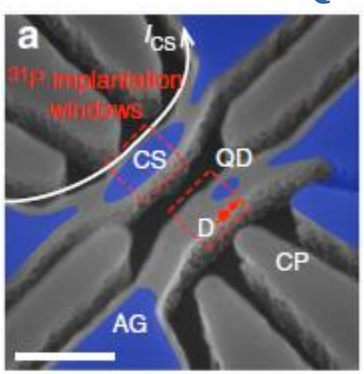
J. J. L. Morton et al., Nature 479, 345–353 (2011)

DOUBLE QD HYBRID QUBIT



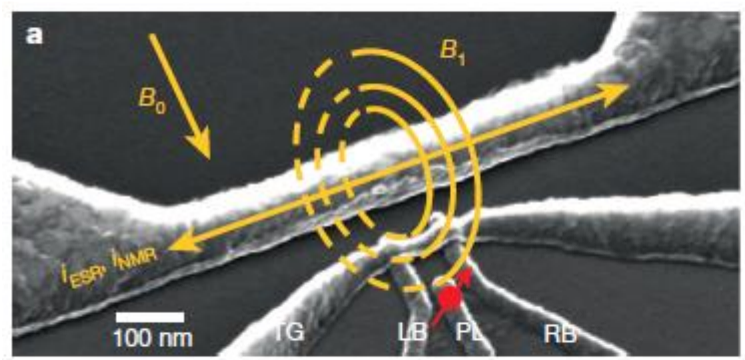
J. C. Abadillo-Uriel et al., Phys. Rev. B 98, 165438 (2018)

QD SPIN-DONOR QUBIT



P. Harvey-Collard, Nature Communications 8, 1029 (2017)

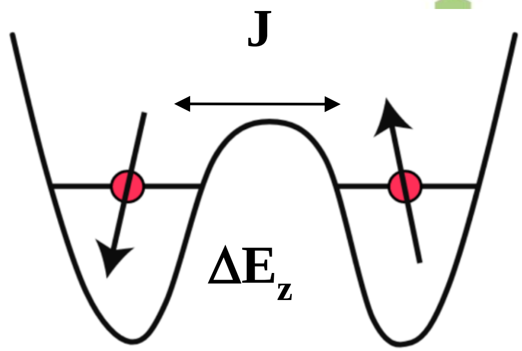
DONOR QUBIT



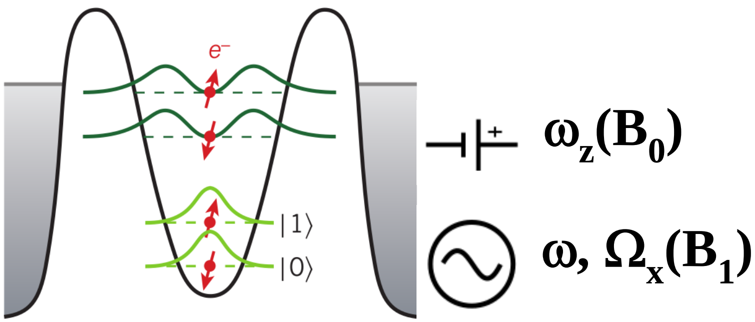
J. J. Pla et al., Nature 496 , 334 (2013)

