. . .working with industry to develop and apply technology, measurements and standards

Quantum Information Storage in the Solid State

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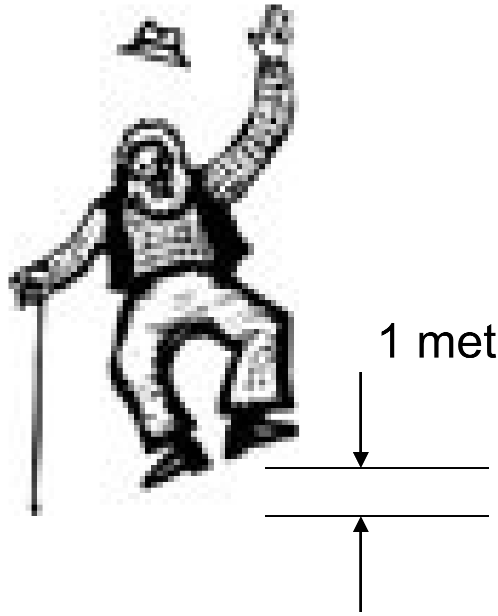
Misnomer? Something.. “took a Quantum Leap!”



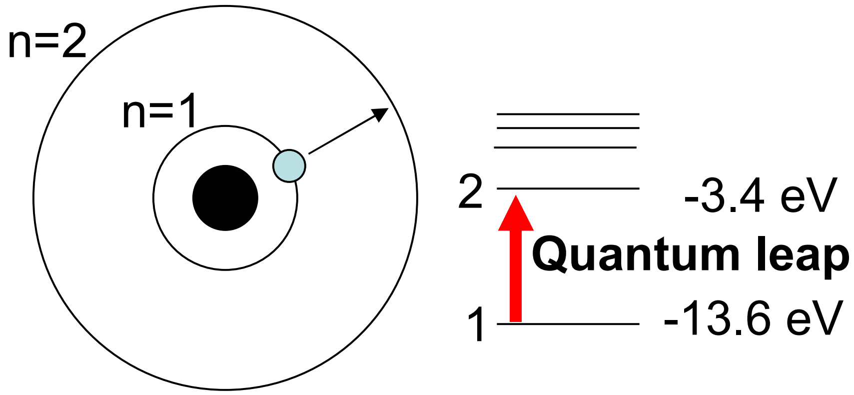
$\Delta E = mgh$

$= (60\ \text{kg}) \times (9.8\ \text{m/s}^2) \times 1\ \text{m}$

$= 600\ \text{kg m}^2/\text{s}^2$

$\Delta E \sim 600$ Joules

Hydrogen atom energy levels



$\Delta E = 10$ electron-volts

1 eV $= 1.602 \times 10^{-19}$ Joules

Quantum Leap - $\Delta E \sim 1 \times 10^{-18}$ Joules

Equivalent of man jumping **0.000 000 000 000 000 001** meters high
< millionth of an atom

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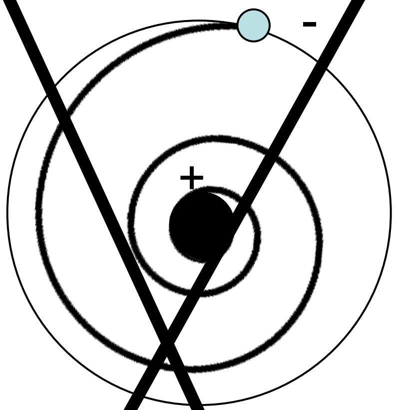
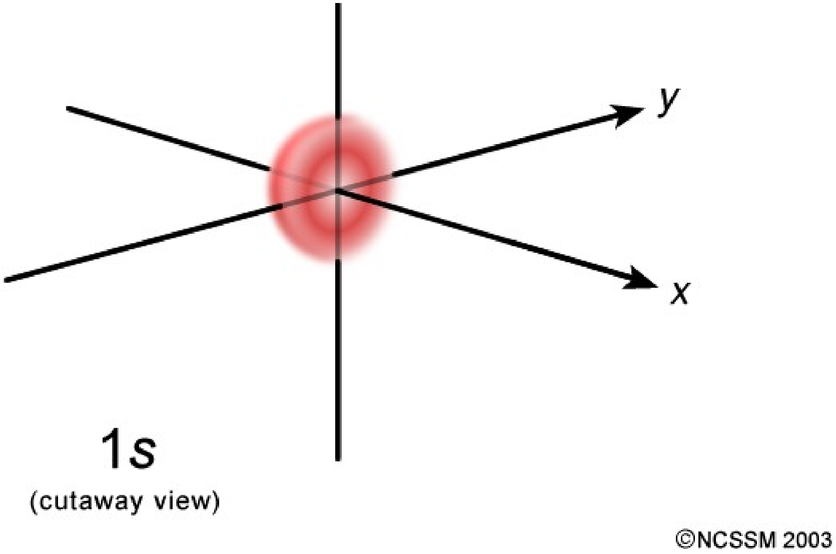
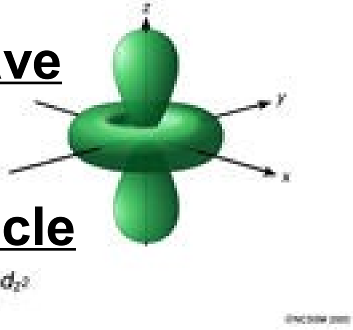
"Quantum Leap" ≡ fundamental change in paradigm

~~Classical Hydrogen~~ => Quantum Hydrogen



- ~~**electron charged particle**~~
  - ~~**accelerating e^- loses energy**~~
  - ~~**spirals in**~~
  - ~~**atom collapses**~~

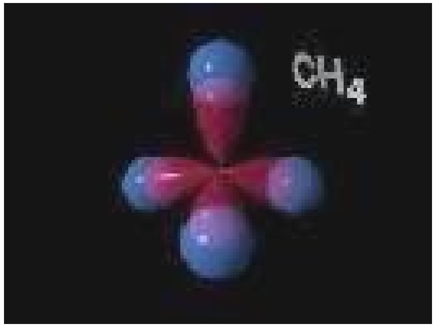




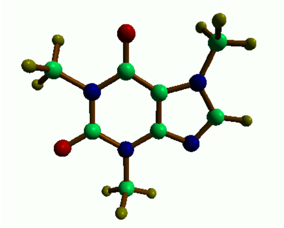
- **electron acts like a wave**
  - **not measured**
- **electron acts like particle**
  - **when measured**
  - **at some position**

Quantum mechanics is Nature’s calculator …very very fast

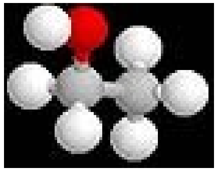
- Example – Self assembly of atoms into molecules



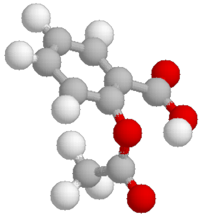
Caffeine



Ethanol

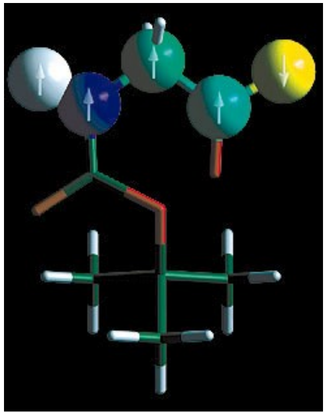


Aspirin



- Difficult for classical computer to simulate the simplest molecule
- Can we turn situation around?
  - make artificial quantum systems.
  - redefine rules=> system solves problem

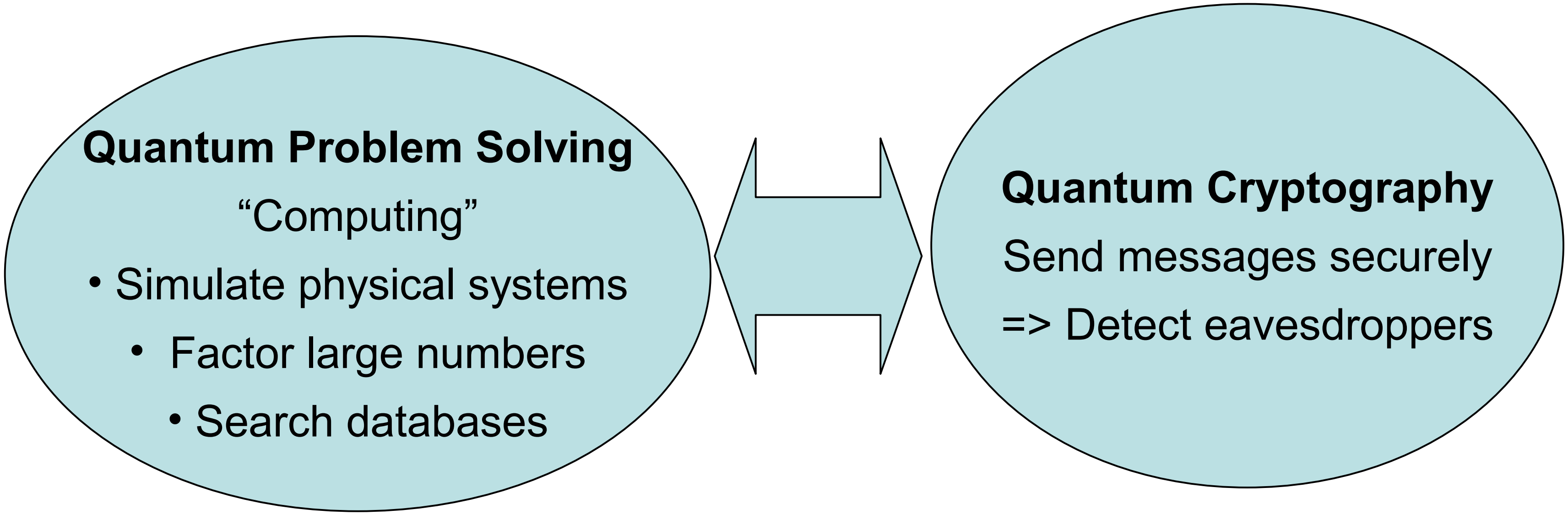
5 “qubit” molecule
NMR



R. Marx, A. F. Fahmy, J. M. Myers, W. Bermel, S. J. Glaser
Phys. Rev. A 62, 012310-1-8 (2000)

BOC-(13C2-15N-2D -glycine)-fluoride

Quantum Information



Quantum Problem Solving

"Computing"

- Simulate physical systems
- Factor large numbers
- Search databases

Quantum Cryptography

Send messages securely

=> Detect eavesdroppers

- What is different about Quantum Information?
- How is it useful?
- Can we control it?
  - Software
  - Hardware

Early history of Quantum Information

"It seems that the laws of physics present no barrier to reducing the size of computers until bits are the size of atoms and quantum behavior holds sway."
Richard Feynman

1970's
Quantum Crypotography
Stephen Weisner
"Conjugate Coding"

1982

1984
Polarized photons
Bennett, Brassard

David Deutsch
"Quantum
Computer"
1985

1991
Entangled photons
Artur Ekert

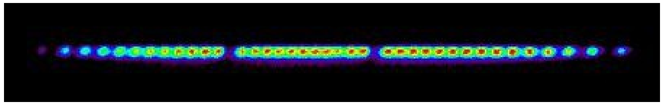
Deutsch, Josza
algorithm
"balanced function"
1992

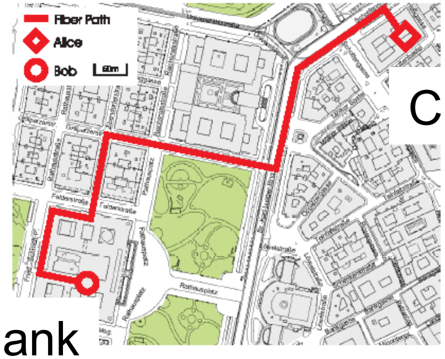
Peter Shor
Factoring
Algorithm
1994

QC - Lov Grover
Quantum Search
1996

Progress in Quantum Information

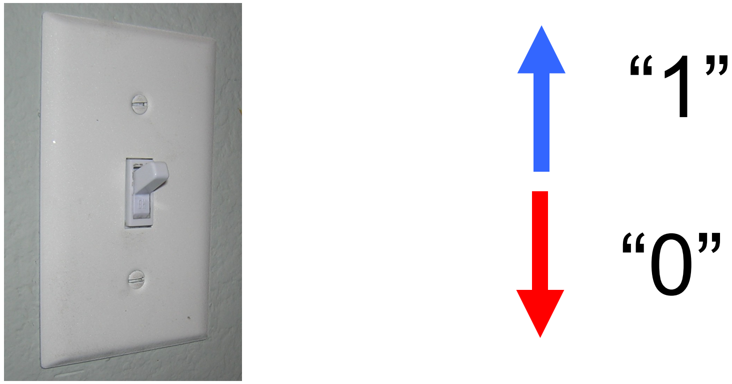
- Quantum Computing
  - Software
    - Quantum error correction – Steane, Shor PRL (1996)
    - Fault tolerant algorithms – Knill, Nature (2005)
  - Hardware
    - NMR quantum computers have reached 5 bits
      - Grovers algorithm - Vandersypen APL (2000)
      - Shor’s alorithm - Nature (2001)
    - Ion traps – demonstrated factoring
      - Semi-classical QFT – Wineland, Science (2005)
      - Quantum error correction – Nature (2004)
      - Six atom Schroedinger Cat State – Nature (2005)
    - Linear optics gate with photons – Franson PRA (2001)
    - Solid state qubits demonstrate 2 coupled qubits
- Quantum cryptography
  - Demonstrated, tested
    - Practical demos - Zeilinger Optics Expr. (2004)
    - 1.45 km through Vienna sewer system
  - Scaling up to commercial products





Quantum Logic – digital

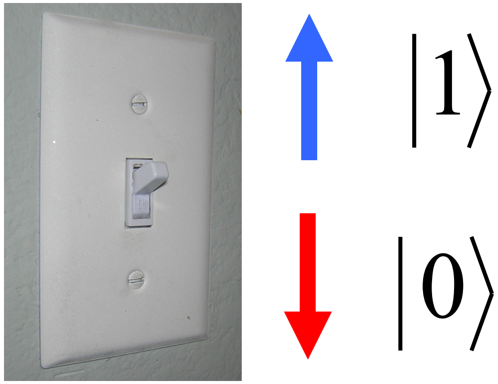
- **Classical Bit**



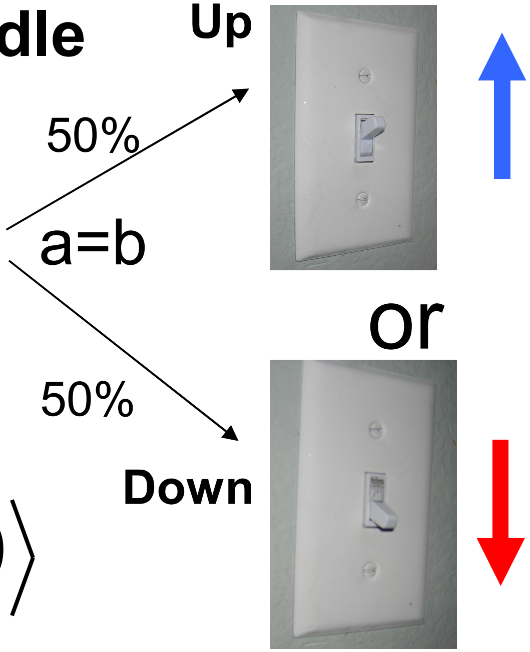
- **Quantum bit (qubit)**

Set in the middle

Measure



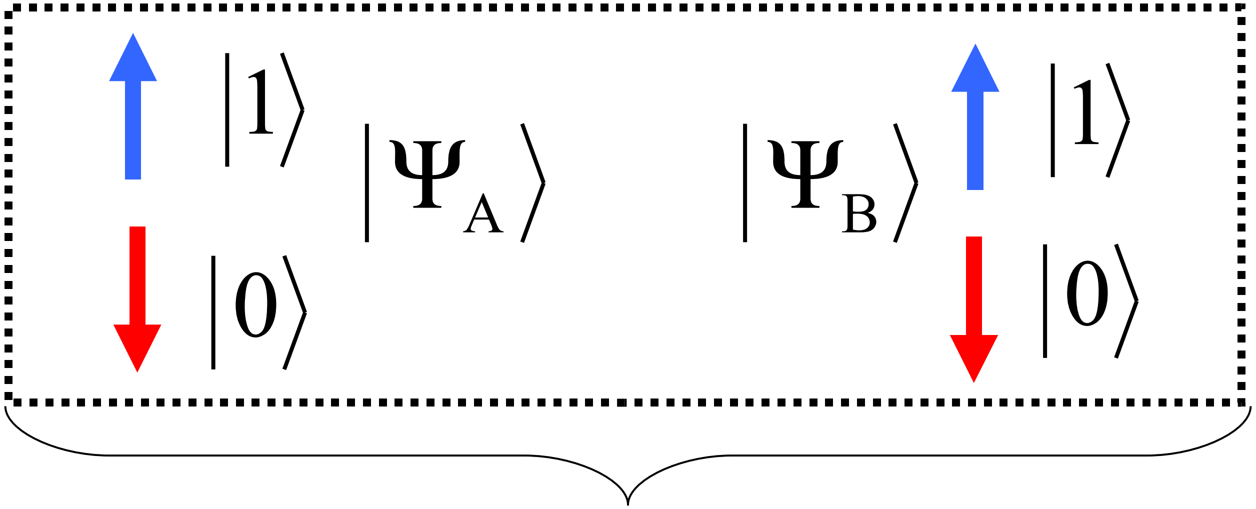
OR



$$\Psi = a|1\rangle + b|0\rangle$$

amplitudes

System of two qubits



$$|\Psi_A\Psi_B\rangle = \underset{\uparrow}{a}|00\rangle + \underset{\uparrow}{b}|01\rangle + \underset{\uparrow}{c}|10\rangle + \underset{\uparrow}{d}|11\rangle$$

2 Qubits => 4 amplitudes

n Qubits => 2^n

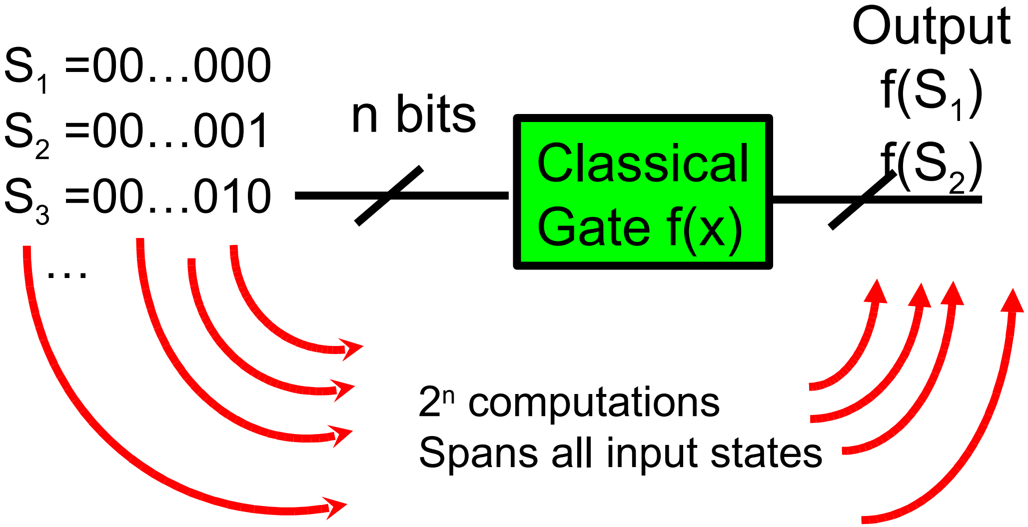
$$\begin{aligned}|\Psi\rangle = {} & a|00..000\rangle \\ & + b|00..001\rangle \\ & + c|00..010\rangle \\ & + \ldots\end{aligned}$$

$2^{128} = 3.4 \times 10^{38}$

Quantum computing – intrinsically parallel

Classical computation:

n bits => 2^n possible states



S_1 =00…000

S_2 =00…001

S_3 =00…010

…

n bits

Classical Gate f(x)

Output

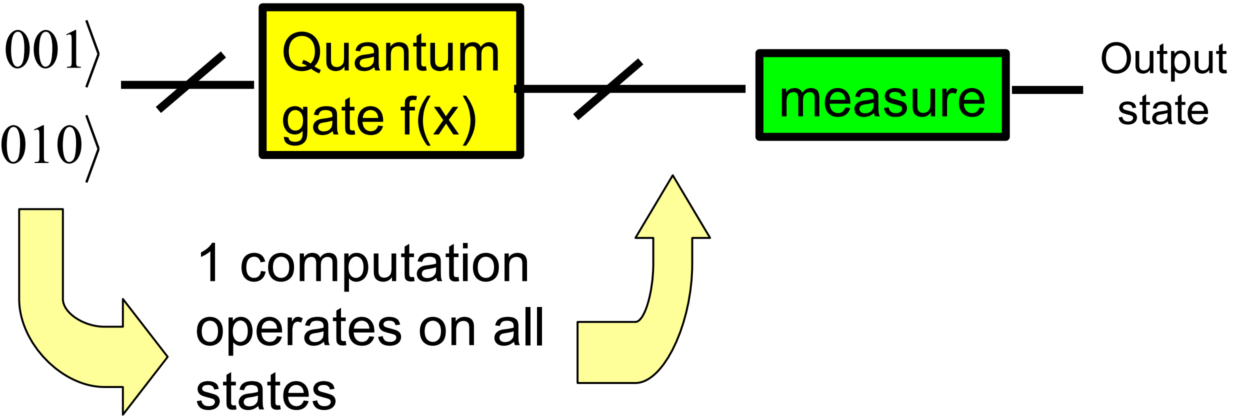
$f(S_1)$

$f(S_2)$

2^n computations
Spans all input states

Quantum computation:

$$|\Psi\rangle = a|00..000\rangle + b|00..001\rangle + c|00..010\rangle + \ldots$$



