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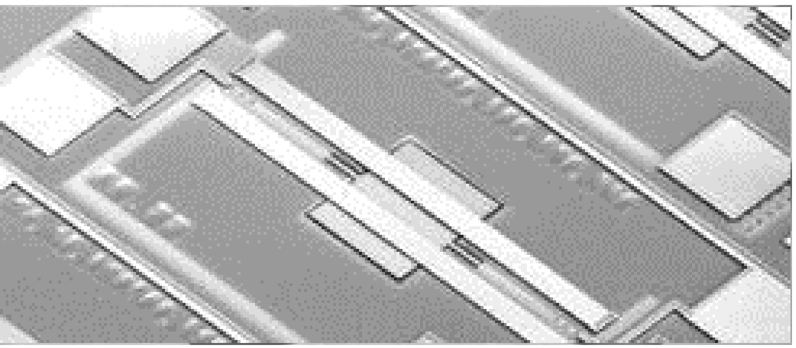

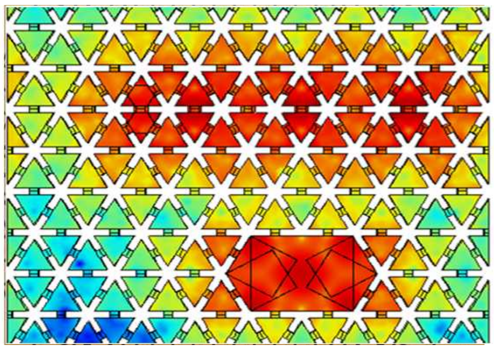

Chip Scale Phonon-Based Scalable Quantum Computing

Susan Clark, Charles Reinke, Troy Olsson, Eduard Bielejec
and Ihab El-Kady

ielkady@sandia.gov

SPIE NDE,
San Diego, CA
Mar. 10, 2015, 9436-23

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Quantum Computing Basics

- ***Classical Computer:***
  - Memory made up of bits,
  - Each bit represents either a 1 or 0.
  - A classical computer with n bits can be in **ONLY** 1 of 2^n possible states.
  - ***e.g. 2 bits:*** (0,1) and (0,1)→ ***2^n:*** (0,0) **OR** (0,1), **OR** (1,0), **OR** (1,1)

- ***Quantum Computer:***
  - Maintains a sequence of qubits.
  - A single qubit can represent a 1, 0, or **ANY** quantum superposition of 1 and 0.
  - a quantum computer with n qubits can be in an arbitrary superposition of up to 2^n different states simultaneously
  - ***e.g. 2 bits:*** $|0\rangle$, $|1\rangle$ and $|0\rangle$, $|1\rangle$ → ***2^n*:** $a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle$; ***with*** $|a|^2+|b|^2+|c|^2+|d|^2=1$

- ***Advantages of "large scale" Quantum Computing:***
  - Fast factorization of large integers → ***Cryptography***
  - Simulation of ***quantum*** many body systems

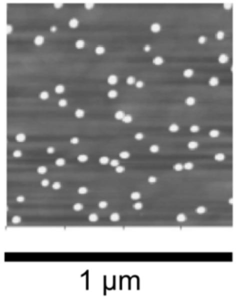
Quantum Computing Basics

- ***Requirements of Quantum Computing:***
  - Coherently Superpose or "***Entangle***" a large number of qubits
  - Ability to address each qubit independently "***local control***"
  - Fast gates "***operations***" before qubits decohere

- ***Types of Qubits:***
  - ***"Stationary"*** *qubits, i.e. trapped/not in motion➔ "**easy**" to encode information on, but "**hard**" to communicate it!*
    - *Trapped atoms*
    - *Trapped ions*
    - *Josephson Junctions*
    - *Quantum dots*
    - *Defect atoms (donor/acceptor) in a strained matrix*
    - *Nitrogen vacancies in Diamond*
  - ***"Flying"*** *qubits, i.e. in motion by default ➔ "**hard**" to encode information on, but "**easy**" to communicate it!*
    - *Photons*
    - *Phonons?*
    - *Polaritons?*
    - *Plasmons?*
    - *Magnons?…etc*

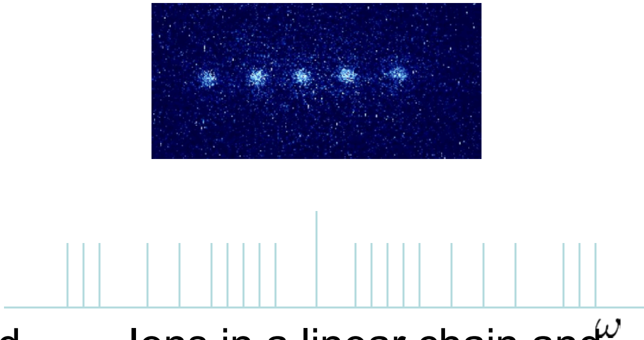
Challenges facing Scalable Quantum Computing

Inhomogeneity



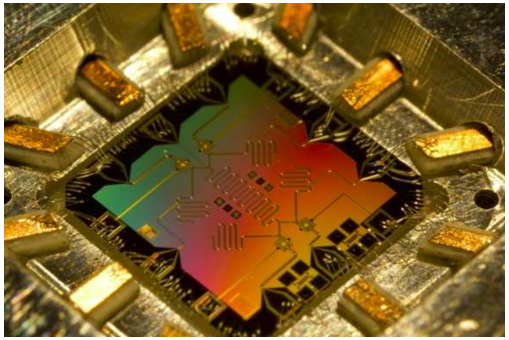
AFM image of self-assembled InGaAs QDs before capping layer
Courtesy Bingyang Zhang, Stanford

Spectral Crowding



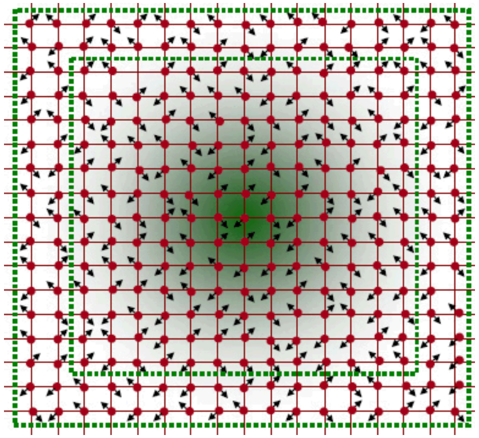
Ions in a linear chain and example spectral lines
Courtesy Francisco Benito, SNL

Stringent Fabrication Demands



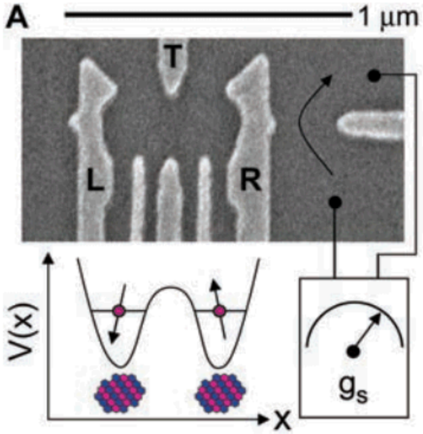
Superconducting chip with four qubits
Photo by Erik Lucero, UCSB,
Featured in BBC News

Decoherence



Liu, Yao, and Sham, *NJP* (2007)

Local Interactions



Petta, *et al.* *Science* (2005)

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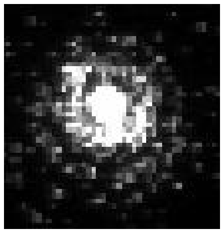
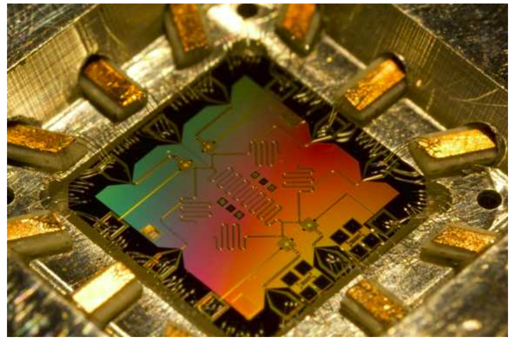
If We Could Create The Perfect Qubit

Homogeneity



Single Atoms

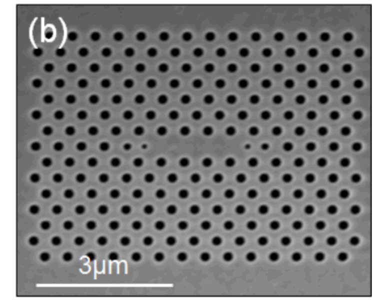
Isolated Transitions



Ability to control interactions via quantum transducers

Sun, *et al. Phys Rev A* (2006)
Mariantoni *et al. Nat. Phys.* (2011)

Relax Fabrication Demands



Radulaski *et al. Optics Express* (2013)

Within current fab abilities
Little impact on qubit perform.
Can be fabricated in mass

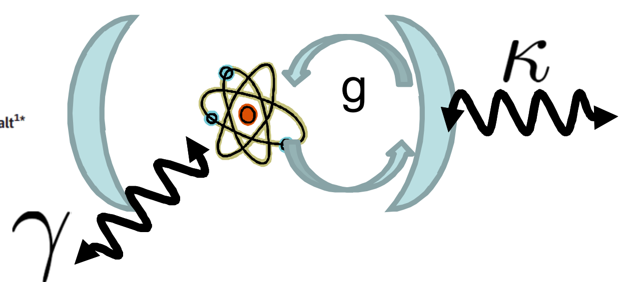
Coherence

Room-Temperature Quantum Bit Storage Exceeding 39 Minutes Using Ionized Donors in Silicon-28

