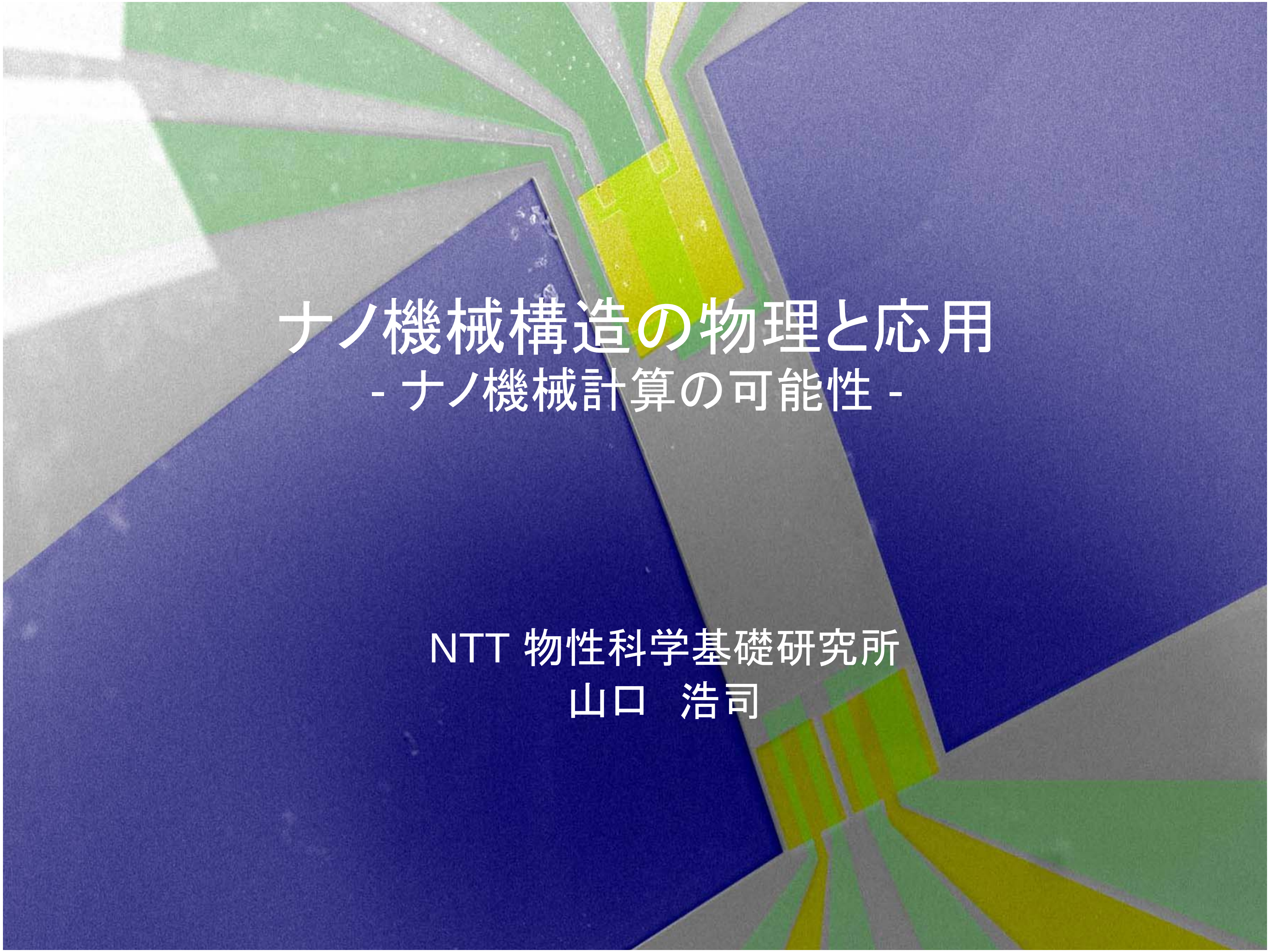


ナノ機械構造の物理と応用

- ナノ機械計算の可能性 -

NTT 物性科学基礎研究所
山口　浩司

What is the minimum energy required to carry out a computation ?

The computation can actually be done with no minimal loss of energy !!

The energy cost comes in the step of erasure of the information; E = kTlog2 per one bit.

⇩

If your computer is reversible, the energy loss could be made as small as you want.

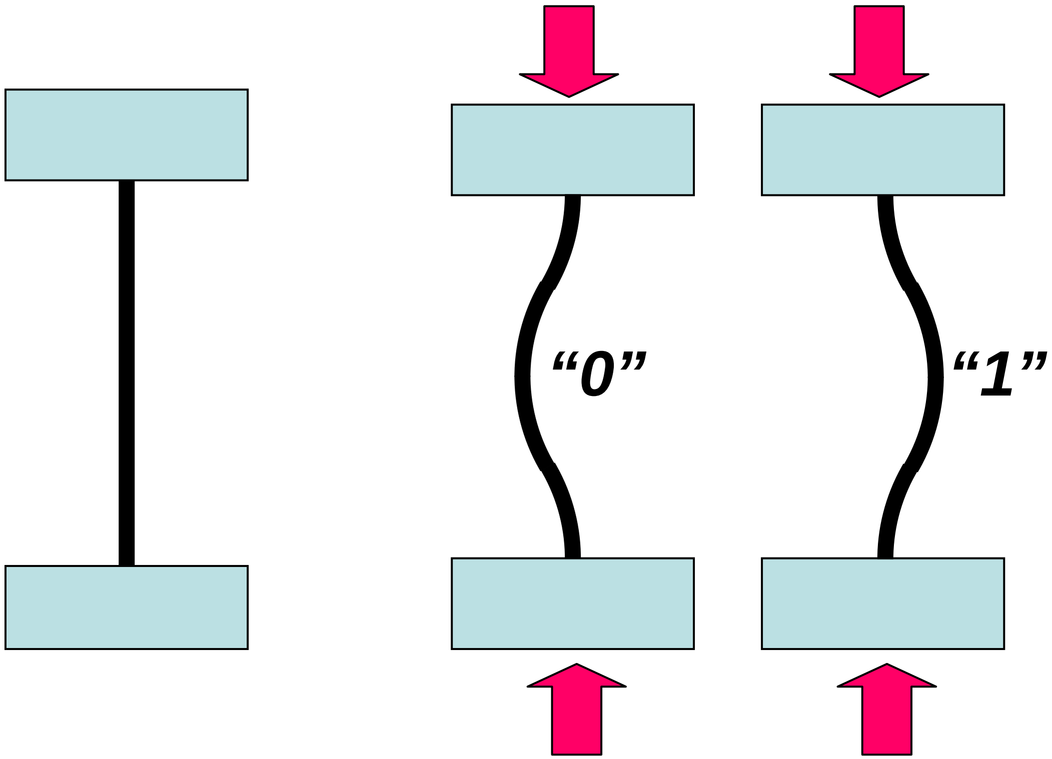
C. H. Bennett, R. Landauer etc.

Two Types of Mechanical Reversible Logic

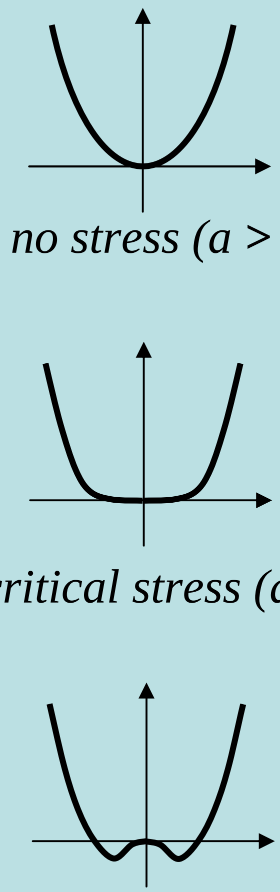
by

Ralph C. Merkle
Xerox PARC
3333 Coyote Hill Road
Palo Alto, CA 94304
merkle@xerox.com

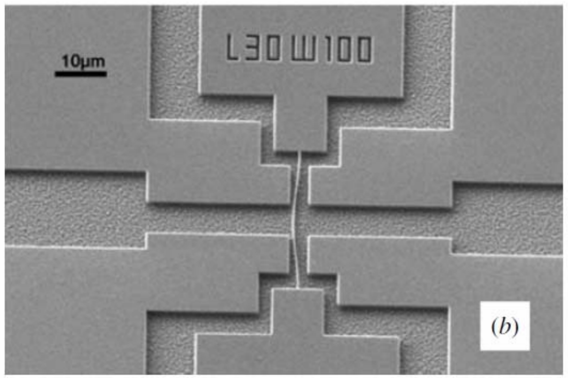
http://www.zyvex.com/nanotech/mechano.html
and Nanotechnology, 4, 114 (1993)

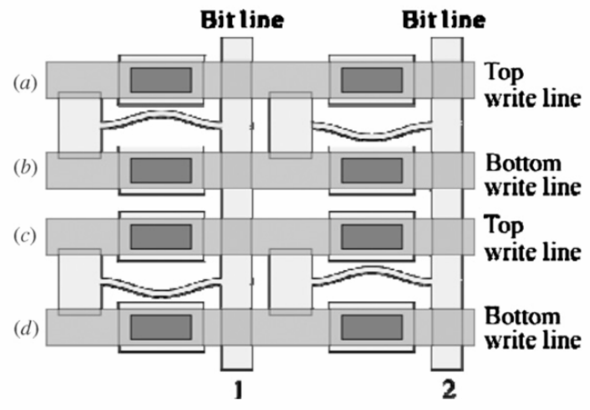


$$V(x) = ax^2 + bx^4, \quad (b > 0)$$

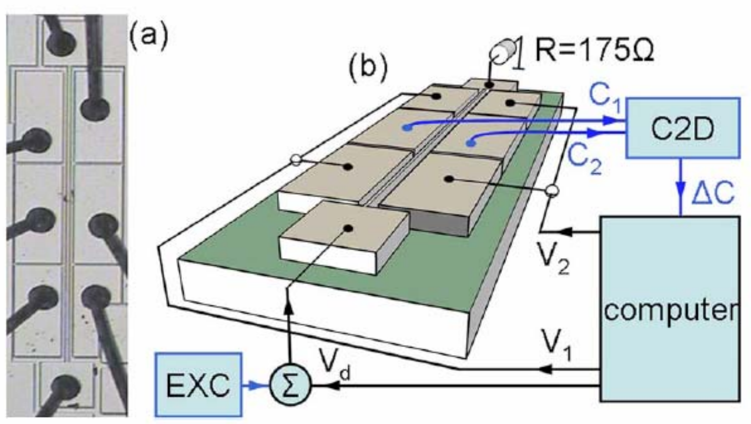


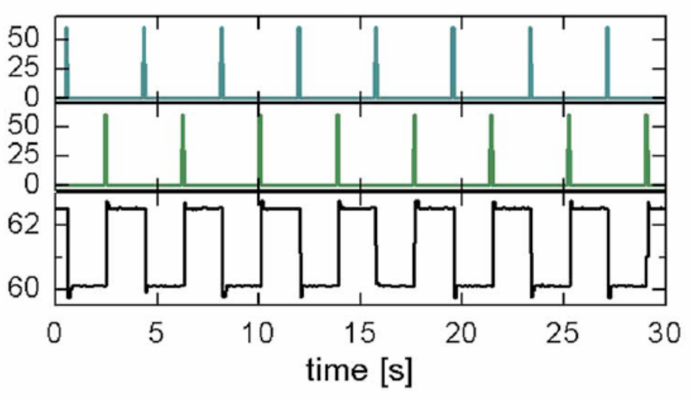
Bistable MEMS memory using buckled beams





B. Charlot et al. J. Micromech. Microeng. 18, 045005 (2008)

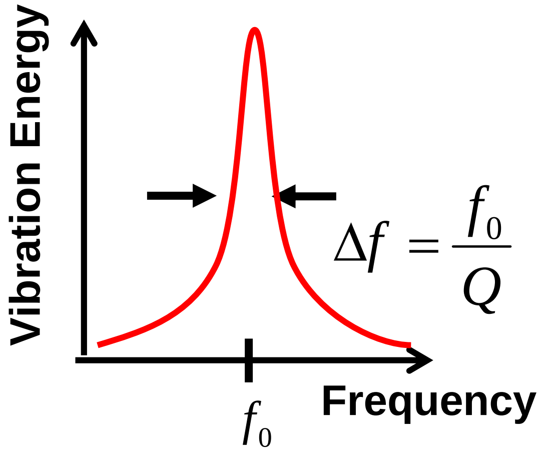




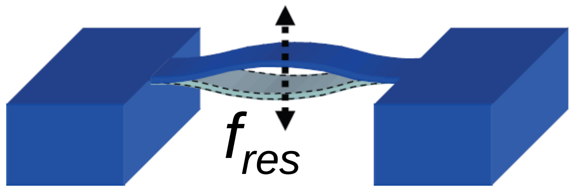
D. Roodenburg et al. Appl. Phys. Lett. 94, 183501 (2009)

Mechanical resonators

Micro/Nanomechanical Resonators



f_0 : 100Hz -1GHz, Q: 10^3 -10^6

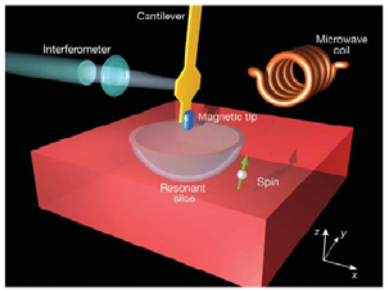


Beam resonator

Equation of motion

$$m\frac{d^2x}{dt^2} + \frac{m\omega_0}{Q}\frac{dx}{dt} + m\omega_0{}^2 x = F\cos\omega t$$

$$x(t) = \frac{f_0}{\sqrt{(\omega_0{}^2 - \omega^2)^2 + \omega_0{}^2\omega^2 / Q^2}}\cos(\omega t - \theta)$$



