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Functional silicon nanoelectro-mechanical information processing devices

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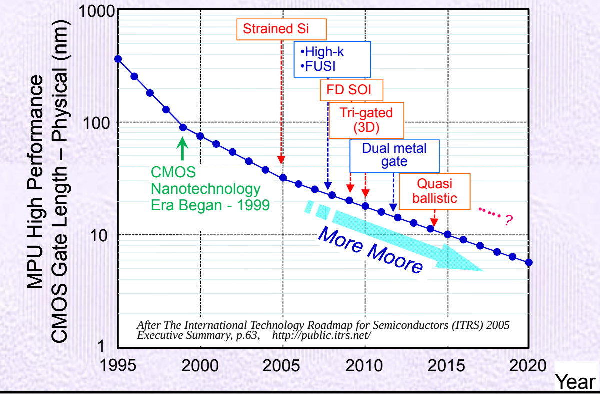
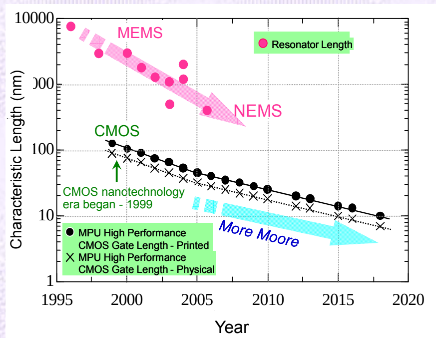
OUTLINE

1. Introduction – Integration of nano electro-mechanical (NEM) structures into Si devices for information processing
2. NEM nonvolatile memory
3. NEM single-electron devices
4. Summary

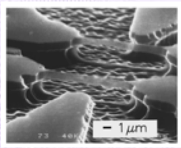
More Moore : CMOS extension ?



MEMS to NEMS : miniaturization trend ?



Progressing high-speed Si based MEMS



1996

Si beam

L = 7.7μm
t = 0.33μm
h = 0.8μm
f_R = 70.72MHz

A.N.Cleland and M.L.Roukes
Appl.Phys.Lett. **69,** 2653 (1996).

Oscillation frequency of a doubly clamped beam

$$\omega_n \propto \frac{t}{L^2}$$

L: beam length
t: beam thickness

2003

3C-SiC beam

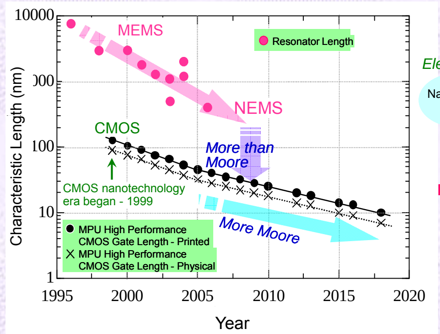
L =1.1 μm
w =120 nm
h = 75 nm
f_R = 1GHz

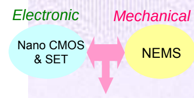
X.M.Henry Huang *et al.*,
Nature **421**,496 (2003).

Over 1 GHz operation possible with size reduction

NEMS integrated into Si nanodevices

Fusion of Nano CMOS / SET and NEMS may lead to extended device performance and even novel functionalities.



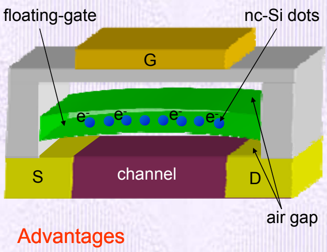


Phase 1:
More than Moore
Extended Performance

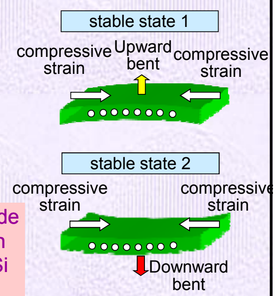
OUTLINE

1. Introduction – Integration of nano electro-mechanical (NEM) structures into Si devices for information processing
2. NEM nonvolatile memory