Quantum gate f(x)

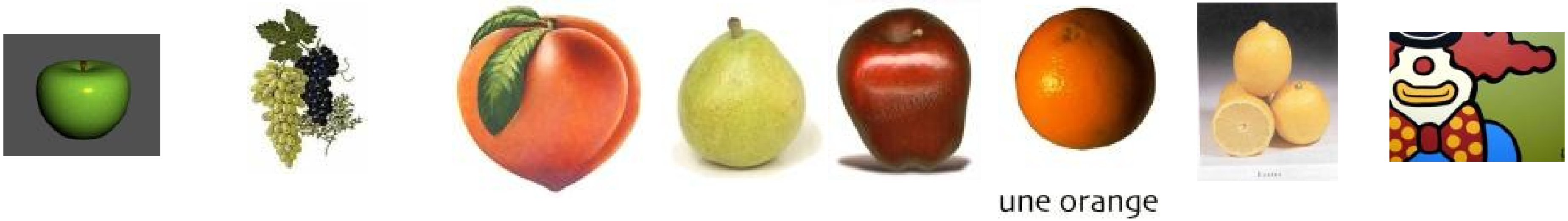
measure

Output state

1 computation operates on all states

Speed up of unsorted data search

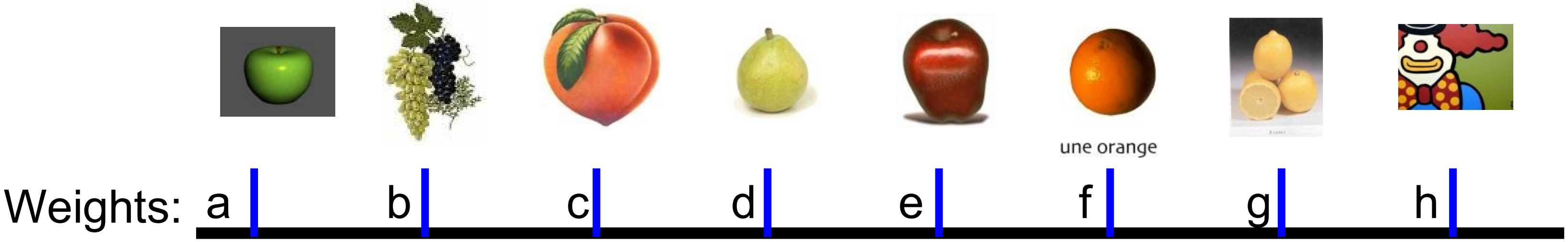
- Classical algorithm:
  - N =8 Items:



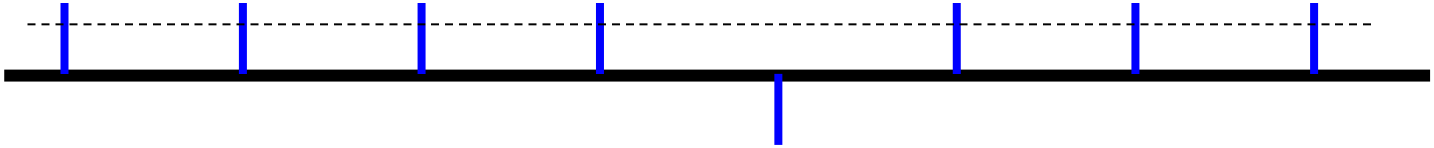
  - On average, need to search N/2 (=4) items to find 
  - : O(N)

- Quantum Algorithm:
  - Compares all coefficients at the same time

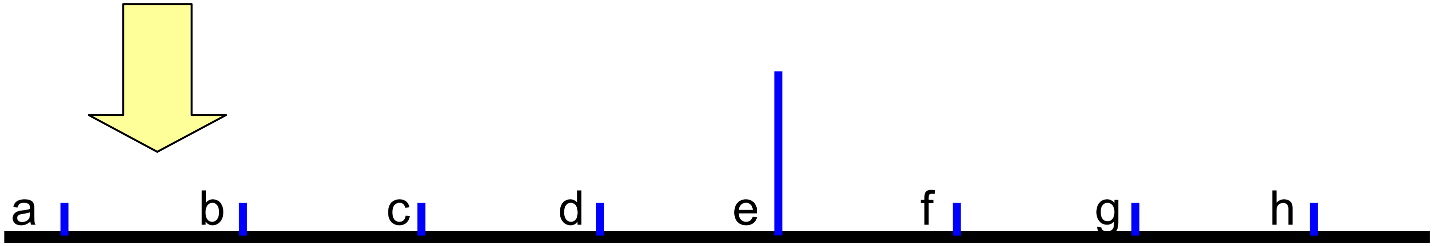
Grover’s Search Algorithm



F() =>change sign if matches

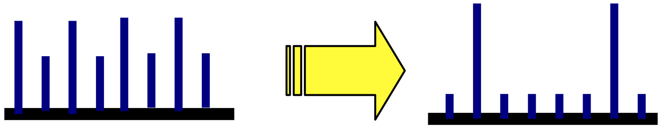


“diffusion” operator - reflect around average



Quantum problem solving is fast

- Grover's algorithms conducts search in $O(N^{1/2})$ vs. $O(N)$
  - ⇒ Quantum systems "recognize" solutions
    - ⇒ classical database doesn't gain for simple search
      - ⇒ N operations to load!
      - ⇒ Resources - NlogN amplitudes for algorithm
  - ⇒ Cryptography Key search algorithms can benefit greatly
- Deutsch – Josza => 1 iteration vs. $O(2^N)$
- Shor's algorithm factors numbers



  - – Quantum Fourier Transform:
  - – Exponential speedup: $O((\log N)^3)$ vs. $O((\log N)^k)$
  - – Global properties of Ψ
- Quantum algorithms take resources & fundamentally different mindset!

Resources - Quantum error correction

- Classical – repetition code, need 3 bits: 0≡000, 1 ≡ 111
  - Single bit flip:
    - 001, 010, 100 => 0
    - 110, 101, 011 => 1
- Quantum – Need to check two variables: $A\left|\overset{\substack{\text{bit}\\ \downarrow}}{0}\right\rangle \overset{\substack{\text{sign}\\ \downarrow}}{\pm} B\left|1\right\rangle$
  - Need 3^2 = 9 bits

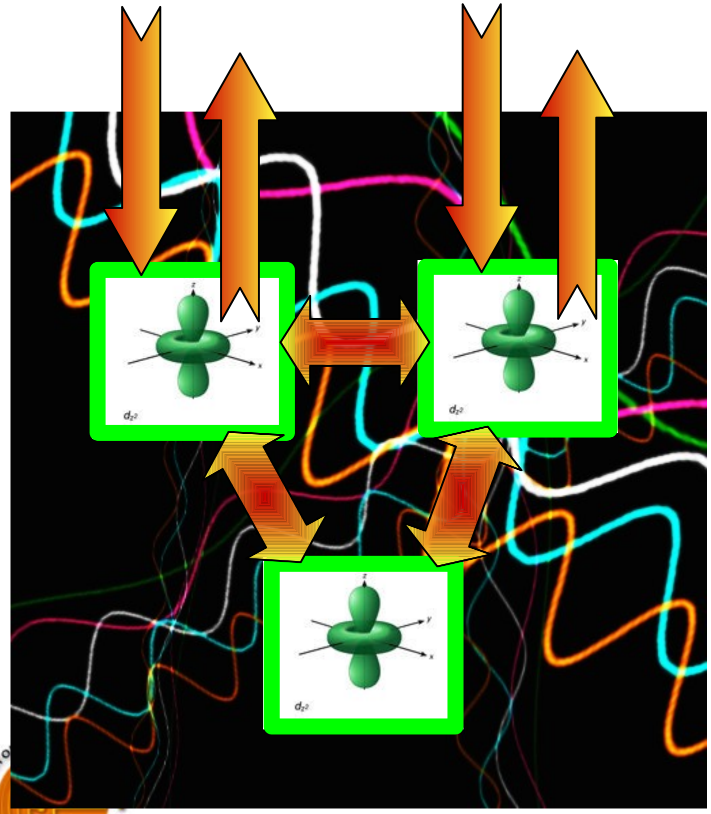
$$\left|0\right\rangle \equiv \left(\left|000\right\rangle + \left|111\right\rangle\right)\left(\left|000\right\rangle + \left|111\right\rangle\right)\left(\left|000\right\rangle + \left|111\right\rangle\right)$$

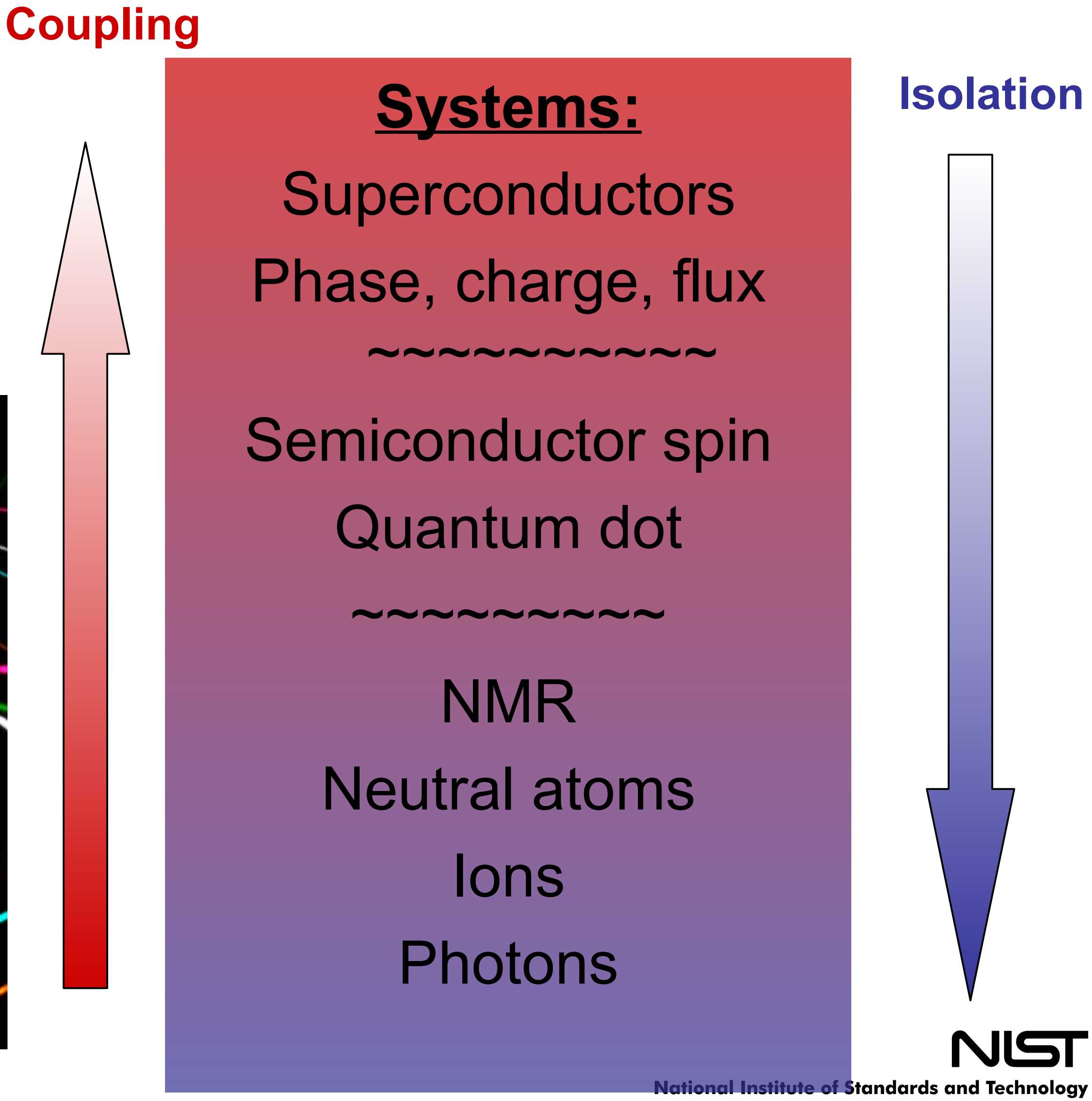
$$\left|1\right\rangle \equiv \left(\left|000\right\rangle - \left|111\right\rangle\right)\left(\left|000\right\rangle - \left|111\right\rangle\right)\left(\left|000\right\rangle - \left|111\right\rangle\right)$$

- Need hardware!

The Quantum Computing Challenge

- Initialize
- Interact
- Measure





Coupling

Systems:

Superconductors

Phase, charge, flux

~~~~~~~~~~~

Semiconductor spin

Quantum dot

~~~~~~~~~~

NMR

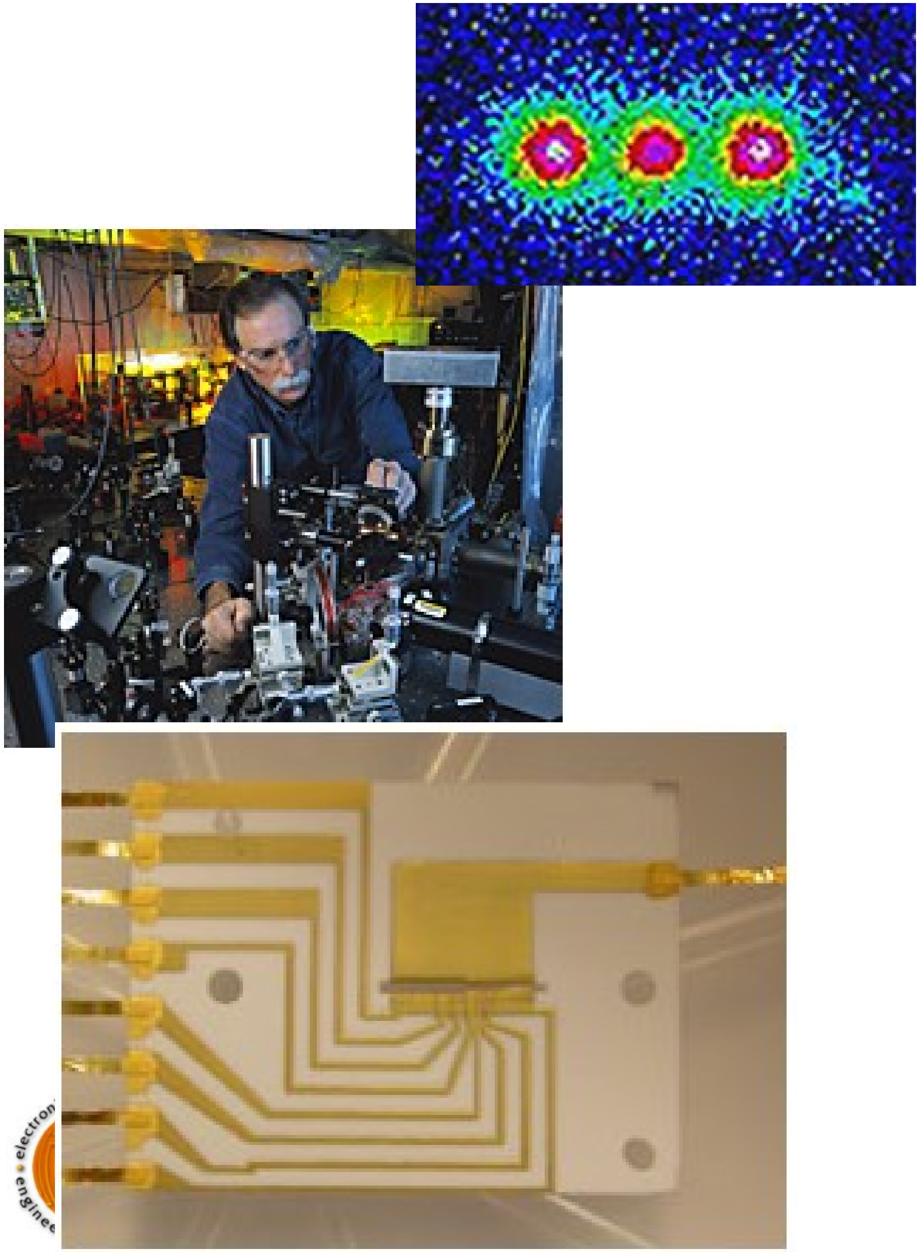
Neutral atoms

Ions

Photons

Isolation

NIST - Quantum computing with trapped ions



- $^9Be^+$ ions - MEMs RF traps
- Addressed with focused lasers
- Shuttle ions around
  - Store
  - interact
- Long coherence times
- Challenge is scaling & interaction:
  - initialization
  - operation
  - measurement

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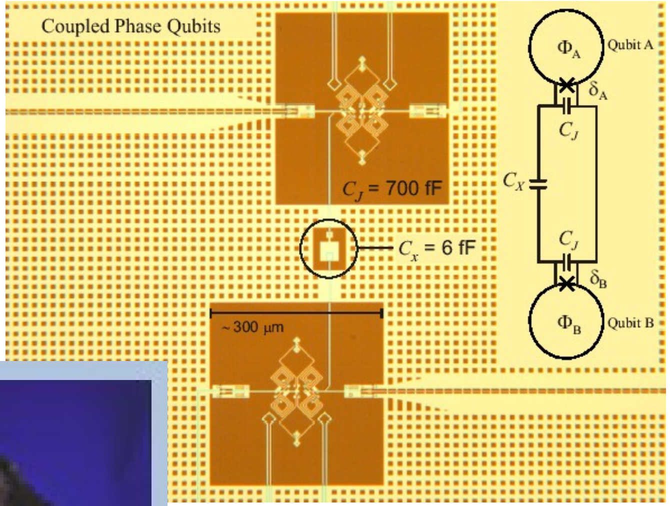
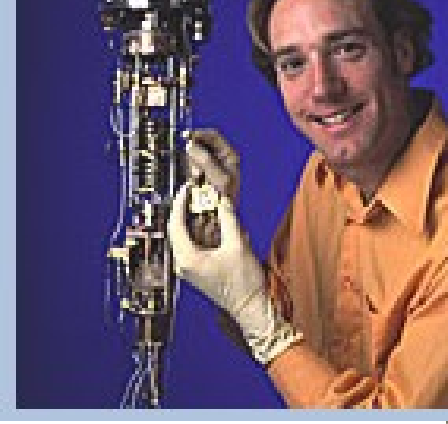
NIST – Quantum computing with superconductors





- Al/AlO$_X$ junctions on Si wafers
  - optical lithography
  - standard processing
- Addressed with RF pulses, DC bias currents
- Couple qubits with capacitors
- Challenge
  - Improve isolation
  - reduce decoherence

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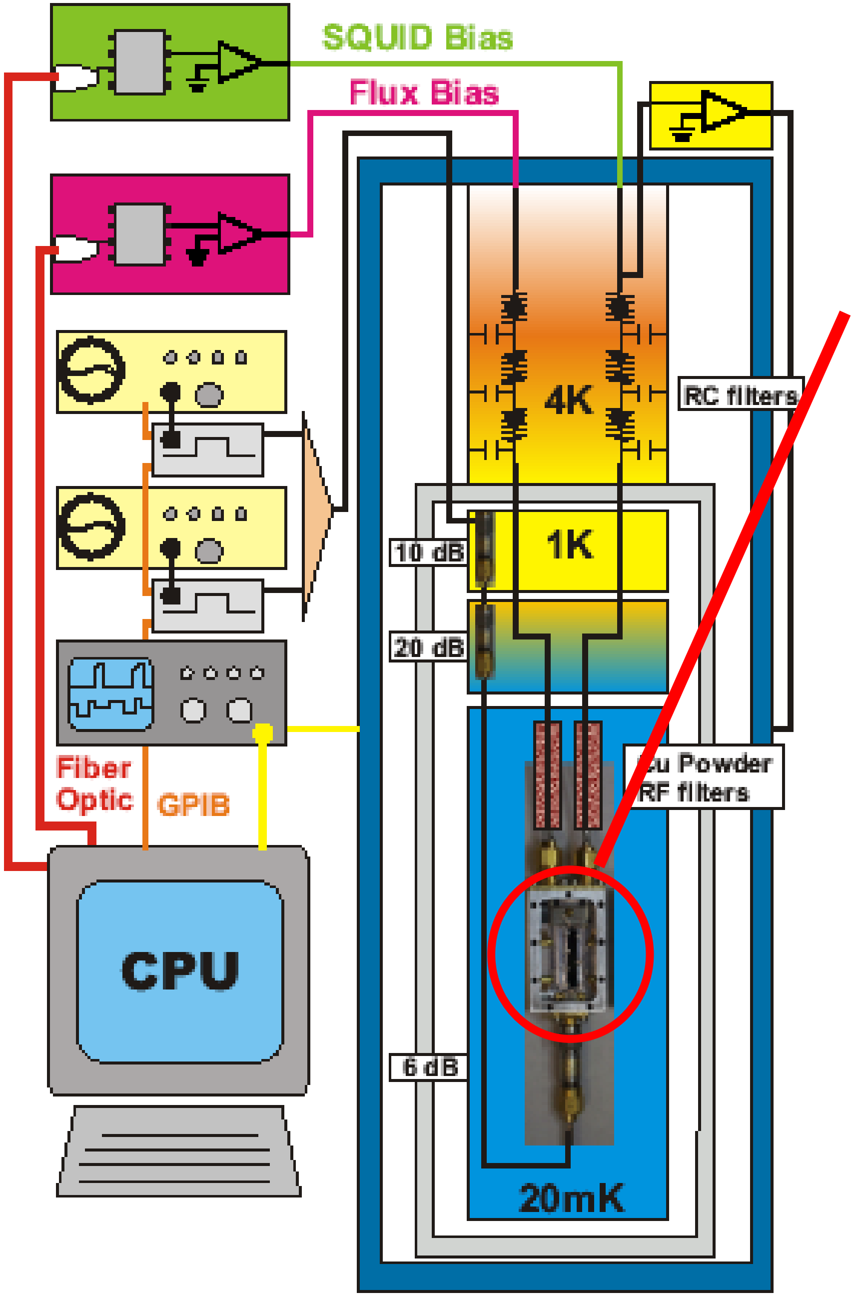
Experimental setup