SPIN QUBITS: ENERGY PROFILES & PHYSICAL CONTROLS

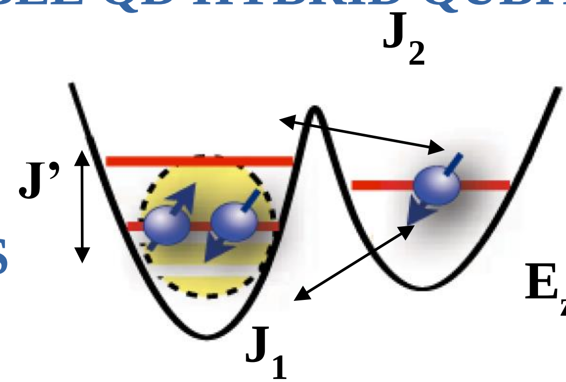
DOUBLE QD SINGLET-TRIPLET QUBIT



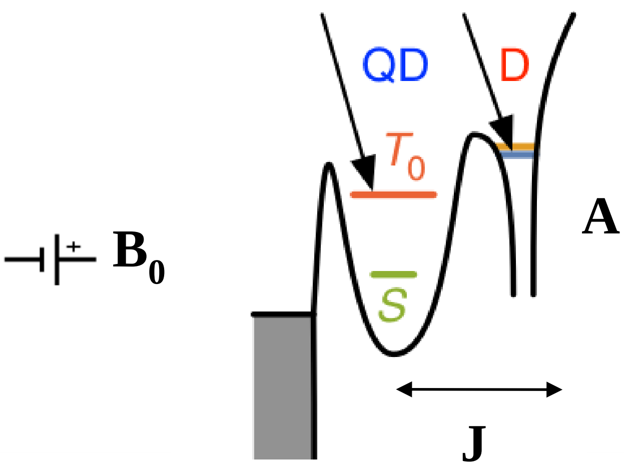
QD SINGLE SPIN QUBIT



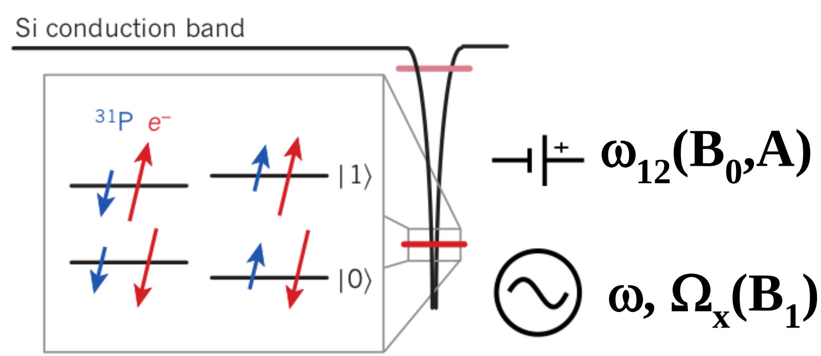
DOUBLE QD HYBRID QUBIT



QD SPIN-DONOR QUBIT



DONOR QUBIT



IMM Consiglio Nazionale delle Ricerche
Institute for Microelectronics and Microsystems

E. Ferraro, M. Fanciulli, M. De Michielis,
J. Phys. Commun. 2, 115022 (2018)

Qubit	Material	f(MHz)	$T_2^*(ns)$	$T_2(ns)$	$Q \equiv T_2^*/T_\pi$	Ref.
Single spin	Si/SiGe	~ 5	$\sim 9 \times 10^2$	3.7×10^4	~ 9	E. Kawakami et al., Nat. Nanotech. 9, 666–670 (2014)
Single spin	^{28}Si	~ 0.3	$\leq 1.2 \times 10^5$	1.2×10^6	≤ 80	M. Veldhorst et al., Nature 526, 410–414 (2015)
Donor spin (e^-)	P in ^{nat}Si	~ 3	55	2×10^5	≤ 1	J. J. Pla et al., Nature 489, 541 (2012)
Donor spin (e^-)	P in ^{28}Si	~ 0.2	$\sim 3 \times 10^5$	1×10^6	~ 108	J. T. Muhonen et al., Nat. Nanotech. 9, 986 (2014)
Singlet-Triplet	Si/SiGe	~ 351	$> 1 \times 10^3$	n.a.	n.a.	K. Takeda et al., arXiv:1910.00771 (2019)
Hybrid	Si/SiGe	$\sim 1 \times 10^4$	~ 11	~ 40	~ 250	D. Kim et al., Nature 511, 70–74 (2014)

Table I. Comparison of different spin-based qubits.

	Semiconductor Single-Spin qubit	Semiconductor Hybrid qubit (Steane code)	Semiconductor Hybrid qubit (Surface code)	Superconductor Flux qubit (DWave like)	Superconductor Transmon qubit (IBM like)	Trapped Ion qubit
Mqb_{ph}/cm^2	8000	830	100×10^2	8×10^{-4}	10^{-5}	2×10^{-5}
$A_{chip}(mm^2)$	25	240	20	25×10^7	2×10^{10}	10^{10}
Ref.	R. Li et al., Science Adv. 4, eaar3960 (2018)	D. Rotta et al., Npj Quant. Inf. 3, 26 (2017)	D. Rotta et al., Npj Quantum Inf. 3, 26 (2017)	R. Harris and et al., Phys. Rev. B 82, 024511 (2010)	J. M. Gambetta et al., Npj Quant. Inf. 655, 3:2 (2017).	B. Lekitsch et al., Science Adv. 3, e1601540 (2017)

Table II. Number of physical qubits per unit surface and area covered by 2 billions of physical qubits. The silicon hybrid qubit footprint refers to the 7 nm technology node.

E. Ferraro and E. ***Prati, Is all-electrical*** **silicon** ***quantum computing feasible in the long*** **term?, Physics Letters A 384 (17), 126352 (2020)**