Nonvolatile NEM momory



Mechanical bistable states

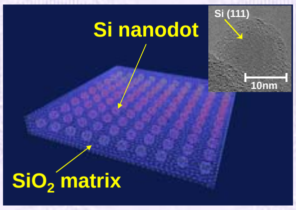


Advantages

- No charge tunneling via gate oxide
- High-speed write/erase operation
- Compatibility with conventional Si process

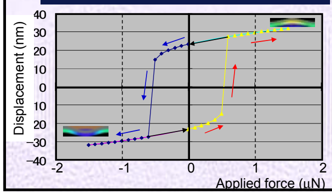
Y. Tsuchiya et al., J. Appl. Phys. 100, 094306 (2006)

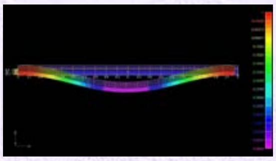
Buckled SiO_2 beam with embedded SiNDs



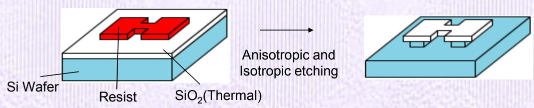
•Beam: 200 × 200 × 20 nm
•Diameter of dots: 10 nm
•Interdot spacing: 10 nm

	Young's modulus	Poisson's ratio
Si	190 GPa	0.27
SiO_2	70 GPa	0.175

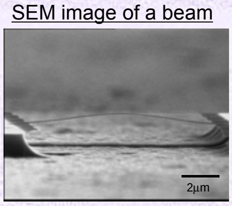




Test beam structure fabrication



SEM image of a beam



Naturally upward-bent bridge structure observed

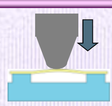
→ Release of stress at Si/SiO_2 interface after undercut

Y. Tsuchiya et al., J. Appl. Phys. 100, 094306 (2006)

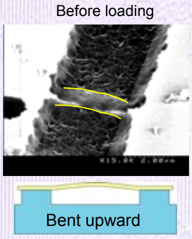
Loading experiment for the beam

Load on the beam using the nano-indentor

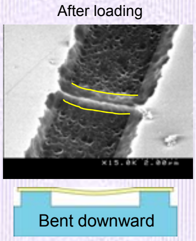
in collaboration with Y. Higo and K. Takashima of Tokyo Institute of Technology