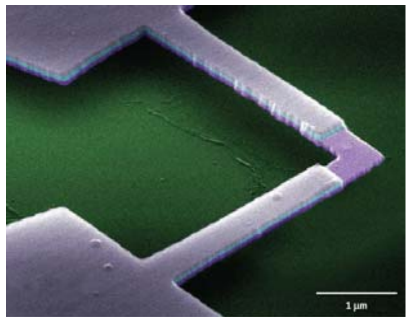
D. Rugar et al. Nature

Ultrasensitive Force/Mass Detection

- *Displacement detection up to femtometer scale (UCSB)*
- *Zeptogram mass sensing (Caltech)*
- *Single spin sensing (IBM)*

Logic Applications

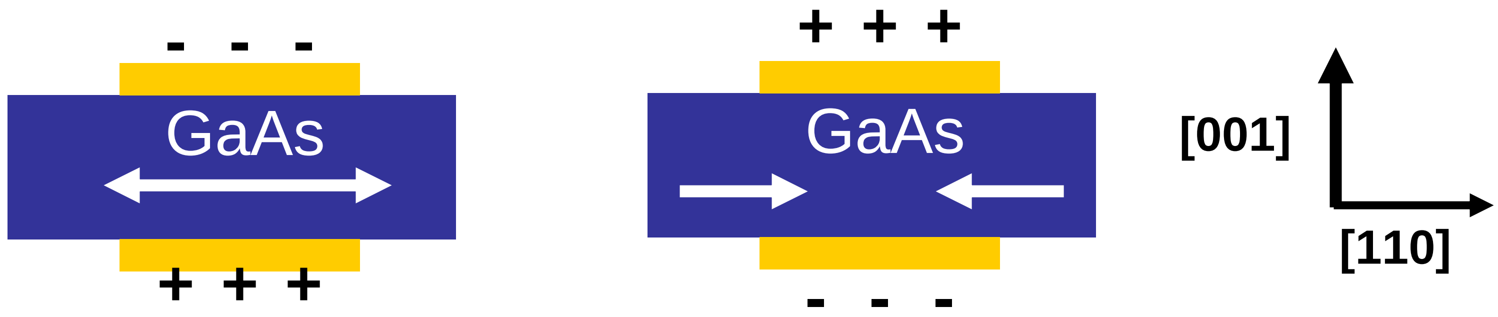
- *Bistability in nonlinear Duffing resonators (Boston, APL 2004)*
- *Mechanical XOR by coupled resonators (Caltech, Science 2007)*

