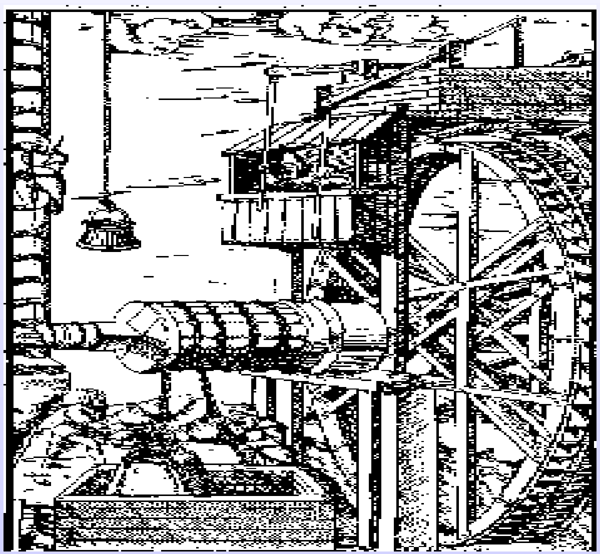
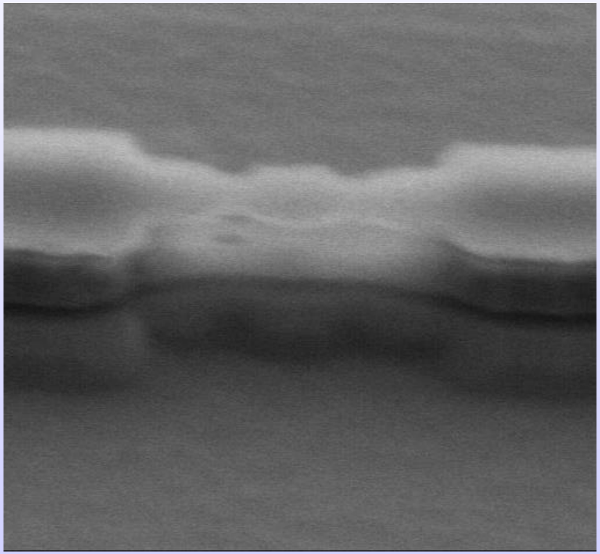
Semiconductor Group

LMU

Nano Acousto Mechanics with Surface Acoustic Waves

F. W. Beil, R. H. Blick, and A. Wixforth





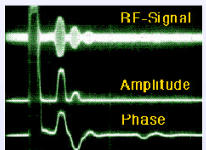
NATO Advanced Research Workshop 2003

NATO OTAN

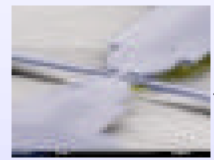
Nano Acousto Mechanics
Who made it happen ?

A. Wixforth
University Augsburg

SAW, 2DEGs



NEMS, 2DEGs

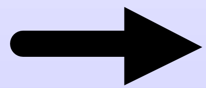


R. H. Blick
University Madison

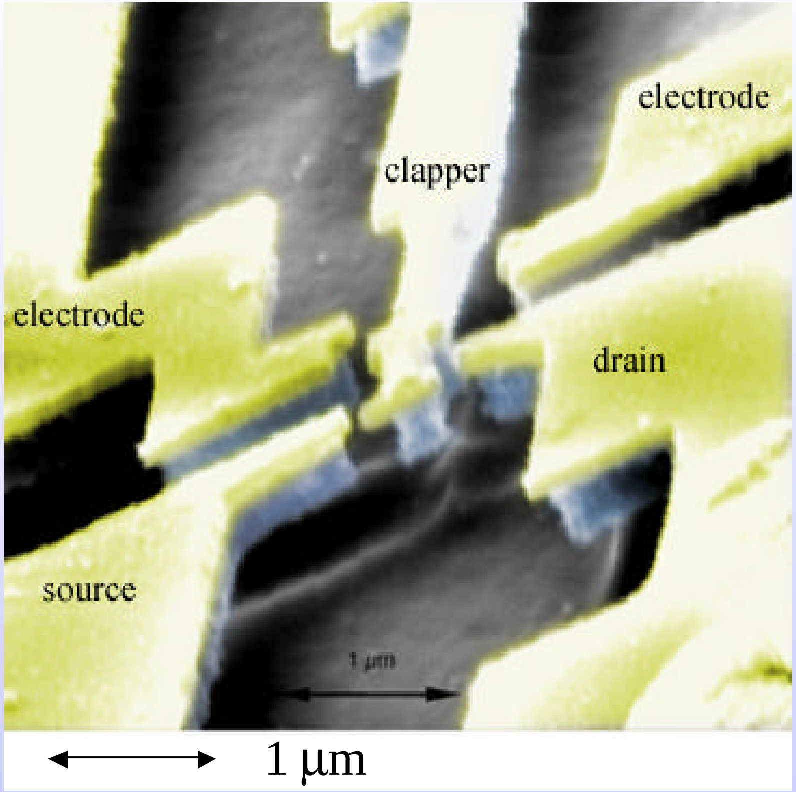
J. P. Kotthaus
University Munich

Knowledge

me
University Munich

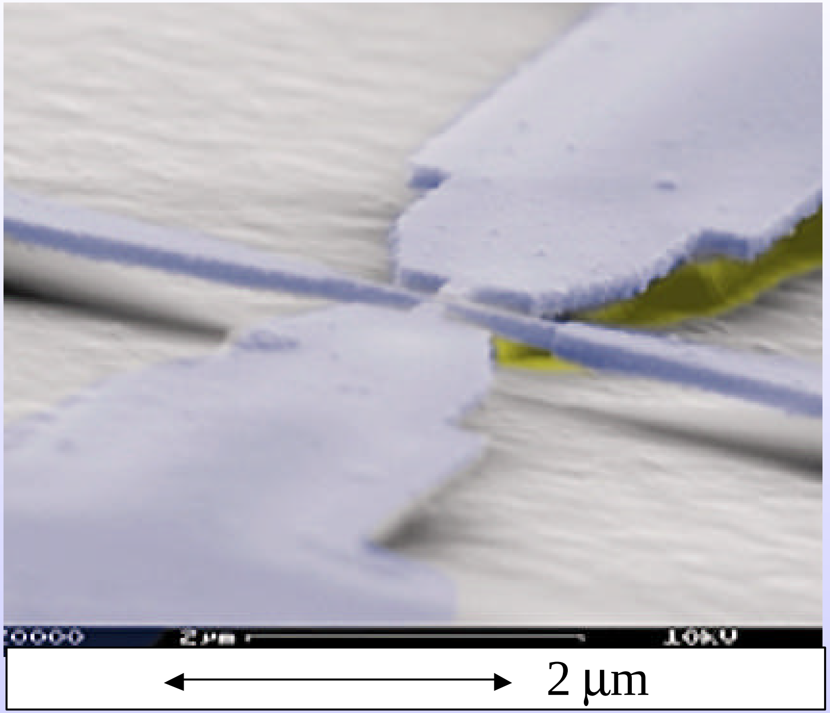


Nano-Electromechanical-Systems (NEMS)



nanomechanical electron shuttle

A. Erbe, C. Weis, W.Zwerger, and R. H. Blick
Phys. Rev. Lett. **87**, 096106 (2001).



nanomechanical beam resonator
width: 80 nm
eigenfrequency: ~100MHz

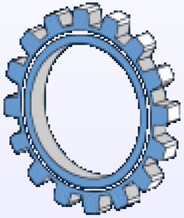
Why small Mechanics ?

Scaling of mechanics with size *L*

$$\begin{pmatrix} mass \\ acceleration \\ velocity \\ frequency \\ power \end{pmatrix} \equiv \begin{pmatrix} L^3 \\ L^{-1} \\ L^0 \\ L^{-1} \\ L^2 \end{pmatrix}$$

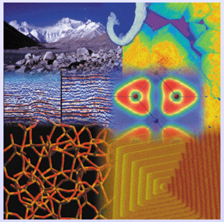
applications

Smaller means higher eigenfrequencies



science

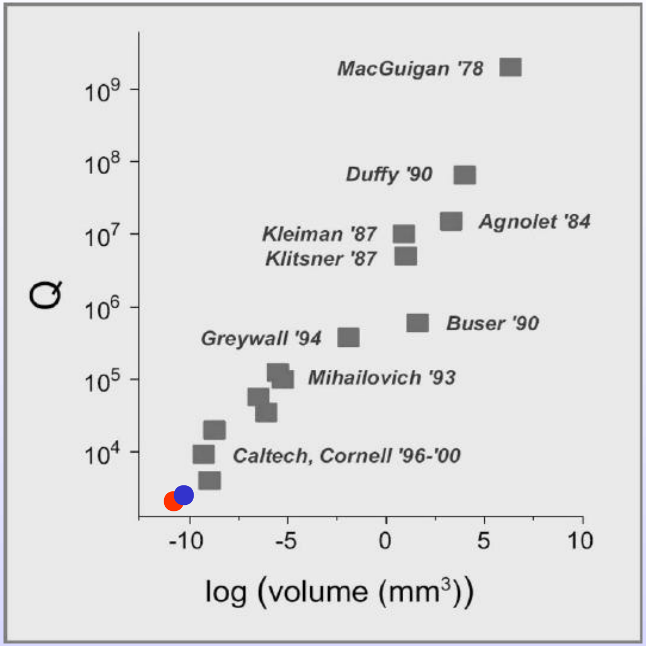
Nonclassical mechanics (`Quantum Mechanics`)



Where are we ?
eigenfrequency: 1 GHz
detectable force: $10^{-14} N/\sqrt{Hz}$
detectable charge: $10^{-3} e/\sqrt{Hz}$

Challenges to meet

Scaling of Q



- **our larger devices**
- **our shorter devices**

$$\text{Size}\downarrow \;\Rightarrow\; \text{Q}\downarrow$$

But why ?

Scaling of forces

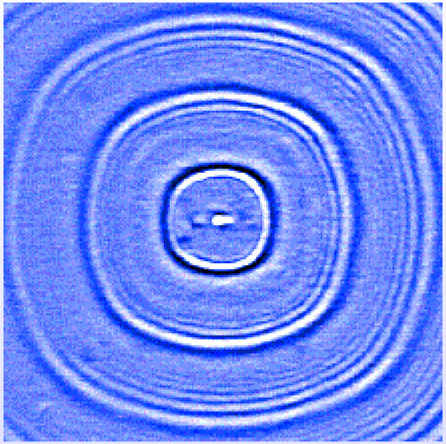
$$\begin{pmatrix} L^1 \\ L^2 \\ L^3 \\ L^4 \end{pmatrix} \equiv \begin{pmatrix} \text{surface tension} \\ \text{electrostatic, magnetic } (J = L^{-1}) \\ \text{magnetic } (J = L^{-0.5}) \\ \text{gravitation, magnetic } (J = L^{0}) \end{pmatrix}$$

Conventional methods exploit electrostatic or magnetic forces to drive nanomechanical systems (NMS)

We have no power on the nanometer scale

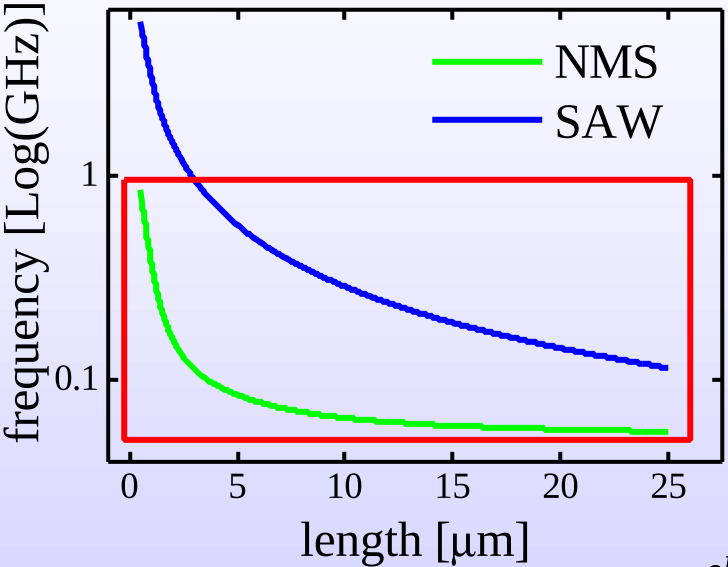
How do we excite NMS ?