Before loading

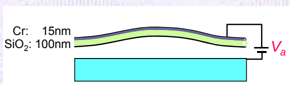


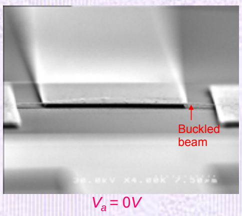
After loading



Y. Tsuchiya et al., J. Appl. Phys. 100, 094306 (2006)

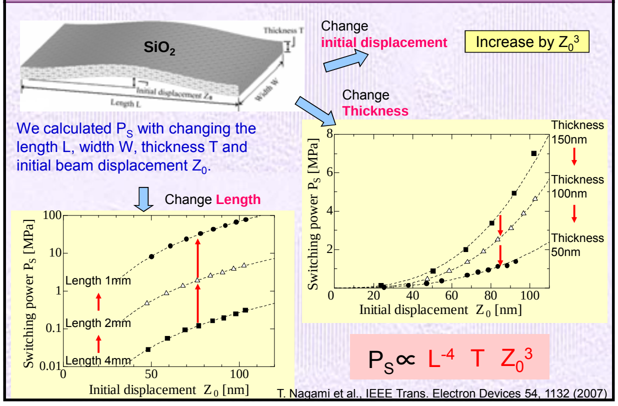
Electrical switching of the beam



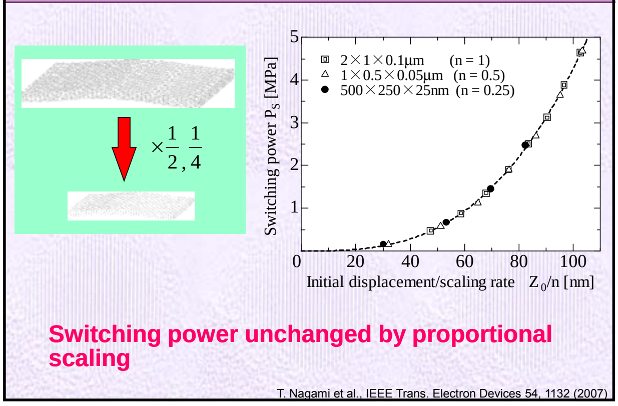


Direct observation of beam mechanical bistability

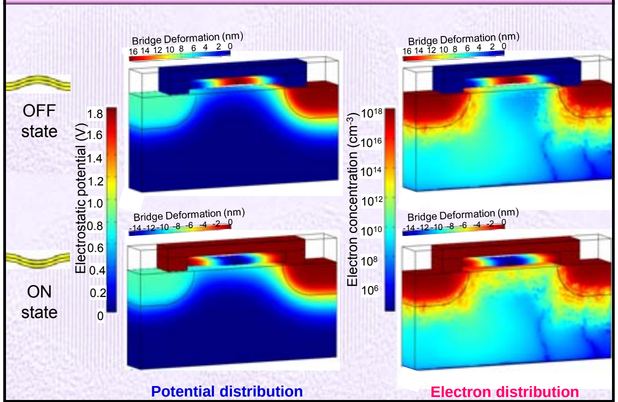
Mechanical properties of buckled FG



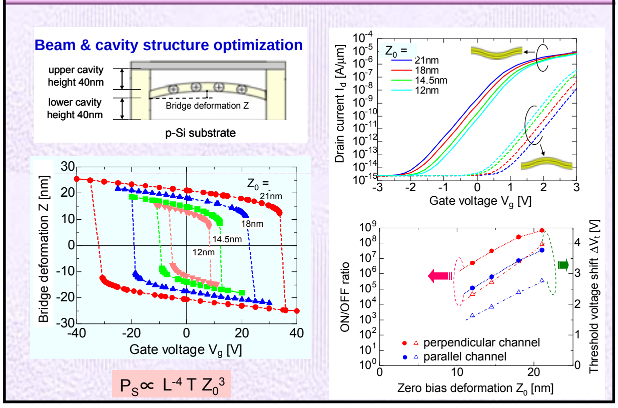
Scaling law for switching power



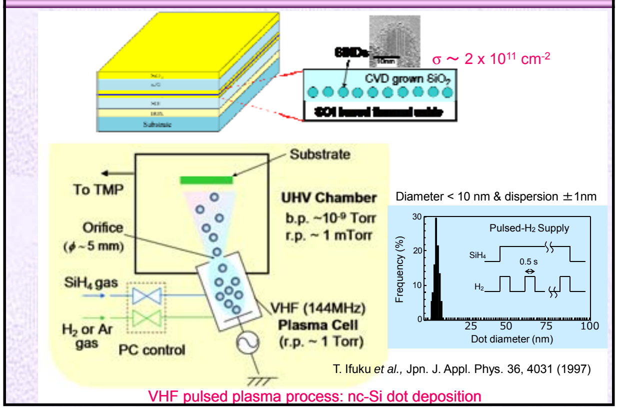
Readout operation of NEM memory



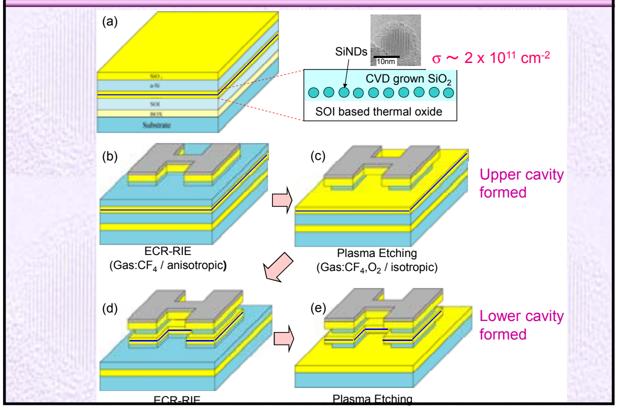
Optimized Readout characteristics



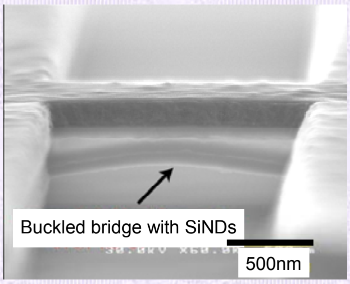
Fabrication of FG with SiNDs

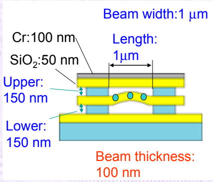


Fabrication of FG with SiNDs

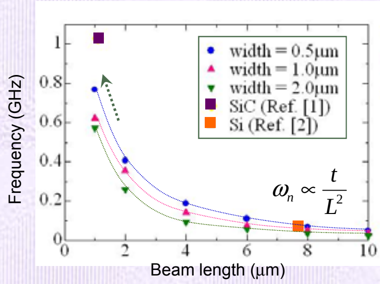


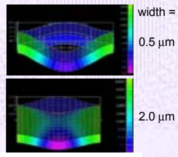