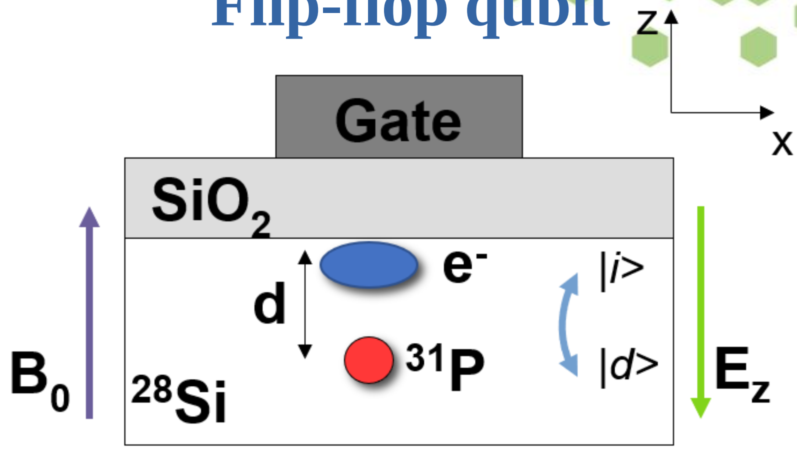
FLIP-FLOP QUBIT

Flip-flop qubit

Encoded states:

$|0> = \; |g \downarrow \Uparrow>$

$|1> = \; |g \uparrow \Downarrow>$



$$\hat{H}_{B_0} = \gamma_e B_0 \left[\hat{\mathbb{1}} + \left(\frac{\hat{\mathbb{1}} + \hat{\sigma}_z^{id}}{2} \right) \Delta_\gamma \right] \hat{S}_z - \gamma_n B_0 \hat{I}_z$$

$$\hat{H}_A = A \left(\frac{\hat{\mathbb{1}} - \hat{\sigma}_z^{id}}{2} \right) \mathbf{S} \cdot \mathbf{I}$$

$$\hat{H}_{Orb} = \frac{V_t}{2} \hat{\sigma}_x^{id} - \frac{d\, e\, (\Delta E_z + E_a \cos(\omega_E\, t))}{2\, h} \hat{\sigma}_z^{id}$$

Two eigenstates:

|g> : e^- ground state

|e> : e^- exited state

Applying a large static magnetic field B_0, (i.e. $(\gamma_e+\gamma_n)B_0 >> A$), the eigenstates of the system are the four qubit states $\{| \downarrow \Uparrow>, | \downarrow \Downarrow>, | \uparrow \Downarrow>, | \uparrow \Uparrow>\}$. Electrically modulating the hyperfine interaction A by E_z causes an Electron Dipole Spin Resonance (EDSR) transition between the states with antiparallel spins $\{| \downarrow \Uparrow>, | \uparrow \Downarrow>\}$, that are in turn chosen to encode the qubit.

Tosi et al., Nature Communications 8, 450 (2017)

Universal quantum gate set

G={H, Λ(S)}, where Λ(S) is a two-qubit gate in which the operation S is applied to the target qubit if and only if the control qubit is in the logical state |1>, for example the CNOT gate.

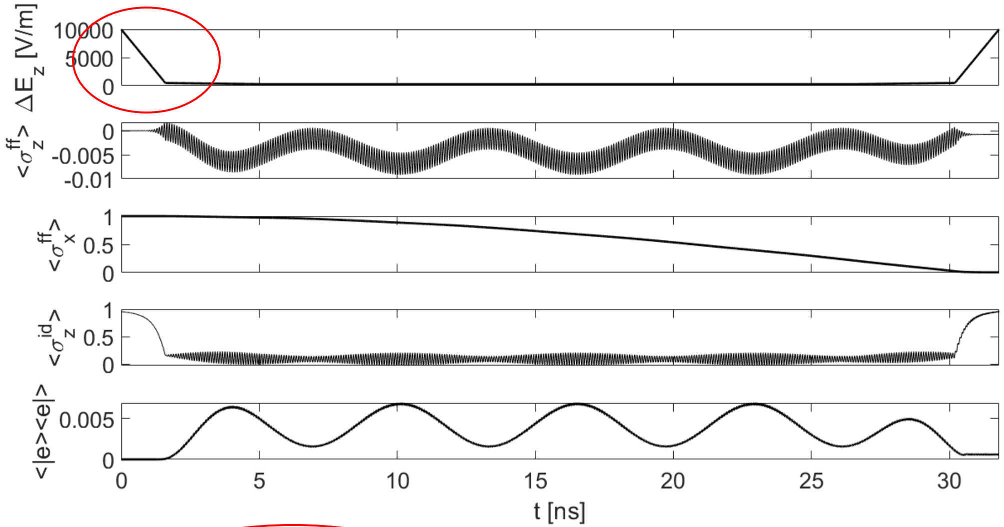
Moreover, a construction of the CNOT gate using only Rz(−π/2), H and sqrt(iSWAP) gates is feasible.

