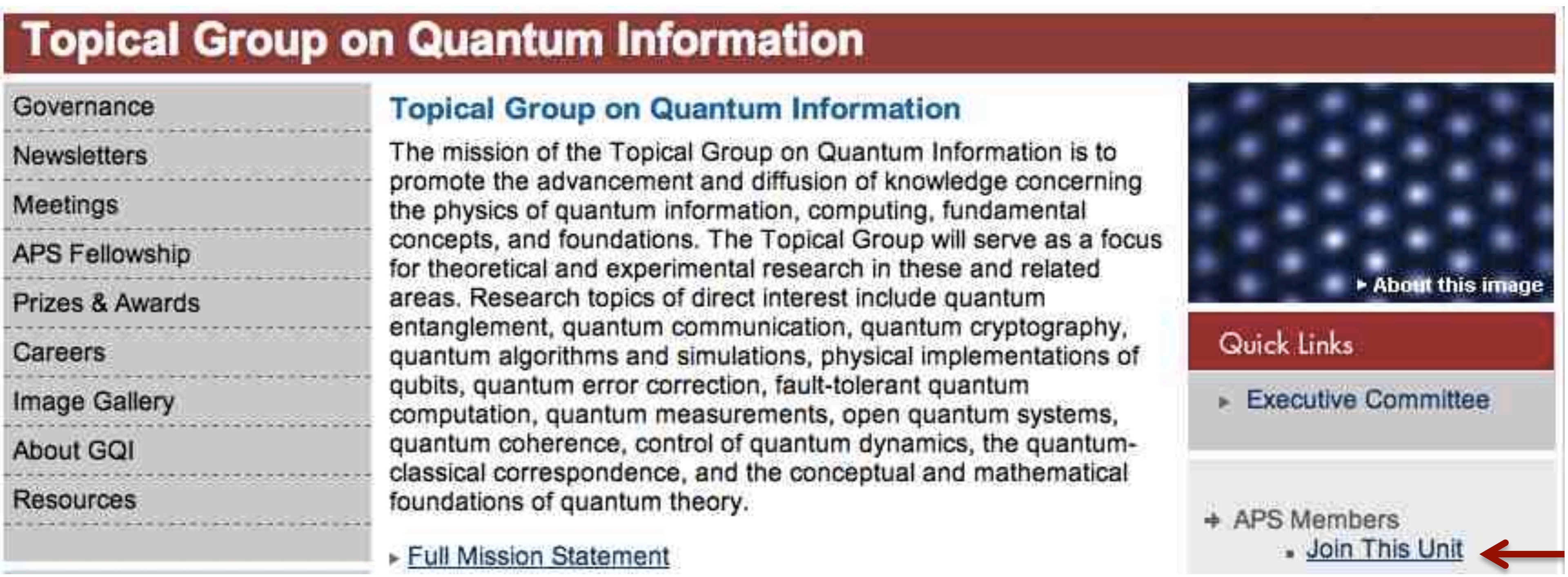
If you haven't already…
…join the APS GQI unit.

http://www.aps.org/units/gqi/

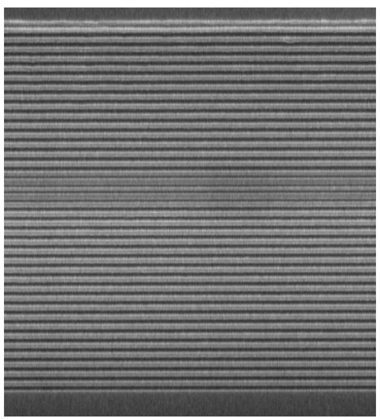


On-chip cavity quantum phonodynamics in silicon

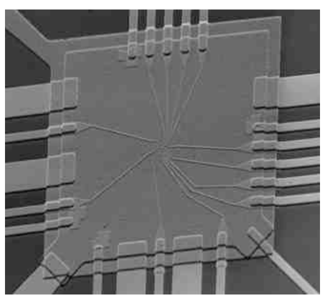
Charles Tahan, Rusko Ruskov, Oney Soykal

Laboratory for Physical Sciences

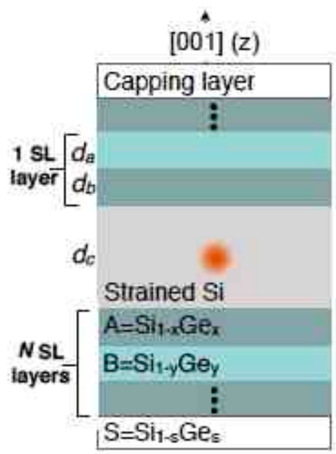
Invited Talk, APS March Meeting 2013



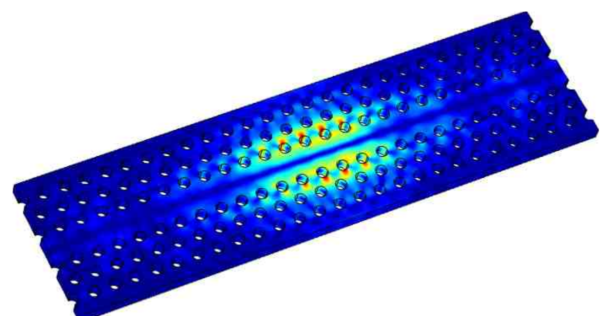
Semiconductor cavity-polaritons



Phonons & Si QDs/donors



Phonon analogue of the polariton

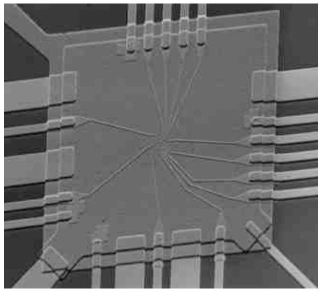


Nanomechanical resonators and acceptor qubits in silicon

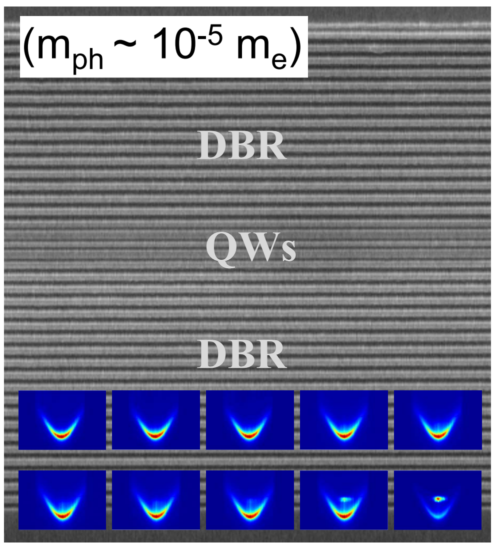
The Laboratory for Physical Sciences

Outline of today's talk

Background and Inspiration

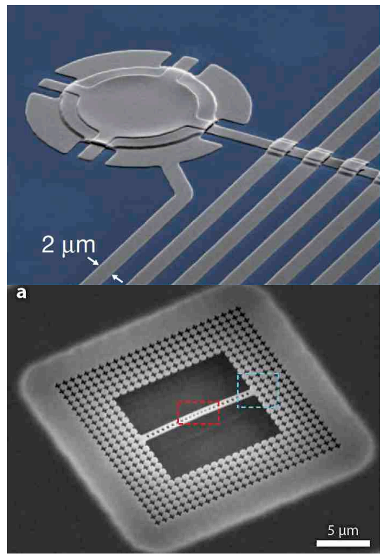


Q. Computing & phonons in Si QDs/donors



Bose-Einstein Condensation (BEC) of microcavity-polaritons

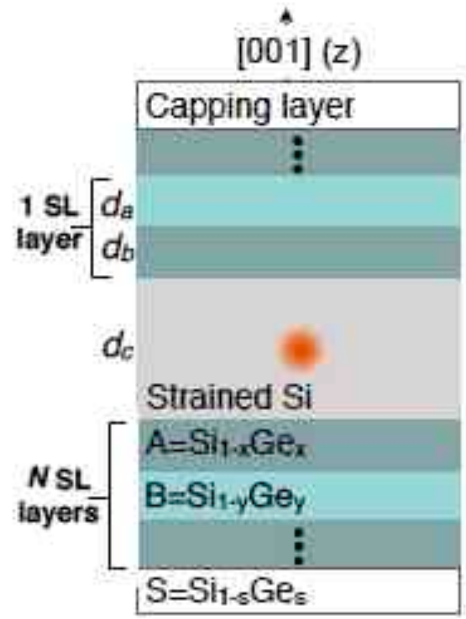
\+



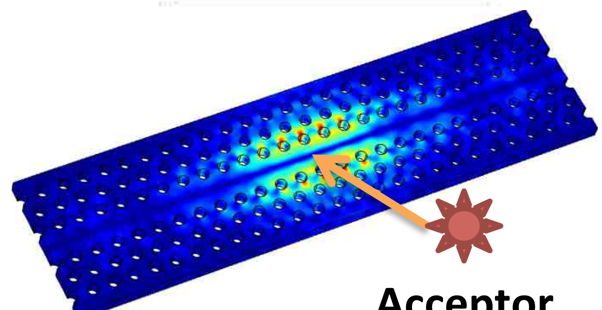
Nano/ Optomechanics

→

Cavity-phonon/qubit systems



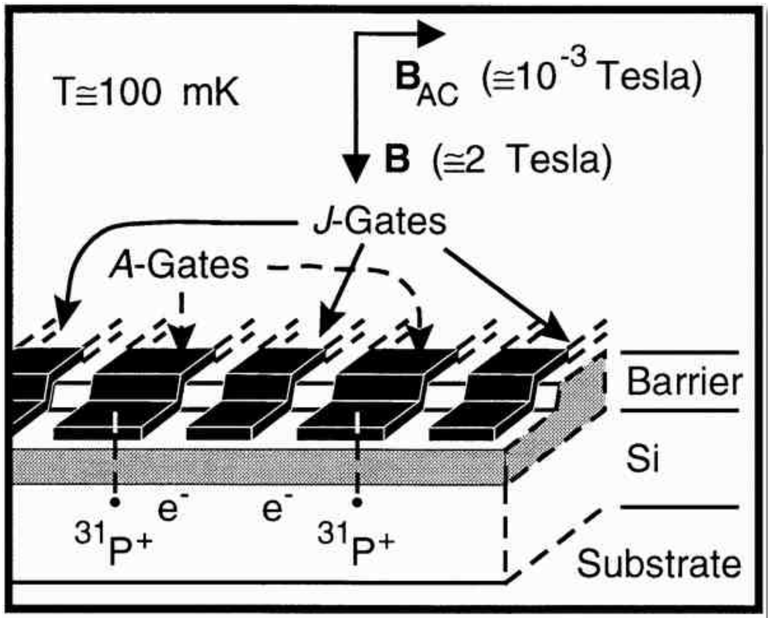
Donor



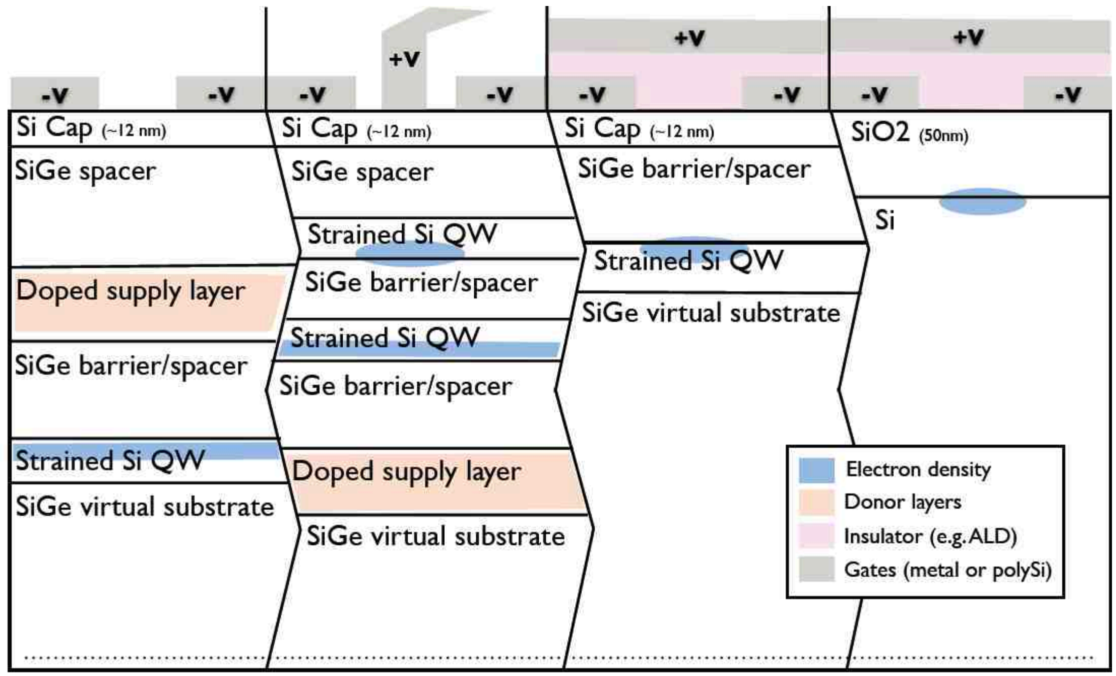
Acceptor

Silicon spin-based quantum computing

Impurity qubits



Quantum dot qubits



a. MODFET-type, depletion mode QD

b. MODFET-type double QW, accumulation mode QD

c. Undoped accumulation mode SiGe QW QD

d. MOSFET-type inversion layer, undoped QD

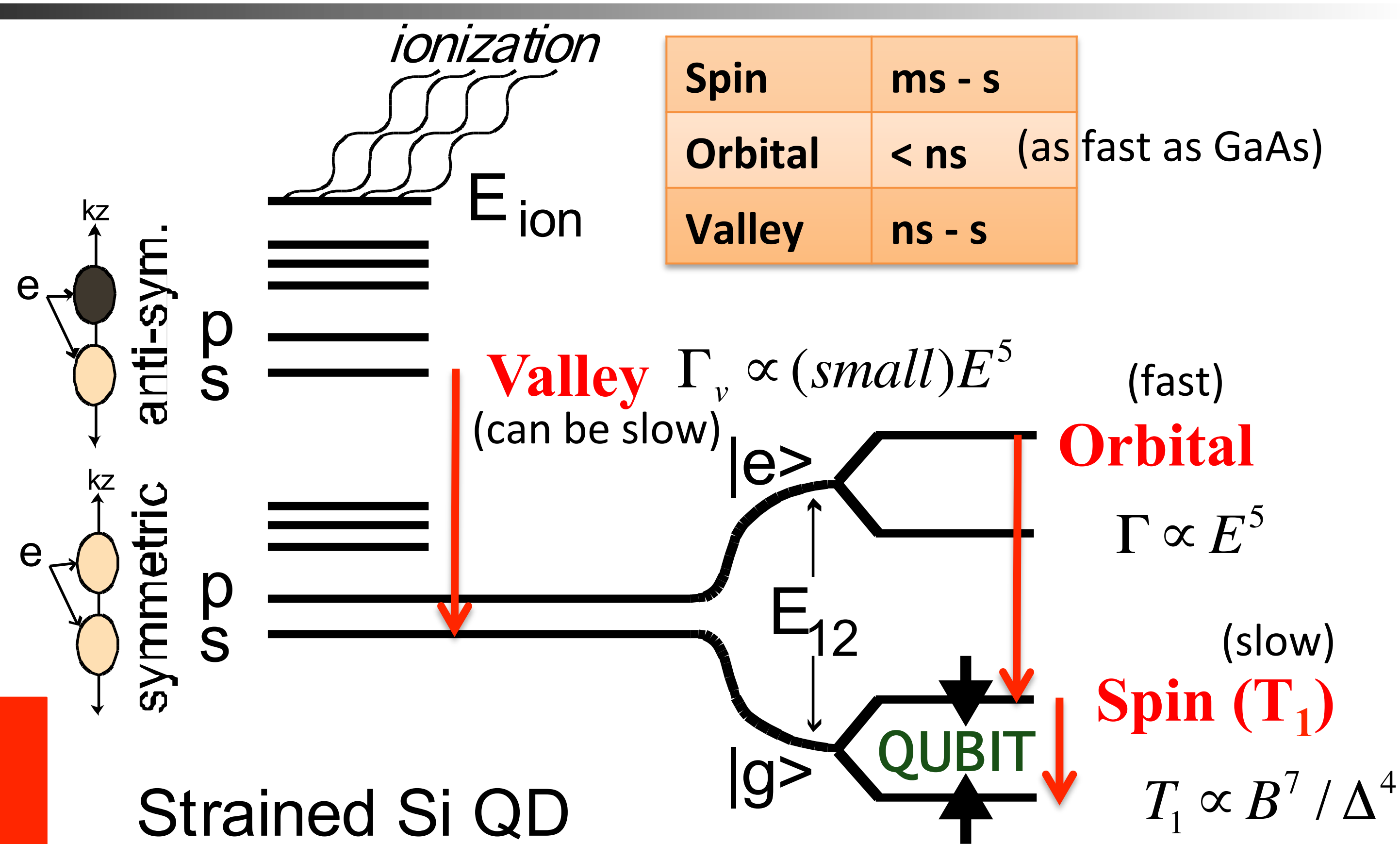
Silicon quantum computing material enablers →
Isotope enrichment, Less defects, Better surfaces, Better interfaces

Understanding phonon relaxation in silicon qubits

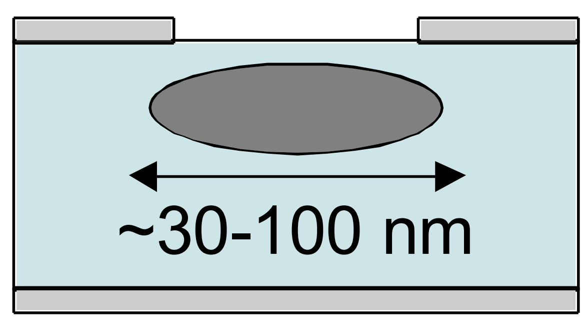
Tahan et al.
1302.0983
1301.0260
0710.4263

Spin	**ms - s**
Orbital	**< ns**
Valley	**ns - s**

(as fast as GaAs)



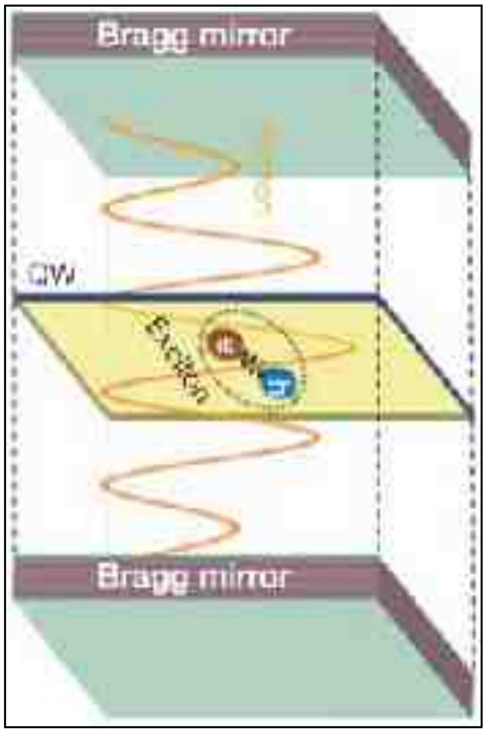
Phonons interact strongly with excited states



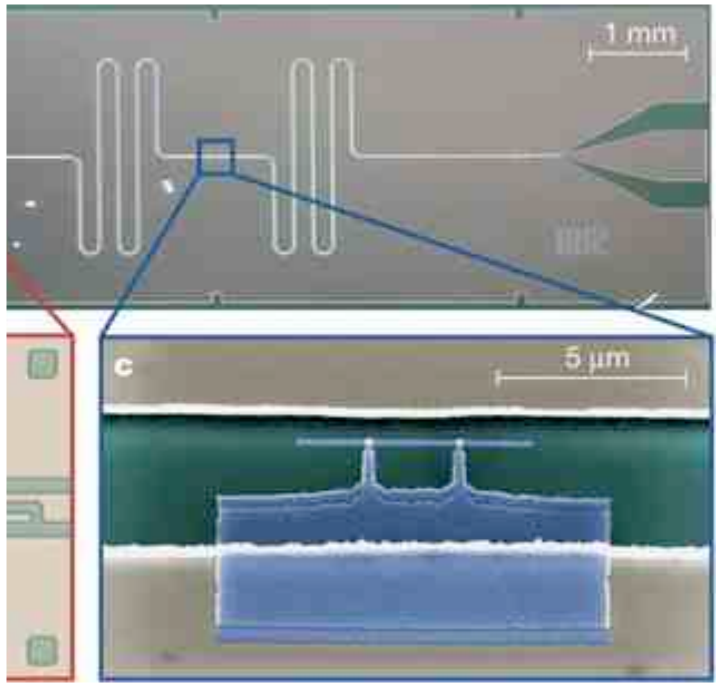
(similar for donors)

Physics of solid-state polaritons (photon + matter)…

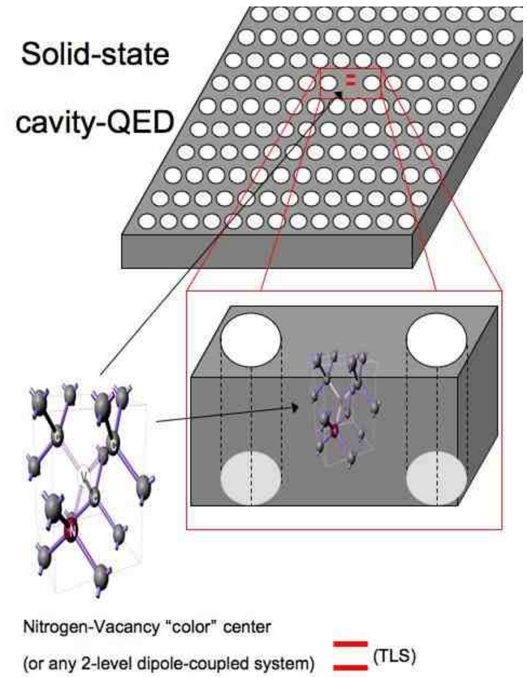
- Polariton = photon + matter excitation



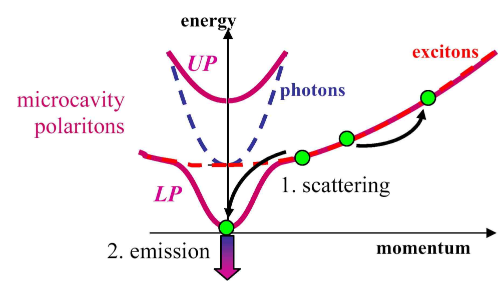
Semiconductor microcavity photon + exciton (electron-hole pair)



Superconducting (microwave cavity-photon + JJ qubit) "Circuit-QED"



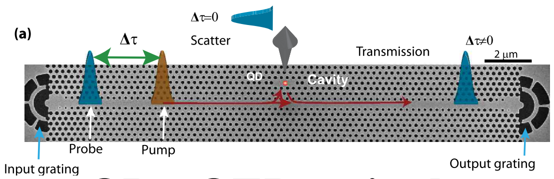
Diamond NV center qubit + photon cavity



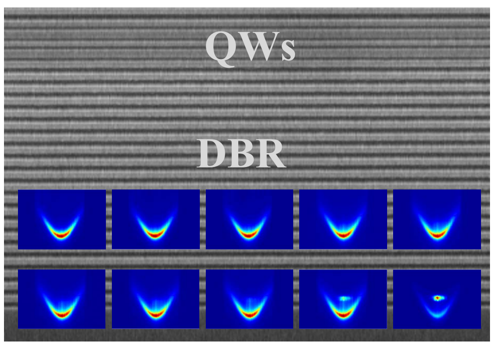
…which enables polaritonic devices & physics

Goal: devices that enable new function or new behavior…

e.g., JJ QC, cavity-QED, lasers, LEDs, amplifiers, switches and polarization modulators, accelerometers, gradiometers, interferometers…

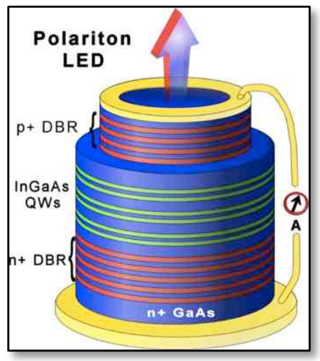


QD-cQED – single photon sources, etc.

