ESSDERC Workshop on Emerging Nonvolatile Memories
14 September 2007

NEMS-based memory devices

Hiroshi Mizuta
School of Electronics & Computer Science, Univ. of Southampton
&
Department of Physical Electronics, Tokyo Institute of Technology

Yoshi Tsuchiya, Shunri Oda
Quantum Nanoelectronics Research Center,
Tokyo Institute of Technology

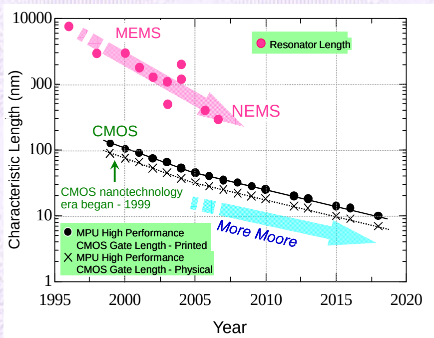
OUTLINE

1. Introduction – Co-integration of NEMS with silicon devices for information processing
2. Bistable NEMS based memory devices
3. Other NEMS memory
4. Summary

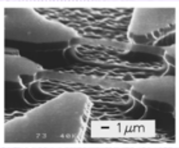
OUTLINE

1. Introduction – Co-integration of NEMS with silicon devices for information processing

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

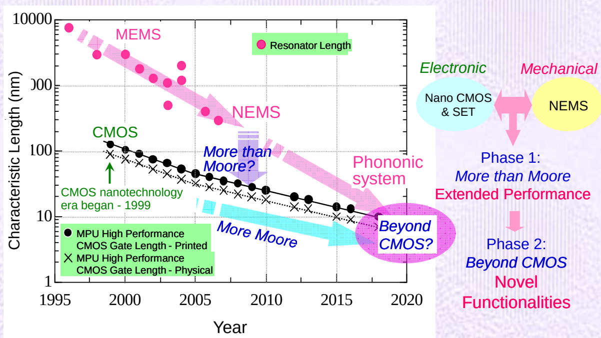
3C-SiC beam
L =1.1 µm
w =120 nm
h = 75 nm
f_R = 1GHz

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.



NEMS integrated into Si nanodevices

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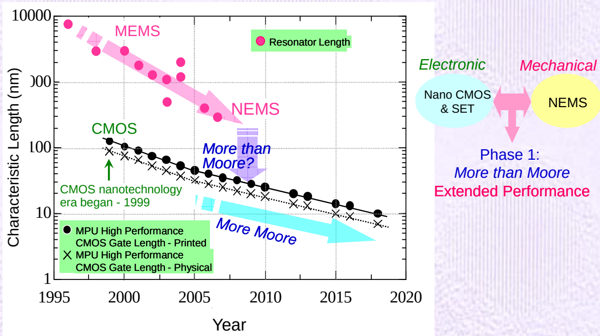
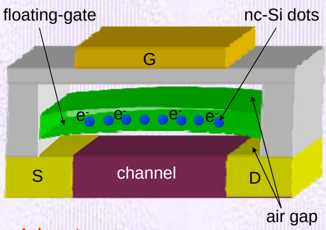


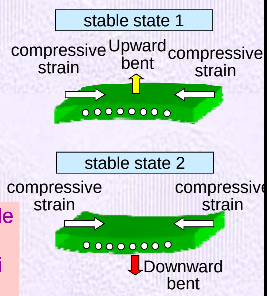
OUTLINE

1. Introduction – Co-integration of NEMS with silicon devices for information processing
2. Bistable NEMS based memory devices

Nonvolatile NEM memory



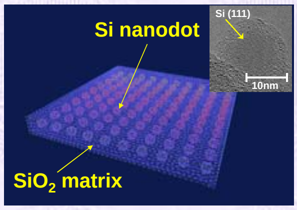
Mechanical bistable states



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

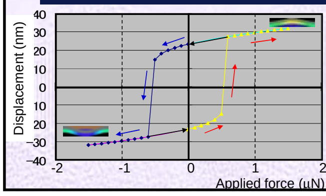
Y. Tsuchiya et al., J. Appl. Phys. 100, 094306 (2006)

