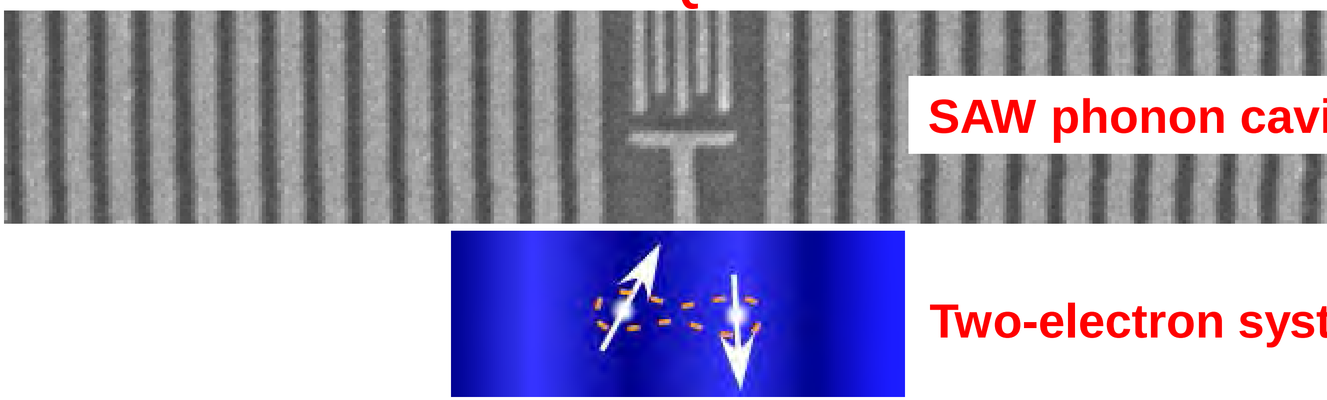
SPICE-Workshop
Quantum Acoustics
May. 17-20, 2016, Mainz, Germany

Cavity Quantum Acoustics with a Double Quantum Dot



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supported by JSPS KAKENHI and TokyoTech Nanotechnology Platform.

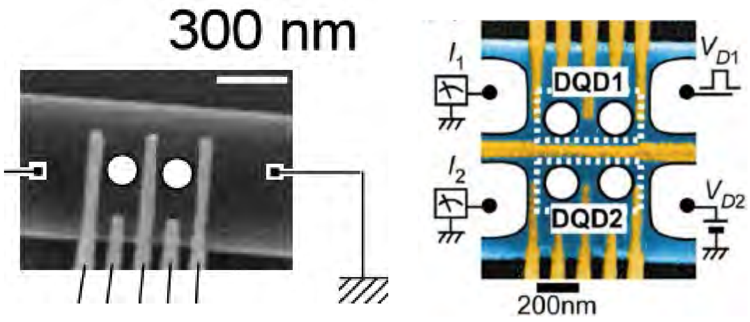
CONTENTS

- **Motivation**
  - Phonon environment for quantum dots
  - Prospect for cavity Quantum Acoustics
- **SAW Phonon cavity**
  - Device design
  - Phononic bandgap in a Bragg reflector
  - Localized cavity modes
    - time-, freq-, and spatial-resolved meas.
- **Transition between electronic states in a DQD**
  - Phonon assisted tunneling
  - *Spin-flip* phonon assisted tunneling
  - Rabi splitting induced by the cavity mode SAW

Dissipation problem in quantum dots

Electronic states in double quantum dot (GaAs)

Charge qubit



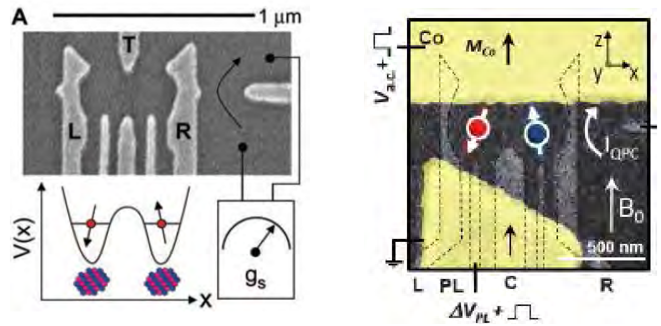
T. Hayashi et al., PRL 91, 226804 (2003).
G. Shinkai et al., PRL 103, 056802 (2009).

T_2^*: charge noise

Sweet spot
Echo technique

T_1: **phonon** scattering

Spin qubit (Pauli spin blockade regime)



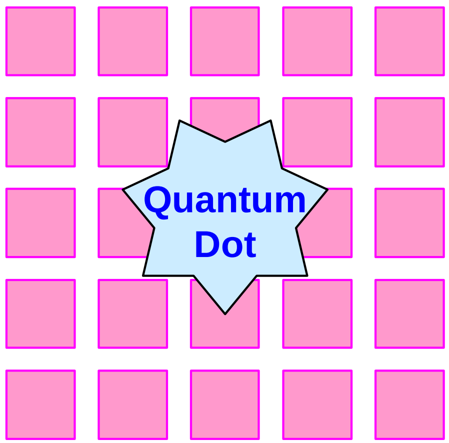
J.R. Petta et al., Science 309, 2180 (2005).
R. Brunner et al., PRL, 107, 146801 (2011).

T_2^*: nuclear spin fluctuation
charge noise (via exchange energy)

Sweet spot, Echo technique
Feedback control

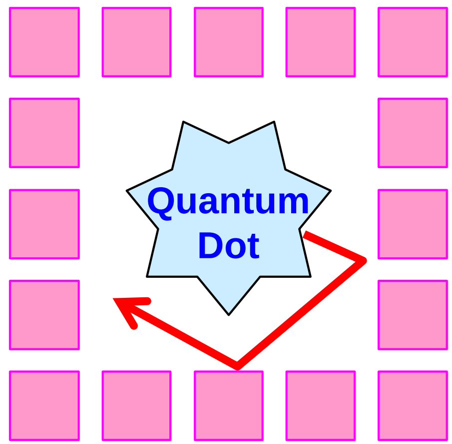
T_1: **phonon** scattering
+ spin-orbit coupling

Phonon environment for quantum dots



No phonon exist.

Suppress dissipation



Confine phonons.

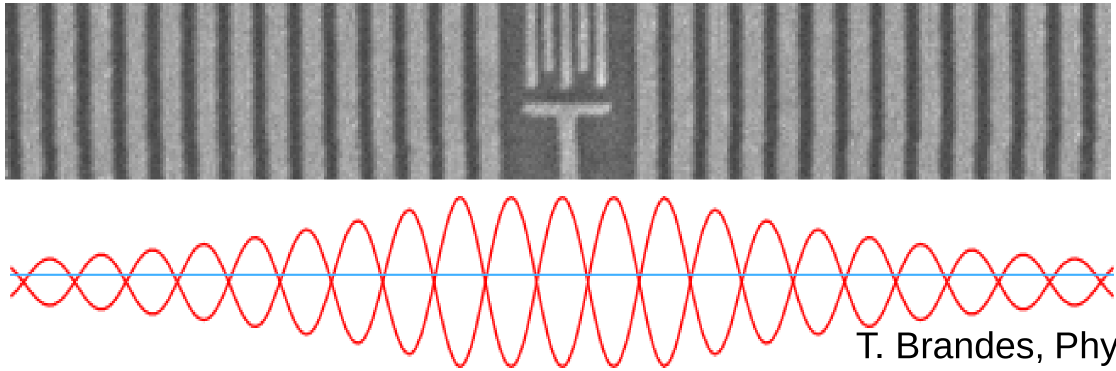
Reuse the lost energy

Acoustic analog of
Cavity Quantum
Electrodynamics (c-QED)

Cavity Quantum Acoustics

DQD in a SAW phonon cavity

Metal gratings work as Bragg reflectors

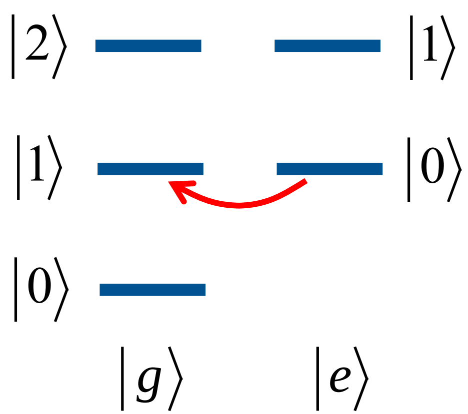


T. Brandes, Phys. Rep 408, 315 (2005).

Some cavity QED effects

Weak coupling

$$g_0 < \kappa, \gamma$$

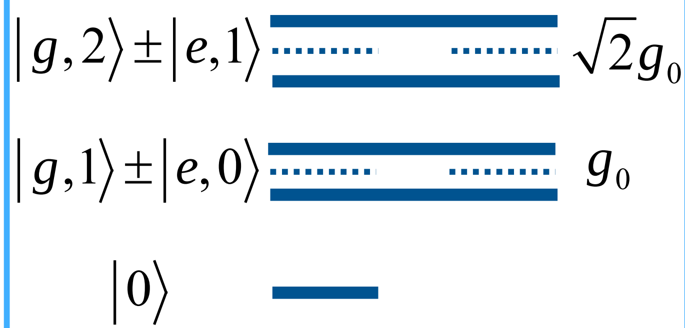


Purcell effect

$$F_P = \frac{3Q\lambda^3}{4\pi^2 V_C}$$

Strong coupling

$$\kappa, \gamma < g_0$$



Vacuum Rabi osc.

$$g_0 = \sqrt{\frac{\mu_{12}^2 \omega}{2\varepsilon_0 \hbar V_C}}$$

Ultra-strong coupling

$$\omega_C \lesssim g_0$$

Breakdown of
rotating frame approx.

Block-Siegert shift

$$0.1 \lesssim \frac{g_0}{\omega_C}$$

T. Niemczyk et al., Nature Phys. 6, 772(2010).
P. Forn-Diaz et al., PRL 105, 237001(2010)

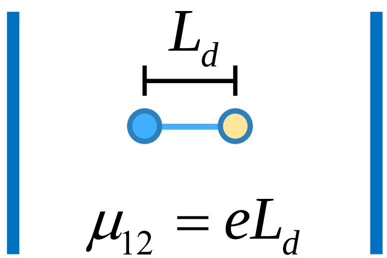
Squeezed vacuum with virtual photons

$$\omega_C \lesssim g_0$$

C. Ciuti et al., PRB 72, 115303(2005).
J. Casanova et.al, PRL 105, 263603 (2010).

c-QED limited by α (fine structure const.)

Conventional cavity-QED (atom – light interaction)



Normalized coupling constant

$$\frac{g_0}{\omega} = \sqrt{\frac{e^2}{4\pi\varepsilon_0\hbar c}\frac{L_d^2\lambda}{V_C}} = \sqrt{\alpha}\sqrt{\frac{L_d^2\lambda}{V_C}} << \sqrt{\alpha} \sim \sqrt{\frac{1}{137}}$$

3D cavity, small atom

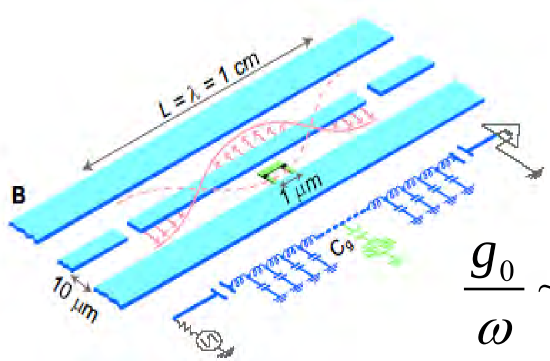
$$V_C >> \lambda^3, L_d << \lambda$$

α: the fine structure constant

Circuit-QED (qubit – microwave interaction)

Coplaner waveguide (1D cavity)

$$V_C \sim L_d^2\lambda$$

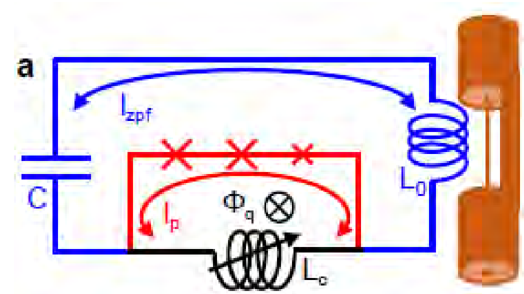


$$\frac{g_0}{\omega} \sim \sqrt{\alpha} \sim \sqrt{\frac{1}{137}} \sim 0.1$$

S. M. Girvin et al., cond-mat/0310670(2003)
A. Wallraff et al., Nature 431, 162 (2004)
M. Devoret et al., Ann. Phys. 16, 767(2007).

LC resonator (0D cavity)

V_C (independent of λ)

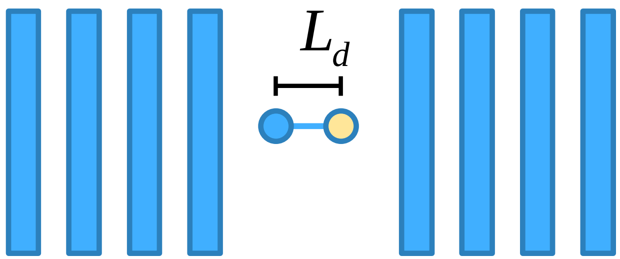


$$\frac{g_0}{\omega} \sim 1$$

F. Yoshihara et al., arXiv:1602.00415.

Acoustic cavity QED

Charge qubit – Surface Acoustic Wave (SAW) phonon



$$\mu_{12} = eL_d$$

3D phonon cavity:

$$V_C \gtrsim \lambda_{SAW}^3 << \lambda_{EM}^3$$

Small mode volume

Small electromechanical coupling constant

$$K^2$$

$$\frac{\text{Electric field energy}}{\text{Total energy (elastic+kinetic)}}$$

Normalized coupling constant

$$\frac{g_0}{\omega} = \sqrt{\frac{K^2 e^2}{4\pi\varepsilon_{GaAs}\hbar v_{SAW}} \frac{L_d^2 \lambda_{SAW}}{V_C}} = \sqrt{\alpha_{SAW}} \sqrt{\frac{L_d^2 \lambda_{SAW}}{V_C}} < \sqrt{\alpha_{SAW}} \sim \sqrt{\frac{1}{13}} \sim 0.28 \quad \text{(GaAs)}$$

α_{SAW} : effective fine structure const for SAW cavity

v_{SAW} : SAW velocity (3×10^3 m/s $<< c = 3\times10^8$ m/s)

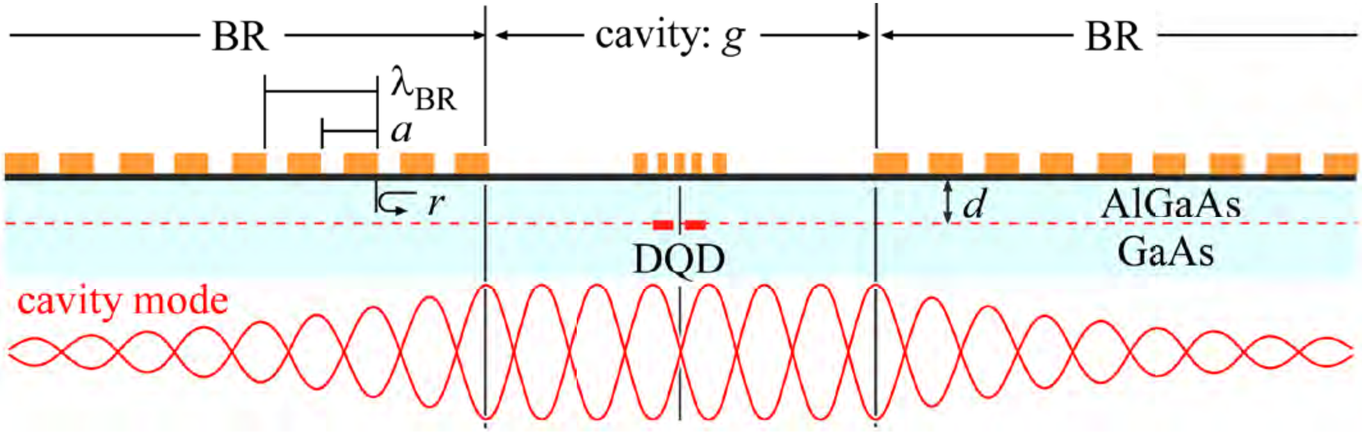
K^2 : electromechanical coupling const. (7×10^{-4} for GaAs SAW)

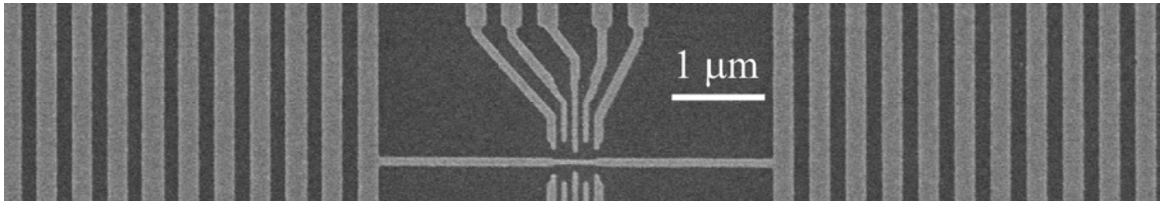
a few % for ZnO SAW

ε_{GaAs} : dielectric const. ($12.5\varepsilon_0$ for GaAs)

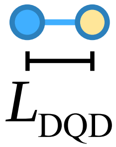
J.C.H. Chen et al., Sci. Rep. 5, 15176 (2015).

