All-Silicon Quantum Computer

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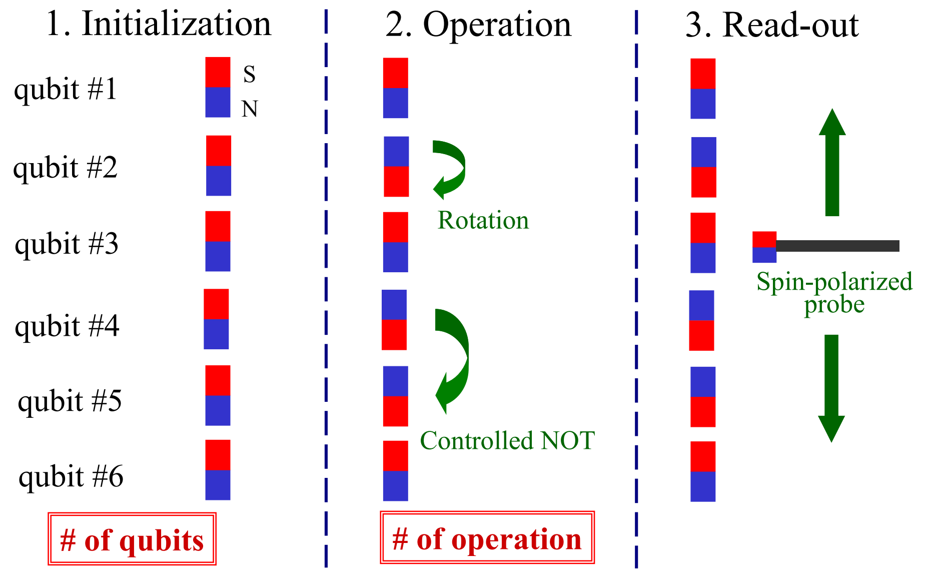
Quantum computation with spins



1. Initialization

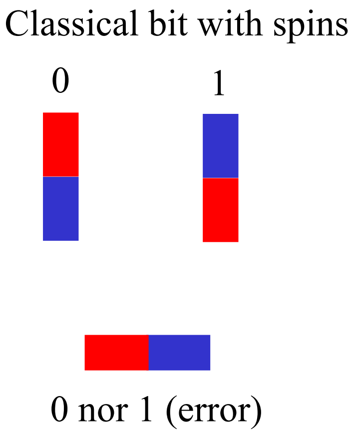
2. Operation

3. Read-out

# of qubits

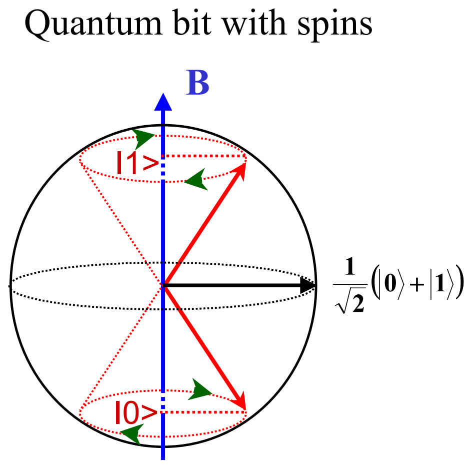
# of operation

Spin quantum bits



Classical bit with spins

0 nor 1 (error)



Quantum bit with spins

$\frac{1}{\sqrt{2}}\left(|0\rangle+|1\rangle\right)$

Quantum spin allows for equal probability of 0 and 1¥

Quantum parallelism

0	0	0	0
0	0	1	1
0	1	0	2
0	1	1	3
1	0	0	4
1	0	1	5
1	1	0	6
1	1	1	7

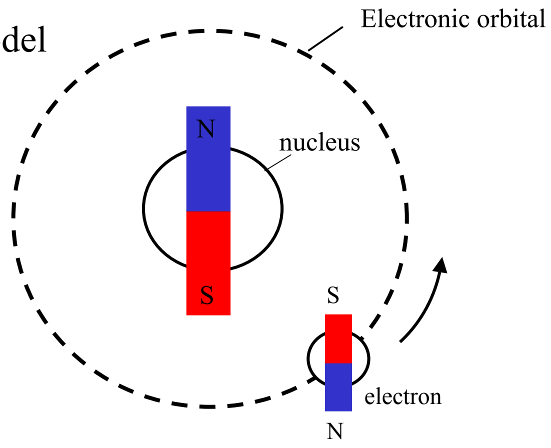
Binary numbers

Decimal numbers

Simultaneous processing of 2^n numbers

Candidates for qubits

Hydrogenic model



1. Nuclear spin
2. Electronic spin

} long decoherence time needed

Figures of merits

1. Scalable # of qubits (n) → 2^n states

2. Large # of total operation $\equiv \dfrac{\text{Phase decoherence time } T_2}{\text{Switching time } t_s}$

qubit	T_2 (sec)	t_s (sec)	# of operation
Electronic state	10^{-9}	10^{-13}	10^{4}
Electronic spin	10^{-6}	10^{-10}	10^{4}
Ion state	10^{-1}	10^{-14}	10^{13}
Nuclear spin	10^{3}	10^{-4}	10^{7}

photon

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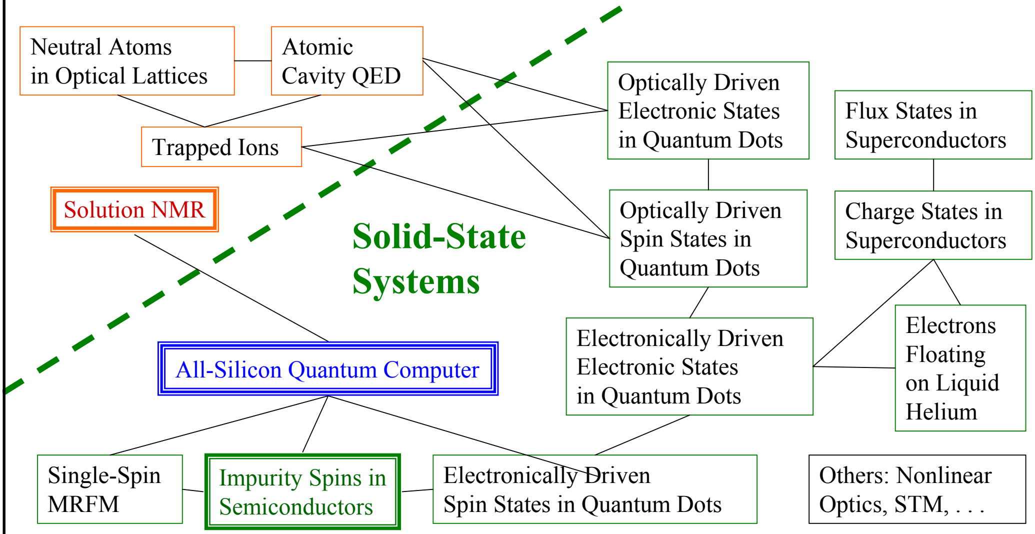
The World of Experimental Quantum Computation



Neutral Atoms in Optical Lattices

Atomic Cavity QED

Trapped Ions

Solution NMR

Optically Driven Electronic States in Quantum Dots

Flux States in Superconductors

Optically Driven Spin States in Quantum Dots

Charge States in Superconductors

Solid-State Systems

All-Silicon Quantum Computer

Electronically Driven Electronic States in Quantum Dots

Electrons Floating on Liquid Helium

Single-Spin MRFM

Impurity Spins in Semiconductors

Electronically Driven Spin States in Quantum Dots

Others: Nonlinear Optics, STM, . . .