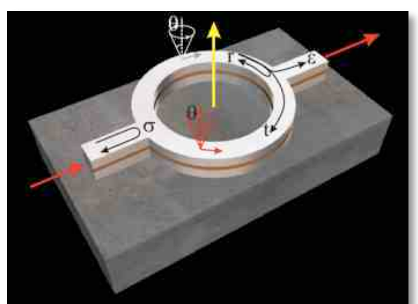


Bose-Einstein Condensation of microcavity-polaritons

e.g., Yamamoto, Littlewood et al.

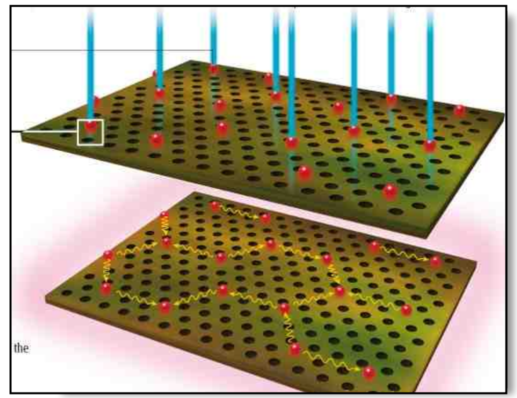


Low threshold condensate lasers



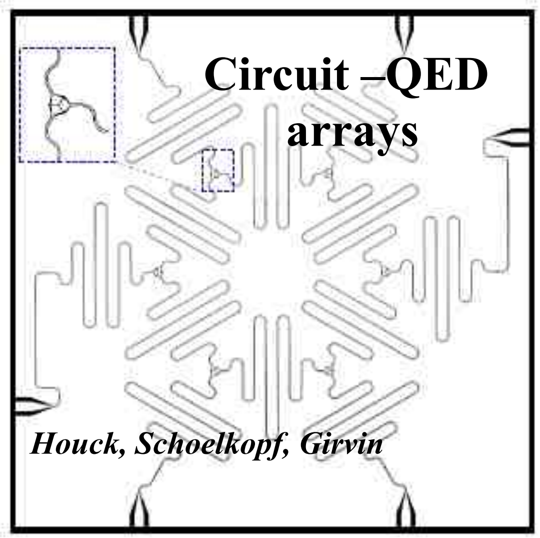
A Light QUID – a "LiQUIDs"?

Coupled cavity-QED: "Solid light"



***Greentree, Tahan, et al* 2005**

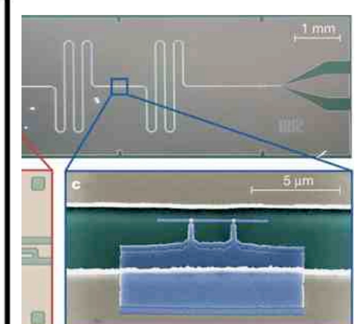
- Quantum simulators
- Parallel single and entangled photon sources
- **Can I do this with phonons?**



Circuit –QED arrays

Houck, Schoelkopf, Girvin

Transmon Quantum Computing



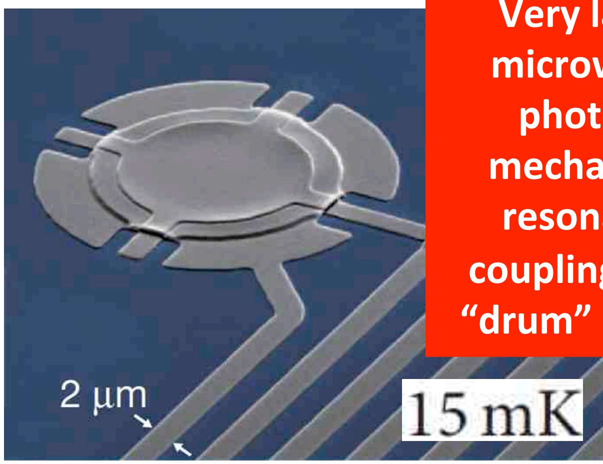
Meanwhile, nano/opto-mechanics becomes a reality

LETTER

doi:10.1038/nature10261

Sideband cooling of micromechanical motion to the quantum ground state

J. D. Teufel[1], T. Donner[2,3], Dale Li[1], J. W. Harlow[2,3], M. S. Allman[1,3], K. Cicak[1], A. J. Sirois[1,3], J. D. Whittaker[1,3], K. W. Lehnert[2,3] & R. W. Simmonds[1]



Very large microwave photon, mechanical resonator coupling with "drum" design

Ω_m of $2\pi \times 10.56$ MHz

$Q_m = \Omega_m / \Gamma_m = 3.3 \times 10^5$

$G/2\pi = 49 \pm 2\ \mathrm{MHz\,nm}^{-1}$

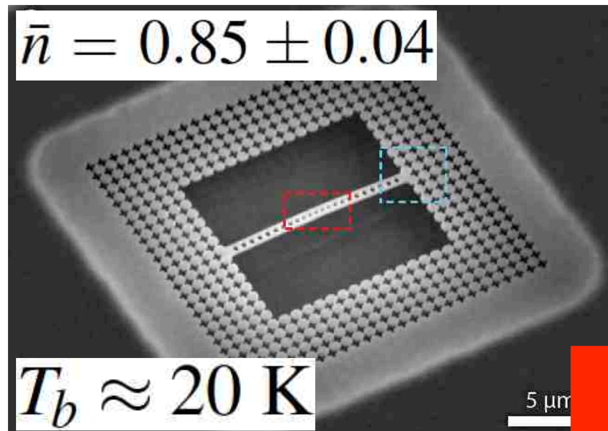
$\omega_c = 2\pi \times 7.54$ GHz

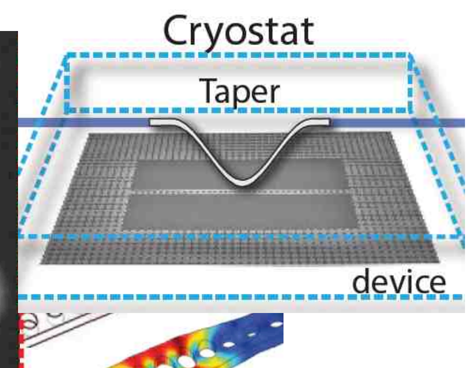
$\kappa \approx 2\pi \times 200$ kHz

Mechanical cooling to well below kT

Laser cooling of a nanomechanical oscillator into its quantum ground state

Jasper Chan,[1] T. P. Mayer Alegre,[1] Amir H. Safavi-Naeini,[1] Jeff T. Hill,[1] Alex Krause,[1] Simon Gröblacher,[1,2] Markus Aspelmeyer,[2] and Oskar Painter[1,*]





$\omega_m/2\pi = 3.68$ GHz

$Q_m \approx 10^5$ ~0.2 K

$g/2\pi = 910$ kHz

High-Q phononic bandgap cavity (etched SOI). Cooling to ground state at 20 K!

$\omega_o/2\pi = 195$ THz ($\lambda = 1537$ nm)

$Q_o = 4 \times 10^5$

Acoustic phonons can be very long-lived in silicon

Low temperatures & low phonon limit: $T = \dfrac{\hbar\omega}{k_B} \approx 35\ K$

see S. Tamura, 1993

1. **Anharmonicity losses**

Main decay channels (isotropic): $LA \rightarrow TA + TA$, $LA \rightarrow LA + TA$

$$\boxed{\Gamma_{LA}^{tot}\ ;\ 4.5\ 10^4\ \nu_{THz}^5 \approx 1.4\ 10^4\ s^{-1} \qquad \nu\ ;\ 0.73\ THz\,(3\,meV)}$$

2. **Phonon scattering off mass fluctuations**

$$\boxed{\Gamma_{imp}\ ;\ 2.43\ 10^6\ \nu_{THz}^4 \approx 7\ 10^5\ s^{-1}}$$

- Enrichment of Si^{28} to 99% decreases the rate by an order of magnitude

- Mean free path:

$$L_{MFP} = v_L / \Gamma_{imp} \approx 1.3\ cm \Rightarrow$$

Natural Silicon

$v_{long} = 9330$ m/s

$v_{tran} = 5420$ m/s

$\rho = 2330$ kg/m^3

Short wave length compared to light

Si^{28}	92.23%
Si^{29}	4.67%
Si^{30}	3.1%

Bulk silicon

Acoustic phonon mean free path ~10 cm at 99% purity @ 700 GHz

Acoustic phonon mean free path ~400,000 meters! in natural silicon @10 GHz

Real nano mechanical system

Painter et al ~ Q~10^5 at 4 GHz ~ 10s of mm

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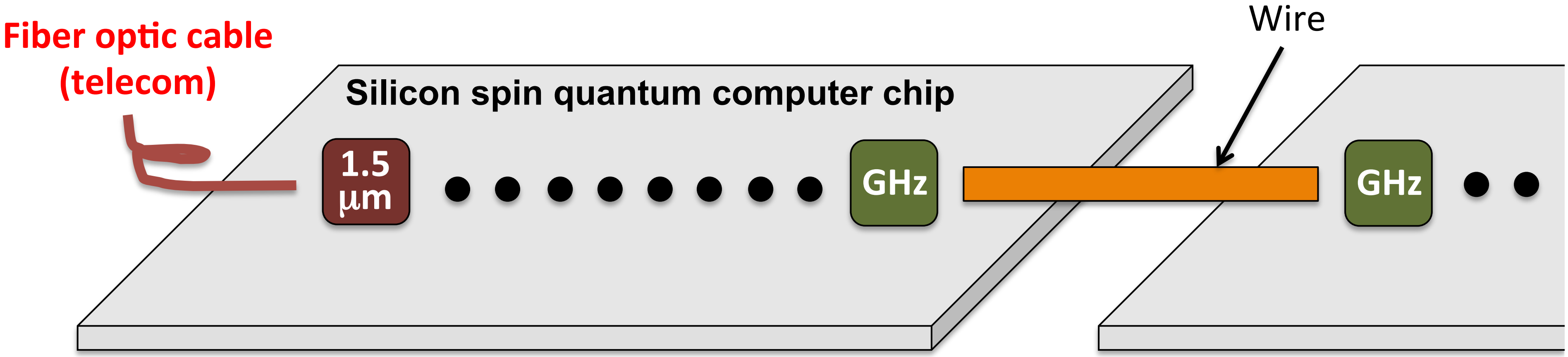
One motivation for QC: Off-chip communication

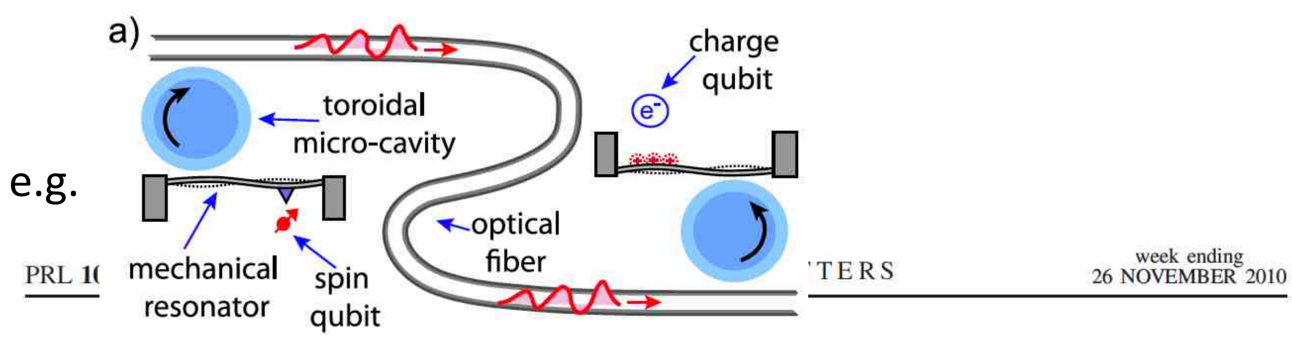


1.5 μm = Quantum component to convert spin to telecom photon

GHz = Quantum component to couple distant spins via wire (microwave regime)

Proposals for *indirect* qubit to telecom photon mechanical transduction via magnetic or electric intermediary

e.g.



Optomechanical Transducers for Long-Distance Quantum Communication

K. Stannigel,[1] P. Rabl,[2,1] A. S. Sørensen,[3] P. Zoller,[1] and M. D. Lukin[2,4]

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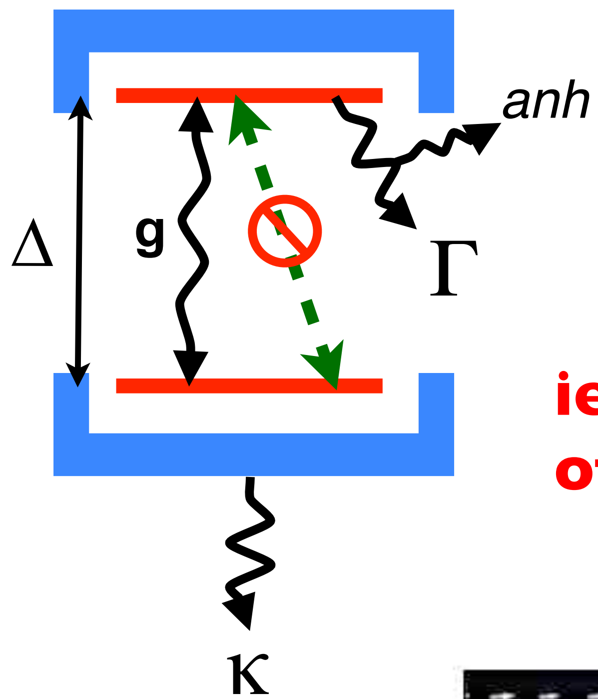
First step: Is a ***direct*** analog of a cavity-polariton possible?

TLS + cavity-phonon



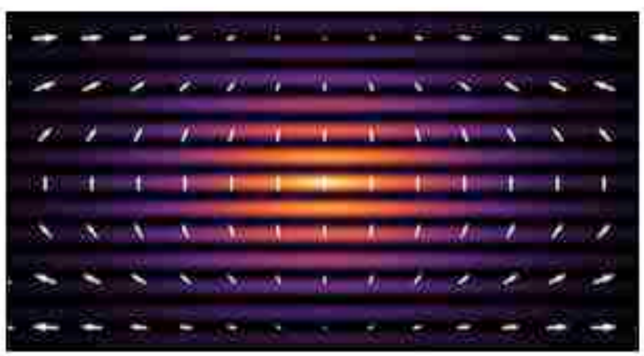
- While strong electron-phonon coupling is of course common in many situations in semiconductors and well studied…
- It is **not obvious** that you could have strong resonant coupling **in the sense of cavity-QED**, in a realizable structure

ie, a *phonon* equivalent of the cavity-polariton?

(not a polaron, not a polariton)

Oney Soykal

Rusko Ruskov



Focus: Vibrations and Electrons Team Up in New Quantum Entity

November 28, 2011

Theorists propose an experiment to observe a "phoniton," a novel hybrid of an electron and a quantum of vibration in a crystal lattice.

Soykal, Ruskov, Tahan, PRL **107**, 234402 (2011)

Direct? Strain (deformation) modulates the energy bands

…Not indirectly via a magnetic field or electric potential

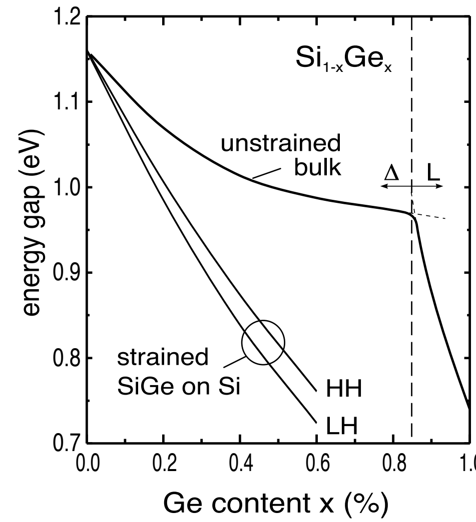
A phonon is just a time-dependent strain.

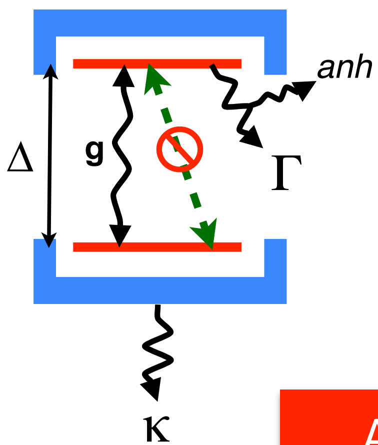
strain tensor $$\varepsilon_{ij}(\mathbf{q},t)^{phonon} = \frac{i}{2}\sqrt{\frac{\hbar}{2\rho v_t q}}\left[\left(\mathbf{e}(t)_i q_j + \mathbf{e}(t)_j q_i\right) a^{\dagger}_{\mathbf{q},t} \exp(-i\mathbf{q}\cdot\mathbf{r}) + c.c.\right]$$

Deformation potential = shift in energy of the band edge per unit elastic strain.

$$H_{electron-phonon} = \sum_{ij} D_{ij}\,\varepsilon_{ij}(r)$$

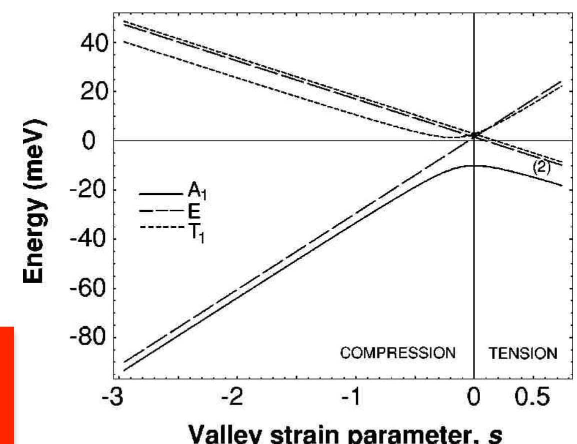
deformation potential $$\Xi^{[001]} = \begin{pmatrix} \Xi_d & 0 & 0 \\ 0 & \Xi_d & 0 \\ 0 & 0 & \Xi_d + \Xi_u \end{pmatrix}$$





Deformation potential can be quite big in semiconductors

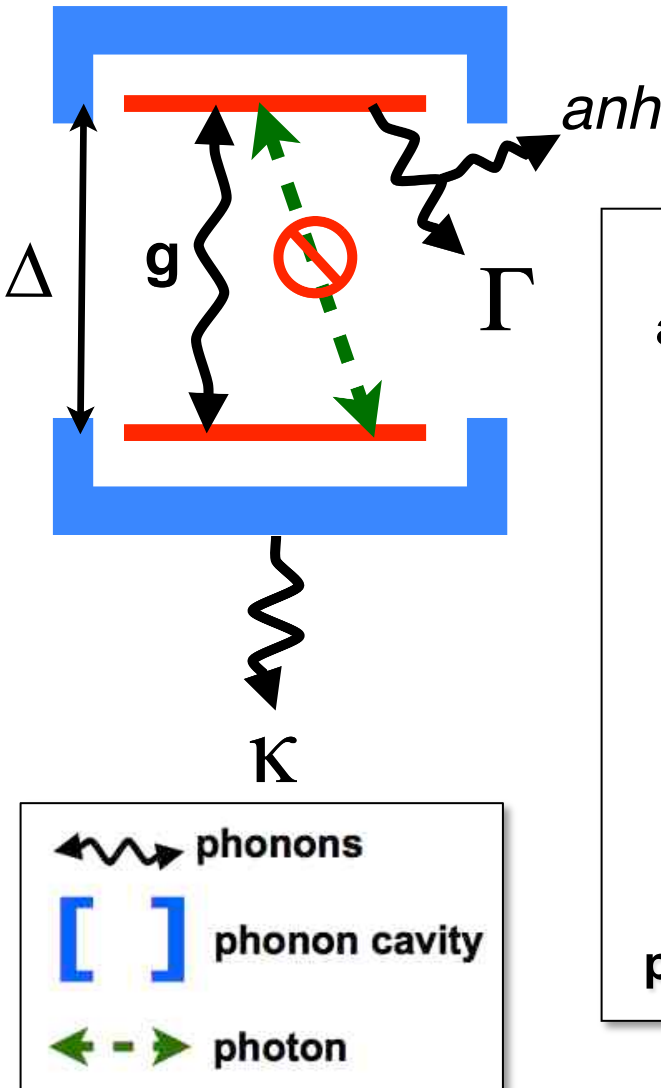
$$D_{ij} > \mathrm{eV}$$



A phonon can drive a transition of an "atom" just like a photon can.

What do we need to achieve "strong coupling" in the sense of cQED?