Kamyar Saeedi,[1] Stephanie Simmons,[2] Jeff Z. Salvail,[1] Phillip Dluhy,[1] Helge Riemann,[3] Nikolai V. Abrosimov,[3] Peter Becker,[4] Hans-Joachim Pohl,[5] John J. L. Morton,[6] Mike L. W. Thewalt[1*]

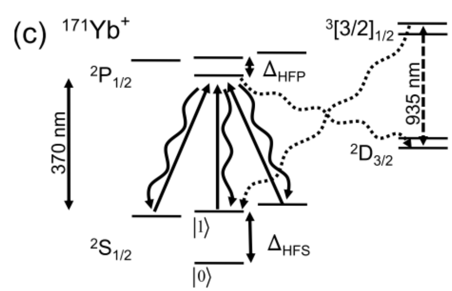
Science **342** 830 (2013)

Strong controlled Interactions



Cavity enhancement

Reliable Measurement



Noek *et al. Optics Lett.* (2013)

The "Phoniton" Qubit

Phonon based quantum computing ,"The Phoniton" , has the ability to provide most, if not all, of the favorable qubit attributes:

Phoniton Qubit* = *Sound-Matter quasi particle

=

Phononic Crystal Cavity

+

Phonon

+

single acceptor atom

=

Homogeneity

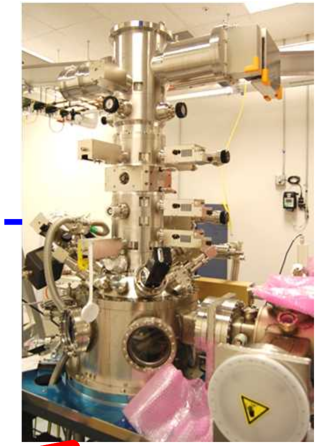
Isolated Transitions

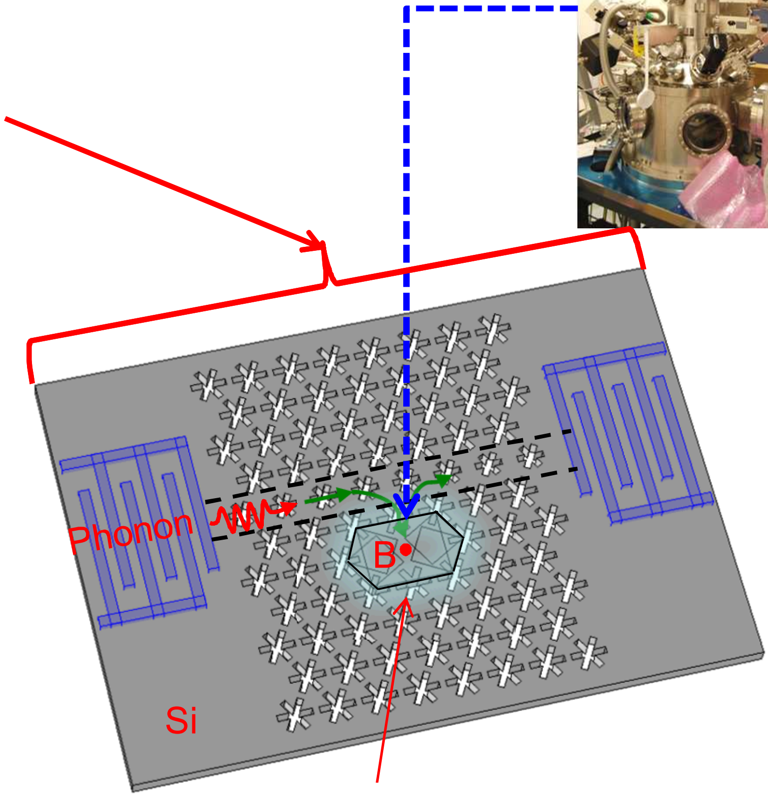
Fabrication Demands

Strong Interactions

Coherence

Reliable Measurement

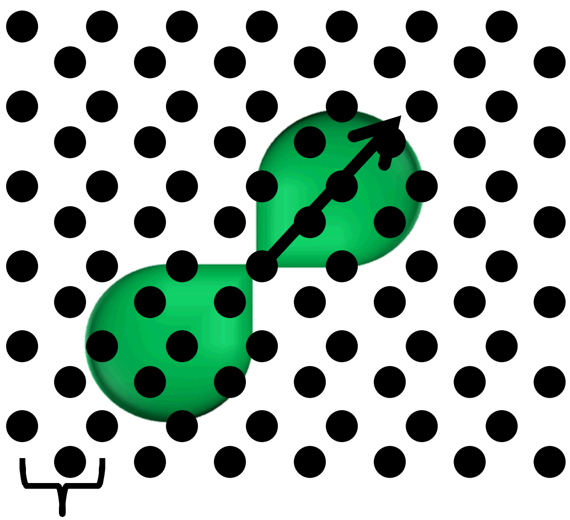




The memory Qubit

Acceptor-bound hole spin system: hydrogenic wavefunction inside semiconductors

Bohr radius $\approx$ 1.3 nm



lattice spacing= 0.54 nm

III	IV	V	VI
B	C	N	O
Al	Si	P	S
Ga	Ge	As	Se
In	Sn	Sb	Te

Impurity Potential

$$U(\mathbf{r}) = \frac{-e^2}{4\pi\varepsilon r}$$

Hydrogen Effective Mass Equation

$$\left(-\frac{\hbar^2}{2m^*}\nabla^2 - \frac{e^2}{4\pi\varepsilon r}\right) F(\mathbf{r}) = EF(\mathbf{r})$$

m^* = effective hole mass ($0.46\ m_0$)

ε = Relative Permittivity (11.7)

Similar structure to donors, but holes interact less with nuclear spins of silicon.

Homogeneity

Coherence

Room-Temperature Quantum Bit Storage Exceeding 39 Minutes Using Ionized Donors in Silicon-28

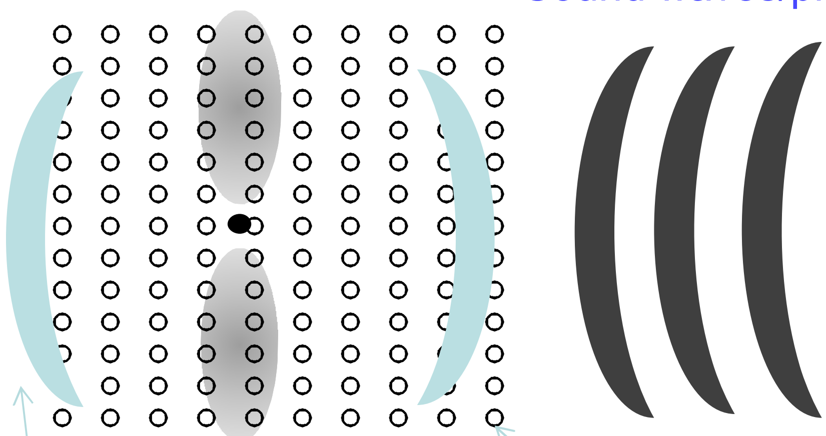
Kamyar Saeedi,[1] Stephanie Simmons,[2] Jeff Z. Salvail,[1] Phillip Dluhy,[1] Helge Riemann,[3] Nikolai V. Abrosimov,[3] Peter Becker,[4] Hans-Joachim Pohl,[5] John J. L. Morton,[6] Mike L. W. Thewalt[1*]

Coupling a phonon to an acceptor spin

arXiv:1208.1776v1 [cond-mat.mes-hall] 8 Aug 2012

On-chip quantum phonodynamics

Rusko Ruskov and Charles Tahan



Makes use of spin-orbit interaction (Larger for holes)

$$H^{ac}_{e,ph}(\mathbf{r}) = \sum_{ij} \hat{D}_{ij}\hat{\varepsilon}_{ij}(\mathbf{r})$$

Deformation potential operator

Strain tensor component

$$\hat{\varepsilon}_{ij}(\mathbf{r}) = \frac{1}{2}\left(\frac{\partial u_i}{\partial r_j} + \frac{\partial u_j}{\partial r_i}\right)$$

Quantized mechanical displacement:

$$\mathbf{u}(\mathbf{r}) = \sum_{\mathbf{q},\sigma}\left(\mathbf{u}_{\mathbf{q},\sigma}(\mathbf{r})b_{\mathbf{q},\sigma} + \mathbf{u}^*_{\mathbf{q},\sigma}(\mathbf{r})b^\dagger_{\mathbf{q},\sigma}\right)$$

$b^\dagger_{\mathbf{q},\sigma}$ creates phonon in mode $\mathbf{q},\sigma$ with energy $\hbar\omega_{\mathbf{q},\sigma}$

Add boundary conditions via a cavity with mode volume V

$$H_g \approx \hbar g^{s',s}_{\mathbf{q},\sigma}\left(\sigma^+_{s',s}b_{\mathbf{q},\sigma} + \sigma^-_{s',s}b^\dagger_{\mathbf{q},\sigma}\right)$$