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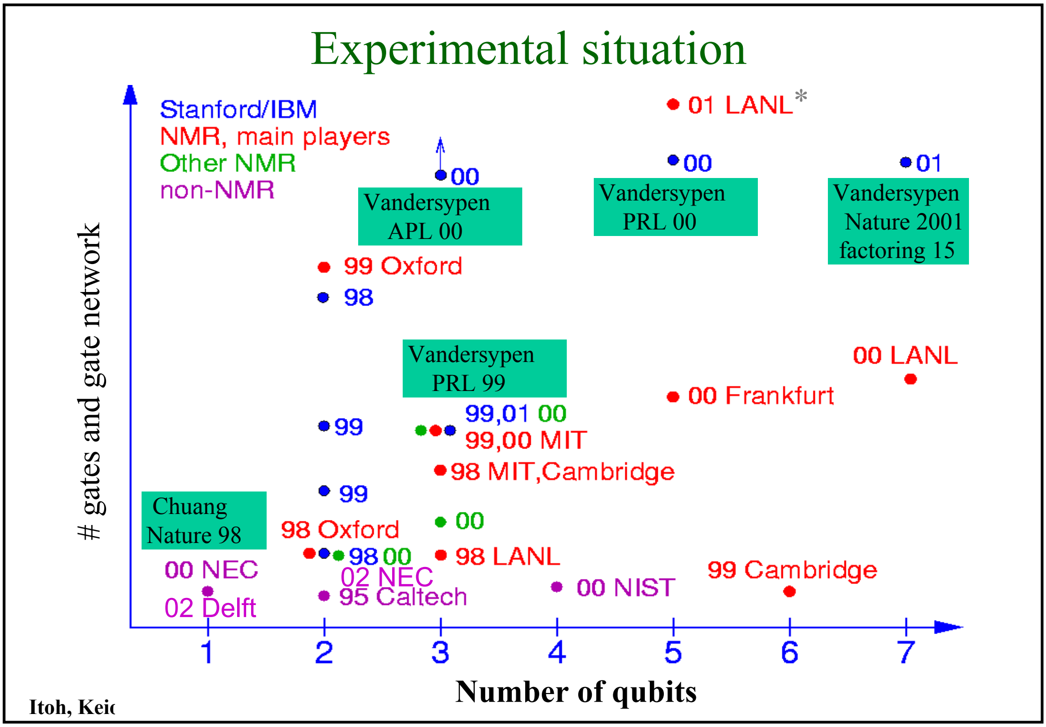

Experimental situation

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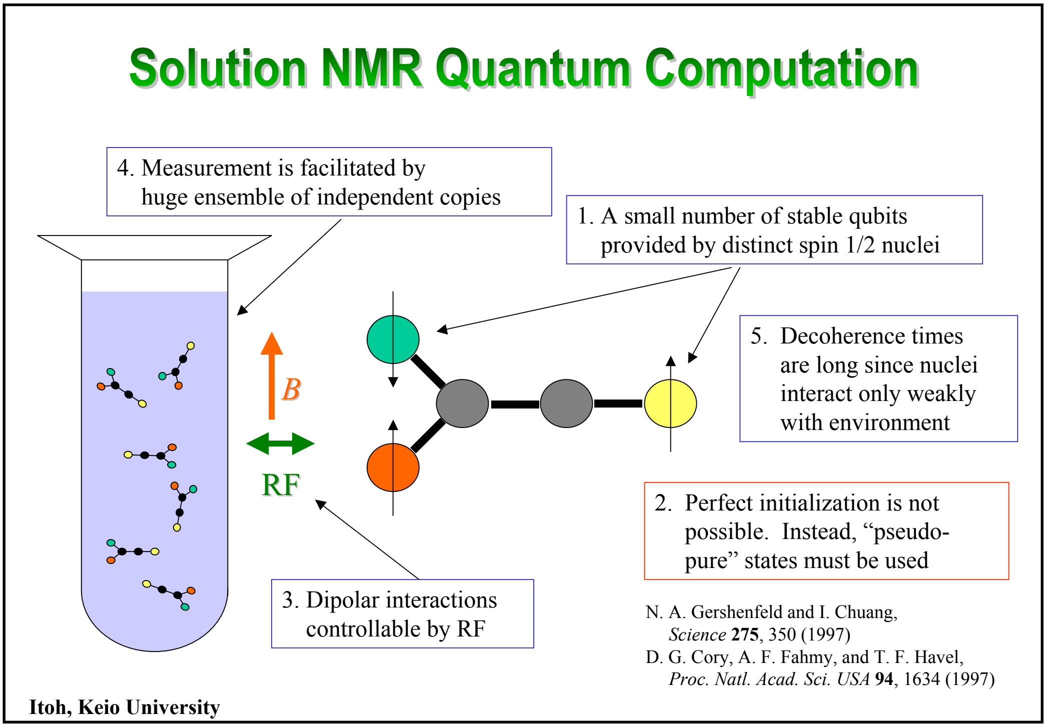

Solution NMR Quantum Computation

4. Measurement is facilitated by huge ensemble of independent copies

1. A small number of stable qubits provided by distinct spin 1/2 nuclei

5. Decoherence times are long since nuclei interact only weakly with environment

2. Perfect initialization is not possible. Instead, “pseudo-pure” states must be used

3. Dipolar interactions controllable by RF

N. A. Gershenfeld and I. Chuang, *Science* **275**, 350 (1997)

D. G. Cory, A. F. Fahmy, and T. F. Havel, *Proc. Natl. Acad. Sci. USA* **94**, 1634 (1997)

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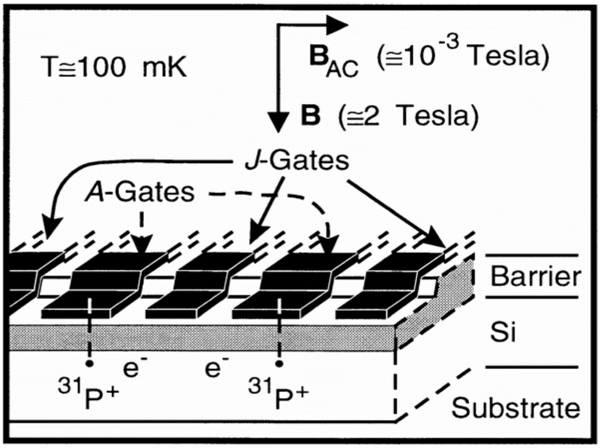
Solid-State Impurity NMR QC



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

1. Isolated impurity nuclei provide qubits
2. Low temperature electrons allow initialization
3. Electron-mediated interactions controlled by gates
4. Single-spin measurement via nuclear-electron coupling is proposed
5. Well-separated impurities have long decoherence times

Motivation

Solution NMR QC

N. A. Gershenfeld and I. Chuang,
Science **275**, 350 (1997)
D. G. Cory, A. F. Fahmy, and T. F. Havel,
Proc. Natl. Acad. Sci. USA **94**, 1634 (1997)

Advantages:
Ensemble measurement
Natural (chemical) fabrication

Disadvantages:
Challenging to scale to many qubits and/or gates
Initialization difficult

Solid-State Impurity QC

B. E. Kane, *Nature* **393**, 133 (1998)
R. Vrijen, *et al., Phys. Rev. A* **62,** 012306 (2000)
G.P. Berman, G. D. Doolen, P. C. Hammel, and
V. I. Tsifrinovich, *Phys. Rev. B* **61**, 14694 (2000).

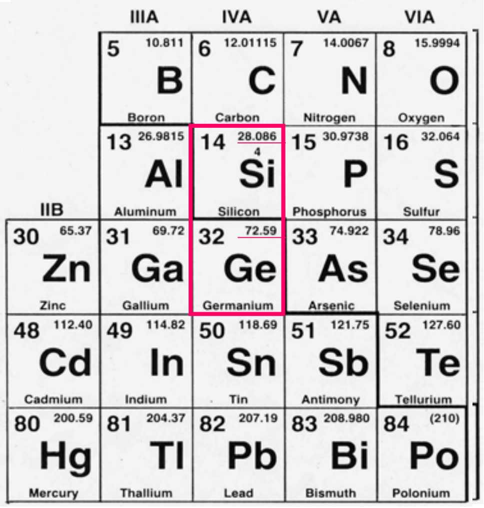
Advantages:
Scalable!
Can cool to low temperatures for initialization

Disadvantages:
Need single-spin measurement
Challenging fabrication

All Silicon QC uses advantages of both!