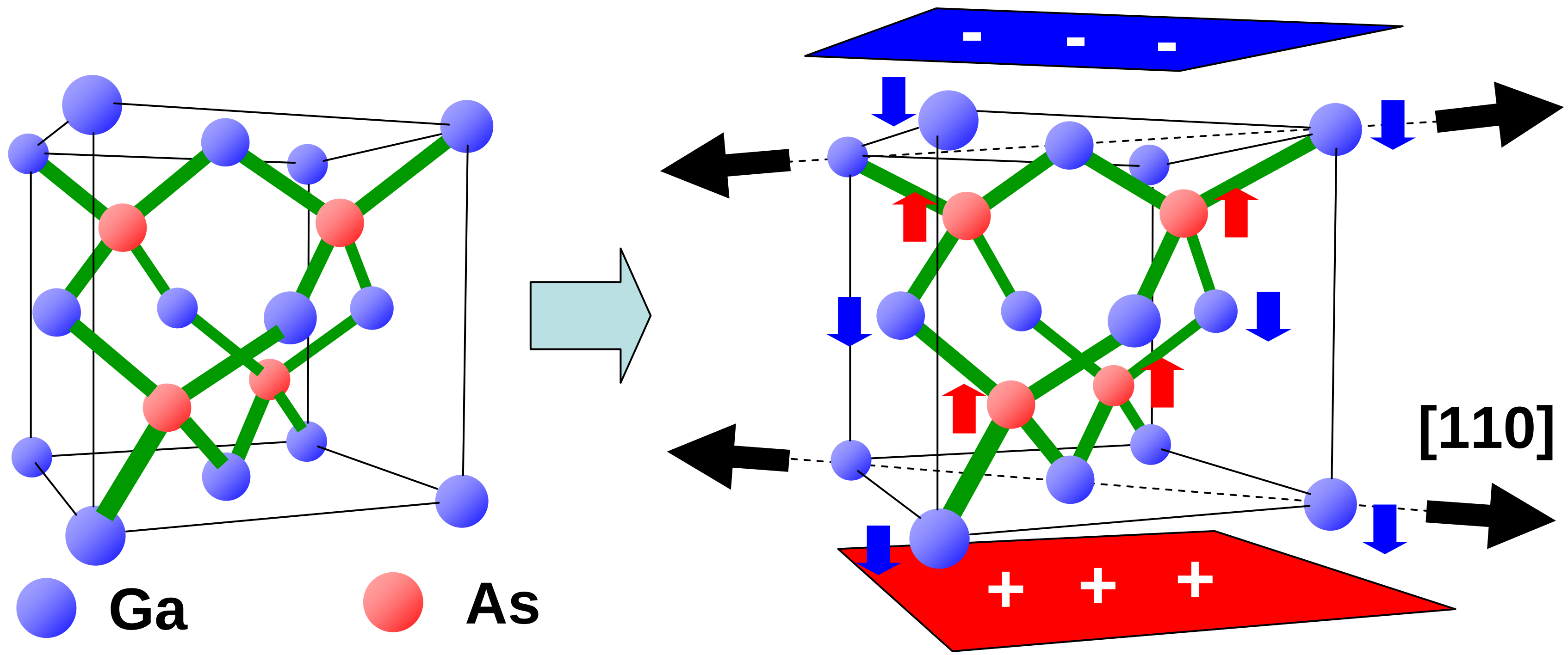


S.C. Masmanidis et al. Science

Piezoelectric effect in Zinc Blende structure

Strain-voltage transduction

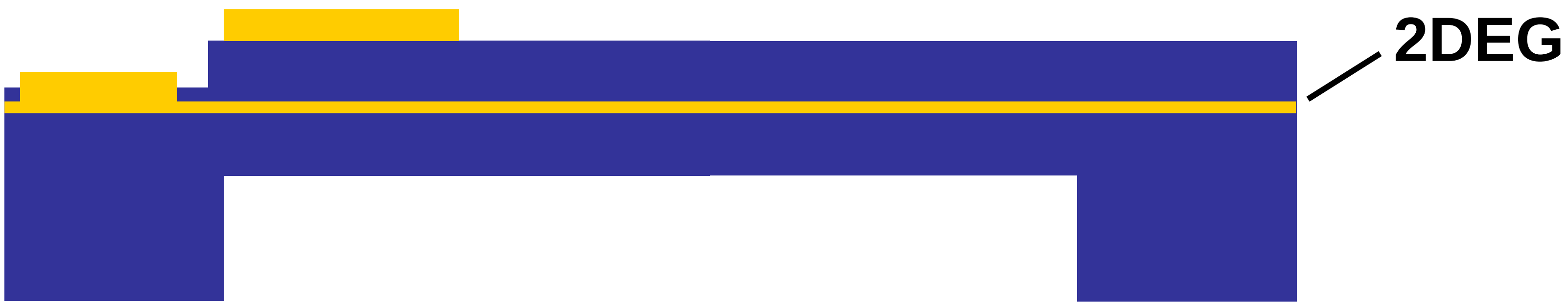




Piezoelectric effect in Zinc Blende structure

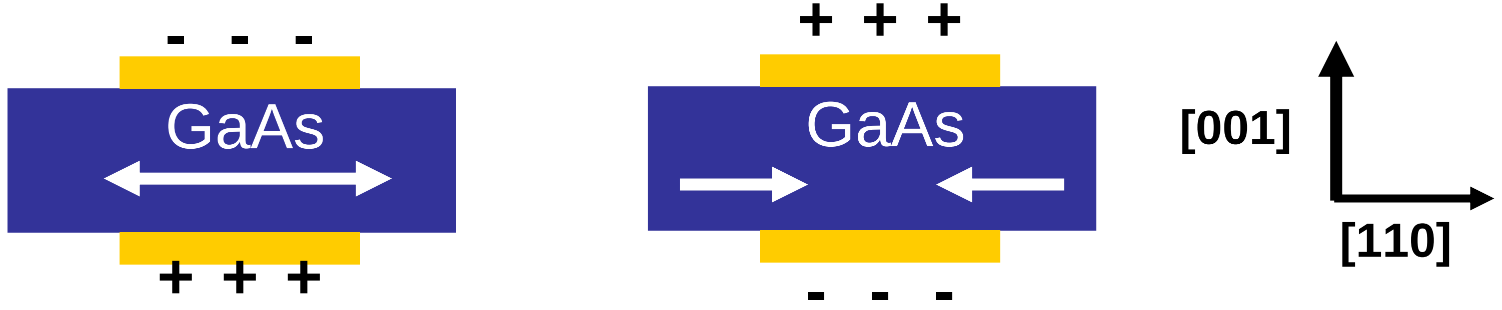
Strain-voltage transduction

Electrical actuation, detection and frequency control

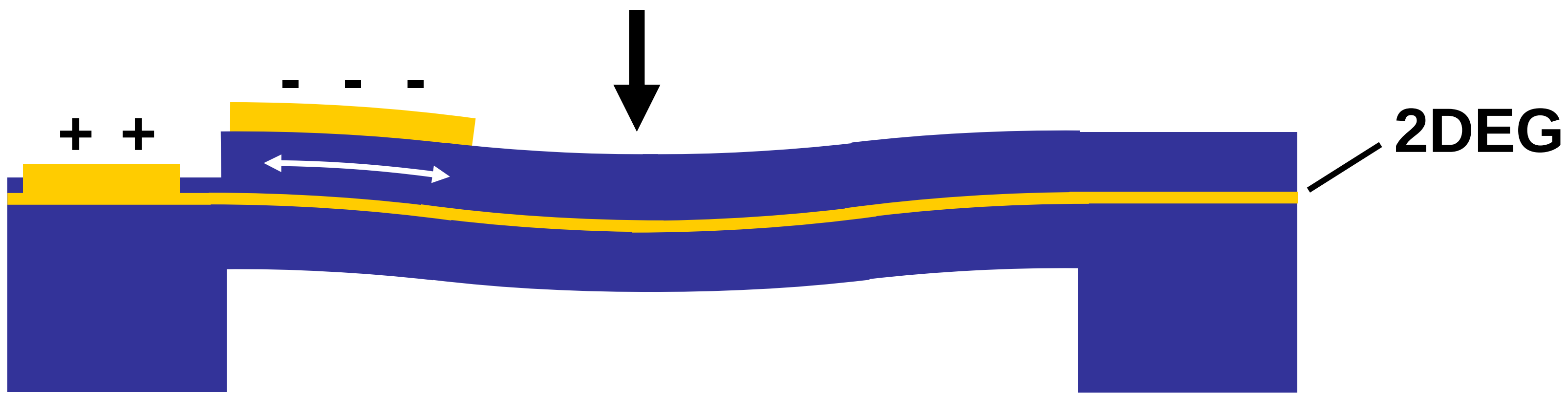


Piezoelectric effect in Zinc Blende structure

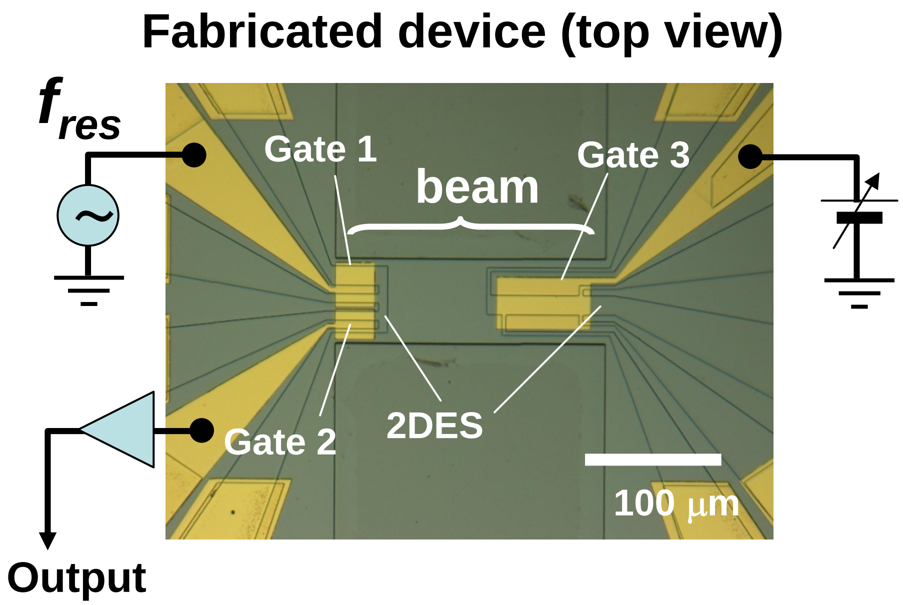
Strain-voltage transduction



Electrical actuation, detection and frequency control



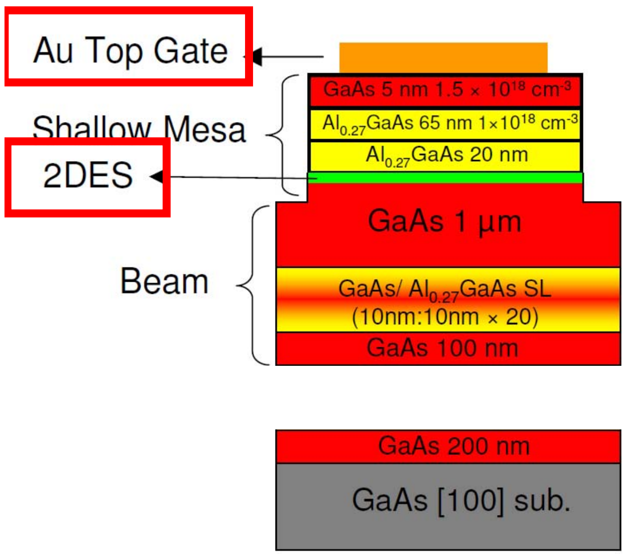
Piezoelectric mechanical resonator

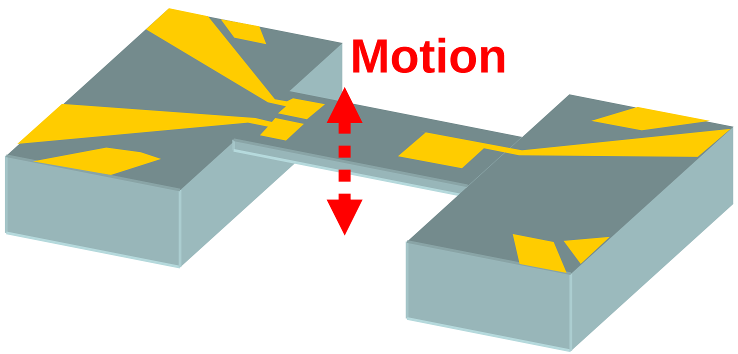


Gate 1: Application of AC voltage
→ Actuation through bending moment

Gate 2: Measurement of generated voltage
→ Beam-motion detection

Gate 3: Application of DC voltage
→ Resonance frequency modulation

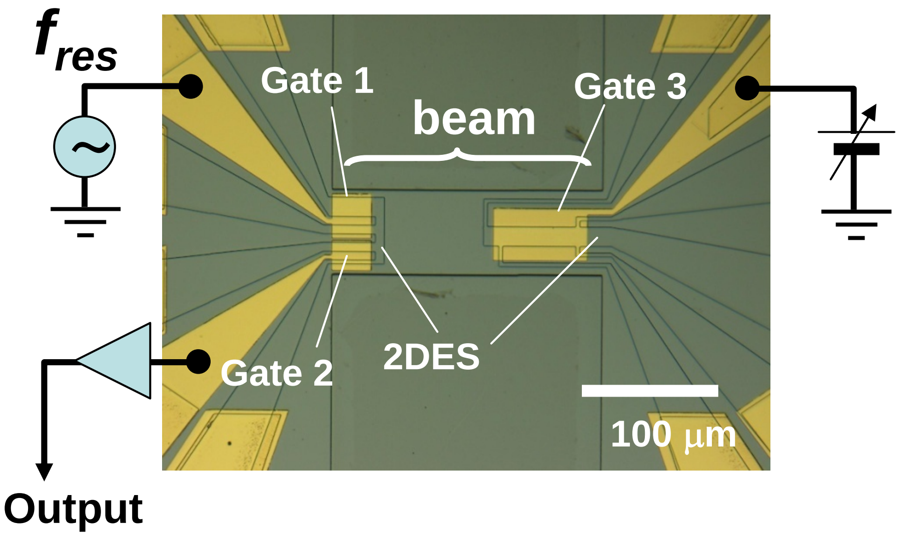




Applied AC voltage induces the vibration.
(f_{res} ~ 140 kHz, amplitude: 10 nm_{rms})

Piezoelectric mechanical resonator

Fabricated device (top view)



Gate 1: Application of AC voltage
→ Actuation through bending moment

Gate 2: Measurement of generated voltage
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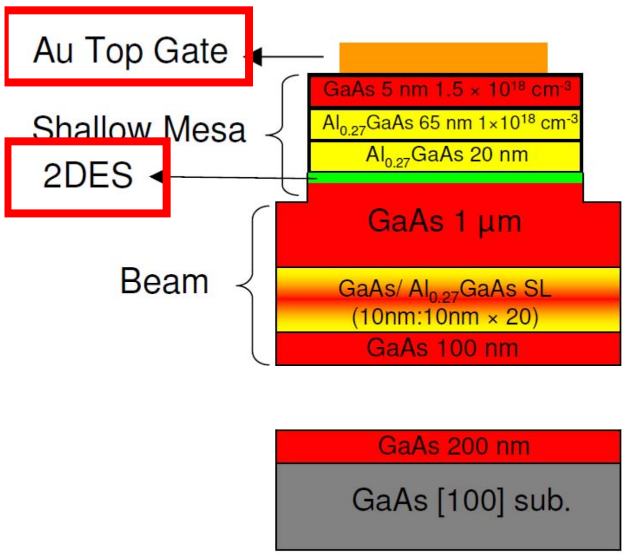
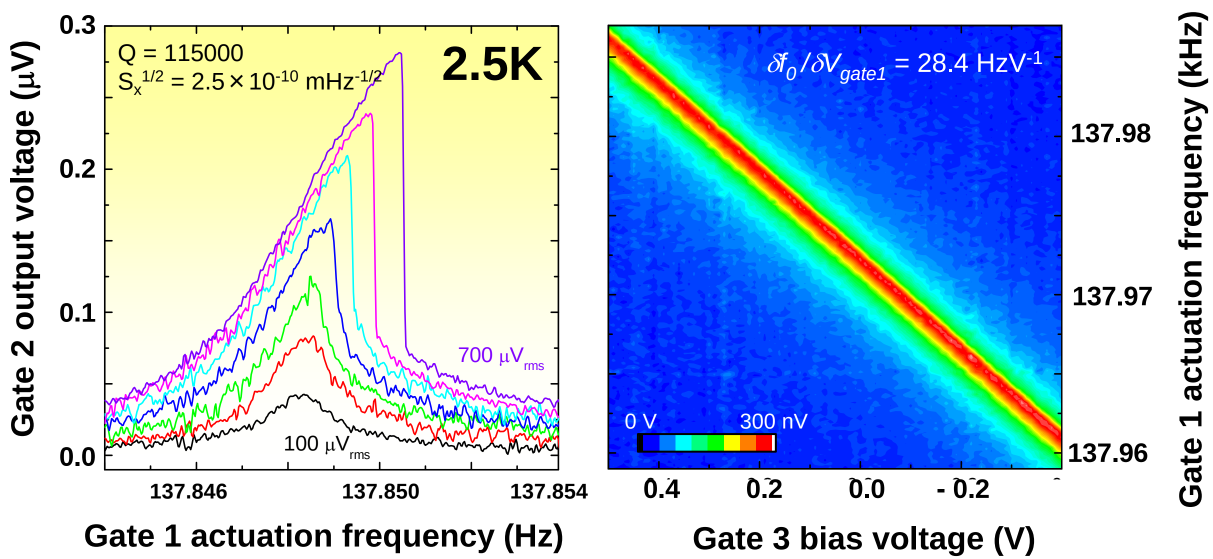
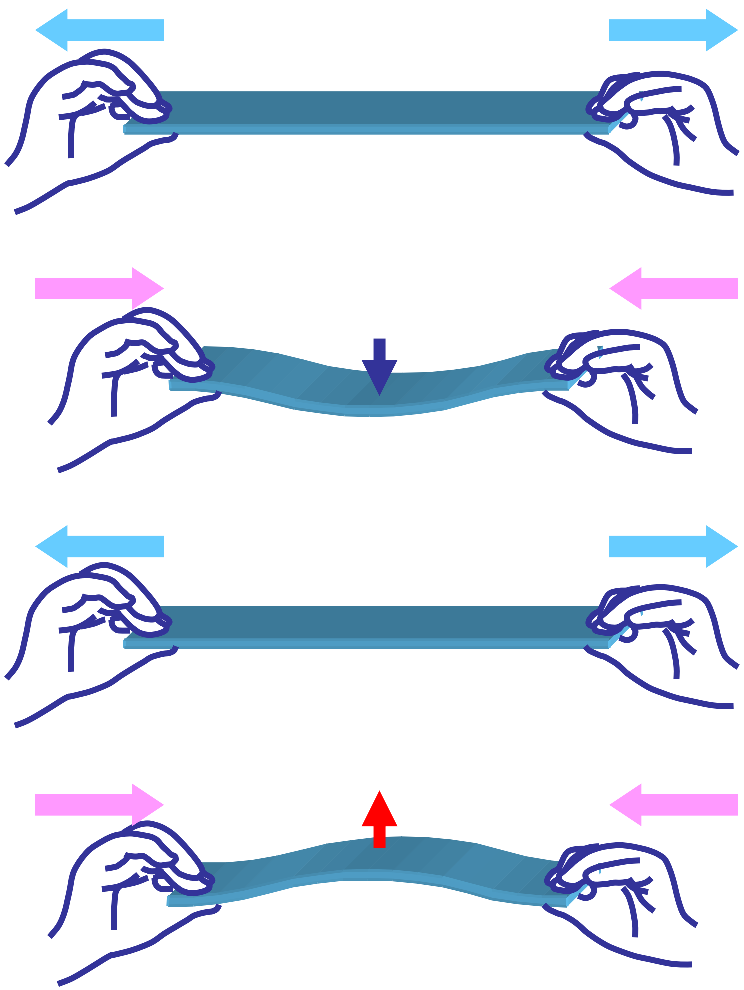
Gate 3: Application of DC voltage
→ Resonance frequency modulation



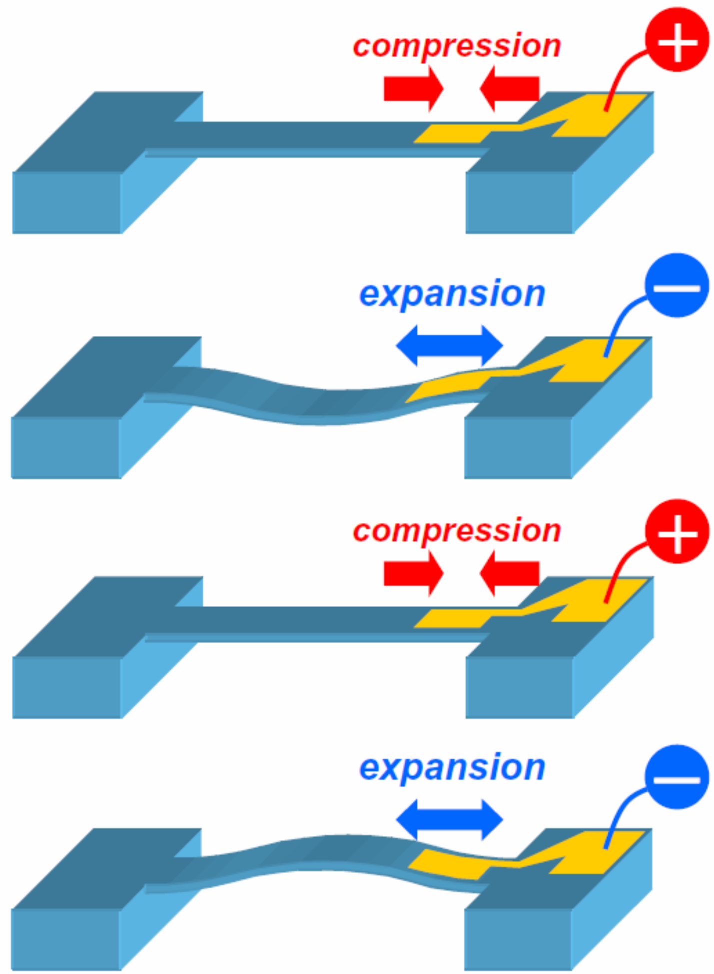


I. Mahboob and H. Y., Appl. Phys. Lett. 92, 173109 (2008)

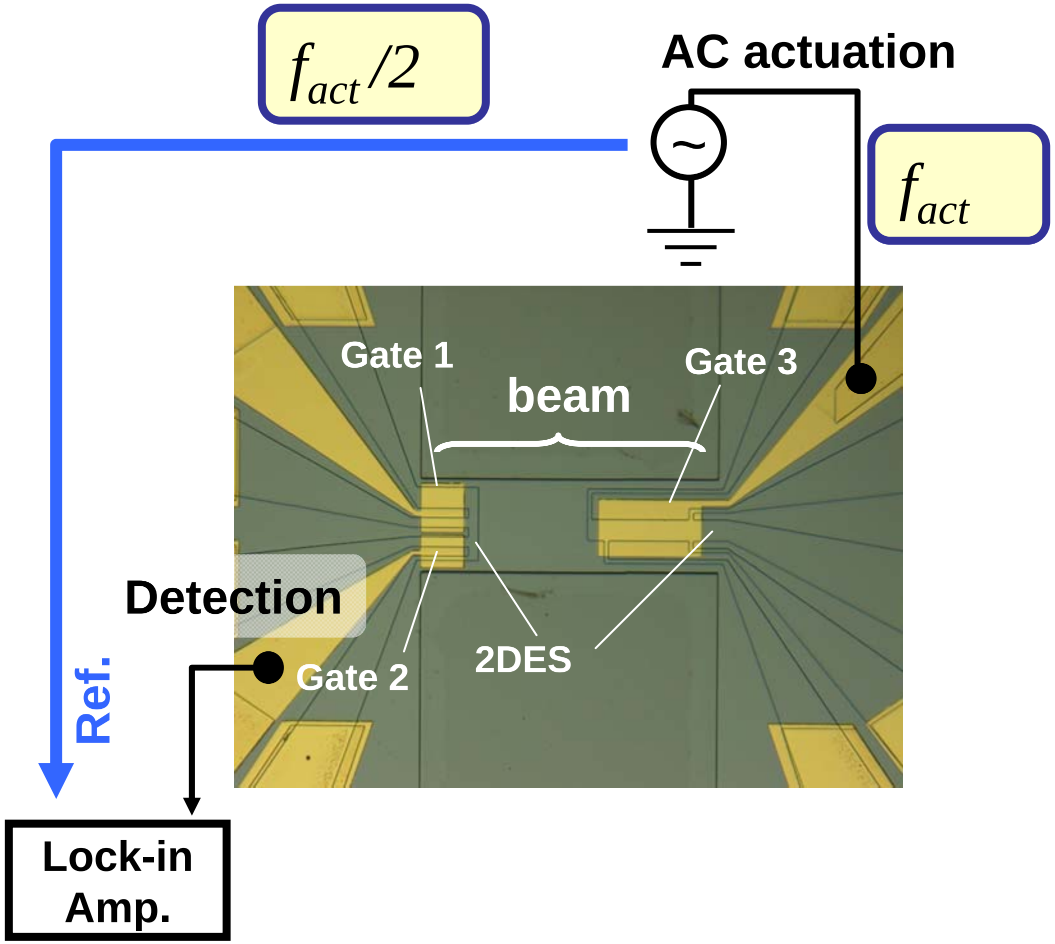
Parametric actuation of mechanical resonance