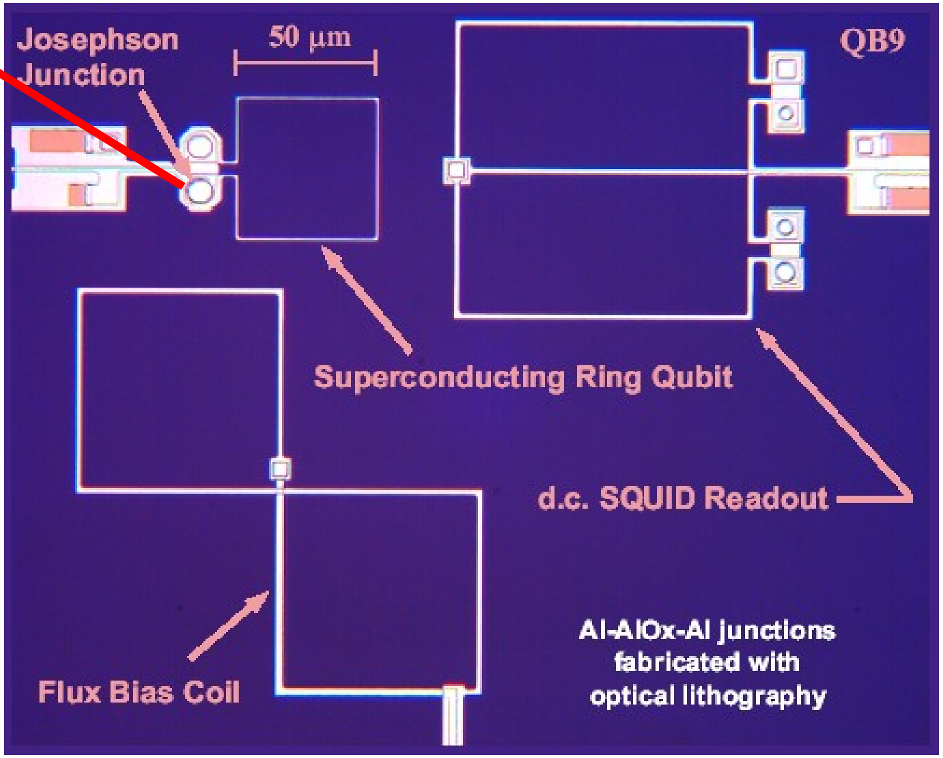
- Qubit is operated at <u>20 mK</u>
    - removes quasi-particles from the superconductor
    - <u>Expected</u> to reduce thermal decoherence sources

Josephson junction phase qubit layout

- Artificial atom
- Large tunnel junctions ~ 10 μm diameter
- Aluminum wiring with SiO_x dielectric

qubit junction

RF in



SQUID Meas.

current bias in

Fabrication – trilayer process (Al)

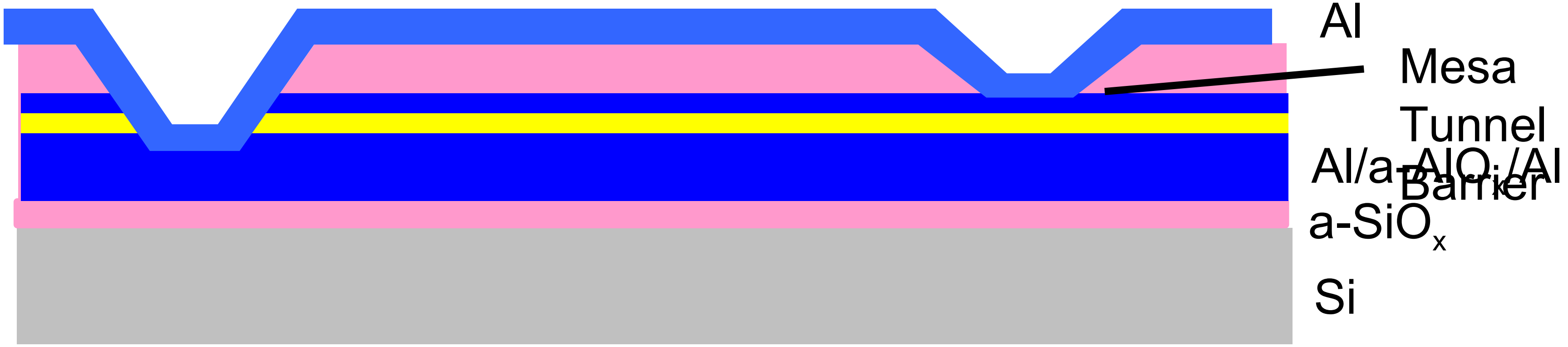
Al – superconductor, T_C ~ 1 K

a-SiO2: amorphous SiO2 - substrate & insulation

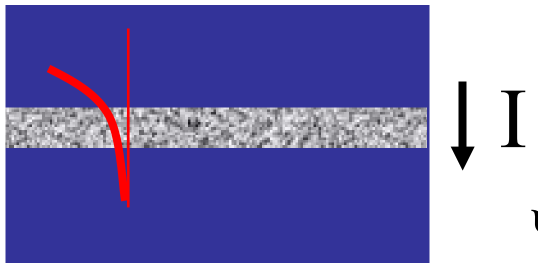
Chemical vapor deposition

a – AlO_x: amorphous Al_2O_3 + OH^- - tunnel barrier

Self passivated oxide ~ 1.5 nm thick



Superconducting Josephson junction phase qubit principle



Top superconductor

Tunnel Junction ~1.5 nm →

↓ I

Bottom superconductor

$\Psi_{top} = \Psi_0$

$\Psi_{bot} = \Psi_0 e^{i\delta}$

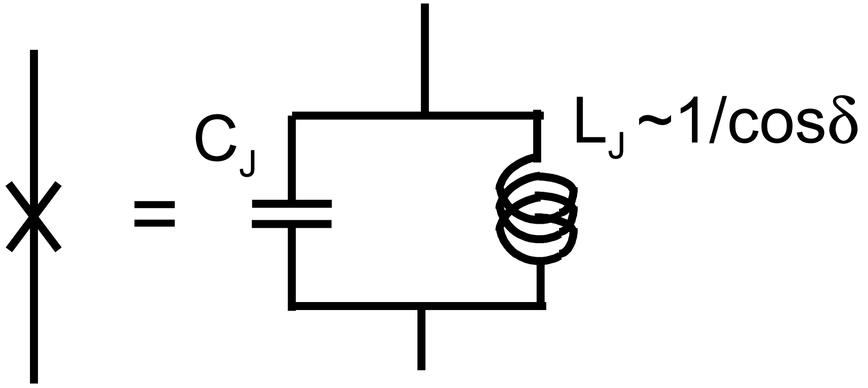
Cooper pair wavefunction

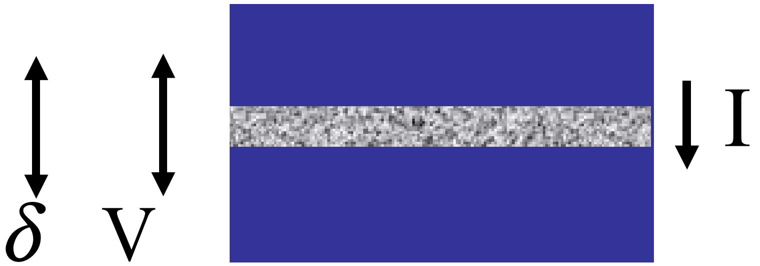
Josephson relations

$$\left\{ \begin{aligned} I &= I_0 \sin(\delta) \\ V &= \frac{\hbar}{2e}\dot{\delta} \end{aligned} \right.$$

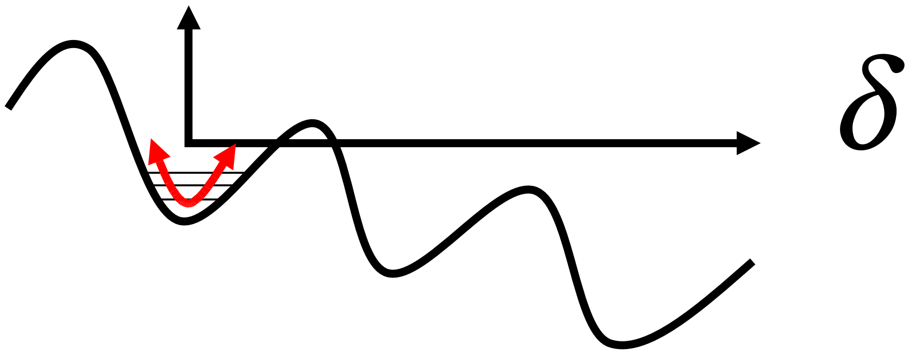
- I depends on δ
- Voltage only when phase is changing

Electrical circuit model of Josephson junction





- Potential: $U \approx -\cos\delta - I\delta$



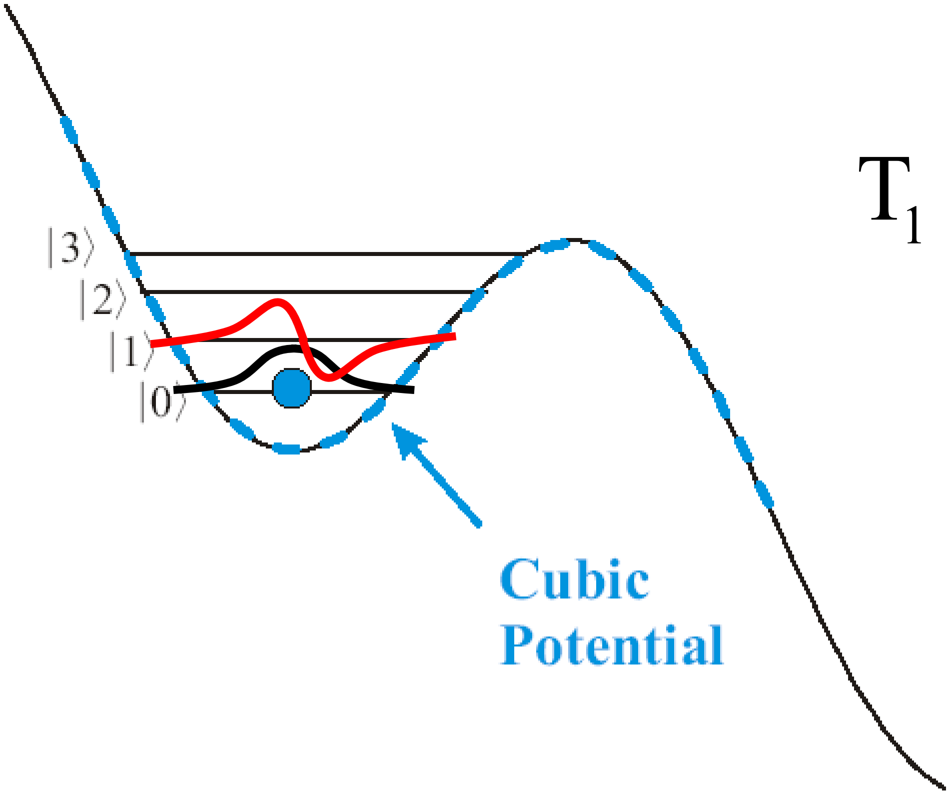
- δ, V across junction will slosh around in minimum
- cosδ is x^2 potential => simple harmonic oscillator
- Need to change potential to get two state system

Quantum behavior - potential that phase qubit lives in

- Increase bias => cubic potential lifts degeneracy

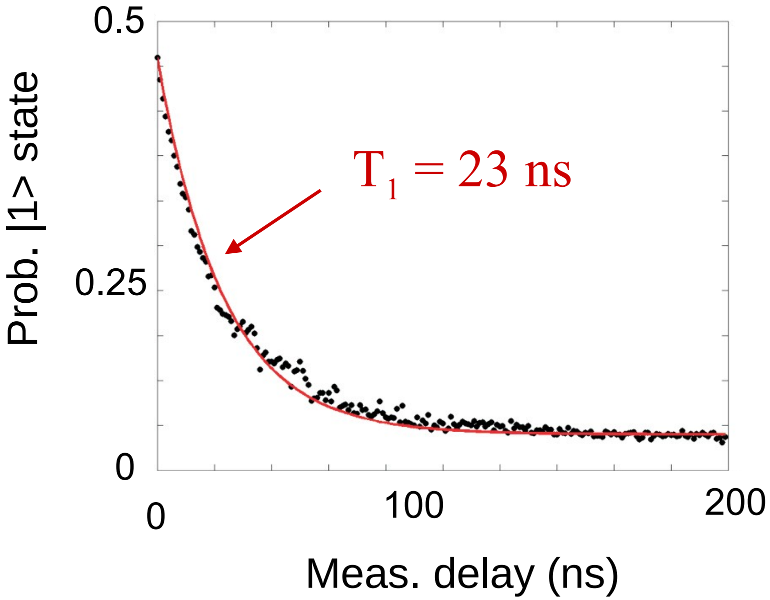
$$\Delta E_{01} > \Delta E_{12} > \Delta E_{23}$$

- Use the |0> and |1> states for information



$$T_1 \equiv \text{lifetime of } |1\rangle$$

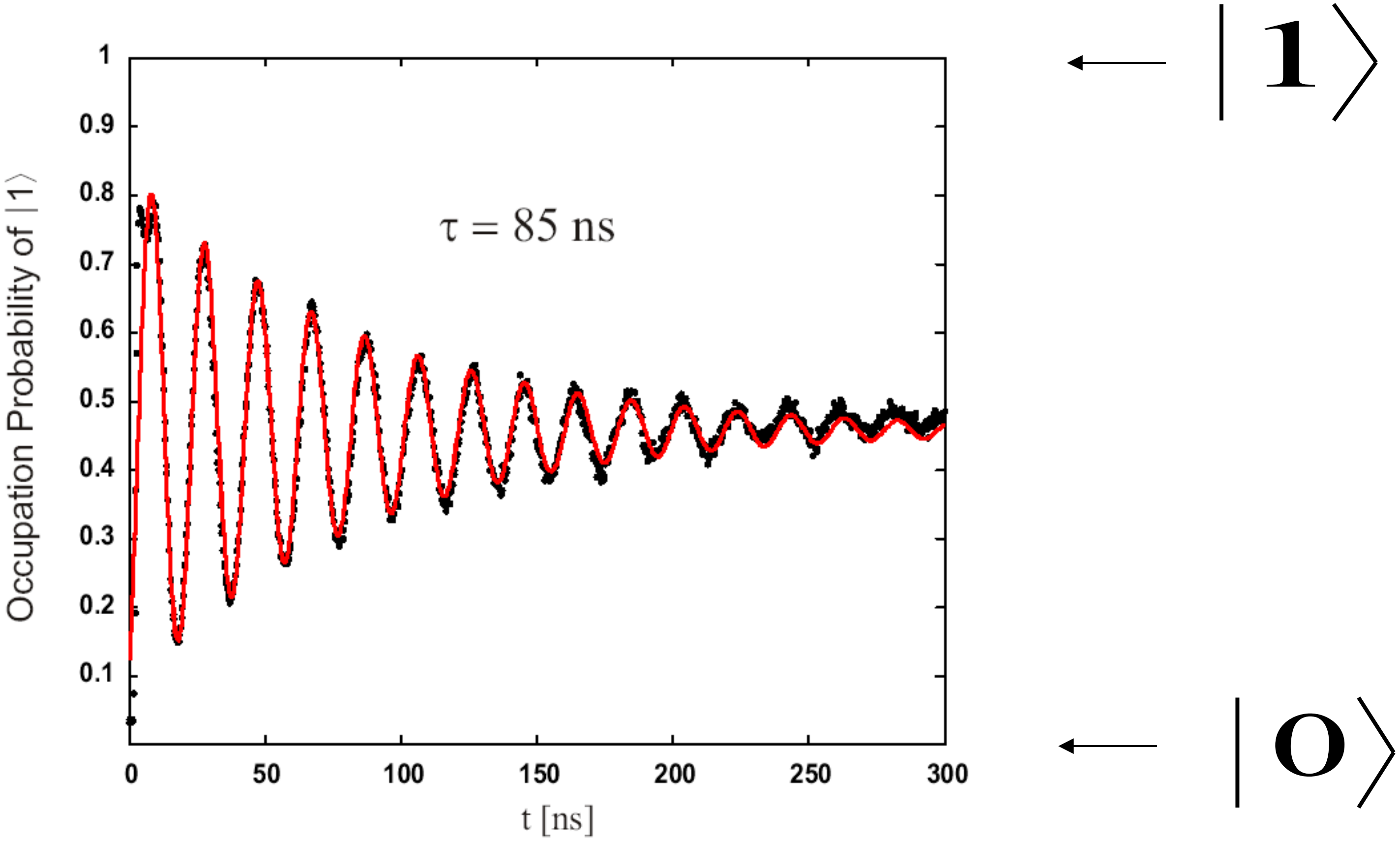
T_1's in phase qubits – historically been short



- 13 μm^2 junctions: T_1 ~ 25 ns
- 70 μm^2 junctions: T_1 ~ 40 to 100 ns

- Loss mostly external to junction

Coherence of first superconducting quantum bit

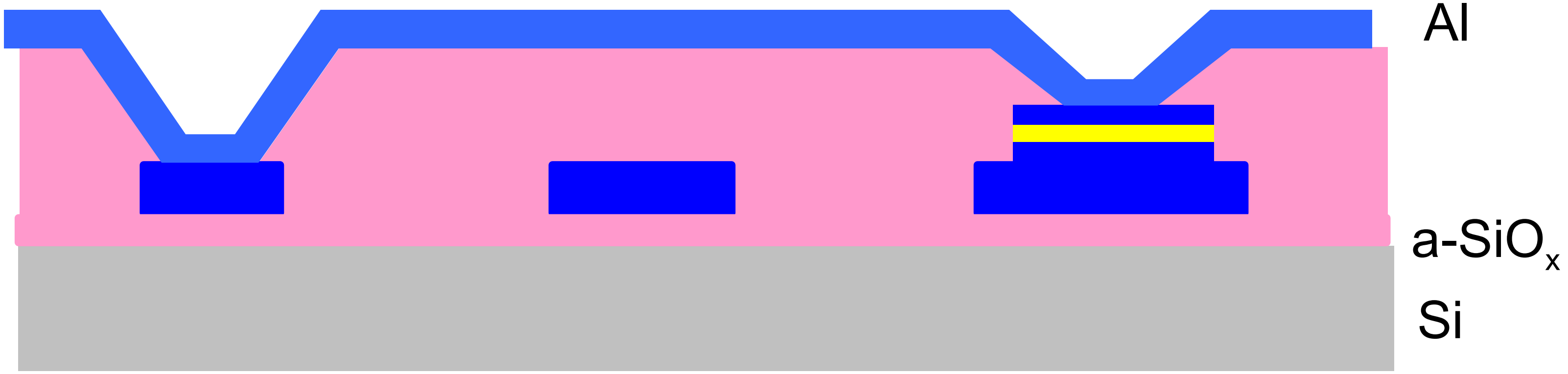


- **Single operation time can be ~ 1 ns**
- **Information in system decayed rapidly ~ 100 ns**
- **Need to preserve information > 10^4 x operation s**

=> Increase coherence times & measurement fidelity!

Materials development – can we improve coherence?