DQD in a SAW phonon cavity





$r \sim 1\%$,
$\lambda_{BR} = 800$ nm



$L_{DQD} \sim 240$ nm,
$\lambda_{BR}/2 = 400$ nm

Two-level systems in a DQD
(charge or spin qubit)

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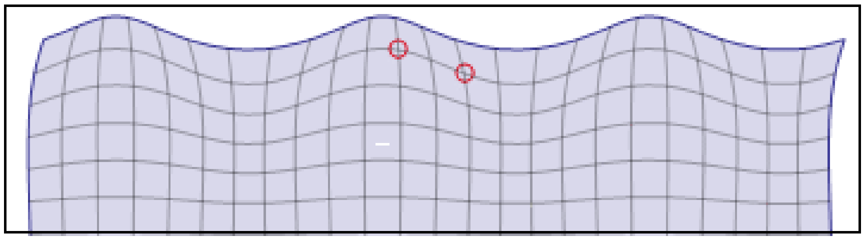
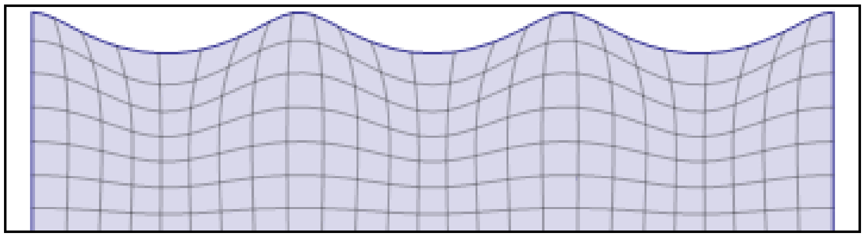
Surface acoustic wave (SAW)

Travelling wave

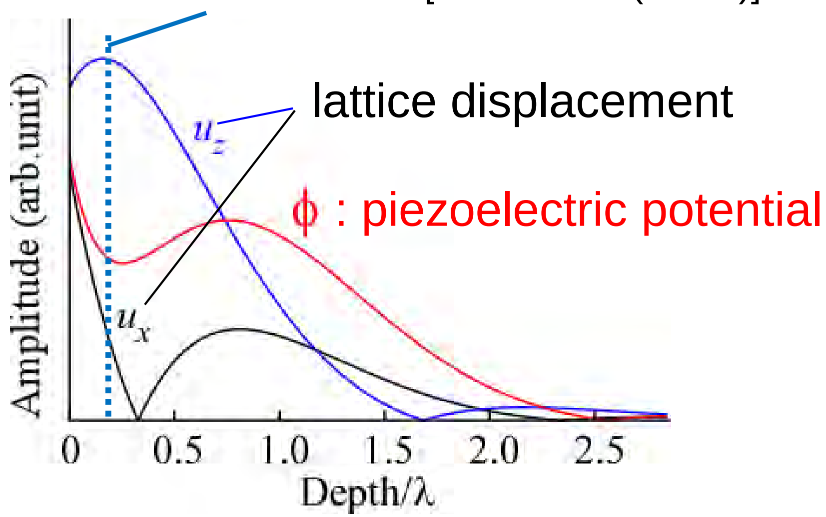


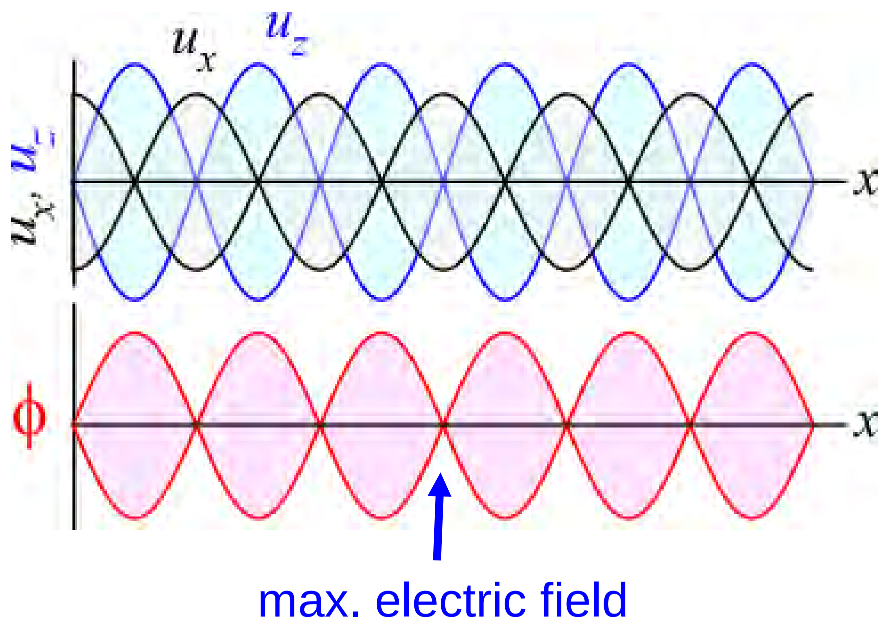
Standing wave



Typical 2DEG (DQD)

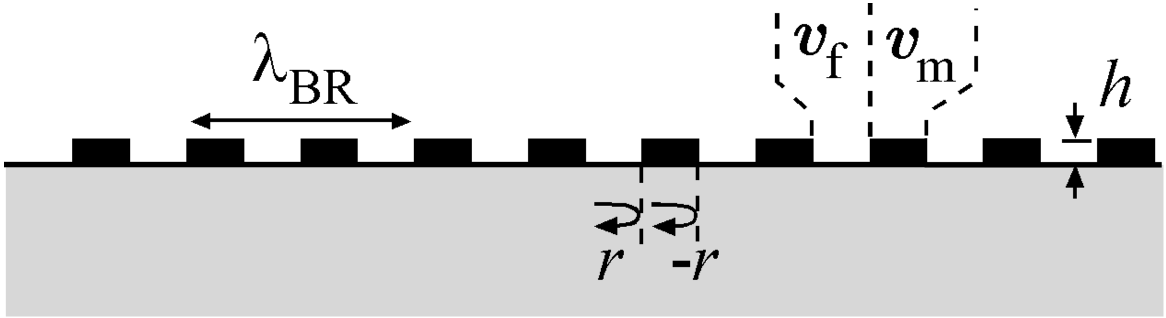
100 nm from surface [λ = 800 nm (3GHz)]





S. H. Simon, Phys Rev B **54**, 13878 (1996).

Phonon bandgap in a Bragg reflector (BR)



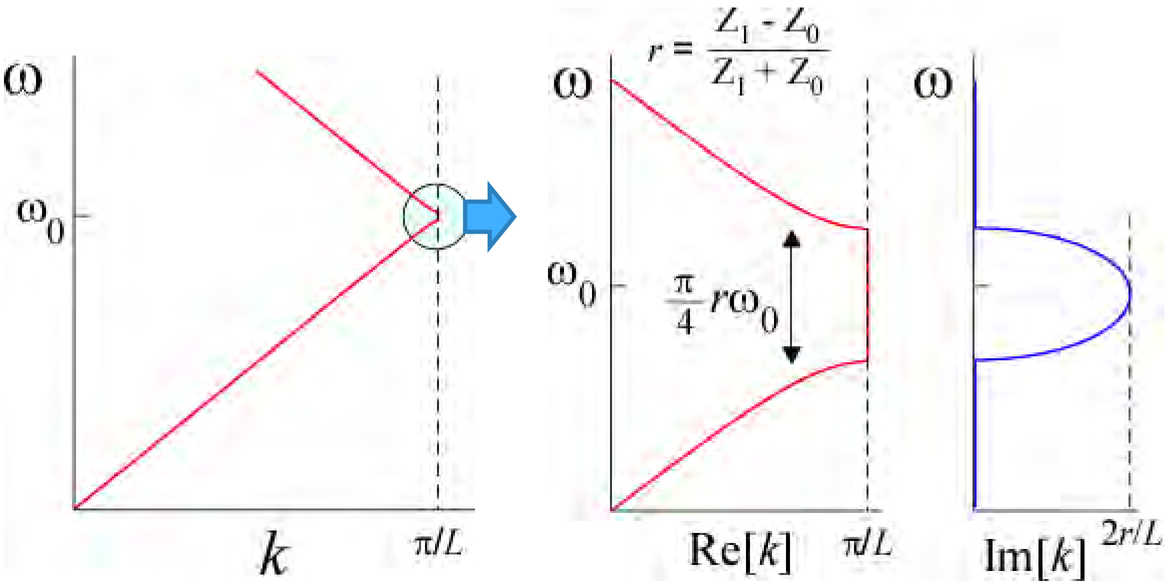
Reflection coefficient

r ~ few %
(Au/GaAs)

$$r = P_z \frac{K^2}{4} + F_z \frac{h}{2\lambda} \simeq F_z \frac{h}{2\lambda}$$

$$\frac{v_m - v_f}{v_f} = P_v \frac{K^2}{2} + F_v \frac{h}{\lambda} \simeq F_v \frac{h}{\lambda}$$

SAW dispersion in a Bragg reflector (BR)

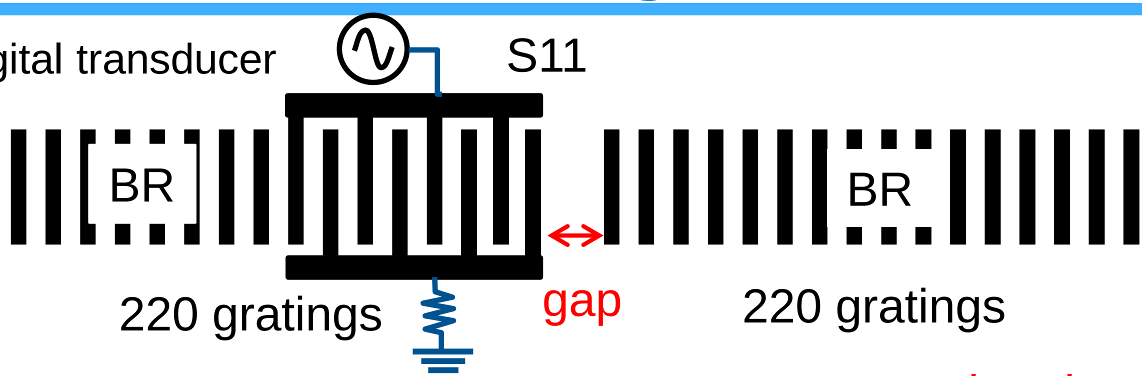


Material parameters

$$K^2, P_v, P_z, F_v, F_z$$

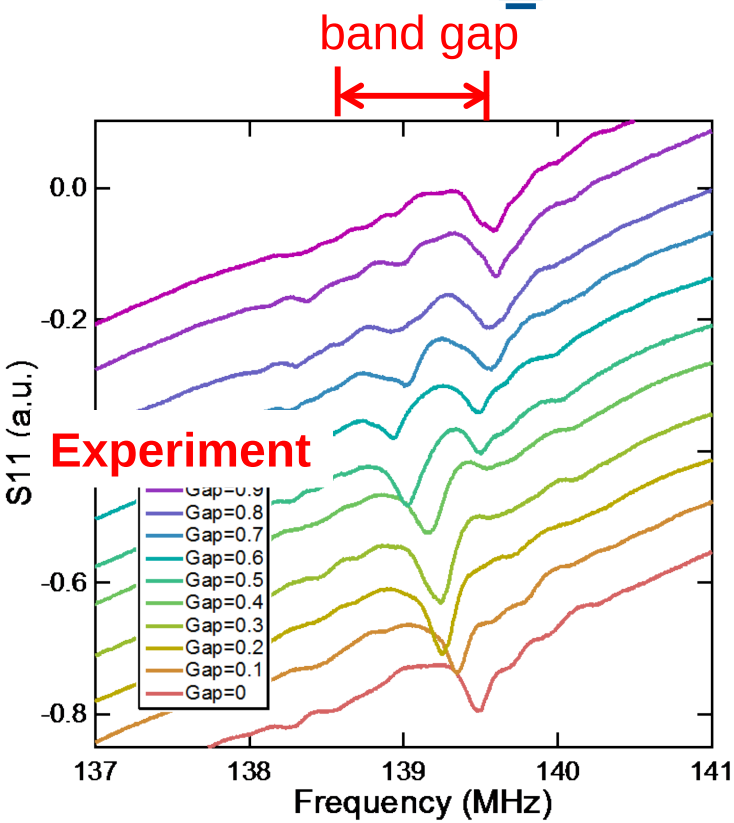
Supriyo Datta,
Surface Acoustic Wave Devices,
Prentice-Hall, 1986

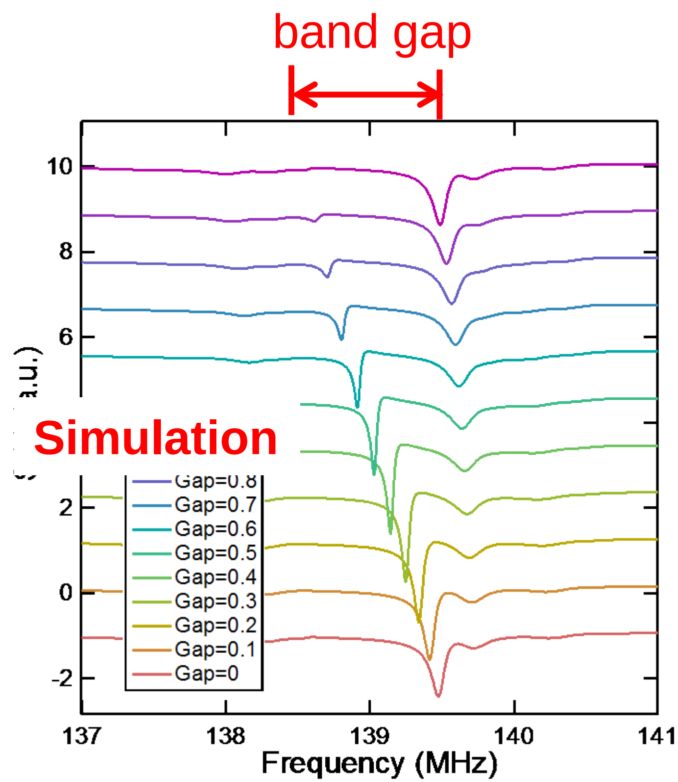
SAW cavity: Ti/Au on GaAs



metal: Ti/Au
(240 nm thick)

Wavelength: 20 um





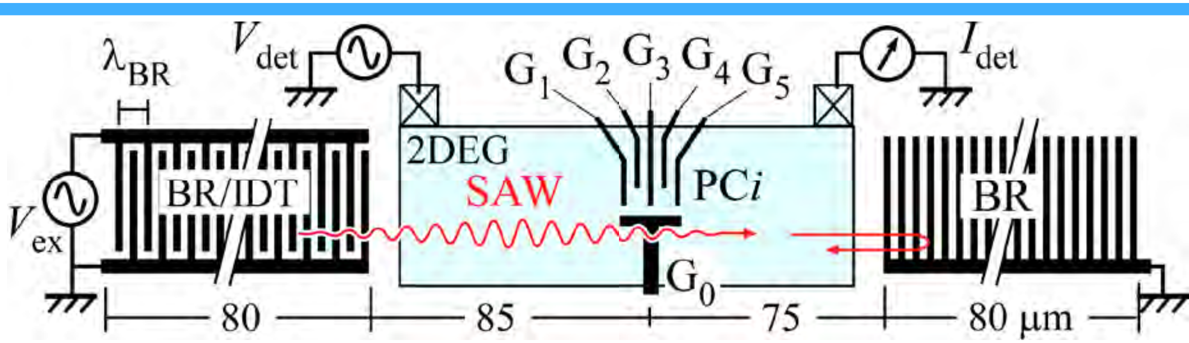
$$r = \beta \frac{h}{\lambda}$$

β = 0.34 (Ti/Au)

1D COM analysis

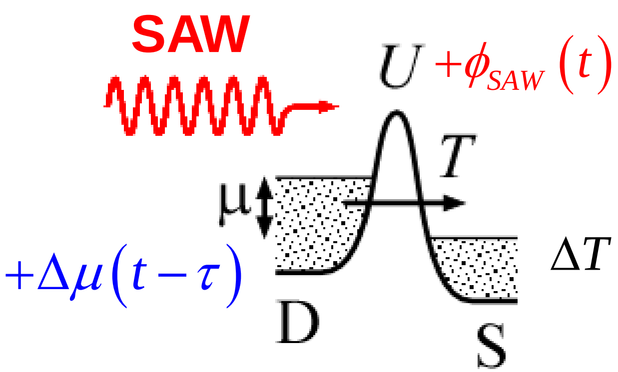
R. Kosaka et al. (unpublished)

Time-resolved piezo-potential meas.



Ti/Au
λ = 0.8 um

QPC detector (tunneling regime)



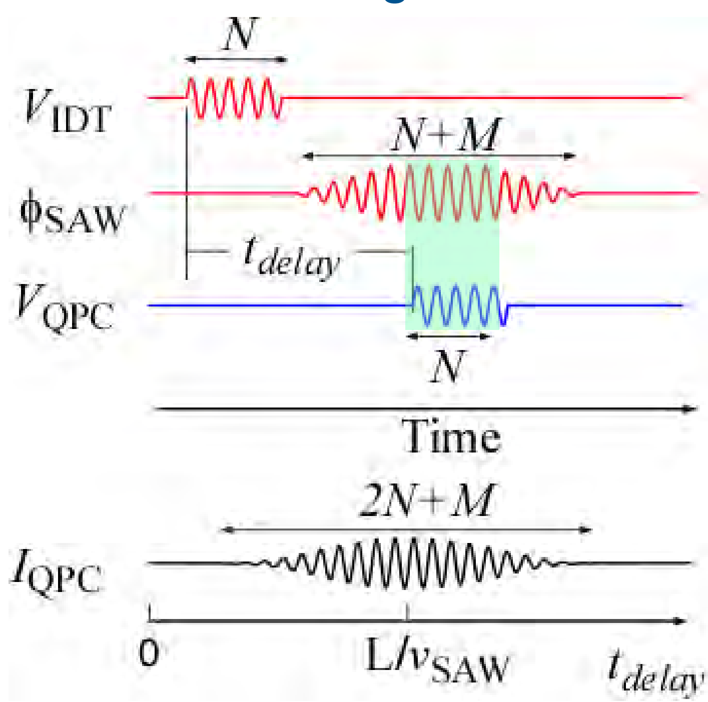
$$\Delta T(t) \propto \phi_{SAW}(t)$$

Detection current (DC)

$$\Delta I(\tau) \propto \frac{1}{T}\int \Delta\mu(t-\tau)\,\phi_{SAW}(t)\,dt$$

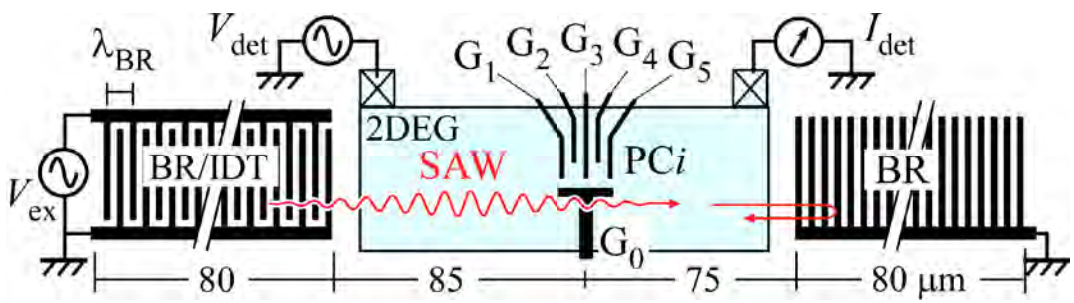
H. Kamata et al., Japan. J. Appl. Phys. 48, 04C149 (2009).
T. Fujisawa et al., AIP Conf. Proc. 1399, 269 (2011).