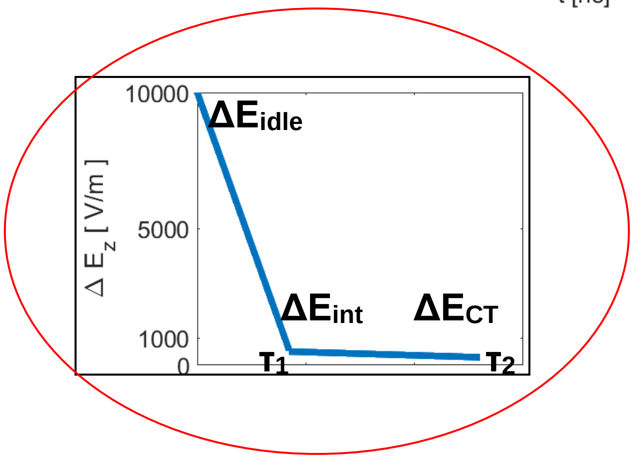
G={Rz(−π/2), H, sqrt(iSWAP)}

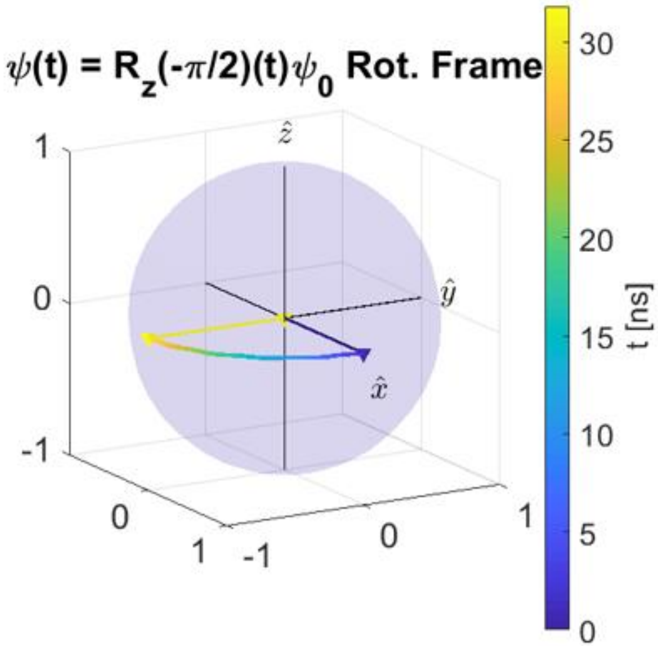
For each gate operation, we consider the effect of the charge noise using the 1/f model for the power spectral density, dominant in the low-frequency regime.

$R_z(-\pi/2)$

ΔE_{idle} [V/m]	ΔE_{int} [V/m]	ΔE_{ct} [V/m]	τ_1 [ns]	τ_2 [ns]	T [ns]	V_t [GHz]	K	T_{gate} [ns]
10000	500	290	1.7	3.5	21.6	11.29	$\simeq 20$	31.9