Coupling strength

Pauli spin operators

Phonon annihilation and creation operators

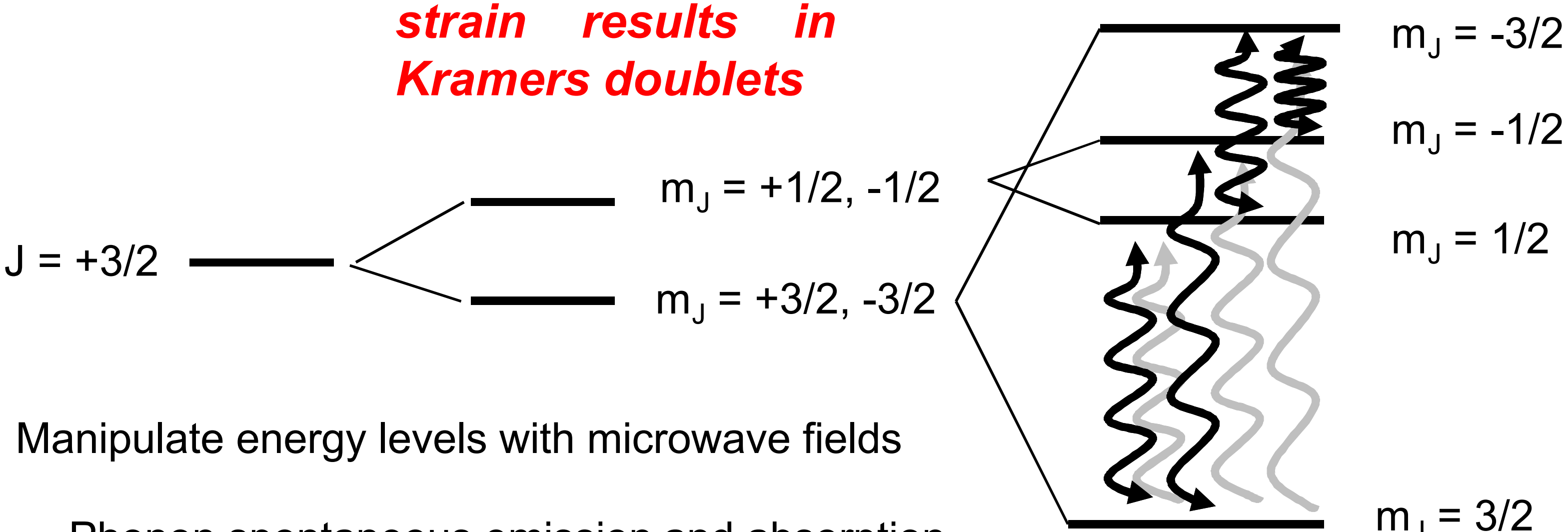
Familiar Jaynes-Cummings Hamiltonian

Energy level scheme of acceptor B-atom in a PnC cavity

Small background strain due to the placement results in Kramers doublets. An applied DC magnetic field results in further splitting and removes degeneracy.

Large magnetic field (1-3 T) splits Kramers doublets

Small background strain results in Kramers doublets



Manipulate energy levels with microwave fields

Phonon spontaneous emission and absorption

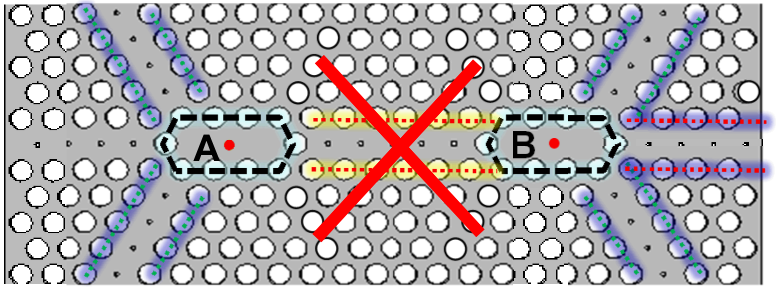
Coupling is via deformation of crystal (phonon) is allowed (compound orbital)

10's of GHz
All microwave transitions allowed

Homogeneity

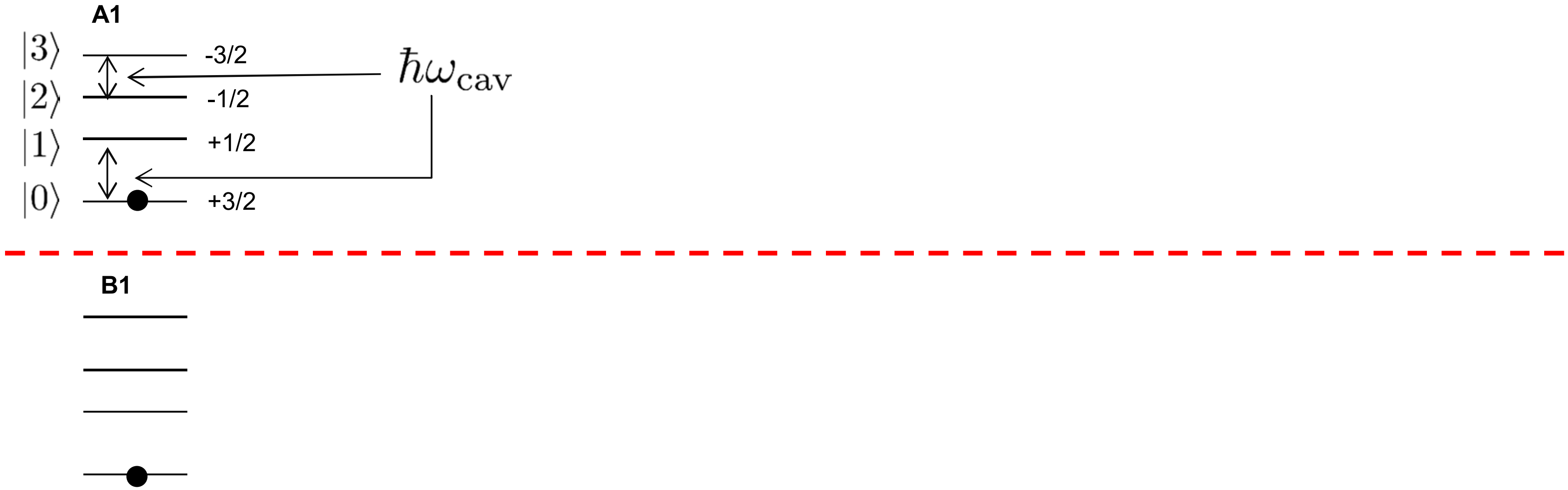
Reliable Measurement

Entanglement Scheme

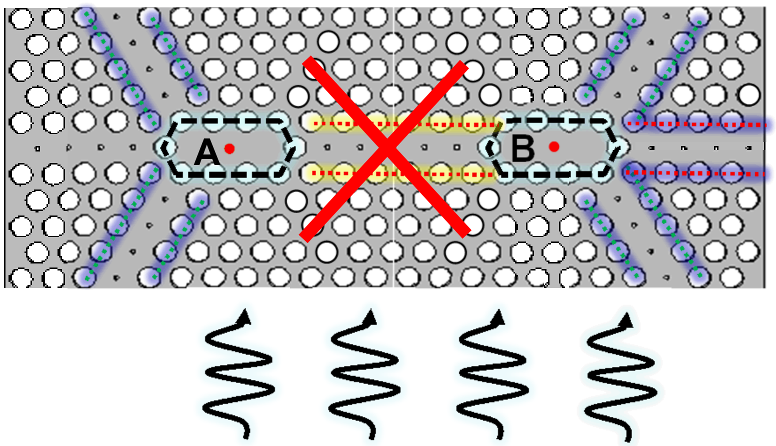


$$|\psi\rangle = |\psi\rangle_a \otimes |\psi\rangle_b$$
$$= |0\rangle_a |0\rangle_b$$

Initialize to |0> state



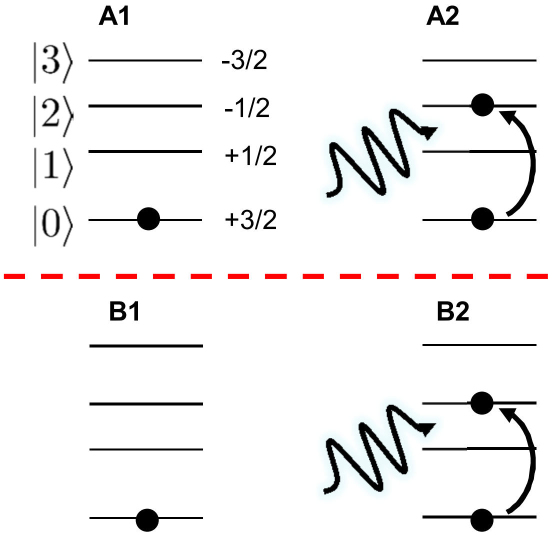
Entanglement Scheme



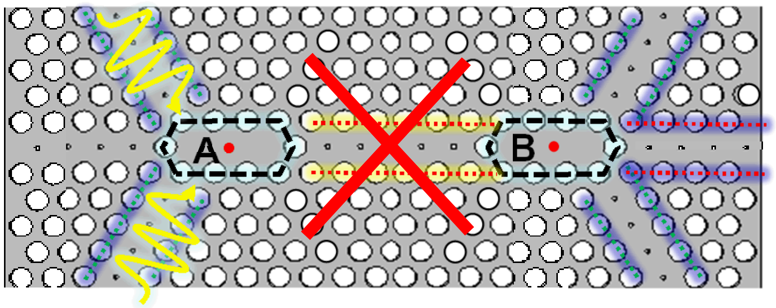
$$|\psi\rangle = \frac{1}{2}\left(|0\rangle_a + |2\rangle_a\right) \otimes \left(|0\rangle_b + |2\rangle_b\right)$$