Surface Acoustic Waves (SAW) & Nanomechanical Systems



SAW propagation on Lithium Fluorid (LiF)

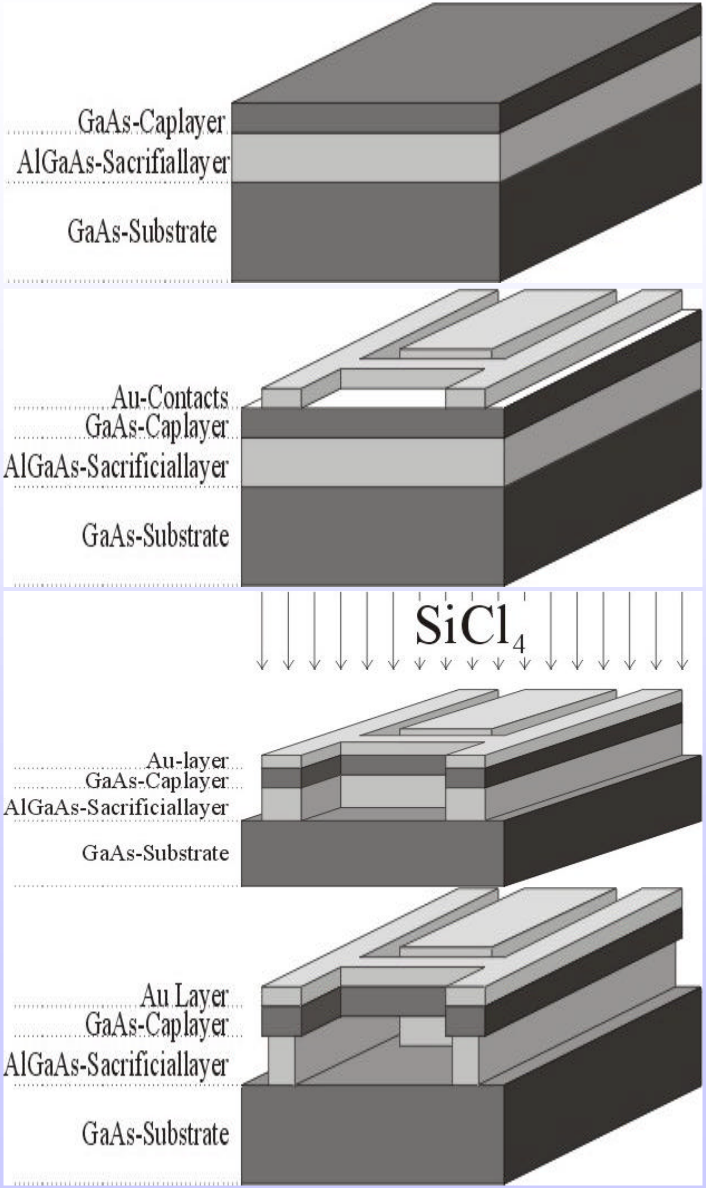
Oliver B. Wright, Hokkaiodo University



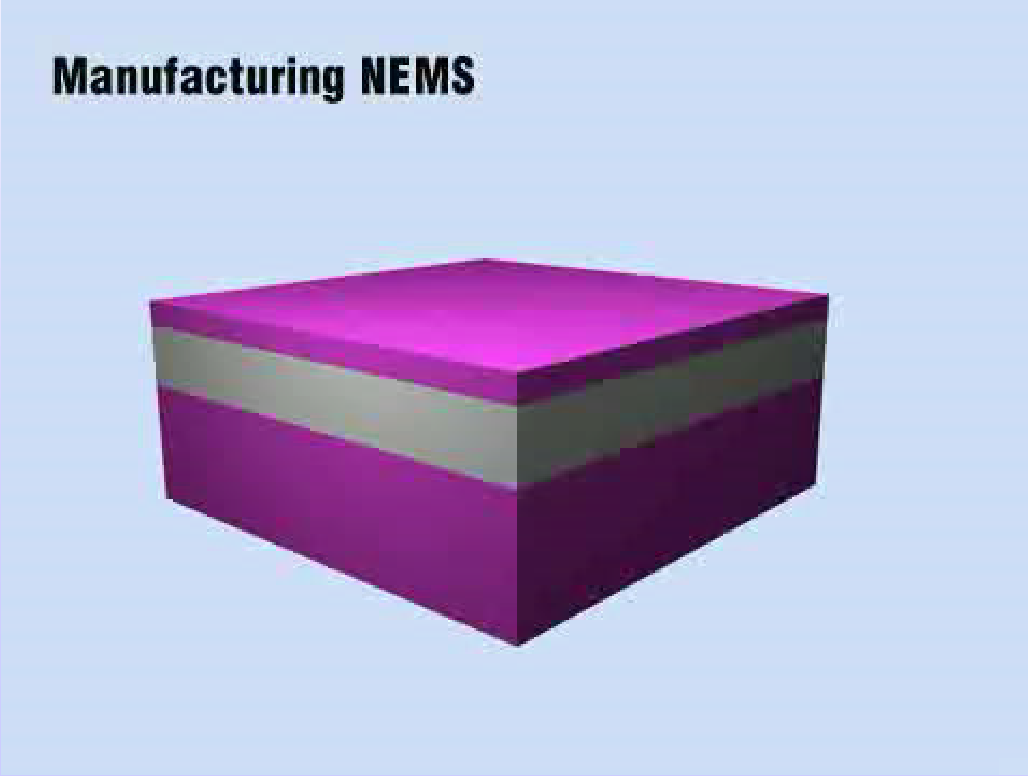
In the early 60´s, NTH´s electronics department decided to devote the core of its basic research to surface acoustic waves.

	SAW	NMS
frequency	0.1 – 1 GHz	0.01-1 GHz
amplitude	~ 1 nm	~ 1nm
dimensions	λ: 0.1 – 10 μm	L: 0.1-1 μm

Fabrication of NEMS

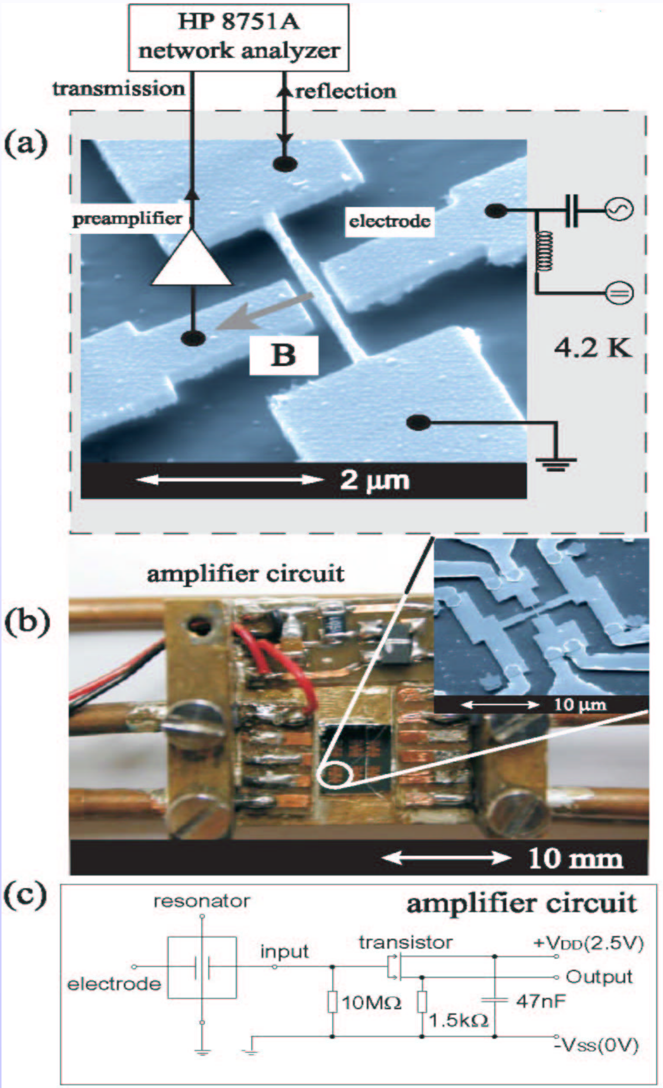


1. Heterostructure with sacrificial layer
2. E-beam lithography
3. Anisotropic RIE etch
4. Isotropic selective wet etch

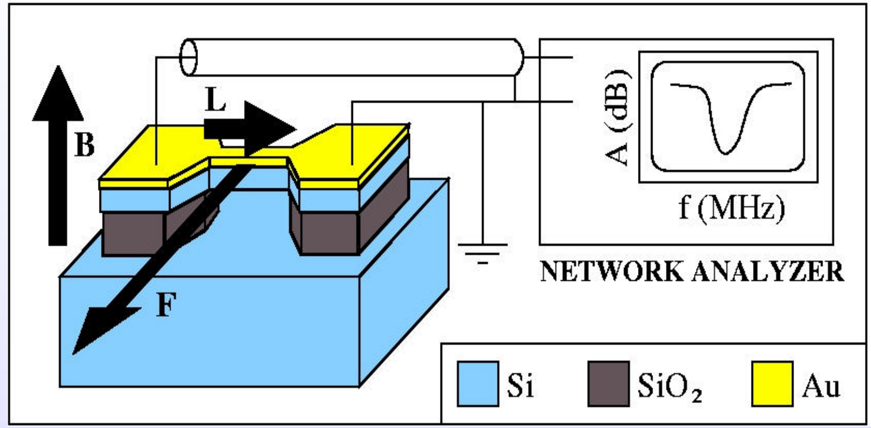


How to move NEMS and detect it ?

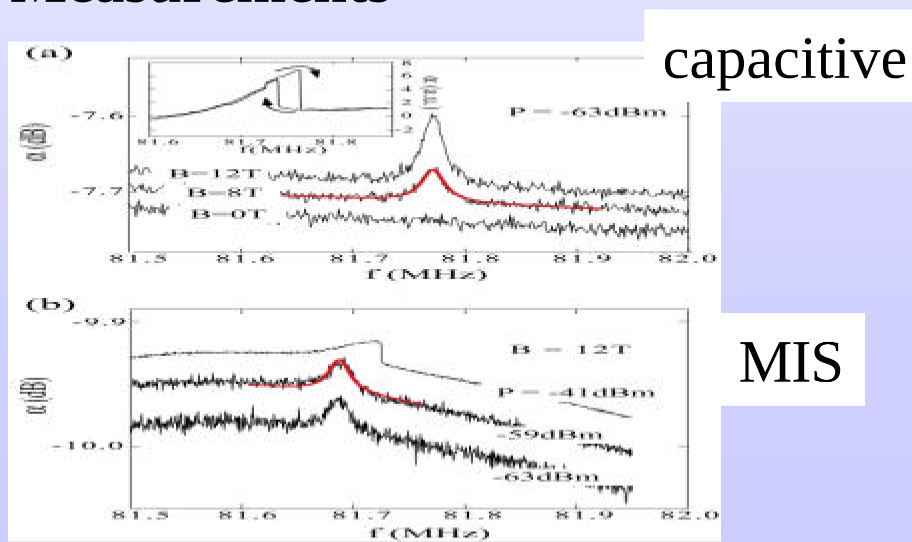
Capacitive coupling



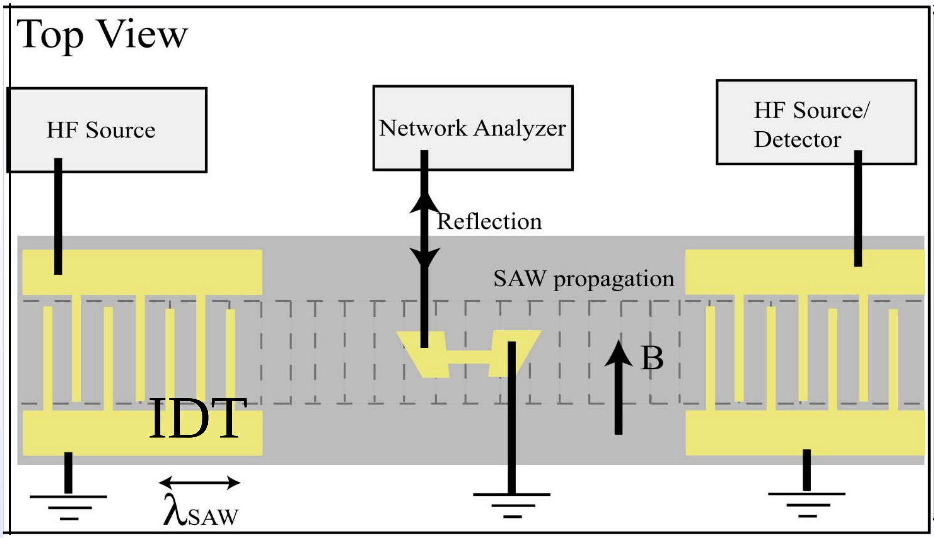
Magneto impedance spectroscopy (MIS)
Lorentz forces