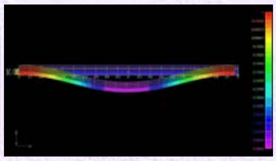
Buckled SiO_2 beam with embedded SiNDs



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

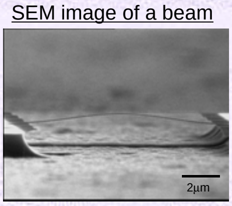
	Young's modulus	Poisson's ratio
Si	190 GPa	0.27
SiO_2	70 GPa	0.175





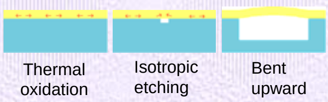
Test beam structure fabrication

SEM image of a beam



Naturally upward-bent bridge structure observed

Release of stress at Si/SiO_2 interface after undercut

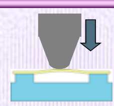


Y. Tsuchiya et al., J. Appl. Phys. 100, 094306 (2006)

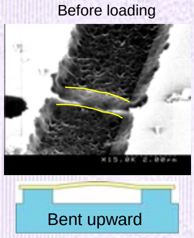
Loading experiment for the beam

Load on the beam using the nano-indentor

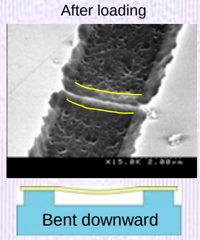
in collaboration with Y. Higo and K. Takashima of Tokyo Institute of Technology



Before loading



After loading



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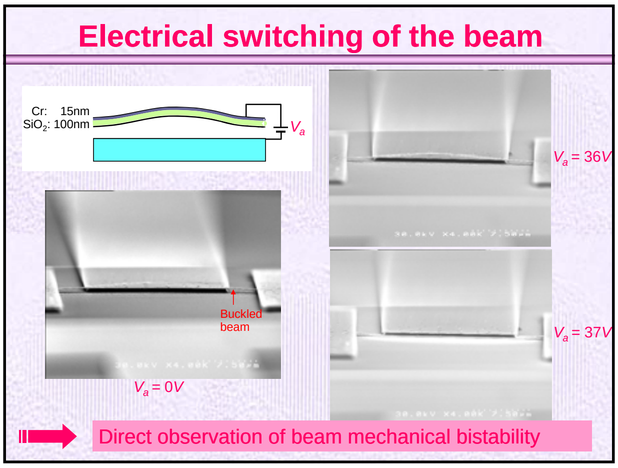
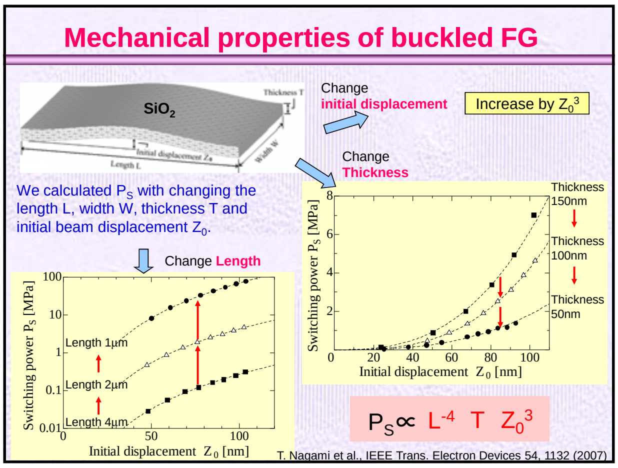
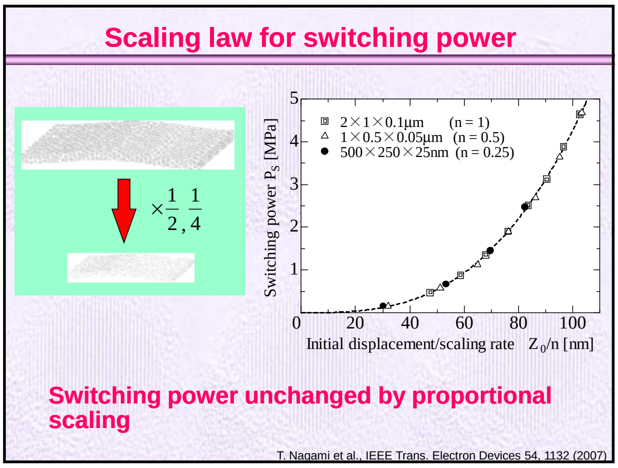
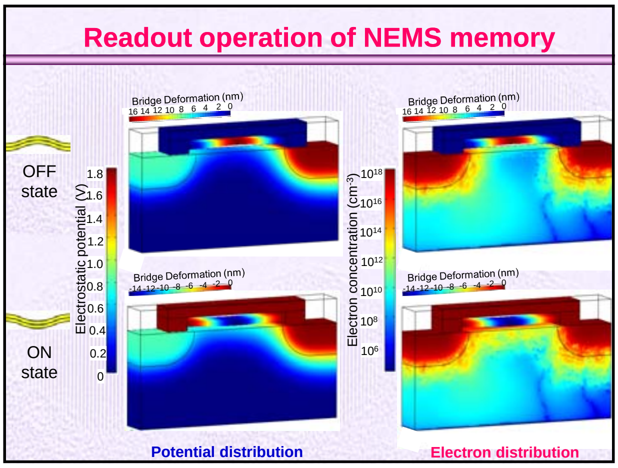
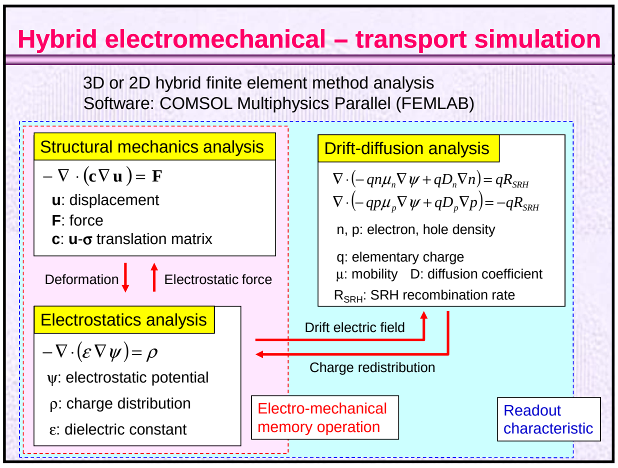