Initialize to |0> state

Global microwave π/2-pulse

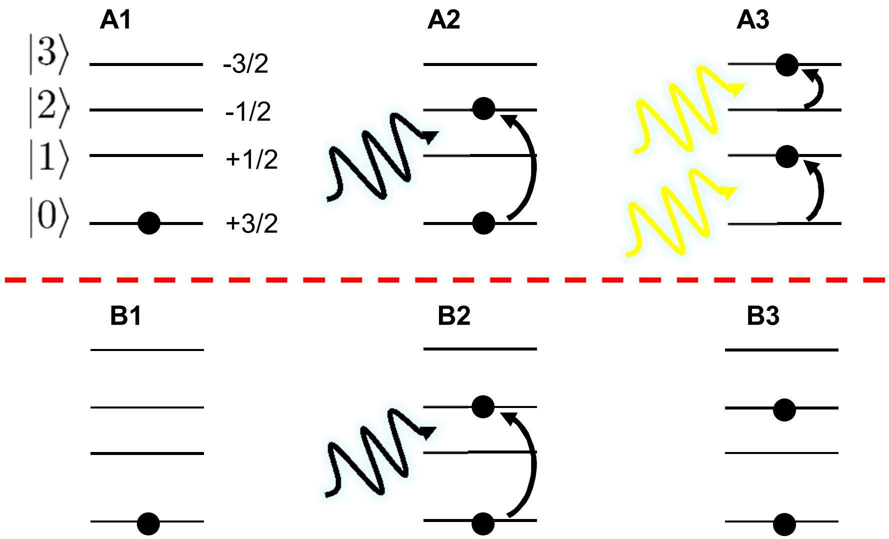


Entanglement Scheme

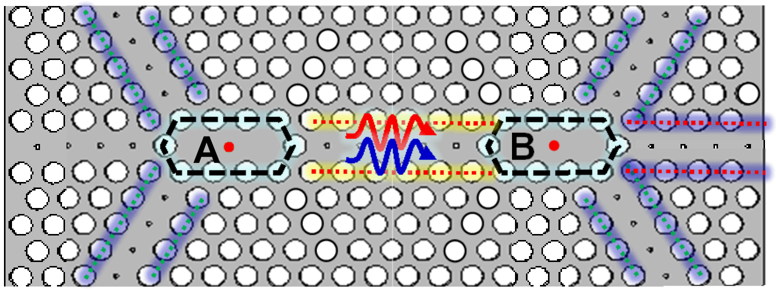


$$|\psi\rangle = \frac{1}{2}\left(|1\rangle_a + |3\rangle_a\right) \otimes \left(|0\rangle_b + |2\rangle_b\right)$$

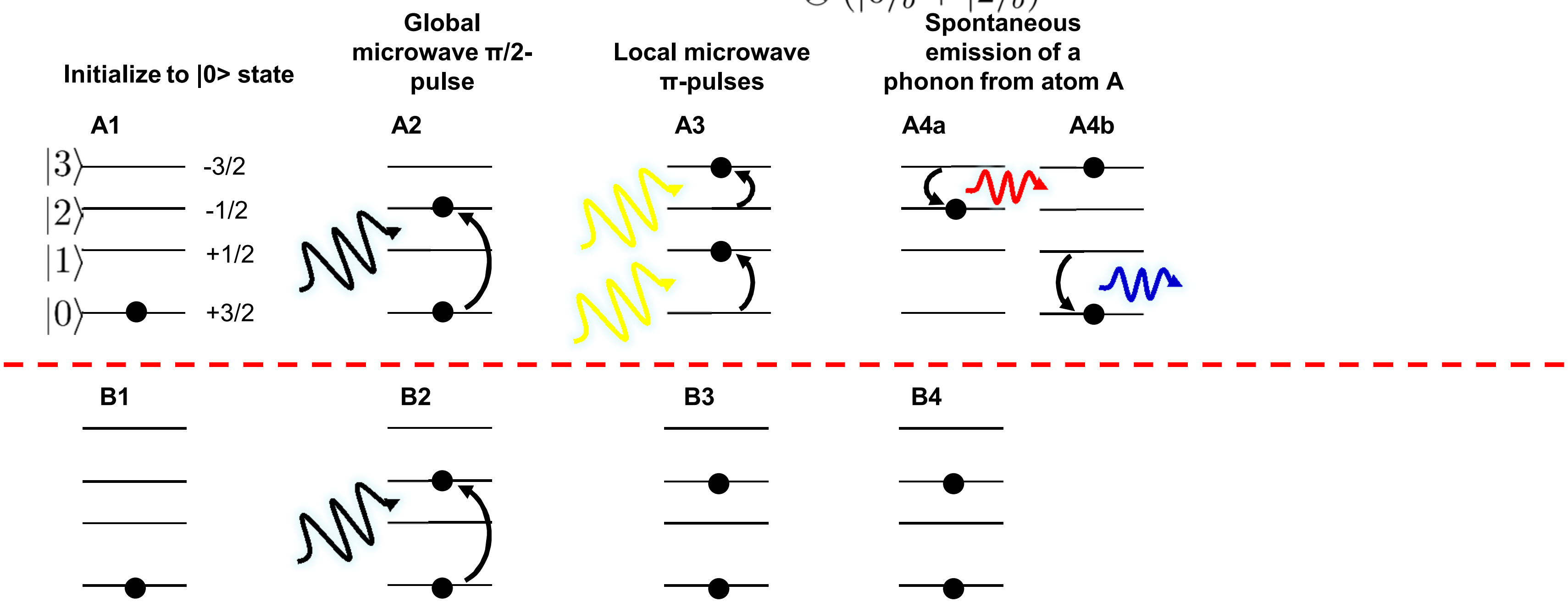
Initialize to |0> state | **Global microwave π/2-pulse** | **Local microwave π-pulses**



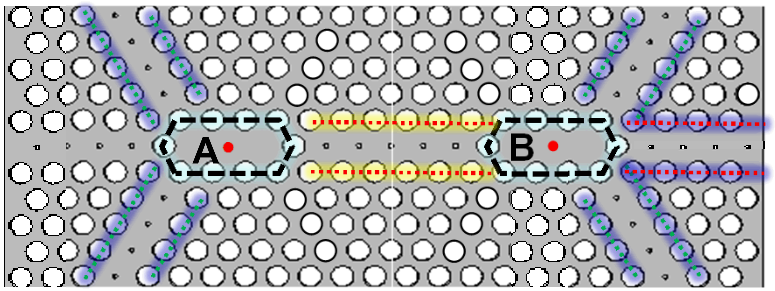
Entanglement Scheme



$$|\psi\rangle = \frac{1}{2}\left(\frac{1}{\sqrt{2}}\left(|1\rangle_a + |2\rangle_a\right)|r\rangle_{\mathrm{ph}} + \frac{1}{\sqrt{2}}\left(|0\rangle_a + |3\rangle_a\right)|b\rangle_{\mathrm{ph}}\right)$$
$$\otimes \left(|0\rangle_b + |2\rangle_b\right)$$



Entanglement scheme

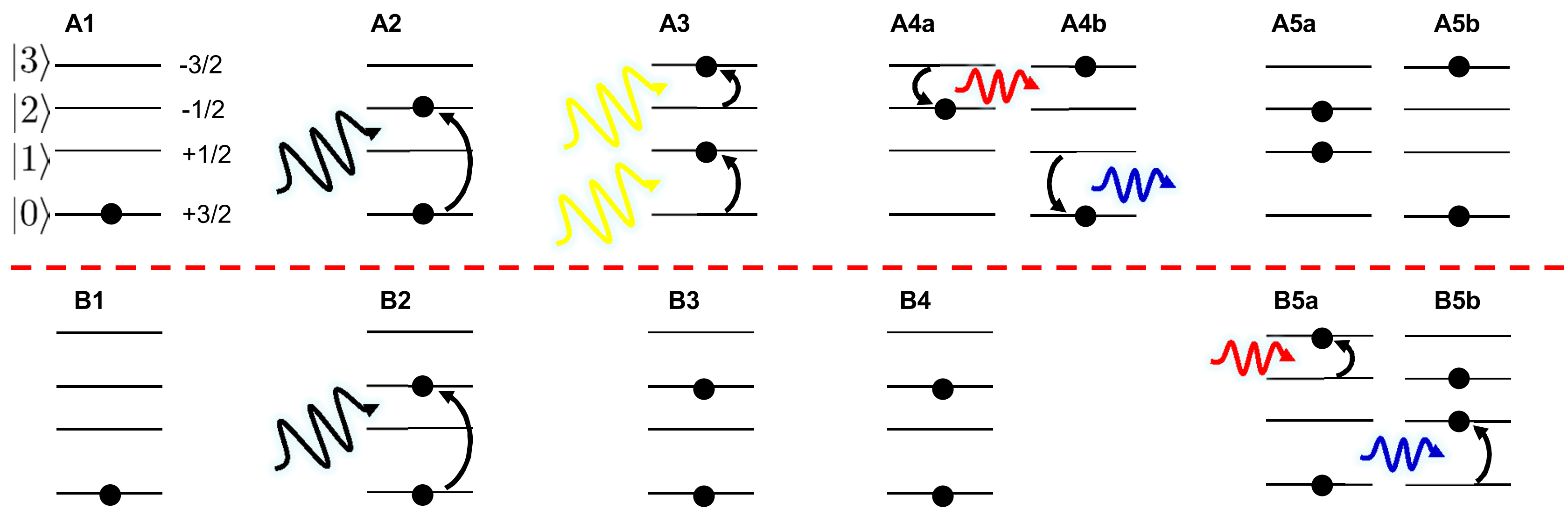


$$|\psi\rangle = \frac{1}{\sqrt{8}}\left(\left(|1\rangle_a + |2\rangle_a\right)\left(|0\rangle_b + |3\rangle_b\right) + \left(|0\rangle_a + |3\rangle_a\right)\left(|1\rangle_b + |2\rangle_b\right)\right)$$