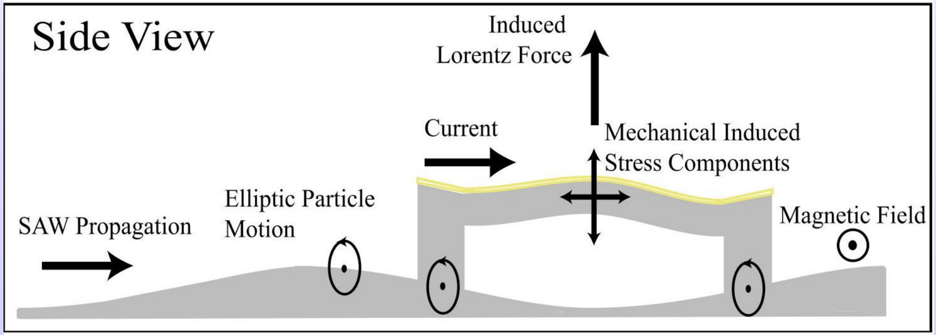


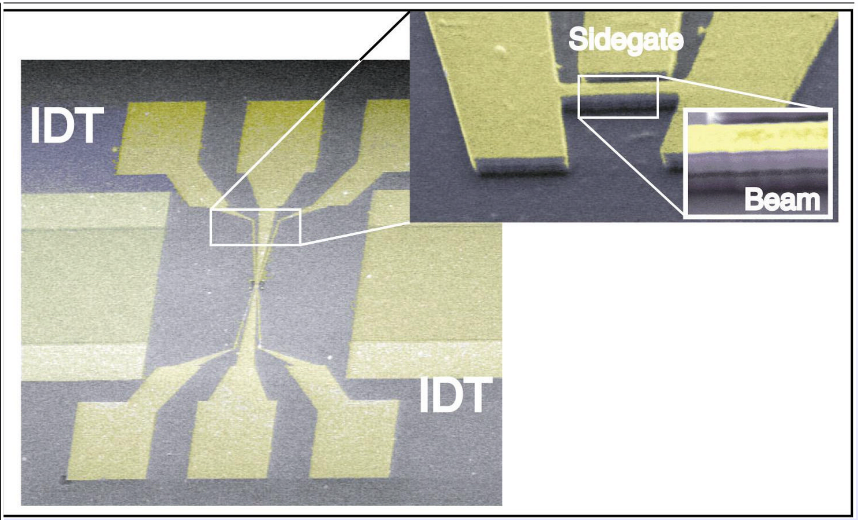
Measurements



SAW & NEMS Experimental Approach







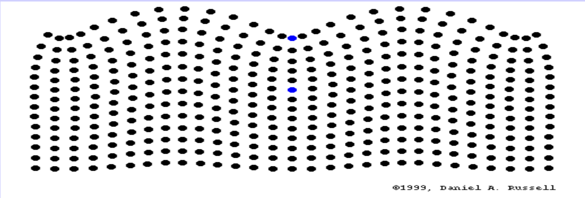
Beam: L=3μm, H=200nm,W=300nm

SAW: F=300MHz,λ=9μm

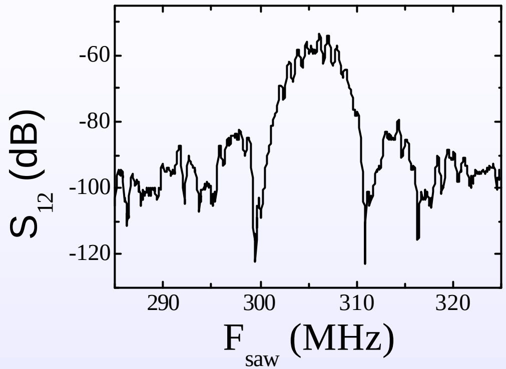
Detect SAW induced changes in beam's resonance by magneto impedance spectroscopy.

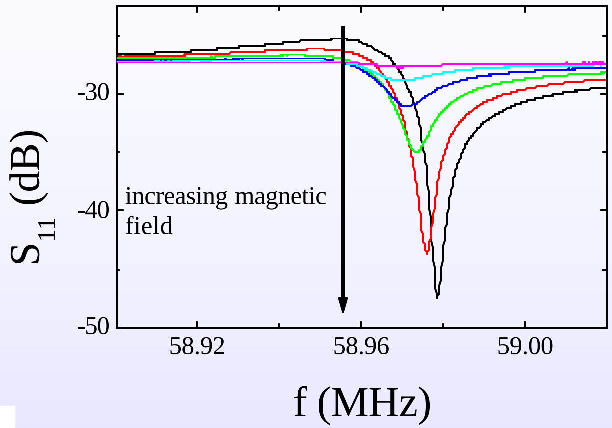
SAW are easily generated by interdigitated transducers (IDTs), with a lithographically defined frequency F_{saw} given by:

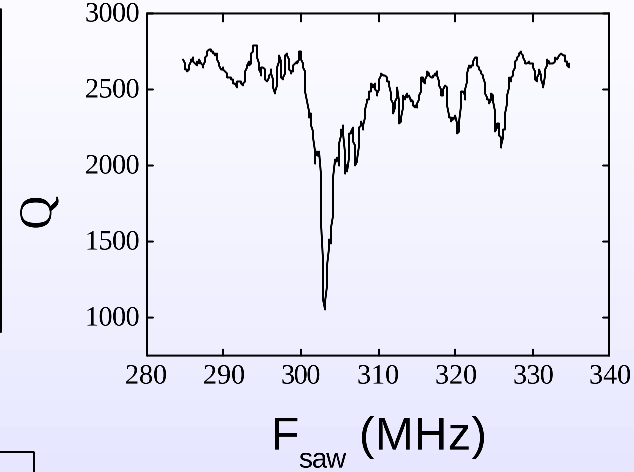
$$F_{saw} = \frac{v_{saw}}{l_{saw}}, v_{saw} = 2865\frac{m}{s}$$

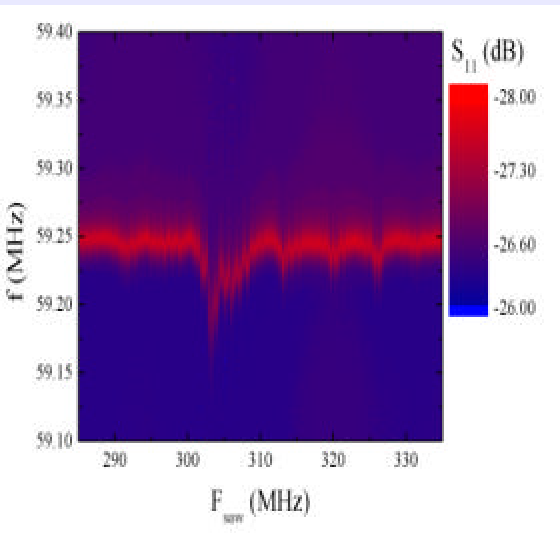


SAW & NEMS Experiments









B=4T; SAW Power=+25dBm

Non resonant coupling

Observed for many samples

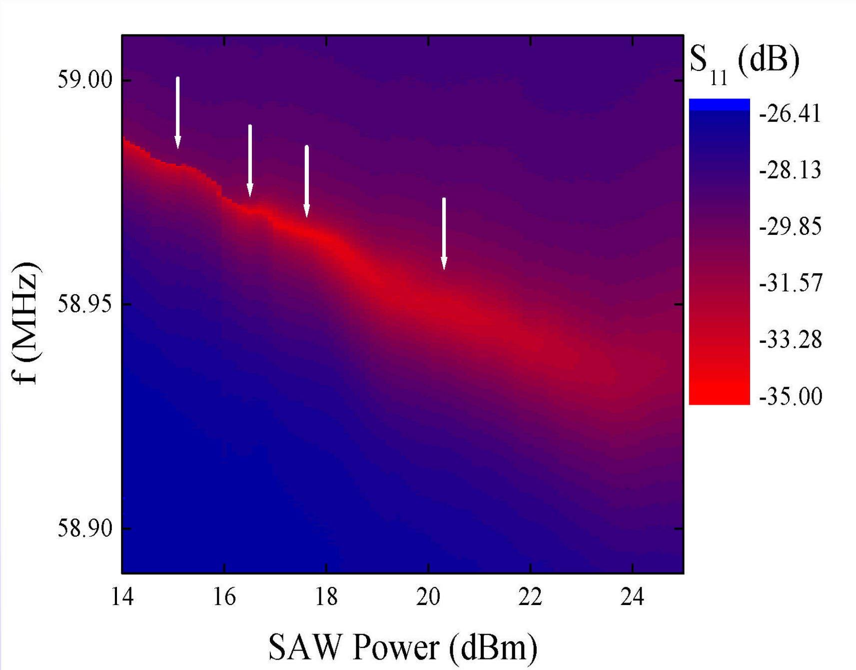
Effective Q-Tuning

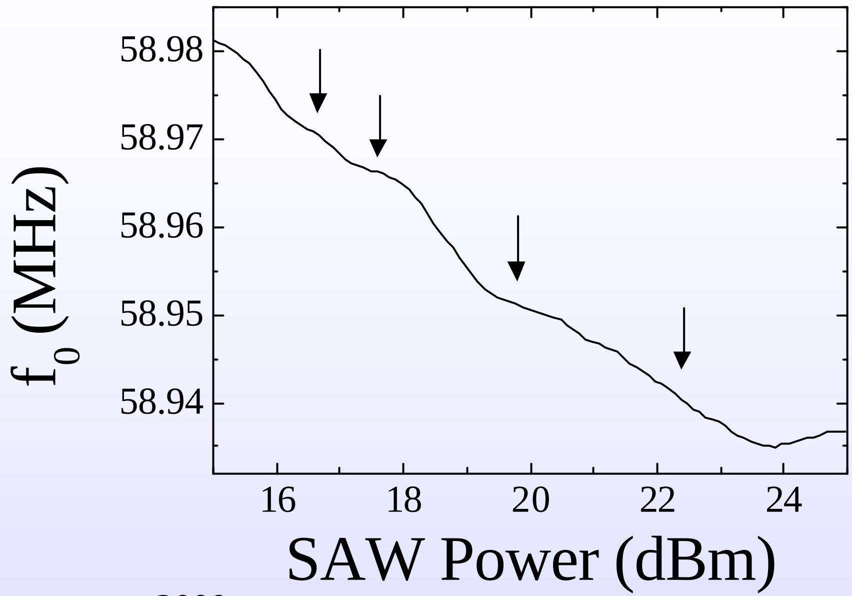
F. W. Beil, A. Wixforth, R. H. Blick
IEEE Sensors 2002

WHY ?