Timing chart

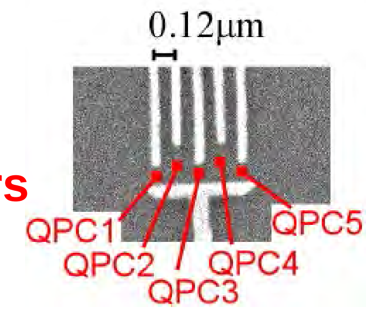


N (= 50) cycles on ***M*** (= 100) pair IDT

SAW packet bouncing between BRs



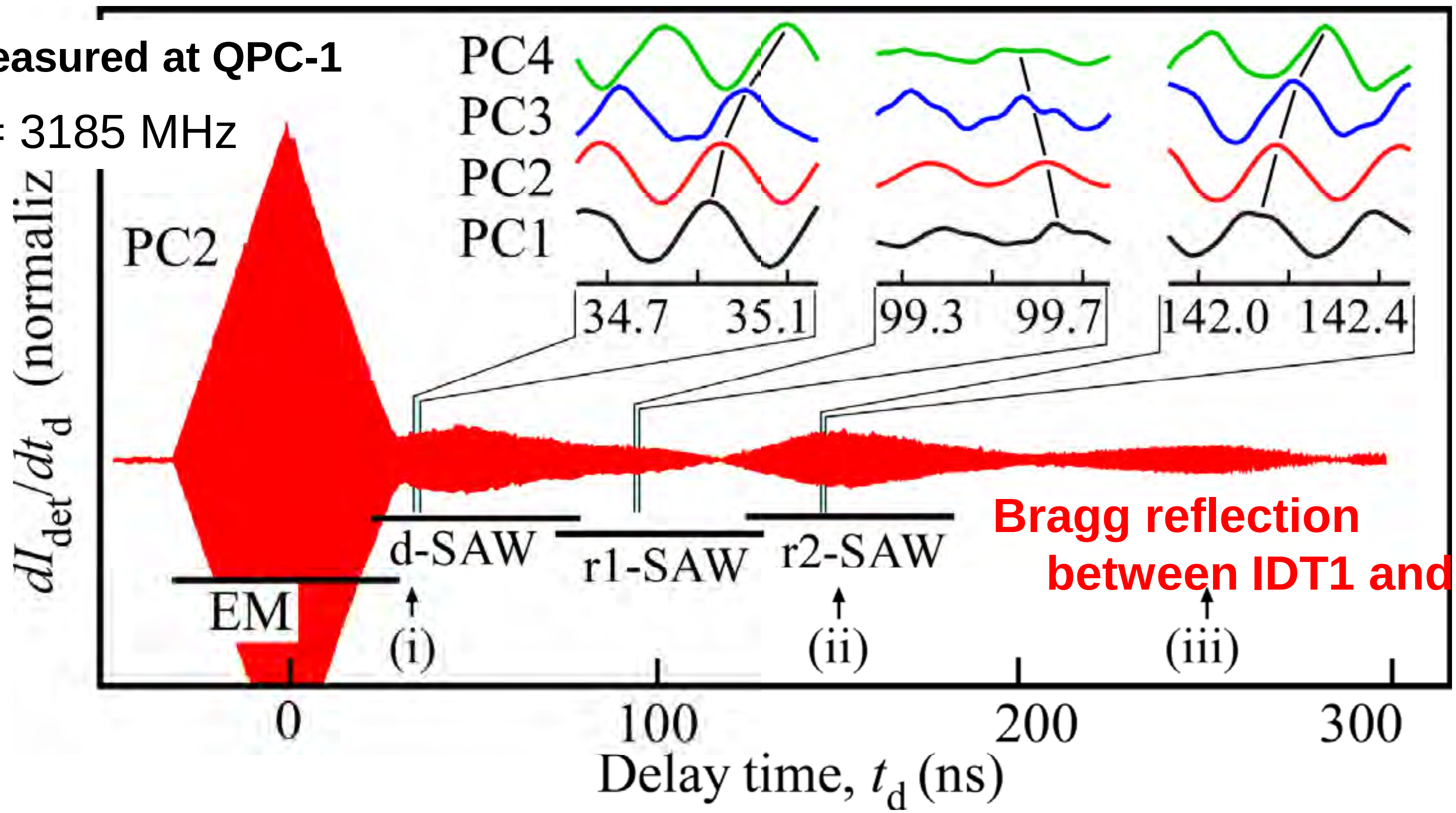
QPC detectors



(in ~λ/8 step)

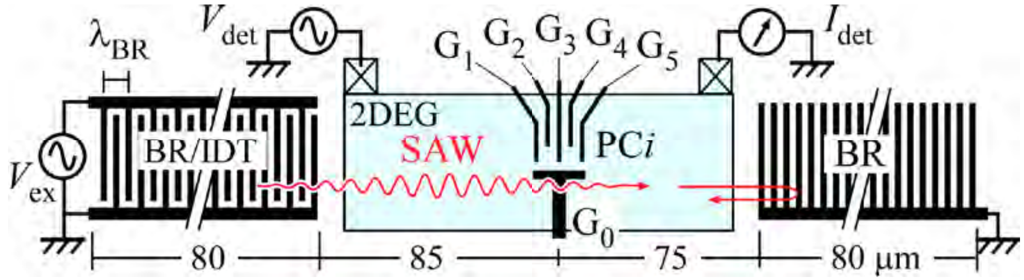
Measured at QPC-1

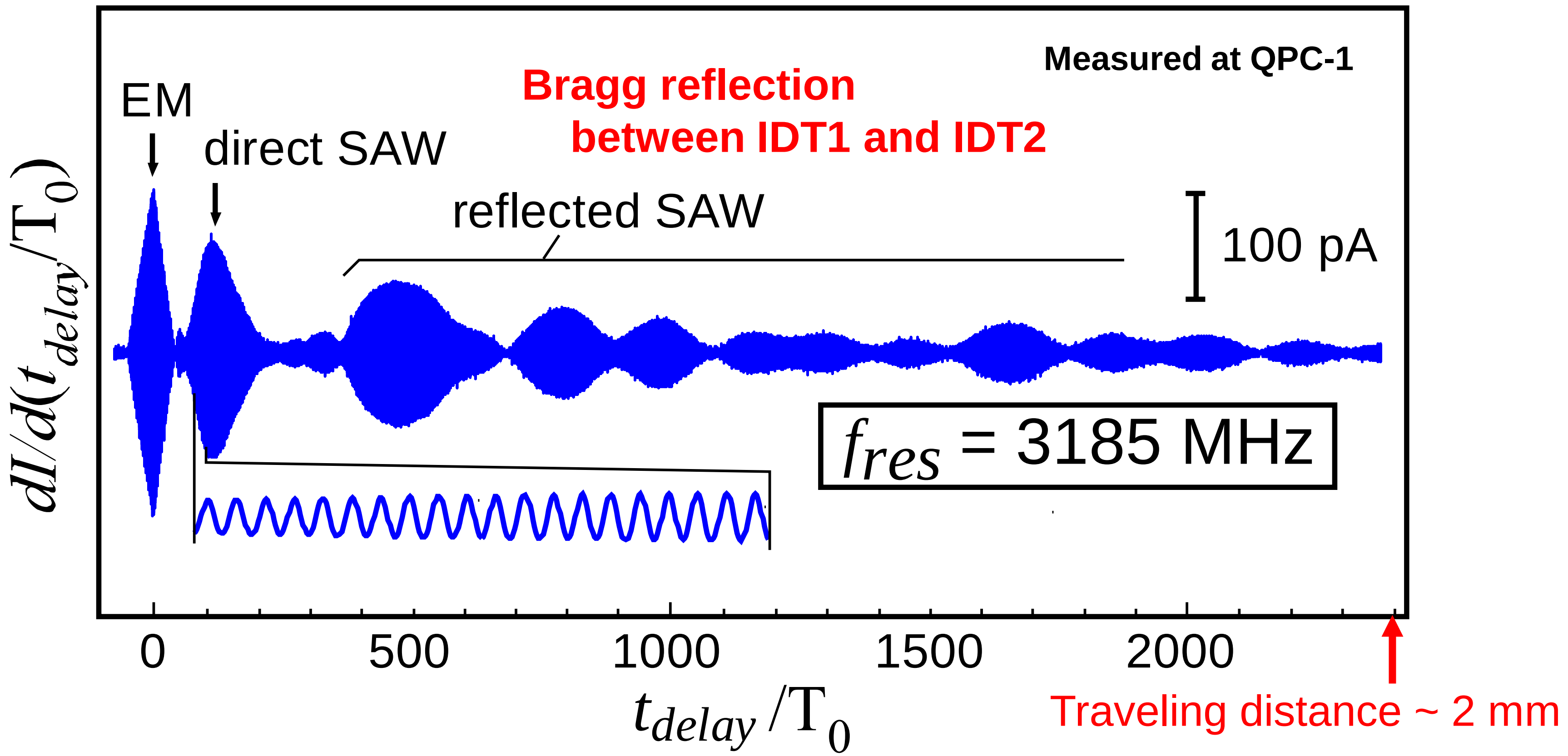
f = 3185 MHz



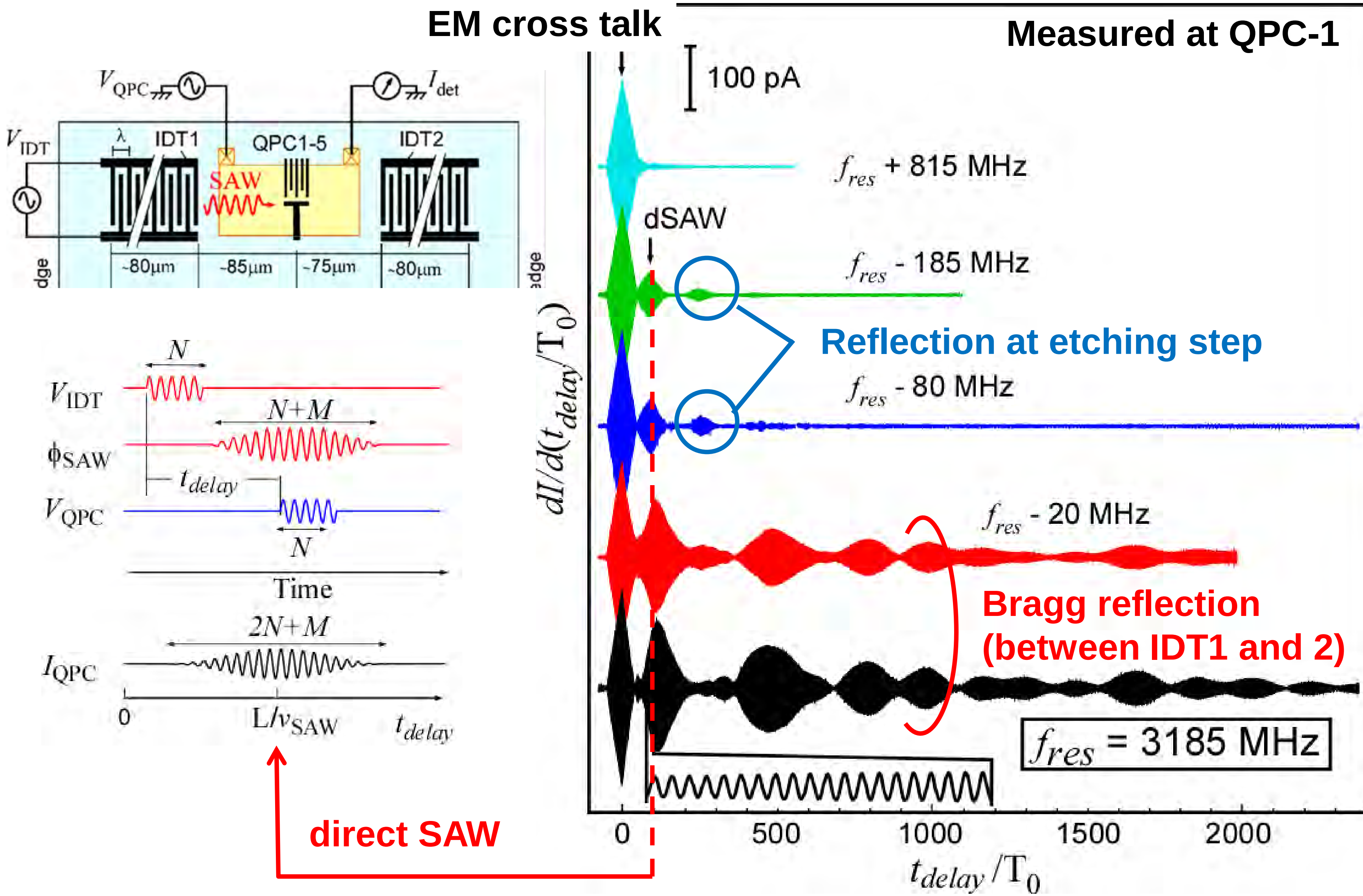
Bragg reflection between IDT1 and IDT2

SAW packet bouncing between BRs

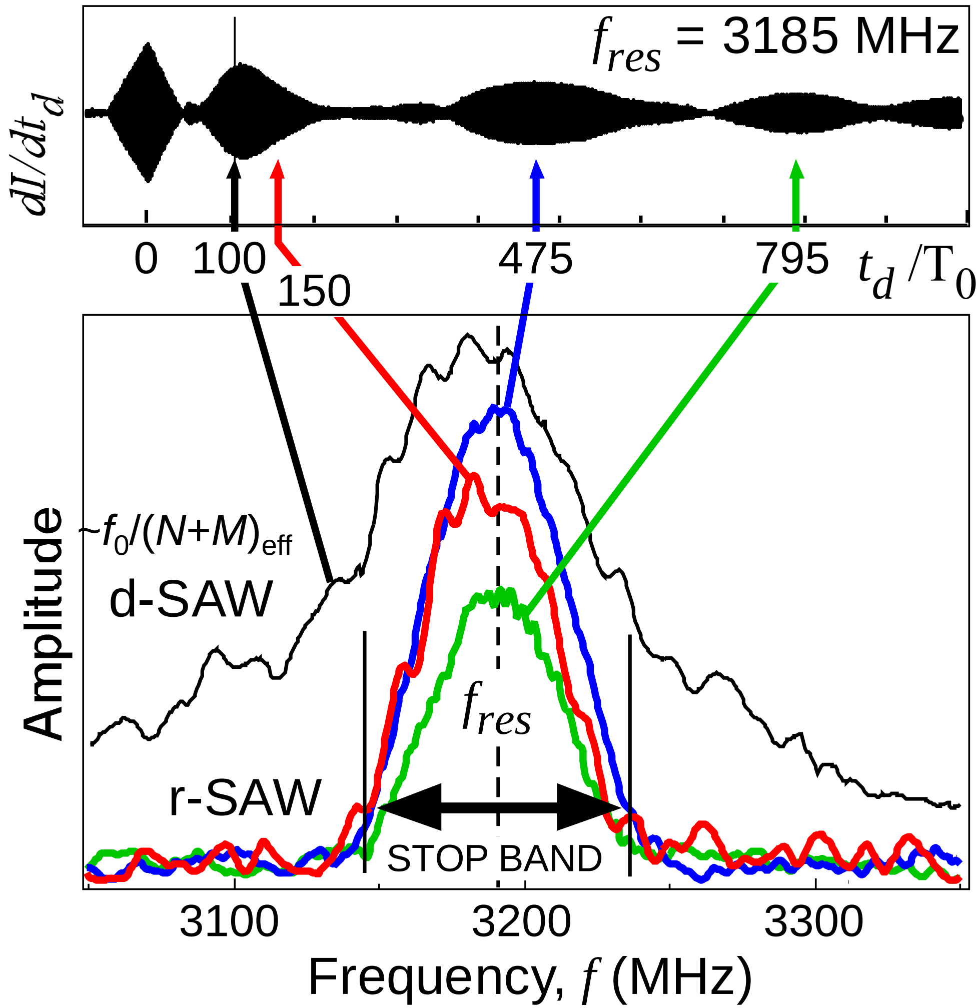




Piezoelectric potential wave

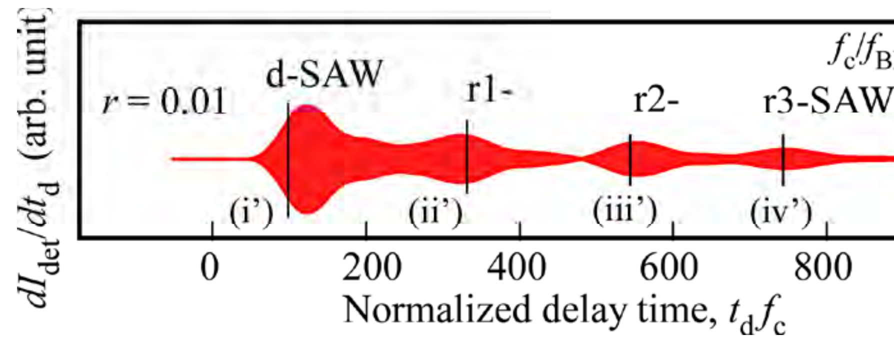


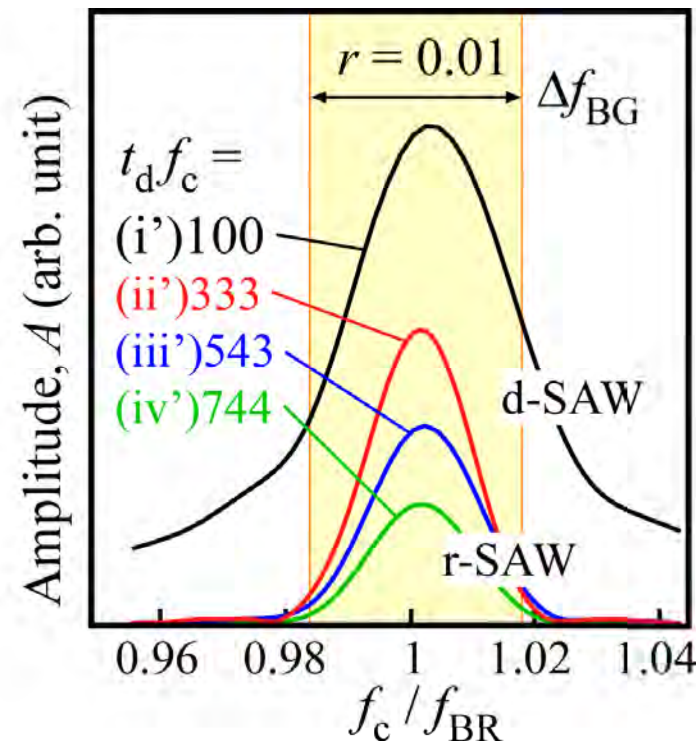
Bragg reflection spectrum : Band gap in the IDT



Numerical Simulation

(1D mode-coupling theory)

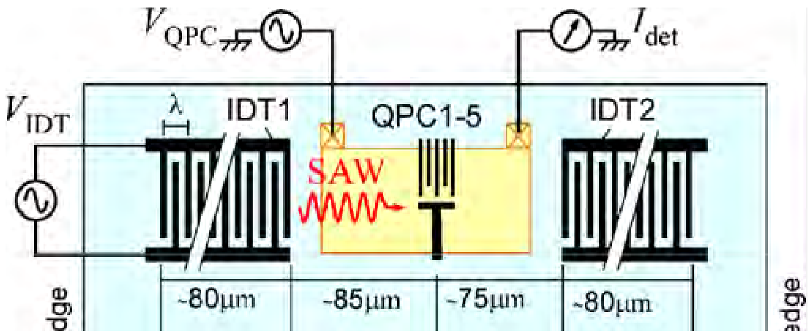


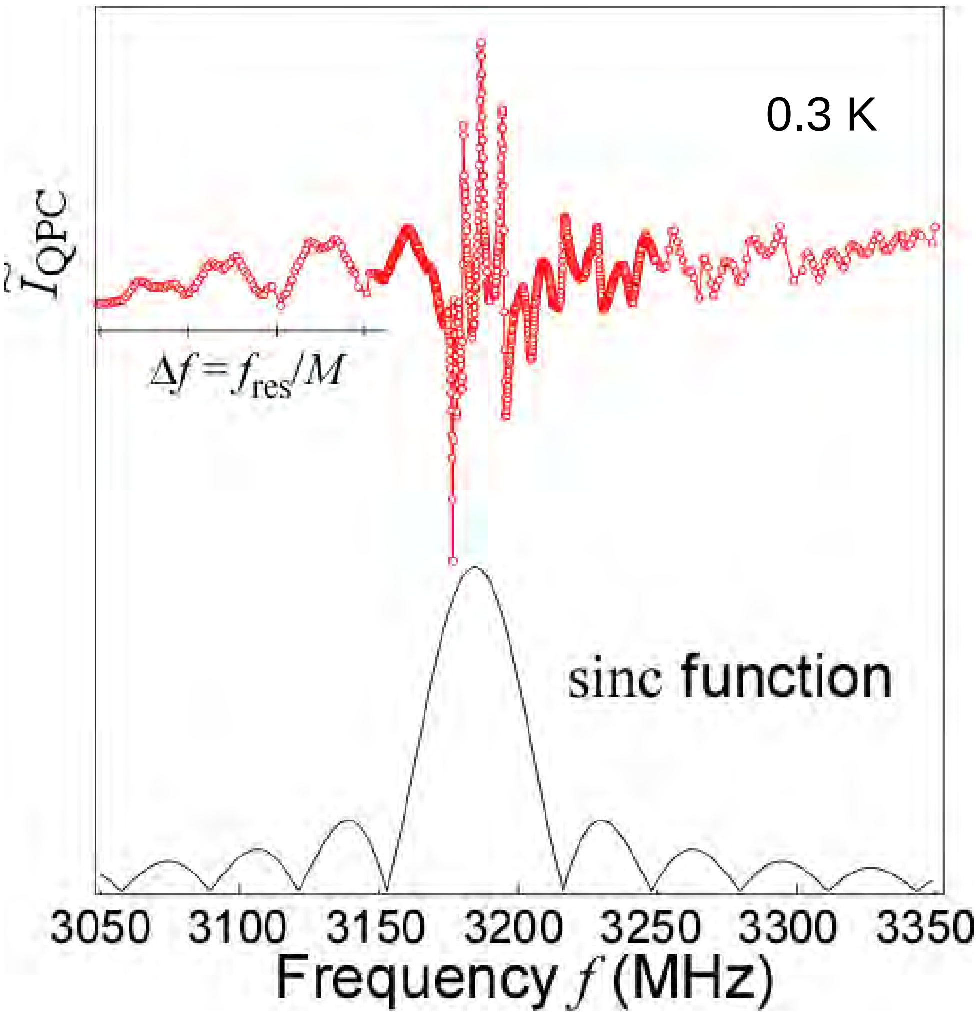


Phonon band gap : $\Delta f / f_0 \sim 3.5\%$

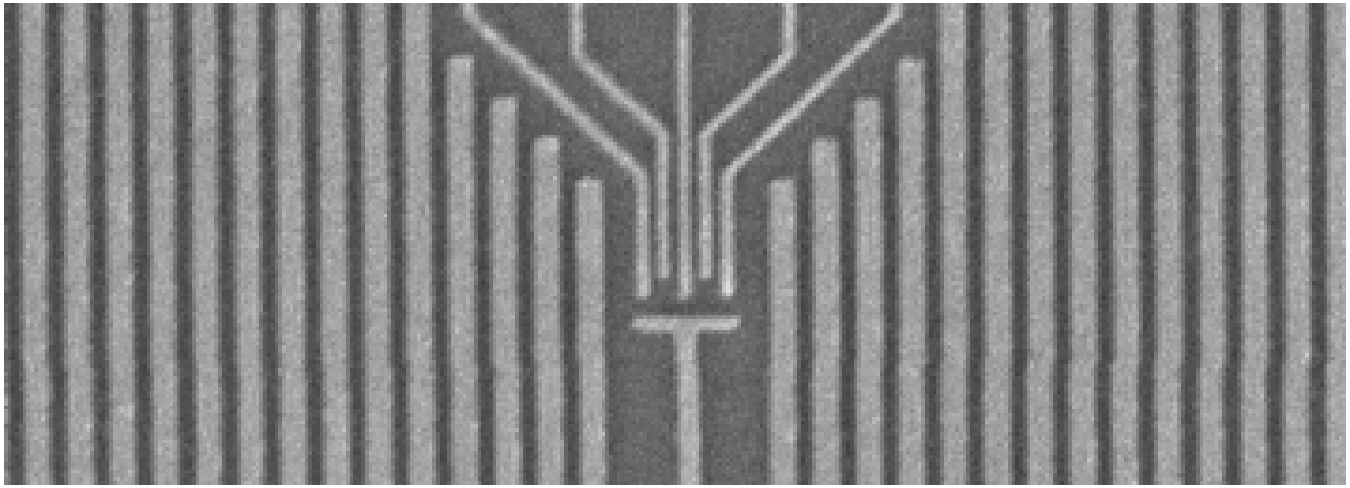
Multiple cavity modes

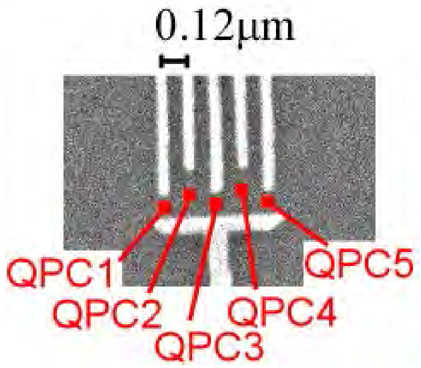
Frequency spectrum
obtained by continuous wave (CW)