Switching to basis:
$$\begin{cases} |x\rangle = 1/\sqrt{2}(|0\rangle + |3\rangle) \\ |y\rangle = 1/\sqrt{2}(|1\rangle + |2\rangle) \end{cases}$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|y\rangle_a|x\rangle_b + |x\rangle_a|y\rangle_b\right)$$

Initialize to |0> state | **Global microwave π/2-pulse** | **Local microwave π-pulses** | **Spontaneous emission of a phonon from atom A** | **Absorption of the phonon by atom B**

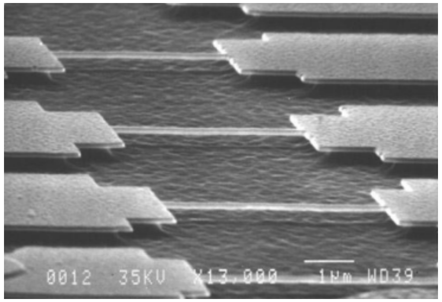


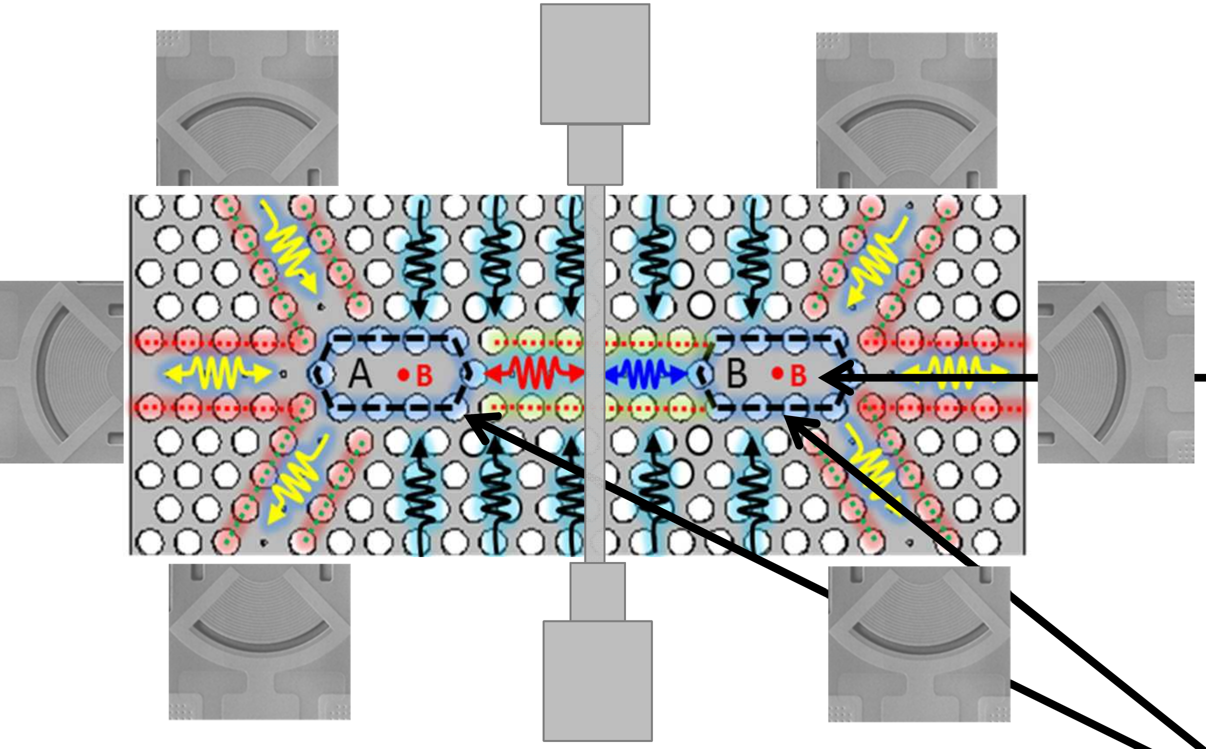
Controlling Interactions and Local Qubit Control

MEMS based cantilever system for **MHz** waveguide control

Focusing AlN transducers for local microwave pulses

Top View:





Impurity acceptor atom at center of cavity

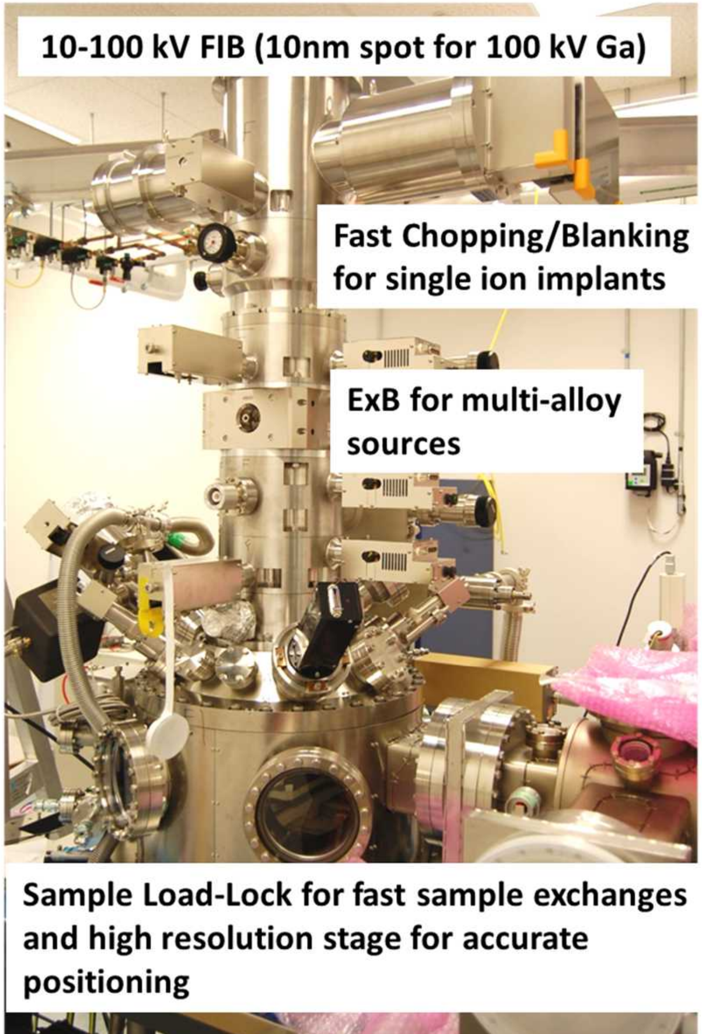
Global Initialization
Local Microwave Pulse
Entangling Phonons