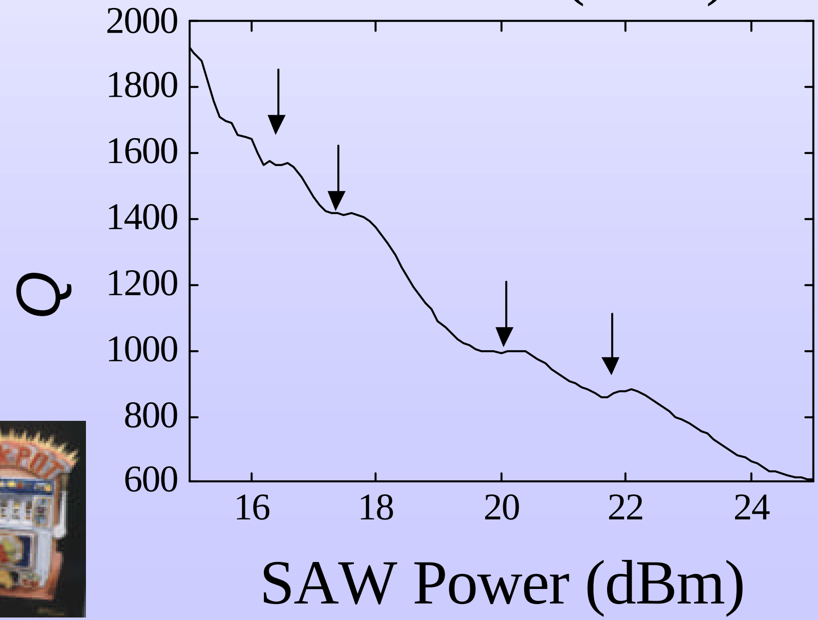
Sample	f	F_{saw}
P_3	303 MHZ	450 MHz
P_5	50 MHZ	305 MHz
Harfe_1	33 MHz	450 MHZ
	38 MHz	450 MHz
	29 MHz	450 MHz
	61 MHz	450 MHz
	62 MHz	450 MHz

Q-Tuning by cw SAW



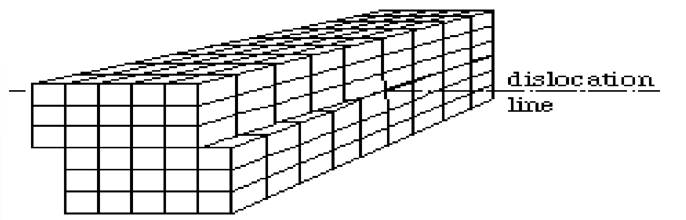


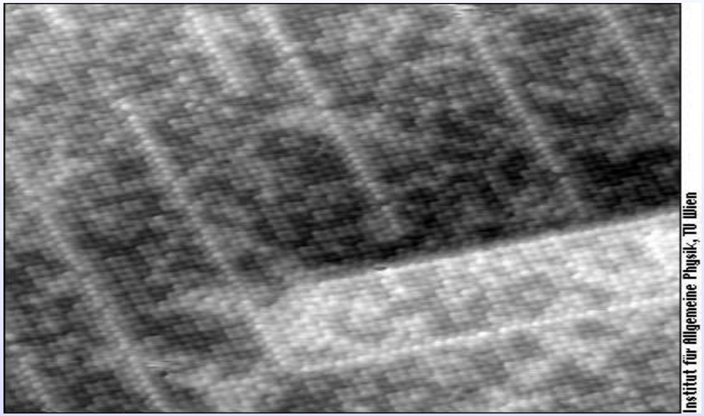
P_{res}=-40dBm, B=12Tesla, F_{saw}=303MHz, T=4K



Step like decrease of Q by increased acoustic loading of the beam

Dislocations





T. U. Berlin

- Dislocations are line imperfections
- Can be described by a vibrating-string model (Granato, Lücke).
- Cause for amplitude dependent internal friction (ADIF).

Measured by:

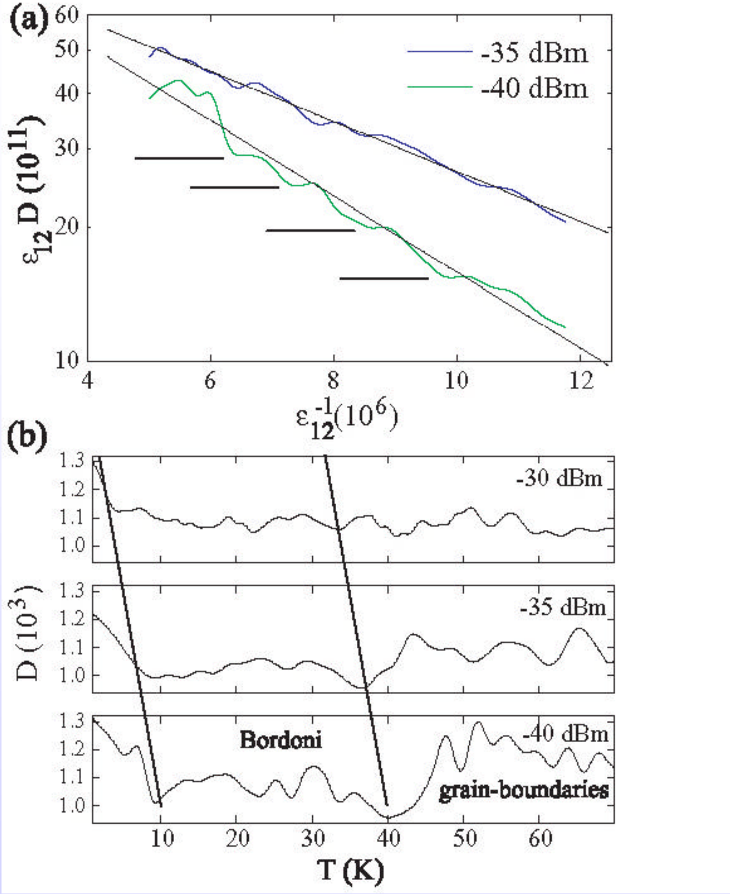
- Temperature dependence of *Q (Bordoni Peak in Au)*
- ADIF

How to make ADIF measurements with NMS:

SAW induced motion of clamping points results in strains ε of 10^{-4} in the beam.

SAW exerts forces on the resonator, orders of magnitudes larger than conventional techniques

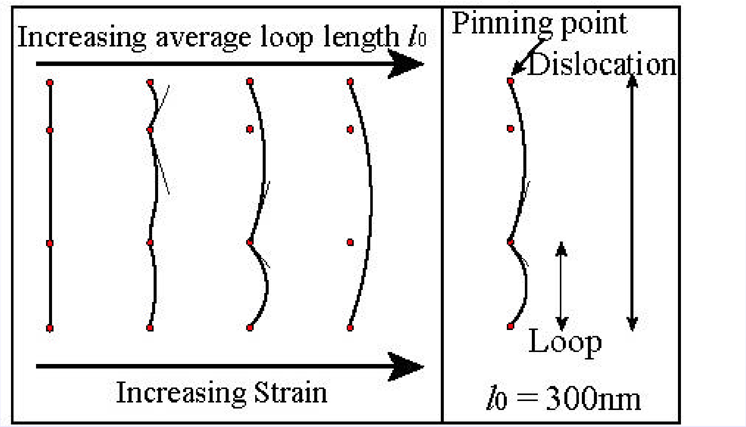
Dislocations – The Evidence



Granato Lücke Plots - Linear

Gold layer is cause for dissipation (grains, dislocations)

ADIF



For a **statistical** distribution of loop lengths:

$$Q^{-1}(e) = (C_1/e)\exp(-C_2/e)$$

$C_2 \approx 1/l$ where l av. loop length

Temperature dependence of *Q*

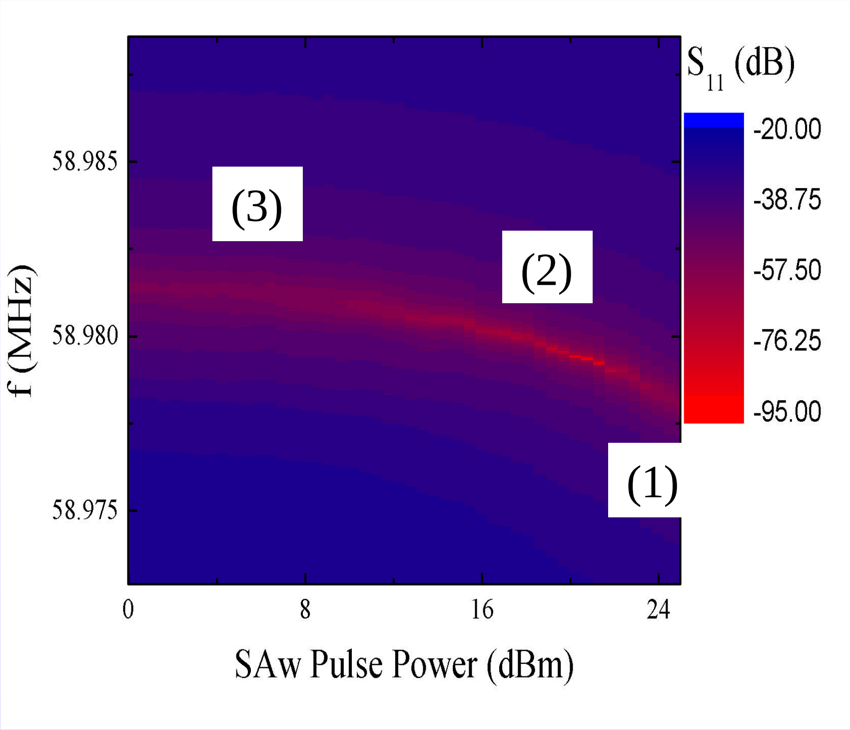
maximum dissipation when

$$wt = 1,\ t = t_0 e^{E/kT}$$

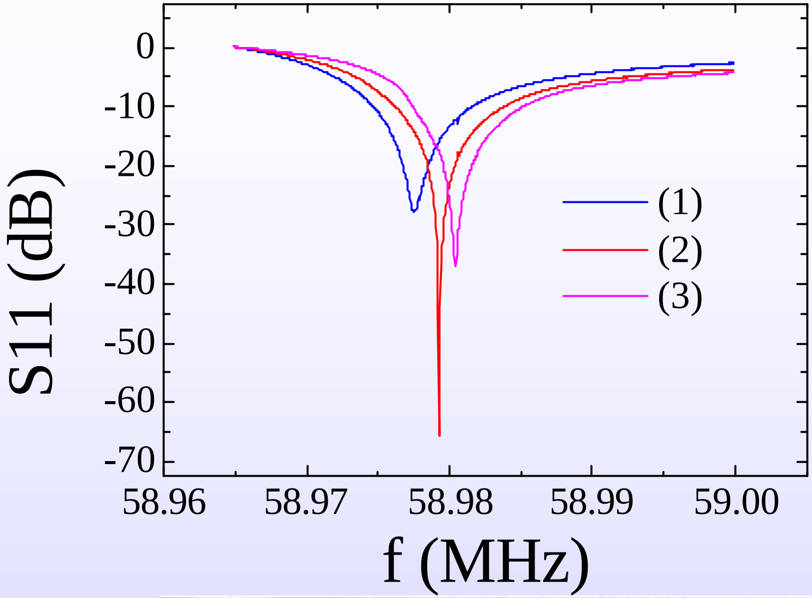
τ relaxation time, E activation energy

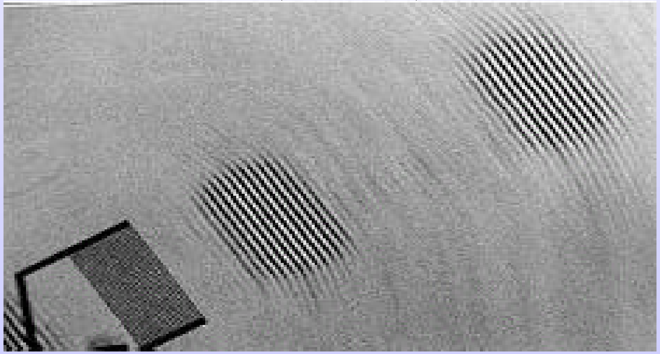
Acoustic excitation

Q enhancement by pulsed SAW

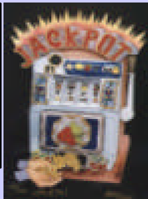


Pulse period: 340ns; Pulse width: 20ns

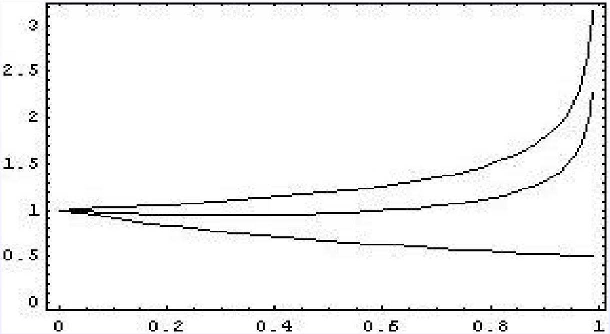


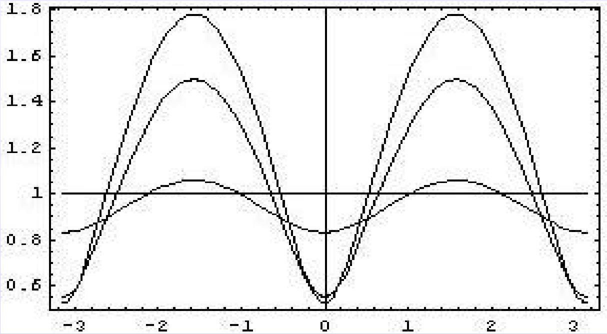


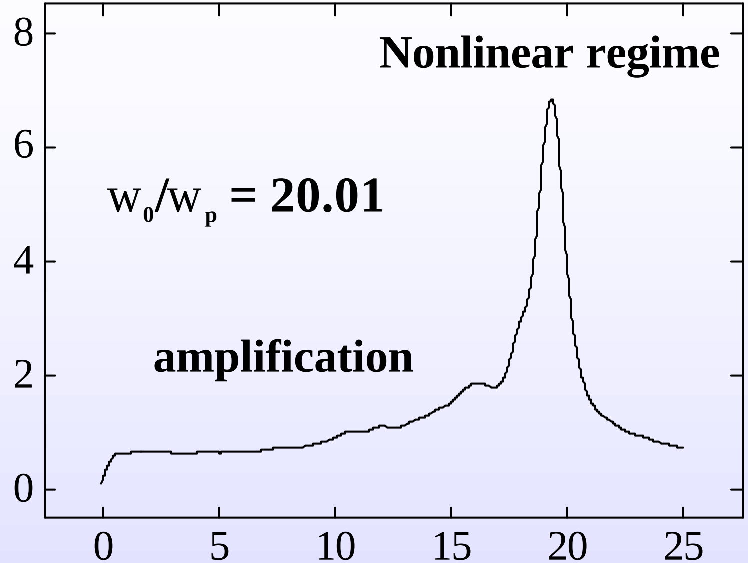
SAW offers direct mechanical excitation which doesn't scale with size *L*.