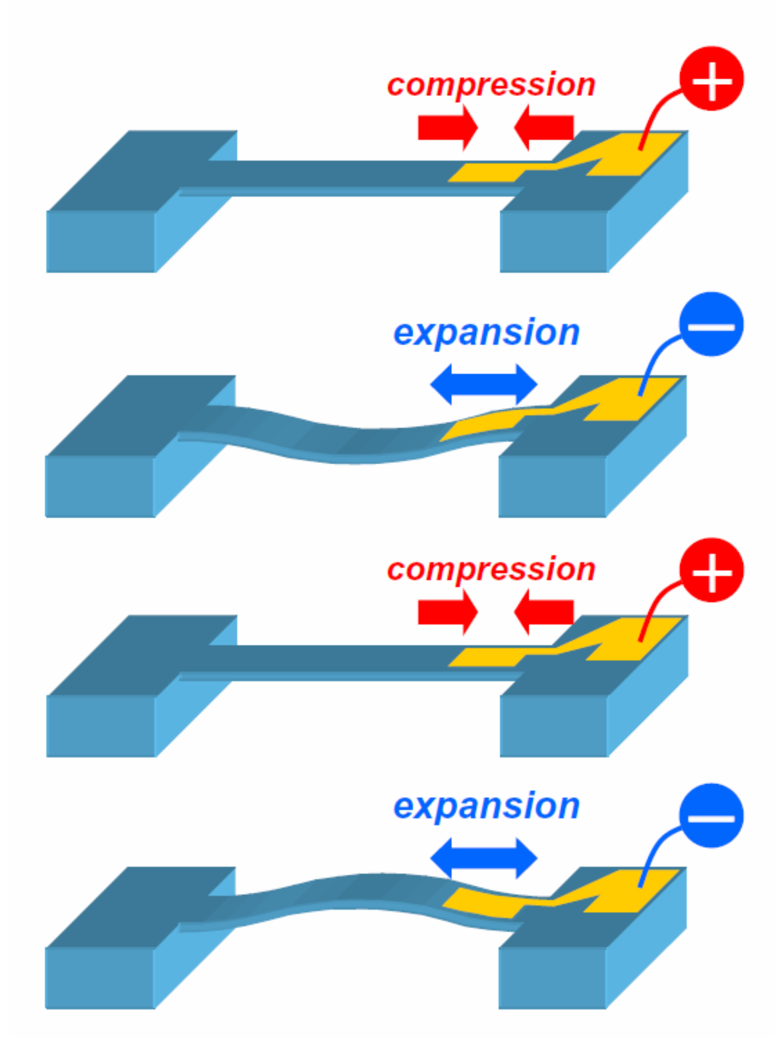


$$f_{act} = 2\, f_{res}$$



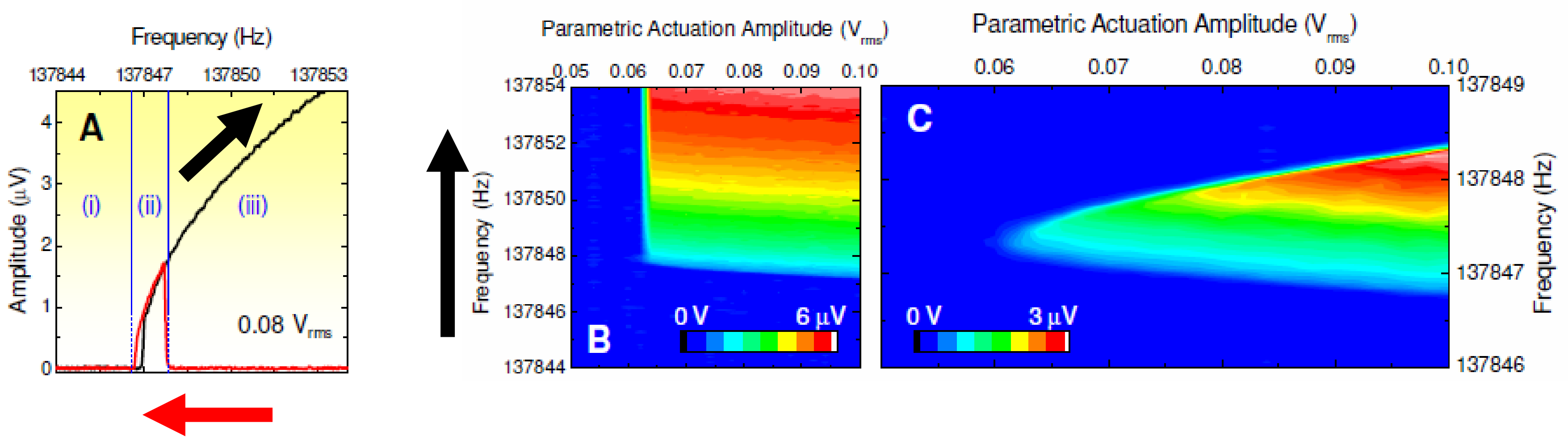
Parametric actuation





$$f_{act} = 2\,f_{res}$$

Frequency response for parametric actuation

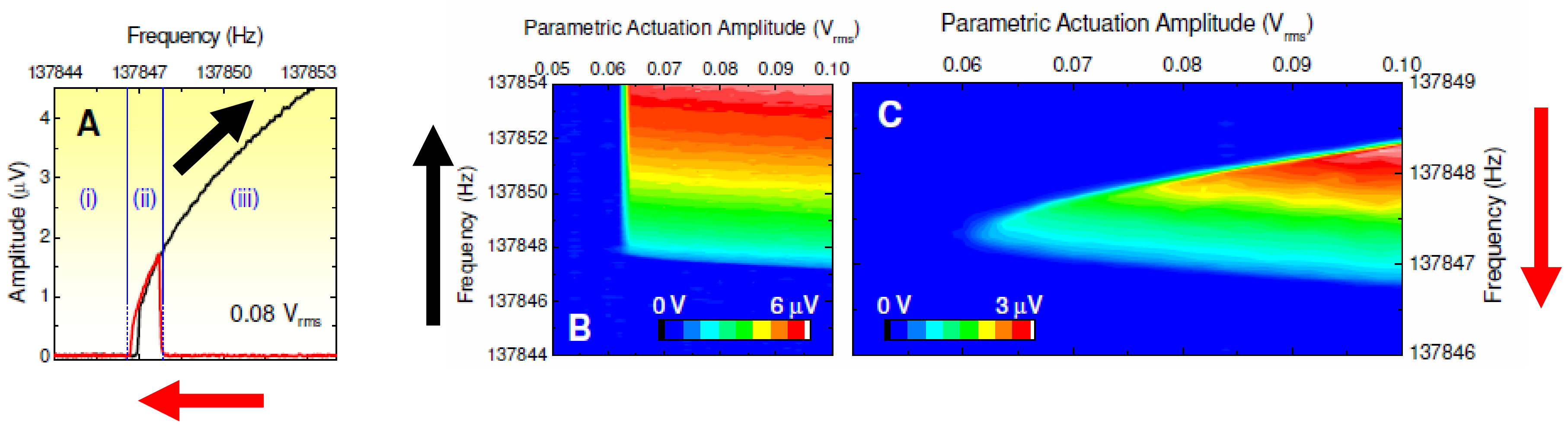


Nonlinear Mathieu-equation

$$\left[m\frac{d^2}{dt^2} + m\omega_0 Q^{-1}\frac{d}{dt} + m\omega_0^2[1+\beta x(t)^2 - 2\Gamma\sin(2\omega t)]\right] x(t) = 0$$

- damping
- fixed spring cst.
- Non-linearity
- Parametric actuation

Frequency response for parametric actuation



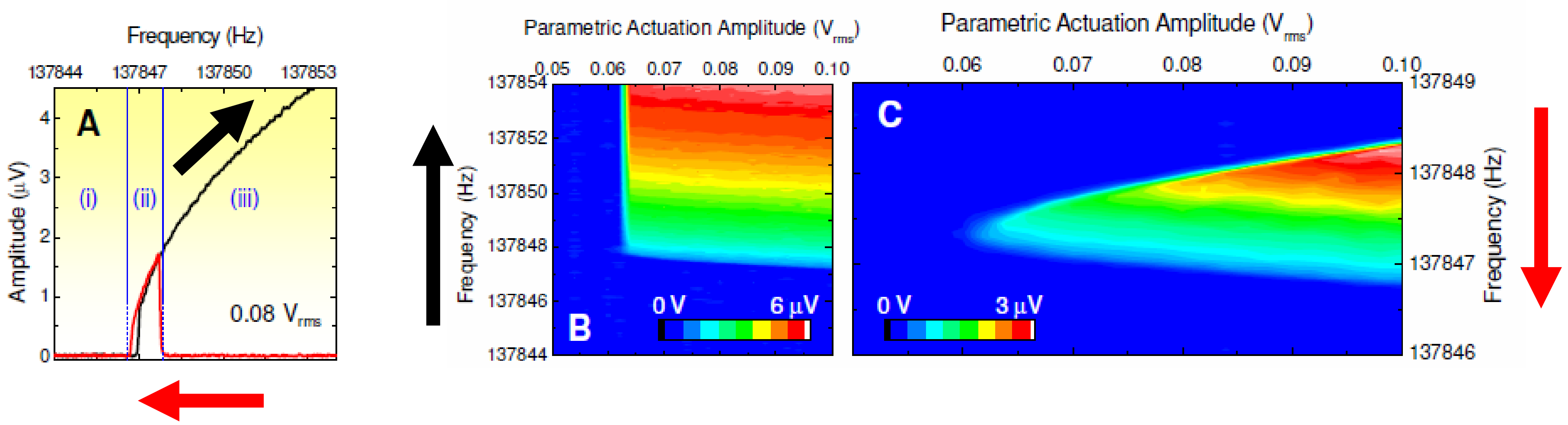
Nonlinear Mathieu-equation

$$\left[m\frac{d^2}{dt^2} + m\omega_0 Q^{-1}\frac{d}{dt} + m\omega_0^2[1+\beta x(t)^2 - 2\Gamma\sin(2\omega t)]\right] x(t) = 0$$

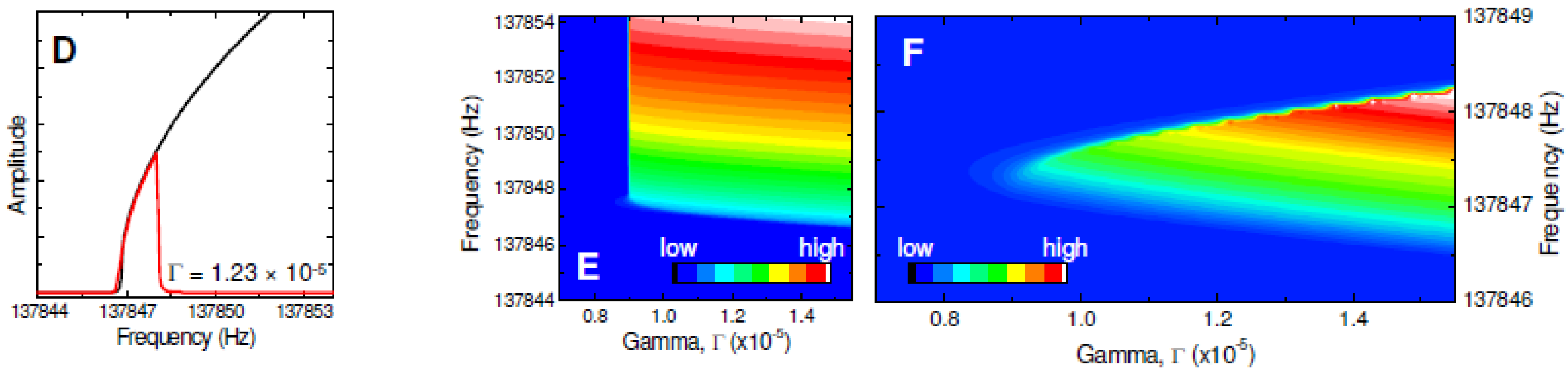
Rotating frame approximation: $x(t) = X_s(t)\sin(\omega t) + X_c(t)\cos(\omega t)$

$$\frac{2}{\omega_0}\dot{X}_s = -Q^{-1}X_s + \Gamma X_s - \left(\frac{2\delta\omega}{\omega_0} + \frac{3}{4}\beta\left(X_s^2 + X_c^2\right)\right)X_c, \quad \frac{2}{\omega_0}\dot{X}_c = -Q^{-1}X_c - \Gamma X_c - \left(\frac{2\delta\omega}{\omega_0} + \frac{3}{4}\beta\left(X_s^2 + X_c^2\right)\right)X_s$$

