**Functional silicon nanoelectromechanical information processing devices**

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**OUTLINE**

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

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**More Moore : CMOS extension ?**

- Strained Si
- High-k (FUSI)
- Tri-gated (3G)
- Dual metal gate
- Quasi ballistic
- NEMS

**MEMS to NEMS : miniaturization trend ?**

- CMOS
- SiC beam
- Over 1 GHz operation possible with size reduction

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**Progressing high-speed Si based MEMS**

- Si beam
  - \( L = 7.7 \mu m \)
  - \( t = 0.33 \mu m \)
  - \( h = 0.8 \mu m \)
  - \( f_R = 70.72 \text{MHz} \)

- 3C-SiC beam
  - \( L = 1.1 \mu m \)
  - \( w = 120 \text{nm} \)
  - \( h = 75 \text{nm} \)
  - \( f_R = 10 \text{GHz} \)

\[ f_R \propto \frac{t}{L} \]

A.N.Cleland and M.L.Roukes

X.M.Henry Huang et al.,

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**NEMS integrated into Si nanodevices**

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

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

2. NEM nonvolatile memory

Nonvolatile NEM memory

Mechanical bistable states

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

Buckled SiO$_2$ beam with embedded SiNDs

Test beam structure fabrication

Loading experiment for the beam

Electrical switching of the beam

Before loading

After loading

Direct observation of beam mechanical bistability
We calculated PS with changing the length L, width W, thickness T and initial beam displacement $Z_0$. The relationship between switching power PS and initial displacement $Z_0$ is given by the equation $PS \propto L^4 T Z_0^3$.

Scaling law for switching power

Switching power unchanged by proportional scaling

Optimized Readout characteristics

Fabrication of FG with SiNDs

Fabrication of FG with SiNDs

Readout operation of NEM memory

Potential distribution

Electron distribution

Fabrication of FG with SiNDs

Switching speed of a simple flat FG

For a simple flat SiO₂ beam with L < 1 μm, over 1GHz frequency can be obtained, but……

Switching speed of a buckled bistable FG

Beam dumping effects on switching speed

Beam oscillation dumping after switching

A variety of nonvolatile RAM candidates

OUTLINE

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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.

Pull-in operation of movable gate

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 $k_B T \ln 2$

Adding new functionalities
- Switching beyond $k_B T \ln 2$?
- Offset charge independent SET
- Functional analog circuits

Tunable threshold SET inverter

Novel threshold gate (hard limiter) can be designed by tuning $C_G$

SETMOS-NEMS as a novel threshold gate

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

SETMOS-NEMS based hybrid neuron cell

Fusion of NEMS & single-electron transistors

NEMSET: strongly-coupled electron-phonon system

Phonon blockade of electrons

Single-electron energy dissipation

Phononic bandgap

Quantum shuttle

Quantization of mechanical displacement

Mechanical modulation of tunnelling rate

NEMSET is an ideal laboratory for exploring strong coupling of single electrons and low-dimensional phonons (Nanophonons)!
NEMSET(1): Mechanically modulated tunnelling rate

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

SiNB with a single QD cavity


NEMSET(2): Phononic bandgap formation

Phononic bandgap

Nanoscale EM phenomena unexplored!

Electronic Devices

Studied well

Studied very well

Studied quite well

Studied very little

Studied well

Nanoscale

Electronic Devices

Atomic scale

Nanoscale

Atomic scale

Electromechanical Devices

Phonon blockade of single-electron tunnelling

Single electron tunnelling induces mechanical excitation as a localized cavity phonon

Energy gap in Coulomb

diamond $\varepsilon_0 \approx 100 \mu eV$


Quantization of mechanical motion?

Thermal occupation number $N_0 = h\omega_B T / M$

$\omega_B = 1.49 \text{ GHz}, T = 110 \text{ mK}$

$N_0 \approx 1$ - quantum regime

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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