Semiconductor Isotope Engineering

Silicon : Si
Germanium:Ge
Silicon-Germanium: SiGe



IIB	IIIA	IVA	VA	VIA
	5 10.811 B Boron	6 12.01115 C Carbon	7 14.0067 N Nitrogen	8 15.9994 O Oxygen
	13 26.9815 Al Aluminum	14 28.086 4 Si Silicon	15 30.9738 P Phosphorus	16 32.064 S Sulfur
30 65.37 Zn Zinc	31 69.72 Ga Gallium	32 72.59 Ge Germanium	33 74.922 As Arsenic	34 78.96 Se Selenium
48 112.40 Cd Cadmium	49 114.82 In Indium	50 118.69 Sn Tin	51 121.75 Sb Antimony	52 127.60 Te Tellurium
80 200.59 Hg Mercury	81 204.37 Tl Thallium	82 207.19 Pb Lead	83 208.980 Bi Bismuth	84 (210) Po Polonium

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Semiconductor Isotope Engineering (2)

List of stable isotopes

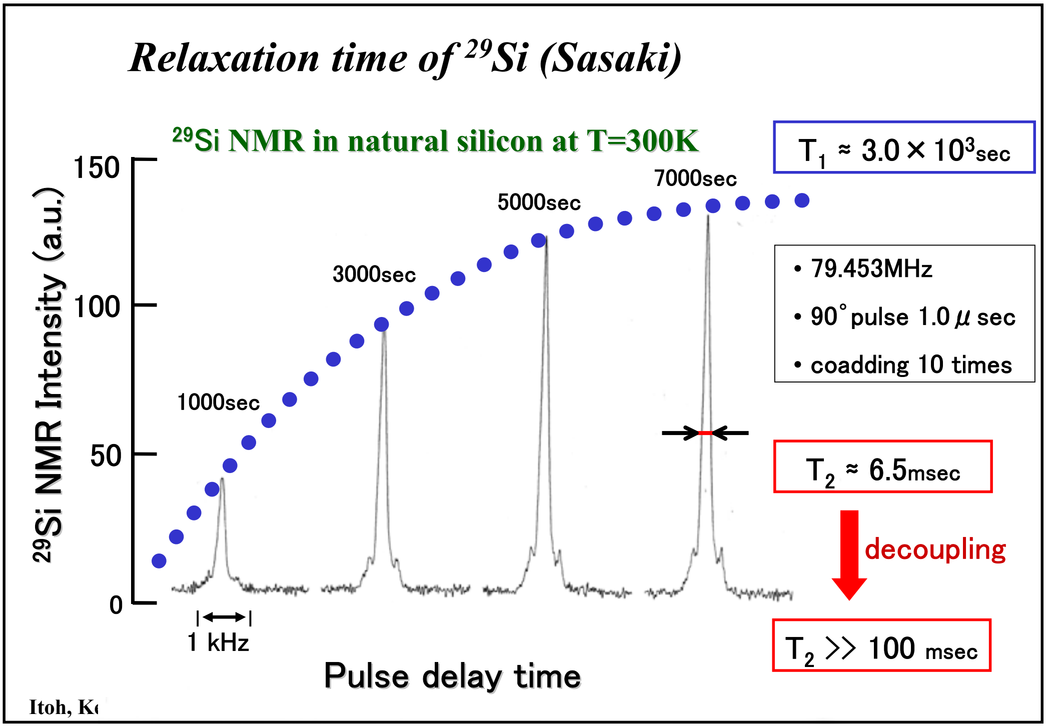
^{28}Si 92.2%
^{29}Si 4.7% → 1/2 （nuclear spin）
^{30}Si 3.1%

^{70}Ge 20.5%
^{72}Ge 27.4%
^{73}Ge 7.8% → 9/2 （nuclear spin）
^{74}Ge 36.5%
^{76}Ge 7.8%

^{69}Ga 60.1% → 3/2
^{71}Ga 39.9% → 3/2 （nuclear spin）

^{75}As 100% → 3/2

Nuclear spin control through manipulation of stable isotopes



Relaxation time of ^{29}Si (Sasaki)

$T_1 \approx 3.0 \times 10^3$sec

- 79.453MHz
- 90° pulse 1.0 μ sec
- coadding 10 times

$T_2 \approx 6.5$msec

decoupling

$T_2 >> 100$ msec

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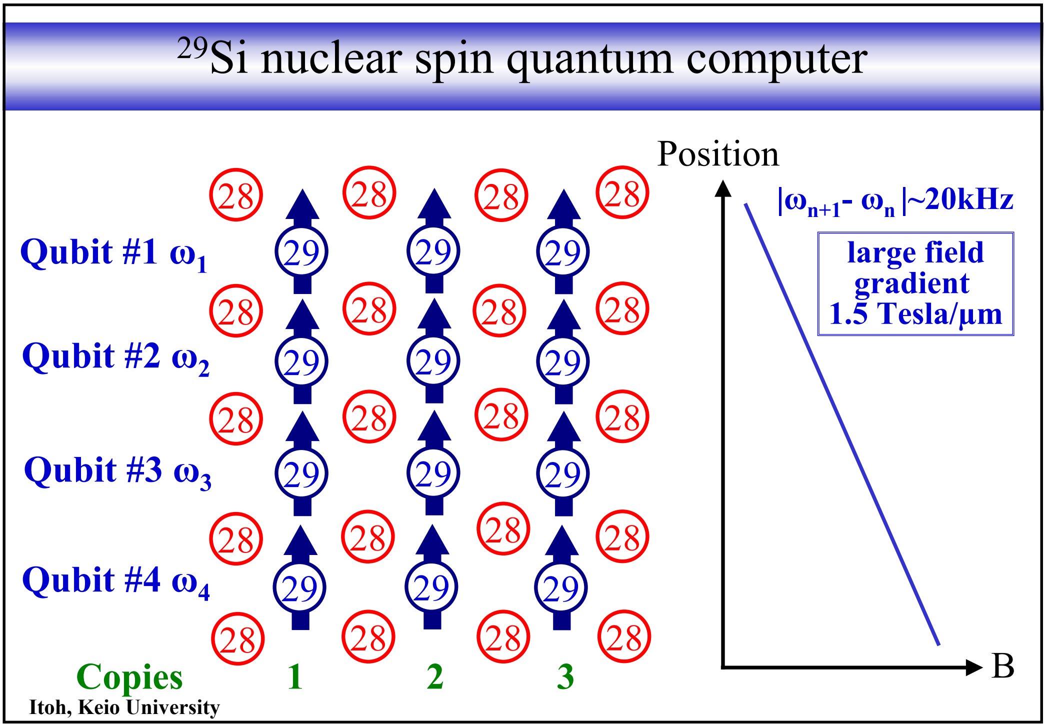

^{29}Si nuclear spin quantum computer

Qubit #1 ω_1

Qubit #2 ω_2

Qubit #3 ω_3

Qubit #4 ω_4

$|\omega_{n+1}- \omega_n|$~20kHz

large field gradient 1.5 Tesla/µm

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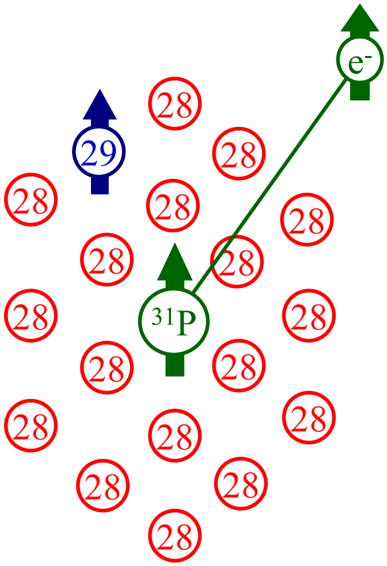
Elimination of background spins



qubits: phosphorus donors in
Si and SiGe
Kane: nuclear spin of ^{31}P
Yablonovitch: electron spin

Elimination of ^{29}Si (s=1/2) and ^{73}Ge(s=9/2) in the background is important!