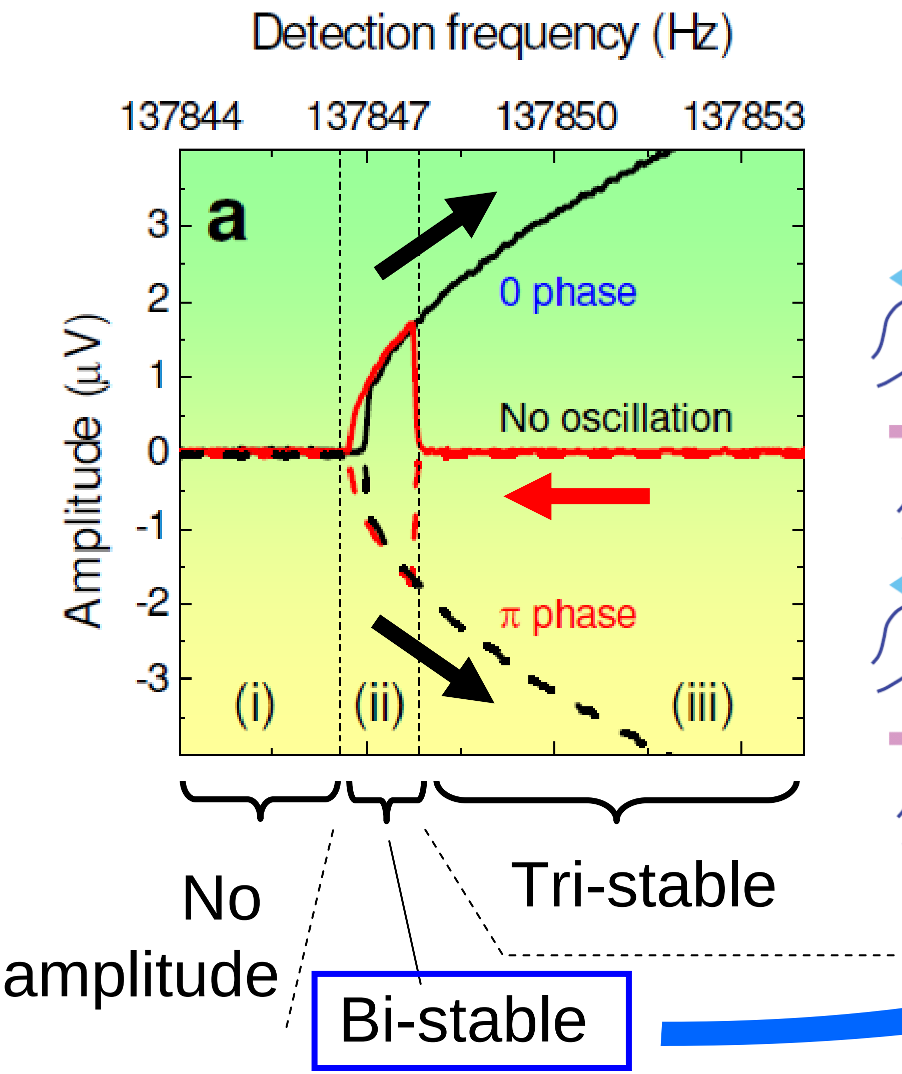
Frequency response for parametric actuation



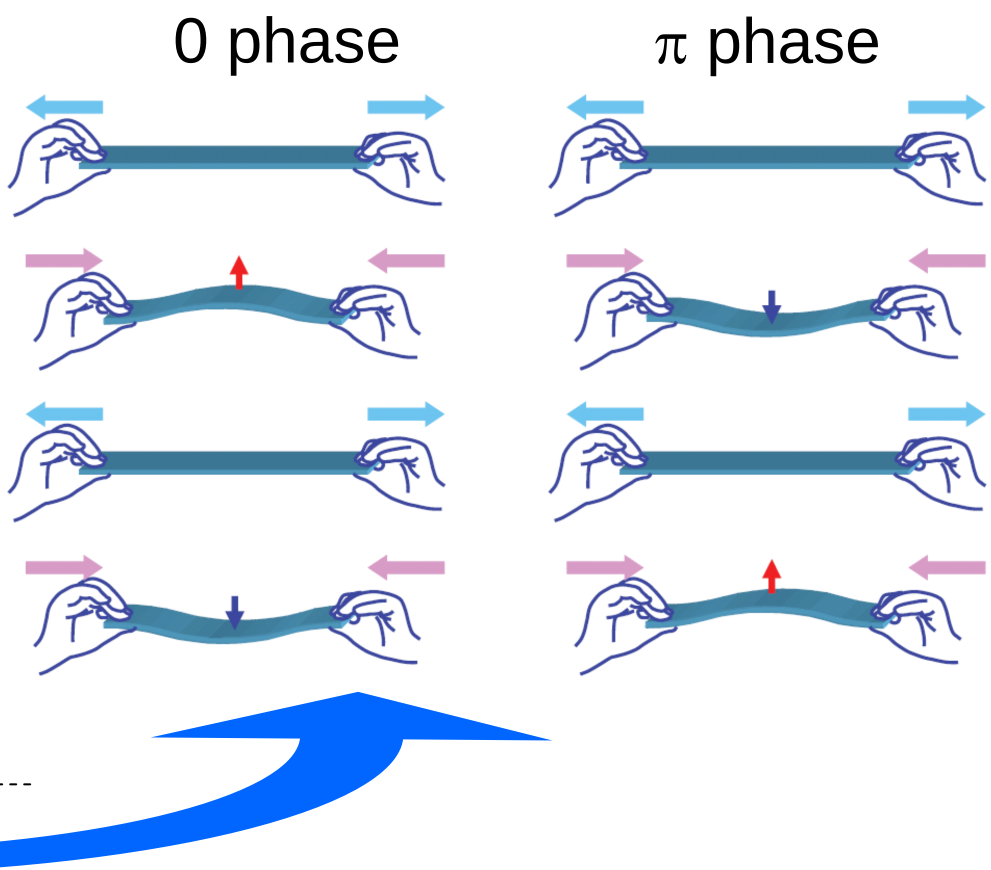
Simulation



Bi- and tri-stabilities in parametric resonator



Origin of bi-stability



Hamiltonian in the rotating frame for parametric resonator

$$\left[m\frac{d^2}{dt^2} + m\omega_0\gamma\frac{d}{dt} + m\omega_0^2[1+\beta x(t)^2 - 2\Gamma\cos(2\omega t)] \right] x(t) = 0$$

$$\Rightarrow \quad H = \frac{p^2}{2m} + \frac{1}{2}m\omega_0^2 x^2 \left[1 - 2\Gamma\cos(2\omega t)\right] + \frac{1}{4}m\omega_0^2 \beta x^4 \qquad (\ \gamma = 0\ )$$

Canonical transformation by a time-dependent generator:

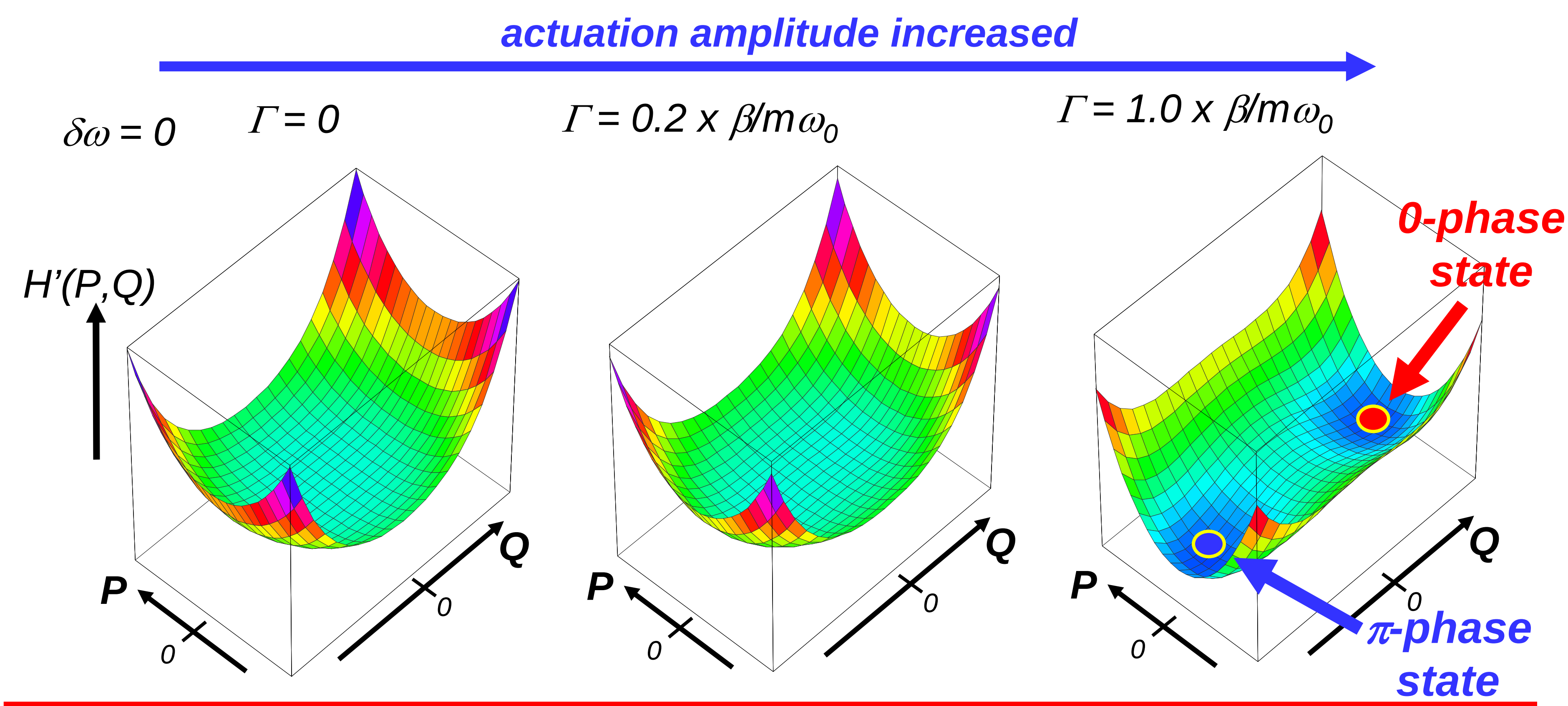
$$F(x,Q,t) = (m\omega x^2 / 2\tan\omega t - \sqrt{m\omega}xQ/\sin\omega t + Q^2/2\tan\omega t)$$

$$x(t) = [P(t)\sin(\omega t) + Q(t)\cos(\omega t)]/\sqrt{m\omega}, \quad p(t) = \sqrt{m\omega}\left[P(t)\cos(\omega t) - Q(t)\sin(\omega t)\right]$$

$$H'(P,Q) = H(p,x) + \frac{\partial F}{\partial t}$$

$$\sim \frac{3\beta}{32m}(P^2+Q^2)^2 + \frac{\omega_0\Gamma}{4}(P^2-Q^2) + \frac{\delta\omega}{4}(P^2+Q^2)$$

Hamiltonian in the rotating frame for parametric resonator

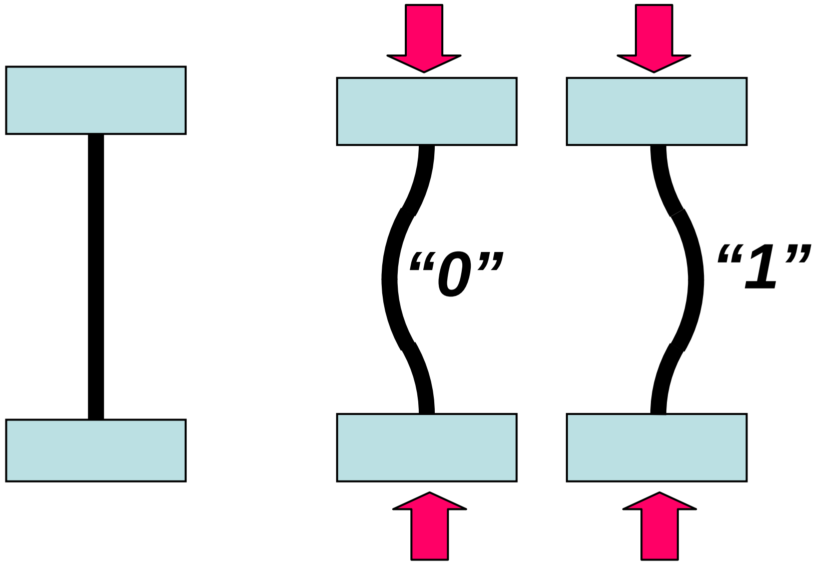


$$H'(P,Q) = H(p,x) + \frac{\partial F}{\partial t}$$

$$\sim \frac{3\beta}{32m}(P^2+Q^2)^2 + \frac{\omega_0\Gamma}{4}(P^2-Q^2) + \frac{\delta\omega}{4}(P^2+Q^2)$$

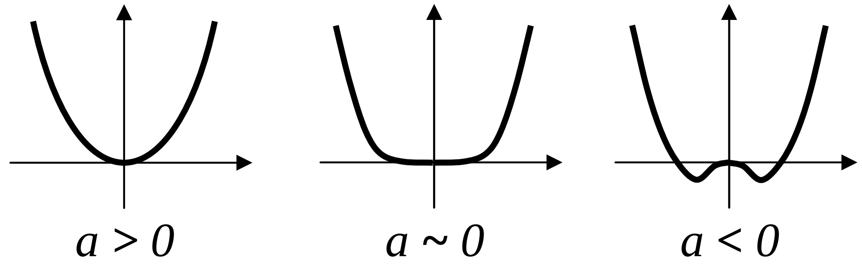
M. Marthaler and M. I. Dykman
Phys. Rev. A76, 010102 (2007)