Single-mode SAW cavity

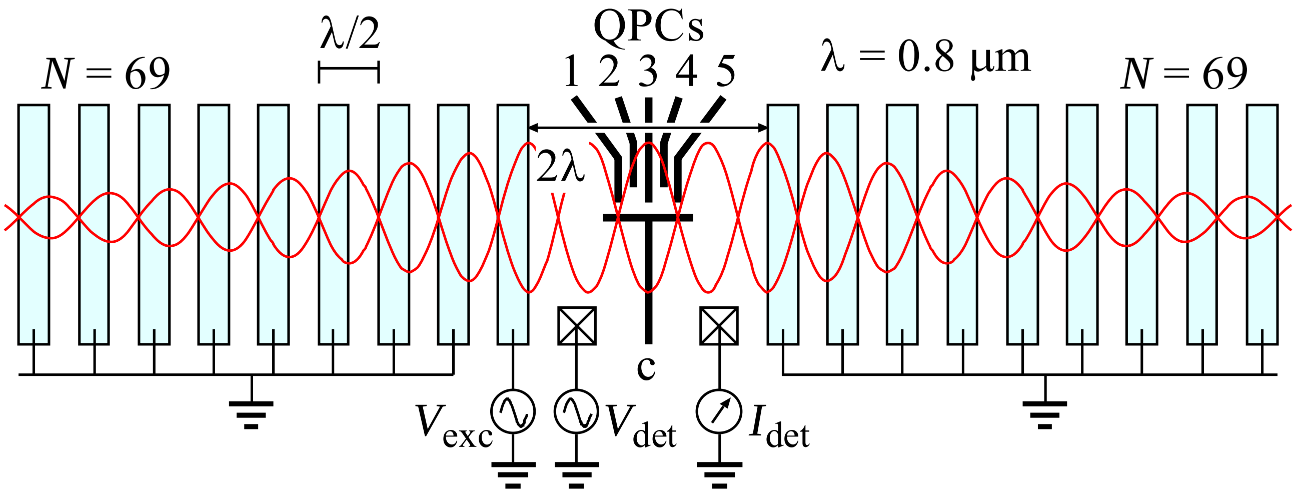




(in ~λ/8 step)

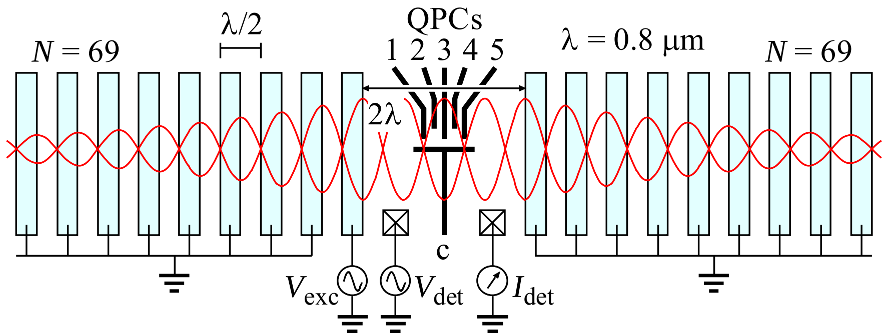
- Narrow gap for a single cavity mode
- Only one excitation electrode

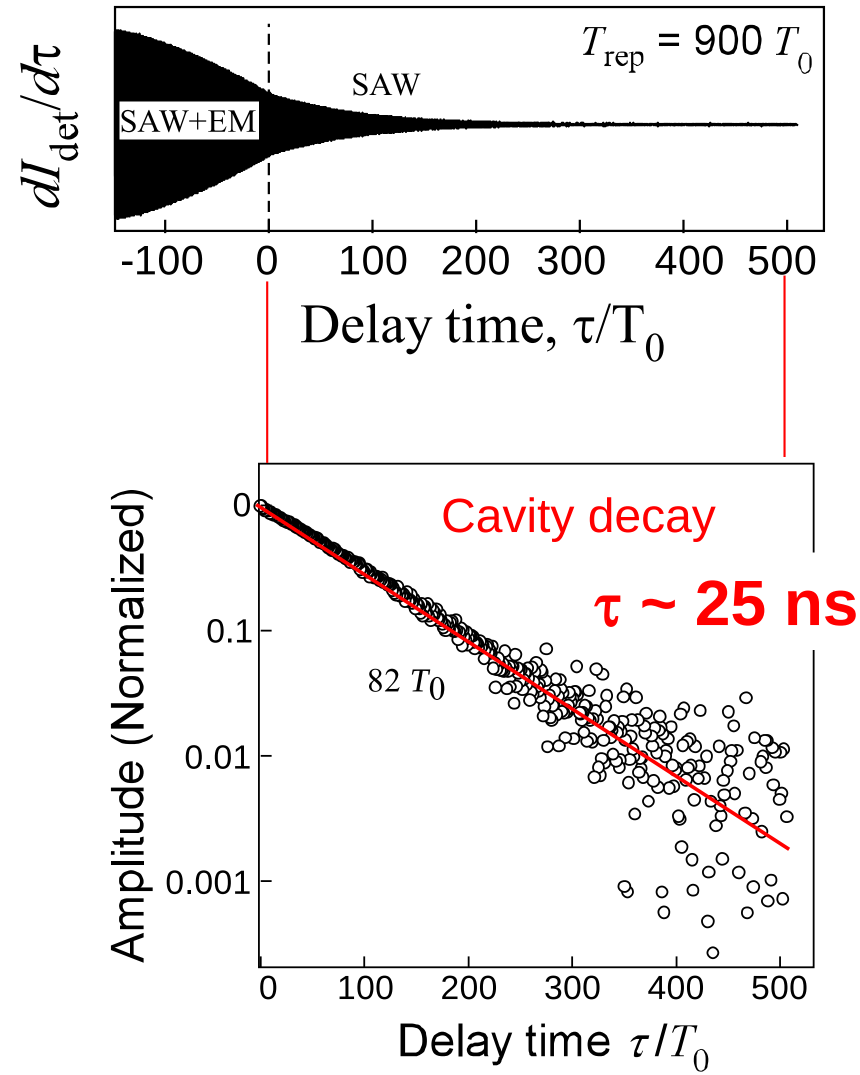
Ti/Au: 40 nm
λ = 0.8 um

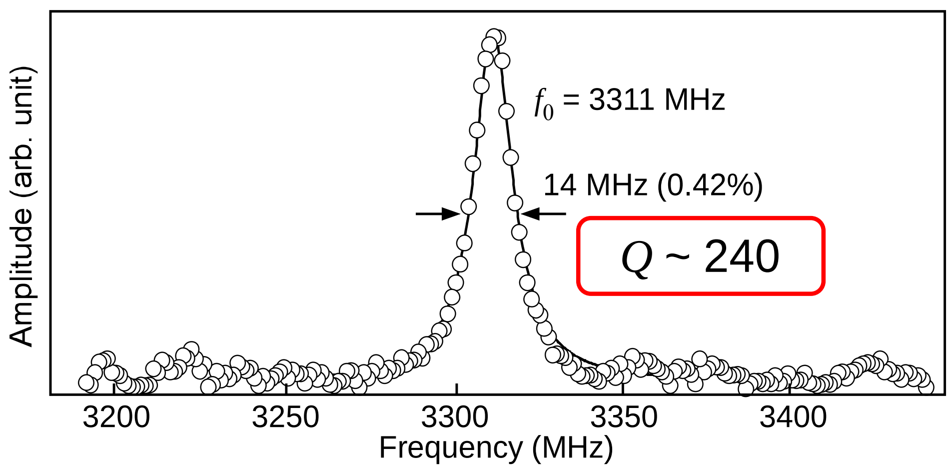


Single-mode SAW cavity

Resonant freq. f_0 = 3.311 GHz

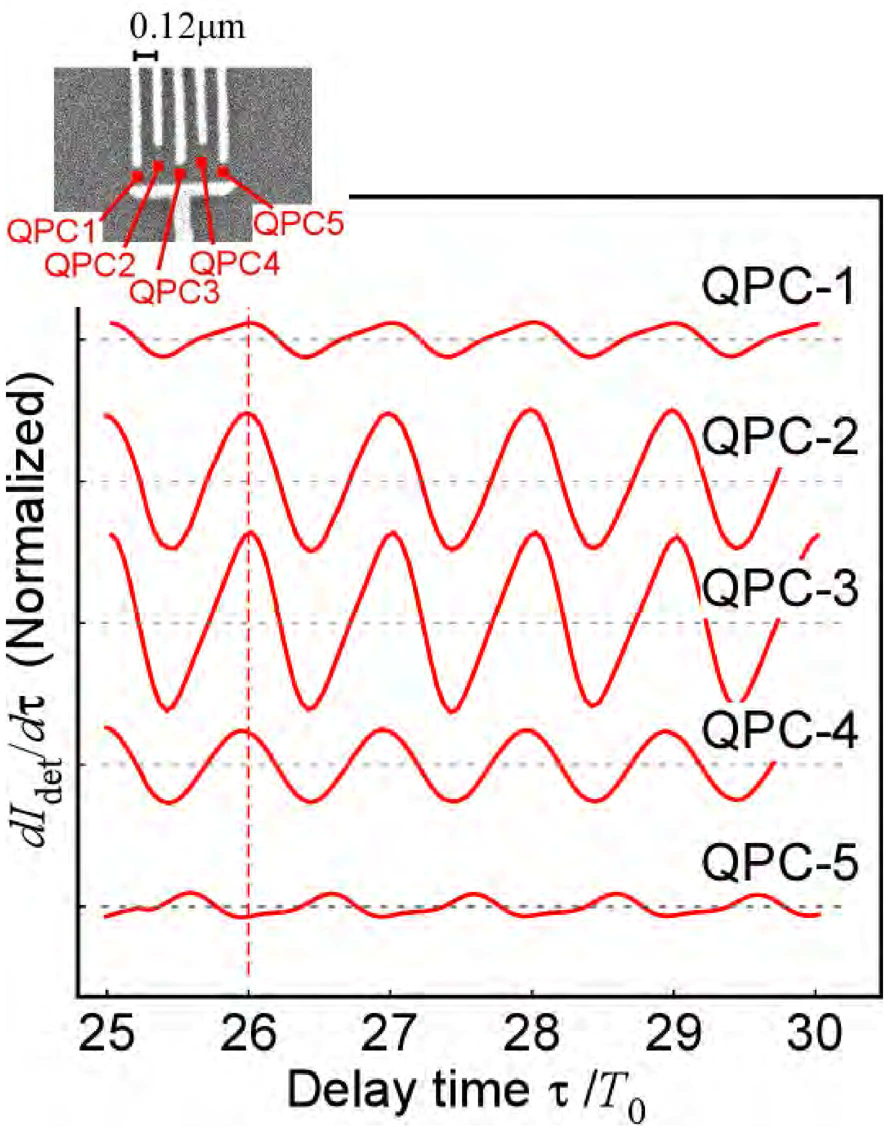






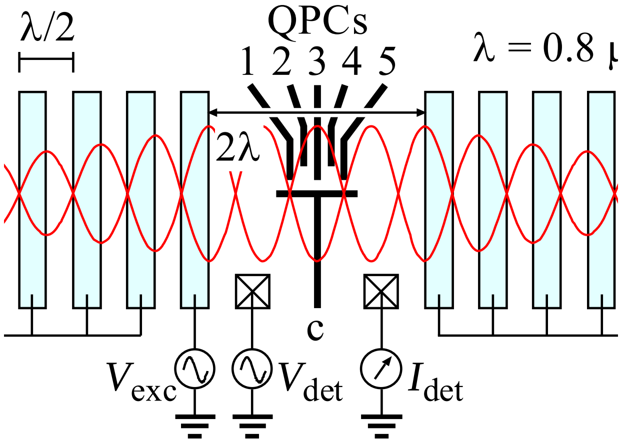
Band gap (~3.5%)

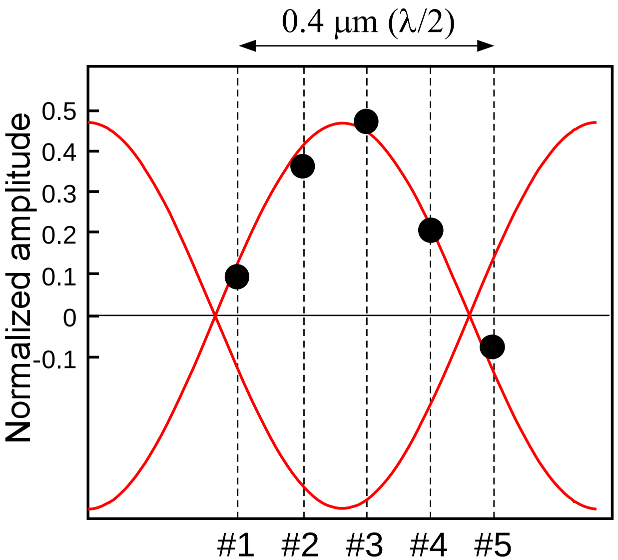
Spatial distribution



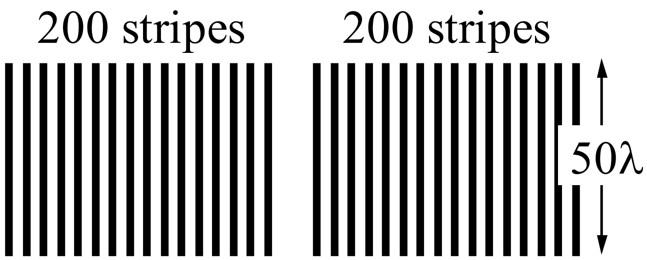
The signal is normalized by the crosstalk.

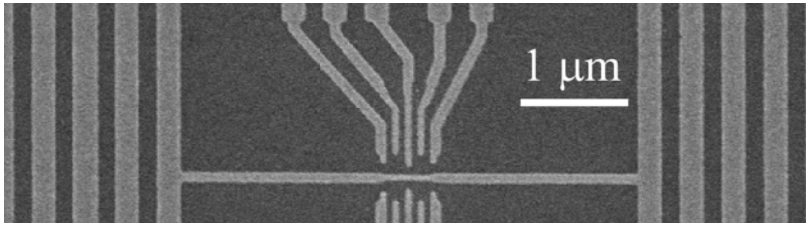
Standing wave

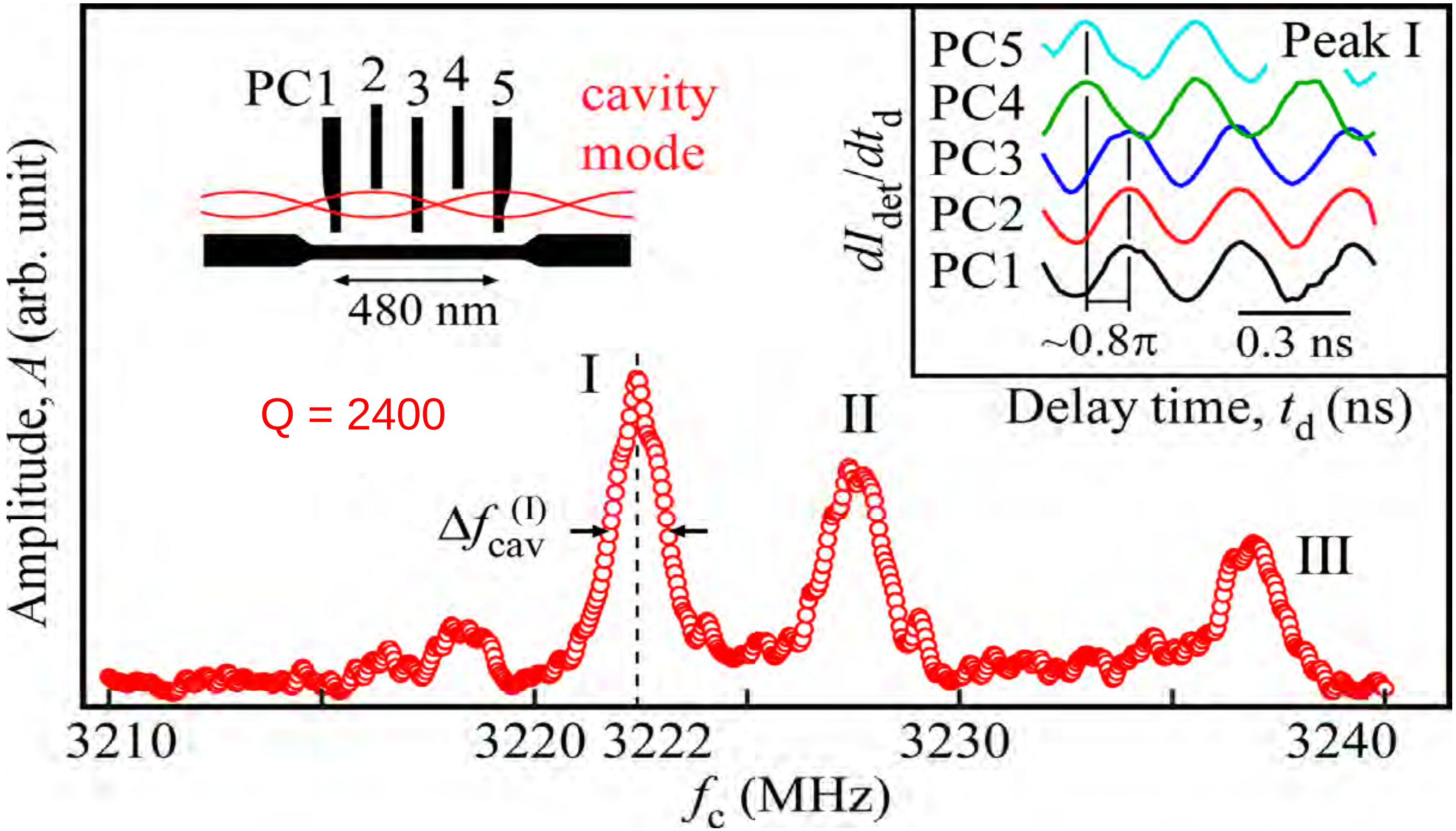




SAW Cavity spectra







Cavity finesse: F

Phonon bandgap: $\Delta f_{\mathrm{BR}} / f_0 \sim 3.5\%$

Cavity resonant width: $\Delta f_{\mathrm{cav}} / f_0 \sim 0.042\%$

Q value: $Q = 2400$

Finesse: $F = \Delta f_{\mathrm{BR}} / \Delta f_{\mathrm{cav}} \sim$ **80**

Resonant frequency: $f_0 = 3222.5$ MHz

Phonon energy: $hf_0 = 13\ \mu\mathrm{eV}$

Phonon number (thermal): $n = 0.0005$ (20mK) $\sim$ 0.05 (50mK)