Acoustic excitation







Parametric resonances for MEMS:
K. L. Turner, et. al. Nature Vol 396, 149

In nonlinear resonators not necessarily phase-matching needed

VOLUME 89, NUMBER 27 PHYSICAL REVIEW LETTERS 30 DECEMBER 2002

Observation of Non-Phase-Matched Parametric Amplification in Resonant Nonlinear Optics

Stéphane Coen,[1,2] David A. Wardle,[1] and John D. Harvey[1]

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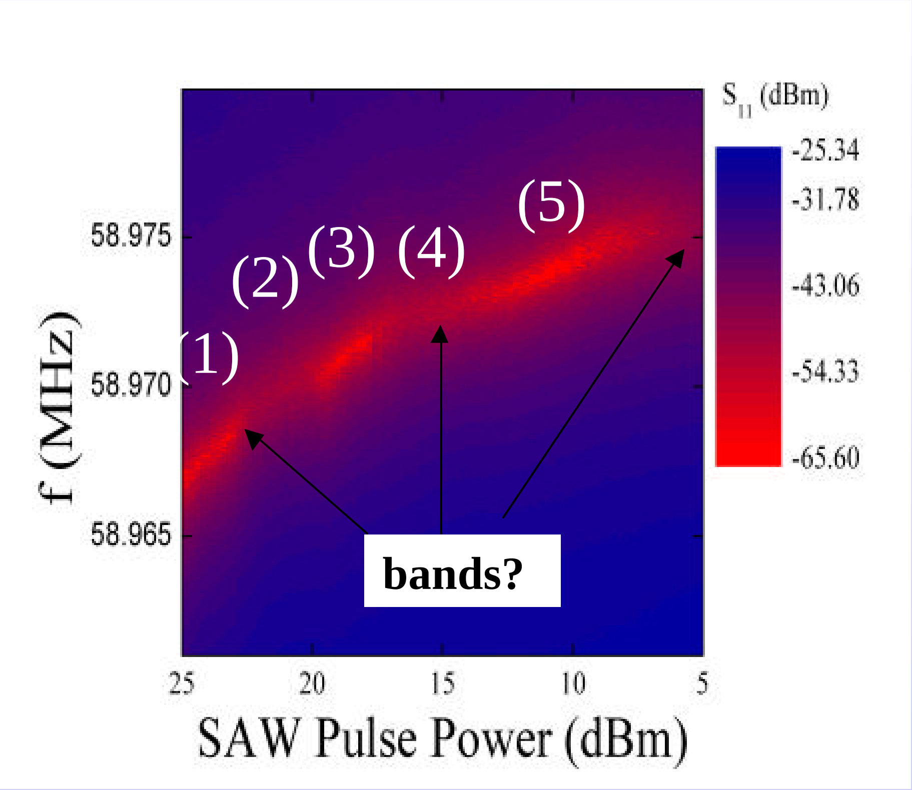
(Received 8 July 2002; published 13 December 2002)

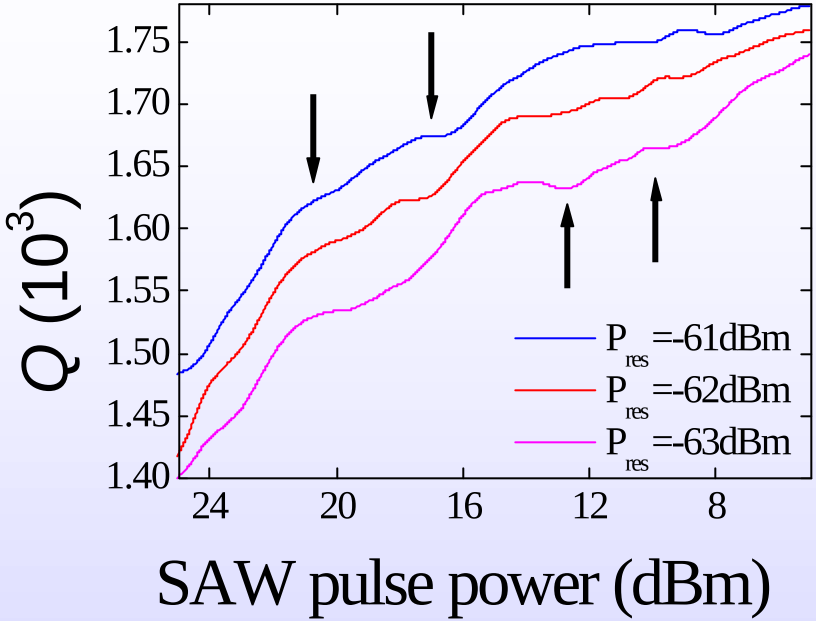
The coupling between a resonant excitation and a nonresonant parametric process in a nonlinear system is studied experimentally under non-phase-matched conditions. Our study performed in the context of anti-Stokes stimulated Raman scattering provides a clear observation of the self-induced phase matching of a parametric process. A close agreement with theoretical predictions is observed.

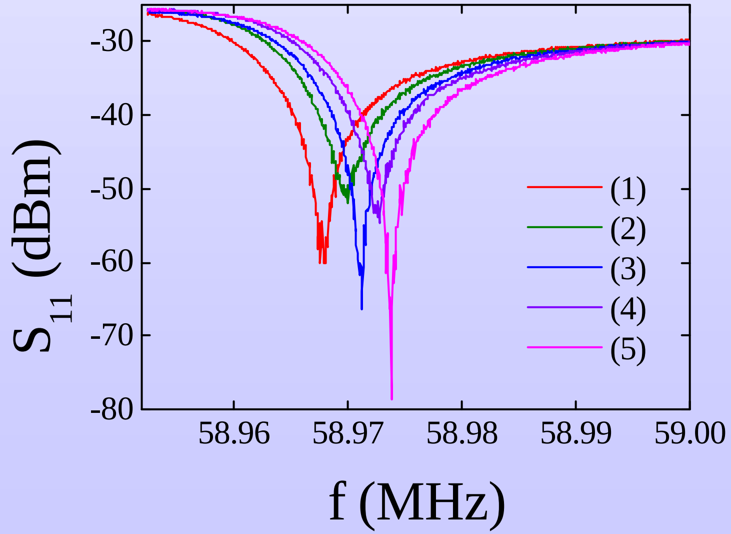
DOI: 10.1103/PhysRevLett.89.273901 PACS numbers: 42.65.Dr, 42.65.Hw, 42.65.Sf, 42.81.–i

Further parametric effects

NEMS impedance spectrum with increasing SAW pulse power



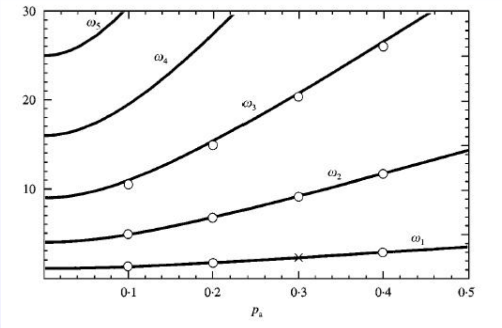




Pulse period: 160ns; Pulse width: 20ns; SAW frequency 303 MHz; B=12T

Fast off-resonant excitation

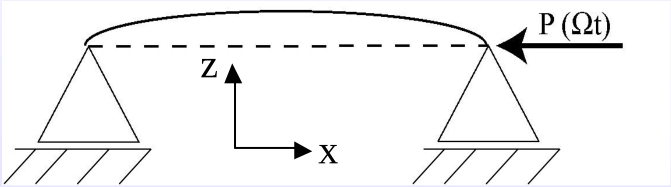
A way of control

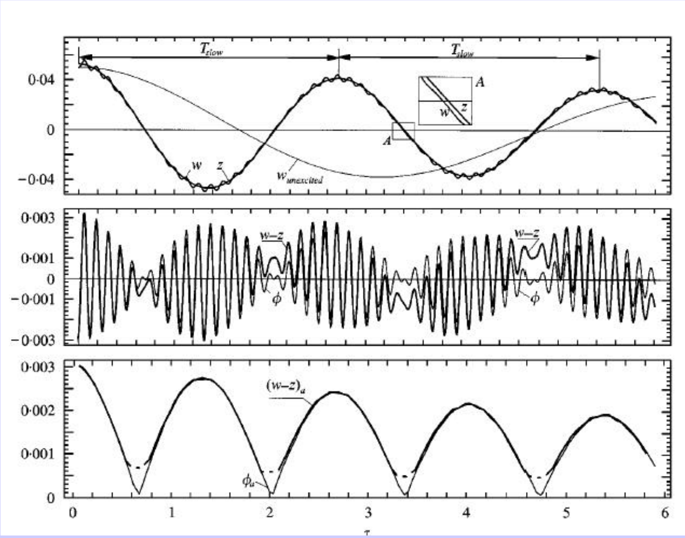


THE INFLUENCE OF FAST EXCITATION ON A CONTINUOUS SYSTEM

D. TCHERNIAK

Department of Solid Mechanics, Technical University of Denmark, Building 404, DK-2800 Lyngby, Denmark





Fast off-resonant excitation may shift equilibria, eigenfrequencies, ...

Divide motion in fast and slow components and write down equation for slow component

$$\frac{\partial^2 z}{\partial t^2} + \left(\frac{1}{p^4} + \frac{1}{2}\Delta\Omega^2\right)\frac{\partial^4 z}{\partial x^4} = 0$$

where $\Delta\Omega$ amplitude of fast excitation.