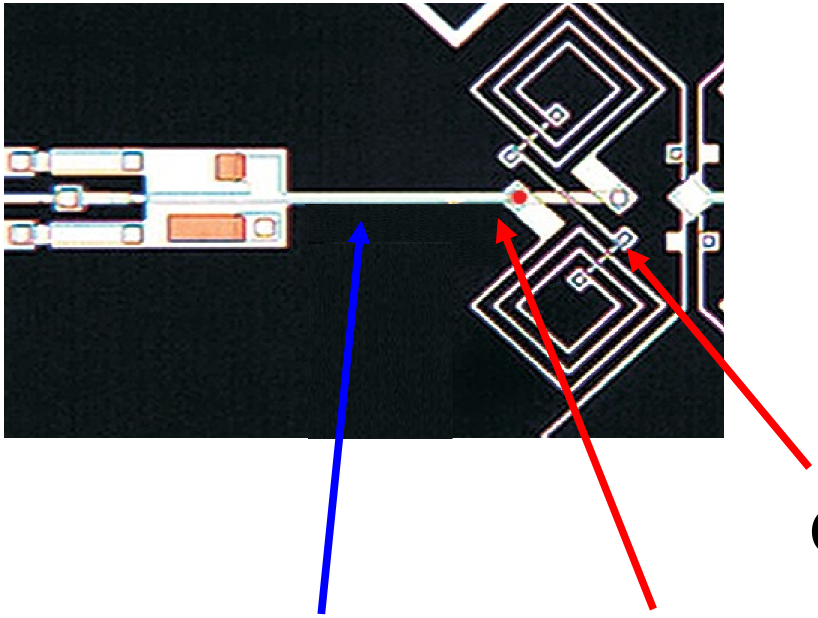
- Absorption in dielectric & junction (a-SiO_2) & (a-AlO_2)
- Gets worse at low temperature (two – level fluctuators)



Focus on:

- Insulators: along traces & around junction
  in substrate
  crossovers
- Tunnel barrier - between superconductors

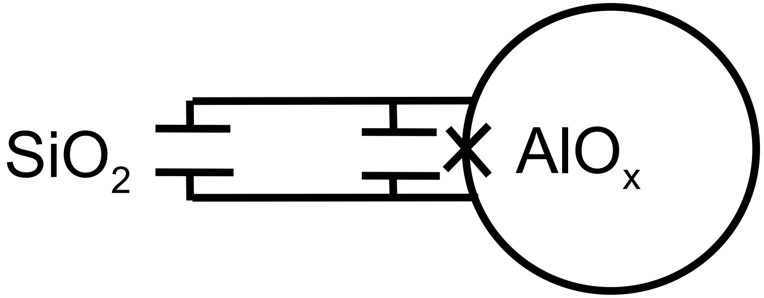
Qubit has SiO_2 Cap in || with J.J. & around lines



Qubit L

Stripline
(C-SiO_2)

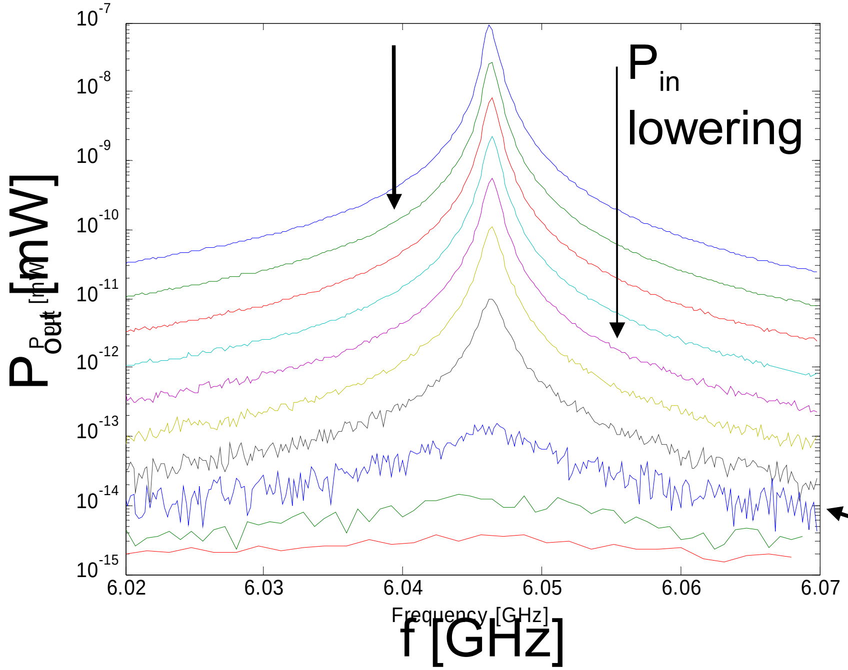
Josephson Junction
(L&C)

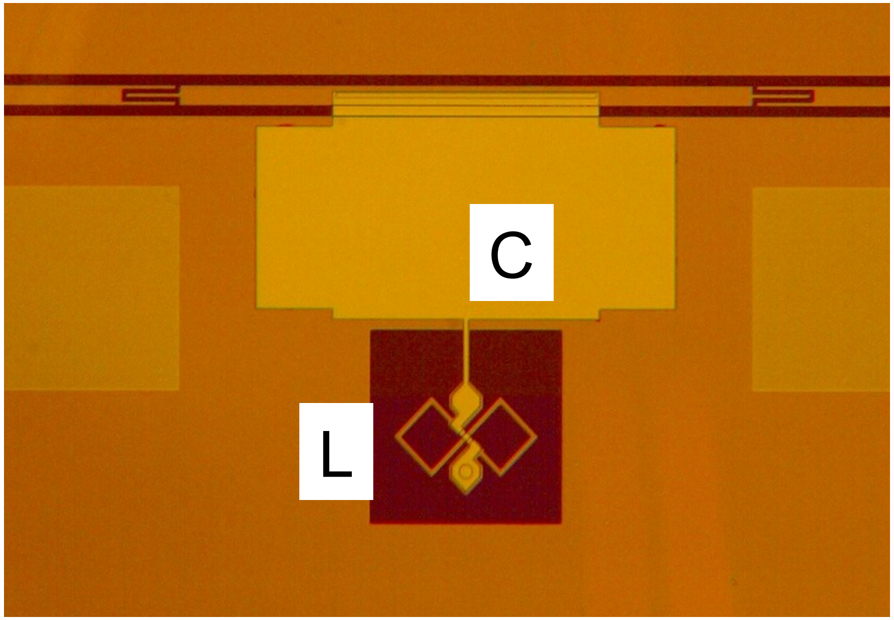


=> Measure “Q” of simple LC resonators at lot T

Parallel plate capacitor resonators w/SiO dielectric

Power dependence to parallel plate capacitor resonators



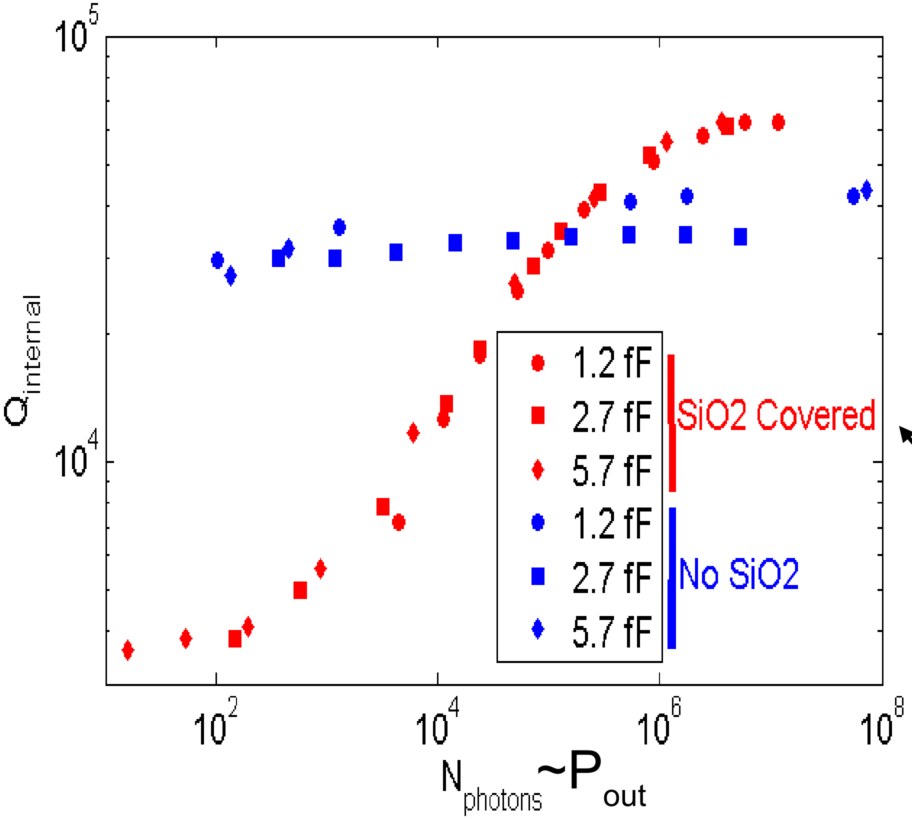


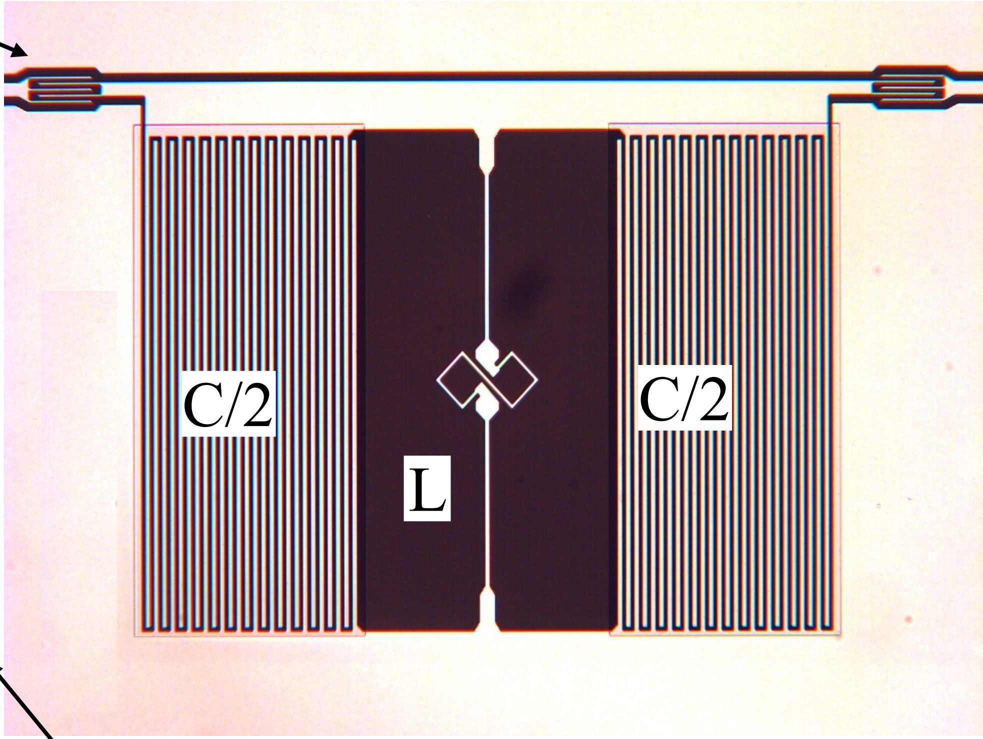
Q of the resonator with SiO_2 goes down as power <u>decreases</u>!

=> Compare to capacitors with vacuum dielectric

Interdigitated capacitor resonators

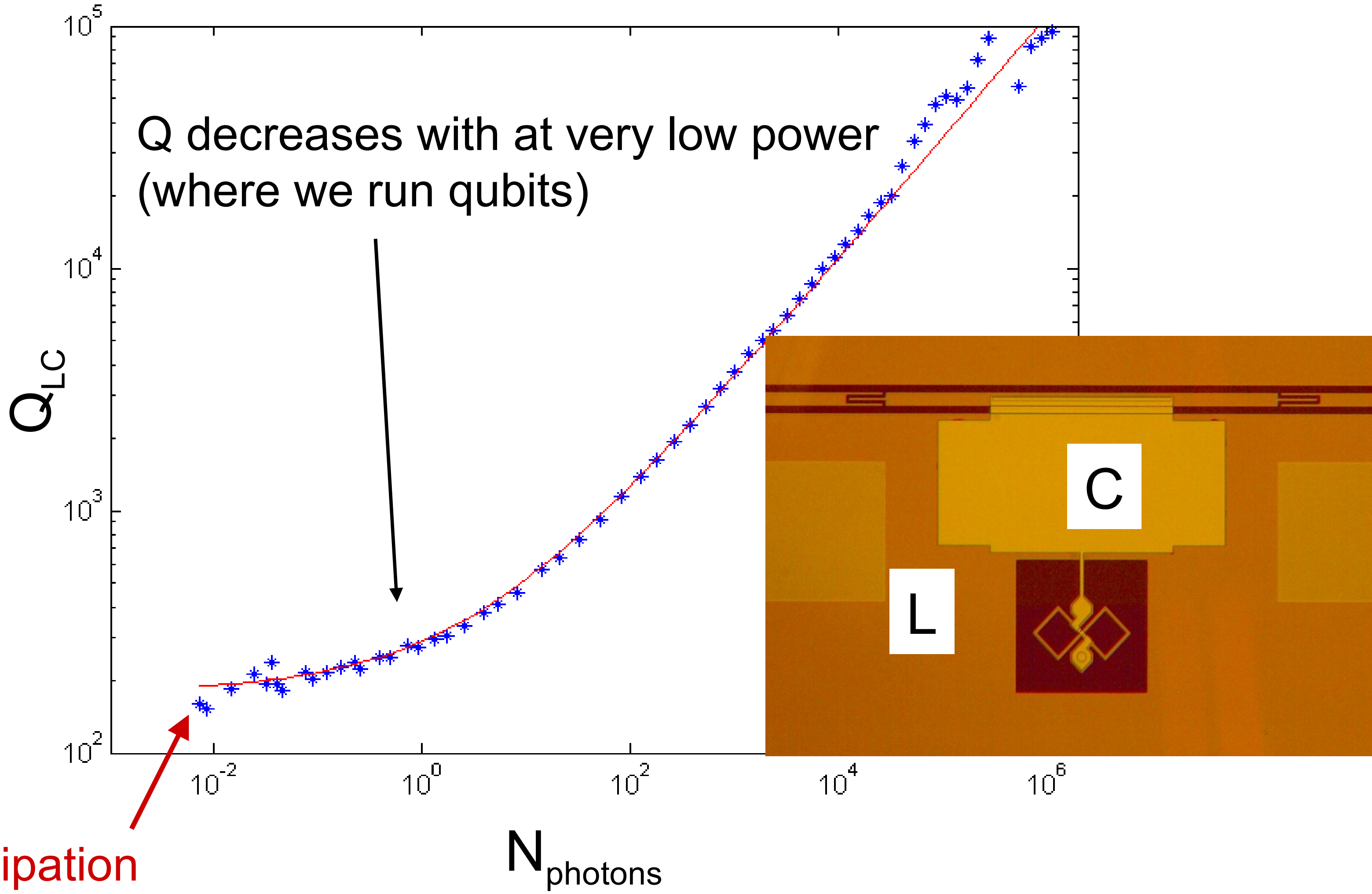
=> With & without SiO2 over the capacitor





Dissipation is in SiO2 dielectric of the capacitor!

Power dependence of Q_{LC} for parallel plate capacitors



Q decreases with at very low power (where we run qubits)

HUGE Dissipation

Explains small T_1!

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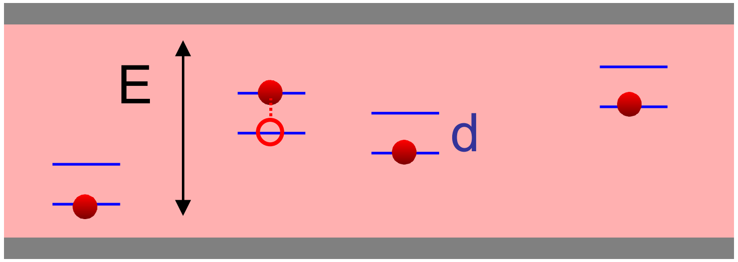
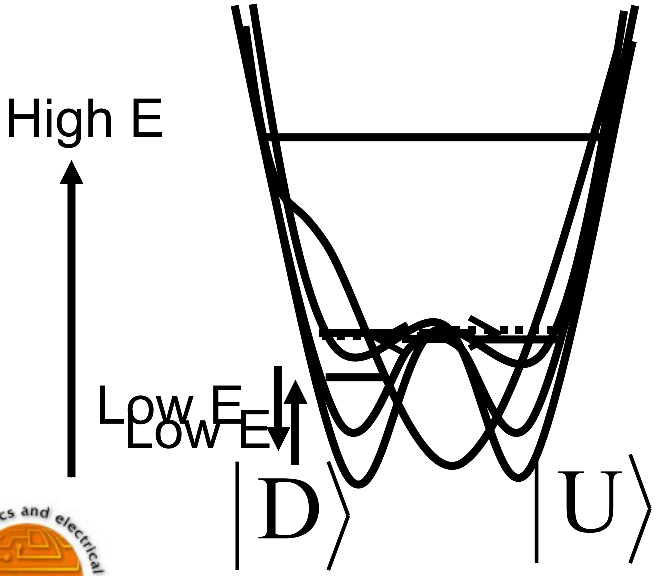
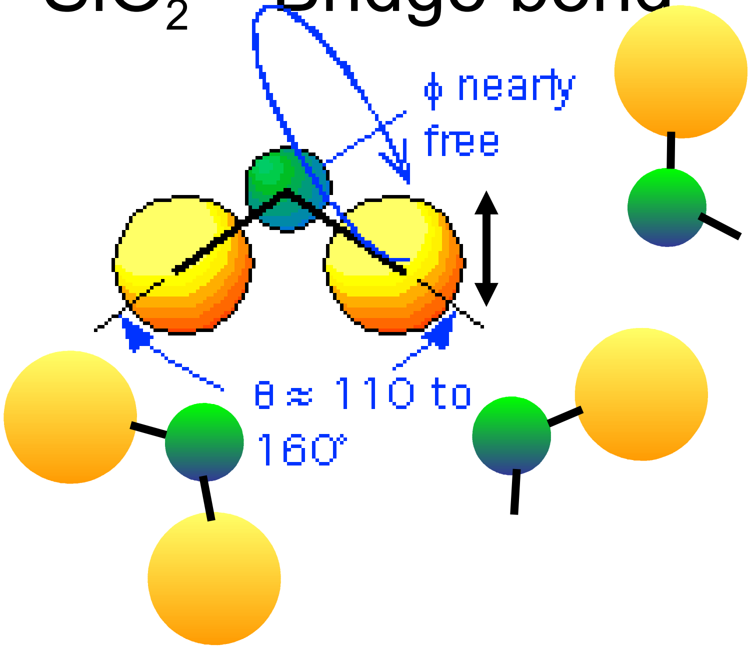
Two-level systems in a-SiO2

Schickfus and Hunklinger, 1975





SiO_2 - Bridge bond

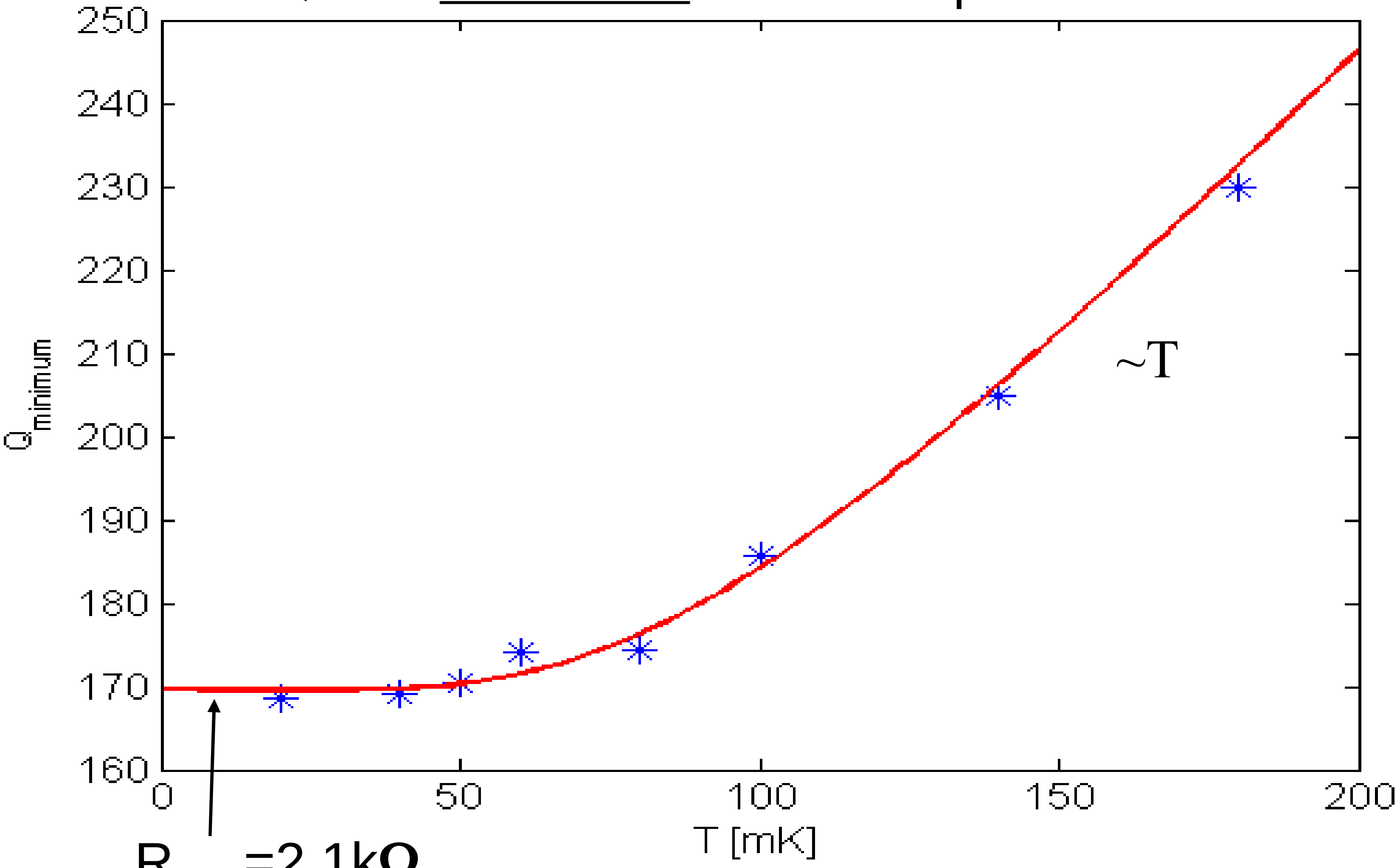


- TLS bath saturates at high E (power), decreasing loss

Amorphous material has all barrier heights present

Temperature Dependence of Q

Q also <u>decreases</u> at low temperature!