Fabrication of FG with SiNDs





Switching speed of a simple flat FG

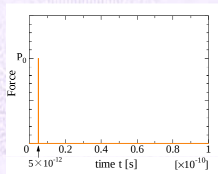




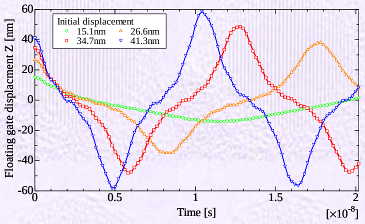
[1] X.M.Henry Huang *et al.*, Nature **421**,496 (2003).
[2] A.N.Cleland and M.L.Roukes, APL **69**, 2653 (1996).

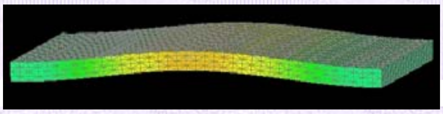
For a simple flat SiO_2 beam with L < 1 μm, over 1GHz frequency can be obtained, but……

Switching speed of a buckled bistable FG



Instantaneous applied force





Length 1μm
Width 500nm
Thickness 50nm

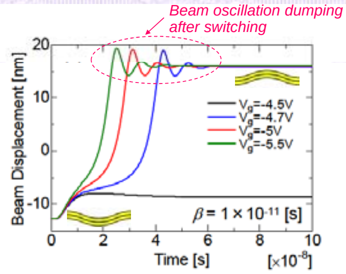
Oscillation at Z_0 = 34.7nm

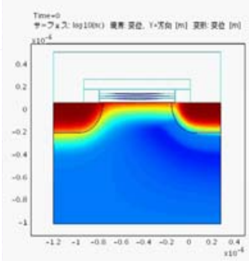
T. Nagami et al., IEEE Trans. Electron Devices 54, 1132 (2007)

Beam dumping effects on switching speed

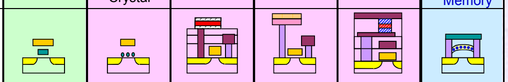
$$m\frac{d^2u}{dt^2}+\xi\frac{du}{dt}+ku=f(t) \qquad \xi=\alpha_{dM}m+\beta_{dK}k$$