Fast off-resonant excitation

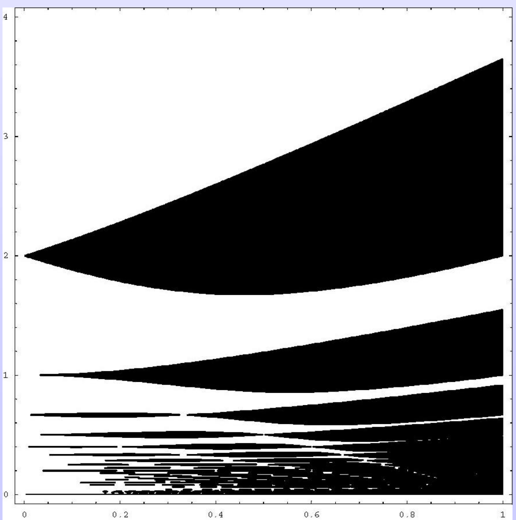
From pulsed fast excitation follows parametric oscillator equation

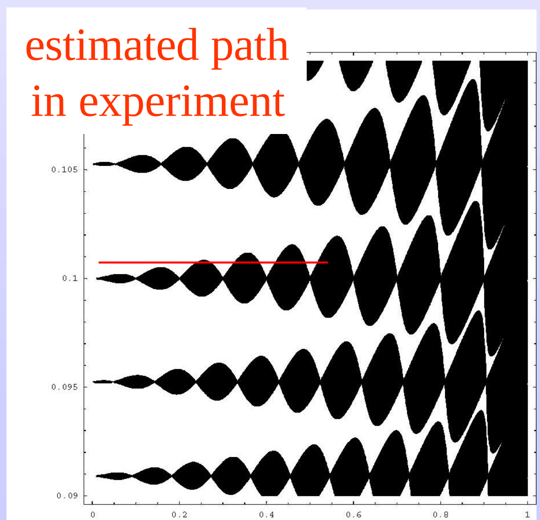
$$\frac{\partial^2 u_1(t)}{\partial t^2} + \left(1 + \frac{p^4}{2}\Delta\Omega(t)^2\right) u_1(t) = 0$$

‚stable‘ and ‚unstable‘ regions are determined by

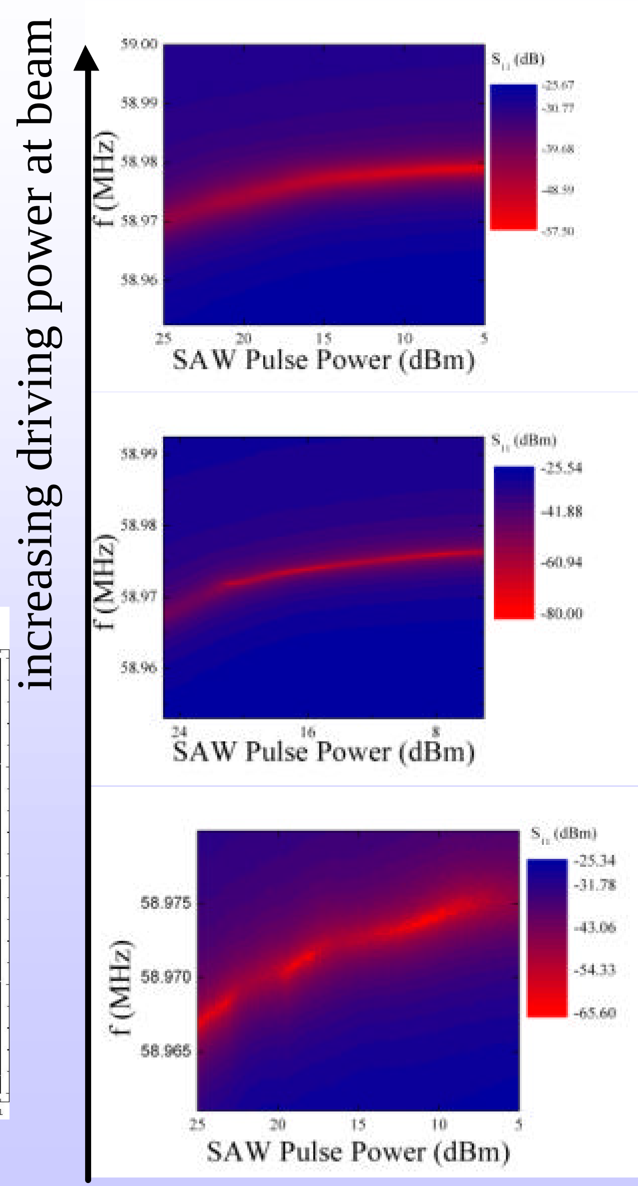
$$\left| \frac{\Omega^2 \cos\left(\frac{2p\Omega}{w}\right) - \Delta\Omega^2 \cos\left(\frac{2p\Delta\Omega}{w}\right)}{\Omega^2 - \Delta\Omega^2} \right| \leq 1$$

Ω/ω



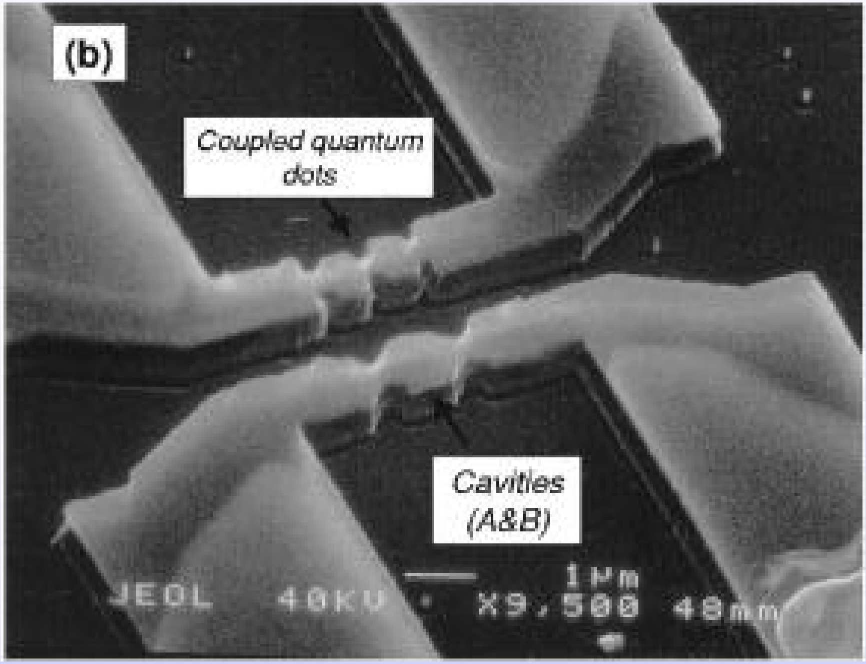


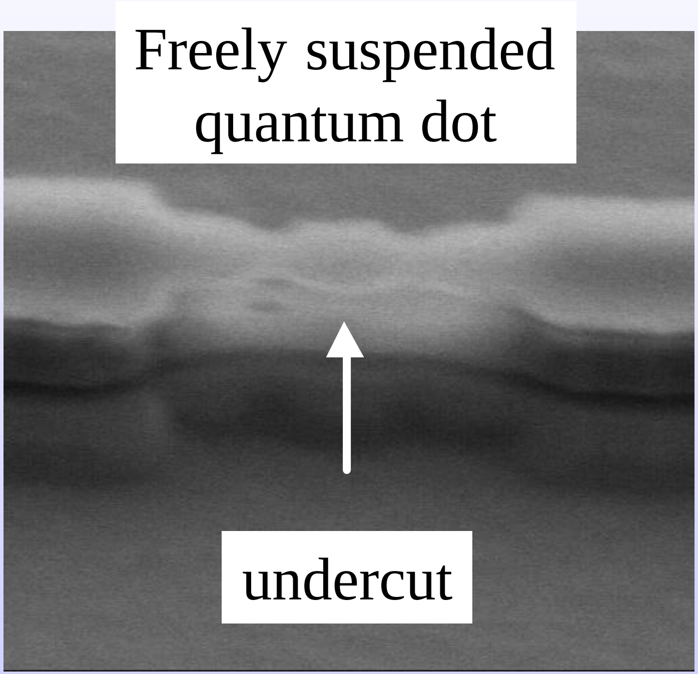
$\Delta\Omega/\omega$



Freely suspended 2DEGs and SAW

2DEG as a `Au-free` detector for motion



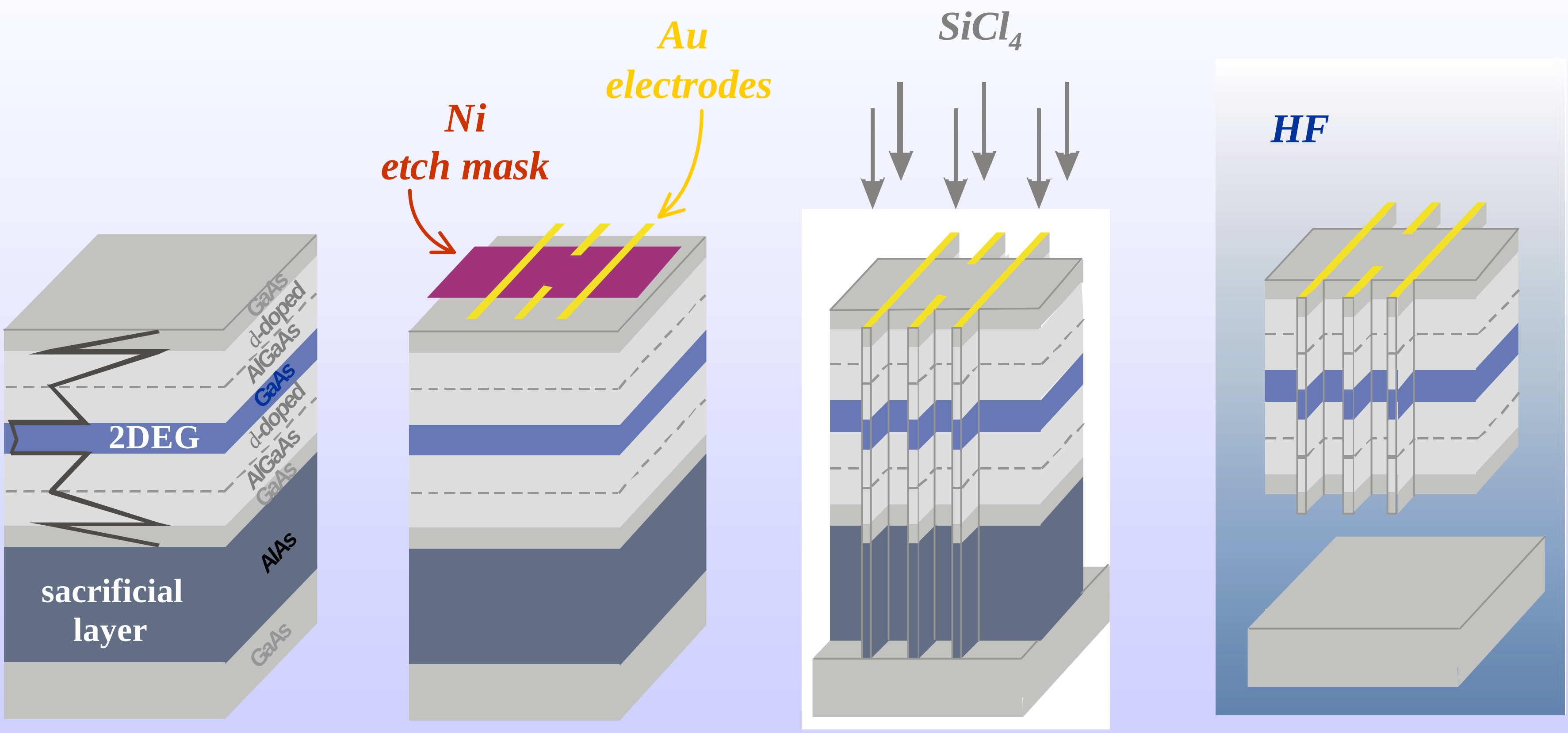


R. H. Blick, et. al.,
PRB 62, 24 17103 (2000)

length of suspended region: 1mm
Gold covered beam replaced by freely suspended 2DEG

sample processing

how to suspend a low-dimensional electron gas



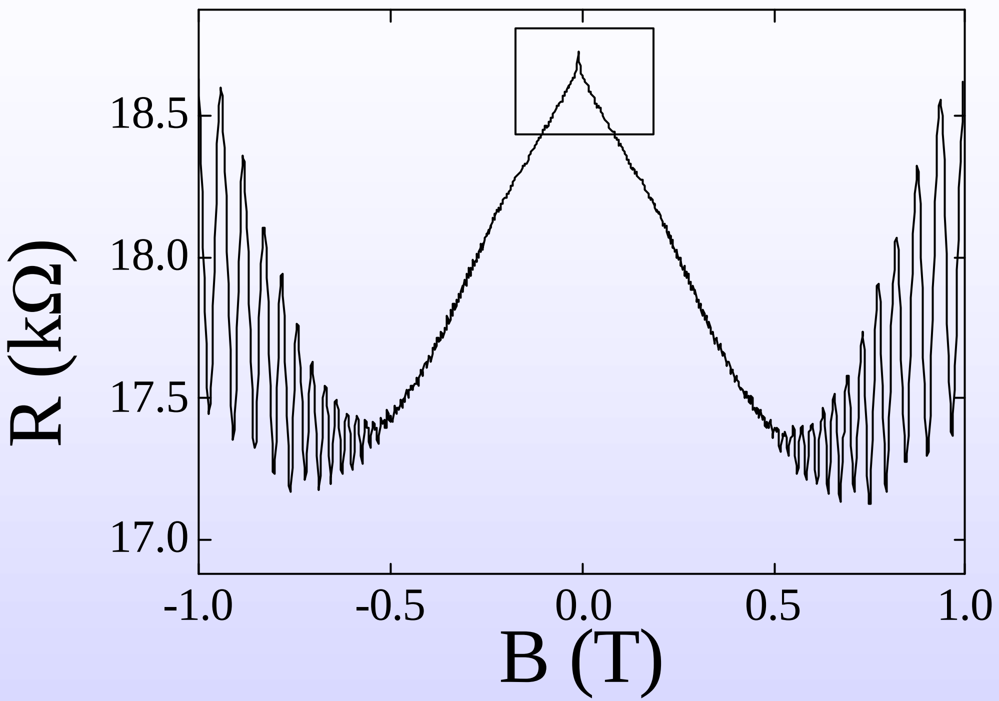
wafer material
n_s = 9.1 · 10^{11} cm^{-2}
m = 234,000 cm^2/Vs