R_{SiO2}=2.1kΩ

$2\pi R_{SiO2} C_{eff} = 27\text{ns}$

Problem - amorphous SiO_2
Why short T_1's in *phase* Josephson qubits?

Dissipation: ~~Idea~~ - Nature:

At low temperatures (& low powers)
environment “freezes out”:

~~dissipation lowers~~

dissipation increases, by 10 – 1000!

Change the qubit design:

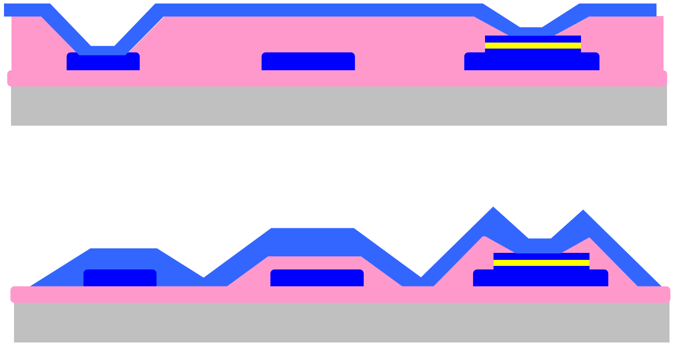
⇒ find better substrates

⇒ find better dielectric & minimize insulators in design

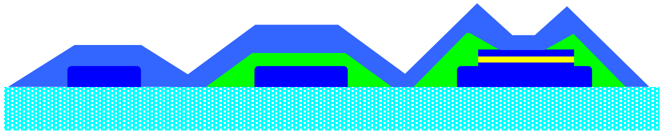
Common insulator/substrate materials

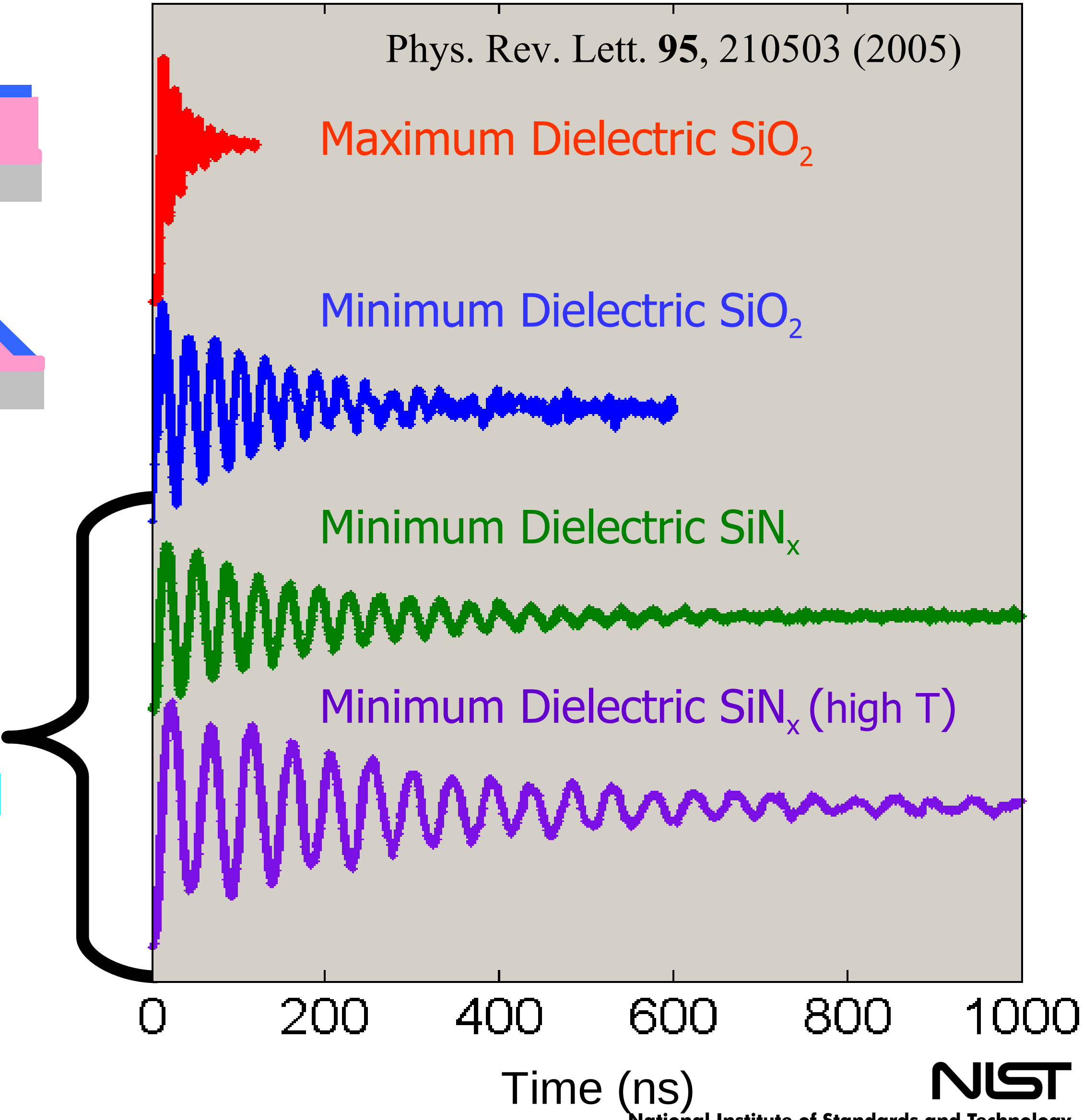
- SiO_2
  - Bridge bond, unstable
    - Amorphous films have uncompensated O^- , H, OH^-
- Si_3N_4
  - N has three bonds – more stable
    - Amorphous films, still have uncompensated charges, H
    - 20% H for low T films, ~ 2% H in high T films
- Al_2O_3
  - Amorphous – high loss, similar to a-SiO2, has H, OH^- in film
  - Single crystal (sapphire) - Very low loss system

Minimize, optimize dielectric & substrate



Sapphire substrate
+ SiN insulator:

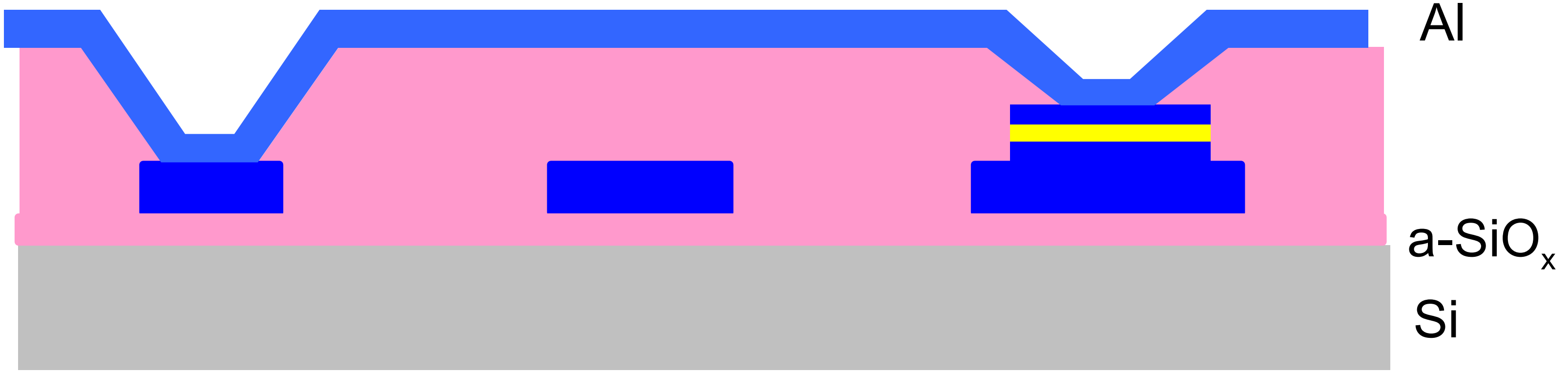



Phys. Rev. Lett. **95**, 210503 (2005)

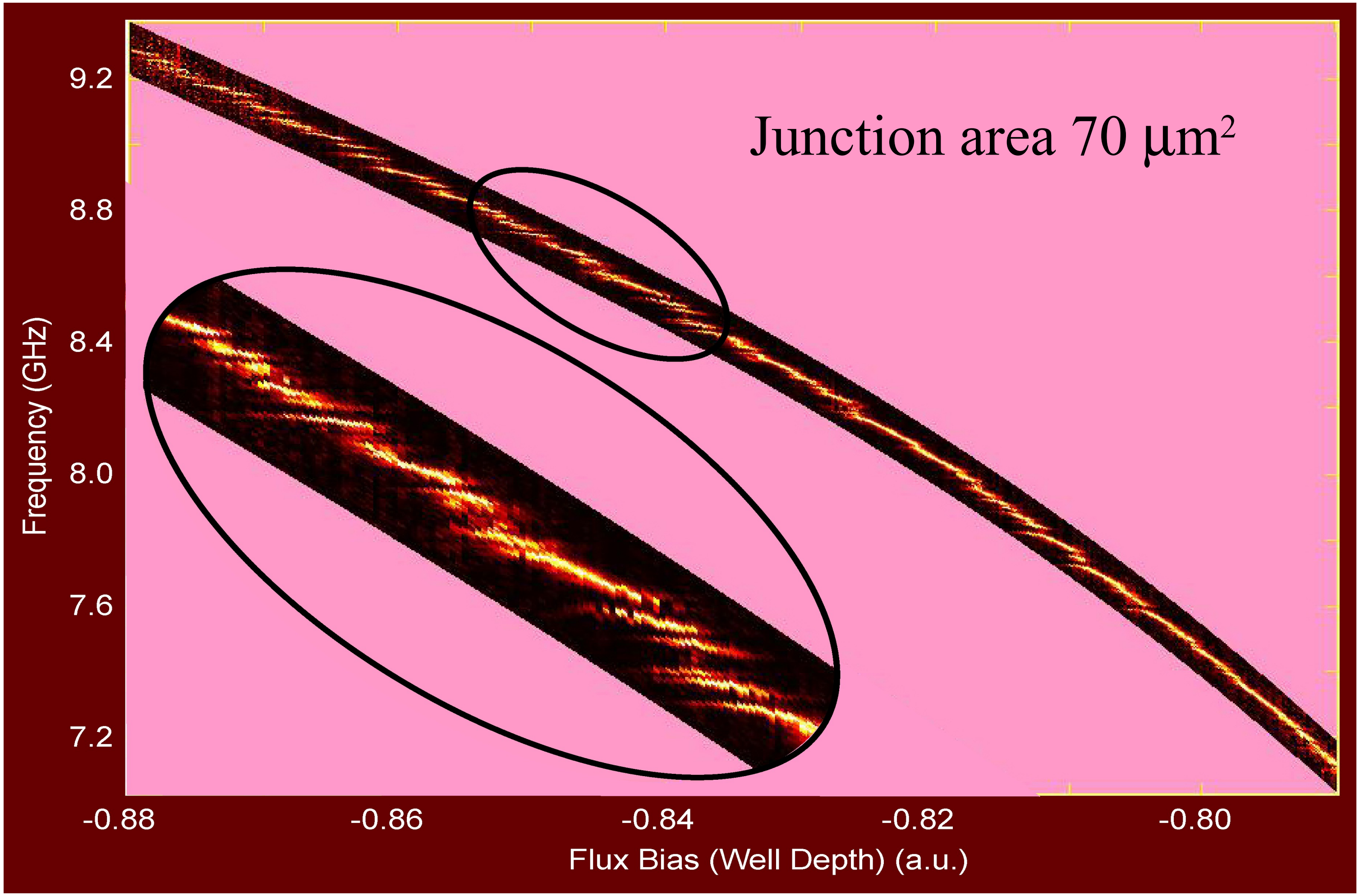
Rabi oscillations > 600 ns !!

Found improvements due to optimized materials in insulators

=> Can we improve the tunnel barrier?



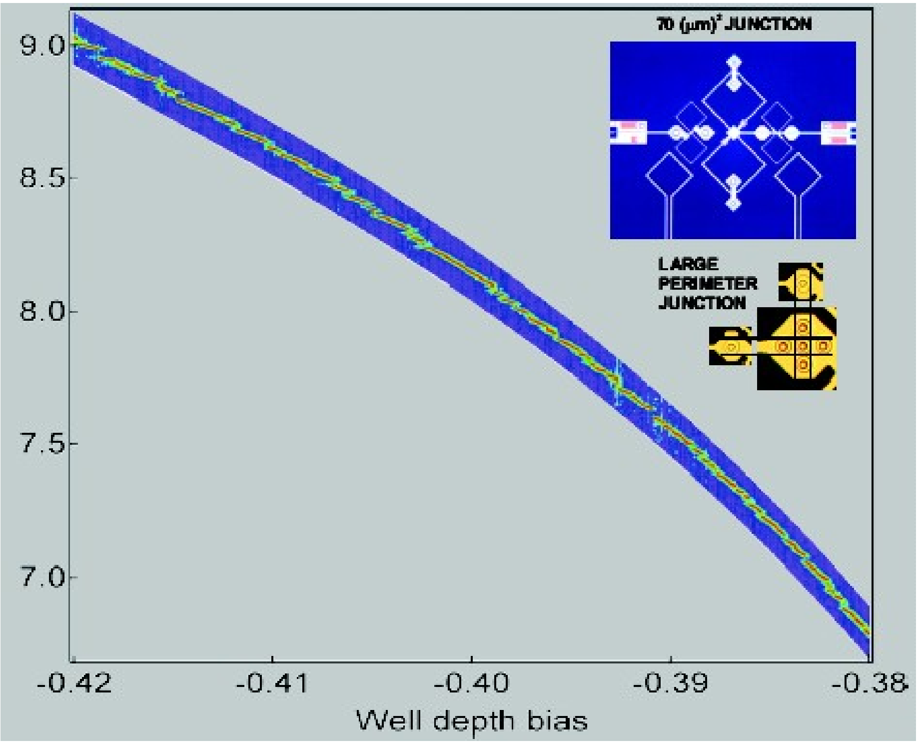
Frequency dependence of Qubits



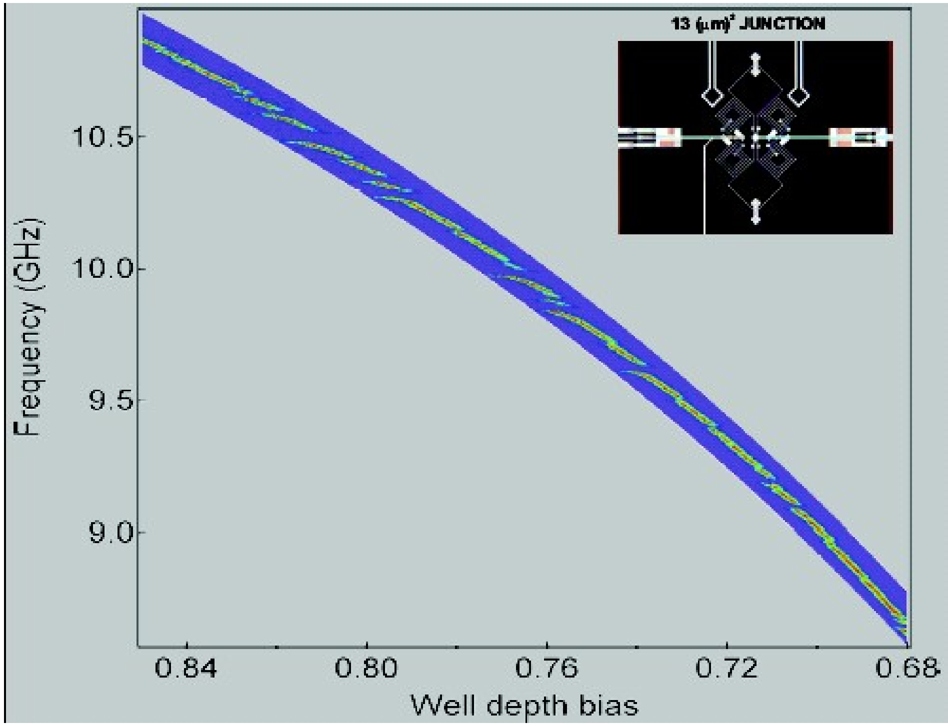
Energy splittings can give rise to energy absorbtion!
Reduces the measurement fidelity

Number of splittings scales with junction size

70 um^2 junction

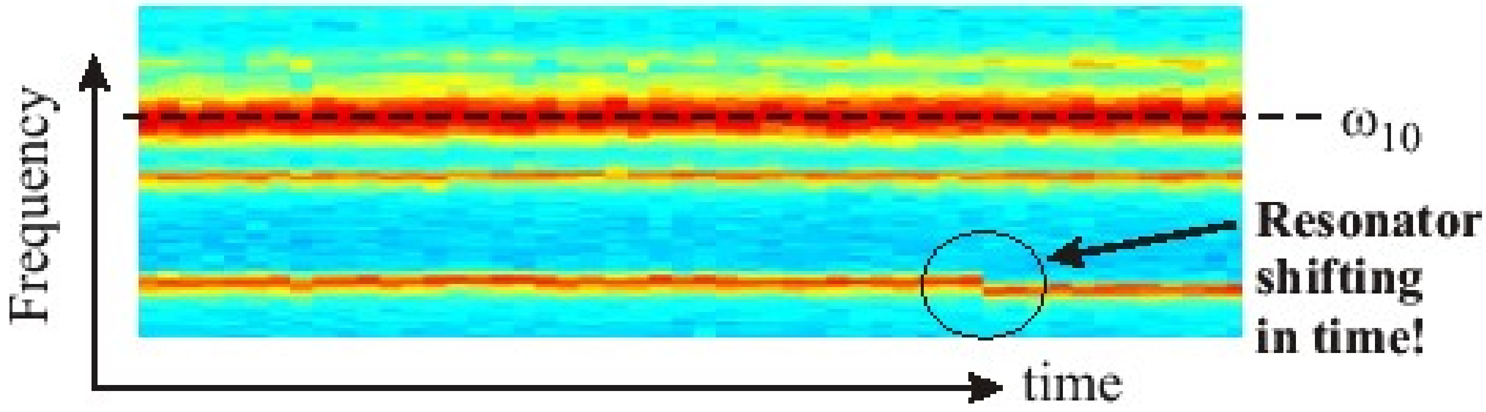


13 um^2 junction

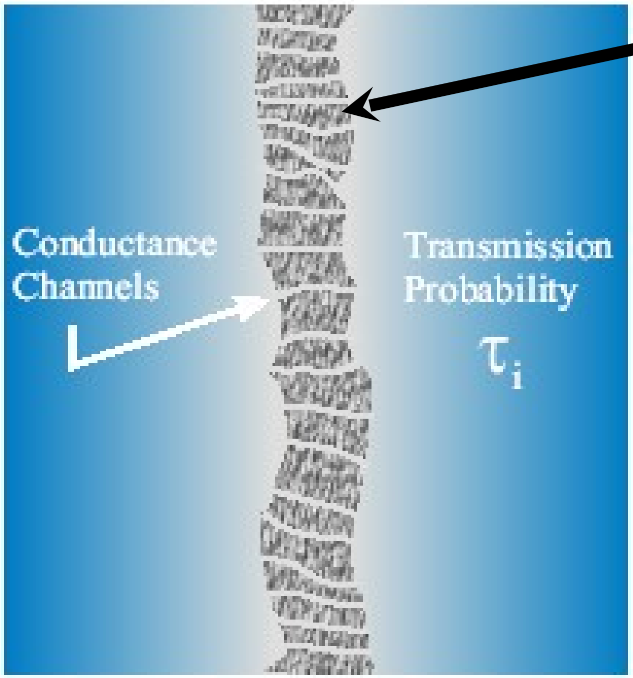


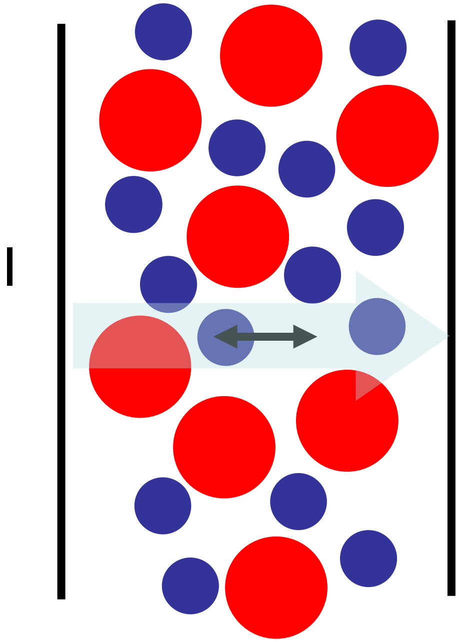
- Smaller area – Fewer resonators, larger splitting (strong coupling)
- Larger area - More resonators, smaller splitting (weaker coupling)

Two level systems in junction



Amorphous AlO tunnel barrier





- Continuum of metastable vacancies
- Changes on thermal cycling
- Resonators must be 2 level, coherent with qubit!