in a dilution refrigerator

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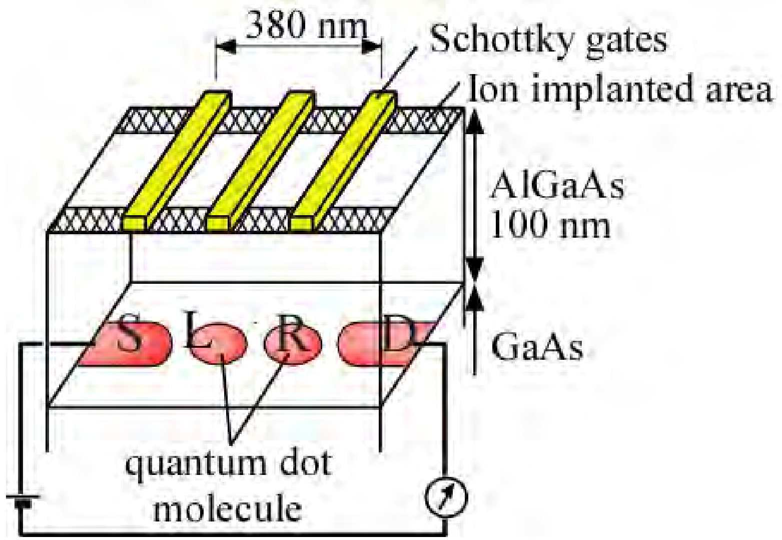
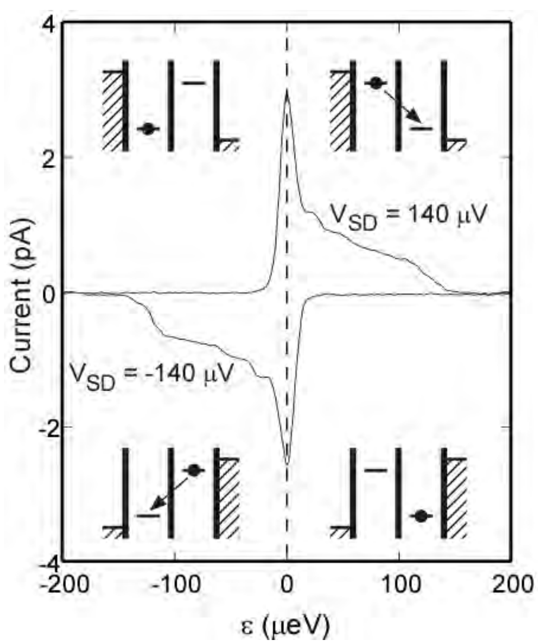
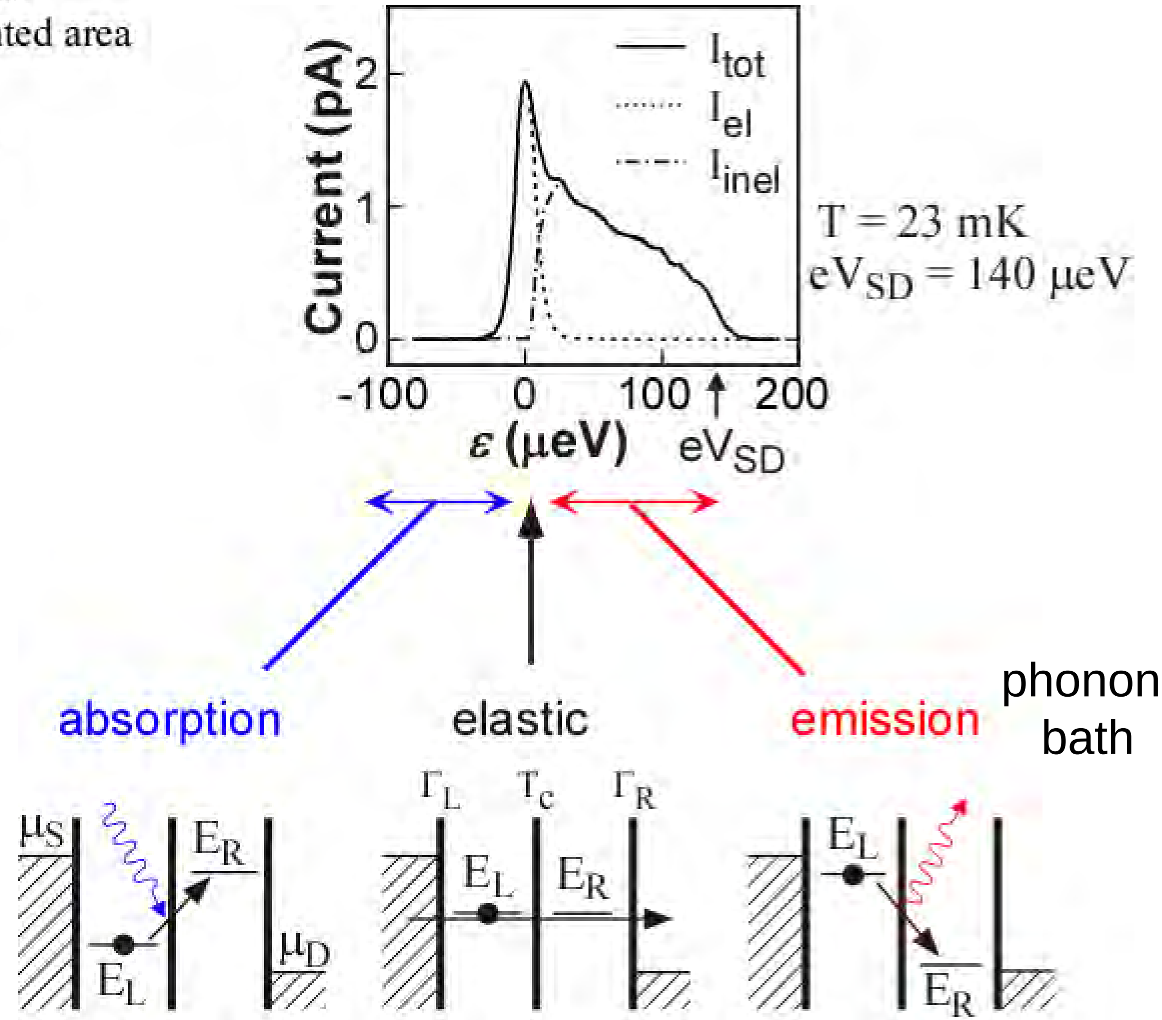
Inelastic tunneling spectroscopy in a DQD

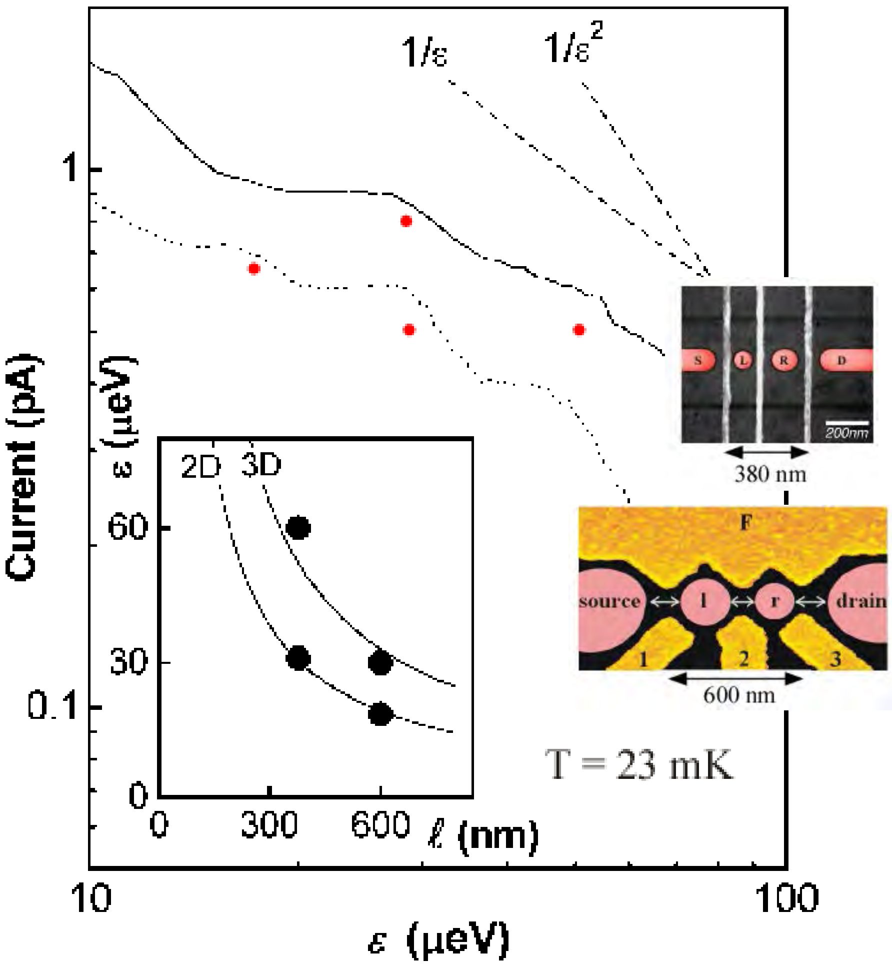






T. Fujisawa, et al., Science 282, 932 (1998).

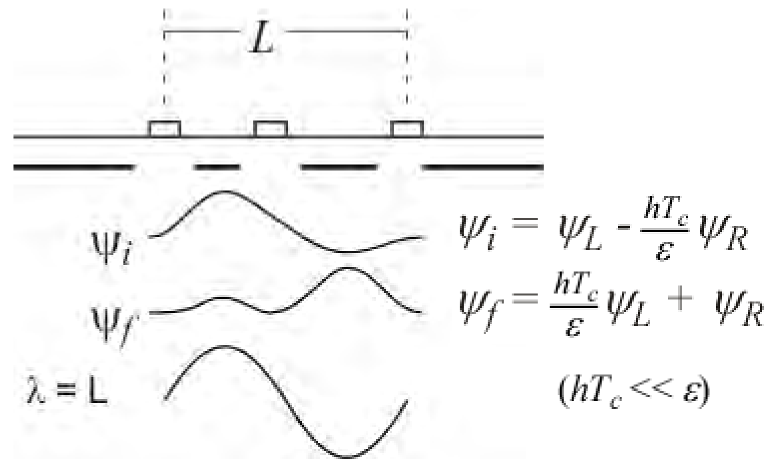
Phonon resonance

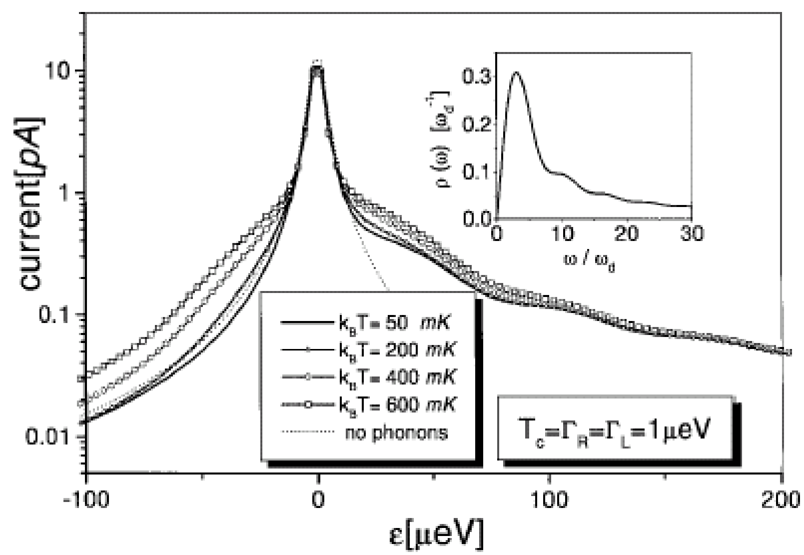


$\ell = \lambda = hs/\varepsilon$

s^{3D} = 4800 m/s (bulk phonon)

s^{2D} = 2800 m/s (2D SAW phonon)





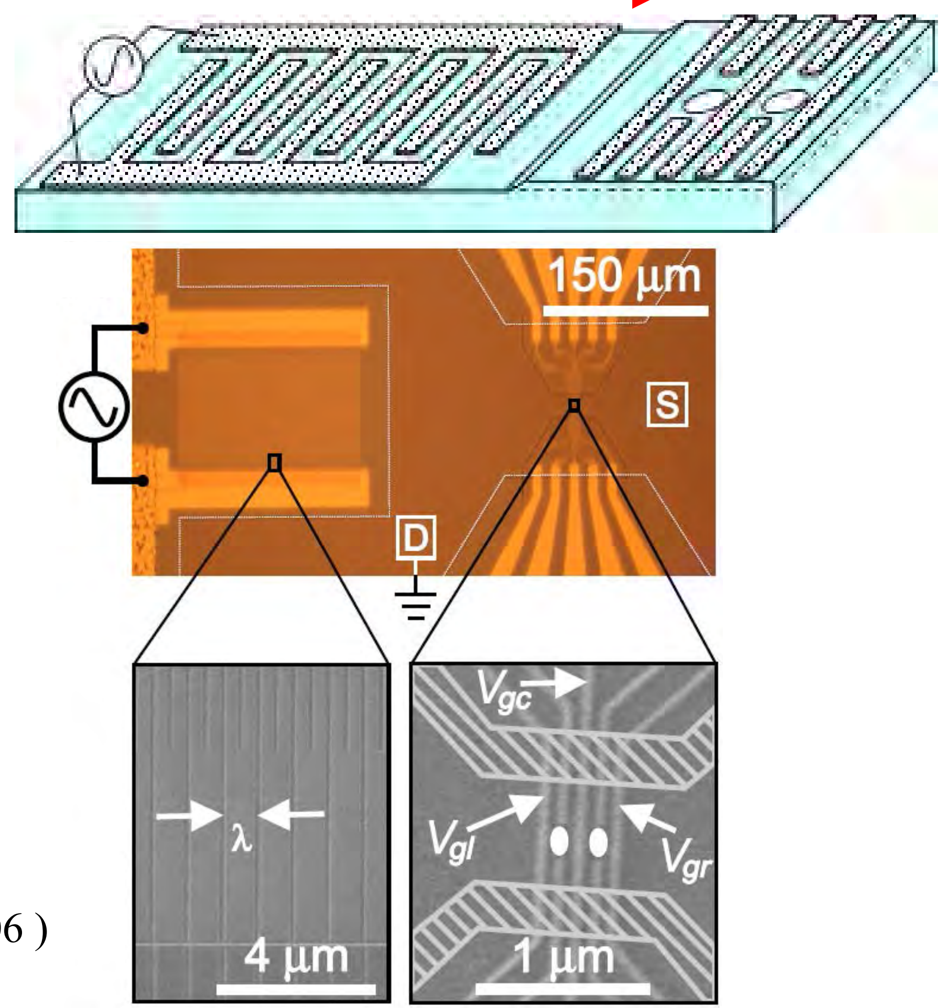
T. Brandes et al., PRL 83, 3021 (1999).

IDT + SAW device

Inter-digital transducer (IDT)

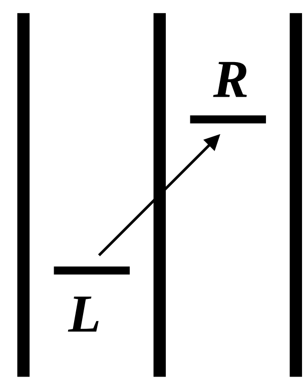
SAW →

Double quantum dot (DQD)



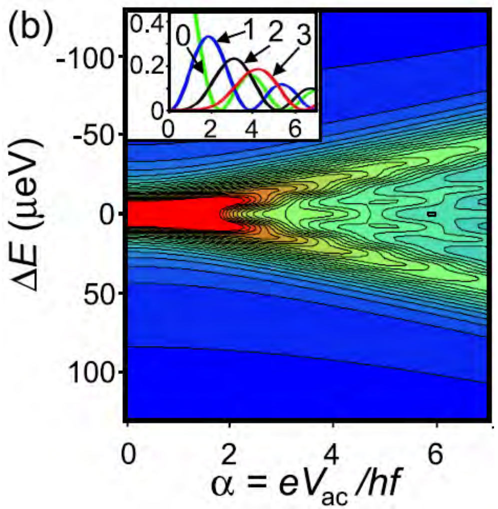
f = 2GHz
hf = 8 μeV
@ λ = 1 μm

E_C ~ 2 meV
Δ ~ 200 μeV
@ D = 0.1 μm

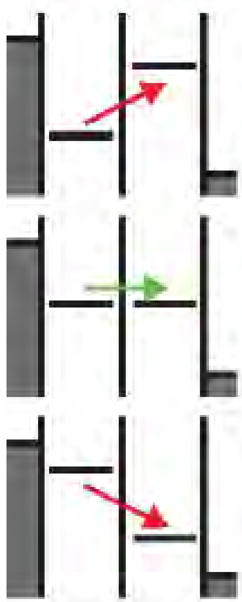


W.J.M.Naber et al. ,
PRL 96, 136807 (2006)