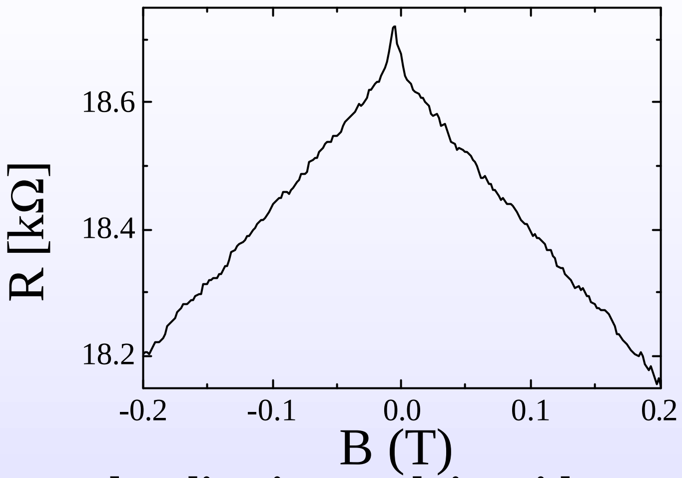
e-beam lithography
1) Au electrodes
2) Ni etch mask

reactive ion etch (ICP RIE)

0.1% hydrofluoric etch

Magnetotransport in suspended 2DEGs

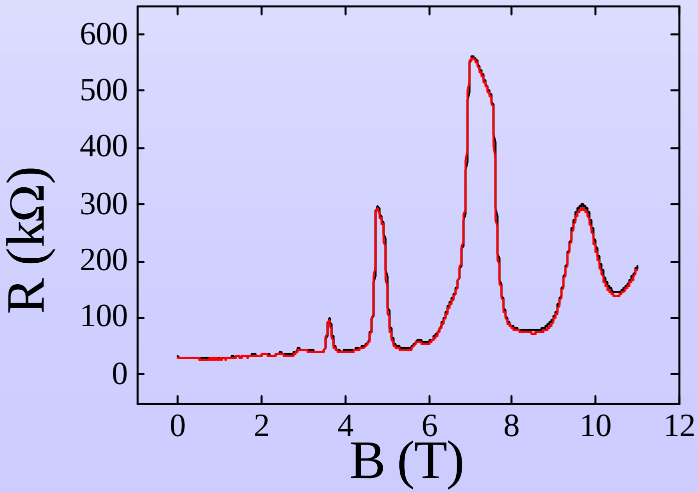




localization peak is evidence for free suspension

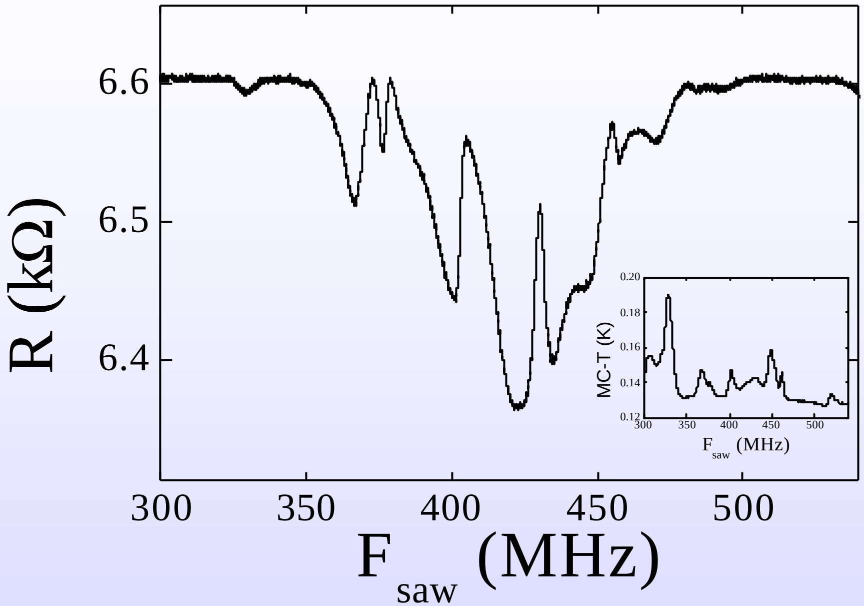
From SdH oscillations

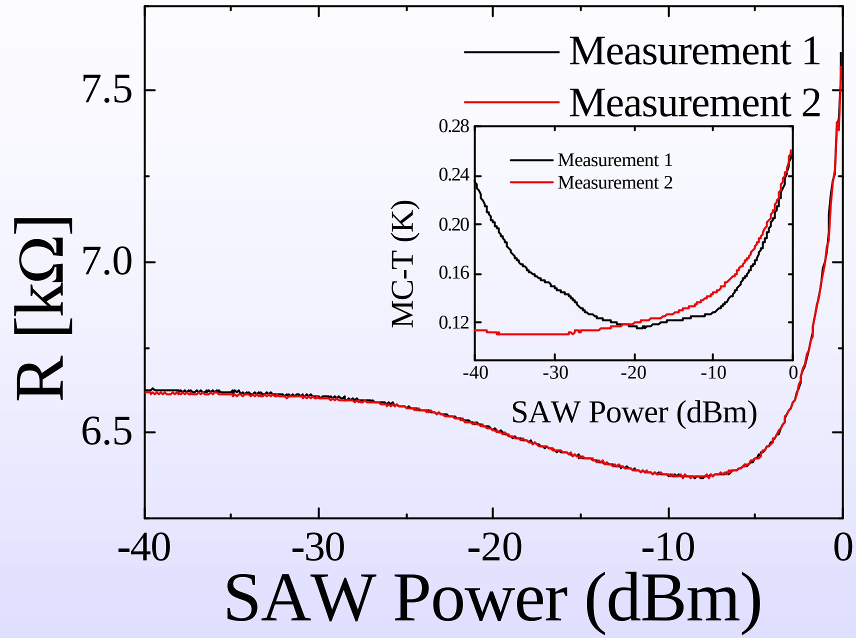
$$n_S \approx 10^{12} \left(\frac{1}{cm^2}\right)$$



E. Höhberger et. al., Physica E 12 (2002)
J. Kirschbaum et. al., APL 81,2 (2002)

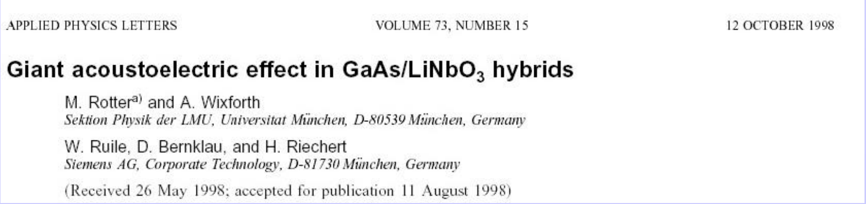
SAW & freely suspended 2DEG





Time domain measurement
over IDT delayline

Acoustic excitation observable
via resistance
acoustoelectric effect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Giant acoustoelectric effect in GaAs/$LiNbO_3$ hybrids

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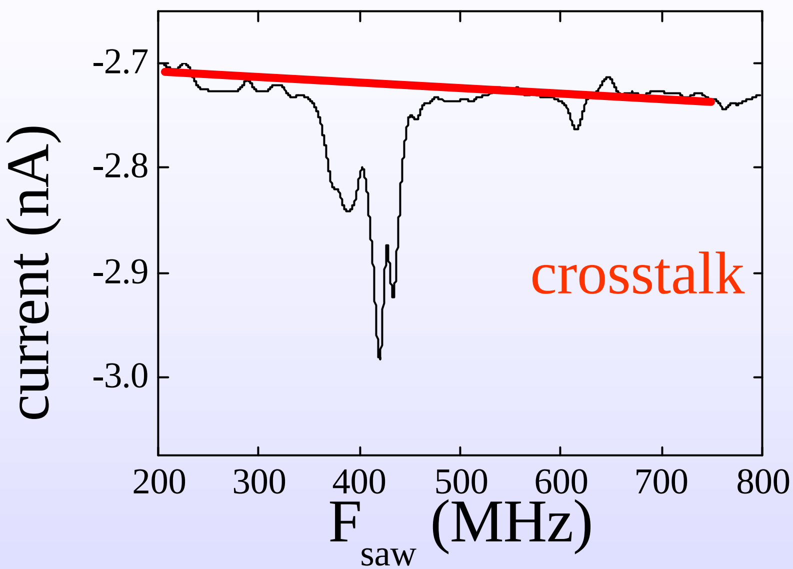
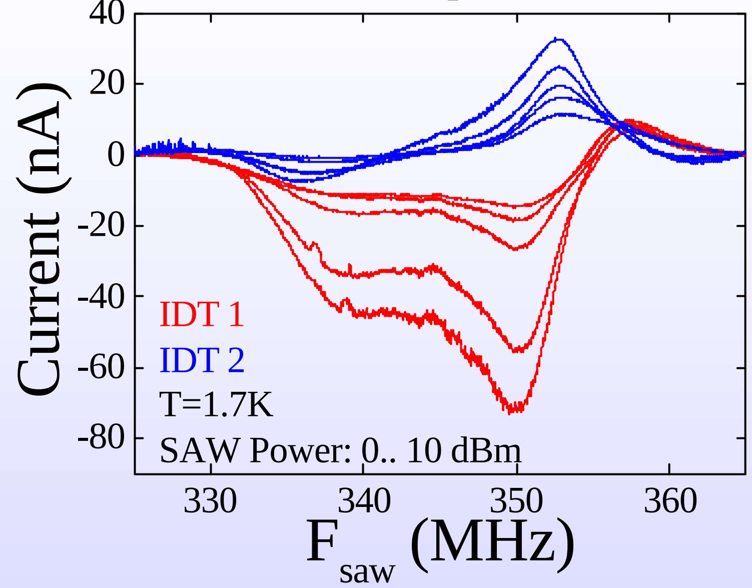
Acoustoelectric current in freely suspended 2DEGs

Sample 1



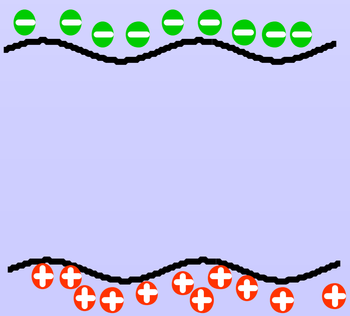
Sample 2



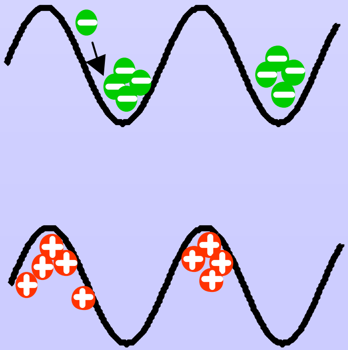
J, Cunningham, V. I. Tylanskii, J. M. Shilton, and M. Pepper Phy. Rev. B 62, 3 (1999) p. 1564

Piezoelectric fields in suspended GaAs beam drive currents

Small SAW amplitudes



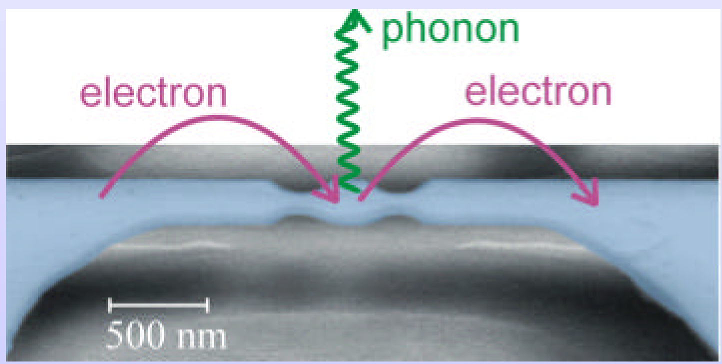
Large SAW amplitudes



Mechanical excitation of free-standing quantum dots:
cavities for electrons AND phonons

quantum dot:

- 0D electron island
- discrete electronic states
- single electron tunneling (SET)



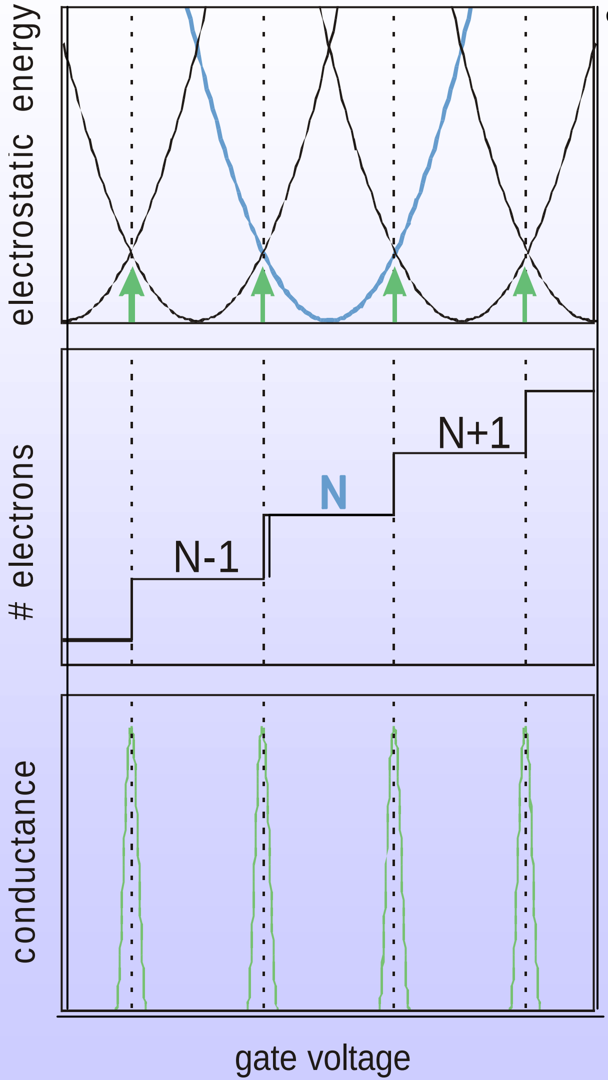
free-standing nanostructure:

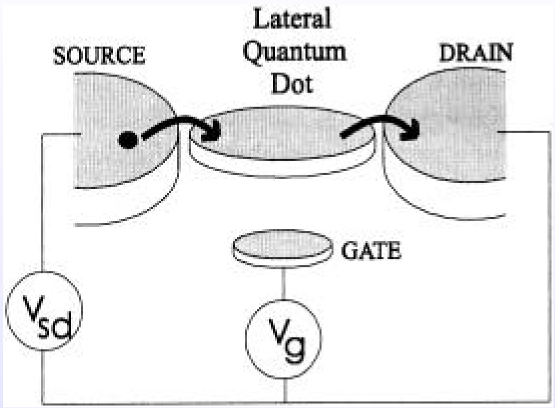
- phonon cavity
- discrete phonon modes
- van Hove singularities

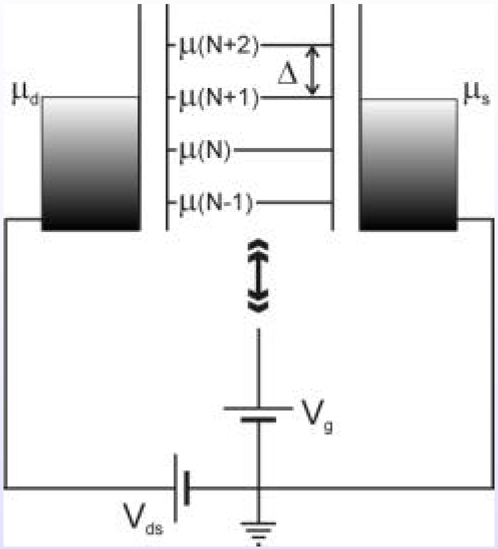
electron-phonon coupling
dissipation

Coulomb blockade

and single electron tunneling







electrostatic energy

$$E(N,Q_g) = \frac{(Ne - Q_g)^2}{2C_\Sigma}$$

electrochemical potential

$$\mu(N+1) = E(N+1) - E(N)$$

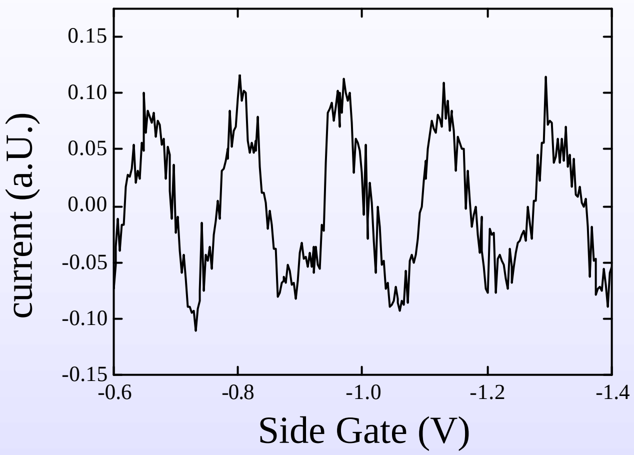
$$= \frac{e^2}{C_\Sigma}(N + 1/2) - \frac{eQ_g}{C_\Sigma}$$

addition energy

$$\Delta = \mu(N+2) - \mu(N+1) = \frac{e^2}{C_\Sigma}$$

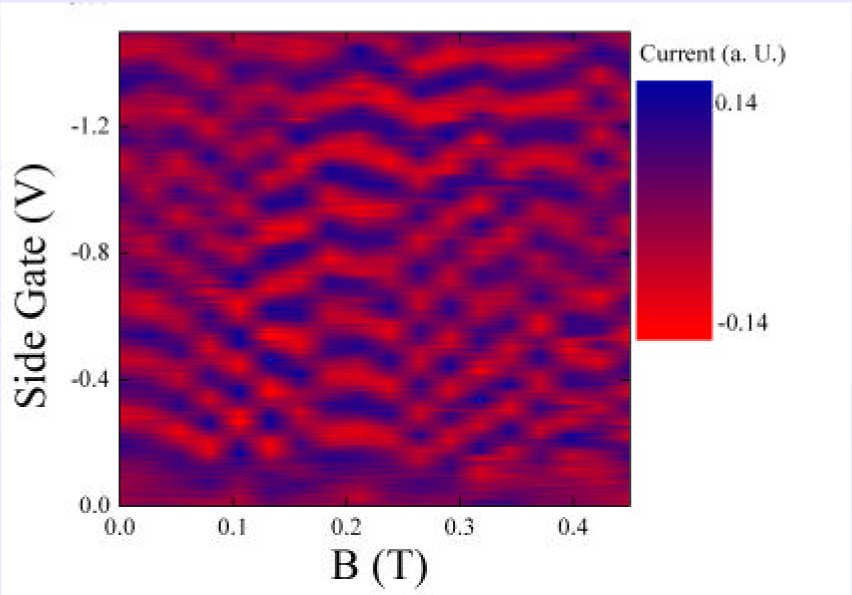
Freely suspended Quantum Dot

Tune the freely suspended 2DEG into the tunneling regime



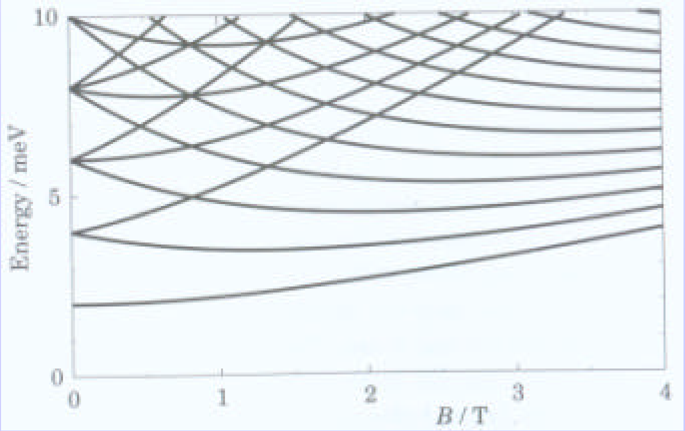
Oscillations in the current against side gate potential

Coulomb Blockade



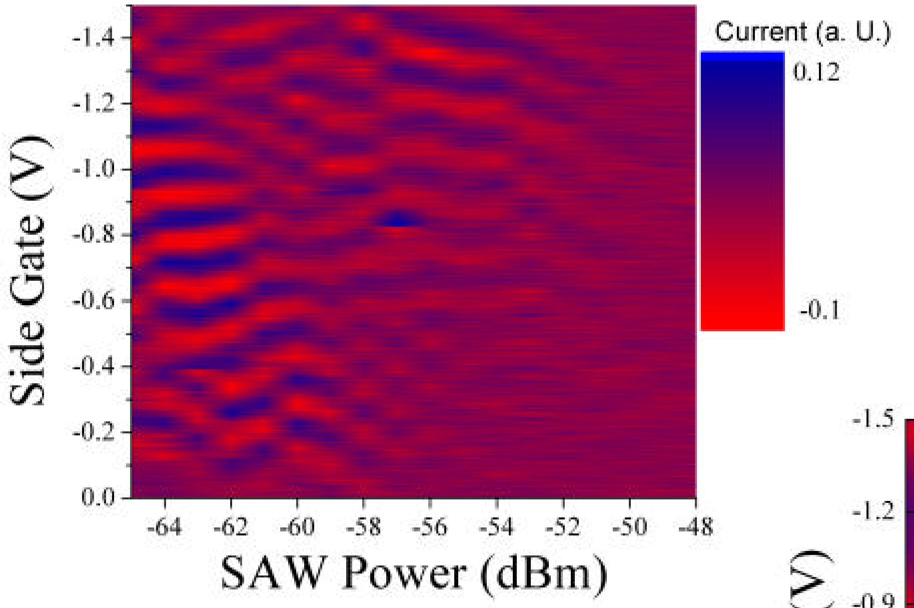
T = 180 mK

Dot in a magnetic field



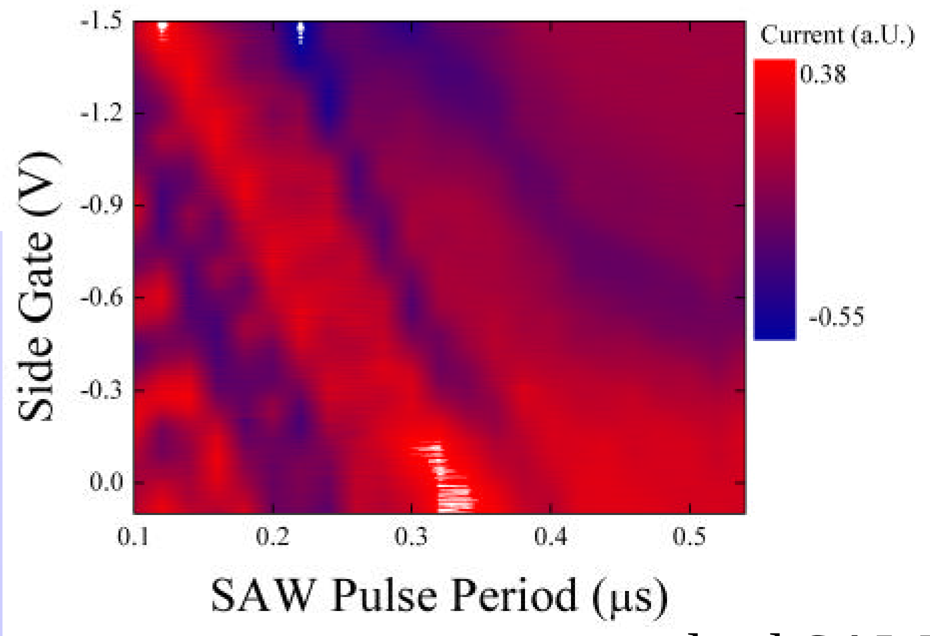
Freely suspended Dot interacting with SAW

cw SAW



•With increased SAW power Coulomb Blockade lifted (heating effect)

•At low SAW powers oscillations get shifted (tuning of the dot)



pulsed SAW

Vision:
Use a freely suspended quantum dot as a detector and drive it with SAW

The End

Thank you very much

Pulsed excitation revisited

A Piecewise Linear Suspension Bridge Model:

Nonlinear Dynamics and Orbit Continuation

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