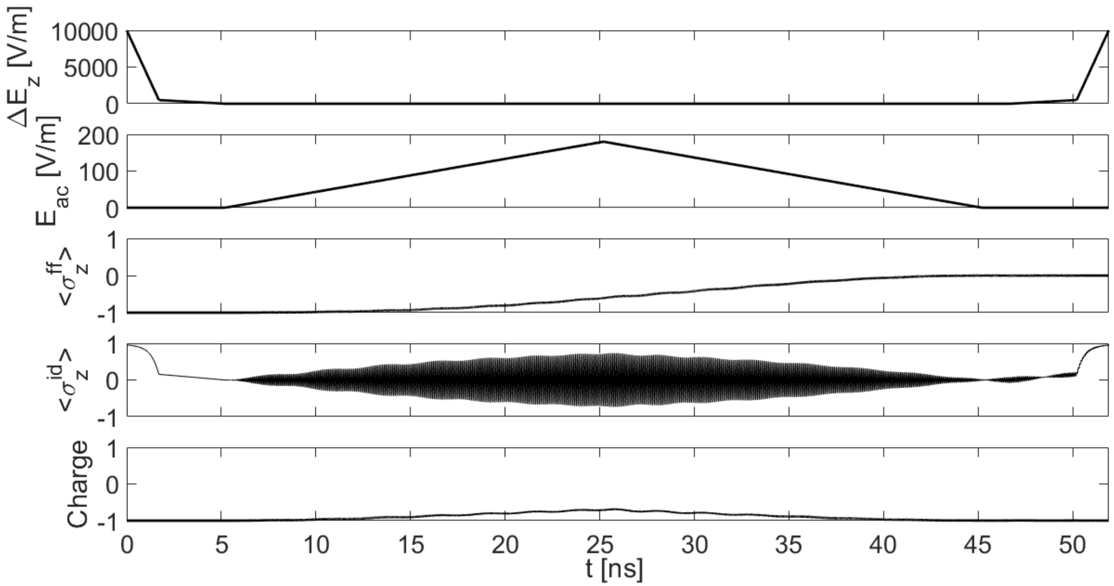




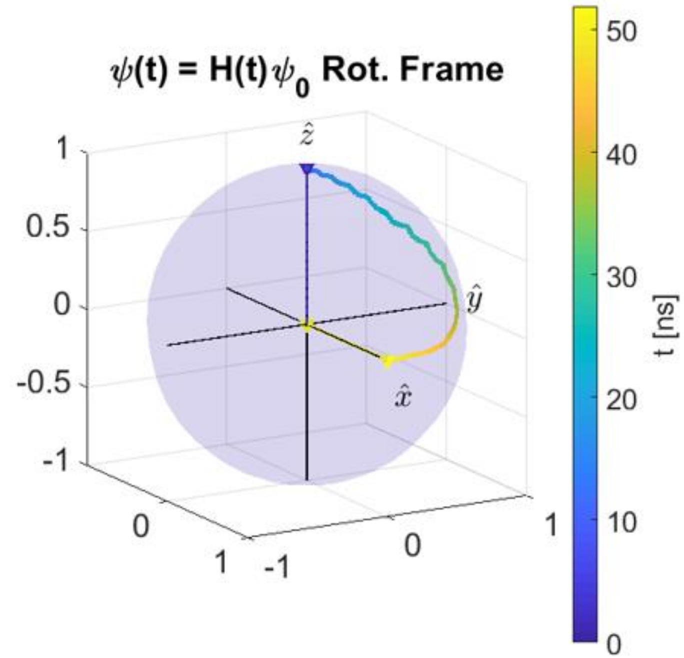
IMM Consiglio Nazionale delle Ricerche
Institute for Microelectronics and Microsystems

Hadamard

ΔE_{idle} [V/m]	ΔE_{int} [V/m]	ΔE_{ct} [V/m]	E_{ac} [V/m]	τ_1 [ns]	τ_2 [ns]	T [ns]	$T_{E_{ac}}^{ON}$ [ns]	V_t [GHz]	K	K_E	T_{gate} [ns]
10000	500	0	180	1.7	3.5	41.5	40	11.5	$\simeq 21$	$\simeq 57$	51.9



Acts on the qubit as a rotation of an angle π around the $(\hat{x}+\hat{z})/\sqrt{2}$ axis



Consiglio Nazionale delle Ricerche
Institute for Microelectronics and Microsystems

1/f noise model

- The 1/f noise model is based on the definition of the Power Spectral Density that is inversely proportional to the frequency and is given by $S(\omega)=\alpha/(\omega t_0)$, where α is the noise amplitude, that does not depend on ω and t_0 is the time unit.
- We generated the 1/f noise in the frequency domain as

$$n(\omega) = m(\omega)^{-1/2} e^{i\varphi(\omega)},$$

where $m(\omega)$ is generated from a standard Gaussian white process and the phase factor $\varphi(\omega) = [0,2\pi]$ is chosen uniformly.
- To obtain the noise in the time domain, we calculate the inverse Fourier transform and then multiply the result by the noise amplitude α