Analogies between buckled beams and parametrically-driven resonators

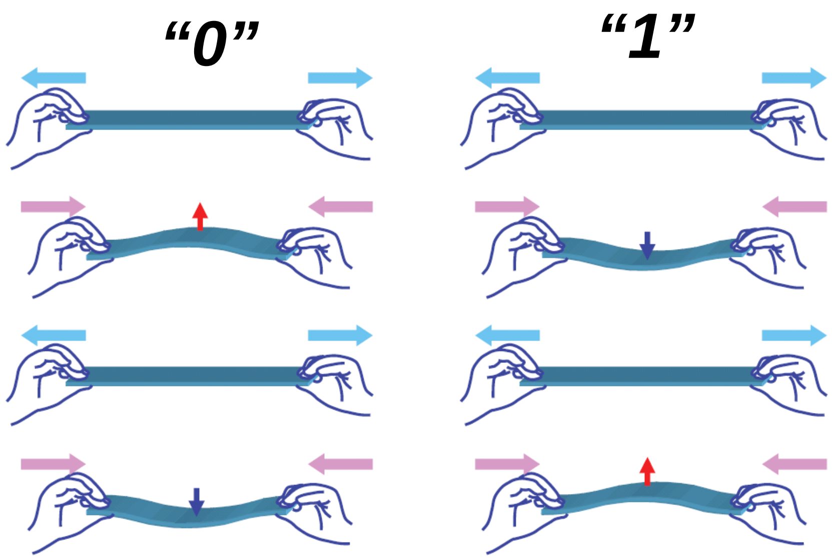


Driving stress: static

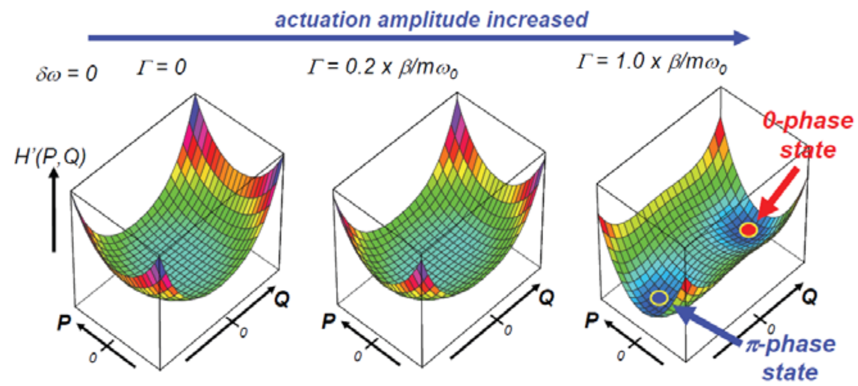
$$V(x) = ax^2 + bx^4, \quad (b > 0)$$



Threshold: yes (Euler's condition)

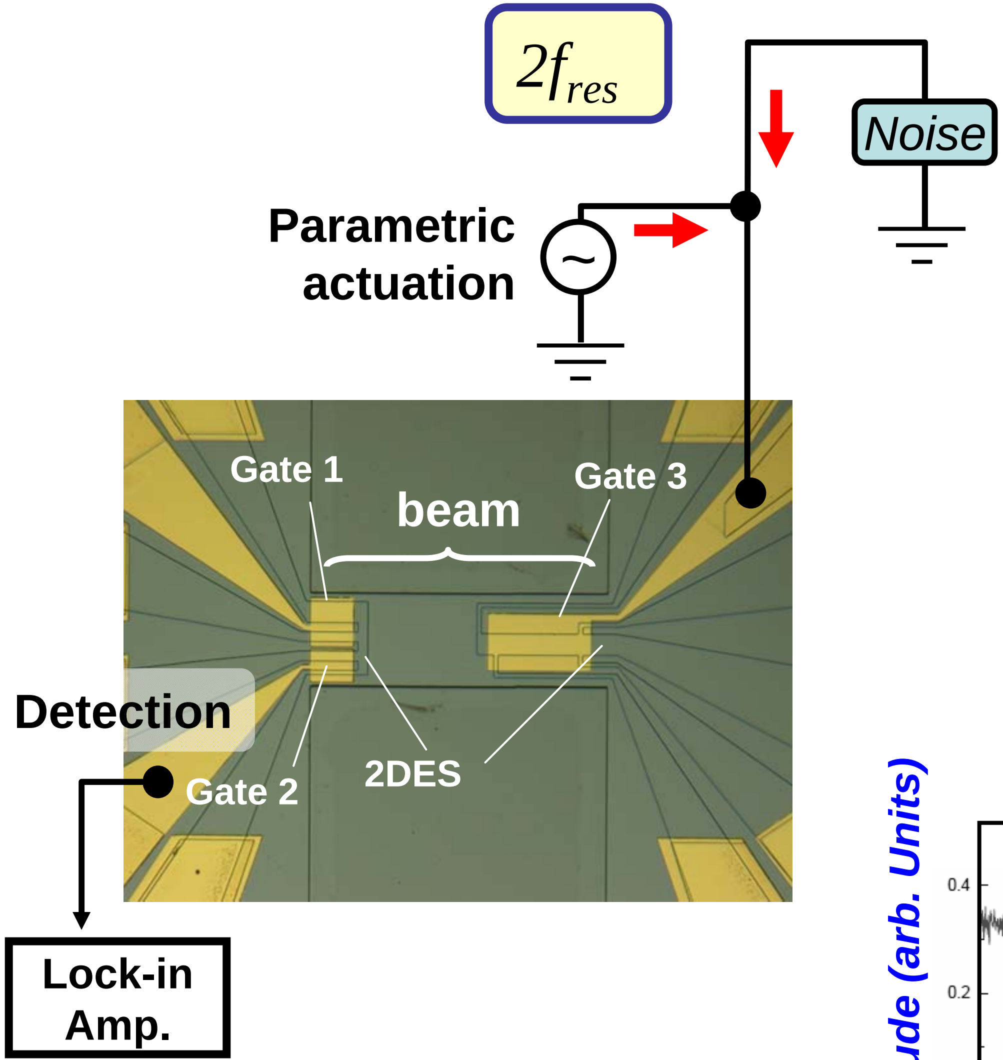


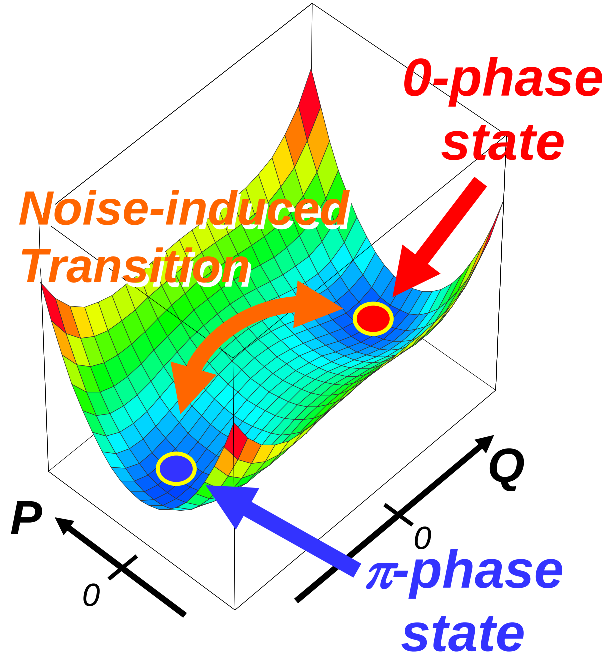
Driving stress: periodic

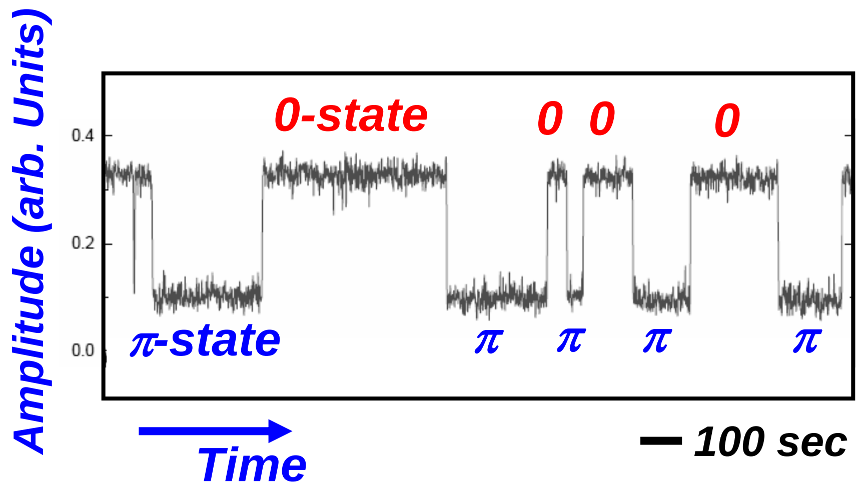


Threshold: yes ($\delta\omega / \omega_0 \sim Q^{-1}$)

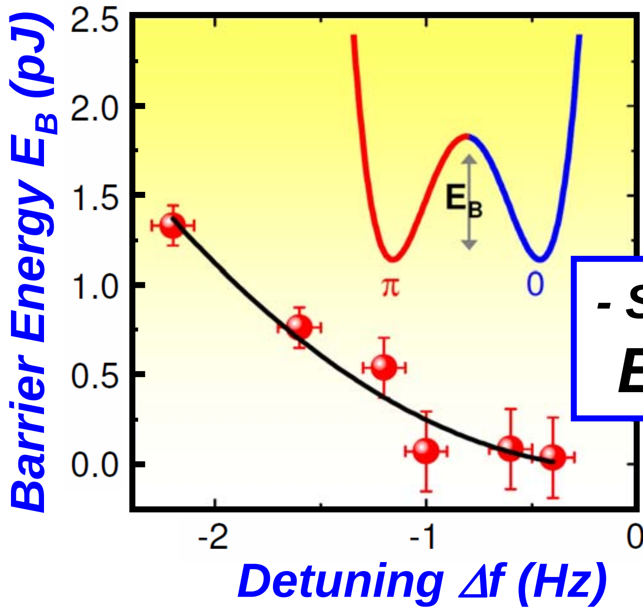
Estimation of Barrier Height







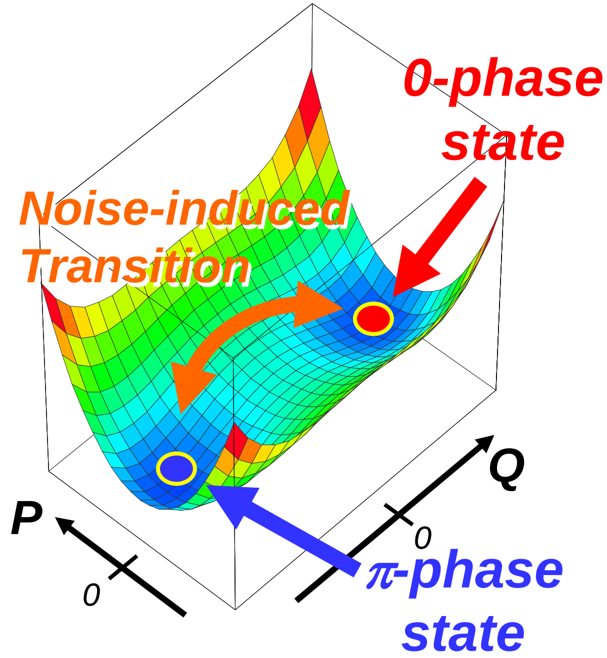
Estimation of Barrier Height

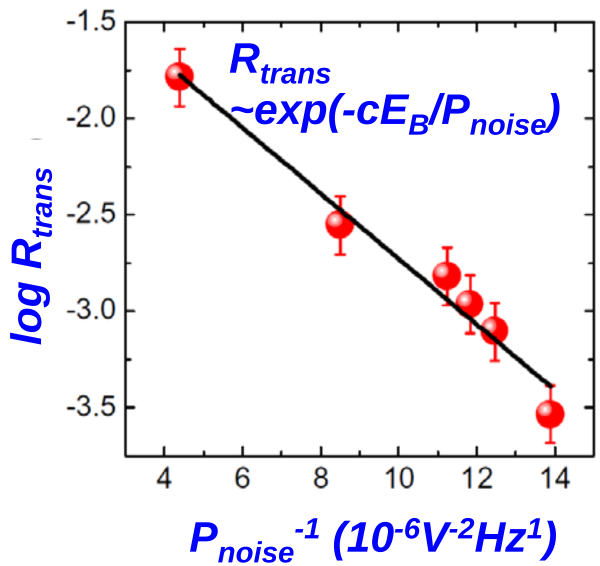


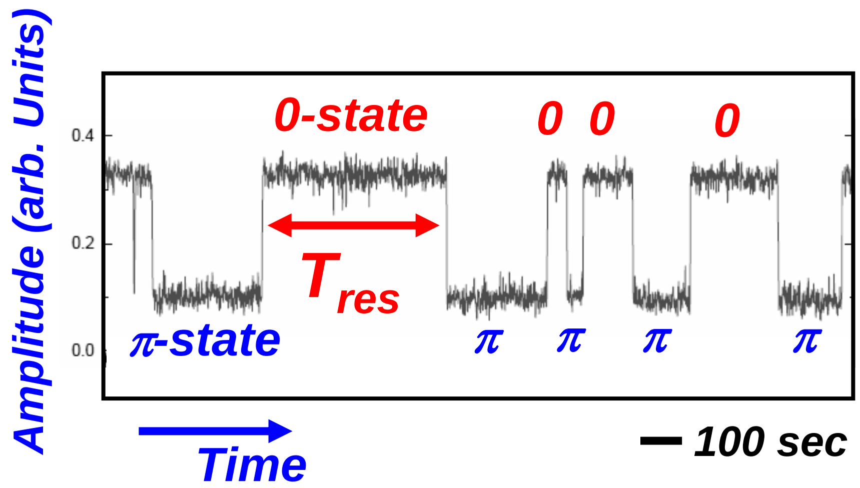
- Scaling law -

$E_B \sim c\Delta f^2$

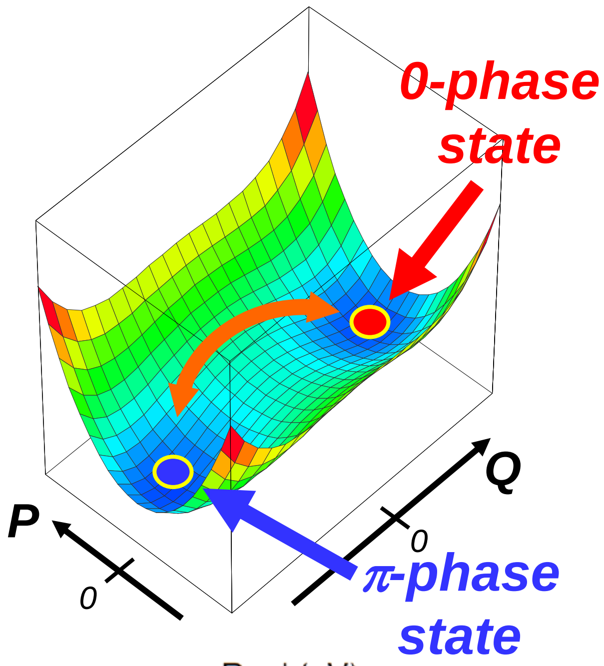
M. Marthaler et al. PRA (2007)
H. B. Chan et al., PRL (2007)