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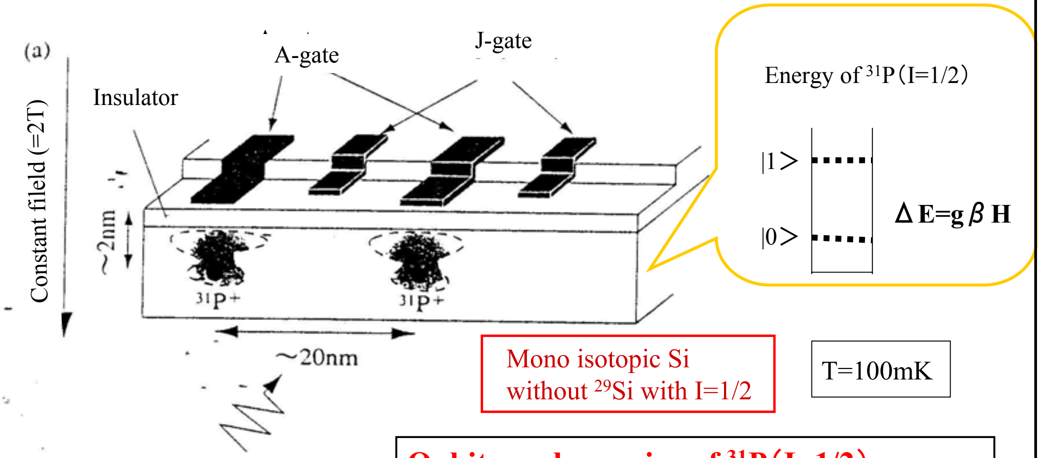
Kane’s nuclear spin quantum computer

Ref. B.Kane,Nature **393**,133(1998)



Mono isotopic Si without ^{29}Si with I=1/2

T=100mK

RF magnetic field
(~10^{-3} T)

Qubit: nuclear spins of ^{31}P（I=1/2）

Operation: A- and J-gates

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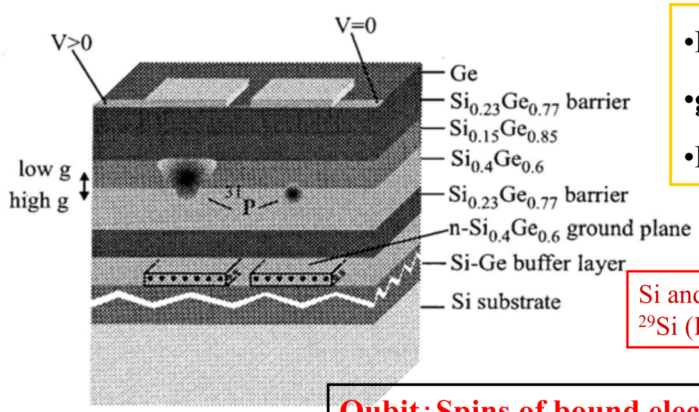
Yablonovitch's ESR quantum computer

Vrijen et al, Phys. Rev. A, 62 12306 (2000)

SiGe hetero structures (ESR trasistor)



- **Band structures**
- **g-values**
- **Bohr radius**

Si and Ge without ^{29}Si (I=1/2) and ^{73}Ge (I=9/2)

Qubit : Spins of bound electrons of ^{31}P（I=1/2）

Operation : A-gate

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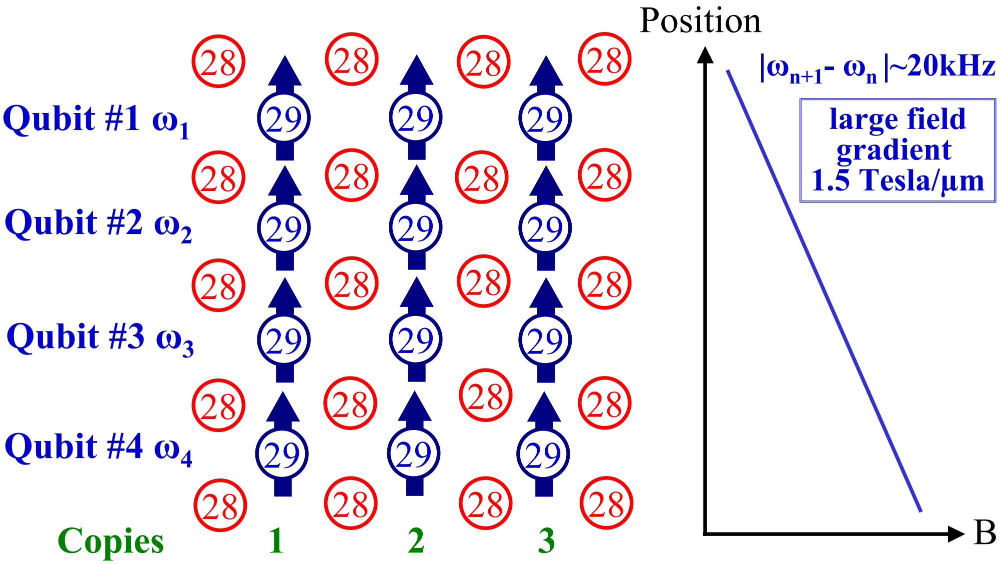
^{29}Si nuclear spin quantum computer



Qubit #1 ω_1

Qubit #2 ω_2

Qubit #3 ω_3

Qubit #4 ω_4

Copies 1 2 3

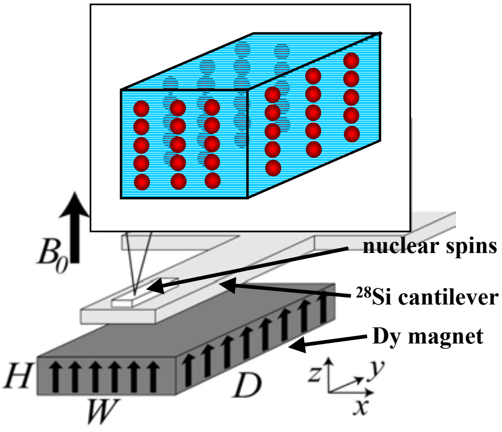
$|\omega_{n+1} - \omega_n|$~20kHz

large field gradient 1.5 Tesla/µm

An all silicon quantum computer

- ***Qubits are spin-1/2 ^{29}Si nuclei in a ^{28}Si crystal***. They are distinguished by a one-dimensional ***field gradient***.
- Initialization is accomplished by cooling, optical pumping, “boosting,” and “pseudo-pure state” techniques.
- Qubit interactions (***decoupling and recoupling***) are accomplished with RF pulse sequences.
- An ensemble of copies, orthogonal to the gradient direction, allow measurement by ***MRFM***.
- Decoherence times are limited by pulse sequence design, crystal purity, and cantilever stability.

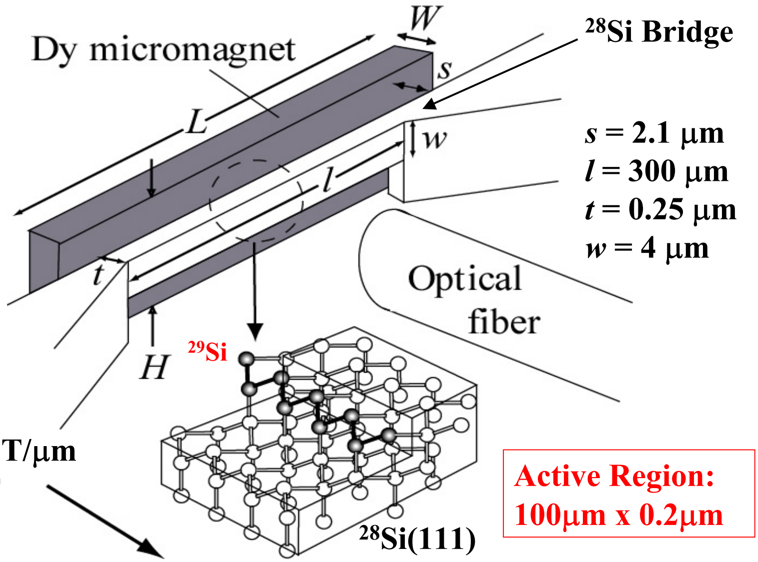
^{29}Si wires embedded in the ^{28}Si matrix



Phys. Rev. Lett. Vol. 89, 017901(2002).