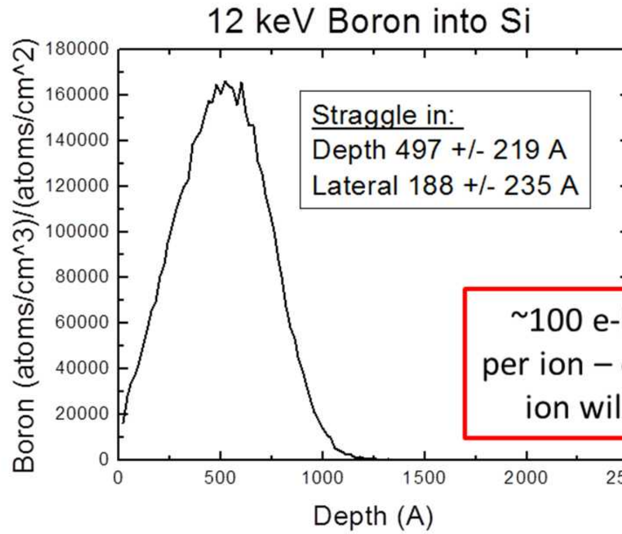
Mechanically coupled cavities

Placement Straggle

Single Boron Acceptor Implantation into Si

- Target a depth of 50 nm and determine the resulting straggle and ionization

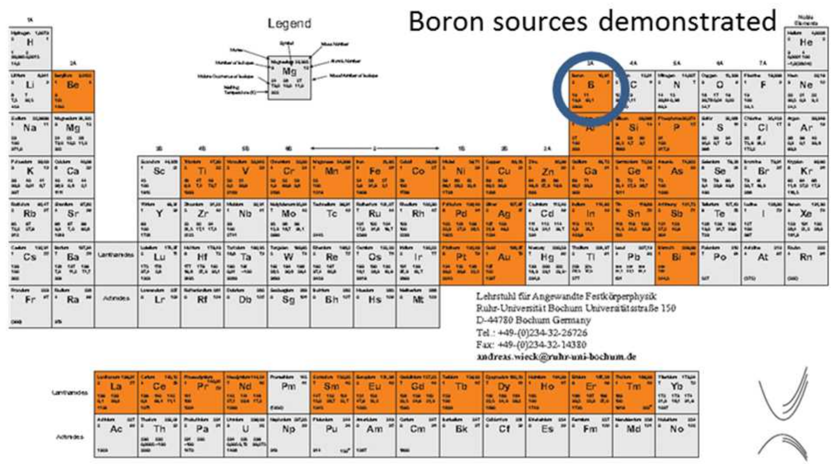




90nm

65nm

~100 e-h pairs produced per ion – detection of single ion will be a challenge

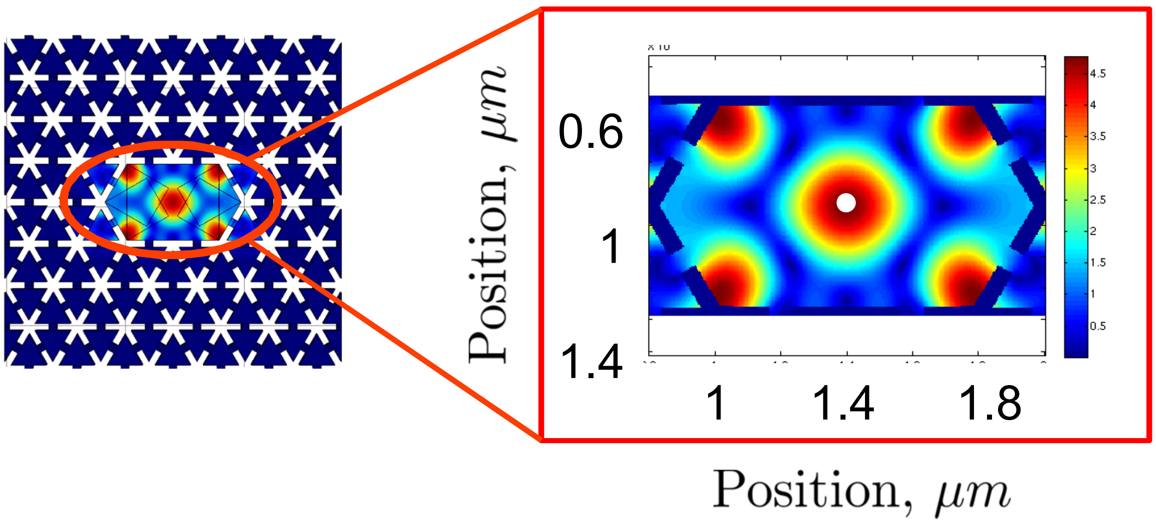


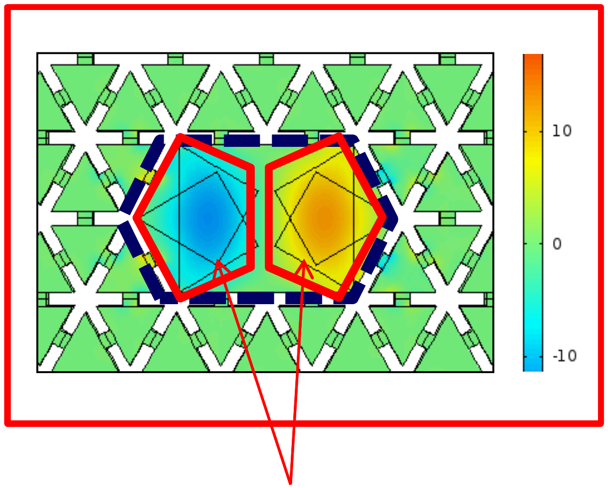
From Professor Weick Ruhr Uni Bochum

Sandia National Laboratories

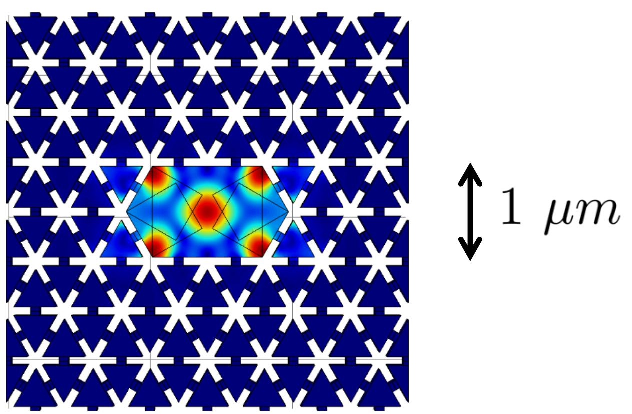
Fabrication demands are low

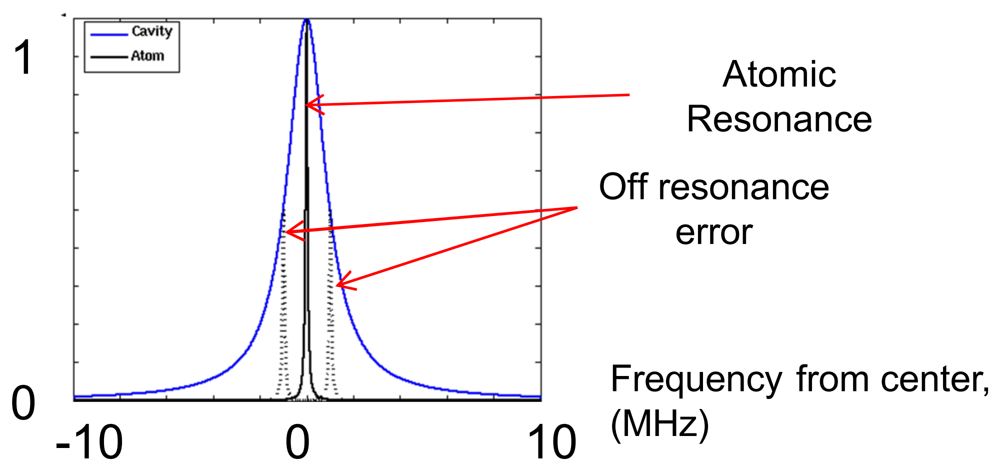
Placing an impurity in a cavity:





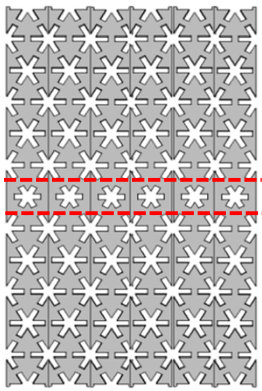
Crystal size not critical:



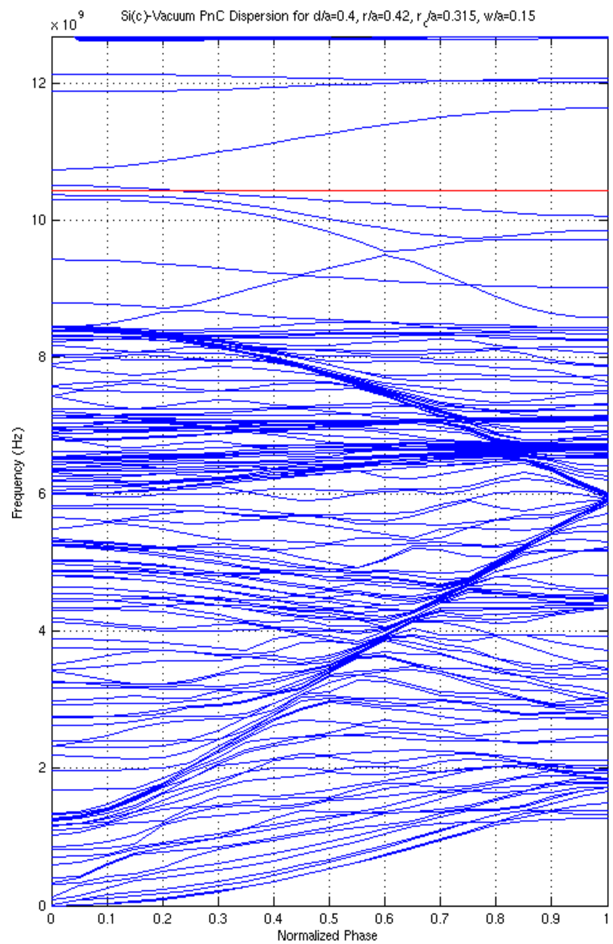


Phonon Based Communication

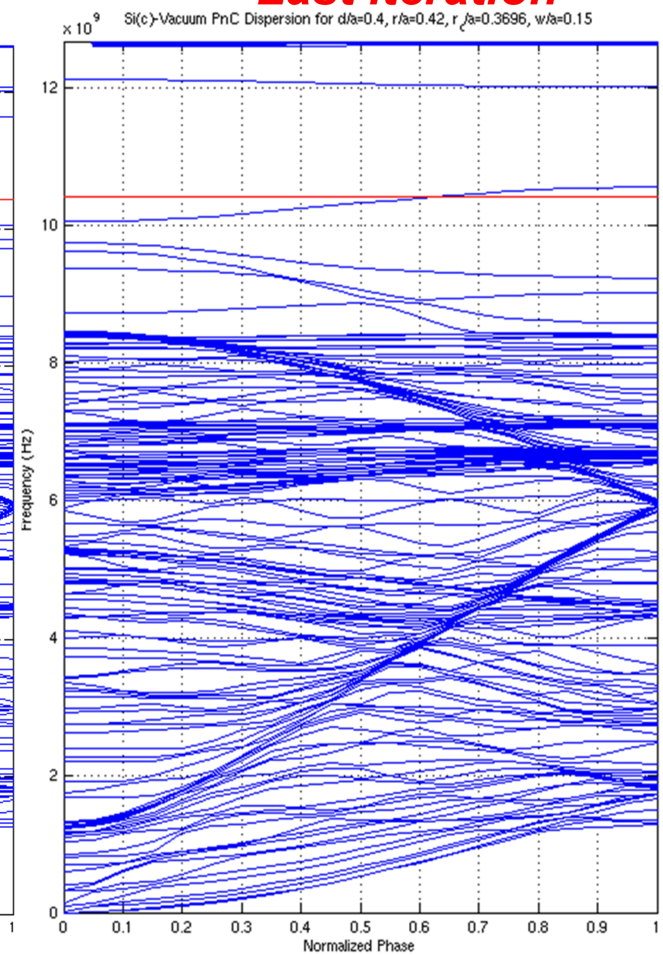
- Optimize wave guide topology so that the waveguide cavity mode intercept
- Try to design single mode waveguide
- OR ensure a clean intercept with no competing modes