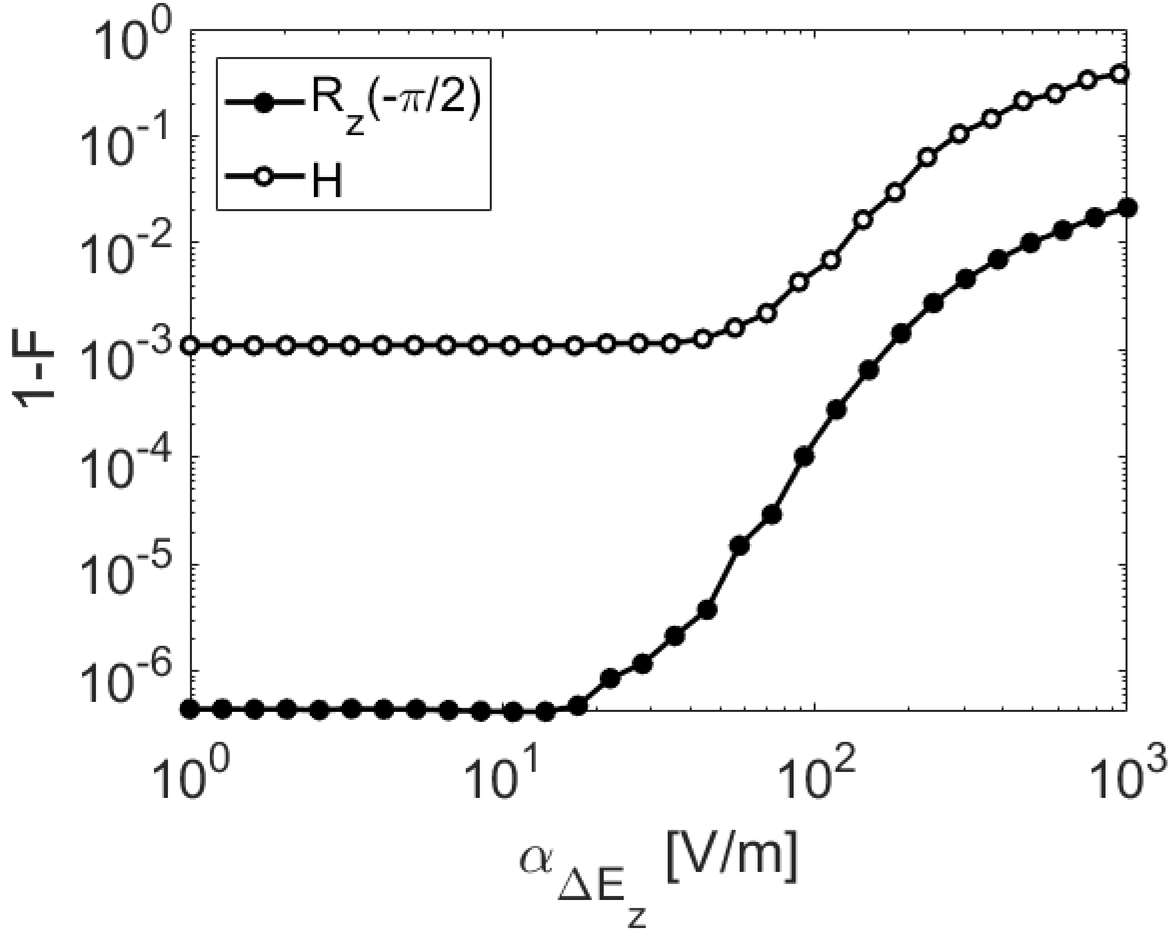
ENTANGLEMENT FIDELITY

$$F = tr[\rho^{RS} \mathbf{1}_R \otimes (U_i^{-1} U_d)_S \rho^{RS} \mathbf{1}_R \otimes (U_d^{-1} U_i)_S]$$

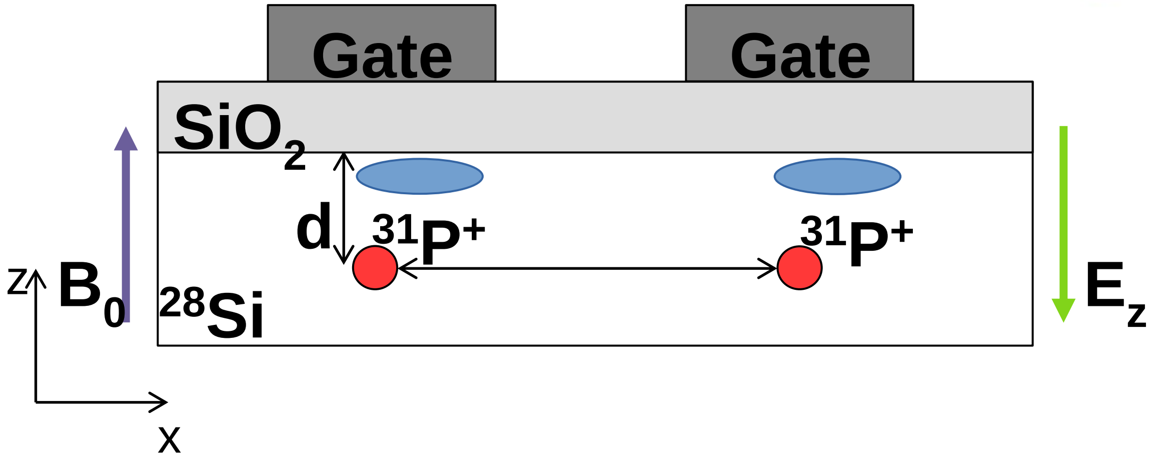
$$\rho^{RS} = |\psi\rangle\langle\psi| \text{ with } |\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

E. Paladino et al., Review of Modern Physics 86, 361 (2014)

Entanglement Fidelity in presence of 1/f noise model



Two flip-flop qubits: the dipole-dipole interaction



The two-qubit Hamiltonian

$$\hat{H}_{2,ff} = \hat{H}_{ff,1} \otimes \hat{\mathbb{1}} + \hat{\mathbb{1}} \otimes \hat{H}_{ff,2} + \hat{V}_{dip}$$

$$\hat{V}_{dip} = \frac{e^2\, d^2}{4\pi\epsilon_0\epsilon_r r^3}\, |i_1\, i_2\rangle \langle i_1\, i_2|$$