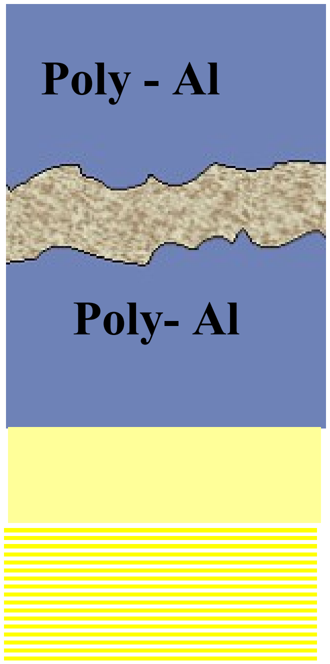
Design of tunnel junctions

What we have:

Amorphous Aluminum oxide barrier

Spurious resonators in junctions

Fluctuations in barrier



Amorphous tunnel barrier

a $-AlO_x - OH^-$ →

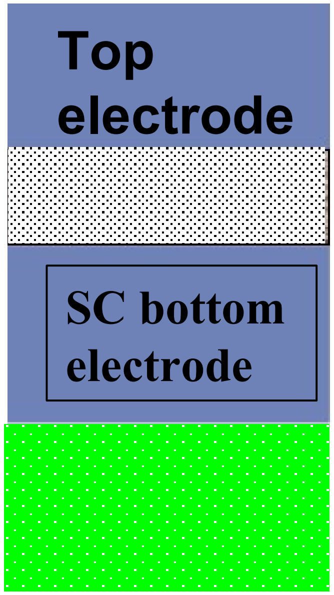
amorphous SiO_2 →

Silicon

What we need:

No spurious resonators

Stable barrier



Crystalline barrier

αAl_2O_3

Low loss substrate

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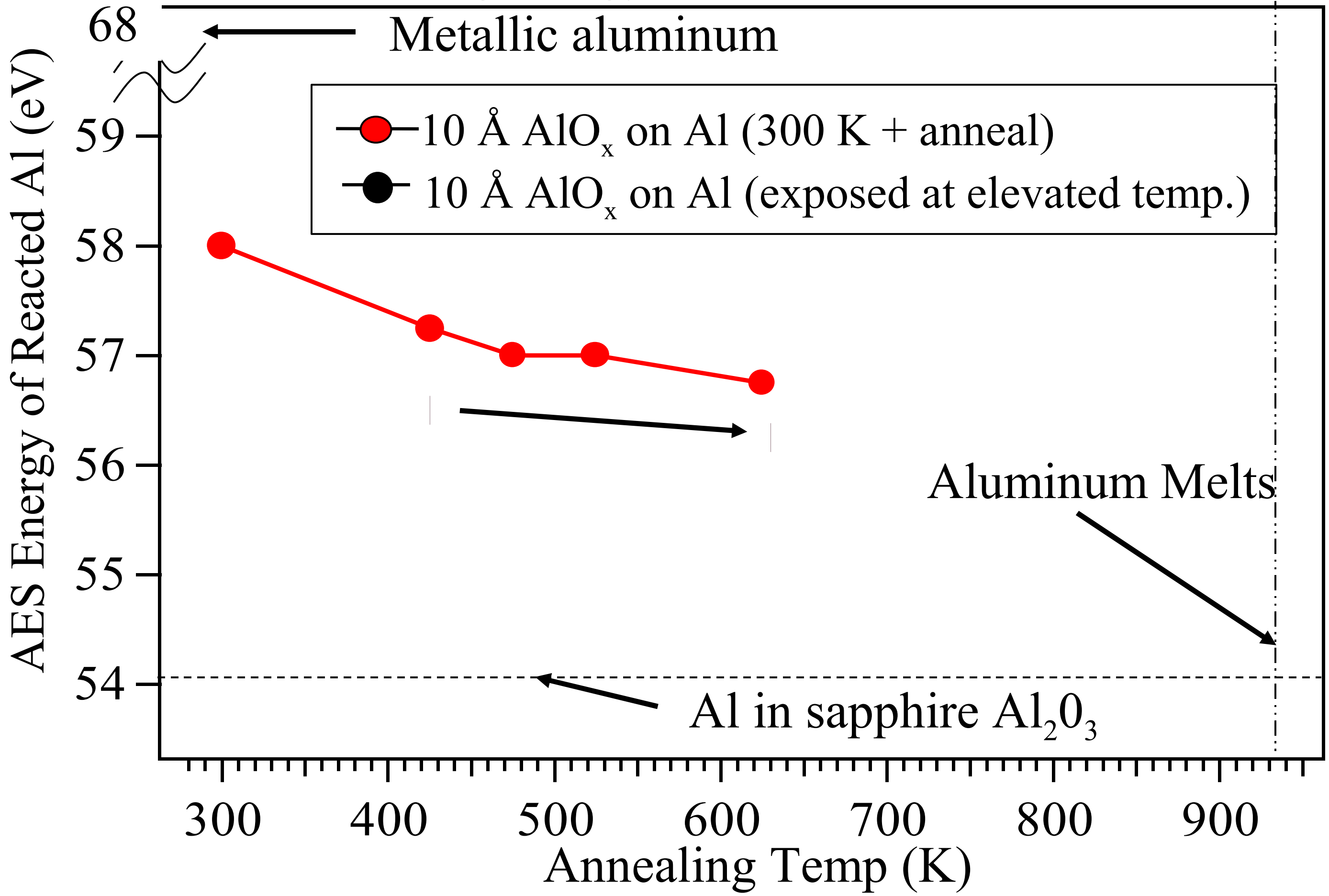
Q: Can we prepare crystalline Al_2O_3 on Al?

- Anneal the natural oxides
- Oxidize at elevated temp.

Binding energy of Al AES peak in oxide



A: No

NIST
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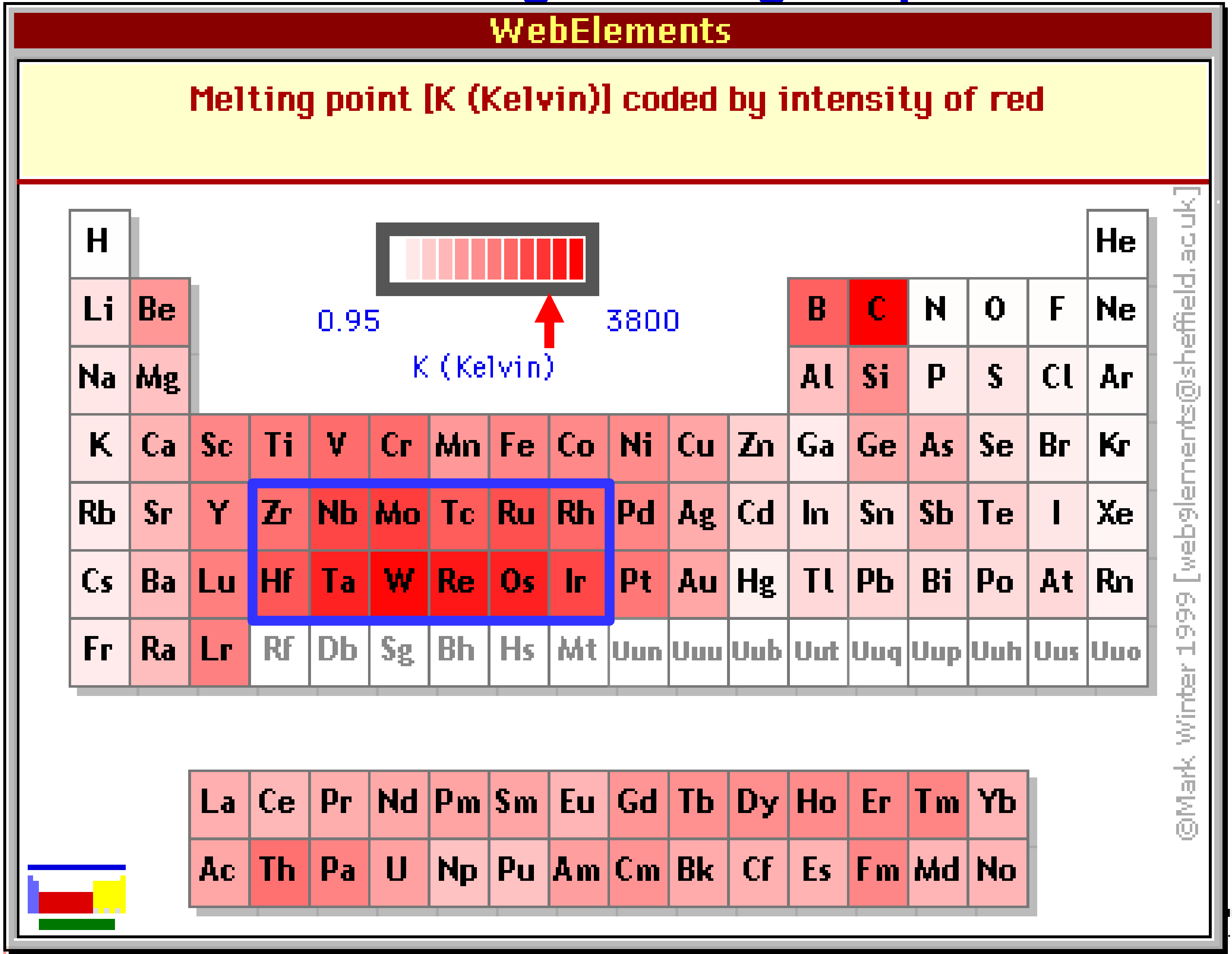
Technology Administration, U.S. Department of Commerce

Chose bottom superconducting electrode to stabilize crystalline Al_2O_3 tunnel barrier

Elements with high melting temperature

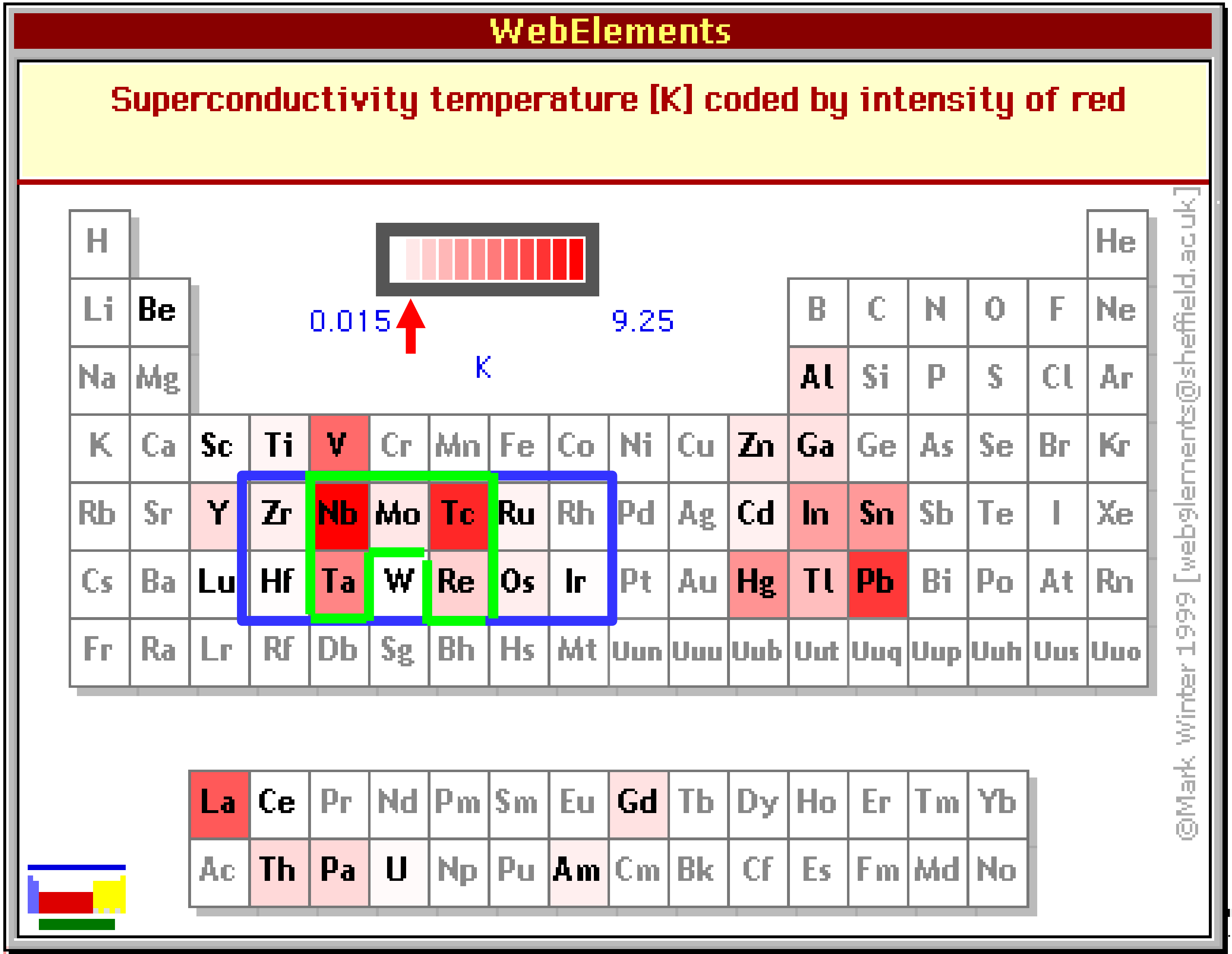


WebElements

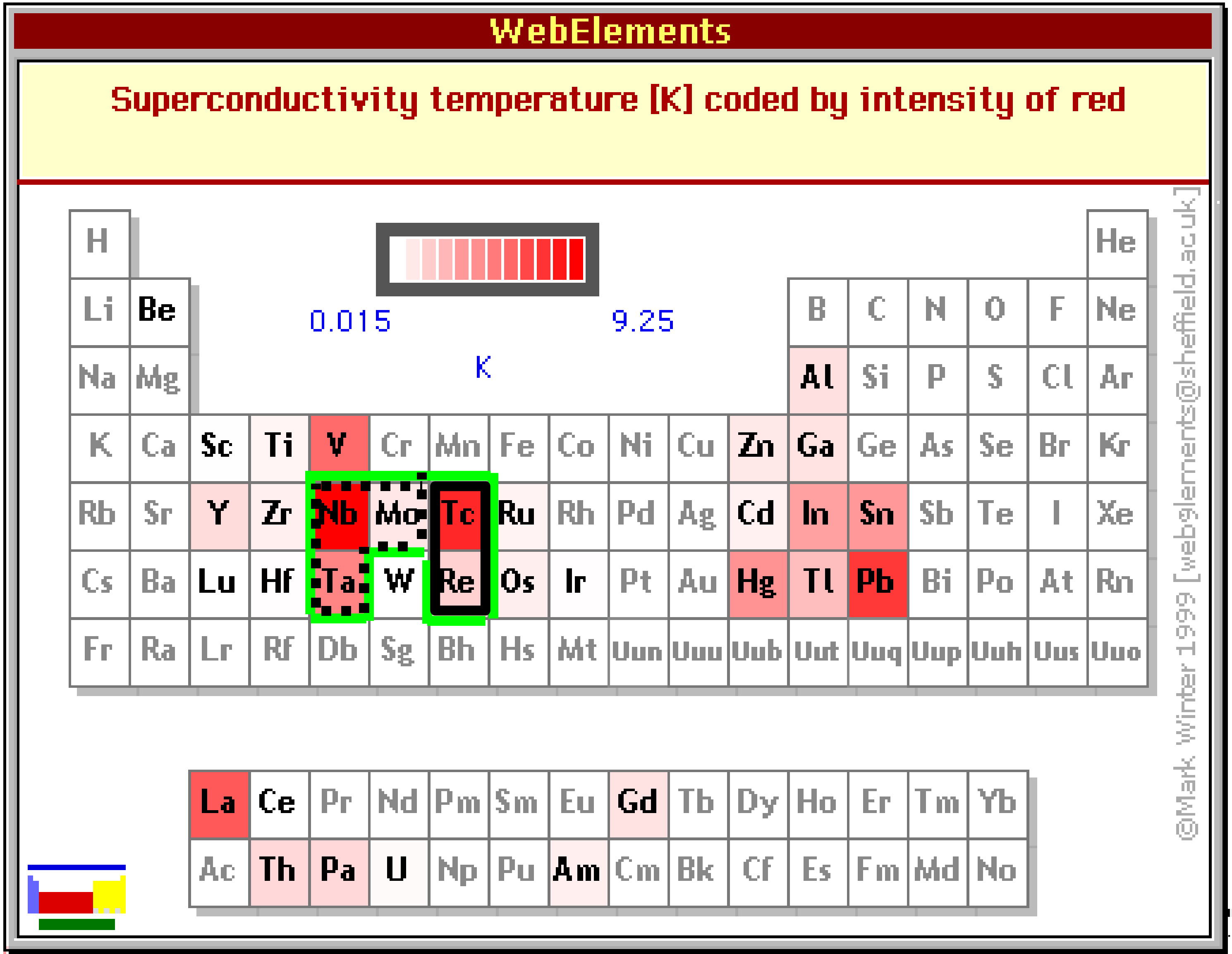
Melting point [K (Kelvin)] coded by intensity of red

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb		
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No		

Elements with T_c > 1K



Elements that lattice match sapphire ($Al_2 0_3$)



WebElements

Superconductivity temperature [K] coded by intensity of red

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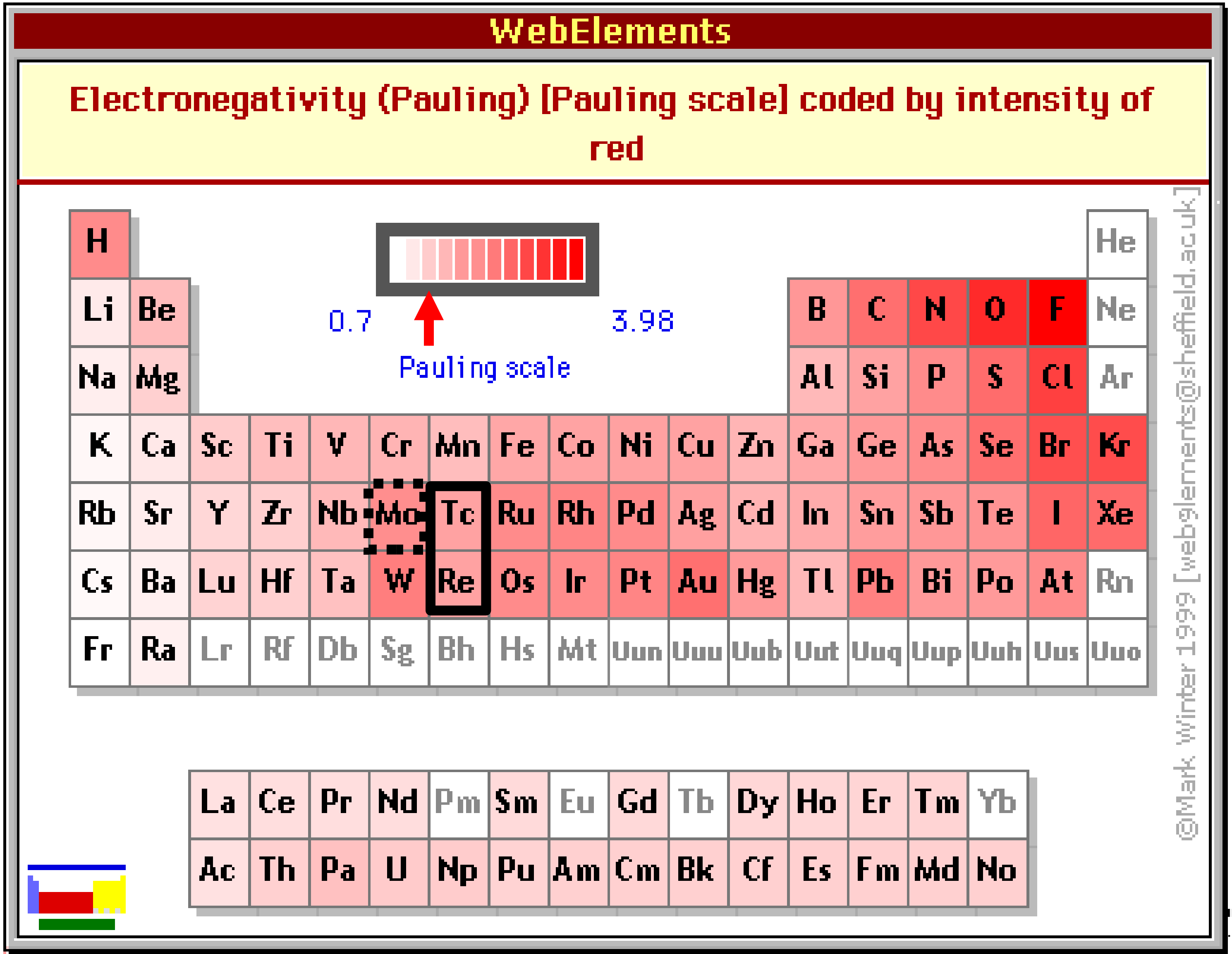
Elements that form weaker bond with oxygen than Al