Alternative configuration

L= 400 μm
W = 4 μm
H = 10 μm

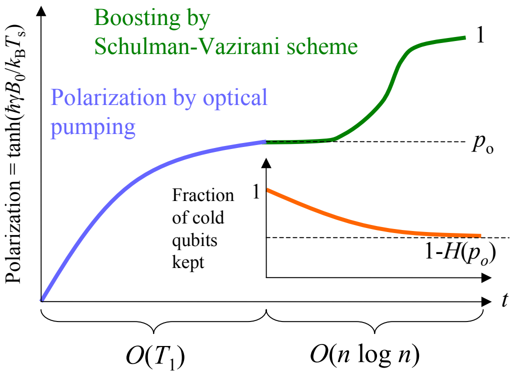


s = 2.1 μm
l = 300 μm
t = 0.25 μm
w = 4 μm

dB^z/dz = 1.4 T/μm
B_0 = 7 T

Active Region:
100μm x 0.2μm

Initialization



Long T_1 means nuclei may be cooled much lower than lattice temperature (Optical Pumping)

Then, excess qubits may be sacrificed to cool a subset (Boosting)

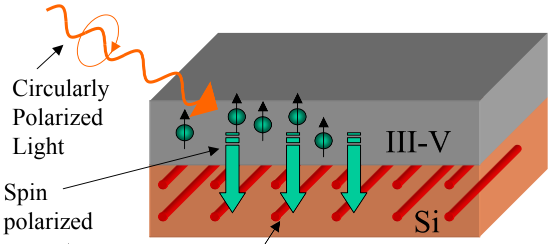
L. J. Schulman and U. V. Vazirani, *Proc. 31st ACM Symp. on Theory of Computing,* 322 (1999)
D. E. Chang, L. M. K. Vandersypen, and M. Steffan, quant-ph/0011055 (2001)

Finally, logical labeling may be used to establish an effective pure state

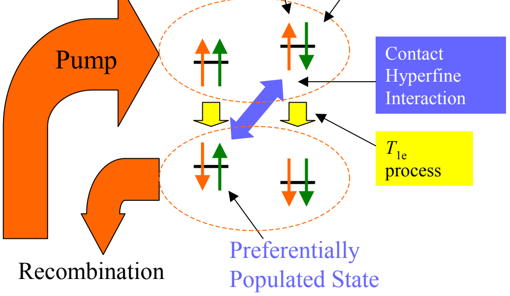
Higher polarization ⇔ Lower T_s
⇔ More logically labeled qubits

N. A. Gershenfeld and I. L. Chuang, *Science* **275**, 350 (1997)
L. M. K. Vandersypen, C.S. Yannoni, M. H. Sherwood, and I. L. Chuang, *Phys. Rev. Lett.* **83**, 3085 (1999)

Polarization by optical pumping

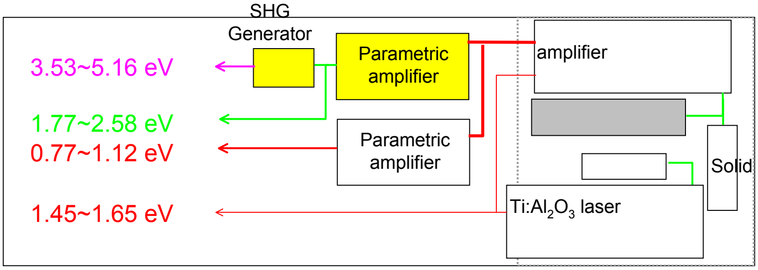


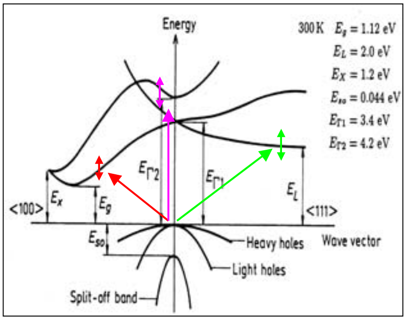
The spin-polarized conduction electrons are cleared away after polarization, removing them as decoherence source



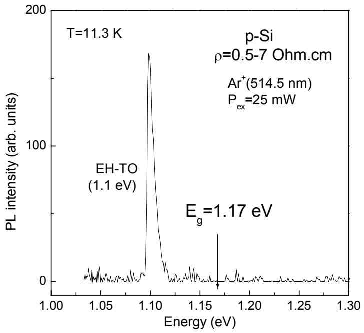
G. Lampel, *Phys. Rev. Lett.* **20,** 491 (1967)
R. Tycko, *Solid State Nuclear Magnetic Resonance* **11,** 1 (1998)

Optical initialization of electron (and nuclear) spins



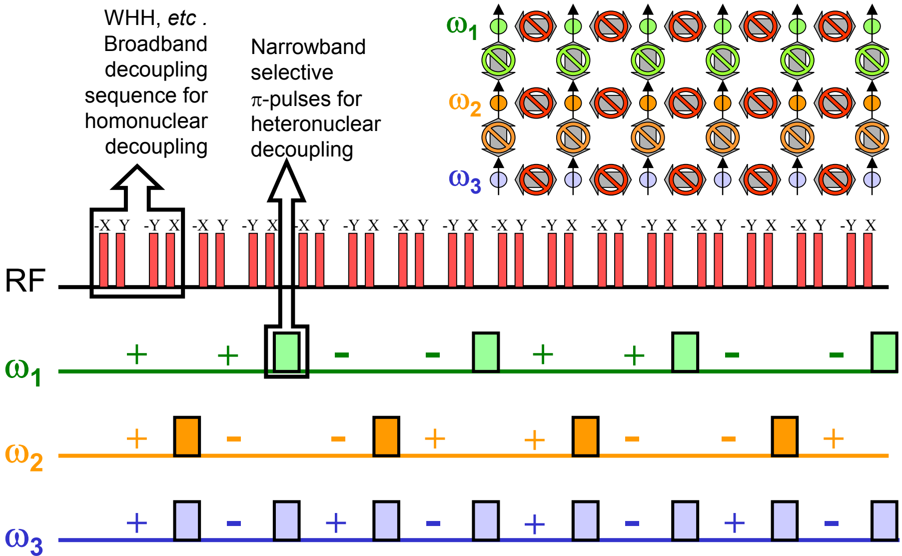


Various excitation of electrons in Si



Si PL

Operation (decoupling)



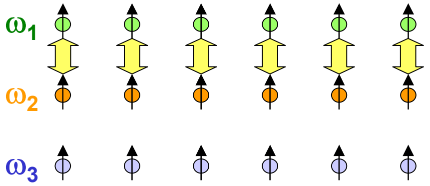
WHH, *etc* . Broadband decoupling sequence for homonuclear decoupling

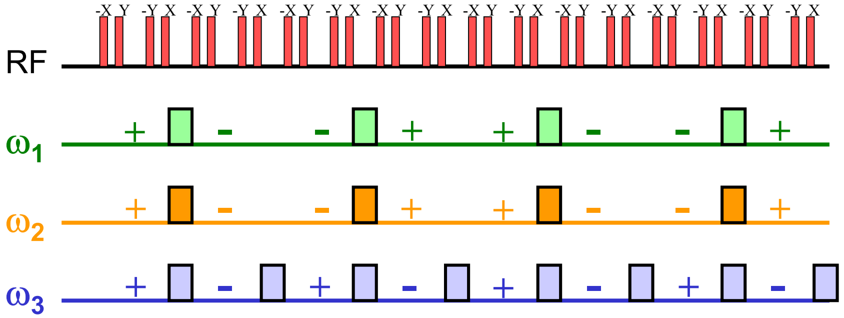
Narrowband selective π-pulses for heteronuclear decoupling

Operation (recoupling)

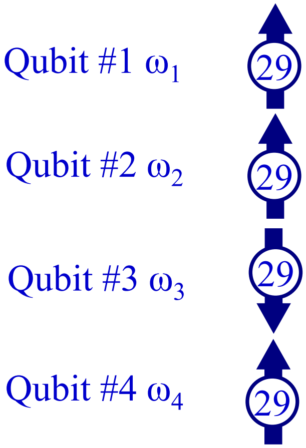
D. W. Leung, I. Chuang, F. Yamaguchi and Y. Yamamoto, Phys. Rev. A, 61(4) 042310/1 (1999)

- Qubits may be selectively recoupled
- Add single spin rotations to make controlled-NOT