TLS + cavity-phonon



Phonon analogue of a polariton: we call it a "phoniton"

Want a "half sound, half matter" composite object in the O(1) phonon regime

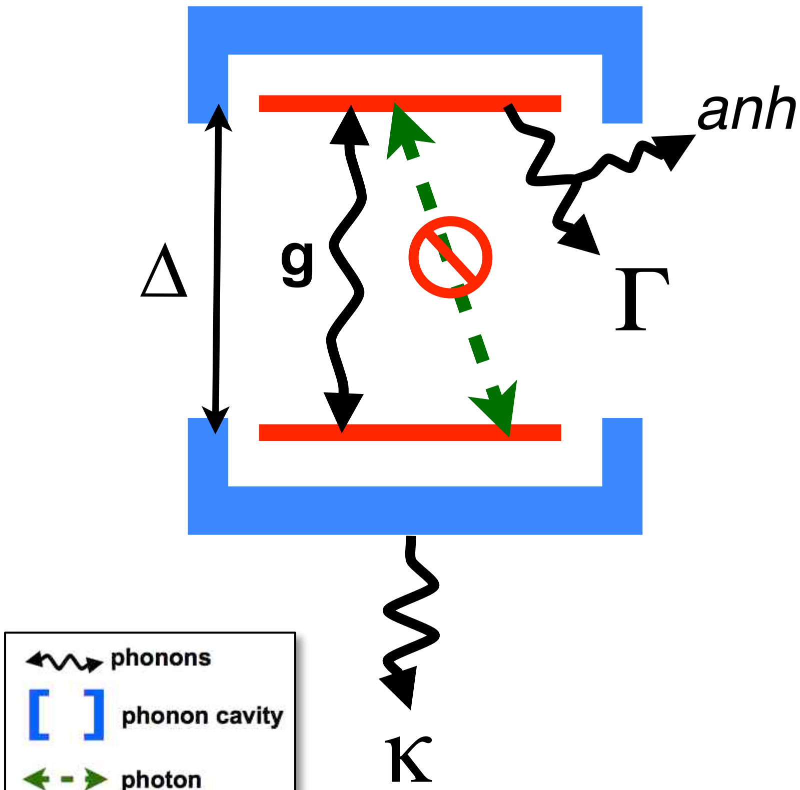
WHAT WE NEED:

1. **Two-Level-System ("atom") driven *solely* and directly by phonons (not photons)**
   1. Preferably coupled to only 1 phonon mode
   2. Emits into cavity mode preferentially
2. **Need long-lived coherent phonon**
   – High Q cavity
   – ~1 phonon limit
3. **Need "strong" coupling between the TLS and the phonon**

$$g > \{\kappa, \Gamma, T_2^*, anh\}$$

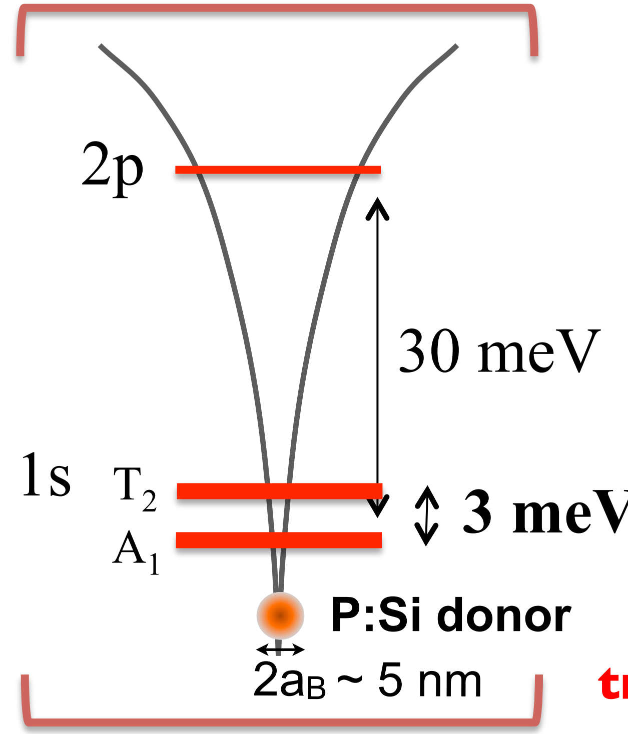
A suitable "atom" TLS = donor valley qubit in *strained* **silicon**

Is a phonon cavity possible at this energy?



$\equiv$

P:Si in <u>[001] strained</u> silicon



Note: Umklapp phonon transition!

phonon velocity: $v_{l(t)} = 9000\ (5400)$ m/s

$$\boxed{\Rightarrow \lambda_{l(t)}[3\text{meV}] = 12\ \ (7)\ \text{nm}}$$

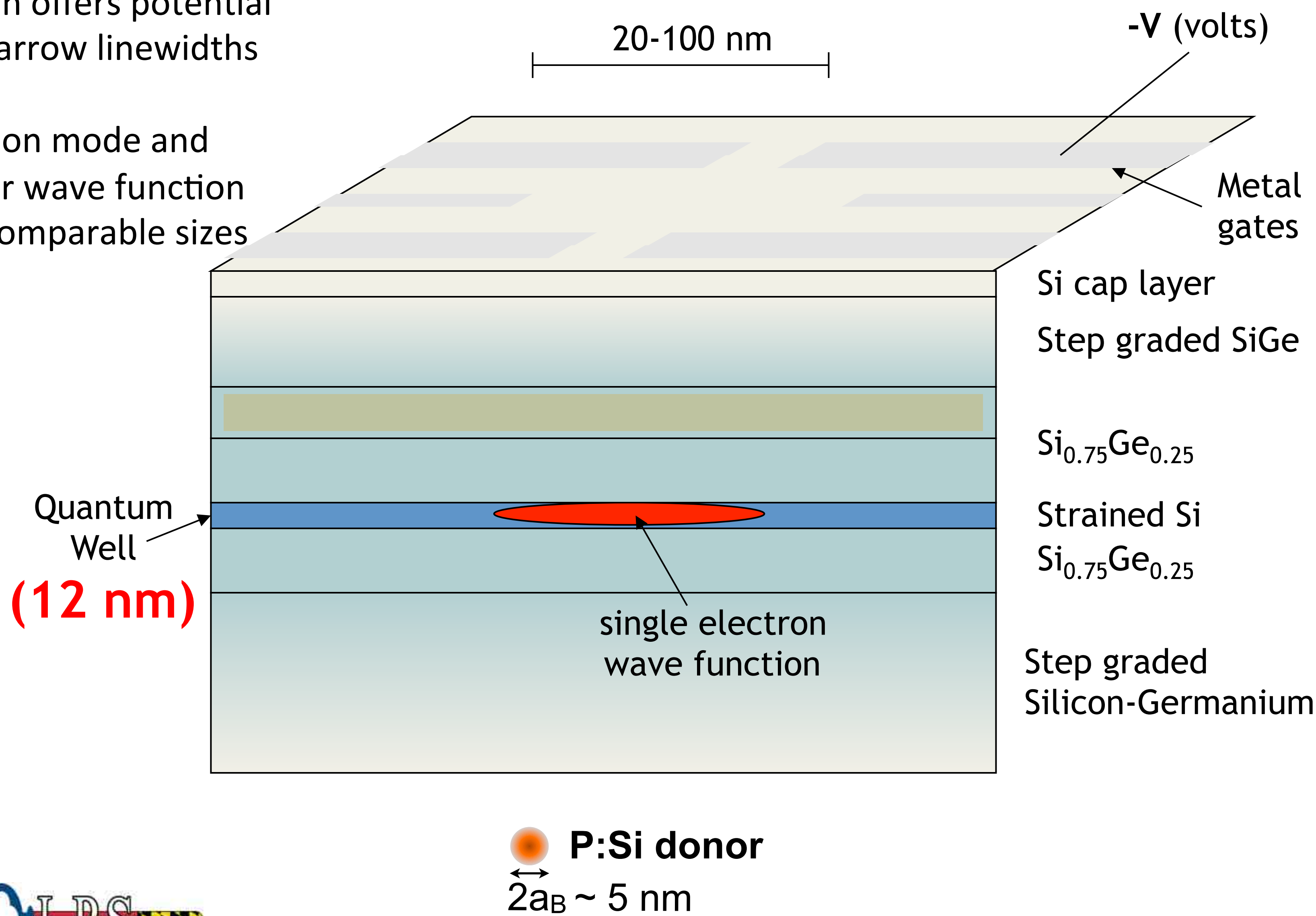
YES

Valley state in strained Si

THIS we can work with.

Typical quantum dot heterostructure in SiGe

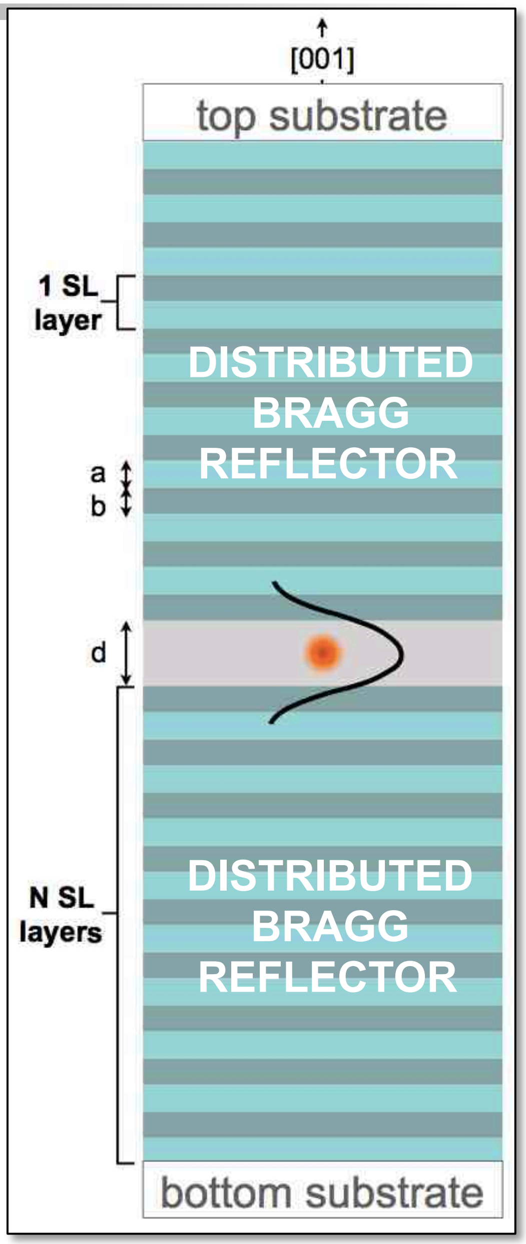
- Silicon offers potential for narrow linewidths
- Phonon mode and donor wave function are comparable sizes



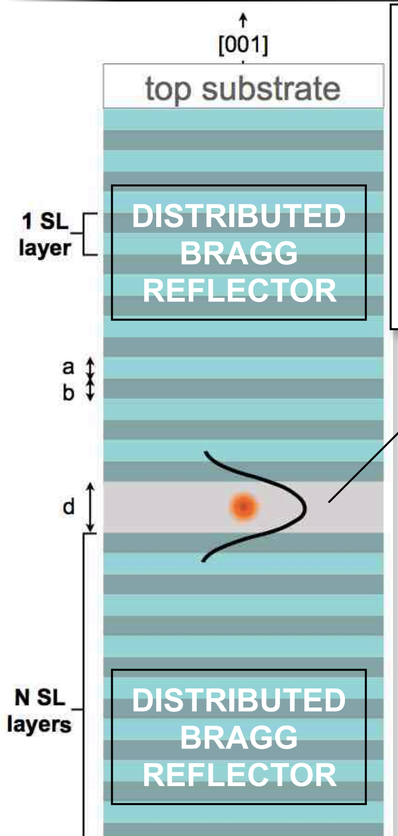
Proof-of-principle in SiGe heterostructure DBR-cavity

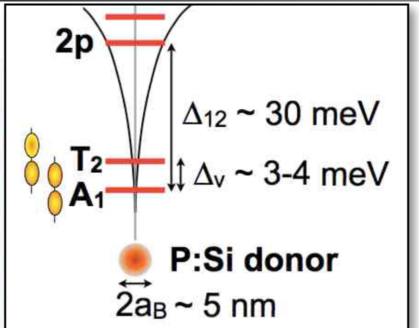
- **Create phonon cavity with acoustic distributed Bragg reflector**
  - Optimized for longitudinal phonon (in 1D case)
  - Mixed mode for micropillar
  - can have very high Qs even at 1 THz
  - Already demonstrated in III-Vs
  - **Umklapp phonon transition: place donor at maximum *displacement***
- **Similar to MBE devices already grown**
  - Long-lived THz acoustic DBR realized in III-Vs

Now that we have a prototype, we can proceed in calculating: *g*, κ, Γ, etc.



g // P:Si TLS cavity-phonon Hamiltonian





$$H^{ac}_{e,ph}(r) = \sum_{ij} D_{ij}\, \varepsilon_{ij}(r)$$

$$\hat{H}_{e,ph} = \sum_{ss'} \sum_{q\lambda} c^{\dagger}_{s'} c_s (b_{q\lambda} + b^{\dagger}_{q\lambda})\, V^{s's}_{q\lambda}$$

$$V^{s's}_{q\lambda} = \left\langle \psi_{s'}; \{q\lambda\} \right| H^{ac}_{e.ph} \left| \psi_s \right\rangle \equiv \hbar g_q$$

A phonon is just a time-dependent strain.

Deformation potential = shift in energy of the band edge per unit elastic strain.

Jaynes-Cummings & RWA

$$\hat{H}_g = \hbar g_q (\sigma^{\dagger} + \sigma^{-})(b_{q\lambda} + b^{\dagger}_{q\lambda})$$
$$\approx \hbar g_q (\sigma^{\dagger} b_{q\lambda} + \sigma^{-} b^{\dagger}_{q\lambda})$$

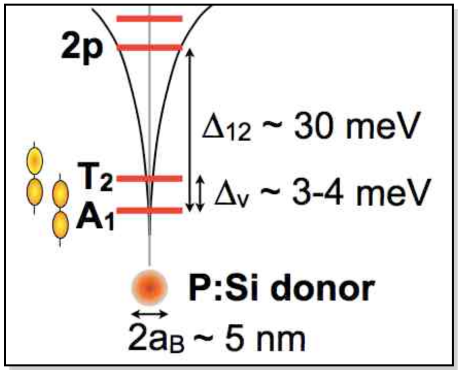
$$\omega_{q\lambda} \approx \omega_{s's},\ \Delta\omega_q = \omega_{s's}$$
$$g_q = \omega_{s's}$$

Total Hamiltonian with couplings to external modes

$$\hat{H}_{tot} = \sum_{q,\lambda} \hbar\omega_{q,\lambda} (b_{q\lambda} b^{\dagger}_{q\lambda} + 1/2) + \frac{\hbar\Delta}{2}\sigma_z + H_g$$
$$+ H_{\kappa} + H'_{anh} + H_{\Gamma} \quad \textit{Loss terms}$$

Jaynes-Cummings Hamiltonian emerges from first-principles derivation

g // Intervalley (Umklapp) process drives the valley qubit

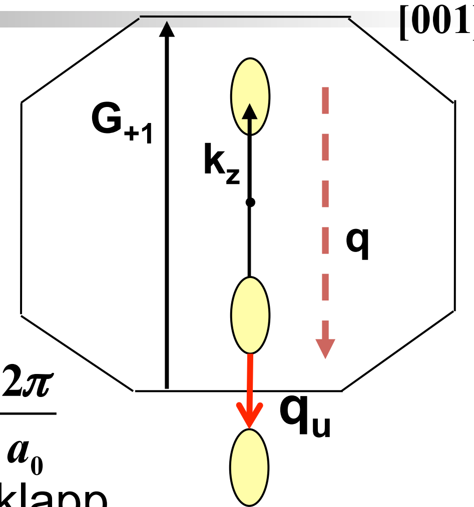


Valley wave functions in strained Si

$$\psi_{T_2}(r) = \left(\psi_{\vec{k}_z}(r) - \psi_{-\vec{k}_z}(r)\right)\Phi_s^z(r)$$

$$\psi_{A_1}(r) = \left(\psi_{\vec{k}_z}(r) + \psi_{-\vec{k}_z}(r)\right)\Phi_s^z(r)$$

$$\psi_{\vec{k}_j}(r) = u_{\vec{k}_j}(r)e^{-i\vec{k}_j\vec{r}} \qquad k_z \approx 0.85\frac{2\pi}{a_0}$$



- **Intravalley & electric dipole transitions are forbidden**

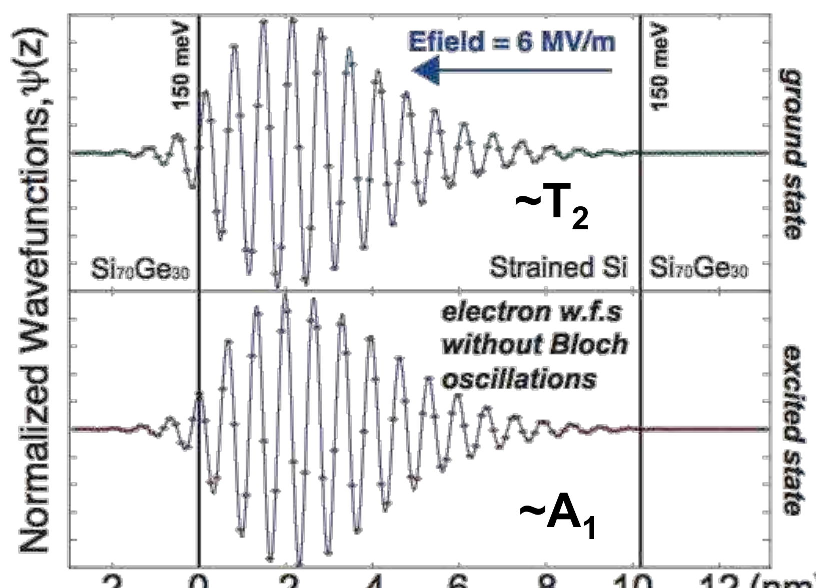
Intervalley Umklapp transition: $q \approx q_u \equiv 2k_z - G_{+1}$

$$V_{ij}^{s's}(q,\lambda) = \left(\frac{\hbar}{2\rho V\omega_{q\lambda}}\right)^{1/2}\left(\Xi_d(q\xi_{q\lambda}) + \frac{1}{2}\Xi_u\left\{(q\hat{k}_i)(\hat{k}_i\xi_{q\lambda}) + (q\hat{k}_j)(\hat{k}_j\xi_{q\lambda})\right\}\right)$$
$$\times\int dr\, e^{-iqr}\,\psi_{s'}^*(r)\psi_s(r)$$

$z \leftrightarrow -z$ Inter-valley matrix element

Valley states: good "acoustic" qubits

- Very small electric dipole moment
- Leads to long relaxation times and insensitivity to charge noise



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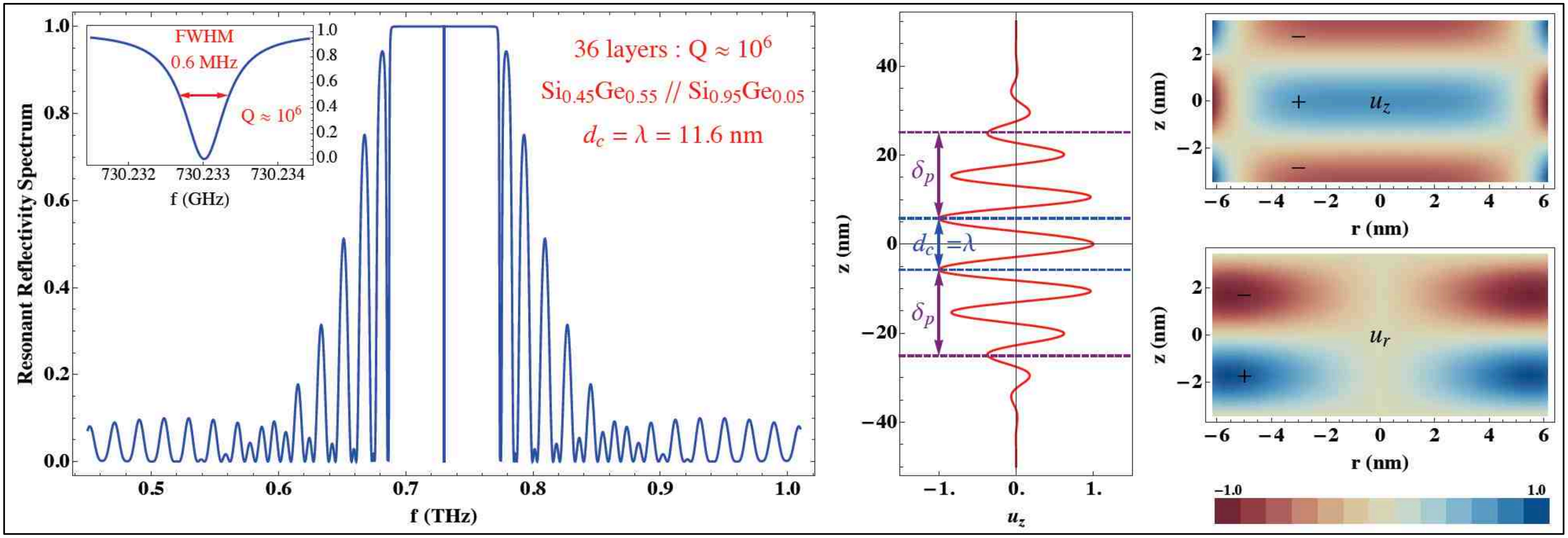
Charles Tahan

κ // 1D and micropillar phonon cavity modes and Qs

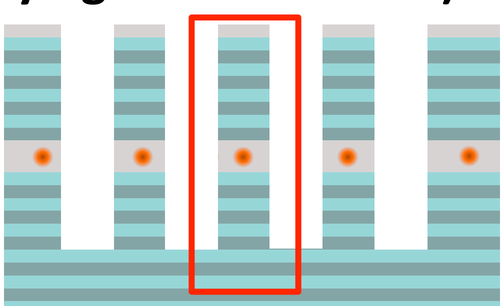


We calculate Q's and displacement/stress fields for both 1D and 3D micropillar cavities (for fundamental and low-lying excited modes).