Electrical switching of the beam
Cr: 15nm
SiO2: 100nm
Va
Va = 36V
Va = 37V
Buckled beam
Va = 0V
Direct observation of beam mechanical bistability


Japanese mechanical bistable device 200 years ago
'Vidro' 'Poppin'
- An instrument with a glass lamella -
'A woman playing a vidro'
Utamaro Kitagawa (1753-1806)


Mechanical properties of buckled FG
SiO2
Change
initial displacement
Increase by Z0^3
Change
Thickness
We calculated PS with changing the length L, width W, thickness T and initial beam displacement Z0.
Change Length
Switching power PS [MPa]
Length 1μm
Length 2μm
Length 4μm
Initial displacement Z0 [nm]
Thickness 150nm
Thickness 100nm
Thickness 50nm
PS ∝ L^-4 T Z0^3
T. Nagami et al., IEEE Trans. Electron Devices 54, 1132 (2007)


Scaling law for switching power
× 1/2, 1/4
2×1×0.1μm (n = 1)
1×0.5×0.05μm (n = 0.5)
500×250×25nm (n = 0.25)
Switching power PS [MPa]
Initial displacement/scaling rate Z0/n [nm]
Switching power unchanged by proportional scaling
T. Nagami et al., IEEE Trans. Electron Devices 54, 1132 (2007)

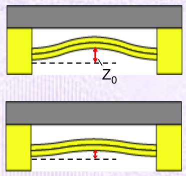

Readout operation of NEMS memory
OFF state
ON state
Bridge Deformation (nm)
Electrostatic potential (V)
Electron concentration (cm-3)
Potential distribution
Electron distribution