mass, damping parameter, stiffness; mass damping, stiffness damping





A variety of nonvolatile RAM candidates

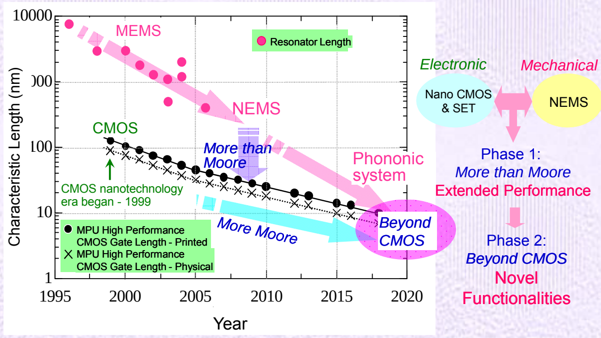
Cell		Flash	Nano-Crystal	FeRAM	PCRAM	MRAM	NEM Memory
Device Structure							
Mechanism of Non-volatility		Charge in Floating Gate	Charge in Nano-dot	Polarization	Phase Change	MR Change	Mechanical bistability
Issues		Program Volt. reduction	Program Volt. reduction	H_2 block CVD	Program Curt. reduction	Program Curt reduction	Power reduction, Shock immunity
Cell Size		4-8 F^2	4-8 F^2	10-20 F^2	8-15 F^2	8-15 F^2	6-10 F^2
Speed	Program	10 us	10 us	<50 ns	100 ns	<50 ns	< 50 ns
	Read	<20 ns	<20 ns	100 ns	<20 ns	<50 ns	<20 ns ?
Voltage		< 12 V	< 12 V	5 V	3 V	3 V	< 10V
P/E Cycle		10^8	10^8	10^{10}	10^{12}	10^{15}	> 10^{12}?

OUTLINE

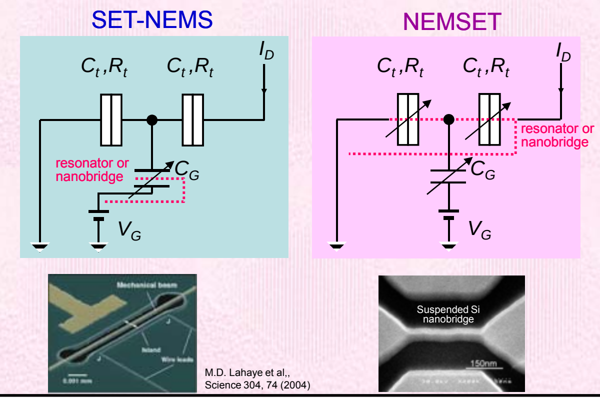
1. Introduction – Integration of nano electro-mechanical (NEM) structures into Si devices for information processing
2. NEM nonvolatile memory
3. NEM single-electron devices

What can we explore in 'real' NEMS ERA?

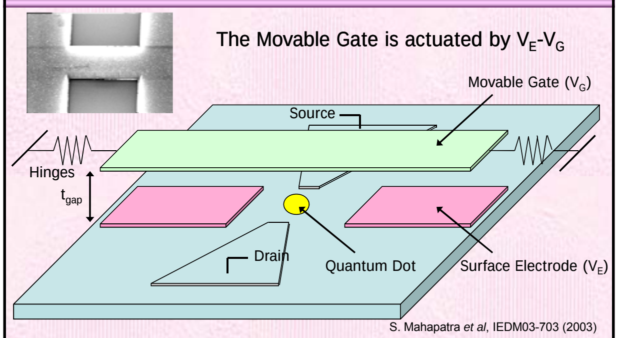
Fusion of Nano CMOS / SET and NEMS may lead to extended device performance and even novel functionalities.