Phonon assisted tunneling



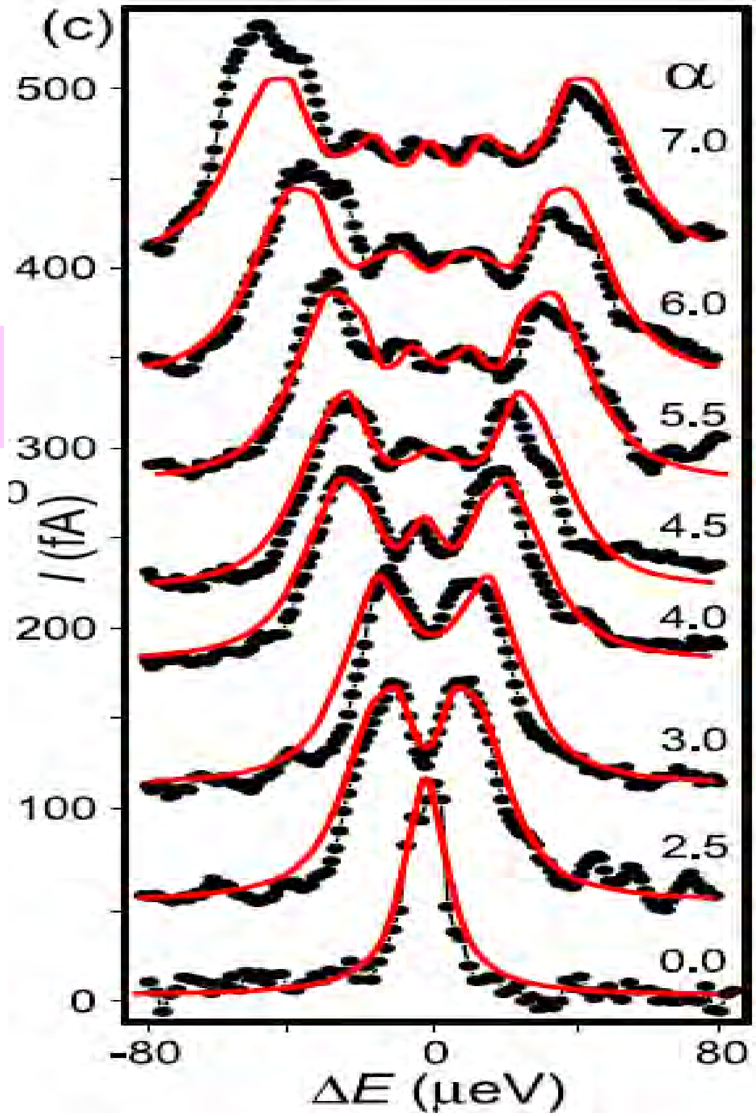
FWHM 14 μeV > hf = 8 μeV



phonon absorption

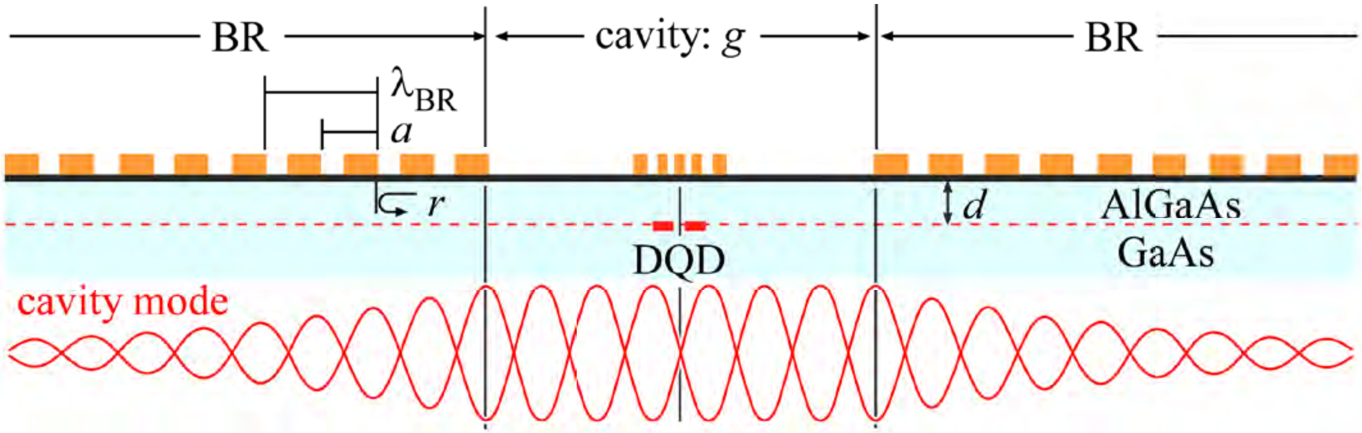
$\varepsilon = nhf$

phonon emission

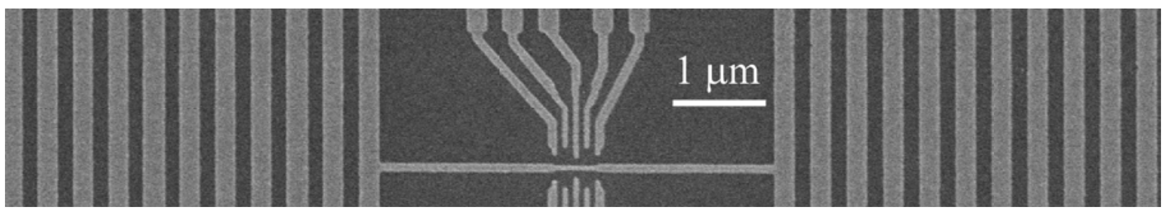


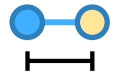
W.J.M.Naber et al. , PRL 96, 136807 (2006)

DQD in a SAW phonon cavity



$r \sim 1\%$,
$\lambda_{BR} = 800$ nm

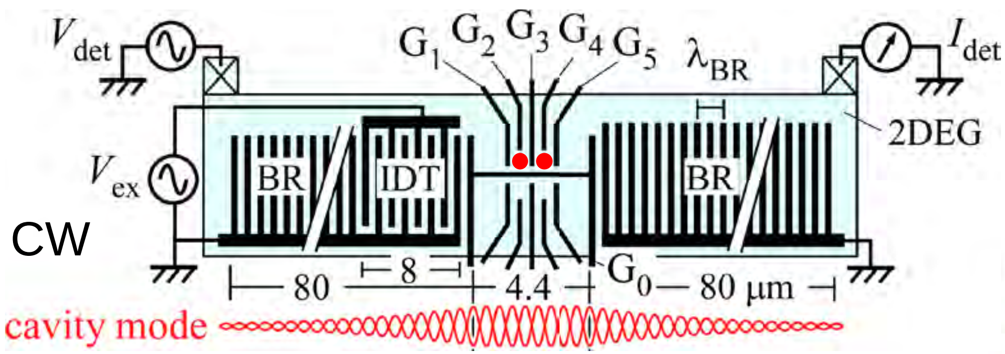




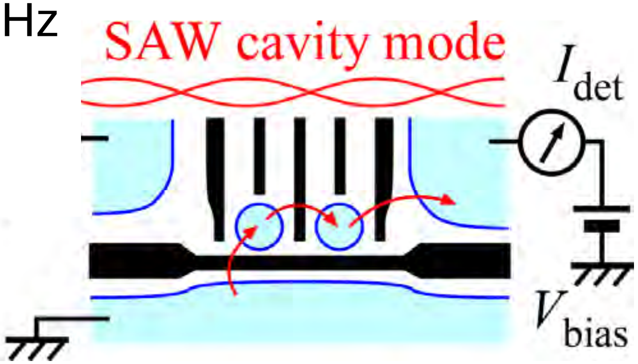
$L_{DQD} \sim 240$ nm,
$\lambda_{BR}/2 = 400$ nm

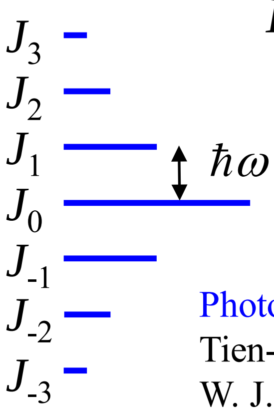
Two-level systems in a DQD
(charge or spin qubit)

Phonon assisted tunneling



f = 3222 MHz



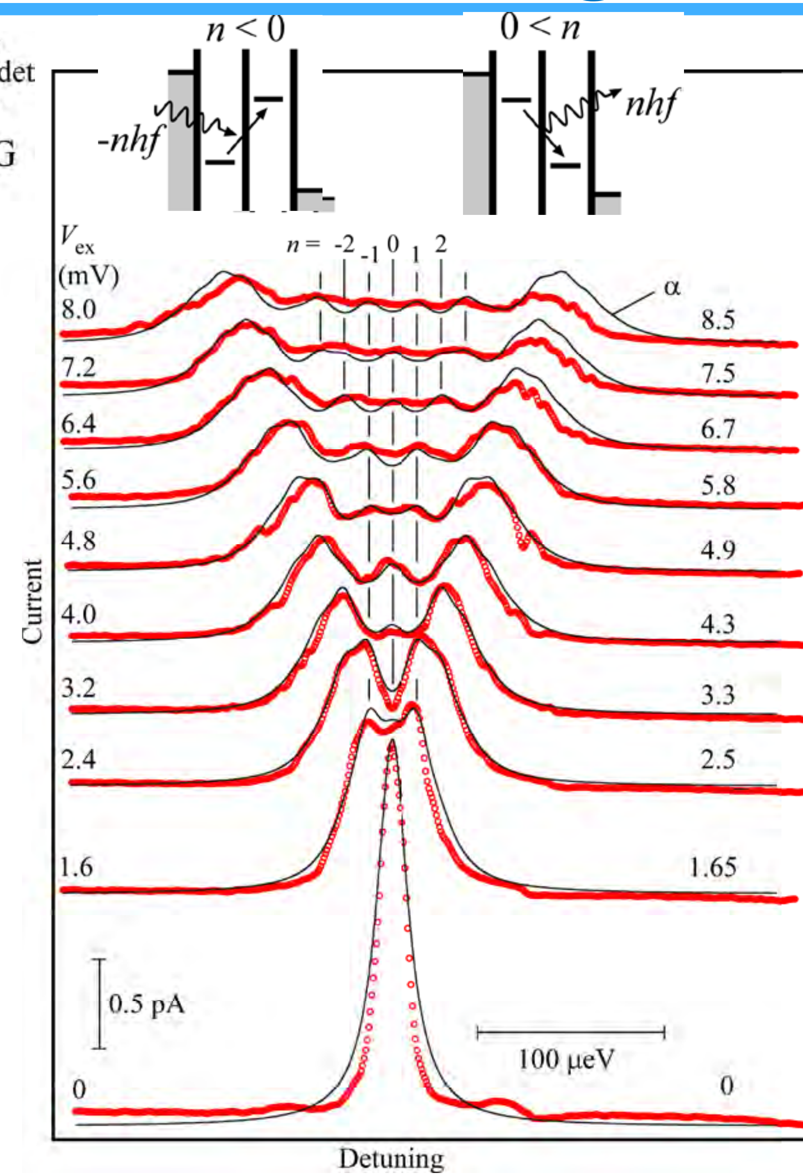


$$H_R = H_{R,0} + eV_{\text{phonon}} \cos \omega t$$

$$\psi_{\text{R}} = \psi_{\text{R},0} \sum_n J_n(\alpha) e^{-in\omega t}$$

$$\alpha = eV_{\text{phonon}} / \hbar\omega$$

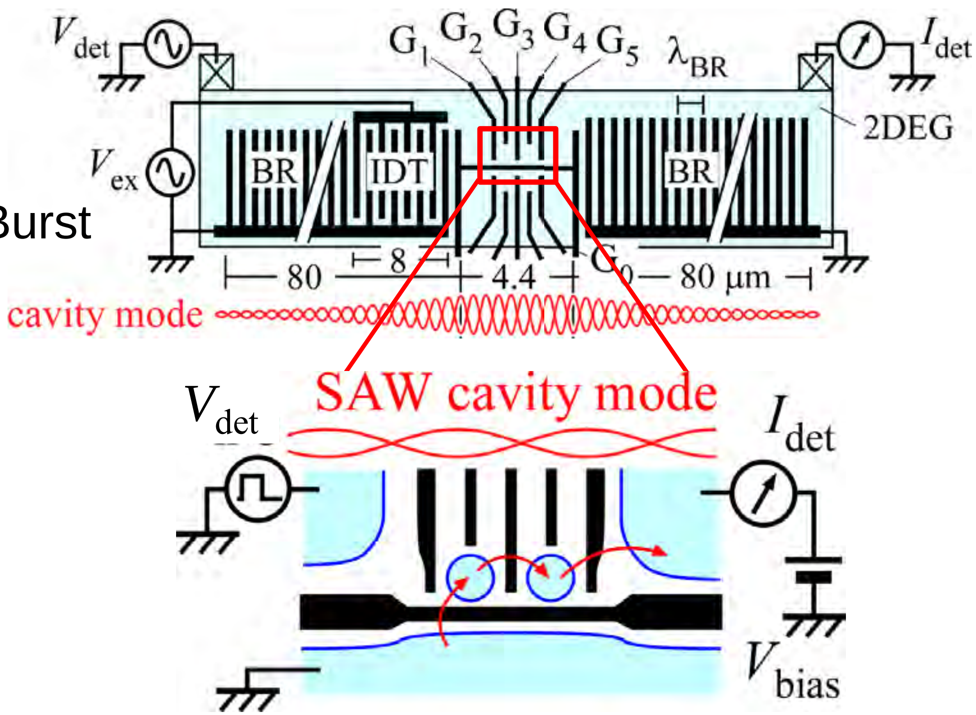
Photon/phonon assisted tunneling
Tien-Gordon theory (1963)
W. J. M. Naber et al., PRL 96, 136807 (2006).



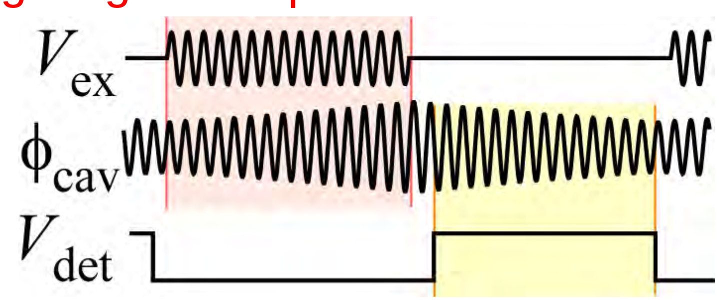
J.C.H. Chen et al., Sci. Rep. 5, 15176 (2015).

Photon vs phonon assisted tunneling

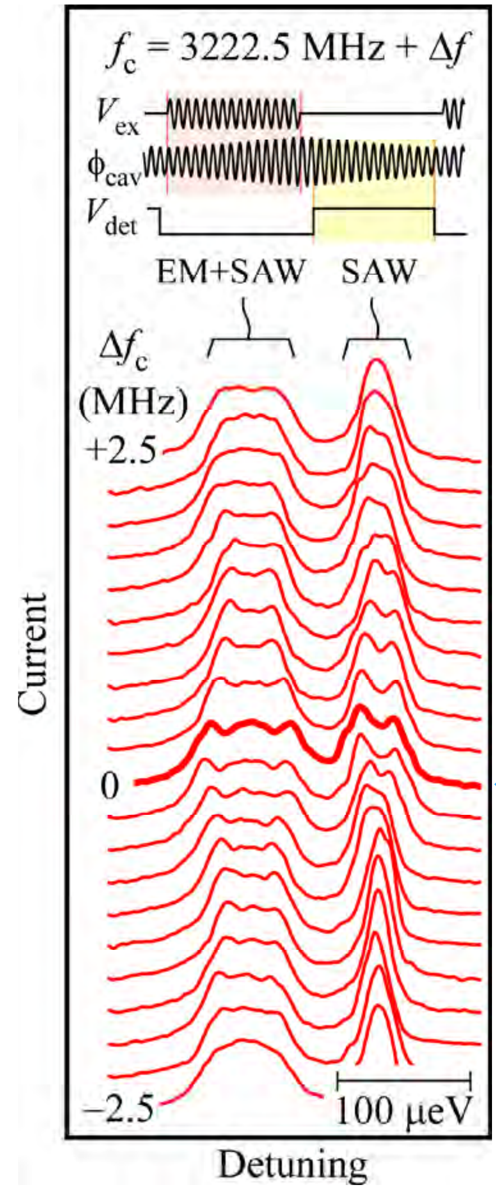
Burst



Time-gating technique



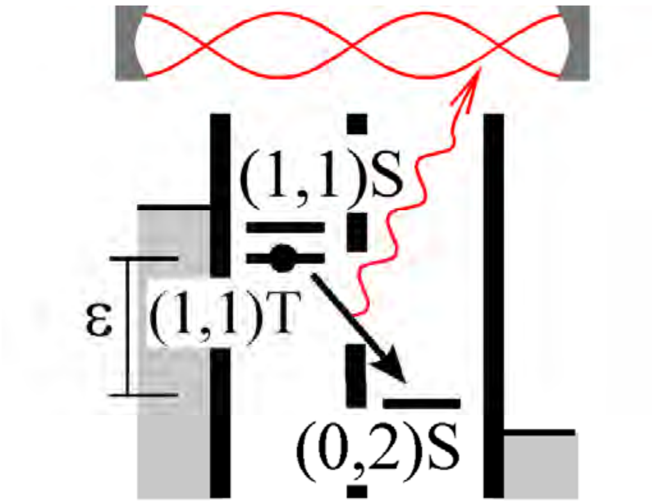
EM+SAW (photon + phonon) **SAW only** (phonon)

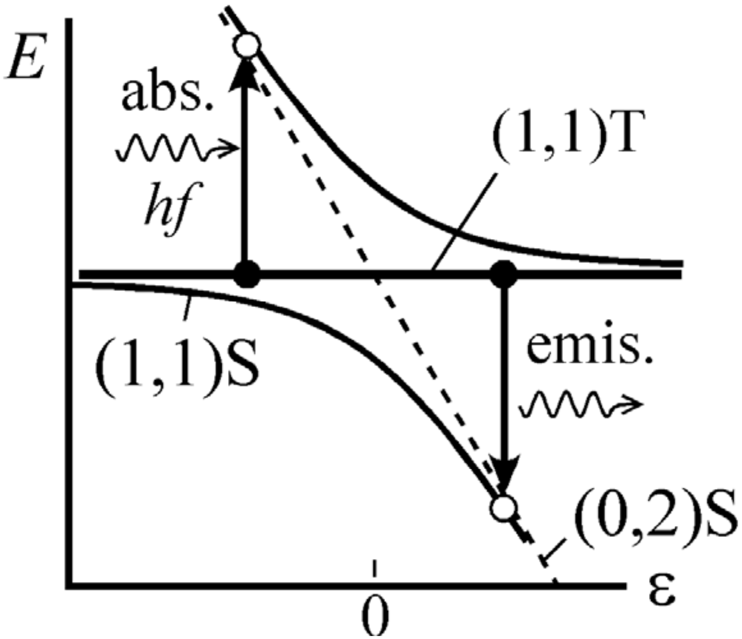


J.C.H. Chen et al., Sci. Rep. 5, 15176 (2015).