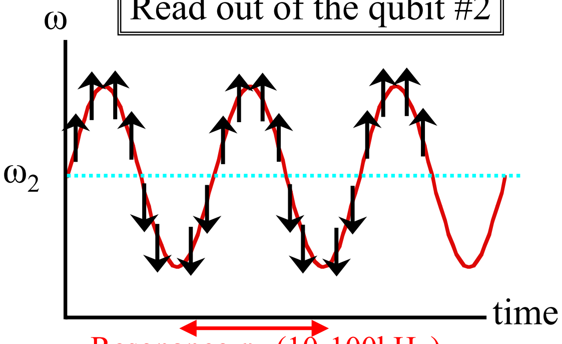




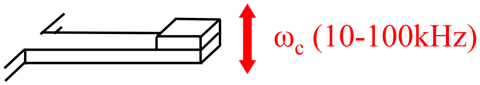
Read-out by the MRFM cantilever



Read out of the qubit #2



Resonance ω_c (10-100kHz) of the cantilever



SNR and number of qubits

Force resolution for a cantilever in the thermal limit:

$$F_{\min} = \sqrt{4kk_B TB/\omega_0 Q}$$

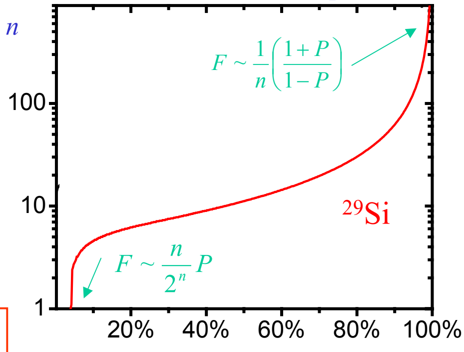
Force generated from a single atomic plane:

$$F(t) = M_z(r,t)\frac{\partial B_z}{\partial z}$$

Magnetization for nuclear spins in plane:

$$M_z = \gamma\hbar IN\left[\left(\frac{1+P}{2}\right)^n - \left(\frac{1-P}{2}\right)^n\right]$$

Number of qubits (n) for SNR = 1 vs. nuclear polarization



nuclear polarization (P)

N = number of qubit copies

n = number of qubits in QC

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Decoherence and th emaximum operation step

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{\gamma^2}{2}\int_{-\infty}^{\infty}\langle\partial B_Z(t)\partial B_Z(0)\rangle dt + \left(\langle[H_{\text{dip}}^{\text{res}},[H_{\text{dip}}^{\text{res}},I^X]]\rangle/\langle I^X\rangle\right)^{1/2}$$

DC spectral density of local fluctuating field

Second Moment due to residual dipolar couplings

Primary Decoherence Sources:

Residual Dipolar Couplings

Reversible in principle

Present sequence: $T_2 \sim 10$ ms

Cantilever Drift

Thermal equilibrium: $T_2 \sim 200$ ms

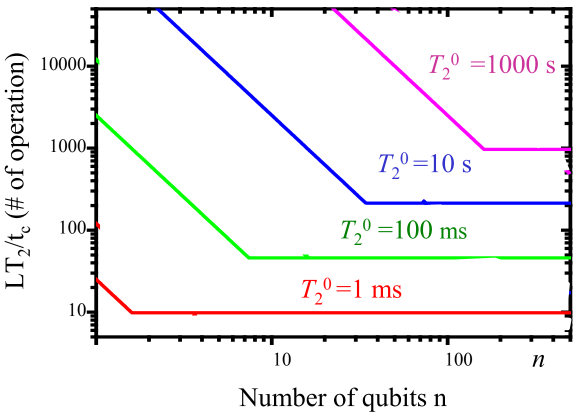
Feedback control ⇒ $T_2 \sim 1$ hour

Paramagnetic Impurities

Assuming very dilute impurities, $T_2 \sim (\omega_0 T_{1e})^{-1/2} T_1 \sim 1$ minute, but much shorter for nuclei near impurity

Clock period $t_c = Ln^2/\Delta\omega$ set by pulse sequence.

⇒ Number of logic gates T_2/t_c is limited



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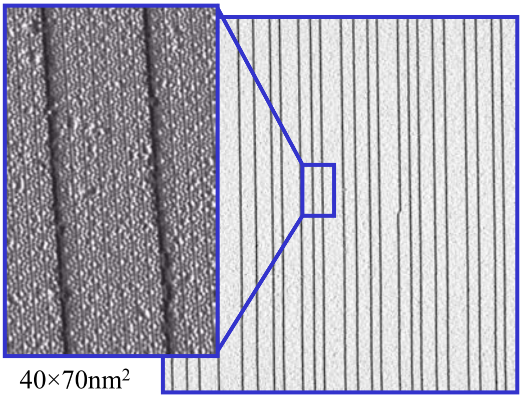
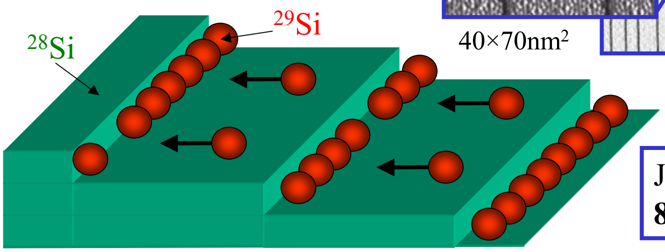
^{29}Si wire fabrication

- Form regular step arrays on slightly miscut ^{28}Si(111)7×7 surface (~ 1° from normal)
- Steps are *straight*, with about 1 kink in 20000 sites.
- ^{29}Si chains formed by "Step Decoration" from ^{28}Si steps
- Angle of miscut controls chain spacing


40×70nm²

340×390nm²



J.-L. Lin, *et al., JAP* **84**, 255 (1998)

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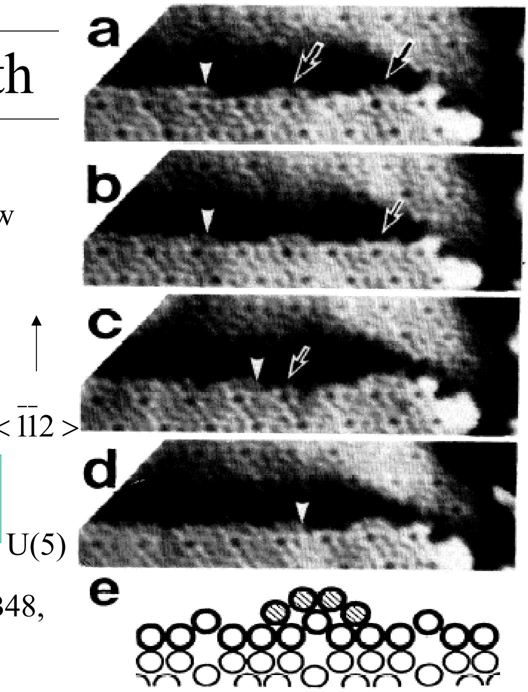
Row-by-row growth

The step-flow growth was observed as the appearance of new adatoms at the edge

Short rows are thermally diffused to form a longer row which is energetically stable

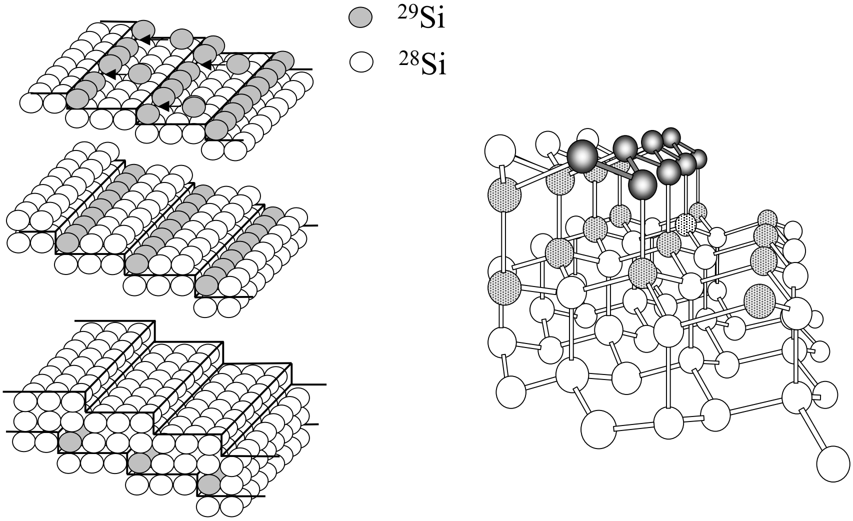
T_{sub} 350℃
Growth rate 0.8×10^{-2}BL/min



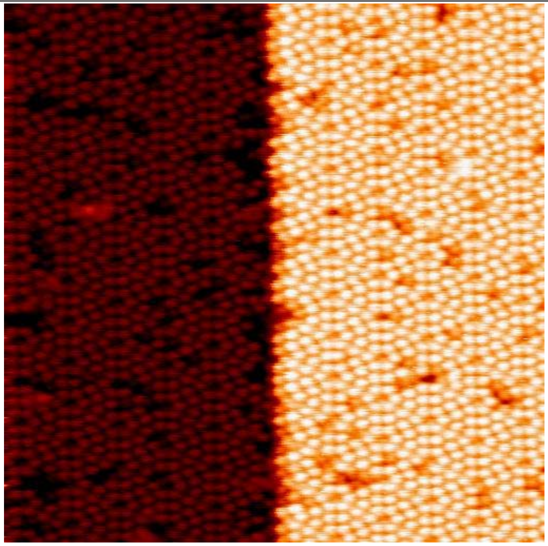
T. Hasegawa, et al., Phys. Rev. B48, 1943 (1995).