Fusion of NEMS & single-electron transistors

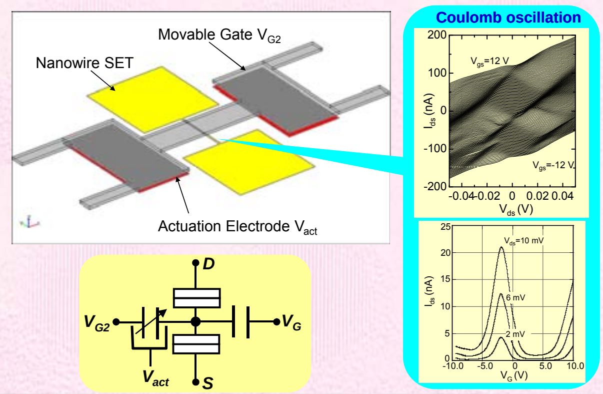


Concept of SET-NEMS: movable gate SET

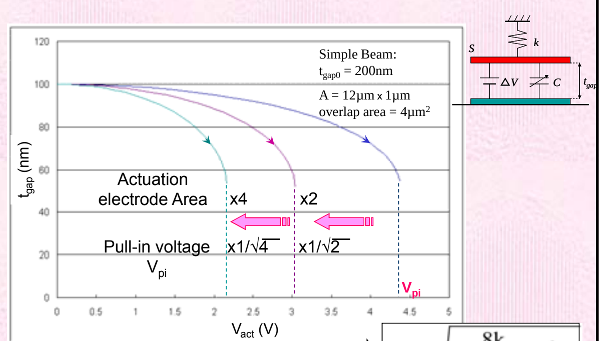


The design of the movable gate in a 3-D context is essential to achieve the expected performance.

SET-NEMS: extended functionalities to SETs

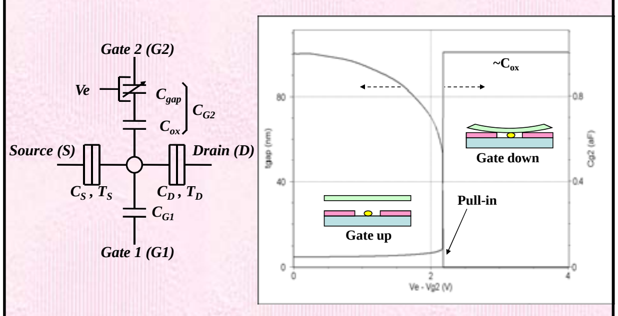


Pull-in operation of movable gate



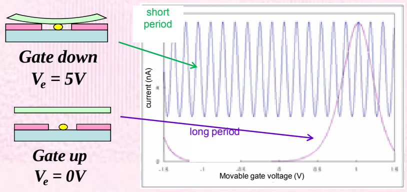
$$V_{pi} = \sqrt{\frac{8k}{27\varepsilon_0 Ww} t_{gap0}^3}$$

Two-state capacitive switch



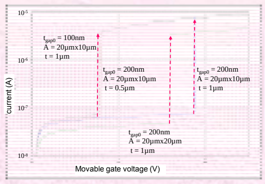
A 20nm thin oxide covers the region underneath (G2). (G2) actually acts as a two-state capacitive switch.

Unique switching properties of SET-NEMS



Change of Coulomb oscillation periodicity

Offset charge independent circuits



S-factor beyond CMOS limit of $k_B T \cdot ln2$?

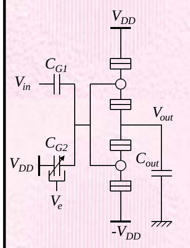
Adding new functionalities

- Switching beyond $k_B T \cdot ln2$?
- Offset charge independent SET
- Functional analog circuits

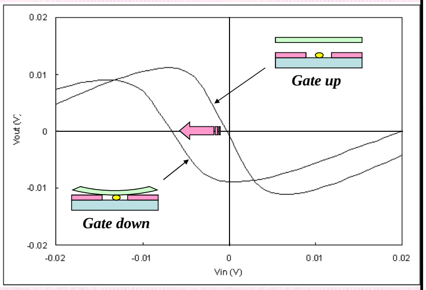
:

B. Pruvost, H. Mizuta and S. Oda, IEEE T-Nano 6, 218 (2007)

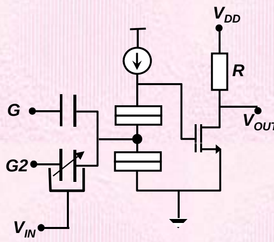
Tunable threshold SET inverter



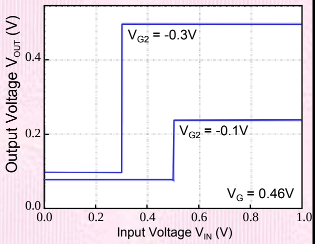
S. Mahapatra *et al*, IEDM03-703 (2003)