Phonon cavity lifetime:

$$\kappa = \omega_\Delta / Q$$

Micropillar standing-mode strain waves:



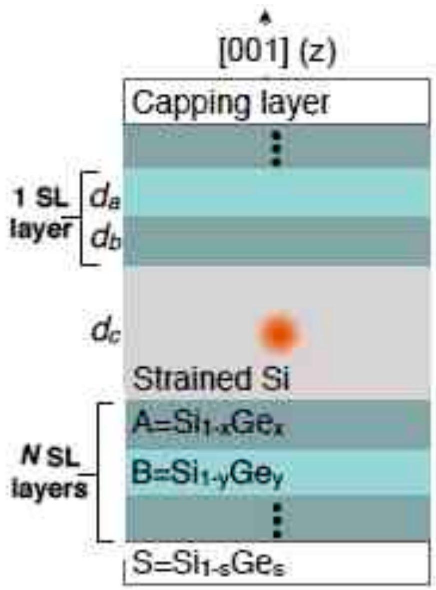
$$u_r(\boldsymbol{r}) = -A\eta_l \left[J_1(\eta_l r) + \frac{2q^2}{\eta_t^2 - q^2} \frac{J_1(\eta_l R)}{J_1(\eta_t R)} J_1(\eta_t r) \right] \sin qz$$

$$u_z(\boldsymbol{r}) = Aq \left[J_0(\eta_l r) - \frac{2\eta_l \eta_t}{\eta_t^2 - q^2} \frac{J_1(\eta_l R)}{J_1(\eta_t R)} J_0(\eta_t r) \right] \cos qz.$$

Cavity-QED versus sound-based "cQED"

parameter	symbol	3D optical	3D microwave	1D circuit-QED	P:Si phoniton	Li:Si phoniton
resonance freq.	$\omega_r/2\pi,\ \Omega/2\pi$	350 THz	51 GHz	10 GHz	730 GHz	142 GHz
vacuum Rabi freq.	$g/\pi,\ g/\omega_r$	220 MHz, $3\,10^{-7}$	47 kHz, $1\,10^{-7}$	100 MHz, $5\,10^{-3}$	2.1 GHz, $1.4\,10^{-3}$	13.8 MHz, $4.9\,10^{-5}$
cavity lifetime	$1/\kappa, Q$	10 ns, $3\,10^{7}$	1 ms, $3\,10^{8}$	160 ns, 10^{4}	$0.22\ \mu$s, 10^{6}	$1.1\ \mu$s, 10^{6}
TLS lifetime	$1/\Gamma$	61 ns	30 ms	$2\ \mu$s	8.2 ns	$22\ \mu$s
atom transit time	$t_{\rm transit}$	$\geq 50\ \mu$s	$100\ \mu$s	∞	∞	∞
critical atom #	$N_0 = 2\Gamma\kappa/g^2$	$6\,10^{-3}$	$3\,10^{-6}$	$\lesssim 6\,10^{-5}$	$\lesssim 3\,10^{-5}$	$\lesssim 4\,10^{-5}$
crit. pho(t,n)on #	$m_0 = \Gamma^2/2g^2$	$3\,10^{-4}$	$3\,10^{-8}$	$\lesssim 1\,10^{-6}$	$\lesssim 2\,10^{-4}$	$\lesssim 6\,10^{-7}$
# Rabi flops	$n_{\rm Rabi} = \dfrac{2g}{\kappa+\Gamma}$	~ 10	~ 5	$\sim 10^{2}$	~ 102	~ 93

λ_l=63 nm for Li



Maximal coupling in 2λ micropilllar cavity:

$$2g/\{\Gamma,\kappa,anh\}\approx 100$$

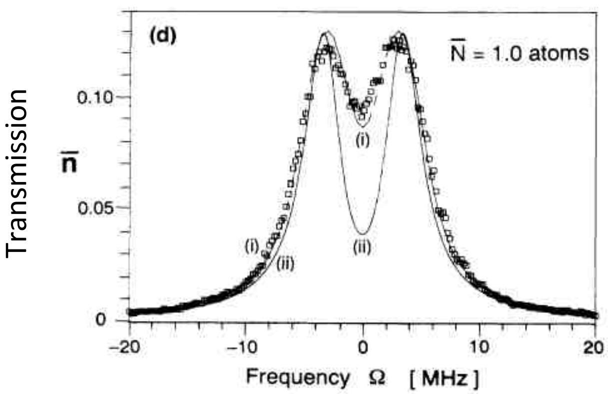
for Phosphorous or Lithium donor

Still appreciable coupling for diameter = 10λ (120 nm) for P

Li:Si valley qubit– *Smelyanskiy, Petukhov, Osipov (2004)*

First Observation of Vacuum Rabi Splitting for a Single *Real* Atom

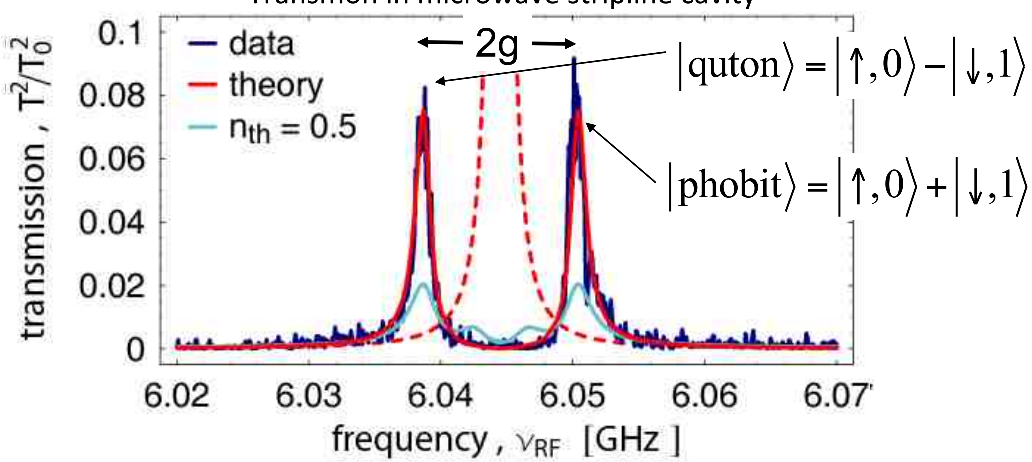
Cs atom in an optical cavity



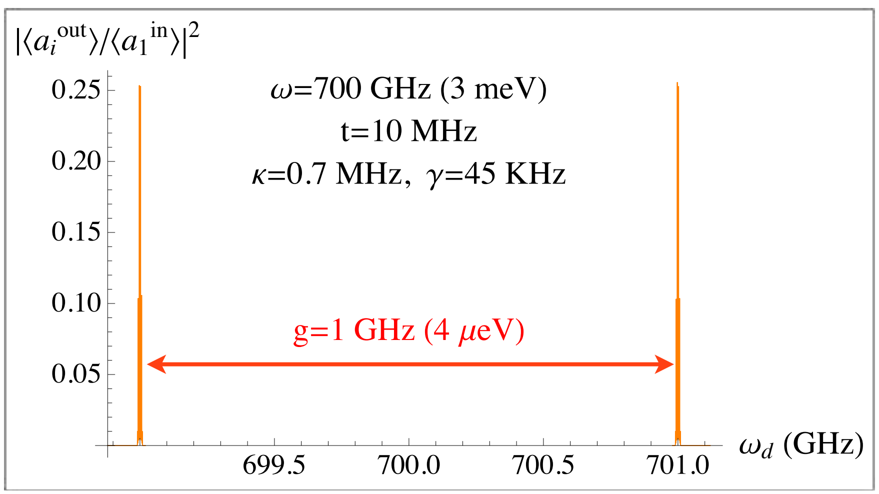
Thompson, Rempe, & Kimble 1992

First Observation of Vacuum Rabi Splitting in circuit-QED (Yale)

Transmon in microwave stripline cavity



First Observation of Rabi splitting in P:Si cavity-phoniton system?

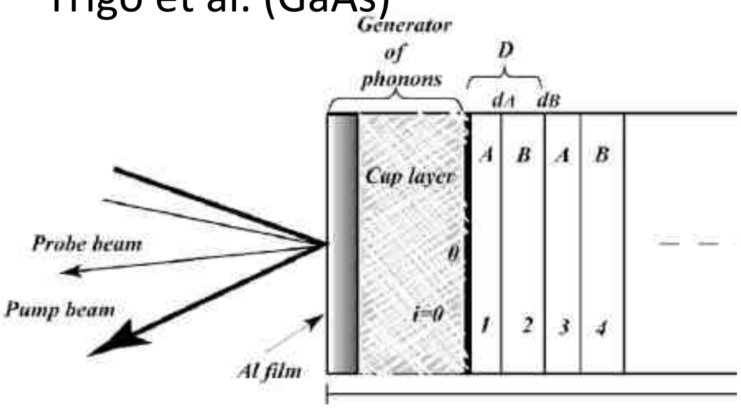


Possible experimental setups

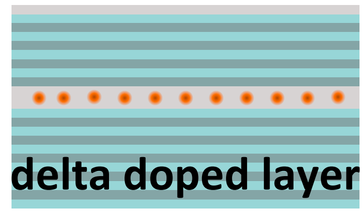
P:Si phoniton	Li:Si phoniton
730 GHz	142 GHz

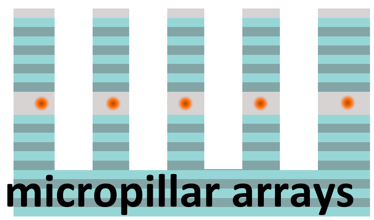
Optical pump-probe

Ezzahri et al. (SiGe)
Trigo et al. (GaAs)

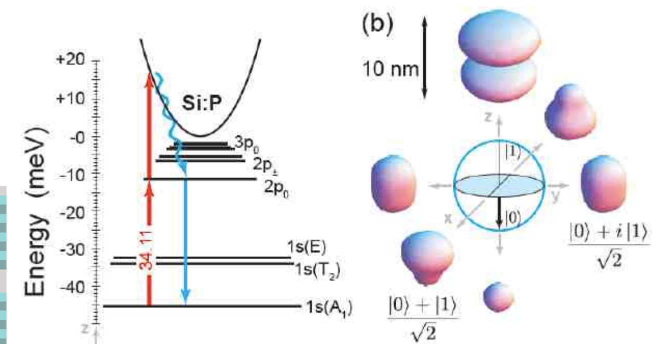


Free electron lasers (drive 1s to 2p transition)



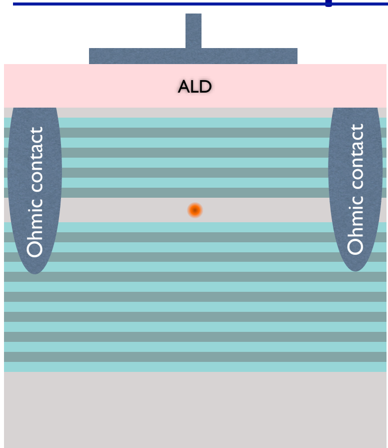


Greenland et al.



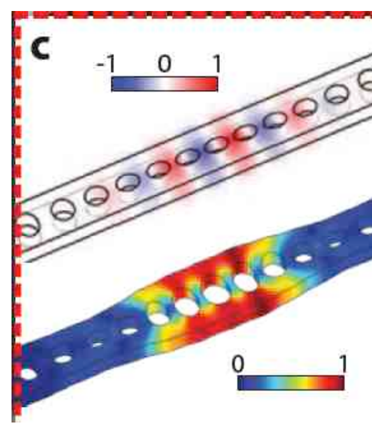
Coherent Control of Rydberg States in Silicon,

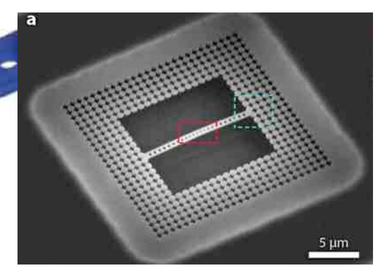
Electron transport in nanostructures



Regge et al.
Boehme et al.
Brandt et al.
Dzurak et al.
Eriksson et al.
…

Nano/opto-mechanical structures





Painter et al.

The Laboratory for Physical Sciences

An aside concerning **terminology**: Polariton? Polaron? *Phoniton?*

An aside concerning **terminology**: Polariton? Polaron? *Phoniton?*

Cavity cooling of a mechanical resonator in the presence of a two-level-system defect

Lin Tian*
University of California, Merced, 5200 North Lake Road, Merced, California 95343, USA

(Received 20 May 2011; published 22 July 2011)

Definitely polariton-like. A *polariton?* NO.

Polariton-like modes, but driven by phonons not photons.

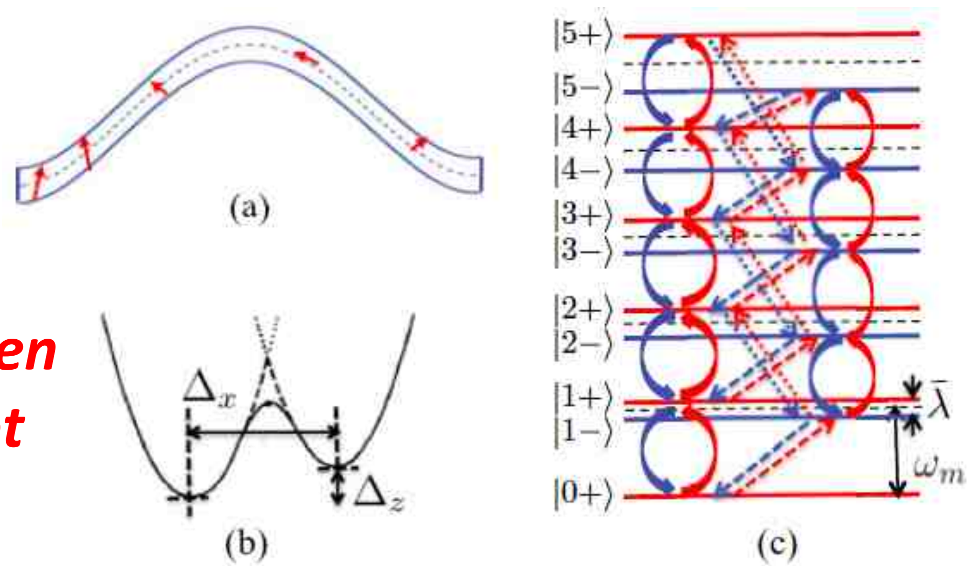


FIG. 1. (Color online) (a) Mechanical resonator couples with TLS defects. (b) Double-well potential model for the TLS. (c) Energy spectrum of the coupled system. The eigenstates are the polariton doublets labeled as $|n\pm\rangle$. The solid (dashed) arrows indicate transitions between states of identical (opposite) polarizations.

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***Polarons, acoustic polarons, …* Different usage & physics. NO.**

Impurity-Bound Hole Polaron in a Cylindrical Quantum Wire

And hundreds more papers….

E. P. Pokatilov (a), V. M. Fomin[1]) (a, b), S. N. Balaban (a), S. N. Klimin (a), and J. T. Devreese[2]) (b)

(a) Universitatea de Stat din

(b) Universiteit Antwerpen (

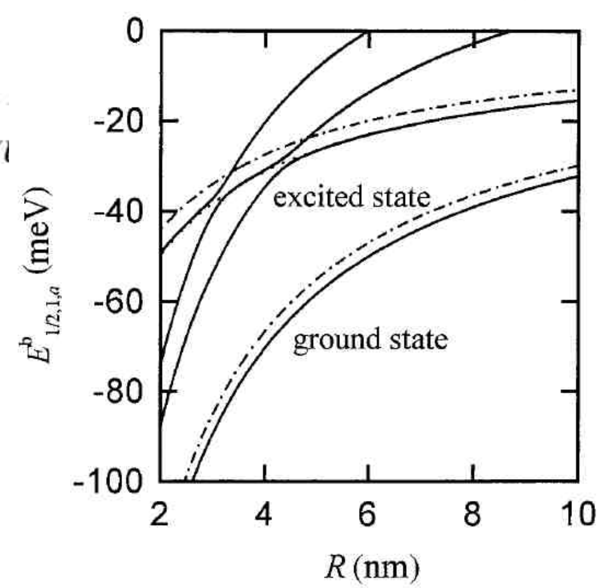

Fig. 2. The binding energies of a bare hole (dash-dotted curves) and of a hole polaron (solid curves). The lower two curves correspond to the ground state and the upper five curves represent the lowest excited states. The binding energy of the hole polaron excited state calculated within the perturbation theory using Eq. (6) is shown by a dotted curve

Polaron effect ("hole polaron") is just a *renormalization* of the energy levels due to phonon(s).

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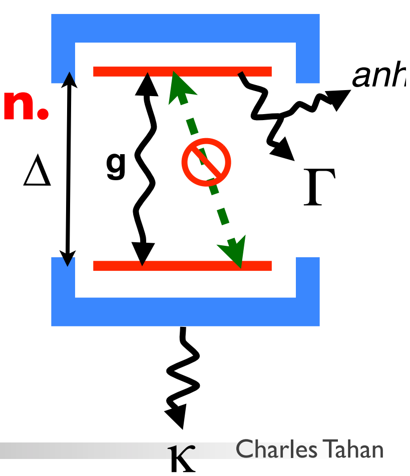
***Polarons, acoustic polarons, …* Different usage & physics. NO.**

Renormalization *of energy levels, etc. due to phonons (e.g.virtual cloud).*

Our case: **cavity-phonon drives resonant TLS**

Most analogous to a polariton, but with a phonon instead of a photon.

Exciton	cavity-polariton
Impurity:Si	cavity-phoniton



An aside concerning **terminology**: Polariton? Polaron? *Phoniton?*

Cavity cooling of a mechanical resonator in the presence of a two-level-system defect

Definitely polariton-lik A *polariton* NO.

43, USA

otons.

Polarons, *acoustic polarons*, .. Different usa & physics. NO.

re papers....

MIN (a),

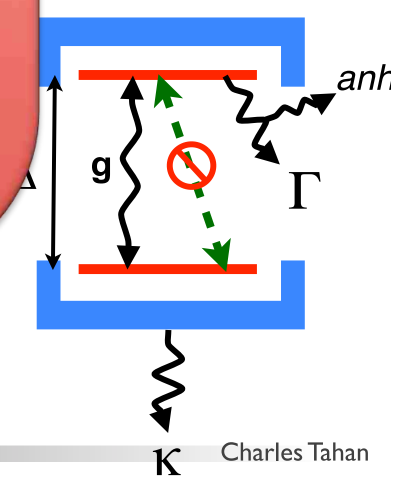
.g.virtual cloud).