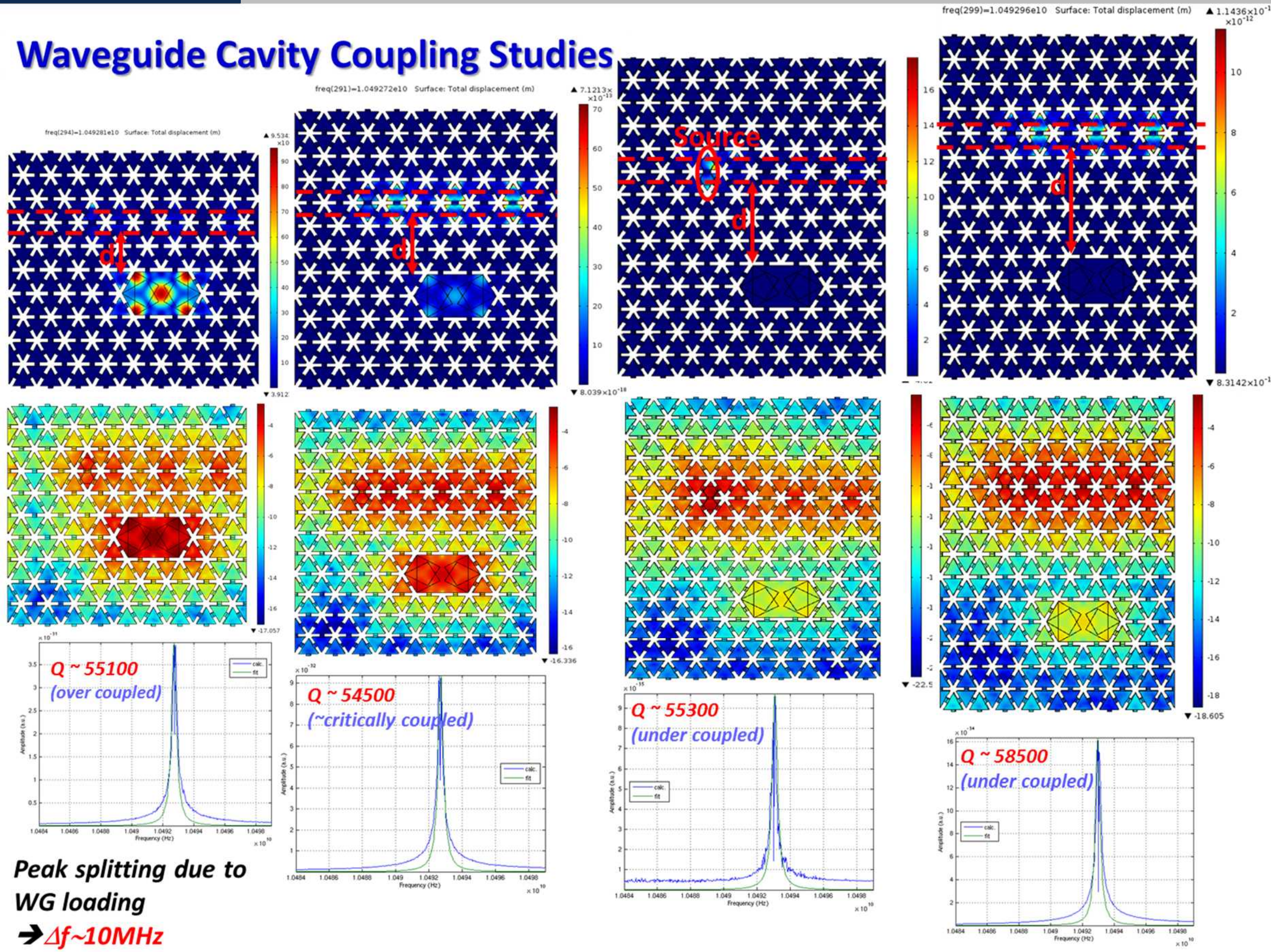
First iteration



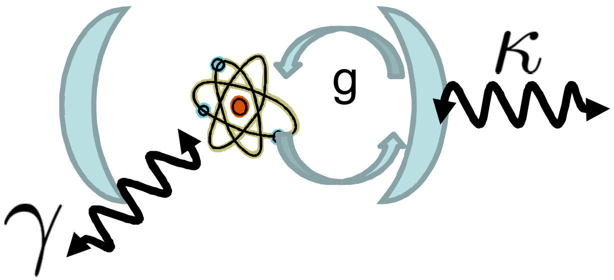
Last iteration



Phonon Based Communication



CQMD: Cavity Quantum Mechanical Dynamics



By straight forward analogy with QED:

γ → **Decay rate of the atom into free-space**

κ → **Decay rate of the cavity field**

g → **Rate of coherent atom-cavity field coupling**

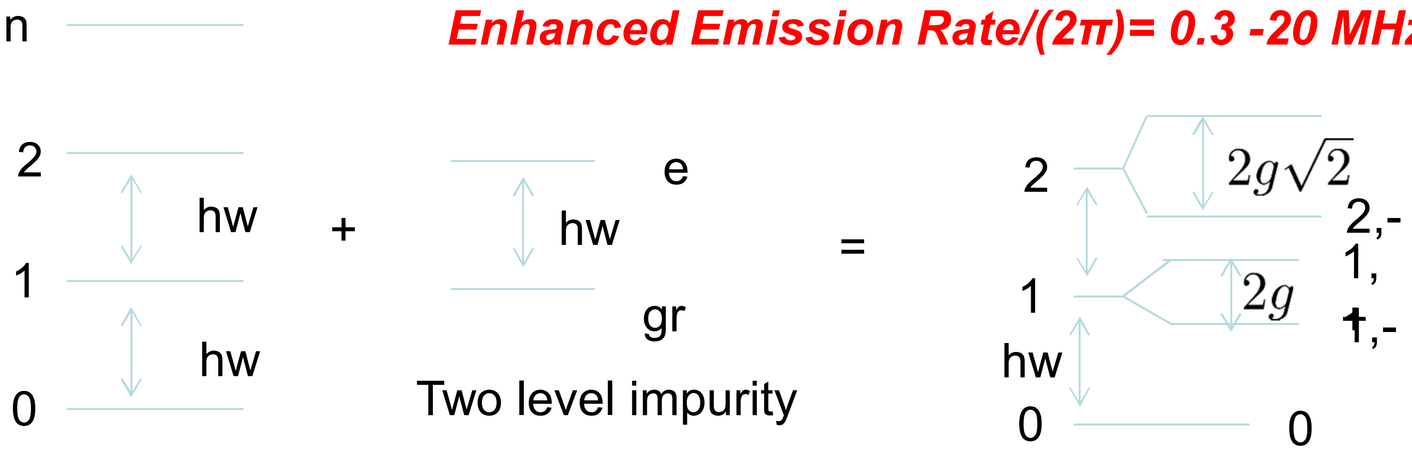
$$g \propto \frac{1}{\sqrt{V}}$$

$$\kappa \propto \frac{1}{Q}$$

$$F = \frac{2|g|^2/\kappa}{n\gamma} \Rightarrow F = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q}{V}$$

Purcell Factor : 15-700

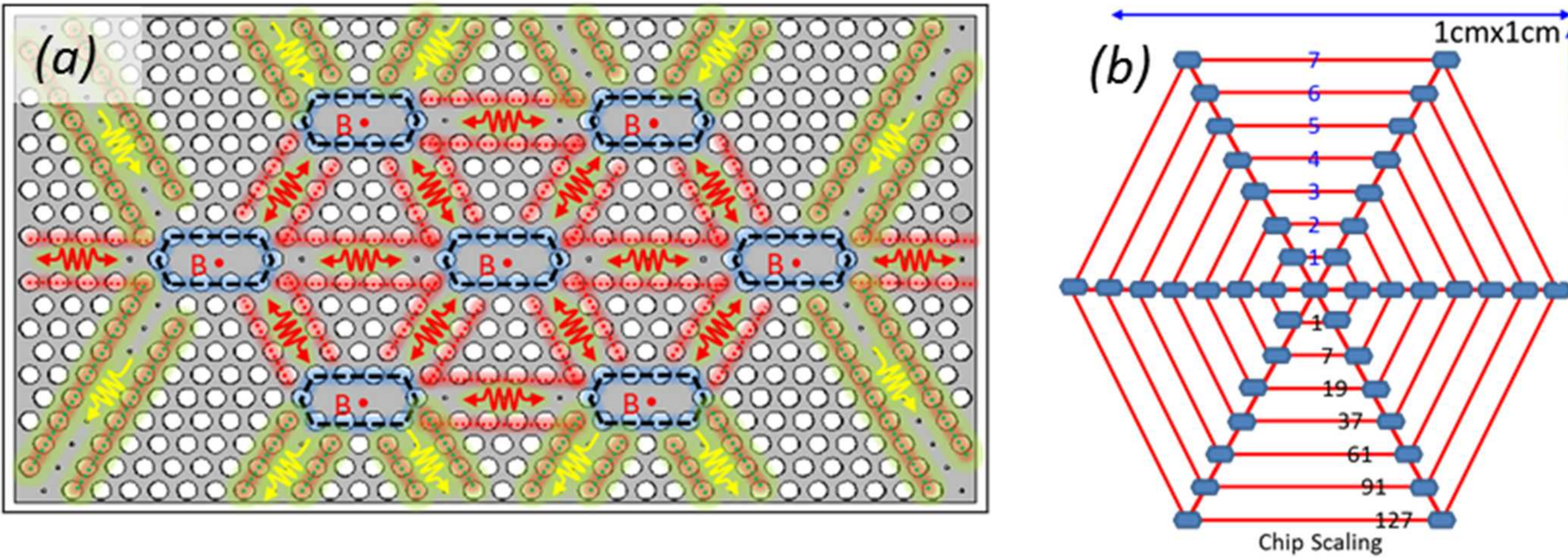
Enhanced Emission Rate/(2π)= 0.3 -20 MHz