(or Mg)



WebElements

Electronegativity (Pauling) [Pauling scale] coded by intensity of red

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

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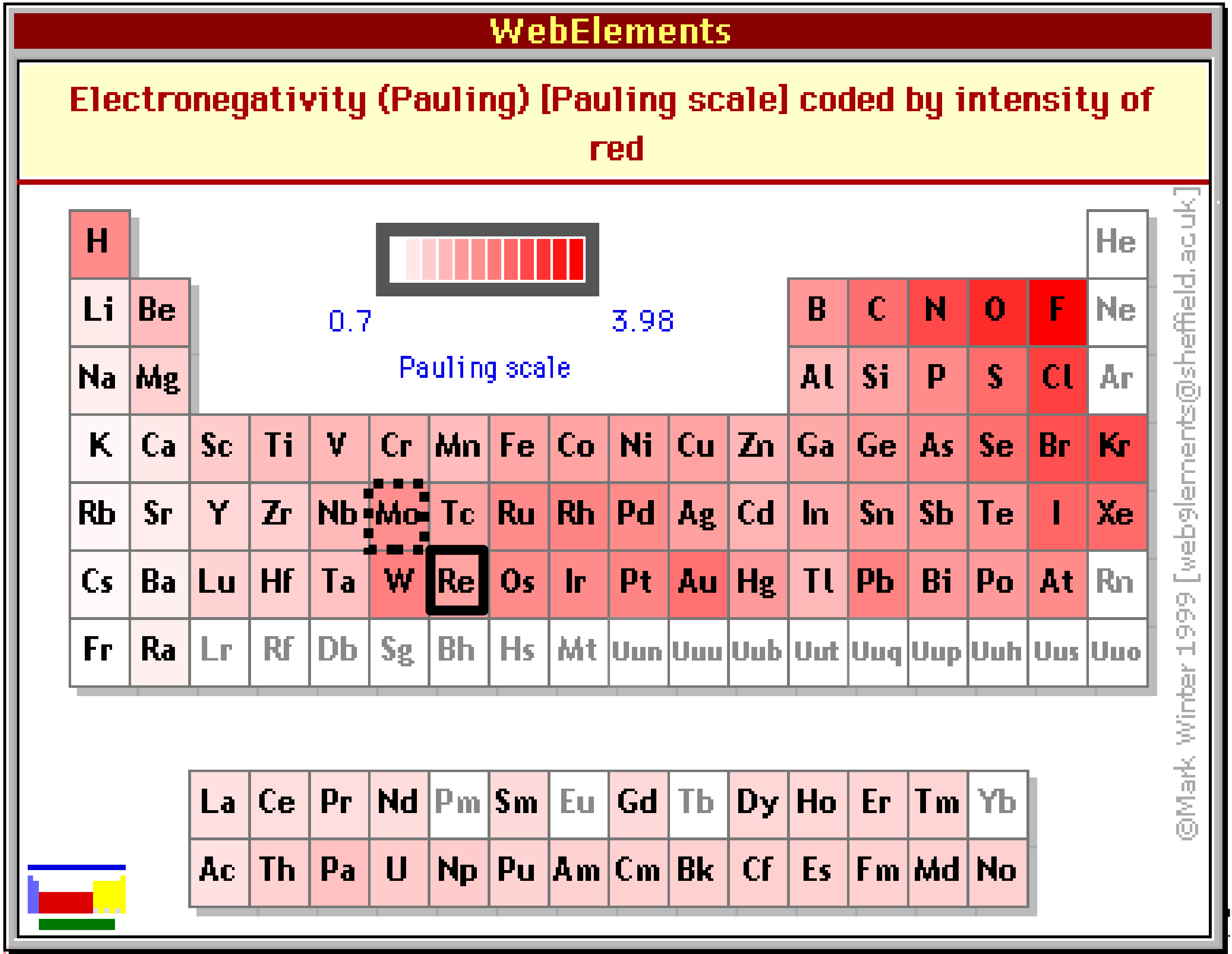
Elements that are not radioactive

⇒ Use Re for Al2O3 barrier

⇒ (or V for MgO tunnel barrier!)



WebElements

Electronegativity (Pauling) [Pauling scale] coded by intensity of red

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

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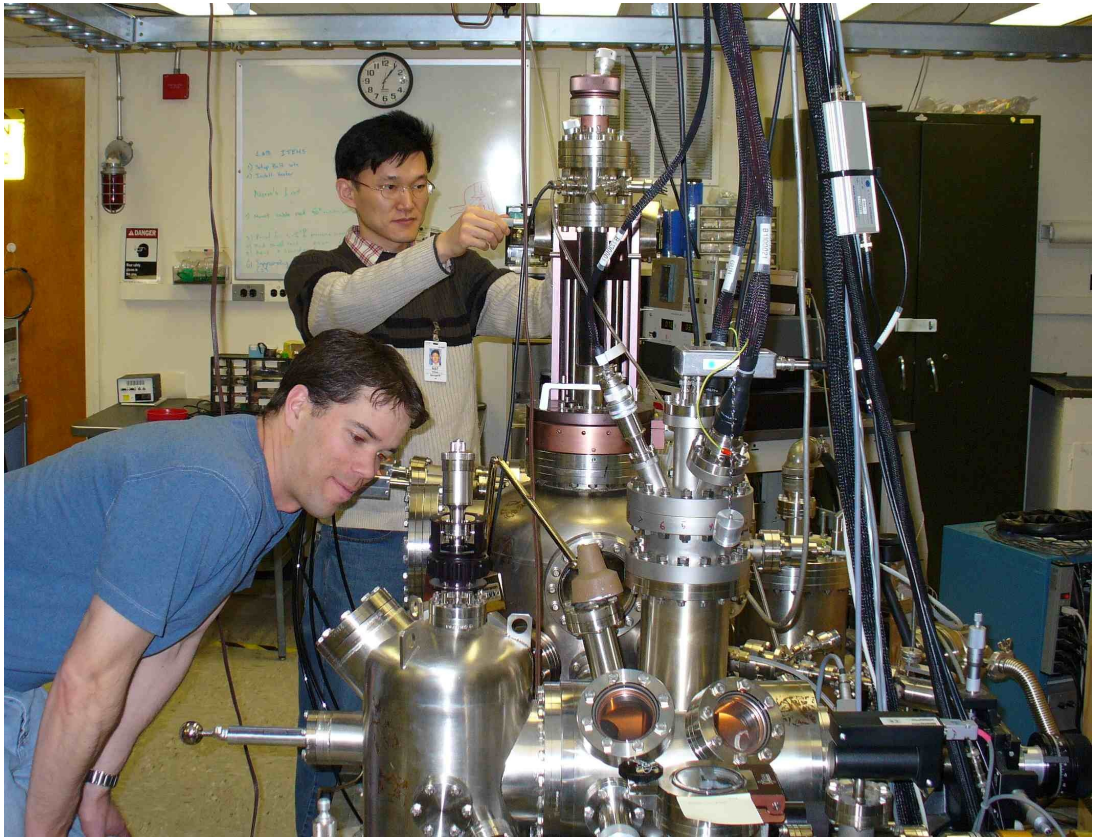
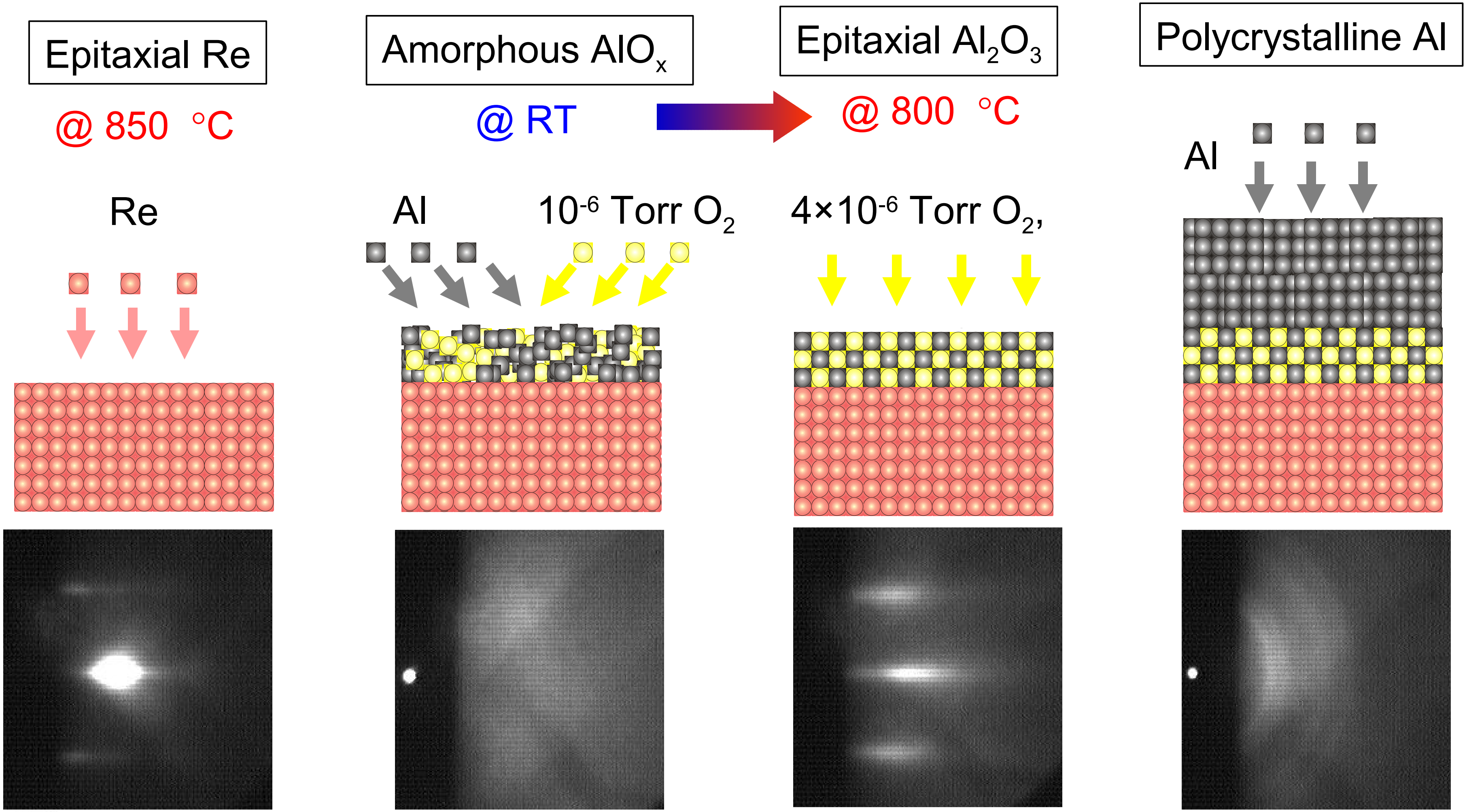
Improvement of Junction Materials



Growth of Epi-Re/Epi-Al2O3/Poly-Al



Epitaxial Re

@ 850 °C

Re

Amorphous AlO_x

@ RT

Al

10^{-6} Torr O_2

Epitaxial Al_2O_3

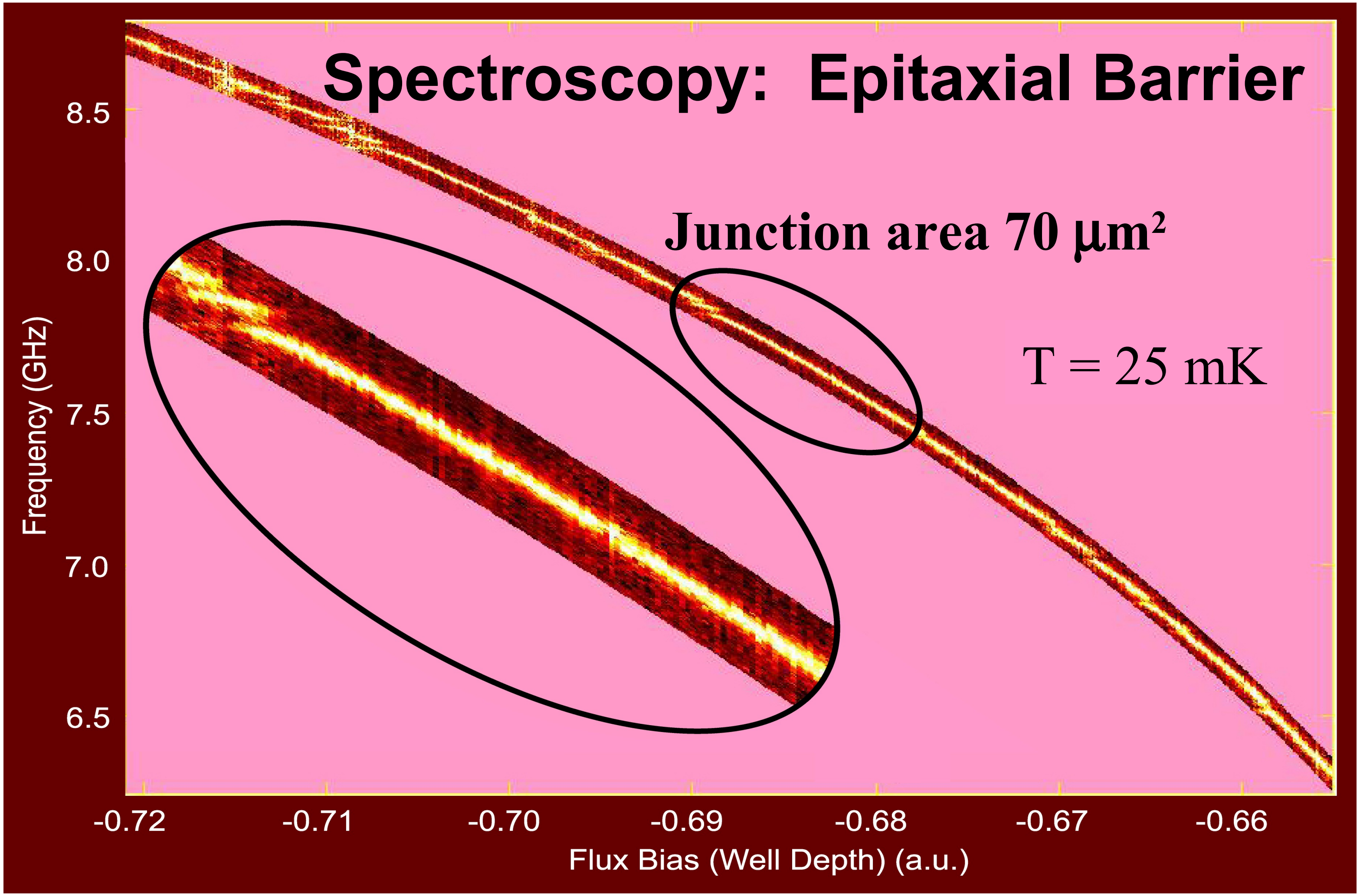
@ 800 °C

4×10^{-6} Torr O_2,

Polycrystalline Al

Al

Improvement of Junction Materials



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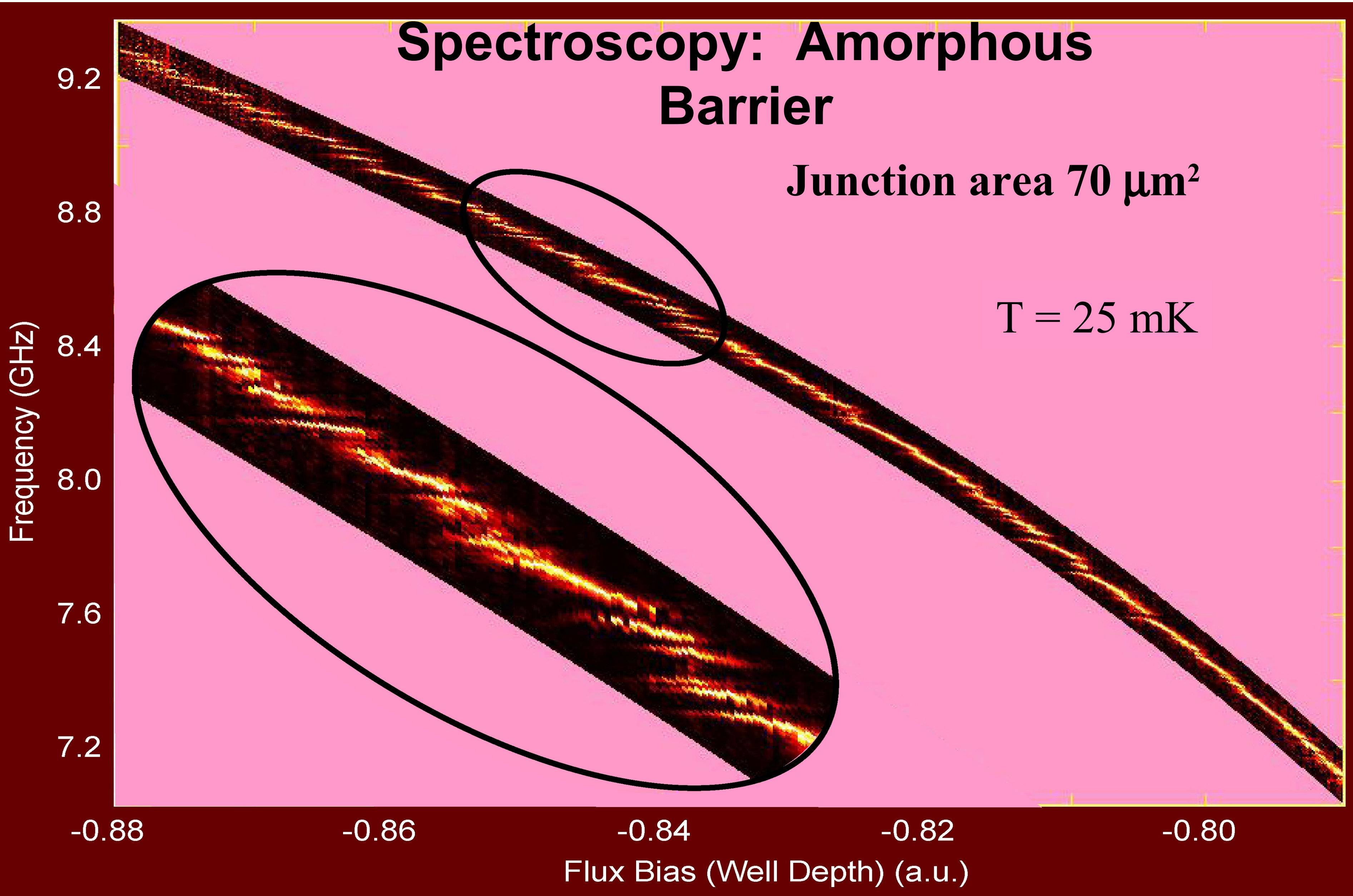
Improvement of Junction Materials