Ito

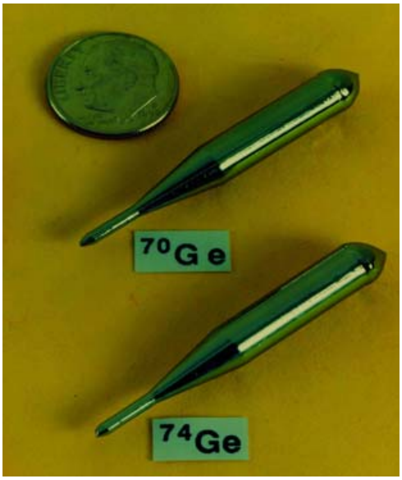
MBE fabrication of ^{29}Si wire copies



Progress at Keio

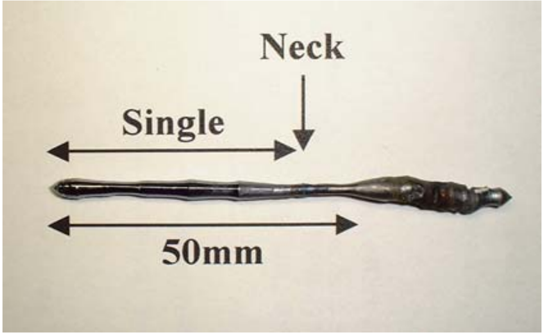


Progress on Isotope Engineering at Keio



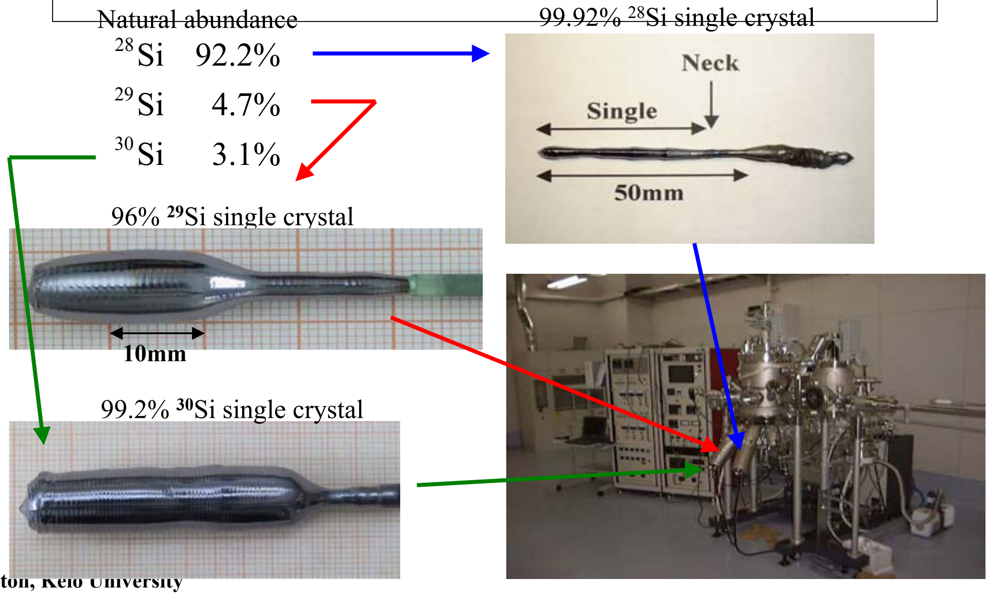
J. Mater. Res. 8, 1341 (1993)

99.92% ^{28}Si single crystal



Jpn. J. Appl. Phys. 38, L1493 (1999)

Isotopically controlled Si fabrication



Natural abundance

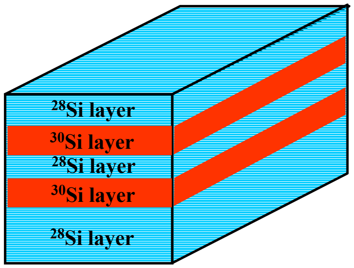
^{28}Si	92.2%
^{29}Si	4.7%
^{30}Si	3.1%

99.92% ^{28}Si single crystal

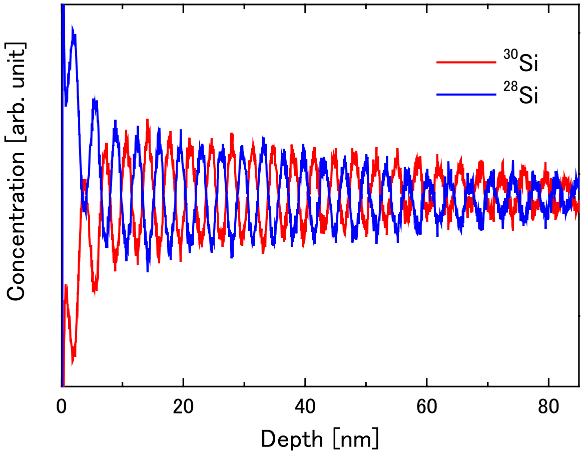
96% ^{29}Si single crystal

99.2% ^{30}Si single crystal

^{28}Si/ ^{30}Si Isotope Superlattices



Depth profile of ^{28}Si and ^{30}Si of the $[(^{28}\mathrm{Si})_{16}/(^{30}\mathrm{Si})_{16}]_{50}$ superlattice



Phonons in Si SLs

Phonons of $(^{28}\mathrm{Si})_n/(^{30}\mathrm{Si})_n$ SLs

Ex) $(^{28.}\mathrm{Si})_4/(^{30}\mathrm{Si})_4$

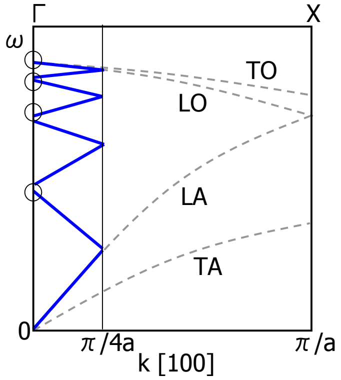


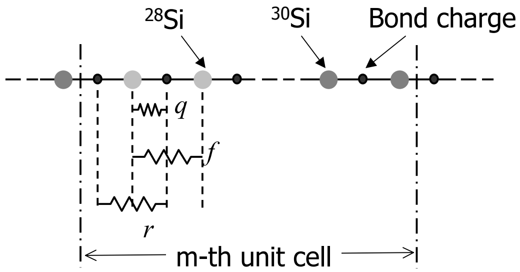
Fig. Si phonon dispersion relation

(------ : bulk Si, ▬ : $(^{28}\mathrm{Si})_4/(^{30}\mathrm{Si})_4$)

Calculation of Phonon Frequency

⇨ Planar-Bond Charge (PBC) Model

P. Molinàs-Mata, A. J. Shields, and M. Cardona, Phys. Rev. B **47**, 1866 (1993)



Raman Spectrum of SL

Raman spectroscopy

$[(^{nat.}Si)_{16}/(^{30}Si)_{16}]_{50}$

Conditions

- ✓ Laser: 514.5 nm
- ✓ Temp.: ~ 4 K

Phonon folded mode can be confirmed.