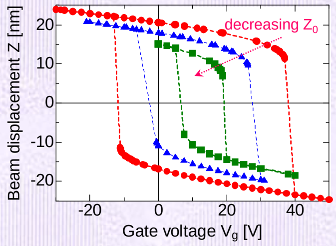

Hybrid electromechanical – transport simulation
3D or 2D hybrid finite element method analysis
Software: COMSOL Multiphysics Parallel (FEMLAB)
Structural mechanics analysis
−∇·(c∇u) = F
u: displacement
F: force
c: u-σ translation matrix
Drift-diffusion analysis
∇·(−qμn∇ψ + qDn∇n) = qRSRH
∇·(−qμp∇ψ + qDp∇p) = −qRSRH
n, p: electron, hole density
q: elementary charge
μ: mobility D: diffusion coefficient
RSRH: SRH recombination rate
Deformation
Electrostatic force
Electrostatics analysis
−∇·(ε∇ψ) = ρ
ψ: electrostatic potential
ρ: charge distribution
ε: dielectric constant
Drift electric field
Charge redistribution
Electro-mechanical memory operation
Readout characteristic

For reducing switching voltage

$P_S \propto L^{-4}\ T\ Z_0^3$

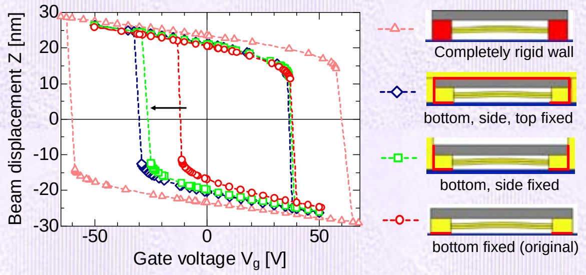
Smaller zero bias displacement leads to lower switching voltage





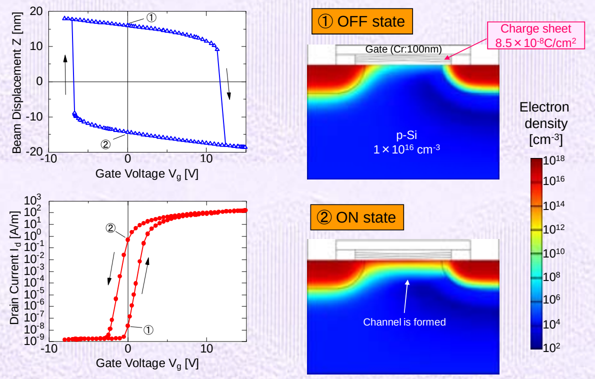
Simple reduction of Z_0 may result in losing bistability.

Effects of cavity structures

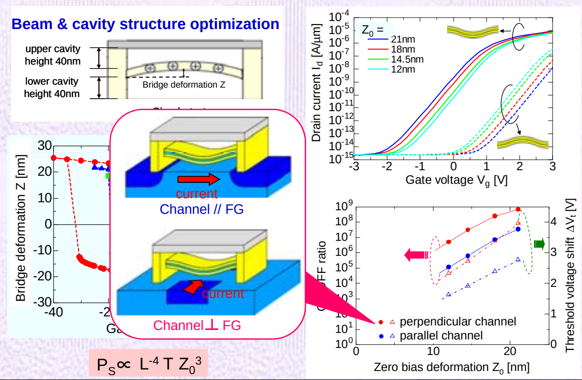


Careful structural design of the FG as well as the outer cavity needed.