Our cas cavity-phon drives resona TLS

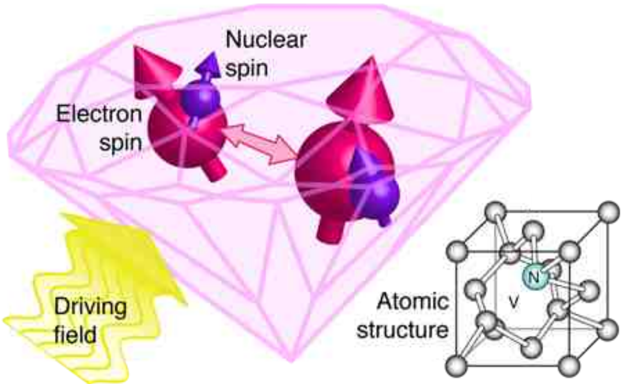
Call it whatever you want,

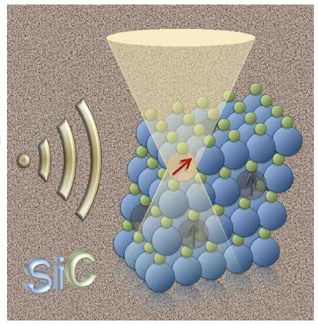
the physics won't mind

Impurity:Si	cavity-phoniton

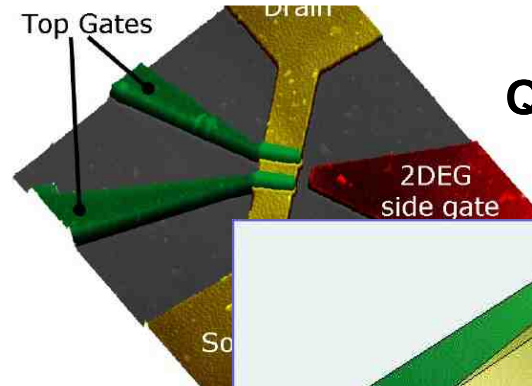


Now that we know it's possible, can think of "better" systems…

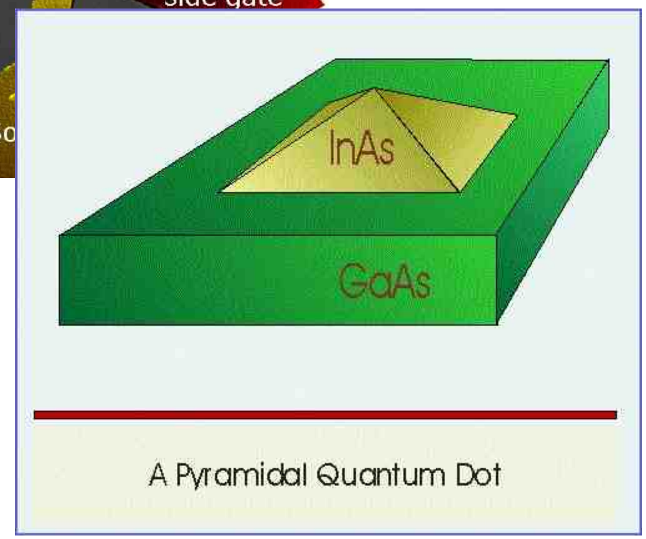


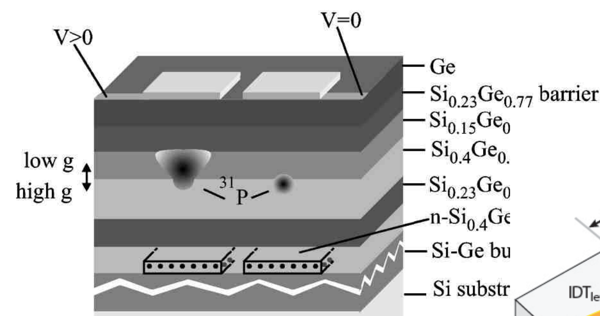


Diamond and other defects

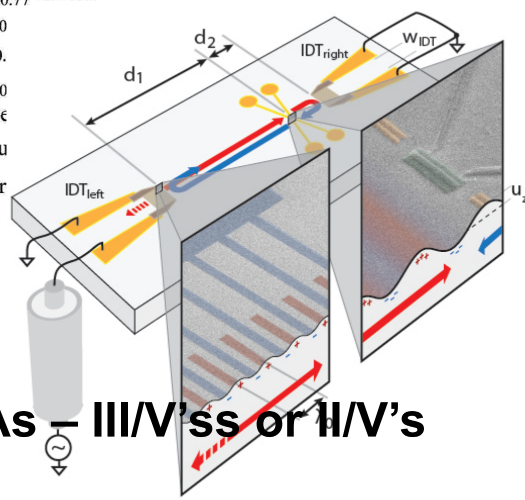


Quantum Dots



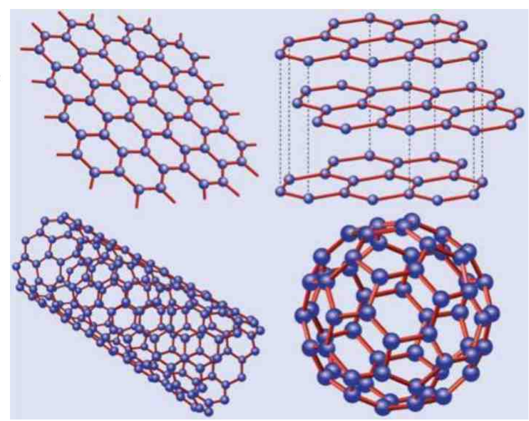


Germanium



GaAs – III/V's or II/V's

Nanowires

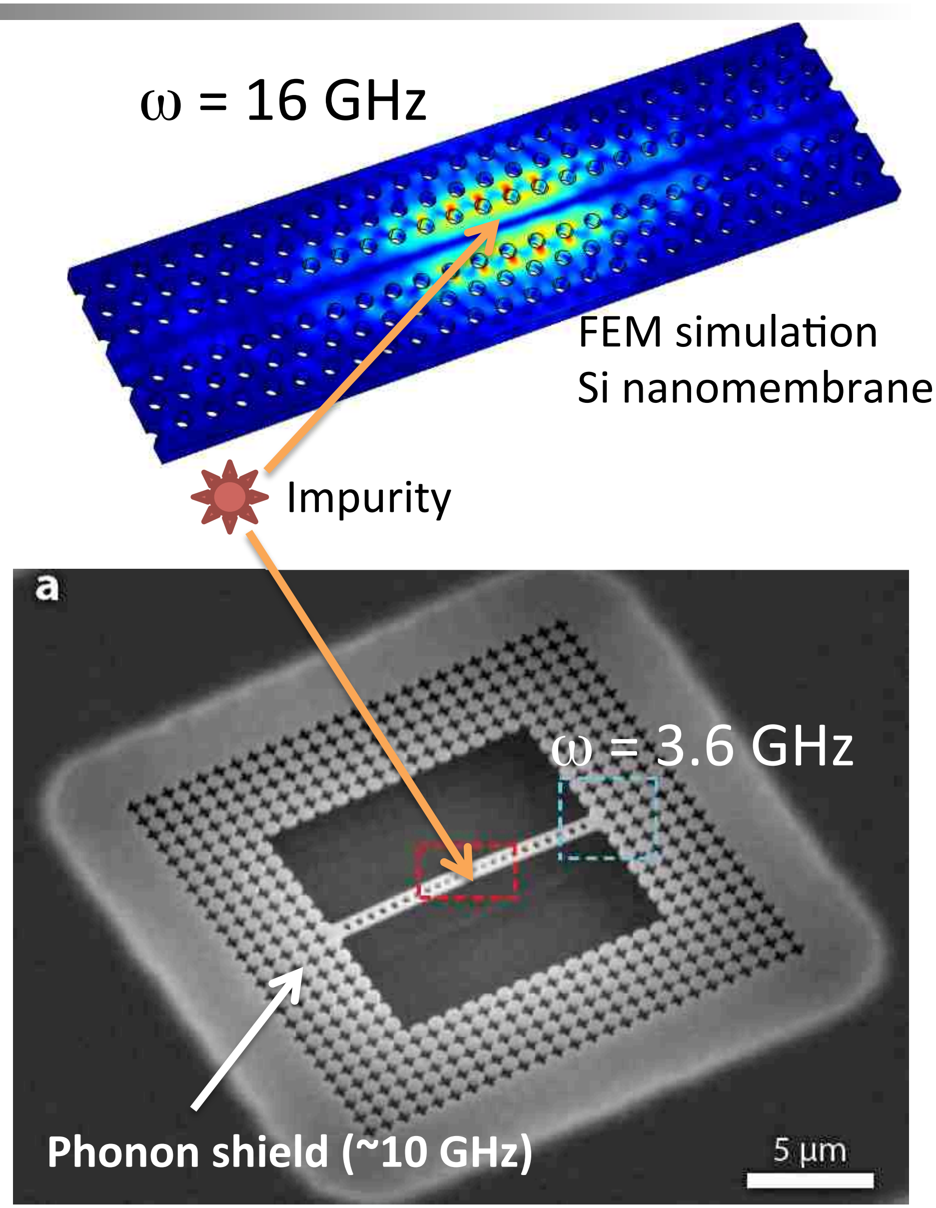


Fullerenes, nanotubes, graphene

Really want a system for "on-chip" phonodynamics

Want compatibility with phononic bandgap on-chip systems

- Nanomechanical resonators – strong coupling, ground state cooling at 20 K, phonon lifetimes 20 microseconds, Q>10^5 realized – in **silicon**
- **P:Si prototype phoniton ~ 730 GHz ☹**
- **1-150 Ghz practical (demonstrated)**
- **Need a compatible transition**
- **Immediate realization possible**



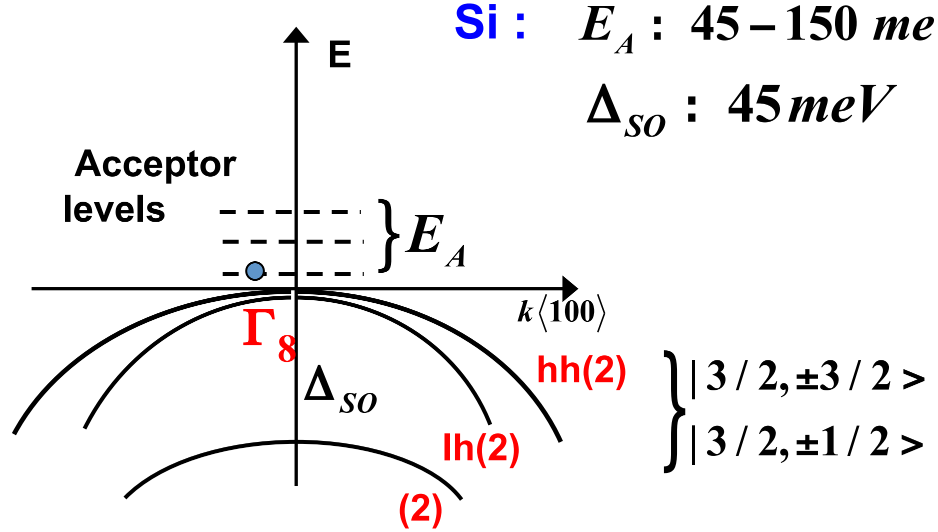
Painter et al.

Look to the **acceptor**: long-lived hole qubits in silicon

- "Good" charge qubit based on acceptor levels
  - $P_{3/2}$ valance band, 4-fold degenerate
  - Degeneracy split by **electric field or strain or B-field**
  - Kramers doublets with B=0, m_J=+-1/2 and m_J=+-3/2
- Long-range electric-dipole coupling between accepter qubits limits T2 in bulk samples

Si : E_A : $45-150\ meV$

Δ_{SO} : $45\, meV$

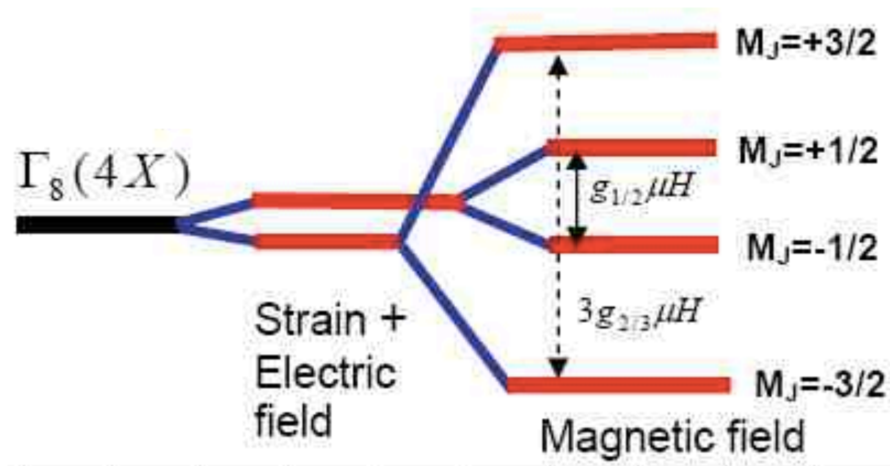


$T_2 = 2.6\ \mu s$ and $T_1 = 7.4\ \mu s$

inter-acceptor spacing of 500 nm

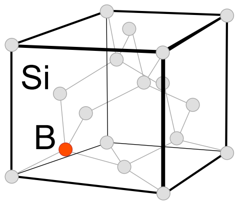
$8 \times 10^{12}\ cm^{-3}$

Golding et al. EPL, 95 (2011) 47004



Proposed for QC: *Golding and Dykman* (2003, arxiv)

From acceptor energy levels to qubits



Magnetic, Strain, and Electric fields give differing qubit arrangements

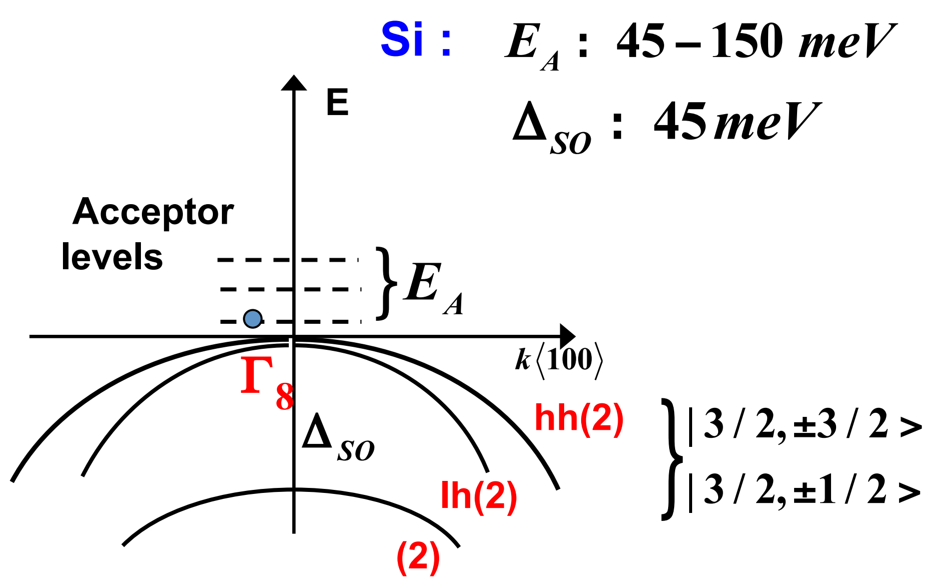
Qubit splitting is strain tunable (huge) | **magnetic field tunable (>100 GHz)** | **And E-field tunable (<1 GHz)**

(4)

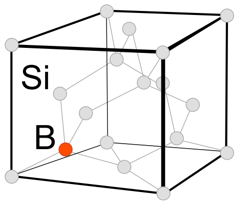
B = 0

Strain = 0

E = 0



From acceptor energy levels to qubits



Magnetic, Strain, and Electric fields give differing qubit arrangements

{+1/2,+3/2} qubit

-3/2 ———

-1/2 ———

+1/2 ———

+3/2 ———

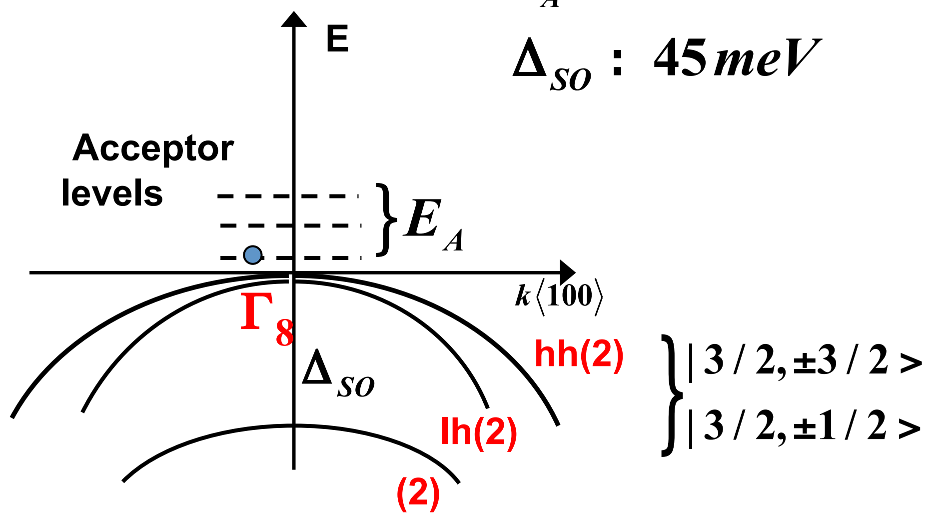
B = 0.5 – 2 T

Strain = 0

E = 0

Si : E_A : $45-150\ meV$

Δ_{SO} : $45\ meV$



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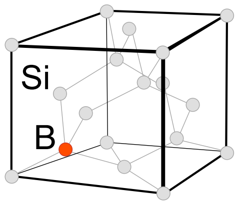
From acceptor energy levels to qubits



Magnetic, Strain, and Electric fields give differing qubit arrangements

{+1/2,+3/2} qubit

-3/2

-1/2

Our qubit

+1/2

+3/2

B = 0.5 – 2 T

Strain = 0

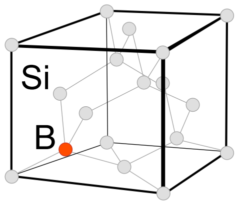
E = 0

phonon

μWaves

- *Qubit TLS is strongly phonon coupled*
- *Qubit is well isolated from other levels*
- *Tunable from 1-50+ GHz*
- *Long lifetime…*

Acceptor energy levels to qubits



Magnetic, Strain, and Electric fields give differing qubit arrangements

{+1/2,+3/2} qubit

-3/2

-1/2

phonon

μWaves

Our qubit

+1/2

+3/2

B = 0.5 – 2 T

Strain = 0

E = 0

…or… {+1/2,-1/2} qubit

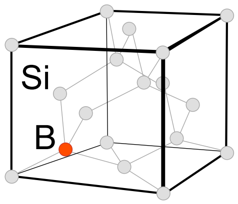
(4)

B = 0

Strain = 0

E = 0

From acceptor energy levels to qubits



Magnetic, Strain, and Electric fields give differing qubit arrangements

{+1/2,+3/2} qubit

-3/2

-1/2

Our qubit

+1/2

+3/2

B = 0.5 – 2 T

Strain = 0

E = 0

phonon

μWaves

...or... {+1/2,-1/2} qubit

+-3/2 (2)

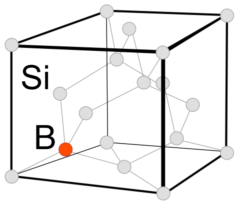
+-1/2 (2)

B = 0

Strain = ε || *z*

E = 0

From acceptor energy levels to qubits



phonon

μWaves

{+1/2,+3/2} qubit

-3/2

-1/2

Our qubit

+1/2

+3/2

B = 0.5 – 2 T

Strain = 0

E = 0

…or… {+1/2,-1/2} qubit

-3/2

+3/2

Alternate qubit

-1/2

X

+1/2

B = 0.5 – 2 T

Strain = ε || *z*

E = 0

"protected" qubit

Phonon-forbidden transition to first order

Very long lifetime

Can "turn on" coupling with E-field

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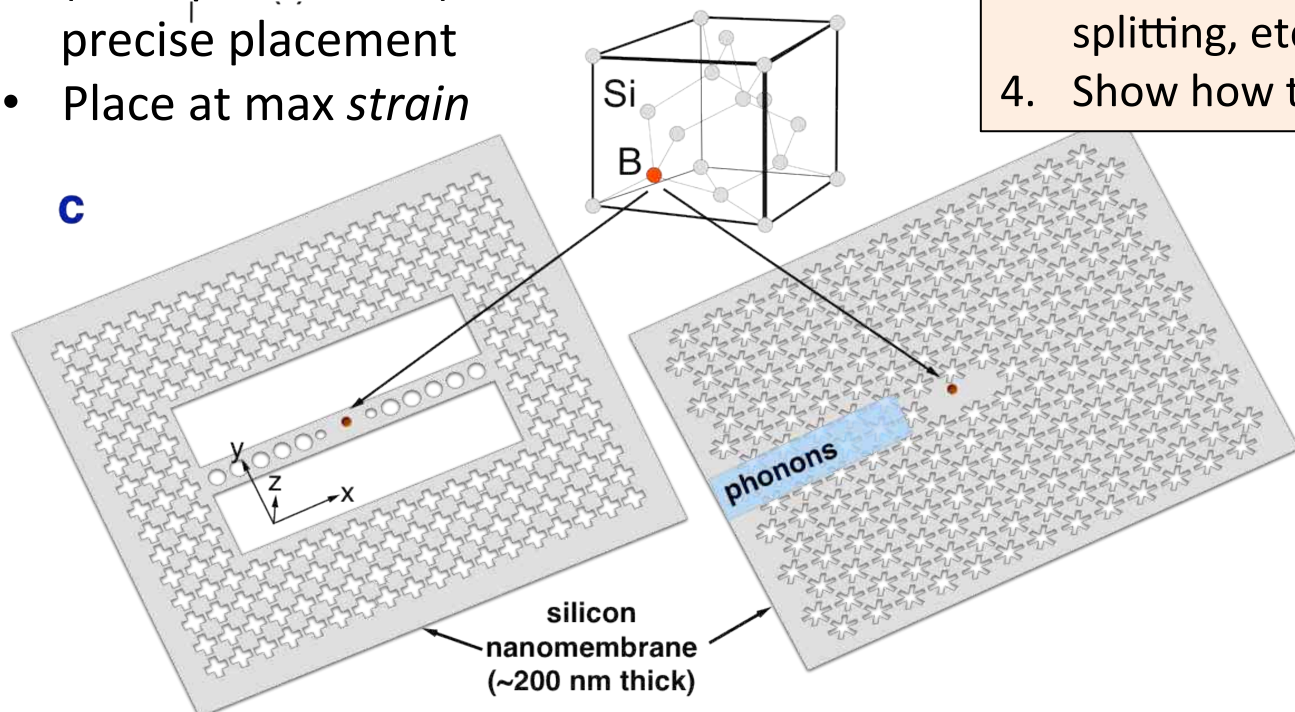
Ruskov, Tahan, arxiv.org/1208.1776

Constructing a phonon-acceptor cavity

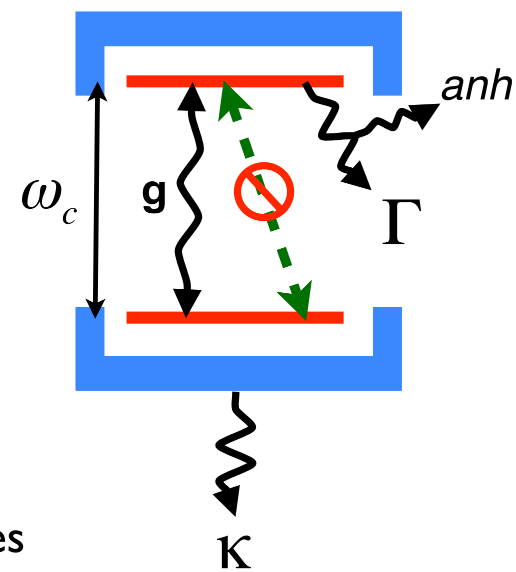
- ~200 nm silicon on insulator (SOI)
- eBeam lithography (400nm – 5000 nm wavelengths)
- Undercut via etching
- Acceptor via light p-doped silicon (or implantation?) – don't need precise placement
- Place at max *strain*

To Do:

1. Understand splitting of acceptor levels with fields
2. Show that strong coupling is possible (calculate g, relaxation, Q, etc.)
3. Predict measurement results (Rabi splitting, etc…)
4. Show how to do measurements

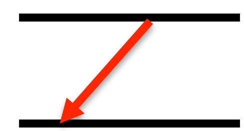


O. Painter-inspired nanomechanical cavities

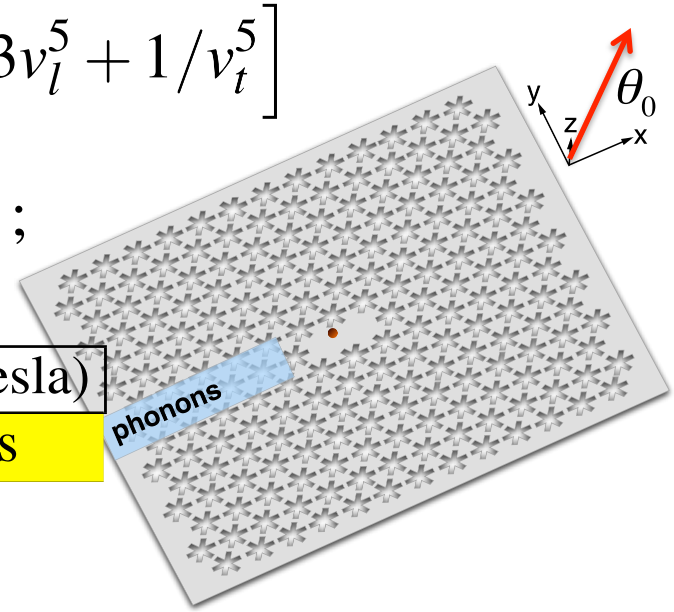


Acceptor qubit phonon relaxation in the bulk (the worst-case)

{+1/2,+3/2} qubit



$$\Gamma_{12}(\theta_0) = \frac{E_{12}^3}{20\pi\rho\hbar^4}\left\{d'^2(\cos^2 2\theta_0 + 1)\left[2/3v_l^5 + 1/v_t^5\right] + b'^2\sin^2 2\theta_0\left[2/v_l^5 + 3/v_t^5\right]\right\};$$



B:Si (1 GHz)	B:Si (4 GHz)	B:Si (8 GHz)	B:Si (1 Tesla)
386.5 μs	6 μs	0.75 μs	0.14 μs

Note, relaxation rates could be better in cavity

For the second allowed phonon transition, $-1/2 \to 3/2$, we obtain:

$$\Gamma_{13}^{\sigma} = \frac{E_{13}^3}{8\pi\rho\hbar^4 v_\sigma^5}\begin{cases}\frac{5}{15}[d'^2 + \frac{3}{4}b'^2], \ \sigma = t_1 \\ \frac{1}{15}[d'^2 + 3b'^2], \ \sigma = t_2 \\ \frac{4}{15}[d'^2 + 3b'^2], \ \sigma = l\end{cases}. \qquad 6)$$