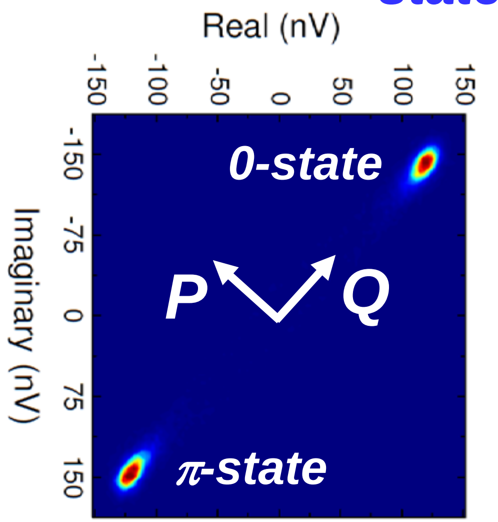


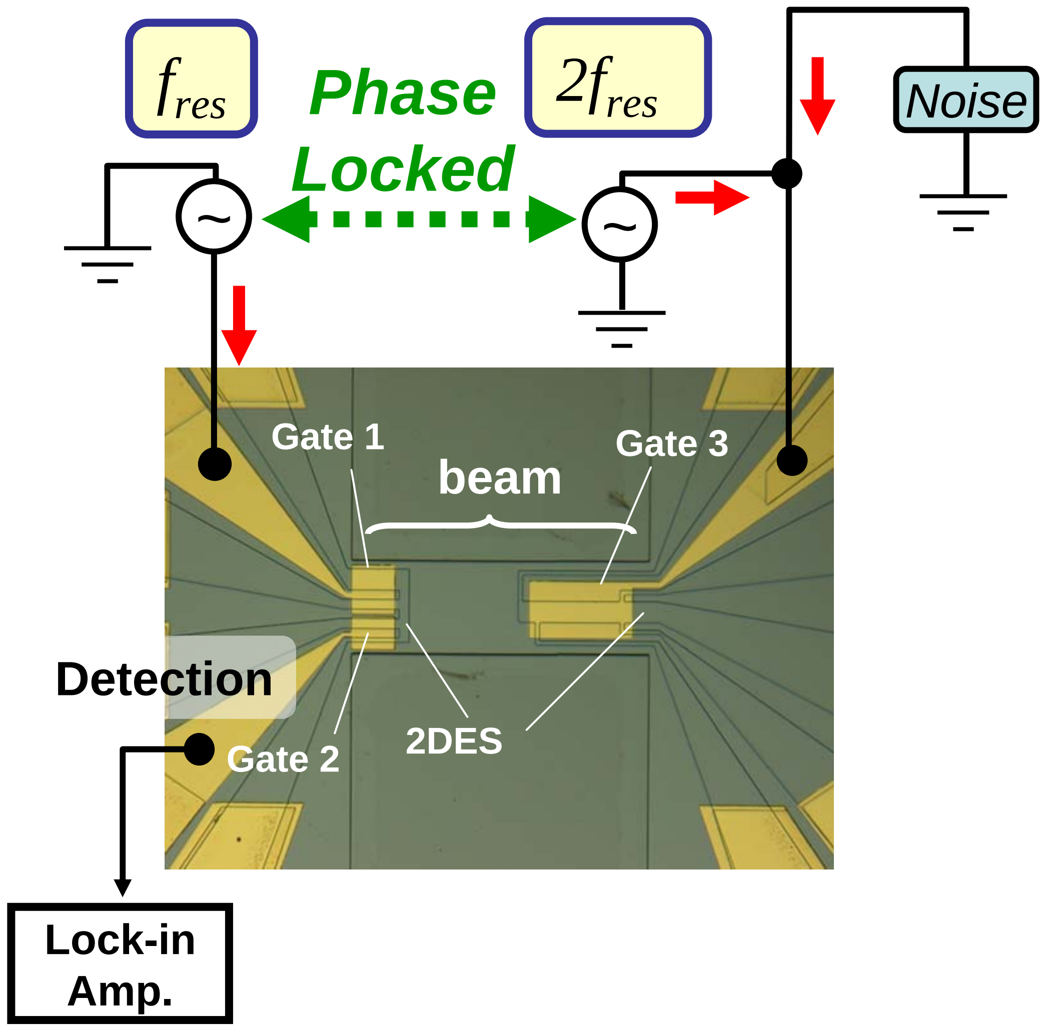




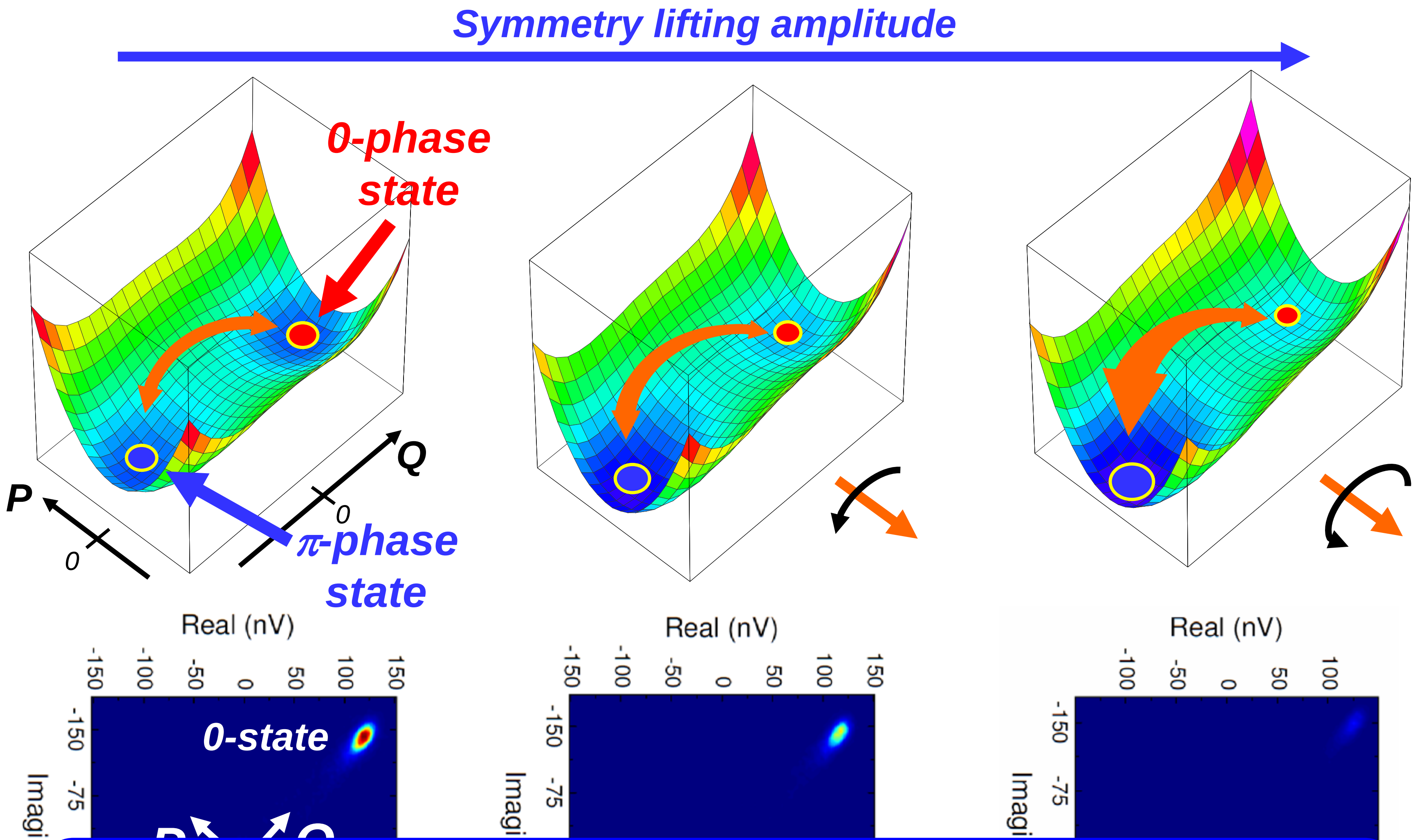
Symmetry Lifting







Symmetry Lifting

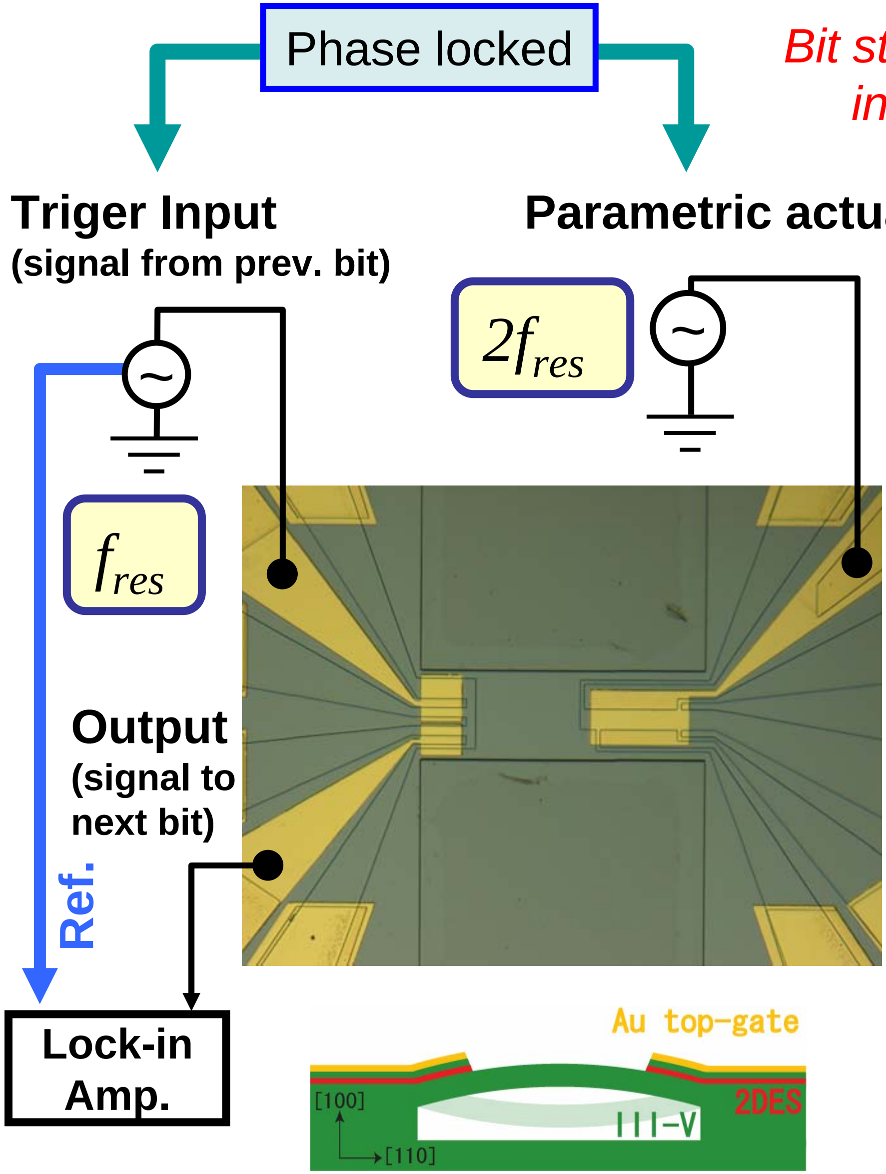


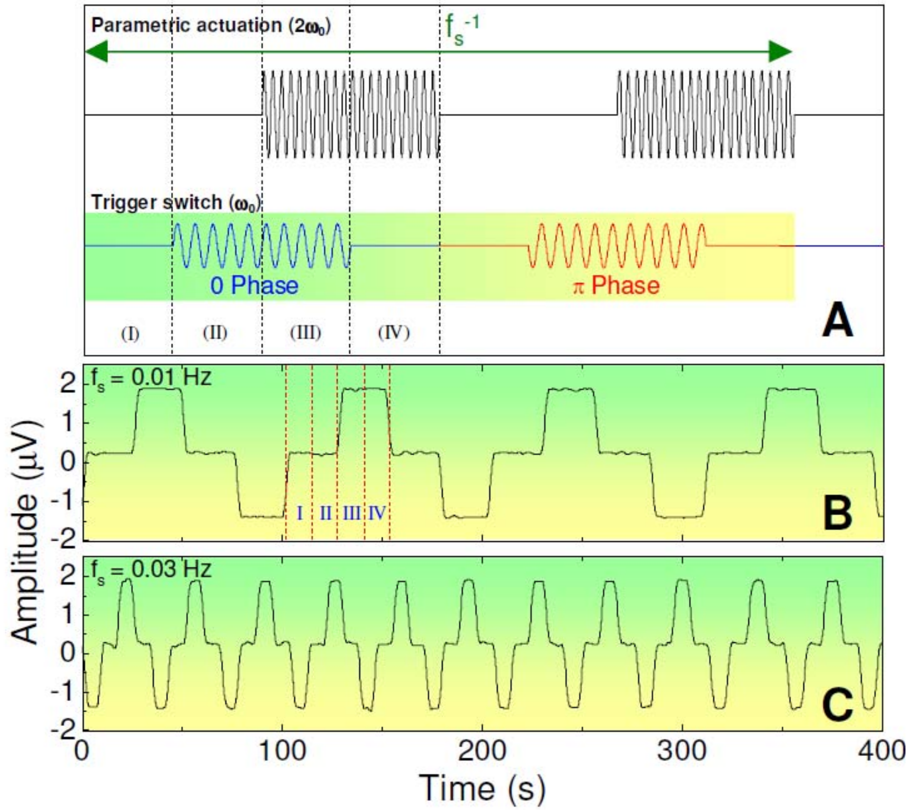
The asymmetry of the double well potential can be electrically controlled.