i_1>, |i_2> : e^- state at the interface

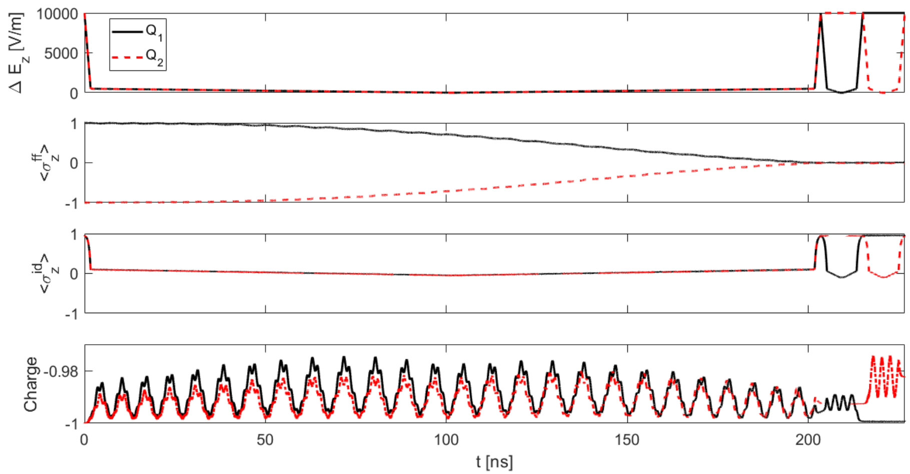
$\sqrt{\text{iSWAP}}$ @ r = 180 nm

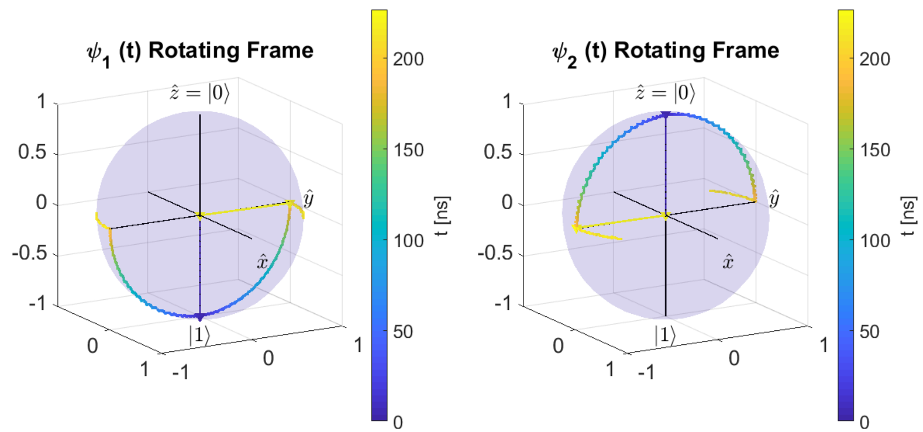
	ΔE_{idle} [V/m]	ΔE_{int} [V/m]	ΔE_{ct} [V/m]	τ_1 [ns]	τ_2 [ns]	T [ns]	V_t [GHz]	K	T_{gate} [ns]
Q_1Q_2	10000	500	0	1.7	99	2	11.58	$\simeq 21$	203.4
$Q_1(Q_2)$	10000	500	0	1.7	3.5	1.2	11.58	$\simeq 21$	11.6

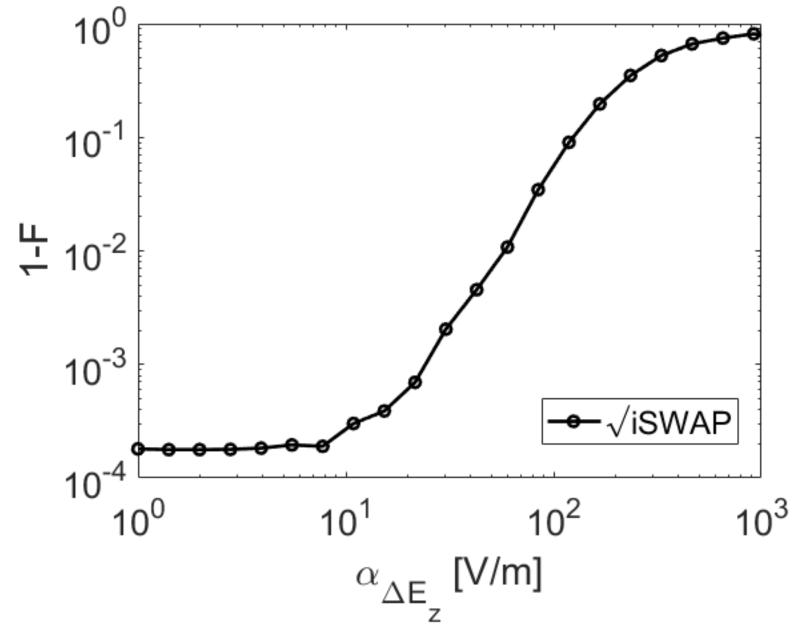
$$\sqrt{i\,SWAP} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & \frac{i}{\sqrt{2}} & 0 \\ 0 & \frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$|\Psi_1(0)> = \; |1>$$