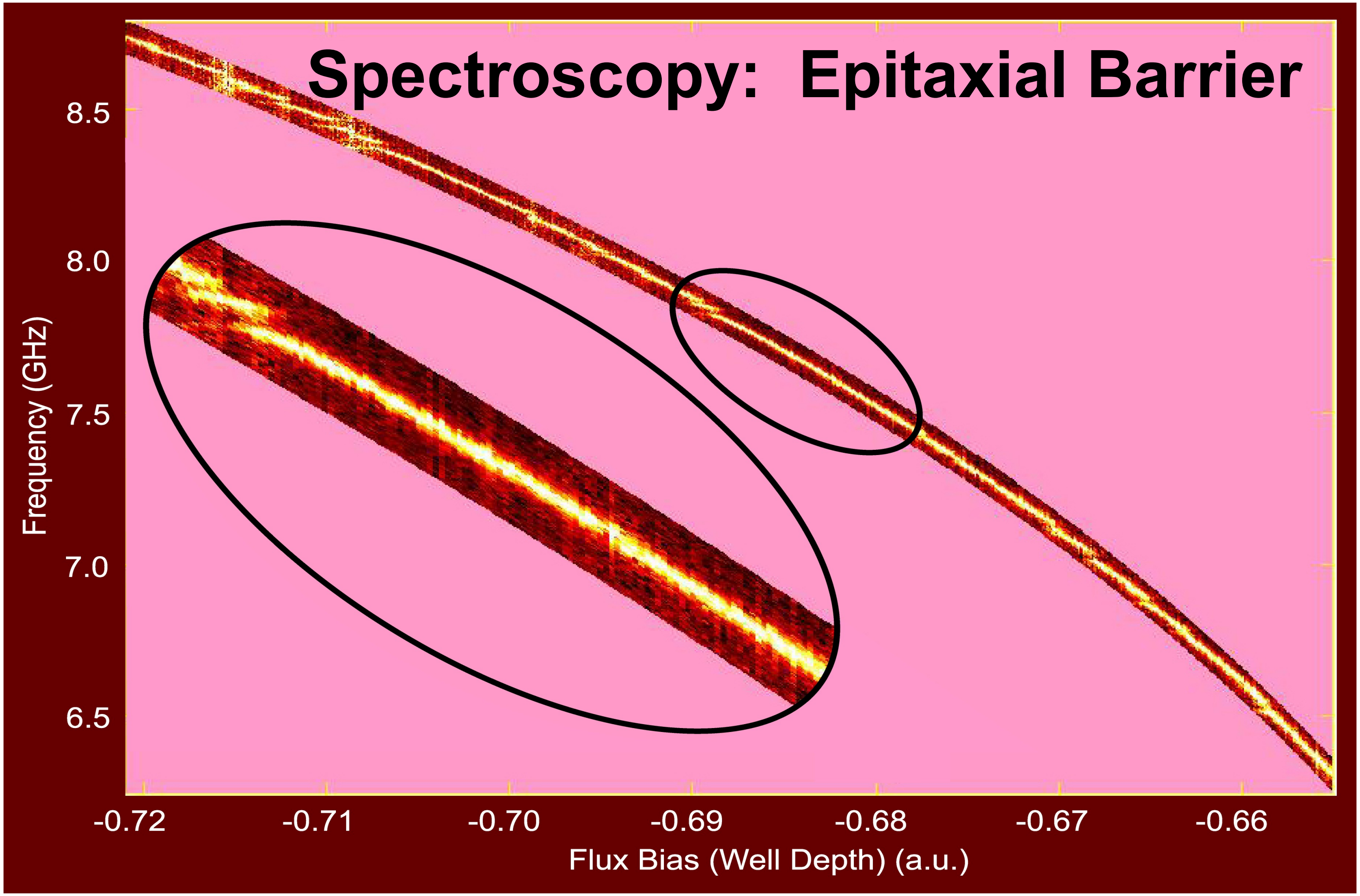


Spectroscopy: Amorphous Barrier

Junction area 70 μm^2

T = 25 mK

Improvement of Junction Materials



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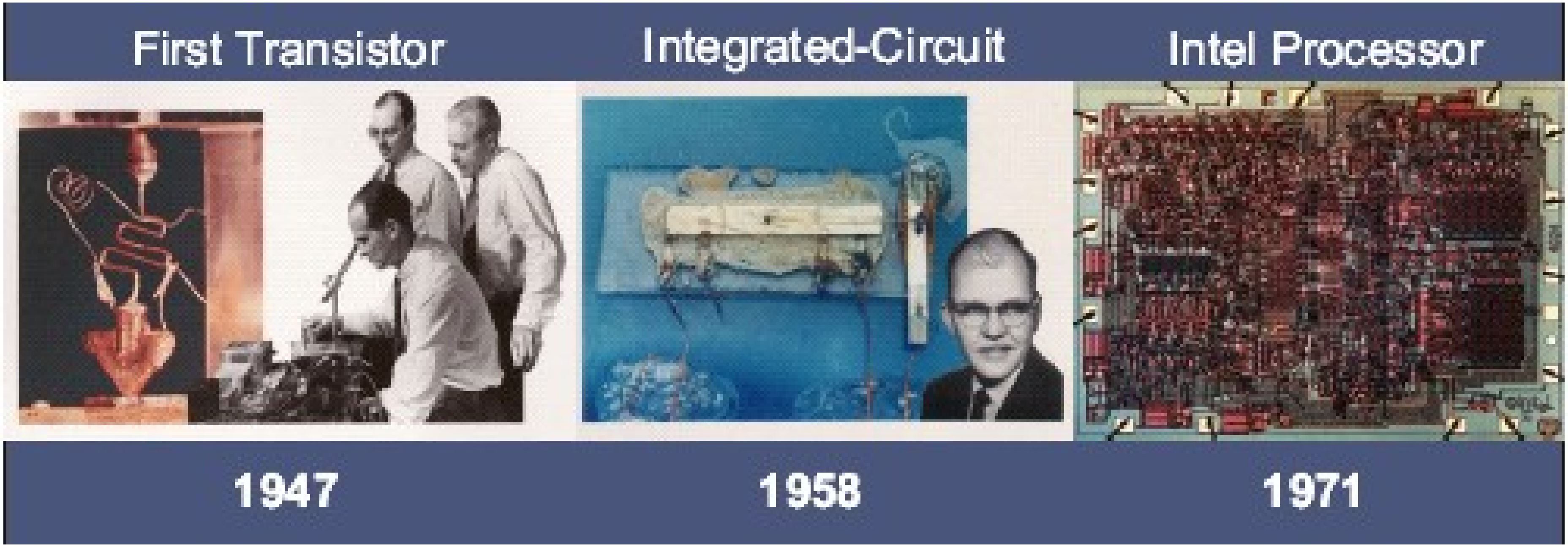
Outlook

- A lot of progress in Quantum Information
- “Quantum Leap” in problem solving – new thinking

  => Algorithms in quantum “coprocessor”
- Storage times need to be 10^4 longer than ops.
- Solid state superconducting systems promising
  - Need factor of 10-100 longer storage times (~10 μs)
  - better fidelity of measurement
- Materials optimization is critical

Shameless optimism slide



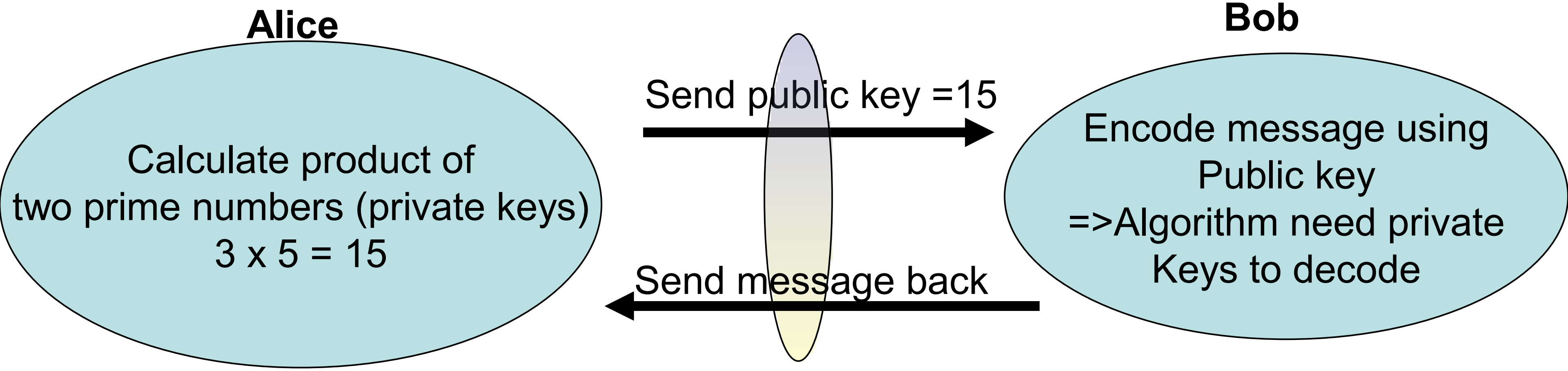
Bardeen
Brattain
Shockley

Kilbey

- How many years in the future is too many?

Classical Cryptography

- Public key



Alice

Calculate product of
two prime numbers (private keys)
3 x 5 = 15

Send public key =15

Send message back

Bob

Encode message using
Public key
=>Algorithm need private
Keys to decode

Eve –
Eavesdropper needs to figure out 15=3x5 to decode – or:

10941738641570527421809707322040357612003732945449205990913842131476349984288934784717997257891267332497625752899781833797076537244027146743531593354333897=
102639592829741105772054196573991675900716567808038066803341933521790711307779
*
106603488380168454820927220360012878679207958575989291522270608237193062808643

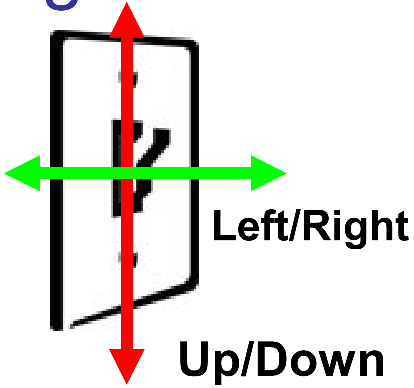
- 7 months to reduce this number into it’s two prime factors

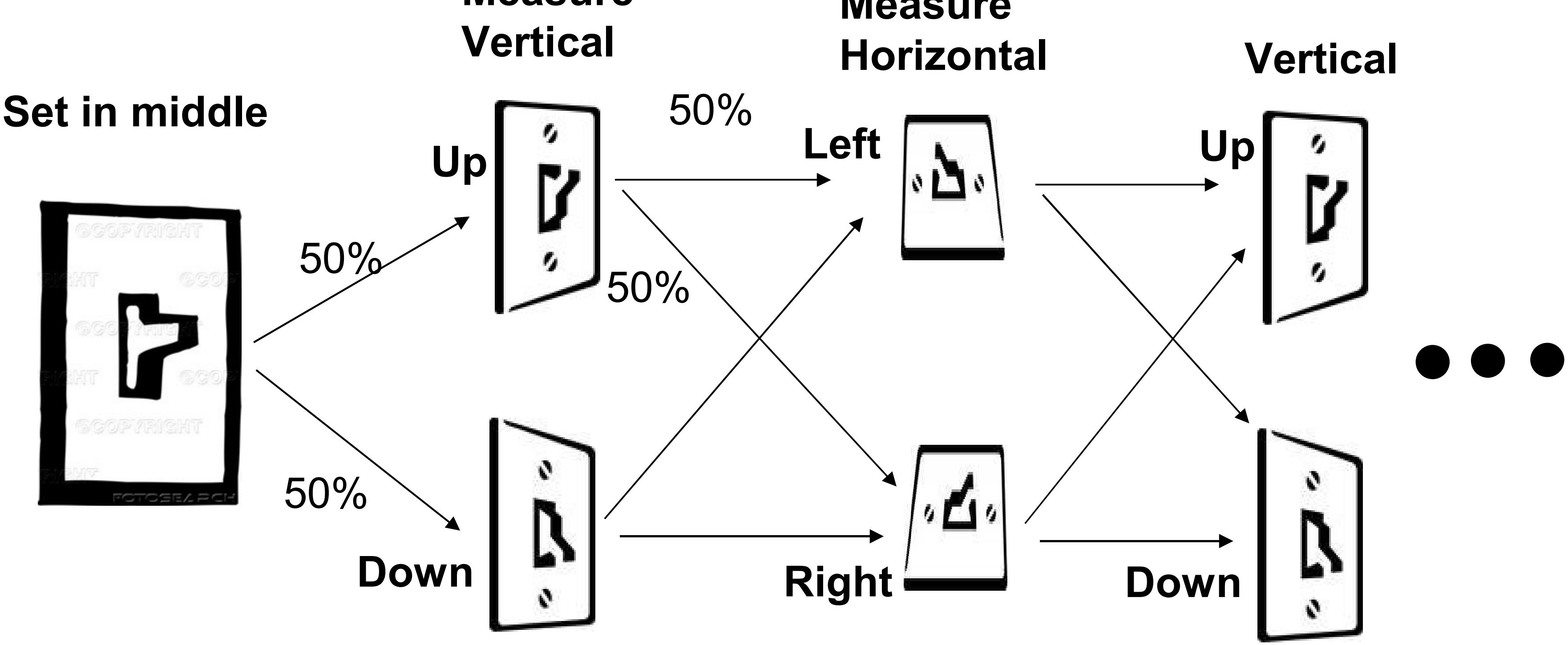
⇒ Need faster factoring - Quantum Computing

⇒ Need code that can’t be eavesdropped - Quantum Cryptography

Quantum Information Logic – based on digital 0&1!

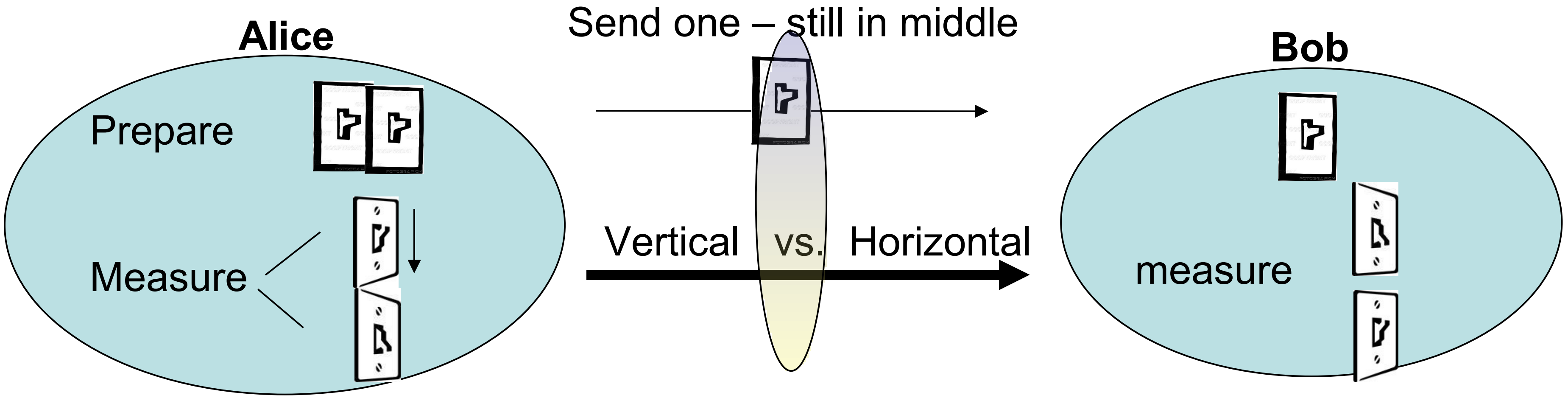
- Can only measure one direction at a time – U/D or L/R
- Quantum systems only remember 1 direction at a time
- Example – 4 way switch





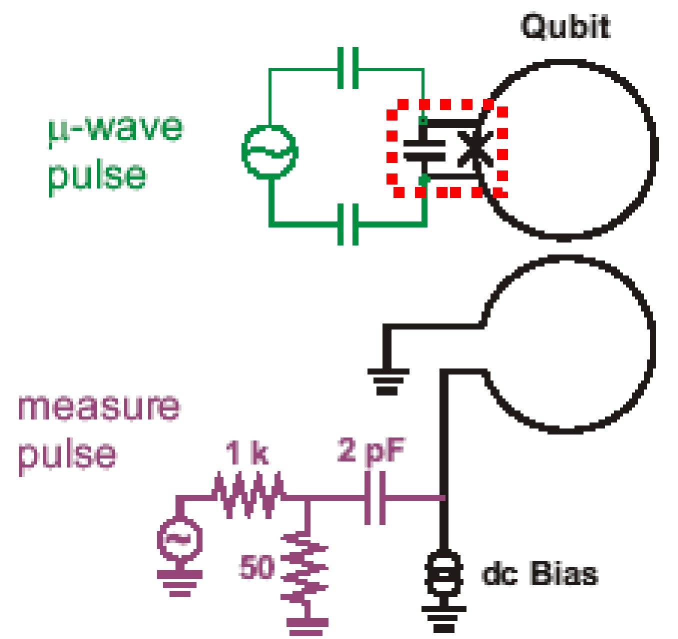
- **Quantum bit - "qubit"**
- **up ≡1, down≡0 - left & right intermediate**

Quantum Cryptography

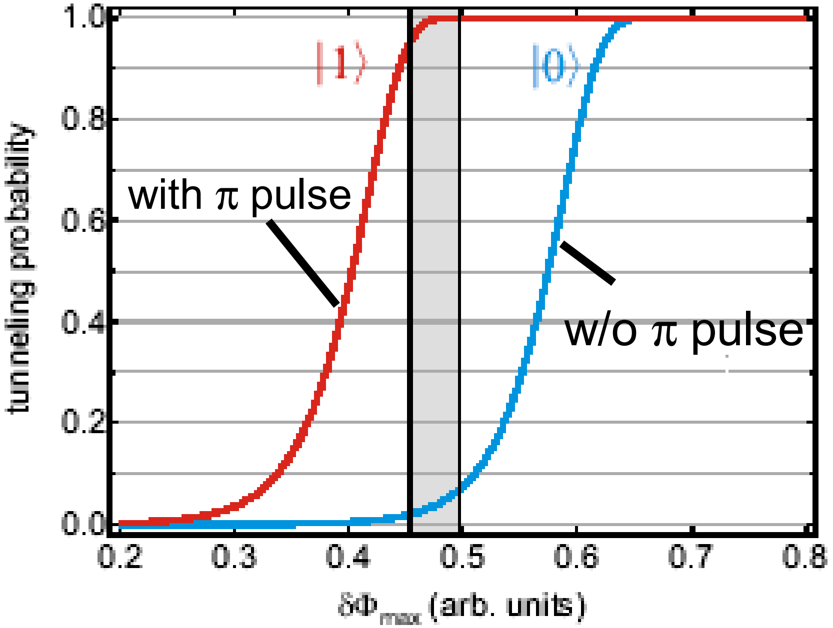


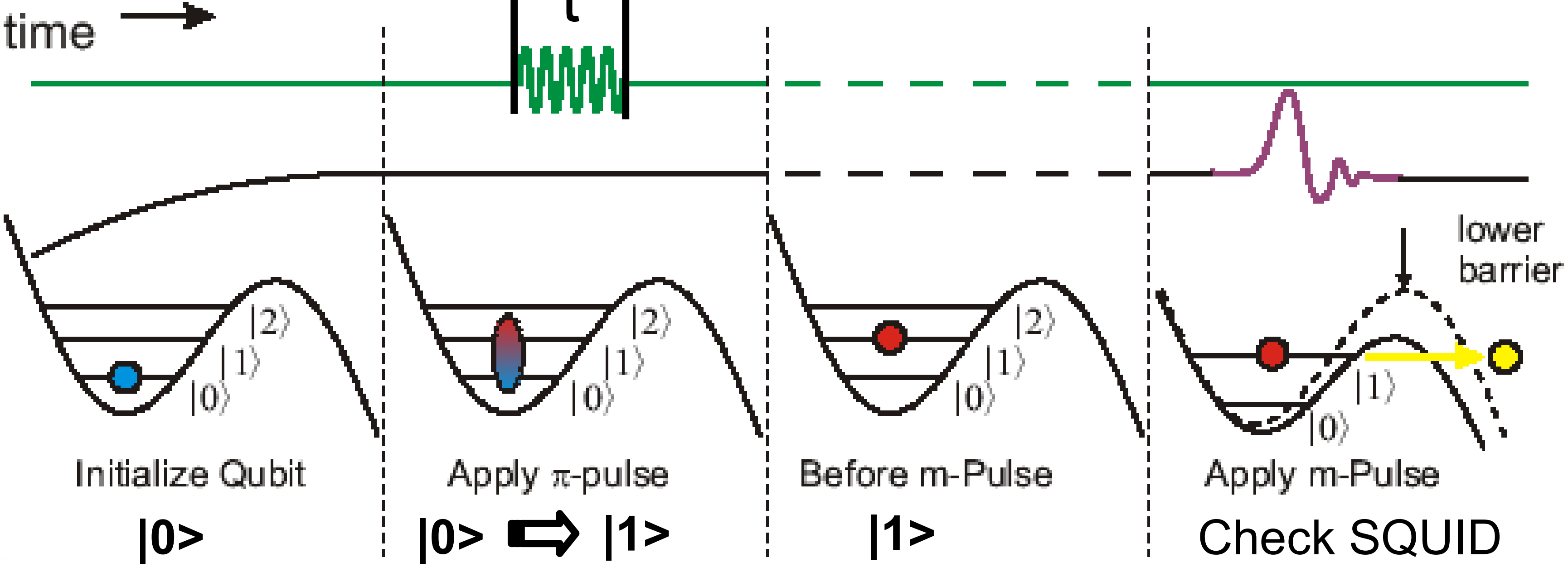
Eve –
Makes a measurement
changes the state of Alice, not Bob
Doesn't know if it is vertical or horizontal!

Prepare state & measure qubit



Readout SQUID





Initialize Qubit

|0>

Apply π-pulse

|0> ⇨ |1>

Before m-Pulse

|1>

Apply m-Pulse

Check SQUID