I. Mahboob, C. Froitier, and H. Yamaguchi, Appl. Phys. Lett. 96, 213103 (2010)

Electromechanical implementation of Parametron

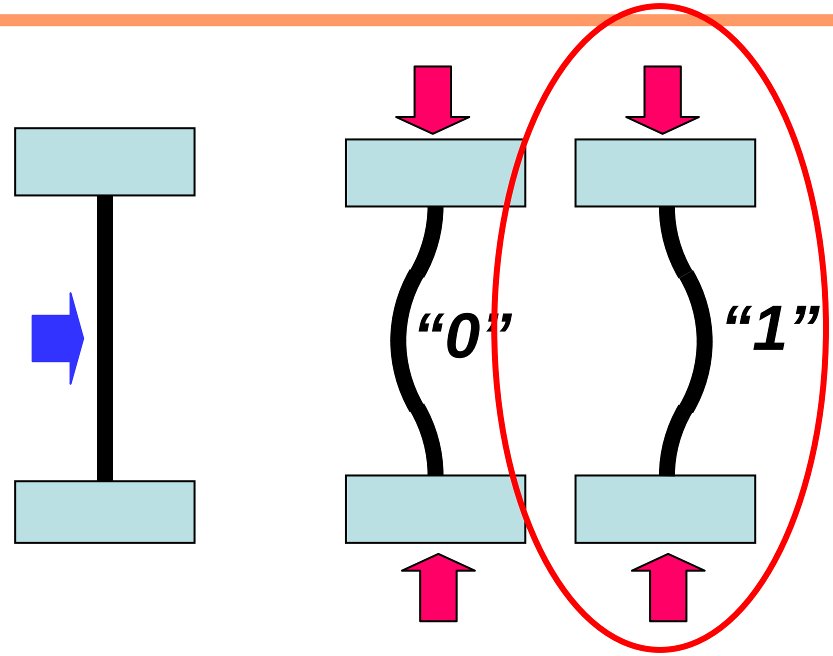
Bit storage and bit reset operation was realized in an equivalent way to the “Parametron”





I. Mahboob and H. Yamaguchi, Nature Nanotechnol. 3, 275 (2008)

Similarity between buckled beams and parametrically-driven resonators

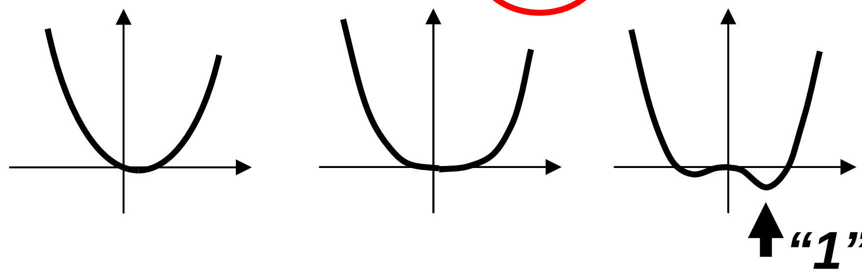


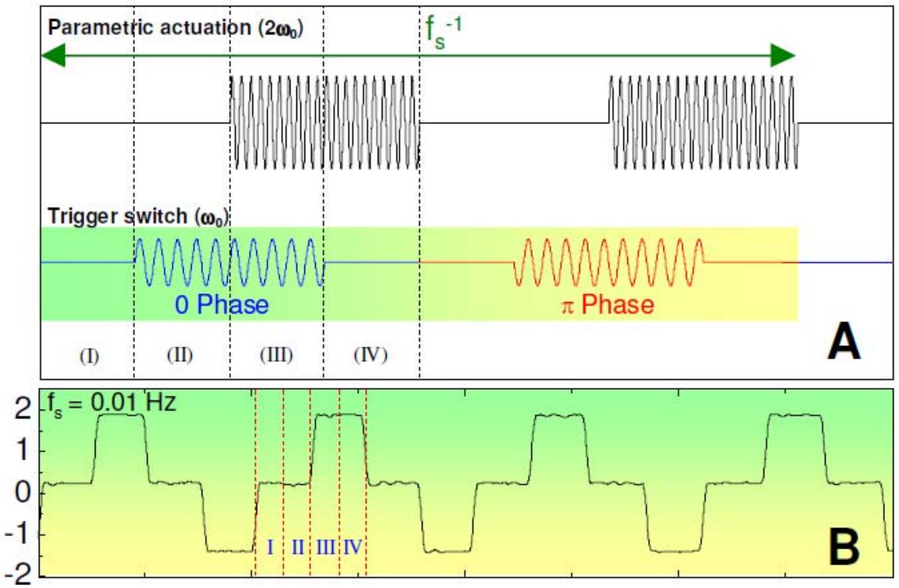
Driving stress: **static**

Threshold: **yes (Euler’s condition)**

Symmetry lifting: **small lateral force**

$$V(x) = ax^2 + bx^4 - \lambda x, \quad (b > 0)$$

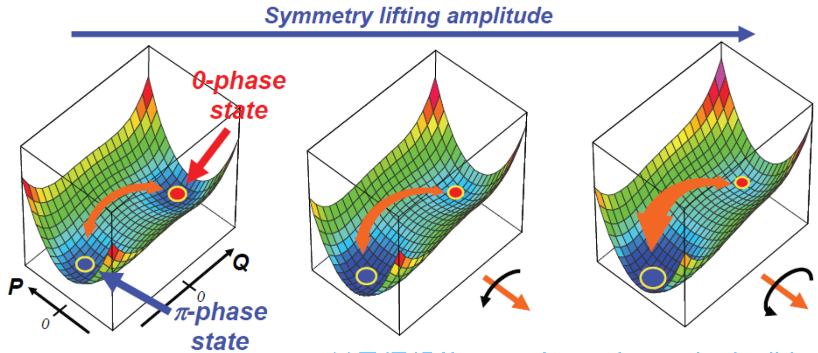




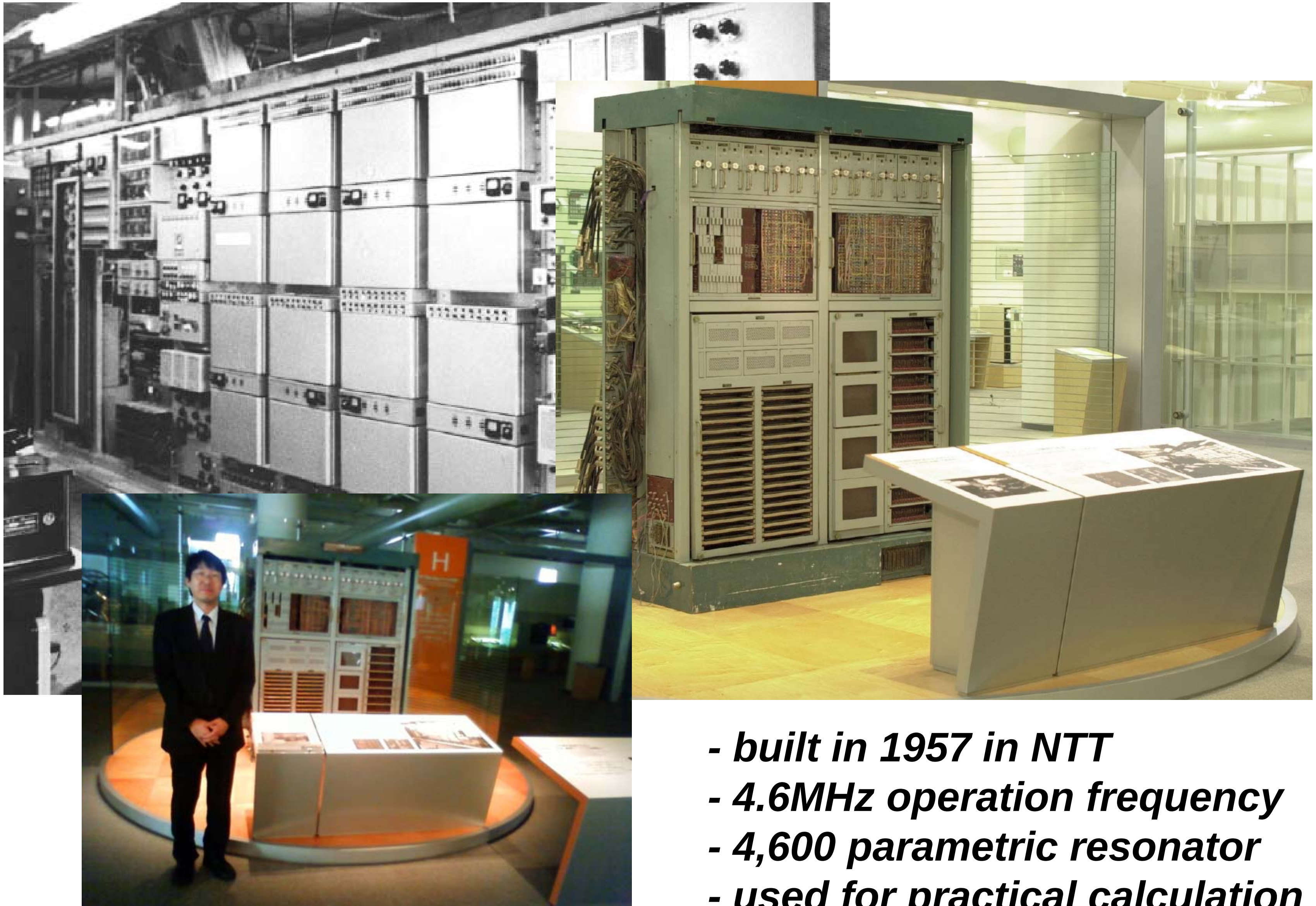
Driving stress: **periodic**

Threshold: **yes ($\delta\omega / \omega_0 \sim Q^{-1}$)**

Symmetry lifting: **small f_{res} actuation**

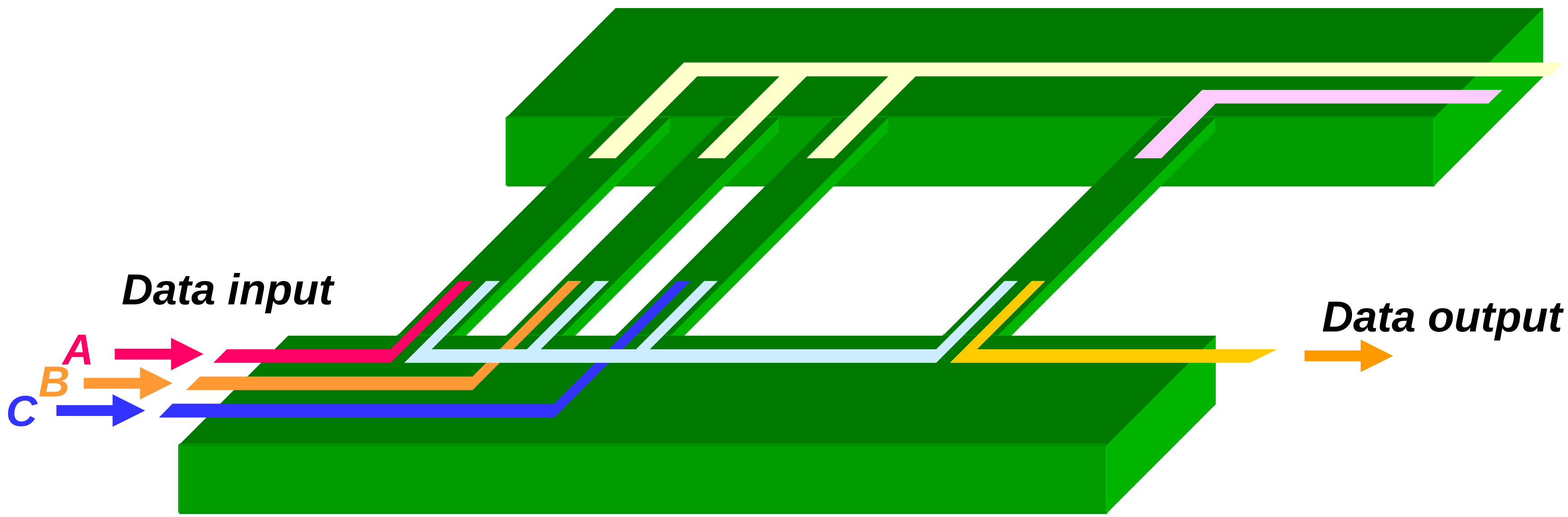


Parametron computer (Musashino-1)



- ***built in 1957 in NTT***
- ***4.6MHz operation frequency***
- ***4,600 parametric resonator***
- ***used for practical calculation***

Concept of "Majority Voter"



A	1	1	1	1	0	0	0	0
B	0	1	0	1	0	1	0	1
C	0	0	1	1	0	0	1	1
Data Output	0	1	1	1	0	0	0	1

B OR C (columns 1–4) | B AND C (columns 5–8)

Can we use it for energy-efficient mechanical logic systems ?

Power consumption

- *Mechanical energy dissipation*

$$P_{mech} = mQf_{res}^{3} x_{act}{}^{2} \sim [L^{2}]$$

Our device (250 x 90 x 1.4 μm^3) : P_{mech} ~ 0.1 pW/bit

Operation speed and integration:

Submicron-long resonators → f_{res} ~ several GHz
Graphene resonators → f_{res} ~ 500GHz ?
Integration density → 1Gbits/cm^2

Conclusion

We fabricated a GaAs/AlGaAs piezoelectric micromechanical resonator and demonstrated its possible applications.

- ***Effective strain-voltage transduction***
- ***Realizing of electromechanical Parametron***
- ***Non-degenerate parametric amplification***
- ***Multiple and parallel logic gates using f-conversion***

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