SETMOS-NEMS as a novel threshold gate

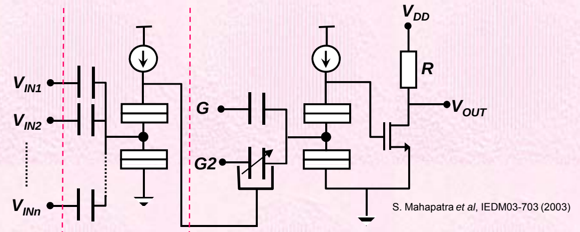


S. Mahapatra *et al*, IEDM03-703 (2003)

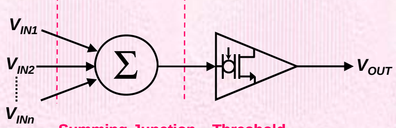


Novel threshold gate (hard limiter) can be designed by tuning C_{G2}

SETMOS-NEMS based hybrid neuron cell



S. Mahapatra *et al*, IEDM03-703 (2003)

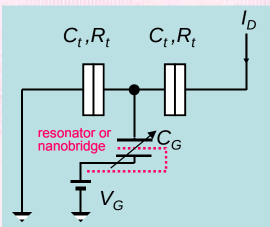


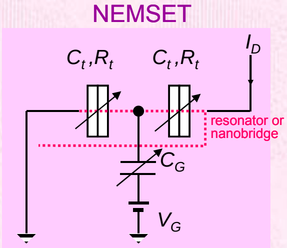
Can be applied for high-density neural networks & A/D converters

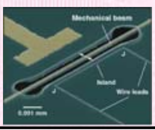
Fusion of NEMS & single-electron transistors

SET-NEMS

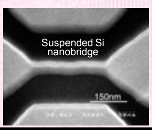
NEMSET



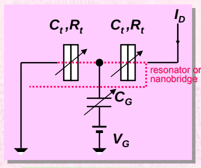




M.D. Lahaye et al., Science 304, 74 (2004)



NEMSET: strongly-coupled electron-phonon system

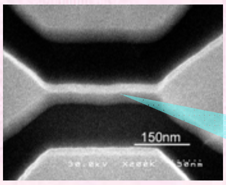


NEMSET is an ideal laboratory for exploring strong coupling of single electrons and low-dimensional phonons (Nanophonons) !

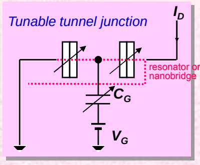
- Mechanical modulation of tunnelling rate
- Phonon blockade of electrons
- Single-electron energy dissipation
- Phononic bandgap
- Quantum shuttle
- Quantization of mechanical displacement

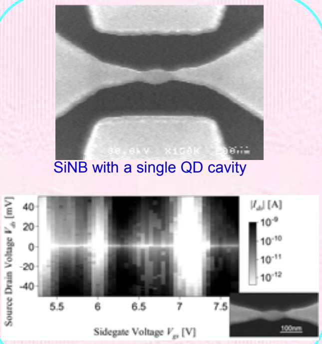
⋮

NEMSET(1): Mechanically modulated tunnelling rate



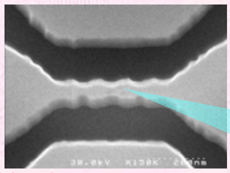
Silicon Nanobridge (SiNB) SET
L = 300nm, W = t = 50nm



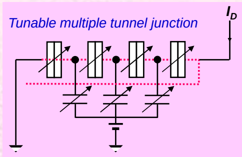


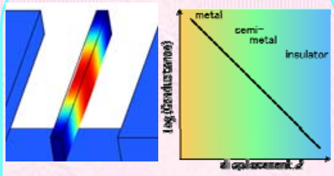
J. Ogi, Y. Tsuchiya, S. Oda and H. Mizuta, submitted to MNE2007