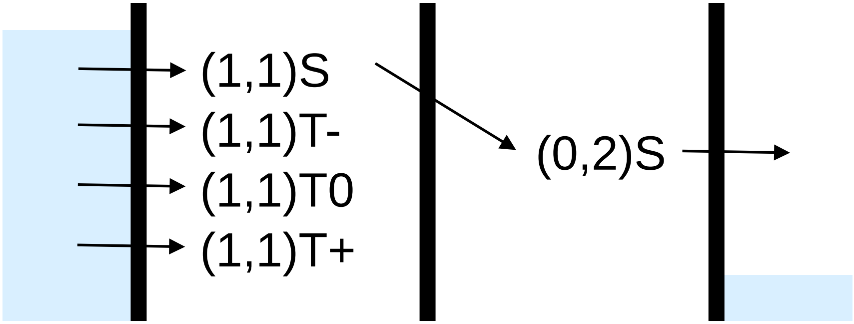
Resonant frequency

Spin-flip phonon assisted tunneling





in the Pauli spin blockade regime



Spin-flip
Phonon assisted tunneling

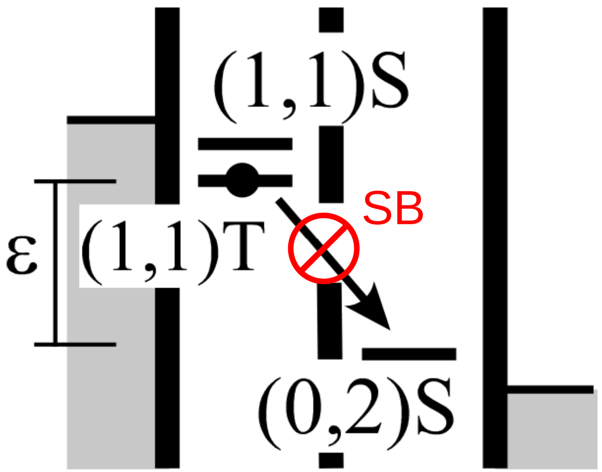
Inhomogeneous
nuclear spin polarization
and
Spin-orbit coupling

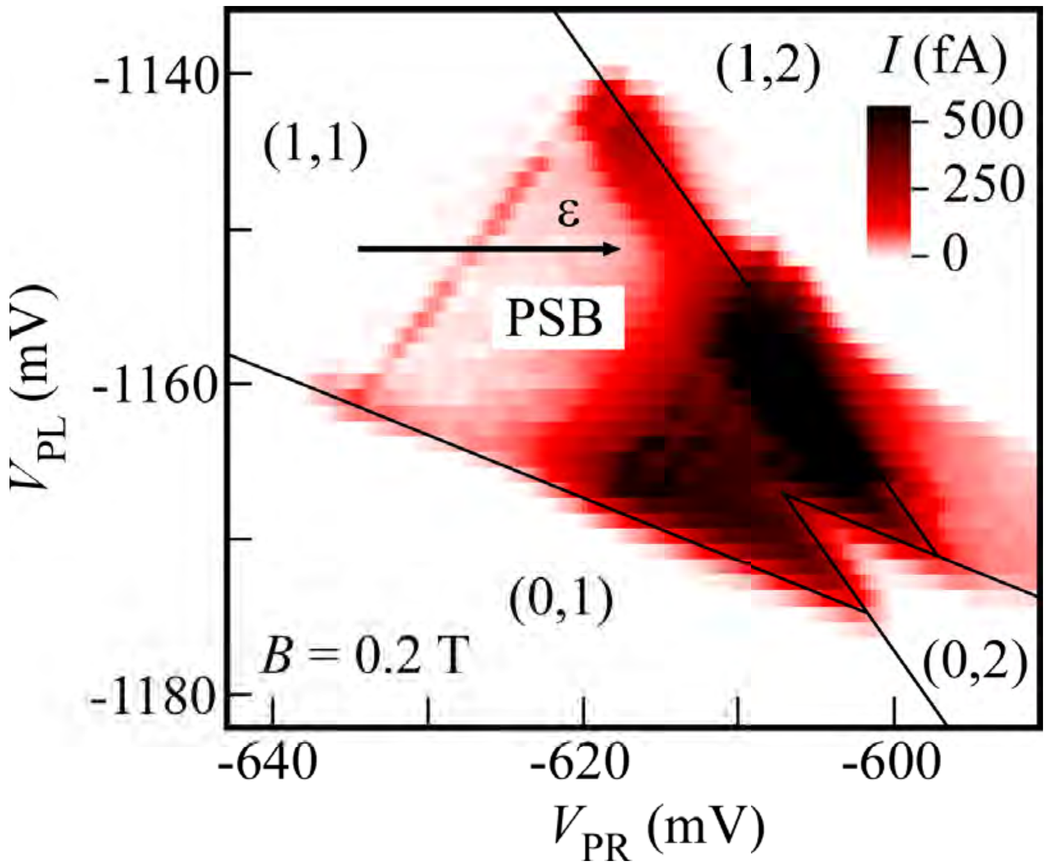
Zero-field
Pauli spin blockade

Pauli spin blockade

B = 0.2 T

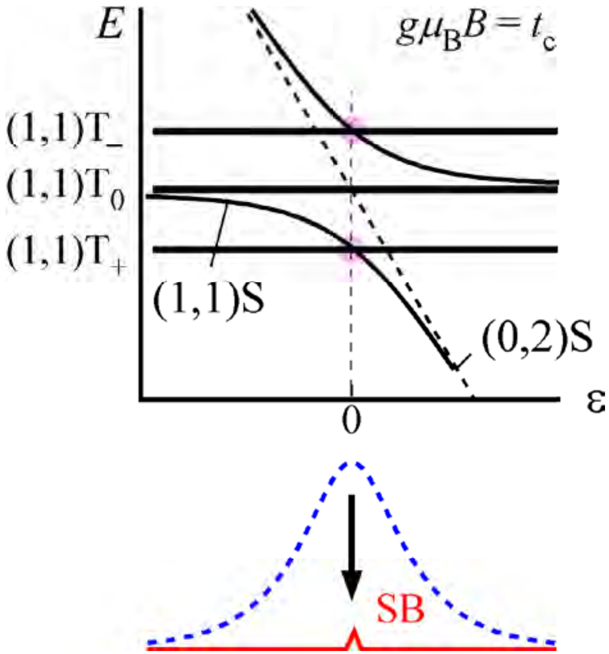
Pauli spin blockade

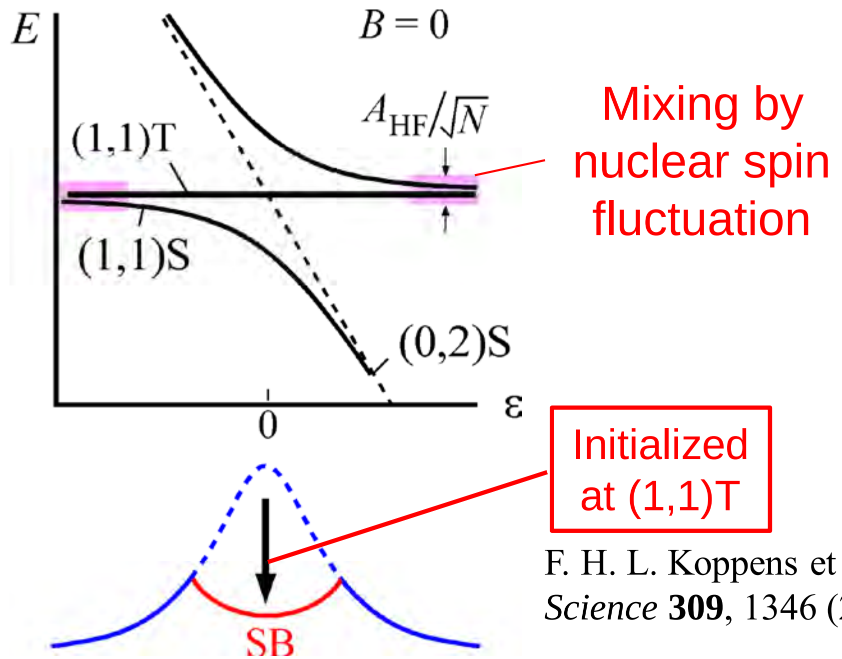




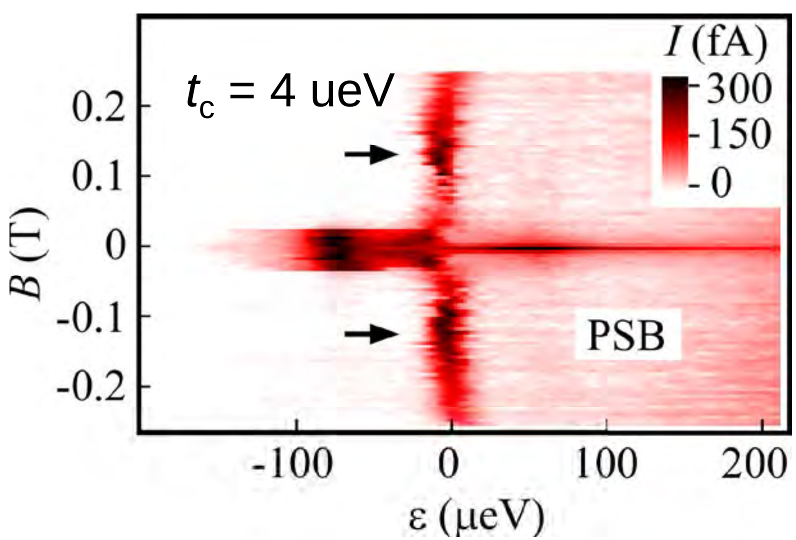
K. Ono et al.,
Science **297**, 1313 (2002).

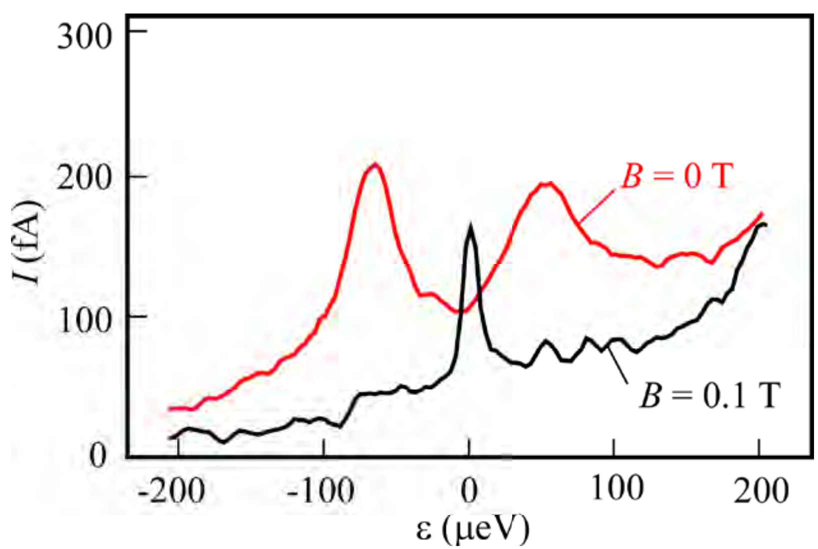
Spin blockade with hyperfine coupling





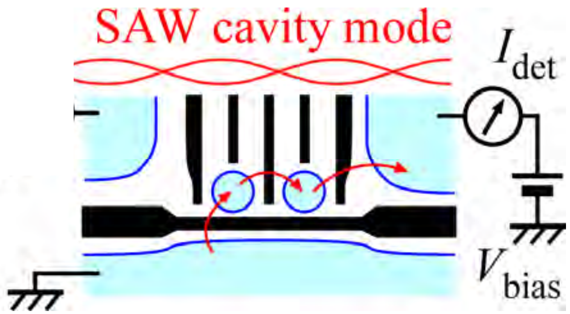
F. H. L. Koppens et al., *Science* **309**, 1346 (2005).

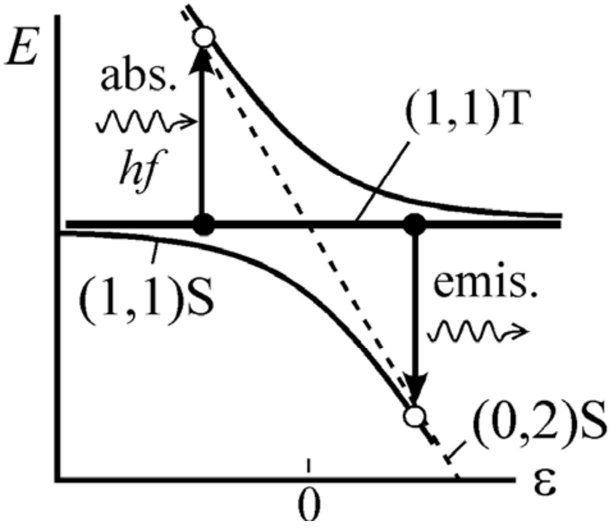


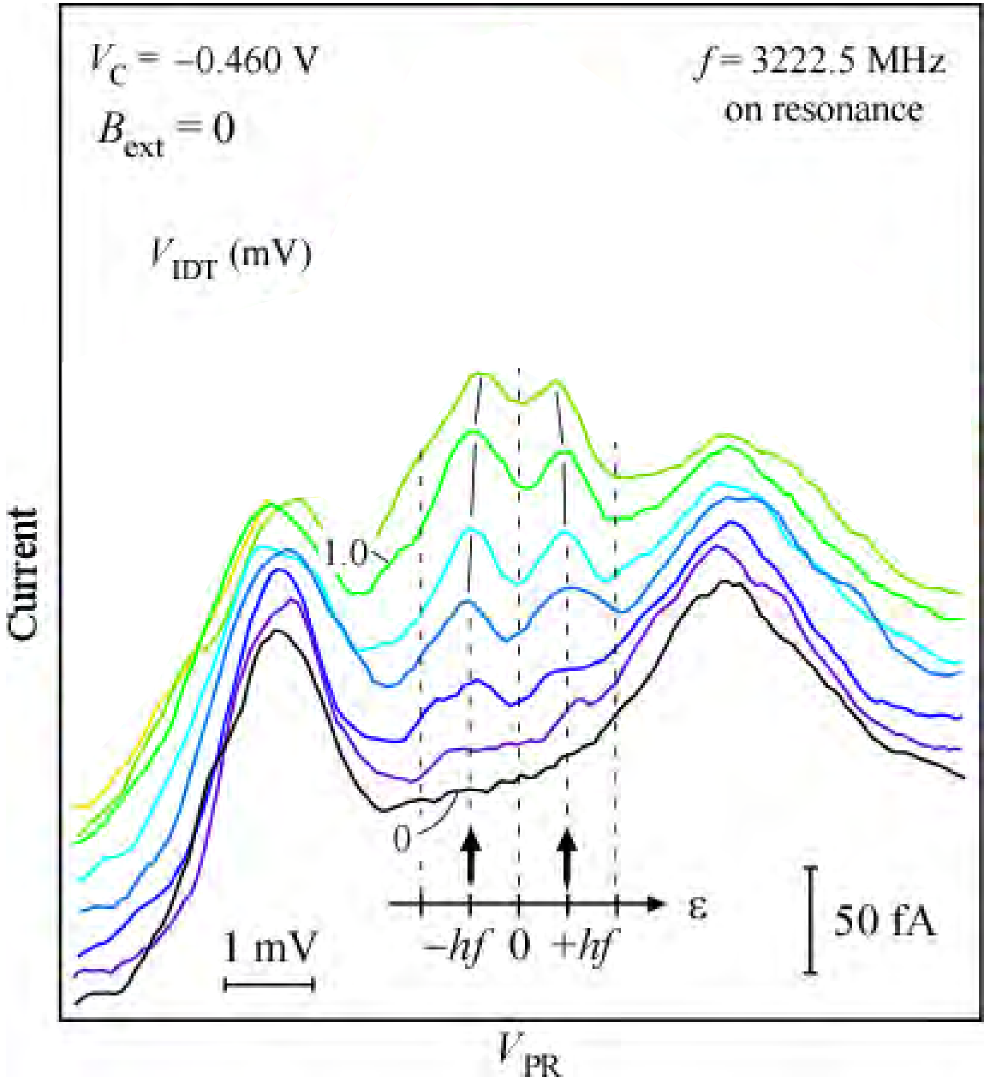


Spin-flip phonon assisted tunneling

CW excitation



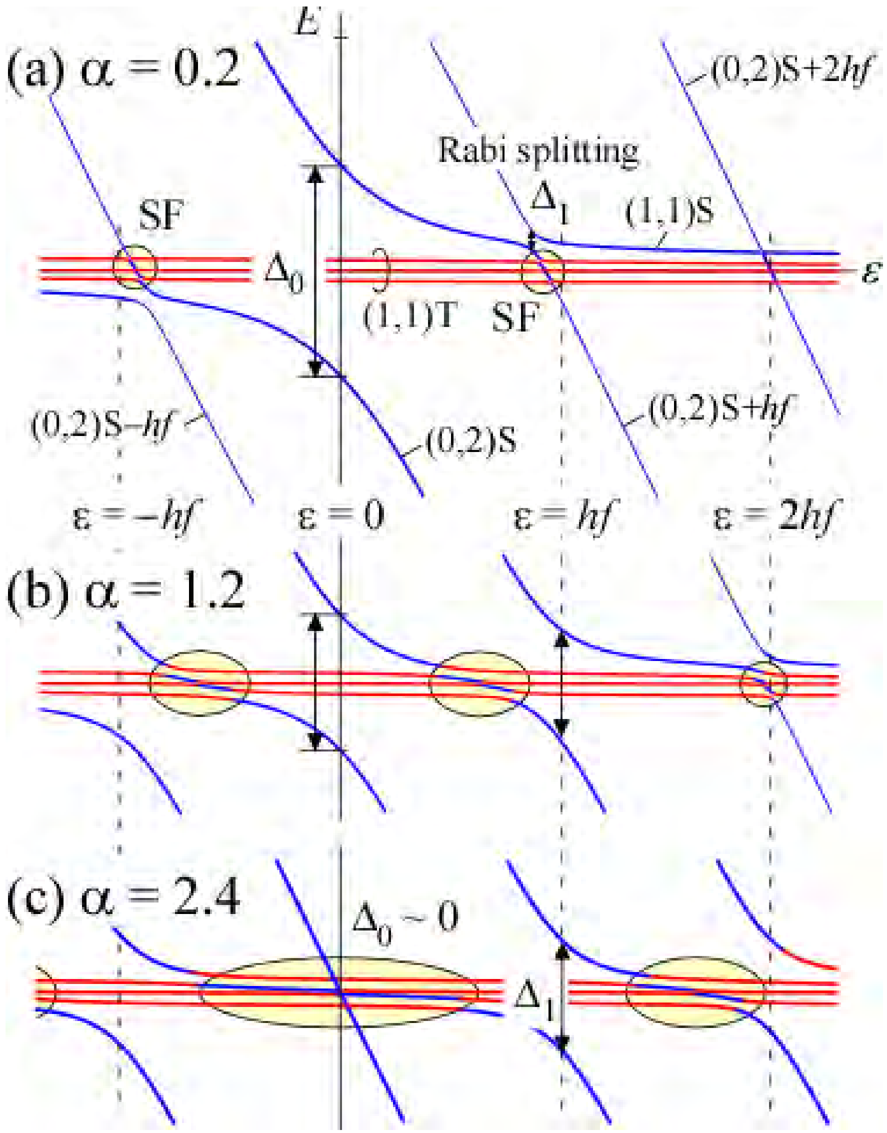




offset vertically for clarity

Y. Sato et at., in preparation.

Floquet quasi-eigenstates



$$H(t) = H_0 + H_1 \cos \omega t$$

$$H_0 = \sum_{i \in \{x,y,z\}} \left(A_i^{(L)} \sigma_i^{(L)} + A_i^{(R)} \sigma_i^{(R)} \right) - \varepsilon |02S\rangle\langle 02S|$$

Random Overhauser field　　Detuning

$$+t_0 \left(|11S\rangle\langle 02S| + |02S\rangle\langle 11S| \right)$$

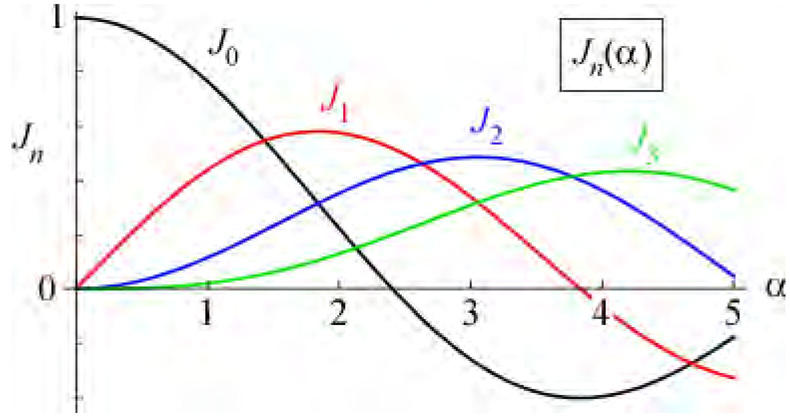
Tunneling

$$H_1 = -\tilde{\varepsilon} |02S\rangle\langle 02S|$$

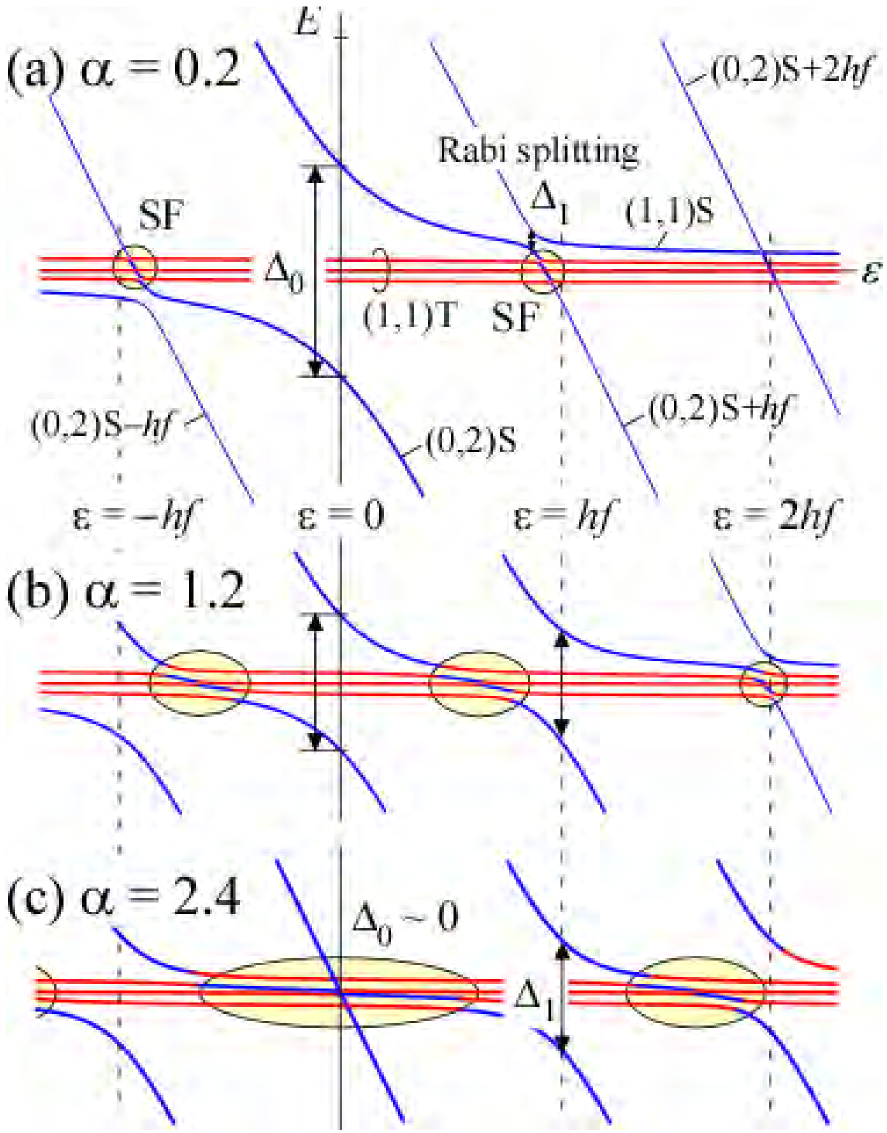
Oscillating detuning energy (SAW field)