Cavity modes

Strong Controlled Interactions

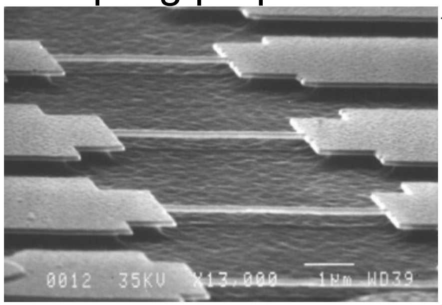
Scale-up Schemes



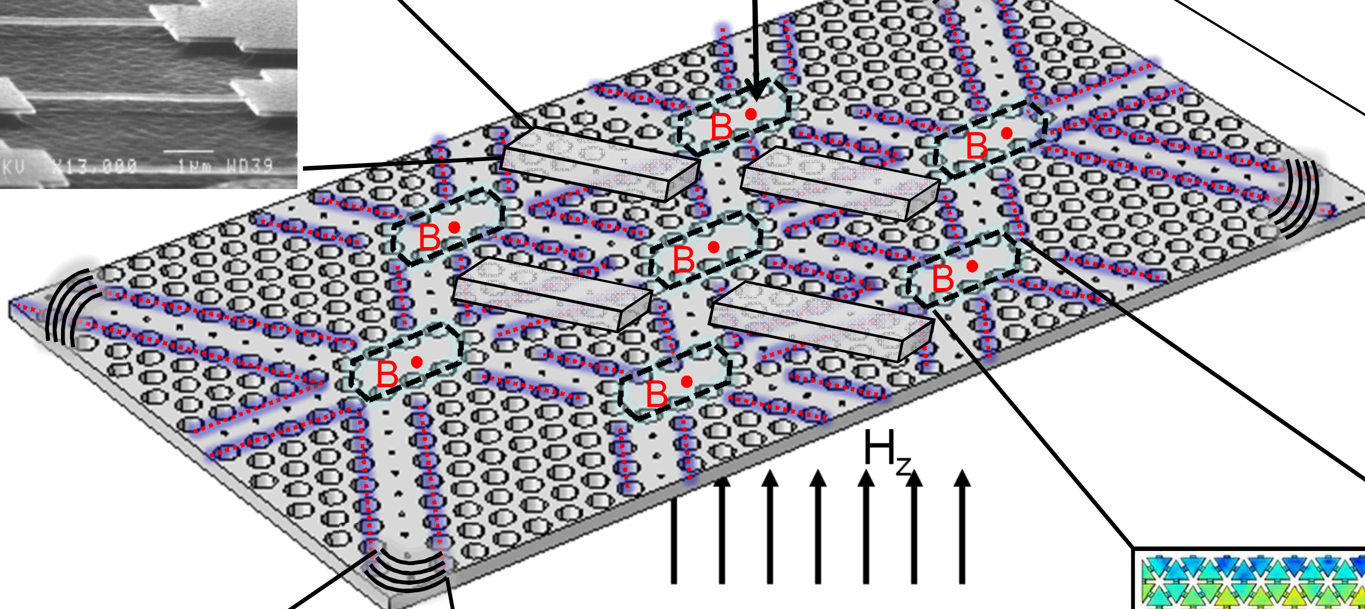
(a) Schematic of possible system scale-up via coupled PnC cavities.
(b) Estimated 127/cm^2 coupled qubits per PnC-chip assuming 100μm min separation between cavities.

The “Phoniton” Chip

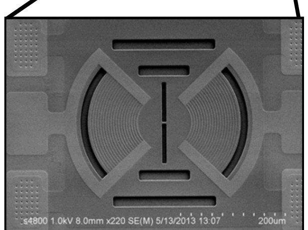
Metal beams over waveguides to alter coupling properties



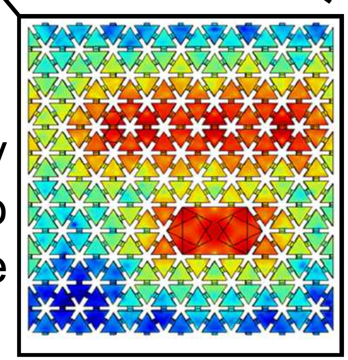
Acceptor impurities implanted in cavity centers



Focusing Transducers



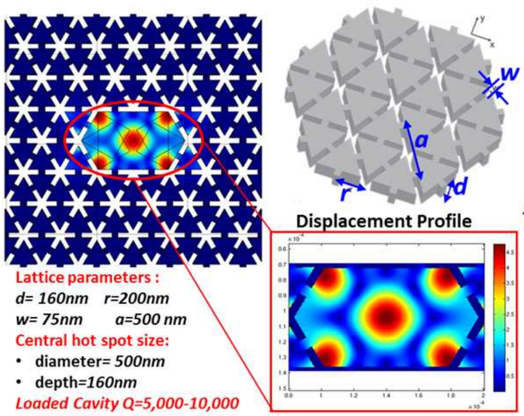
Phononic Crystal Cavity Critically Coupled to Waveguide

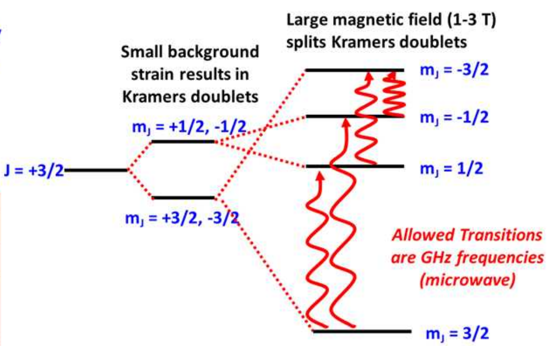


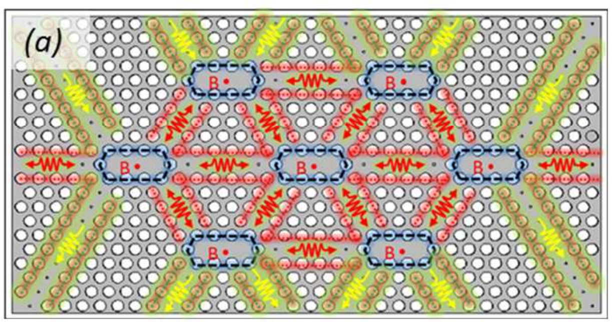
Summary and Conclusion

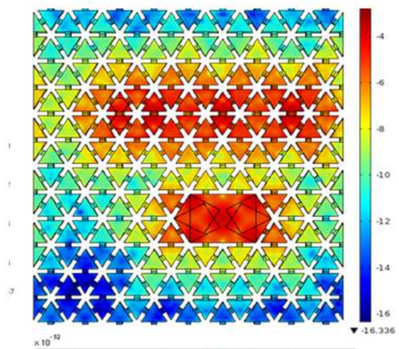
Sandia National Laboratories

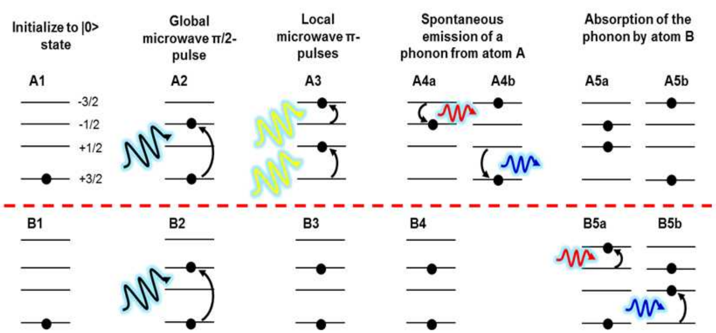
Promising qubit system with low fabrication demands:

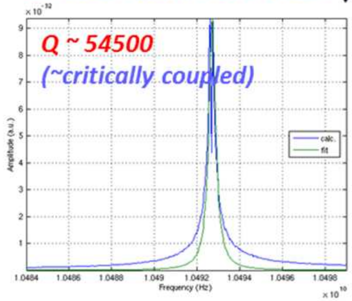












Homogeneity

Atomic Levels

Local magnetic field tuning

Isolated Transitions

MEMS cantileavers open and close waveguides

Fabrication Demands

1) Silicon
2) Errors have minor effect

Strong Interactions

Enhanced by the cavity

Coherence

Acceptors

Reliable Measurement

No cycling transition,
Low loss in waveguide