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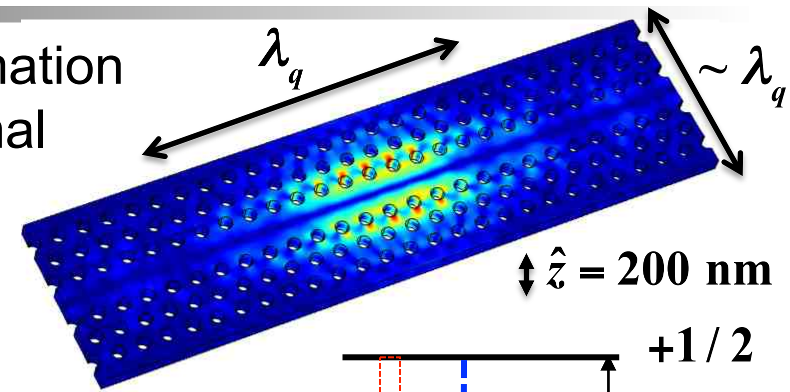
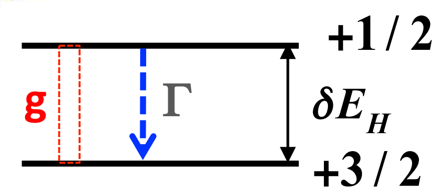
Acceptor TLS coupling to a cavity-phonon mode

- Plane wave mode is a very good approximation
- For $|+3/2> \rightarrow |+1/2>$ transition, the maximal coupling is:

$$|g_{max}| = \frac{d'}{2}\left(\frac{\hbar\omega_{\vec{q}\sigma}}{2\rho V\hbar^2 v_t^2}\right)^{1/2} \propto \frac{\sqrt{q}}{\sqrt{V}}$$



Qubit levels



Dispersive strong coupling! As well as strong coupling

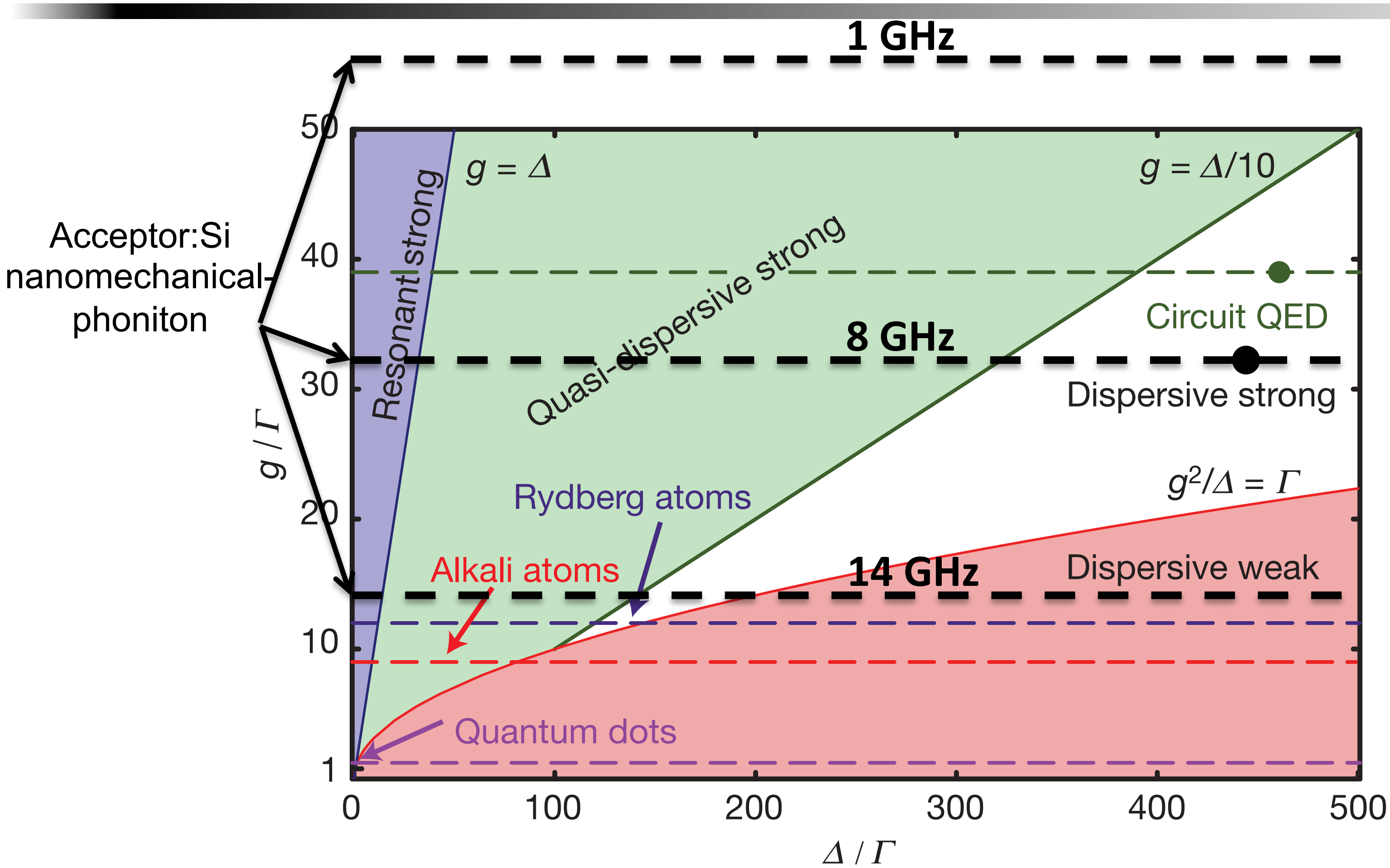
λ_q	$2\chi = 2g^2/\Delta$	ω	g_{max}	$\kappa = \omega/Q$	Γ(bulk)	n_{Rabi}	g/ω
390 nm	**4.3 MHz**	14 GHz	**21.4 MHz**	1 μs	0.1 μs	**34**	0.15%
5400 nm	**0.08 MHz**	1 GHz	**0.41 MHz**	16 μs	385 μs	**80**	0.04%
circuitQED*	**17 MHz**	5.7 GHz	**105 MHz**	0.64 μs	84 ns	100	1.8%
QD-QED*	**No**	325 THz	**13.4 GHz**	5.5 ps	27 ps	0.8	0.0004%

$V = z\lambda_q^2,\ Q = 10^5$

* Schuster, Photon resolving, old 1D-QED
* Edo Waks et al.

LPS The Laboratory for Physical Sciences

Strong dispersive coupling achieved



"In the white region QND measurements are in principle possible with demolition less than 1% allowing 100 repeated measurements."

Resolving photon number states in a superconducting circuit

D. I. Schuster[1*], A. A. Houck[1*], J. A. Schreier[1], A. Wallraff[1†], J. M. Gambetta[1], A. Blais[1†], L. Frunzio[1], J. Majer[1], B. Johnson[1], M. H. Devoret[1], S. M. Girvin[1] & R. J. Schoelkopf[1]

In the dispersive (off-resonant) limit, the atom cavity detuning is larger than the coupling, $\Delta \gg g$, and only virtual photon exchange is allowed, keeping the atom and photon largely separable (red and white regions in Fig. 1). The atom (photon) now acquires only a small photonic (atomic) component of magnitude $(g/\Delta)^2$, and an accompanying frequency shift, $2\chi = 2g^2/\Delta$. In this case, the dispersive and rotating wave approximations apply, and the system is described to second order in g/Δ by the quantum version of the a.c. Stark hamiltonian[1]:

$$H = \hbar\omega_r(a^\dagger a + 1/2) + \hbar\omega_a\sigma_z/2 + \hbar\chi(a^\dagger a + 1/2)\sigma_z$$

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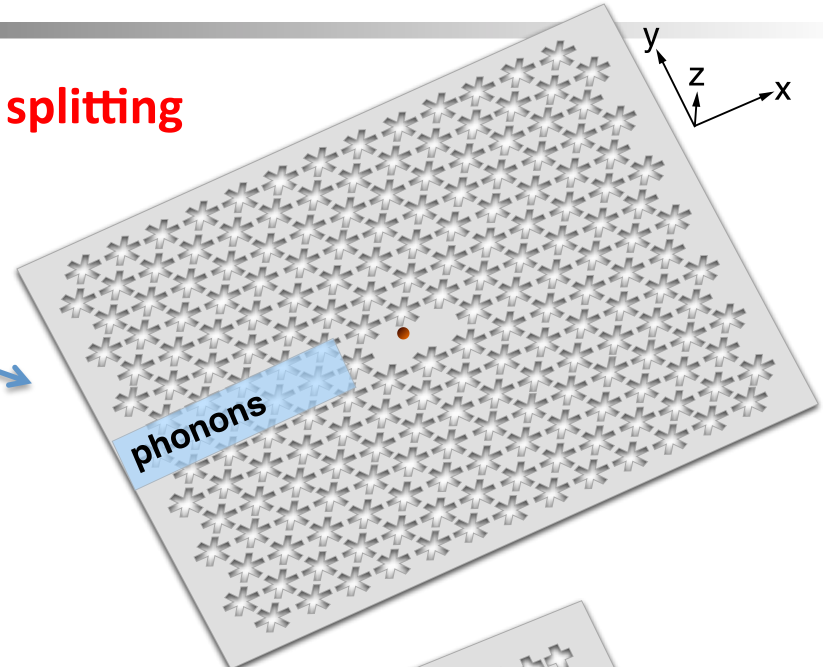
How do we actually do the measurement?

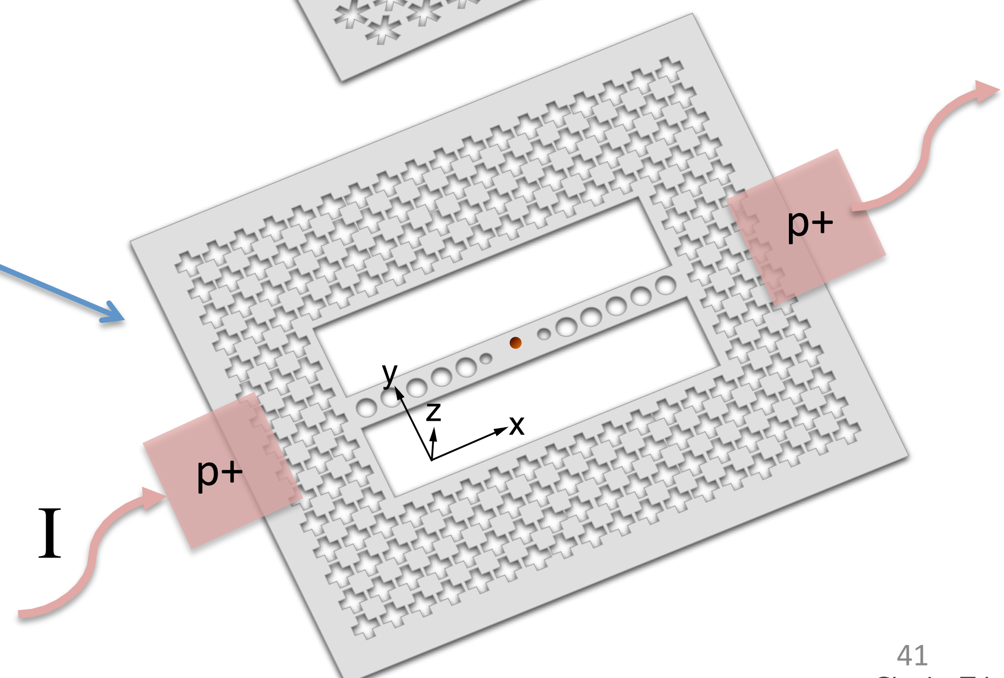
Want to first measure the "vacuum" Rabi splitting

- **Coherent phonon source?**
  - Analogous to microwave sources in circuitQED
  - Heterodyne/homodyne



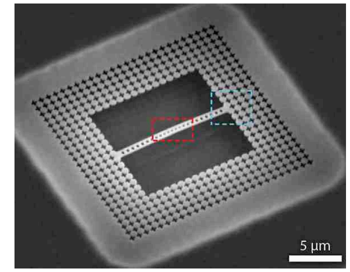
- Hole transport?
  - spectroscopy

- STM probe?
  - Spin dependent tunneling?

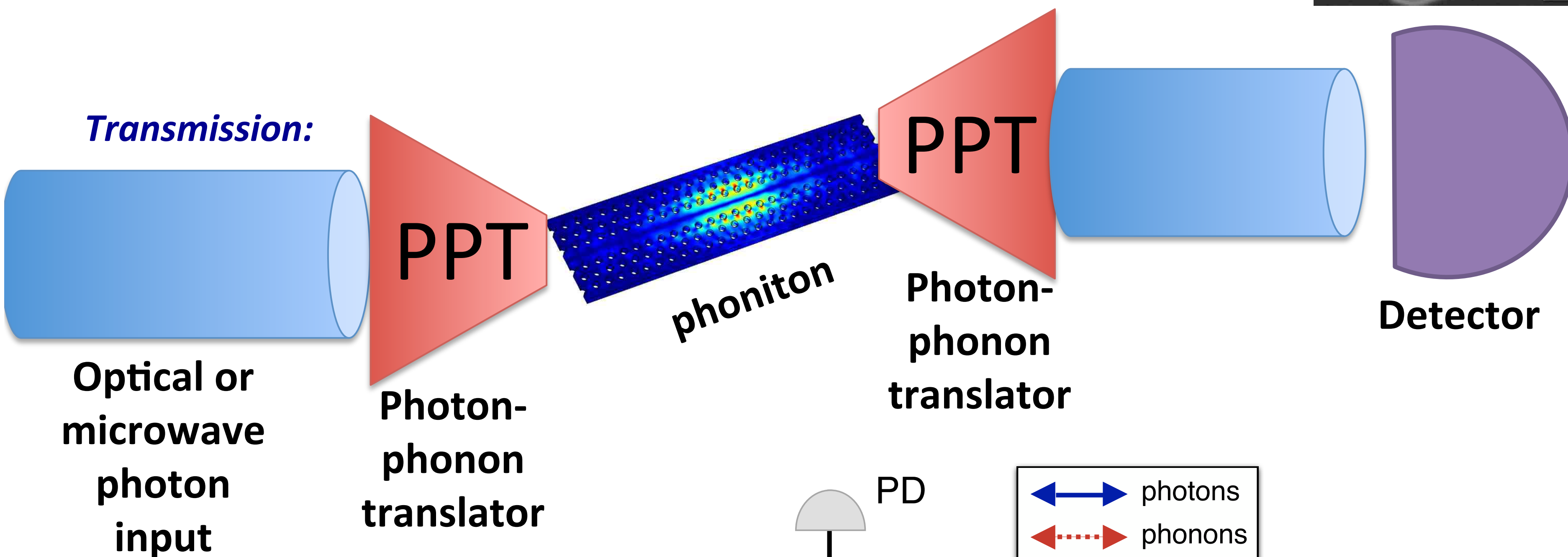


1) Use quantum optics and a photon-phonon translator

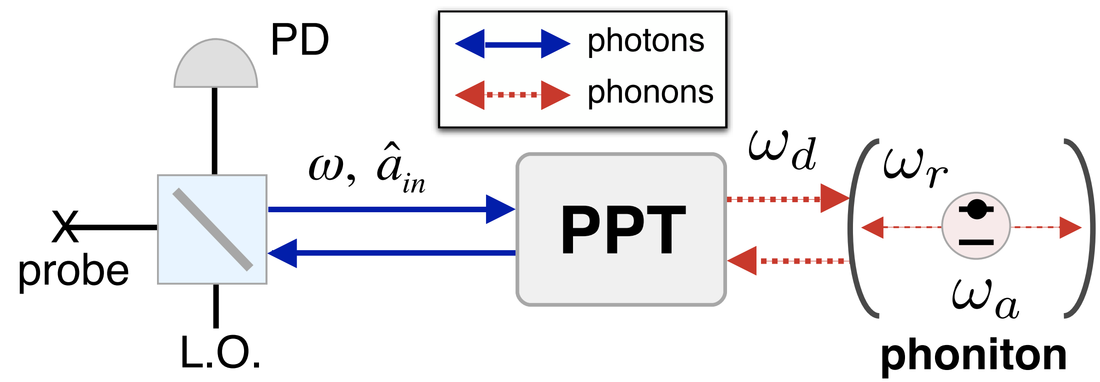
- How to probe phonon/donor physics w/o "phonon industry"?
- Usa a quantum coherent **Photon-Phonon Translator**
  - Amir H. Safavi-Naeini, Oskar Painter (2010)



Transmission:

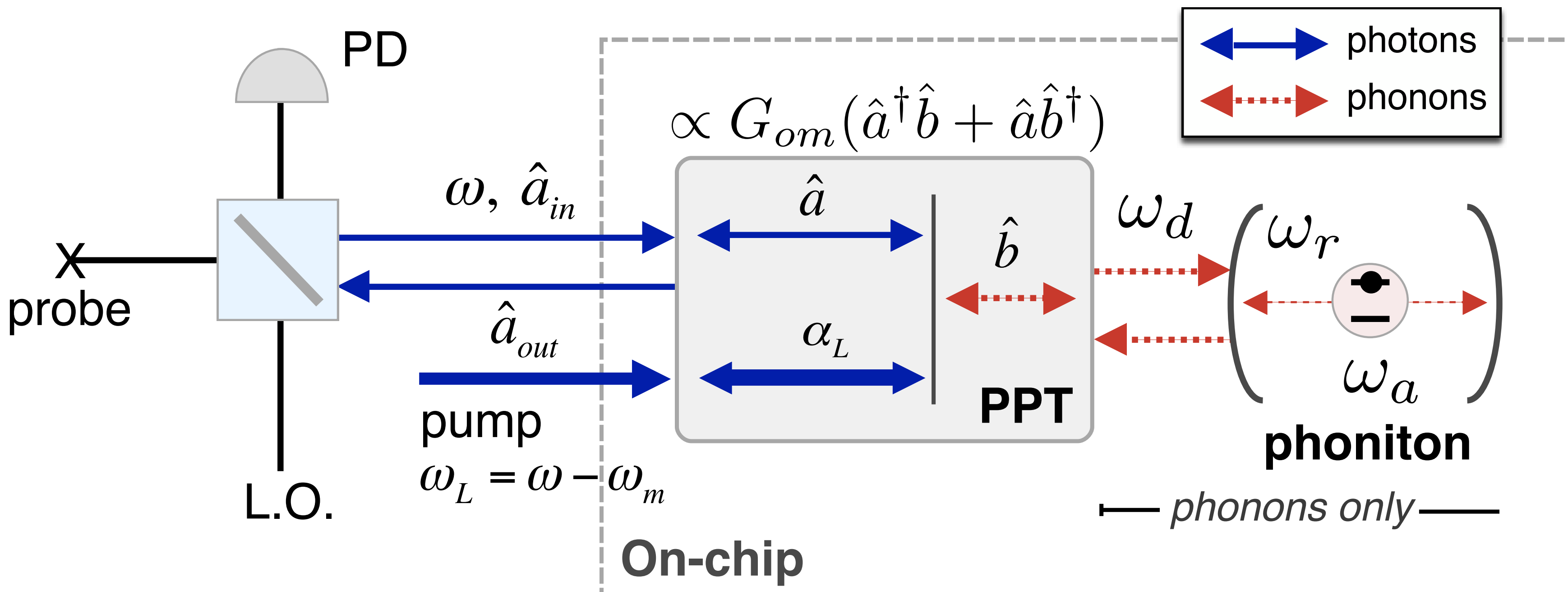


Reflection:



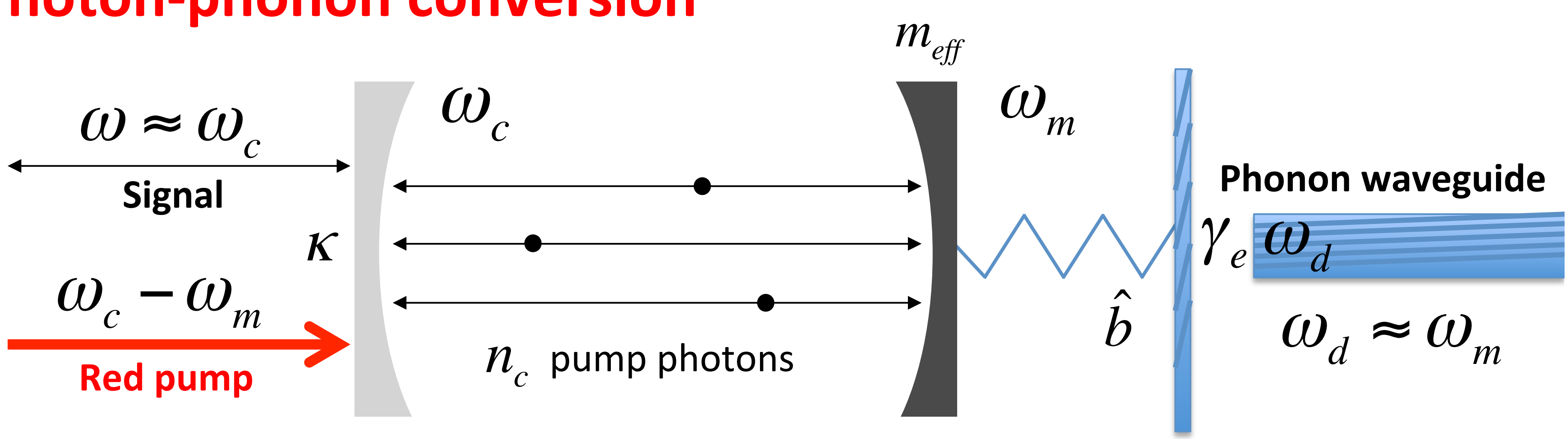
Making a photon-phonon translator

- PPT introduced by Painter group (Caltech)
- Extension of optomechanical coupling/cooling physics
- Input: weak signal (probe) and strong pump (to satisfy energy conservation and increase conversion efficiency)
- Translation efficiency can approach 100% (92% internal already achieved in double-PPT device)



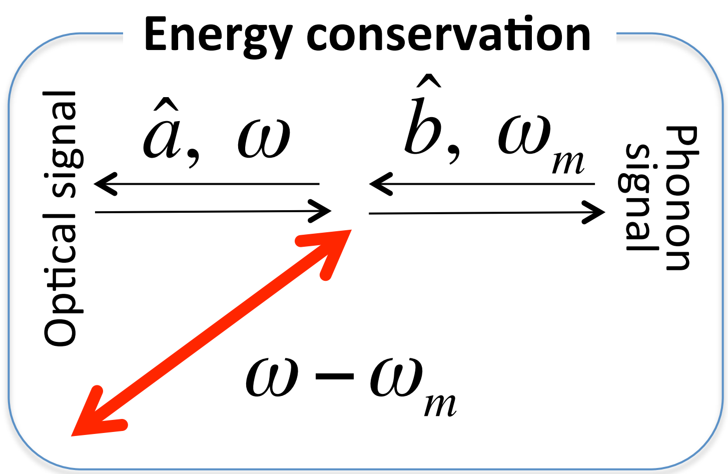
The PPT (via an intro to optomechanics)

Photon-phonon conversion



Now, the pump amplifies the probability of photon-phonon conversion.