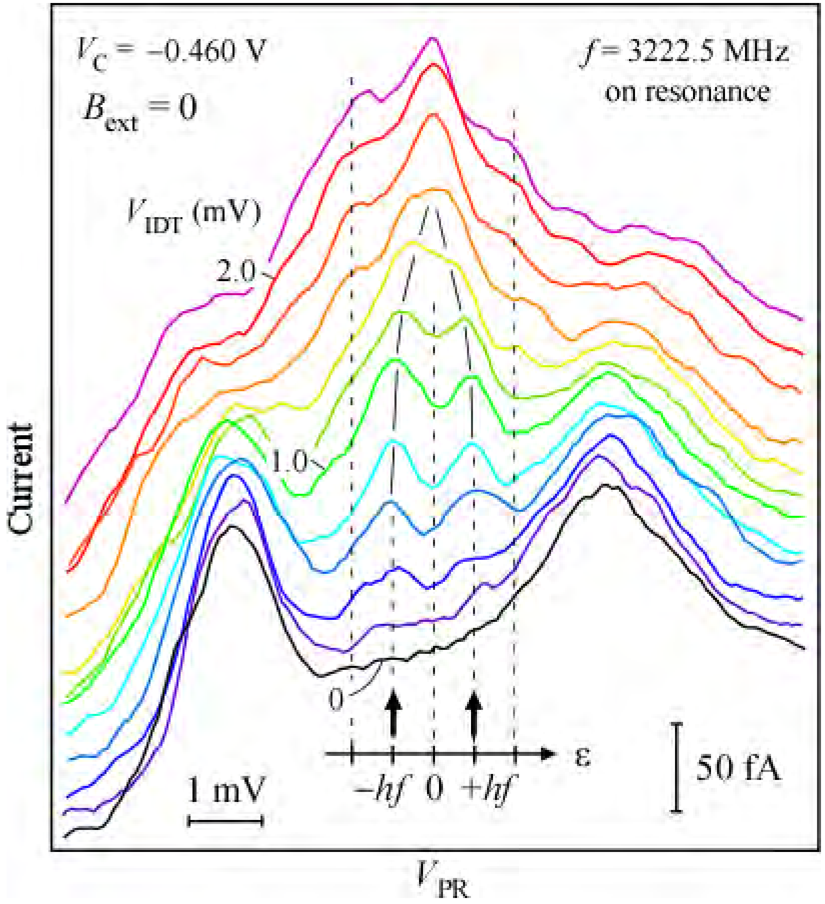
$$\boxed{\alpha = \frac{\tilde{\varepsilon}}{\hbar\omega}}$$

Normalized amplitude



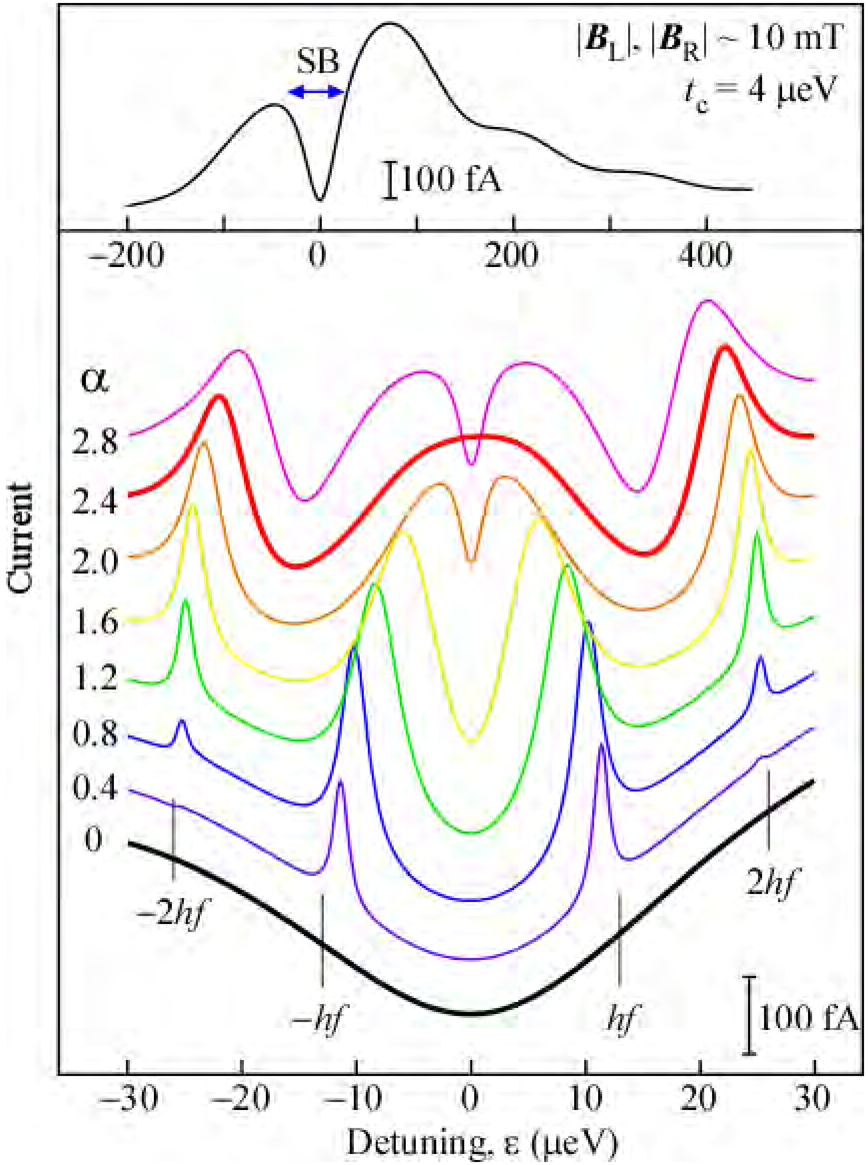
PAT peak shift





The peak shift originates from the Rabi splitting.

Numerical calculations



Floquet – Lindblad master equation

$$\frac{d}{dt}\rho = \mathfrak{L}[\rho] = M(t)\rho$$

$$H(t) = H_0 + H_1 \cos \omega t$$

Coupling to the leads

Cotunneling

spin exchange with the leads

Dissipation

phonon emission

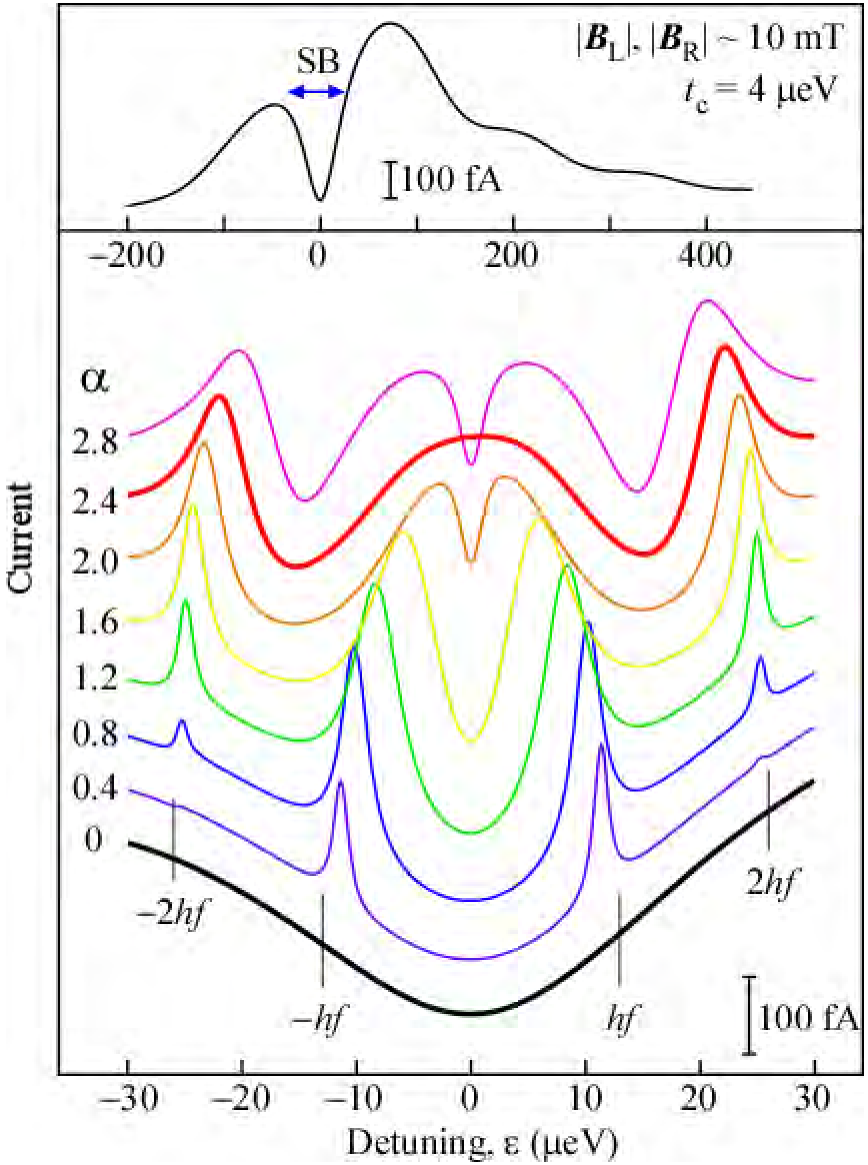
Dephasing

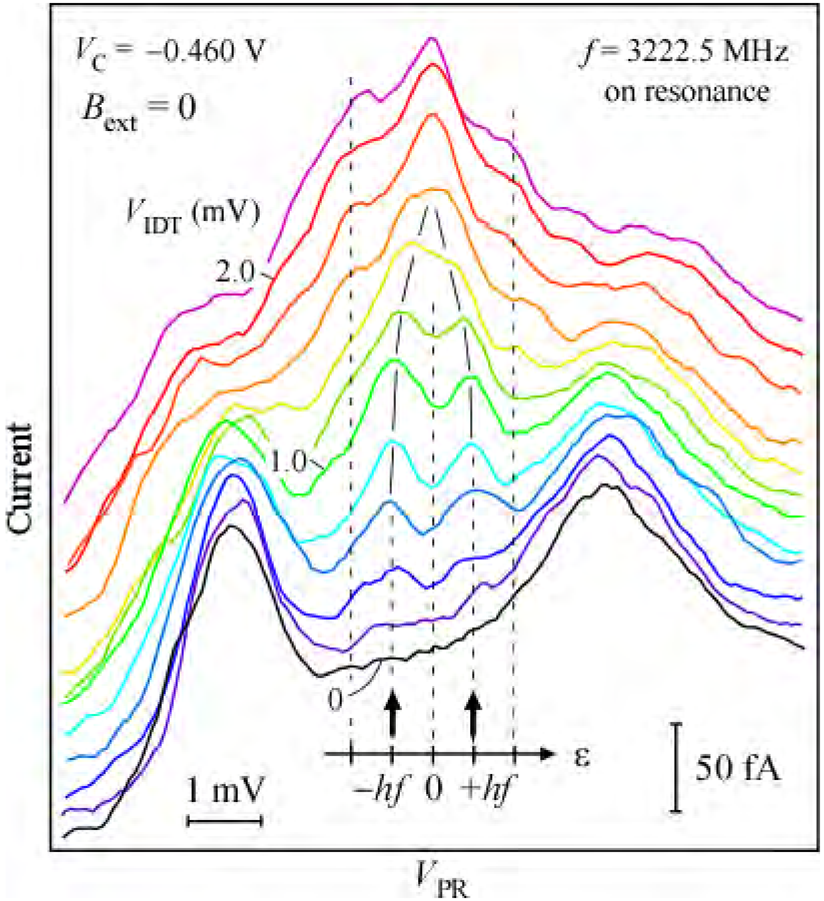
The quasi-steady state can be obtained by solving

$$\rho_0(t) = \rho_0(t+T)$$

$$= \exp\left[\int_0^T M(t)\,dt\right]\rho_0(t)$$

Numerical calculations

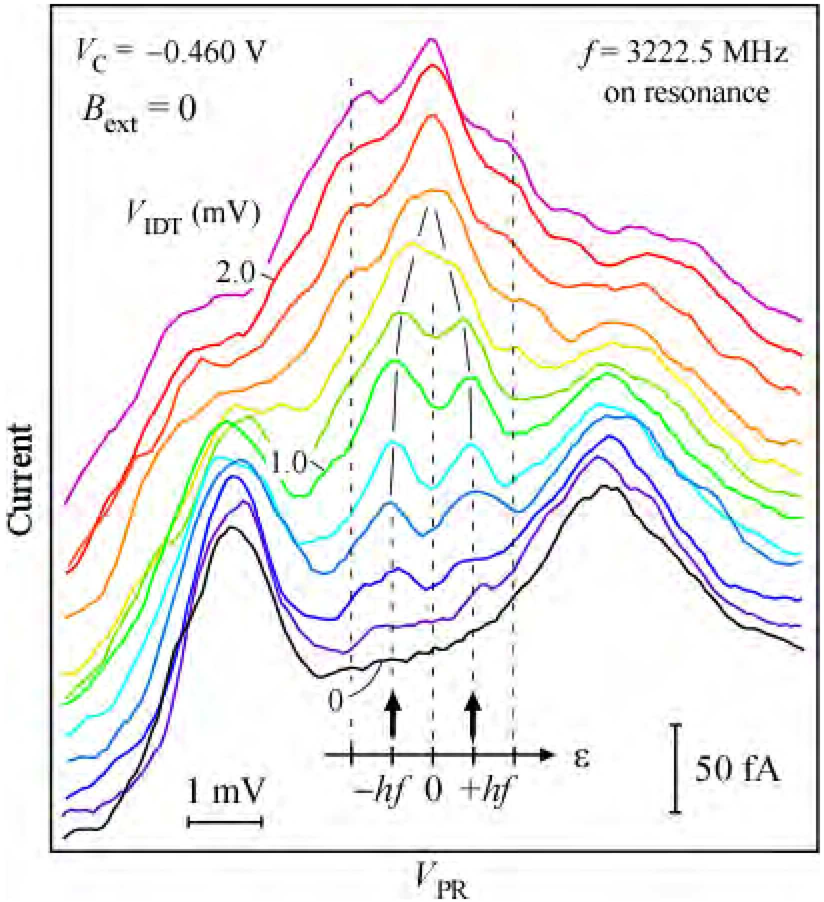


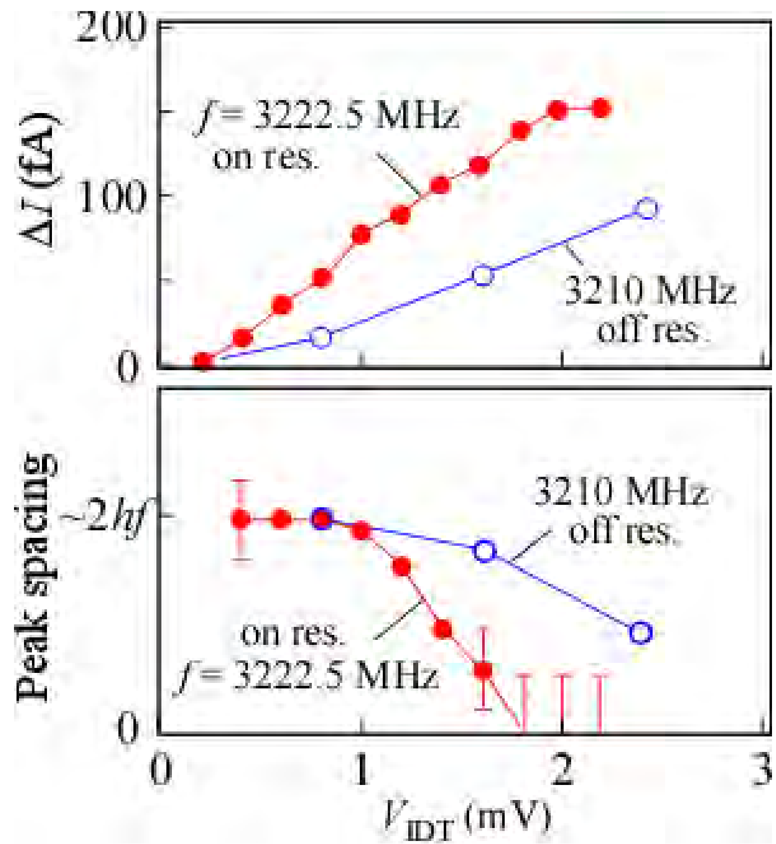


Phonons or photons

Phonons (only at the resonant frequency)
+
Photons (electrostatic cross talk)

- on resonance
  photon + phonons
- off resonance
  photon





The Rabi splitting

Maximum Rabi splitting under an intense SAW field

$$\Delta_1 = 2t_c J_1(\alpha)$$

$$\Delta_{1,\max} \simeq 1.2t_c \ \ (\text{at } \alpha \simeq 1.9)$$

~5 μeV (1.2 GHz)

Vacuum Rabi splitting (crude estimate)

Vacuum fluctuation in the detunig

$$\tilde{\varepsilon} = \frac{1}{\pi}\sqrt{\frac{\lambda^2 K^2 \hbar\omega}{\varepsilon_r \varepsilon_0 V}} \sin\left(\frac{\pi d}{\lambda}\right) \exp\left(\frac{-z}{\delta}\right)$$

Mode volume

$$V = D \times L \times W \sim 1\lambda \times 30\lambda \times 50\lambda = 1500\lambda^3$$

Vacuum Rabi splitting

$$\Delta_{1,\text{vac}} \sim 0.03\ \mu\text{eV}\ (7\ \text{MHz})$$

SUMMARY

- **Motivation**
  - Phonon environment for quantum dots
  - Prospect for cavity Quantum Acoustics

- **SAW Phonon cavity**
  - Device design
  - Phononic bandgap in a Bragg reflector
  - Localized cavity modes

- **Transition between electronic states in a DQD**
  - Phonon assisted tunneling
  - *Spin-flip* phonon assisted tunneling
  - Rabi splitting induced by the cavity mode SAW