$$|\Psi_2(0)> = \; |0>$$

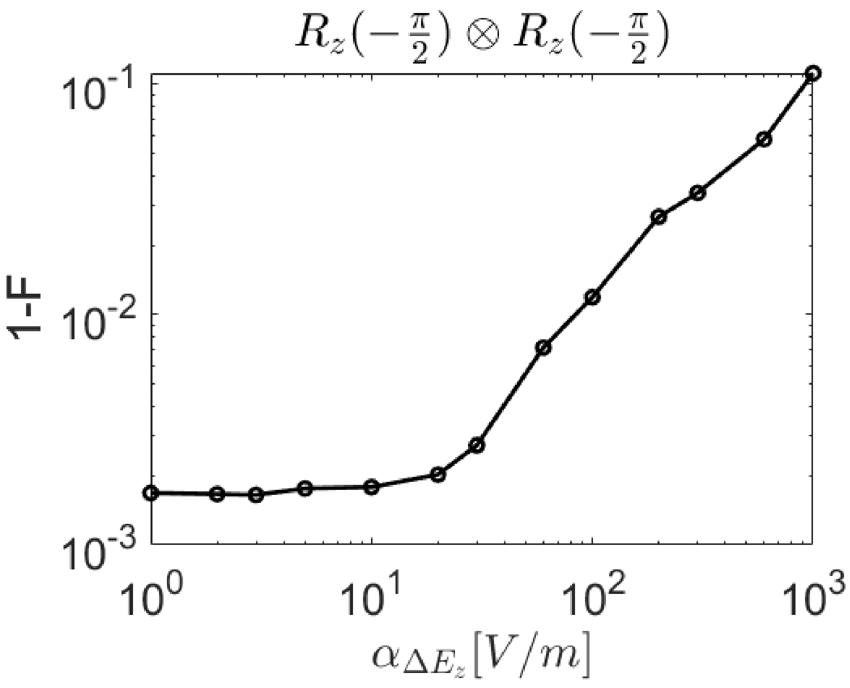


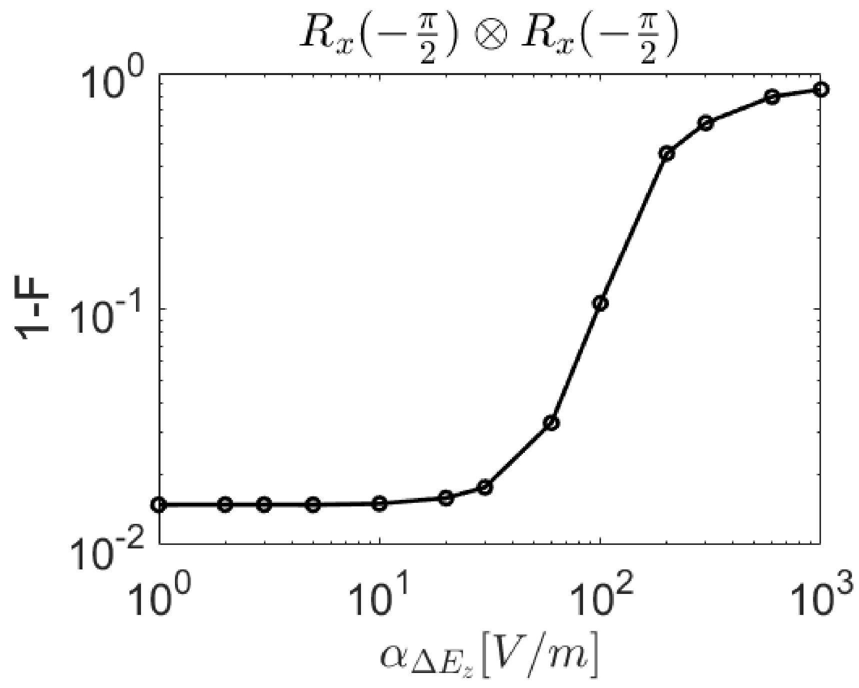




Consiglio Nazionale delle Ricerche
Institute for Microelectronics and Microsystems

Transversal gates for Quantum Error Correction: some preliminary results @ r=360 nm





The infidelity is compared with its ideal value where the qubits does not interact

Conclusions

Quantum computation by **flip-flop qubits**, donor based qubits in which the logical states are encoded in the donor nuclear and its bound electron.

A **universal set of quantum gates** composed by {Rz(−π/2), H, sqrt(iSWAP)} has been presented and the noise effect on the entanglement fidelity has been studied.

The noise model adopted shows a **1/f spectrum**, typical of qubit sensitive to charge noise.

Results are very promising in correspondance to a realistic noise level around 50 V/m, we obtain F>= 99.999% for the Rz(-pi/2) and 99.8% for the H gate. The two-qubit gate sqrt(iSWAP) may be realized with a fidelity above 99.5%.

Study on parallel one and two qubit operations for **QEC** code.

IMM Consiglio Nazionale delle Ricerche
Institute for Microelectronics and Microsystems

E. Ferraro, D. Rei, M. Paris and M. De Michielis, arXiv:2104.14341 (2021)