Readout operation of NEMS memory

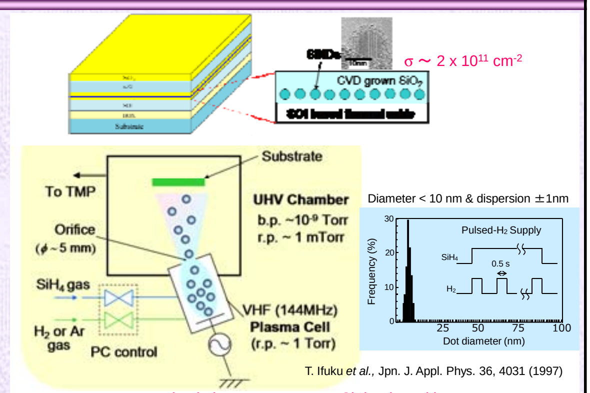


Optimized Readout characteristics



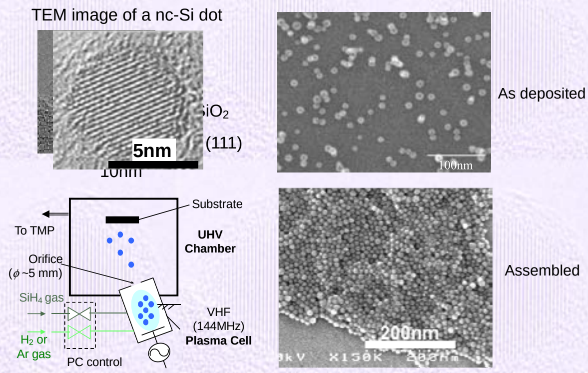
$P_S \propto L^{-4}\ T\ Z_0^3$

Fabrication of FG with SiNDs

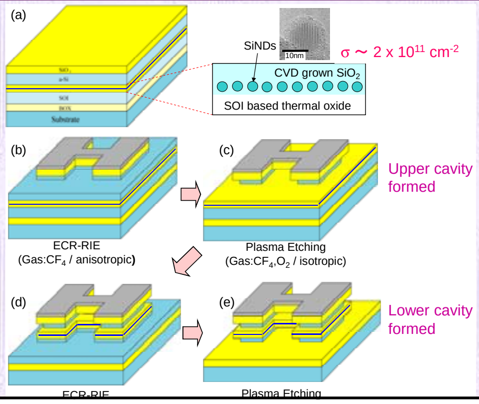


VHF pulsed plasma process: nc-Si dot deposition

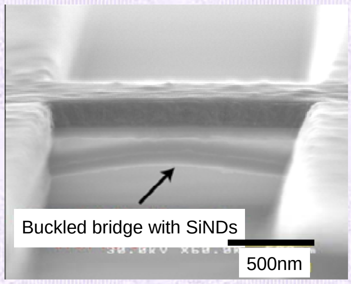
Fabrication of FG with SiNDs

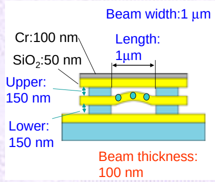


Fabrication of FG with SiNDs



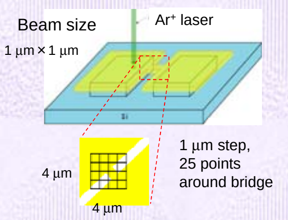
Fabrication of FG with SiNDs

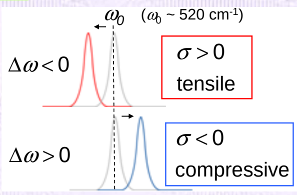




Mechanical stress analysis using µRS

Micro-Raman spectroscopy (µRS)





Jobin-Yvon U-1000
- 514.5 nm Ar^+ laser source
- 1 µm spot diameter
- Resolution ~0.15 cm-1 wave number

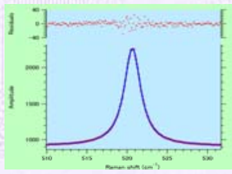
$$\sigma[\mathrm{MPa}] = -434 \times \Delta\omega[\mathrm{cm}^{-1}]$$

σ: Stress $\quad \Delta\omega = \omega - \omega_0$

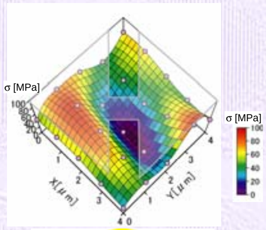
ω : Raman mode frequencies of Si in presence of stress

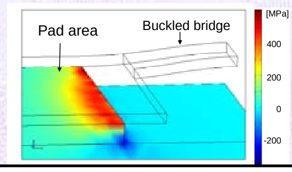
I. De Wolf, Semicond.Sci.Technol.11(1996) 139-154.

Mechanical stress analysis using µRS



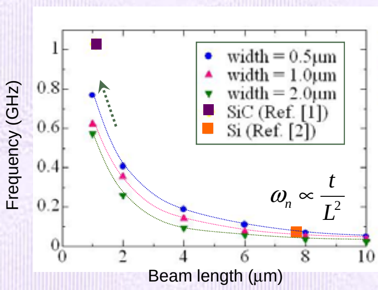
Peak determined by using Lorenzian fitting