Works in both directions.



Effective beam-splitter Hamiltonian

$$H_{res}^{PPT} = G\left(\hat{a}^t \hat{b} + \hat{a}\hat{b}^t\right)$$

$$G \sim g_{om}\sqrt{n_c}$$

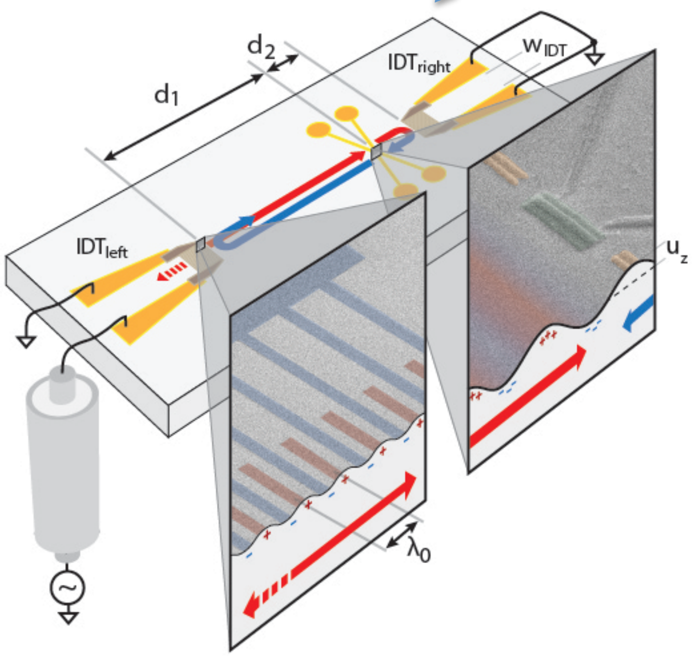
2) Go all phonon, all on chip: a SAW+SET system in silicon?

Towards the quantum regime with propagating acoustic waves: Local probing in a GHz echo chamber

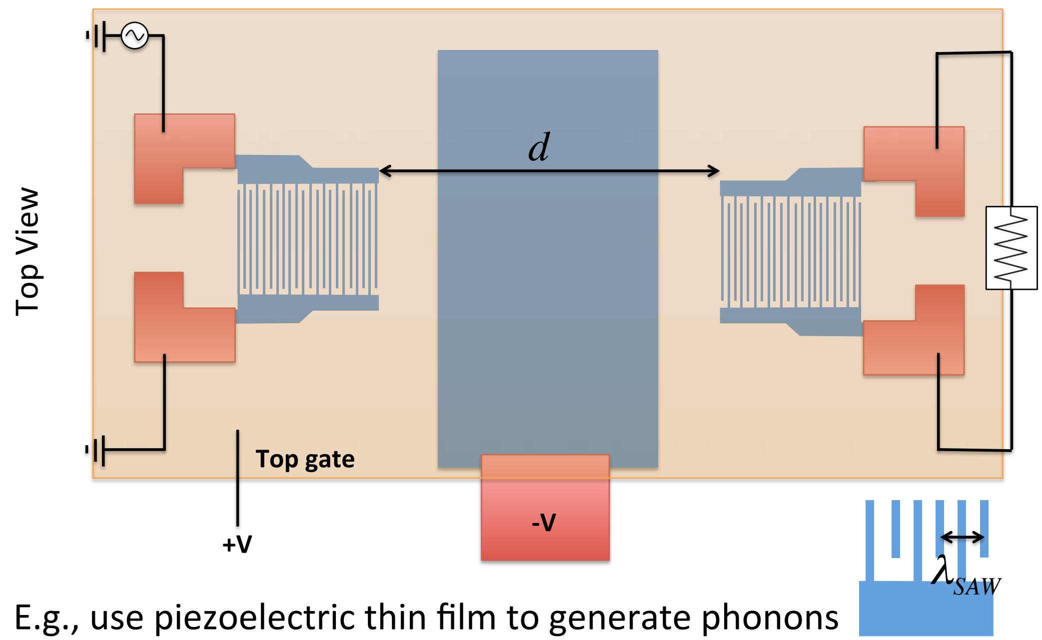
Martin Gustafsson†, Paulo V. Santos††, Göran Johansson† and Per Delsing†

Nature Physics (2012)

GaAs



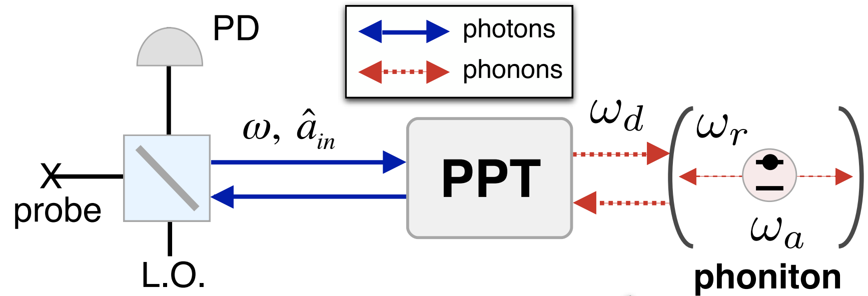
Something similar in silicon?

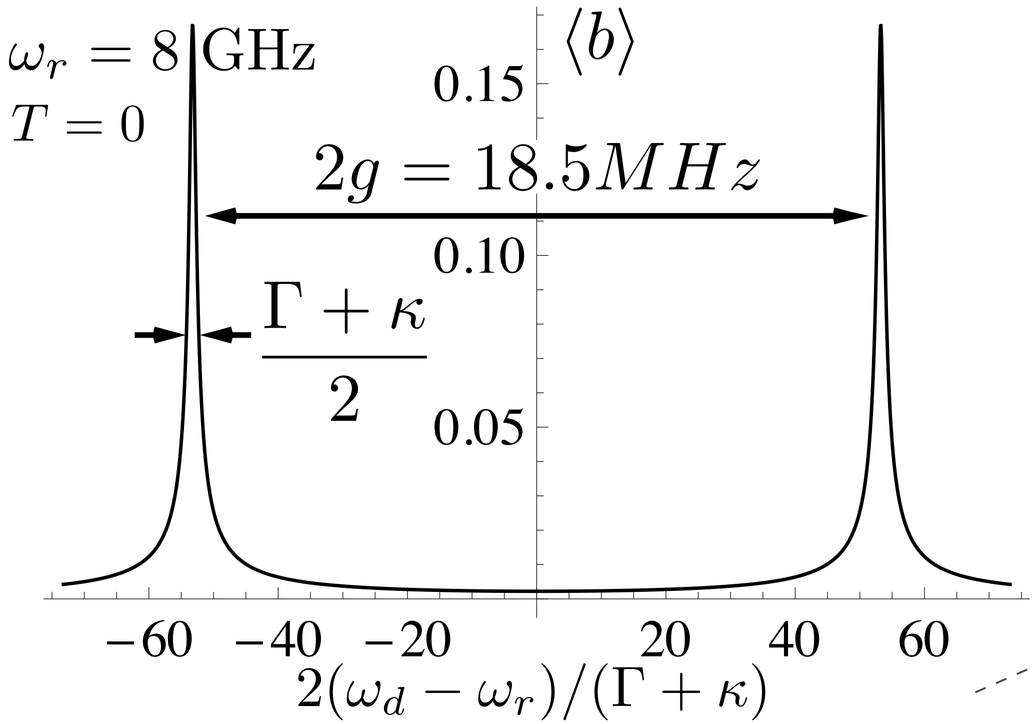


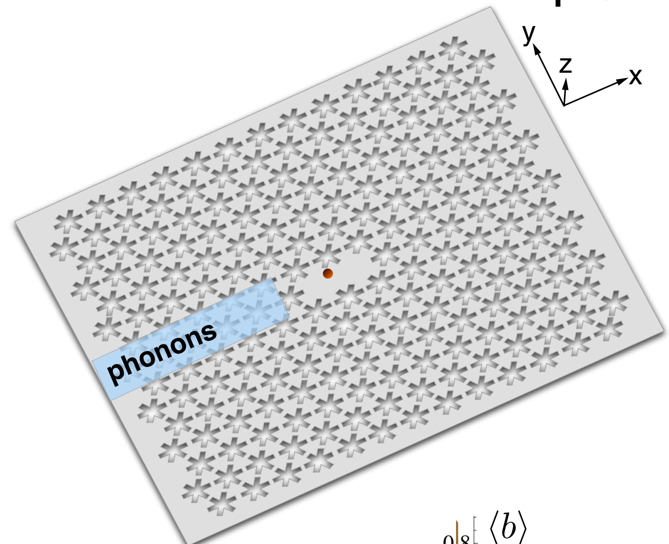
E.g., use piezoelectric thin film to generate phonons

"Quantum optics" signatures: Observing the Rabi splitting (T=0)

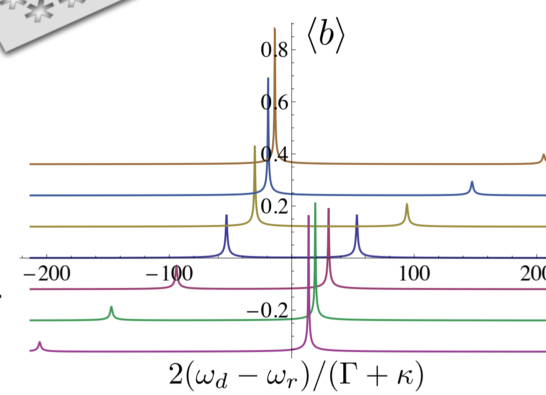
- In either case, quantum optics like experiment
- **Sweep the phonon probe signal around the mechanical resonance ω_r**
- Averaged phonon cavity field amplitude <*b*> is the observable





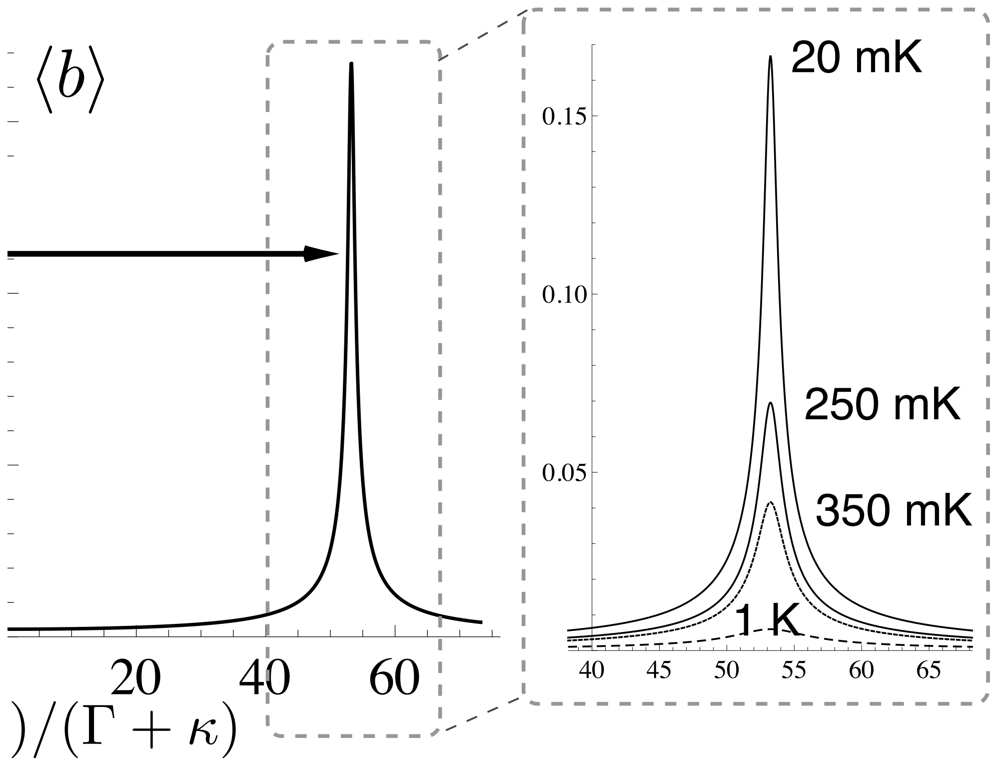


And as a function of detuning...



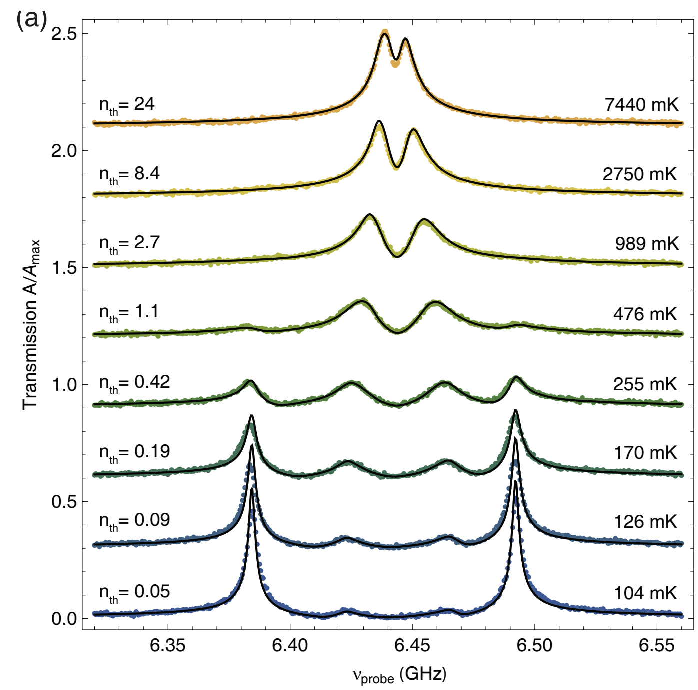
What temperature do the peaks disappear?

Our calculations for phonon/acceptor cavity:



(assuming two state approximation and full equilibrated phonon cavity)

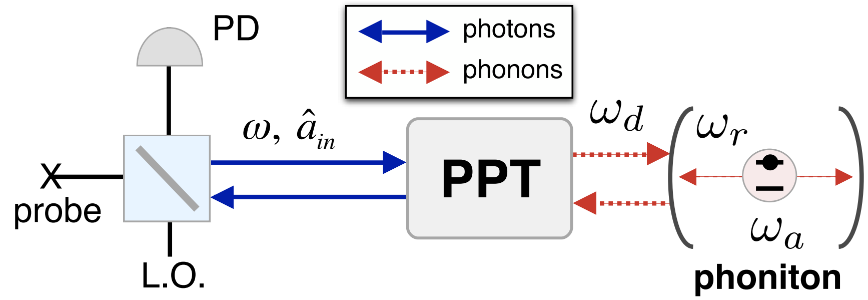
Circuit-QED experiment:

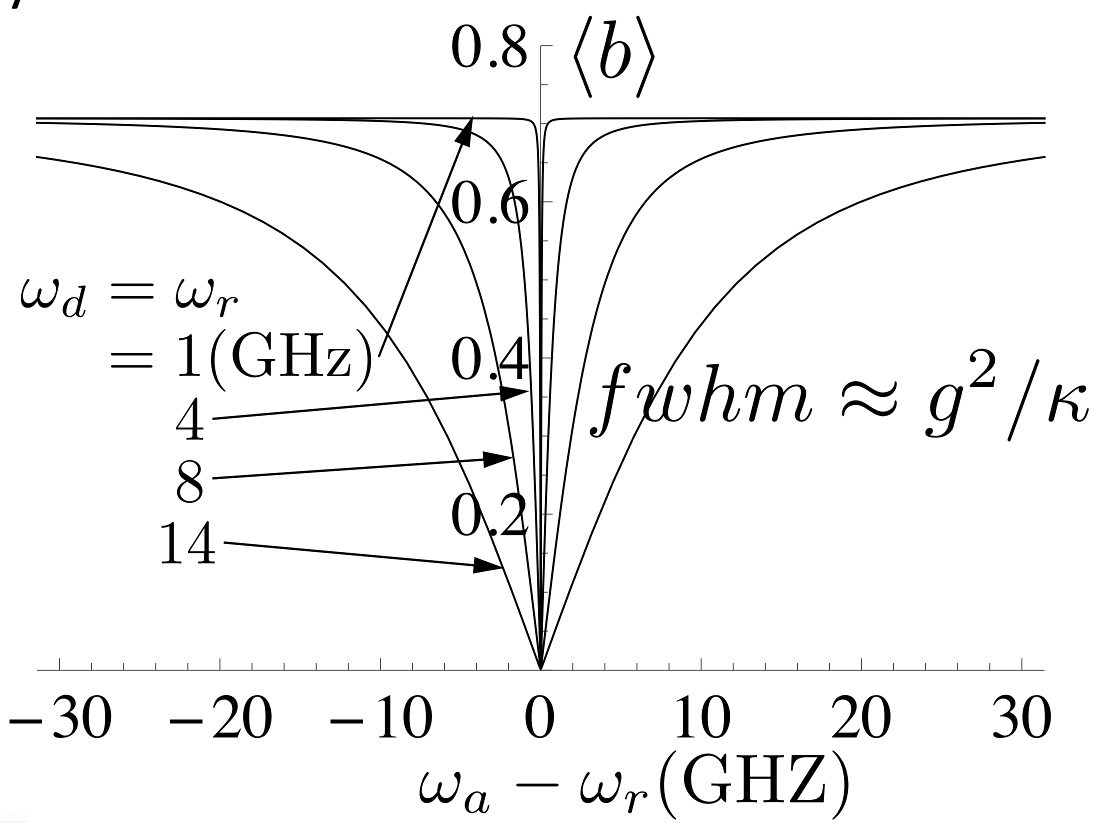


Fink…Wallraff, PRL 105, 163601 (2010)

An even easier way to measure g

- Sweep the qubit detuning (**via the B-field**) while keeping the probe input in resonance with the phonon cavity





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Acceptor ionization and possibility of active cooling

What about using optomechanical cooling?

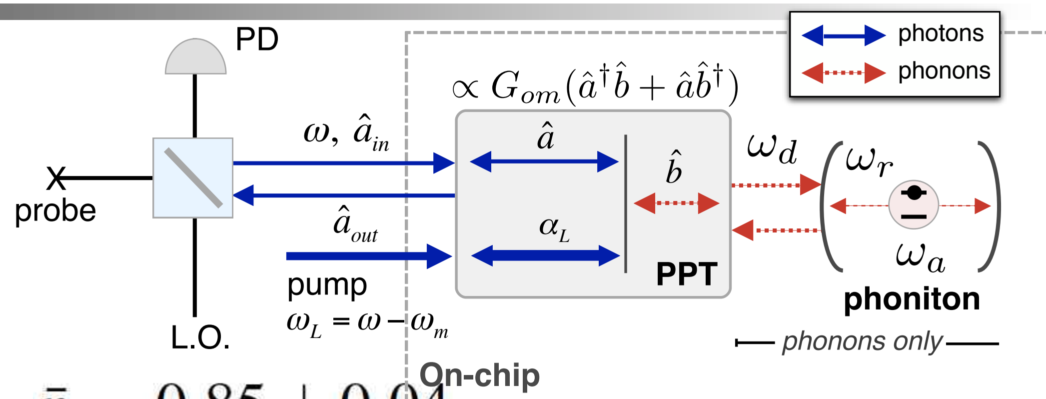
- Optical phonon ~ 0.82 eV
- Si bandgap ~ 1.1 eV
- B:Si, E_A ~ 0.044 eV
- m_A ~ 0.23 m_e

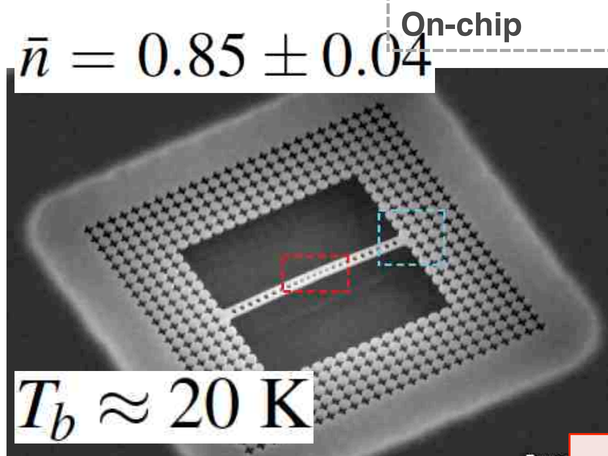
$$\sigma_{phot} \propto 1/E_f^{3.5}$$

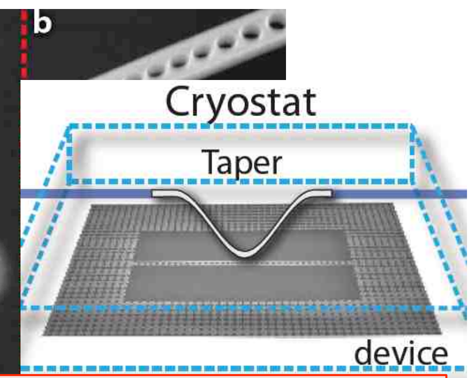
$$E_f = \hbar\omega - E_A$$

$$\sigma_{phot} \approx 8.6 \times 10^{-23}\ \mathrm{m}^2,$$

$$\tau_{phot} = \frac{2V}{n_c c \sigma_{phot}}$$







$\omega_m/2\pi = 3.68$ GHz

$Q_m \approx 10^5$ ~0.2 K

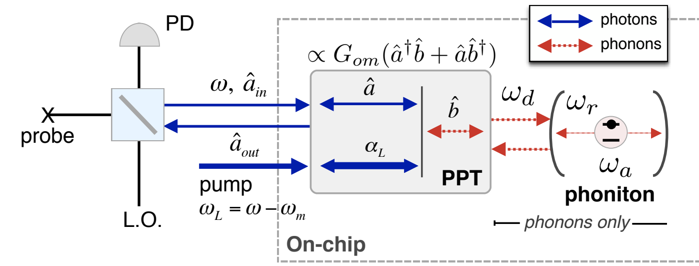
Cooling to ground state at 20 K

Painter et al.