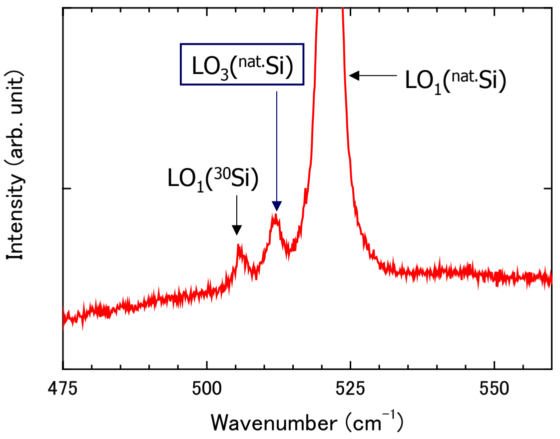


Fig. Raman spectrum of $[(^{nat.}Si)_{16}/(^{30}Si)_{16}]_{50}$ superlattice

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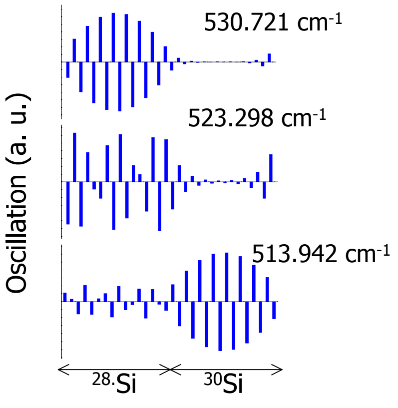
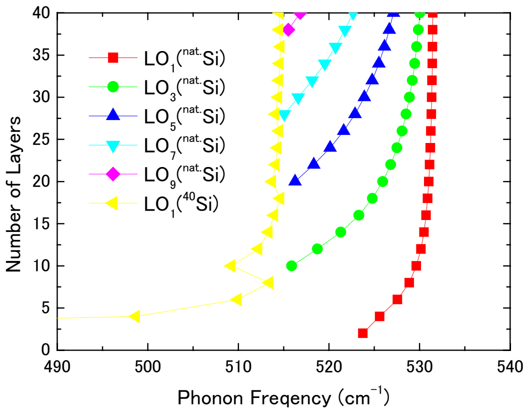
Expected Raman Peaks

Ex) $(^{28.}Si)_{16}/(^{30}Si)_{16}$

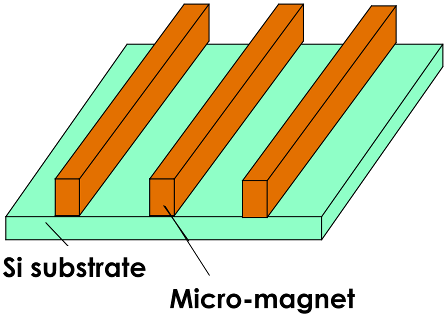


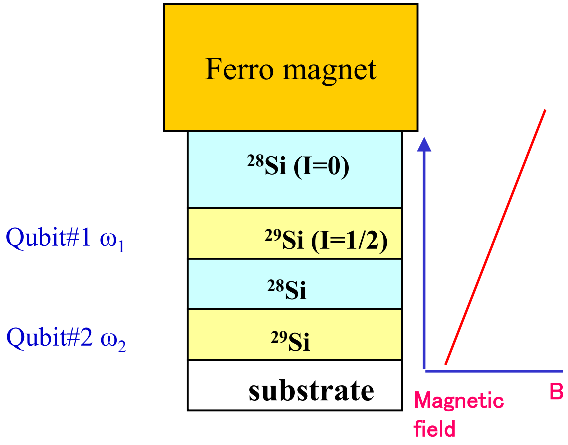
Oscillation of atoms



Expected Raman peaks of $(^{nat.}Si)_n/(^{30}Si)_n$ superlattices calculated by PBC model (n: even numbers)

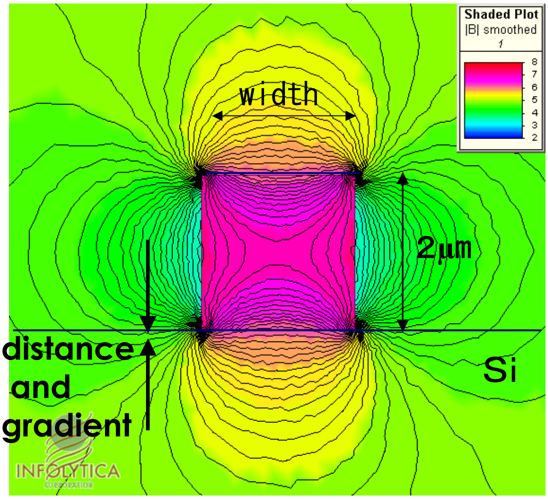
Micro-magnet fabrication

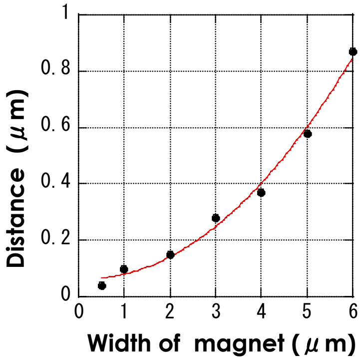


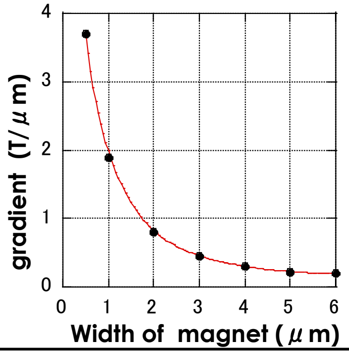


Homogeneity and Strong gradient

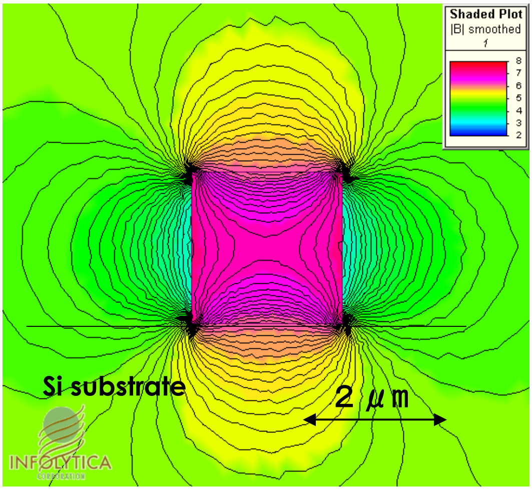
Magnetic field simulation



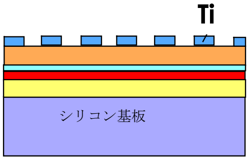




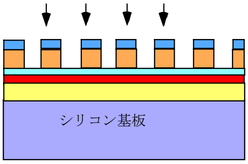
Field simulation and micro-fabrication



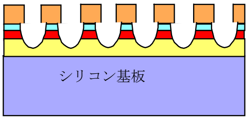
NH$_3$/CO/Xe reactive etching of NiFe



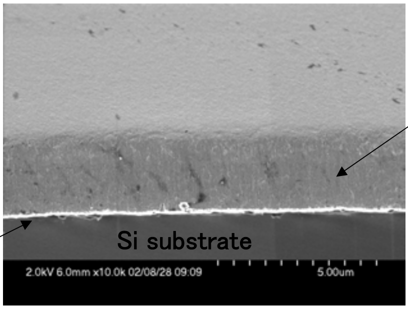
SF$_6$ reactive etching of Si

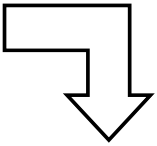


Optical pumping and NMR

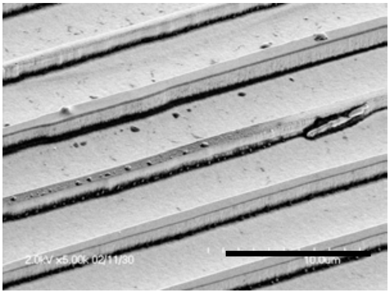


Sputter growth growth and reactive ion etching of NiFe



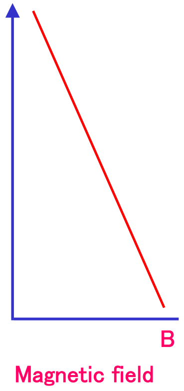


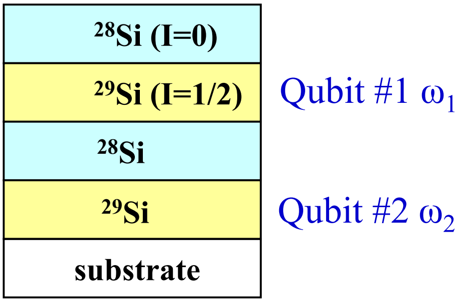
After reactive ion etching



Next-step: $^{29}Si/^{28}Si$ isotope superlattice

Proof of concepts





^{28}Si (I=0)

^{29}Si (I=1/2) Qubit #1 ω_1

^{28}Si

^{29}Si Qubit #2 ω_2

substrate

In-plane coupling of ^{29}Si
may severely limit the scaling

Summary

- **Semiconductor Isotope Engineering**
- **New quantum computation scheme exclusively with silicon**
- **Fabrication of the all silicon quantum computer at Keio**

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