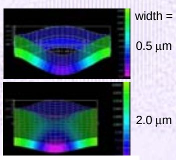


Tensile stress of about 100MPa observed around the beam edges

Switching speed of a simple flat FG



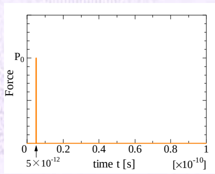
$$\omega_n \propto \frac{t}{L^2}$$



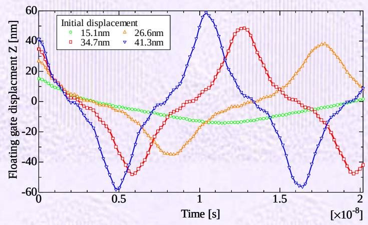
[1] X.M.Henry Huang *et al.*, Nature **421**,496 (2003).
[2] A.N.Cleland and M.L.Roukes, APL **69**, 2653 (1996).

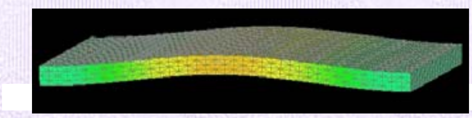
For a simple flat SiO_2 beam with L < 1 µm, over 1GHz frequency can be obtained, but……

Switching speed of a buckled bistable FG



Instantaneous applied force





Length 1µm
Width 500nm
Thickness 50nm

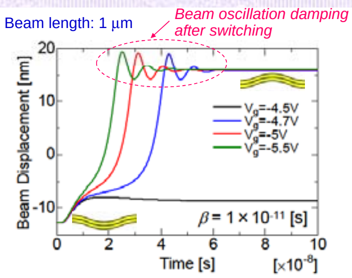
Oscillation at Z_0 = 34.7nm

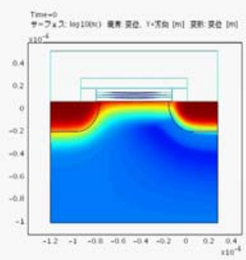
T. Nagami et al., IEEE Trans. Electron Devices 54, 1132 (2007)

Beam damping 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	NEMS-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}?

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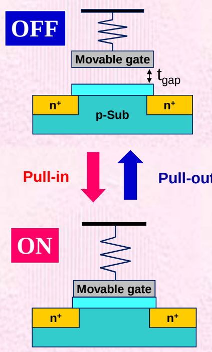
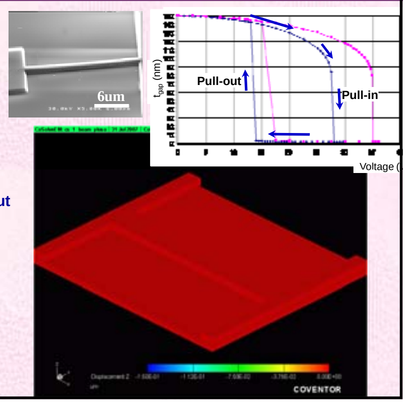
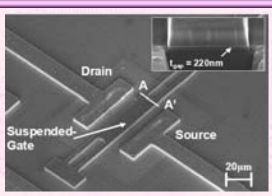
Suspended-Gate MOSFET

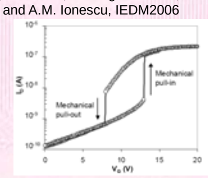


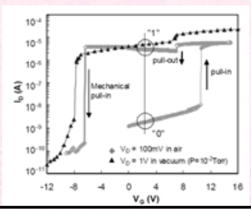


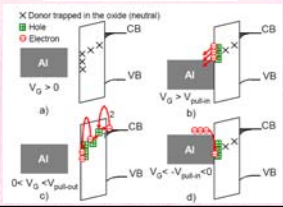
SG MOSFET based NEMS memory



N. Abelé, A. Villaret, A.Gangadharaiah, C. Gabioud, P. Ancey and A.M. Ionescu, IEDM2006







SUMMARY

Introduction of bistable NEMS into MOS may provide a new memory device with high-speed operation & serious nonvolatility:

- Scaling rule for a buckled FG shown
- Mechanical bistability demonstrated
- FG / cavity structure optimized for lowering programming voltage (<10V) with maintaining high ON/OFF ratio (~10^5)
- Experimental FG with embedded nc-Si dots fabricated
- Switching speed less than 50 nsec shown for 1 μm FG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T. Shimada (now of Quantum 14 Co.)