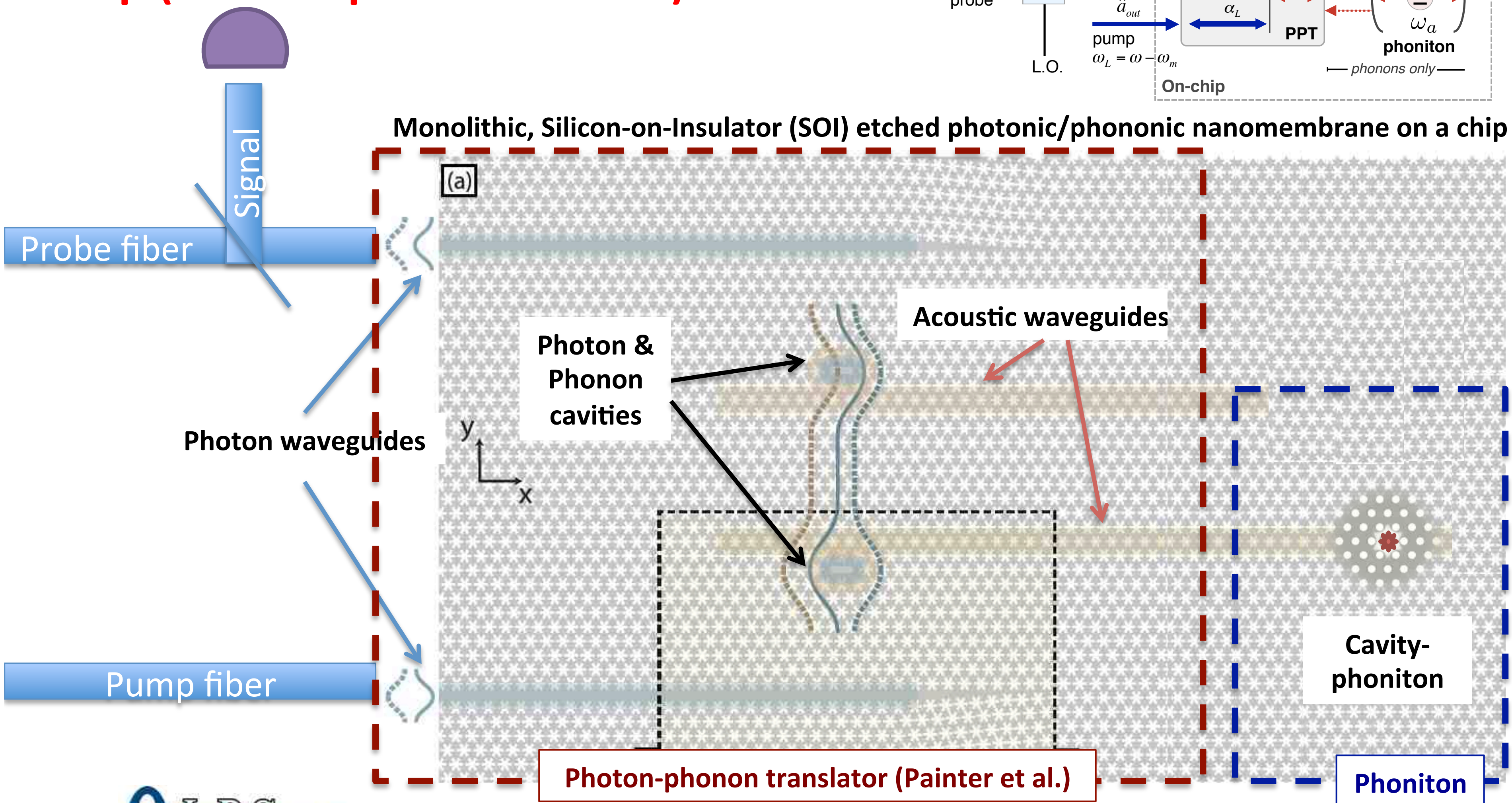
e.g. for 10 photons, one gets an acceptor lifetime of 12 microseconds, assuming 100% photon wave function overlap -> keep photons away!

Example: Optical access via on-chip PPT + cavity-phoniton

What it looks like integrated in a single chip (a cut-n'-paste rendition):



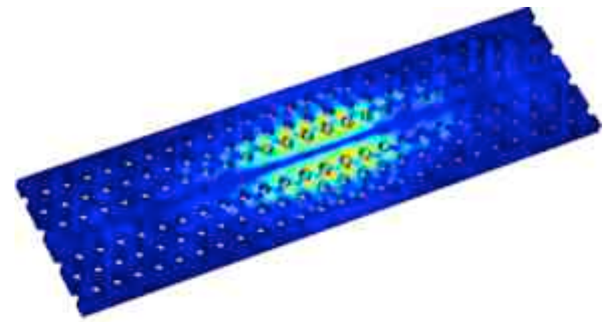
Monolithic, Silicon-on-Insulator (SOI) etched photonic/phononic nanomembrane on a chip

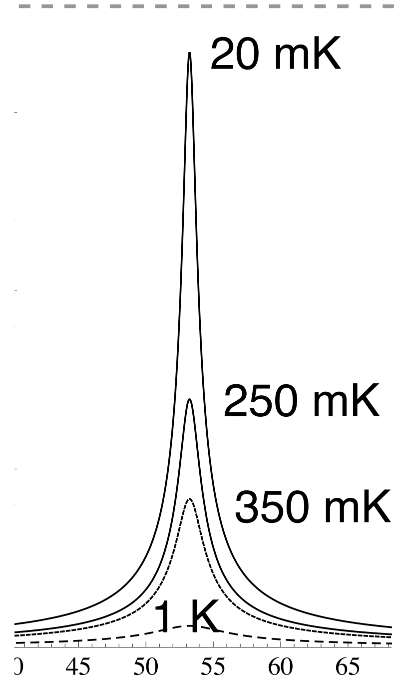


Photon and phonon wavelengths are roughly the same.

Why is the acceptor-cavity system so exciting?

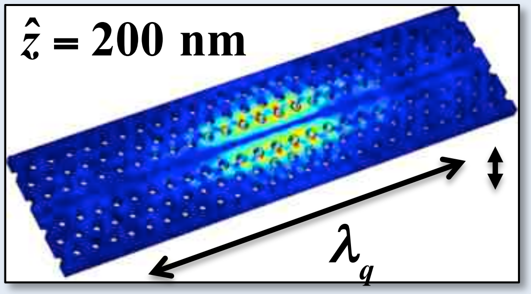
- **Silicon is an extremely promising material system for nanomechanics**
  - And it will get better as materials/processes improve
- **Engineered a new quantum system**
  - Half-phonon/half-matter: phoniton
  - **A non-linearity for coherent acoustic phonons**
    - **The phonons can be the quantum object too**
  - **Access to the acceptor qubit: spin readout**
    - **Optical (telecom) access to spin qubit in silicon!**
  - **Probably need a dil fridge unless you figure out how to do cooling without ionizing the acceptor (which is possible)**
- **Acceptor:Si nanomechanical:phoniton realizable**
  - Acceptors interesting in their own right – **might be there already!**
  - **Different physics than valley transiton - "Normal" dipole transition: place acceptor at max *strain*** – *not just a one-off*
  - Nice energy range, Fully tunable – two modes of operation
  - Compatible on chip, "Simple" construction
  - **Building block of more complex quantum sound devices**





3 more things this system gives us…

Phonon environment engineering



$$\lambda_{ph} = 500 - 5000 \text{ nm}$$

(Corresponding to accepter qubit energy splitting)

When $\lambda_{ph}/2 > z$, phonon emission should be suppressed.

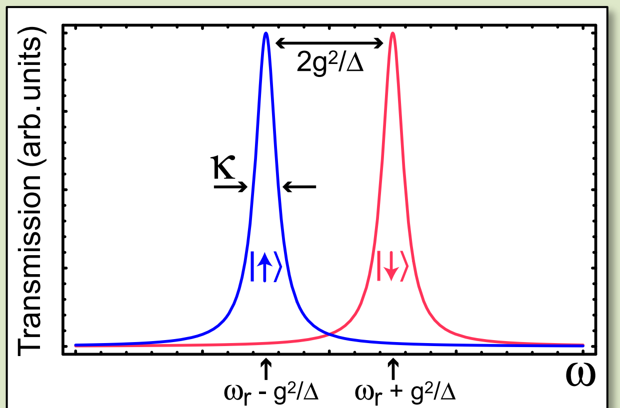
+ active cooling may/ should be possible.

= engineer environment to work at high temp?

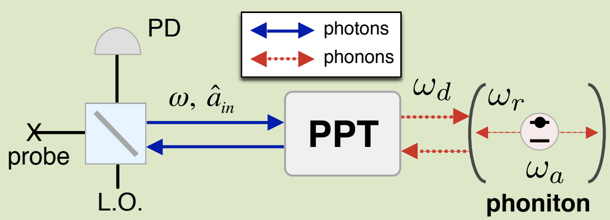
Dispersive phonon readout/Optical readout

Dispersive acceptor qubit readout

$$\chi_{phonon} = 2g^2/\Delta = 4 \text{ MHz}$$



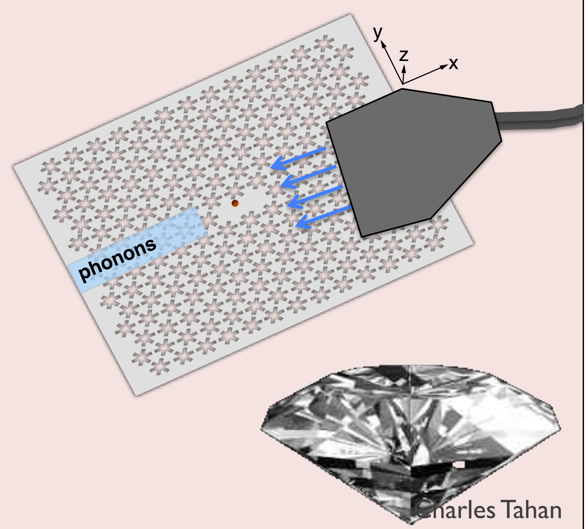
Circuit QED, Blais et al.



Microwave qubit control

Acceptor dipole coupling: (bigger than for NVs)

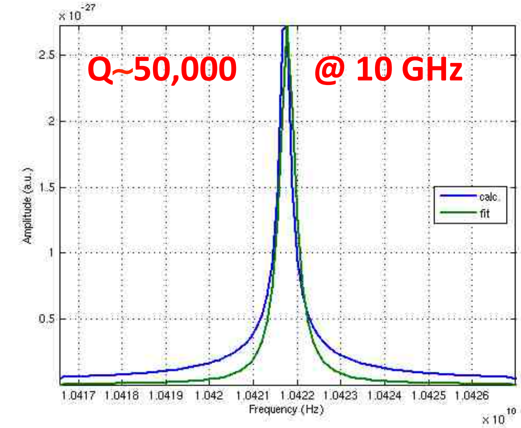
$$p_E \approx 30\mu_B / c$$



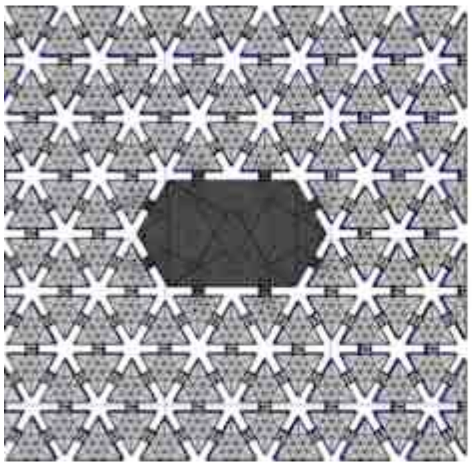
Optimized Cavity Mode, straggle not an issue

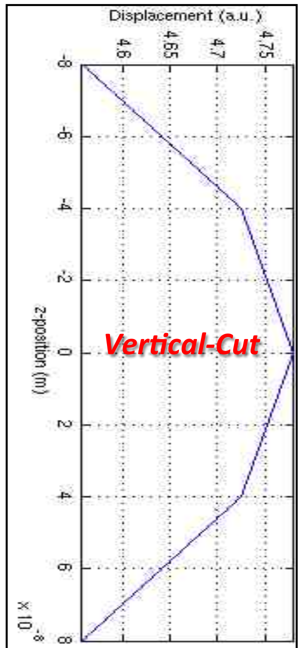
Advantages:

- Maximum strain central lobe is 500nm in diameter!
- Basically resolves the straggle problem
- (d;r;w;a) = (160;200;75;500) nm.
- With Material loss Q~49,691!



Structure L2 Hexagon

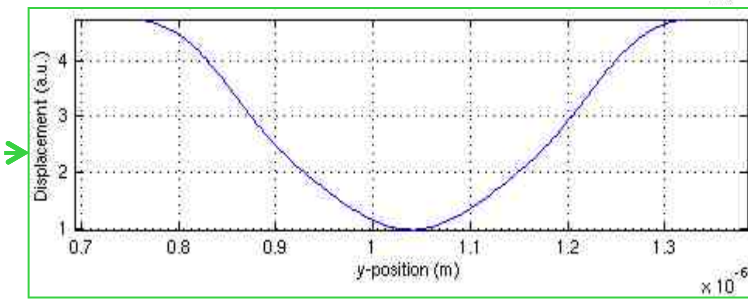


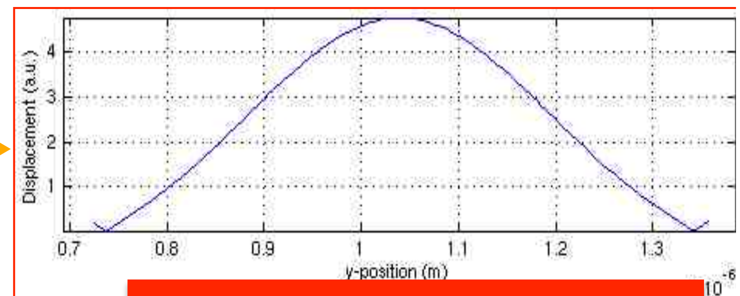


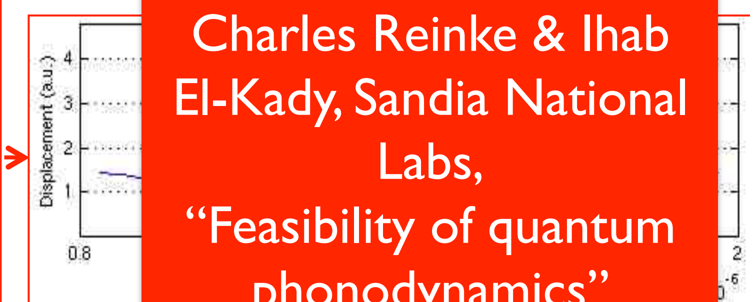
Recall Straggle Constraints:

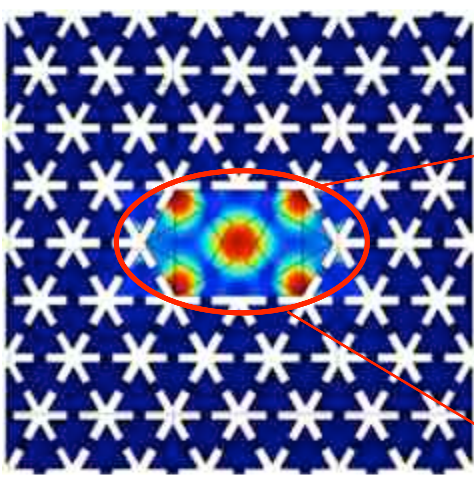
Vertical: ~ 50nm ± 20nm

Horizontal: ~ 20nm ± 25nm

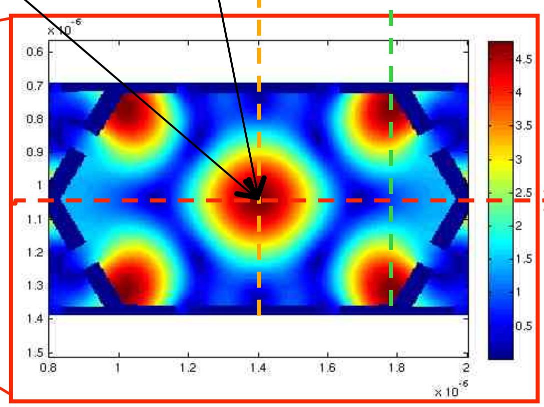








Mode

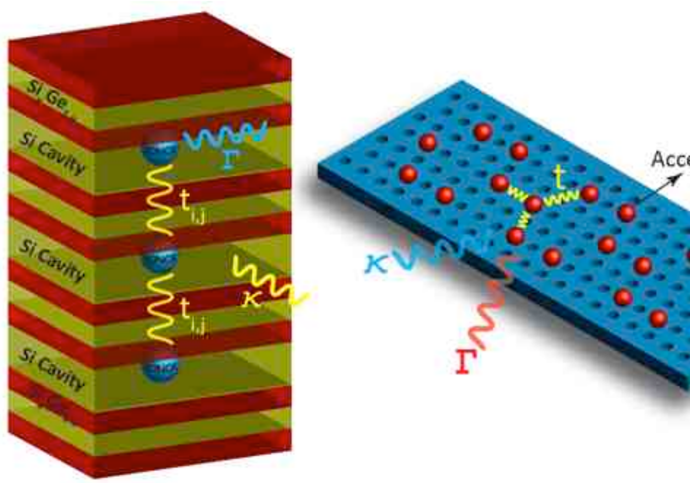


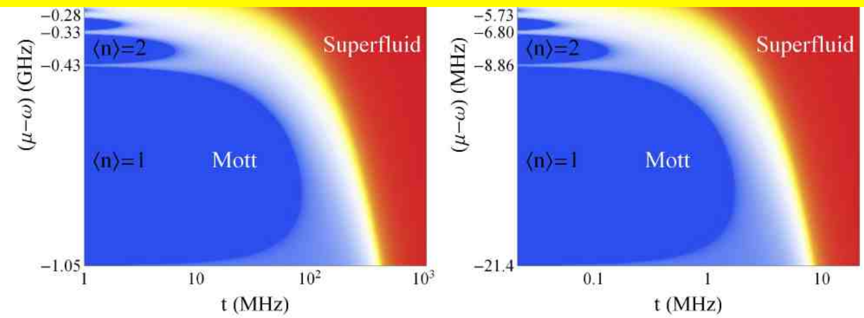
Charles Reinke & Ihab El-Kady, Sandia National Labs,
"Feasibility of quantum phonodynamics"

Charles Tahan

Toward engineered quantum many-body phonon systems

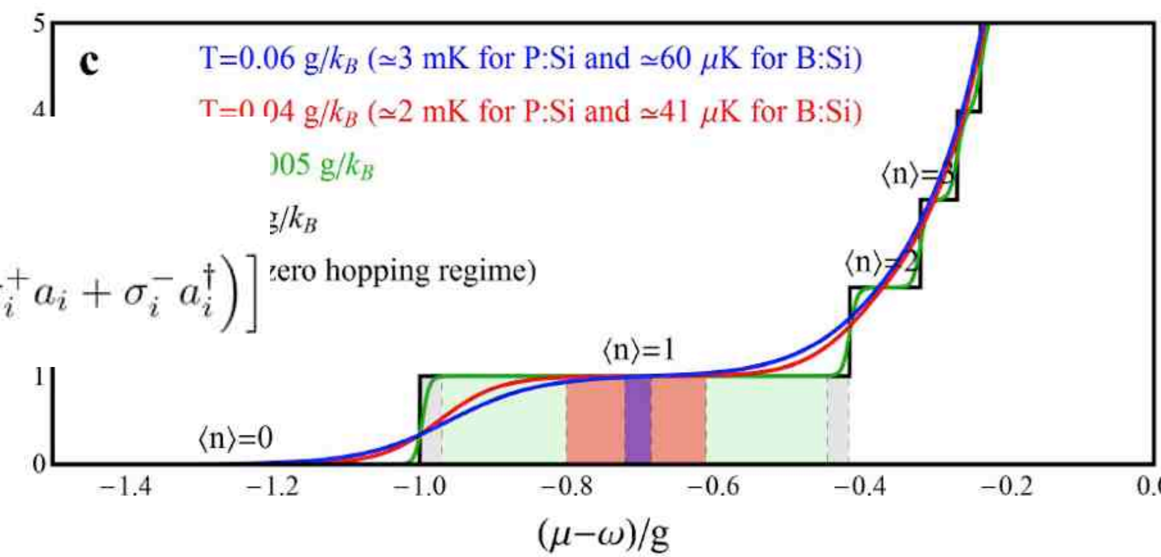
Talk: U41.00004 : Quantum many body systems with qubits and phonons in the solid state
Oney Soykal, 11:51 AM–12:03 PM, **Thursday**, March 21, 2013 - Room: 350





$$\mathcal{H}_{JCH} = \mathcal{H}_{JC} - \sum_{\langle i,j \rangle} t_{ij} a_i^\dagger a_j,$$

$$\mathcal{H}_{JC} = \sum_i \left[\varepsilon \sigma_i^+ \sigma_i^- + \omega a_i^\dagger a_i + g \left(\sigma_i^+ a_i + \sigma_i^- a_i^\dagger \right) \right]$$



Soykal, Tahan, http://arxiv.org/abs/1302.5769

Thank You

- ***Rusko Ruskov***, ***Yun-Pil Shim***, ***Oney Soykal***

Some papers:

1. "**Sound-based analogue of cavity-QED in silicon**", Phys. Rev. Lett. 107, 234402 (2011) - http://arxiv.org/abs/1106.1654
2. "**On-chip quantum phonodynamics**" - http://arxiv.org/abs/1208.1776
3. "**Relaxation of excited spin, orbital, and valley qubit states in single electron silicon quantum dots**" - http://arxiv.org/abs/1301.0260
4. "**Spin-valley lifetimes in a silicon quantum dot with tunable valley splitting**" - http://arxiv.org/abs/1302.0983
5. **"Toward engineered quantum many-body phonon systems" -** http://arxiv.org/abs/1302.5769

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Talk: U41.00004 : Quantum many body systems with qubits and phonons in the solid state
Oney Soykal, 11:51 AM–12:03 PM,
Thursday, March 21, 2013 - Room: 350

Talk: W26.00007 : A new mechanism for spin and valley relaxation in silicon quantum dots
Rusko Ruskov, 4:06 PM–4:18 PM,
Thursday, March 21, 2013, Room: 328