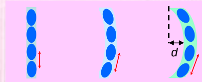
NEMSET(1): Mechanically modulated tunnelling rate



SiNB SET with a multiple quantum dot (QD) cavity



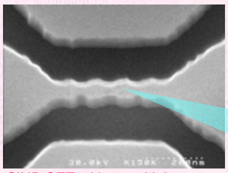




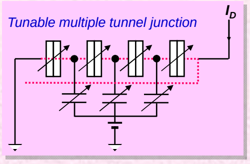
Electromechanical modulation of tunnelling rate?

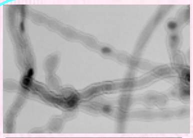
J. Ogi, Y. Tsuchiya, S. Oda and H. Mizuta, submitted to MNE2007

NEMSET(1): Mechanically modulated tunnelling rate



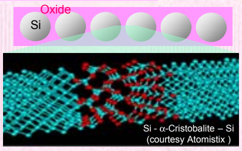
SiNB SET with a multiple quantum dot (QD) cavity





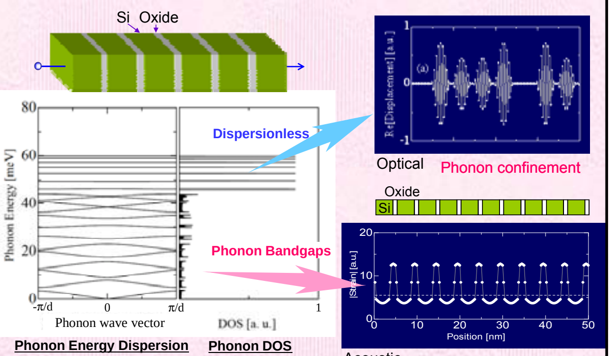
Si nanochain
(in collaboration with Cambridge Univ.)

assembled SiNDs



Acoustically-mismatched heterostructure

NEMSET(2): Phononic bandgap formation

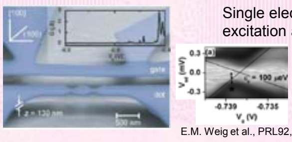


Phonon Energy Dispersion Phonon DOS

Uno, Mori, Nakazato, Koshida and Mizuta, J. Appl. Phys. 97, 113506 (2005) & Phys. Rev. B72, 035337 (2005)

NEMSET(3): Even more exotic phenomena .....?

- *Phonon blockade of single-electron tunnelling*



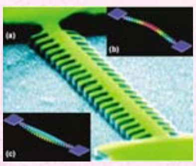
Single electron tunnelling induces mechanical excitation as a localized cavity phonon

$\hbar\Omega_{ph} \approx 3\hbar c_L / z = 73\mu V$

⟺ Energy gap in Coulomb diamond ε_0 ~100 μeV

E.M. Weig et al., PRL92, 046804-1 (2004)

- *Quantization of mechanical motion?*



Thermal occupation number $N_{th} = k_B T / hf$

f = 1.49 GHz, T = 110mK

⟹ N_{th} ~ 1 : quantum regime

A. Gaidarzhy et al., Phys. Rev. Lett. 94, 030402 (2005)

Nanoscale EM phenomena unexplored!

Electronic Devices

Studied well | Studied very well | Studied very well

Atomic scale | **Nanoscopic scale** | **Macroscopic scale**

Studied quite well | Studied very little | Studied well

Electromechanical Devices

SUMMARY

- Fusion of Si nanodevice and NEMS may provide enhanced performance and even new functionalities to 'conventional' Si devices for information processing
- NEM memory with high-speed operation & superior nonvolatility: any chance to compete with other emerging memories?
- SET-NEMSs and NEMSETs with more functionalities and new switching principle: still lots of space to explore !!

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- Hitachi Central Research Laboratory
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- Nagoya University
  S. Uno