Lecture 8
NEMS and Piezoelectric Transistor

ELEN 6907, Columbia University

Emerging Nanoelectronic Devices

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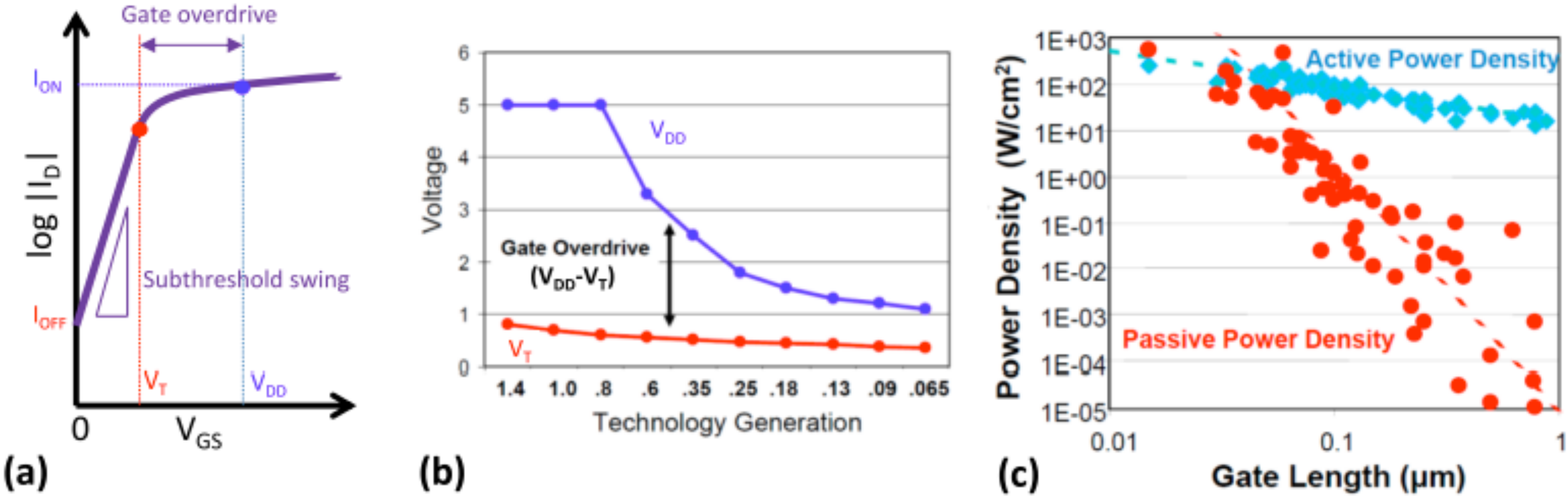
Outline

- Motivation for mechanical switching
- M/NEMS basics
- M/NEMS fabrication
- NEMS (electrostatic) digital logic example
- NEMS (piezoelectric) digital logic example
- NEMS (piezoresistive) digital logic example
- NEMS circuits

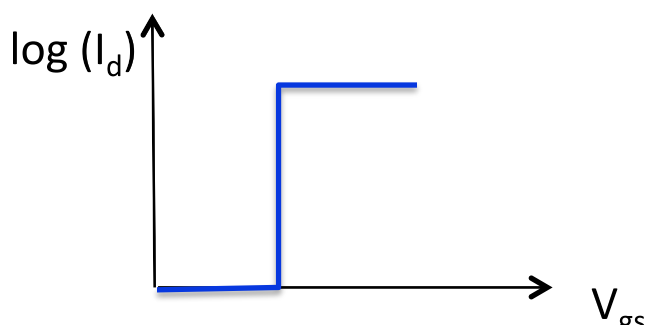
Motivation for mechanical switching

- The problem we've come to know so well:



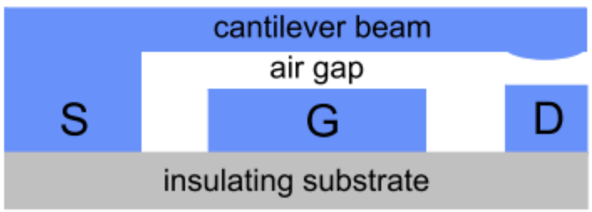
T. Liu *et al.*, *NEMS Switch Technology* (Book Chapter in *Emerging Nanoelectronic Devices*), preprint (2014).

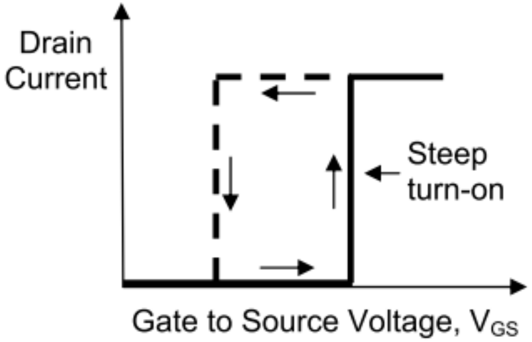
- The perfect switch:



M/NEMS (Micro/NanoElectroMechanical System) basics

- Electrical contact (current flow) achieved by mechanical manipulation of a material



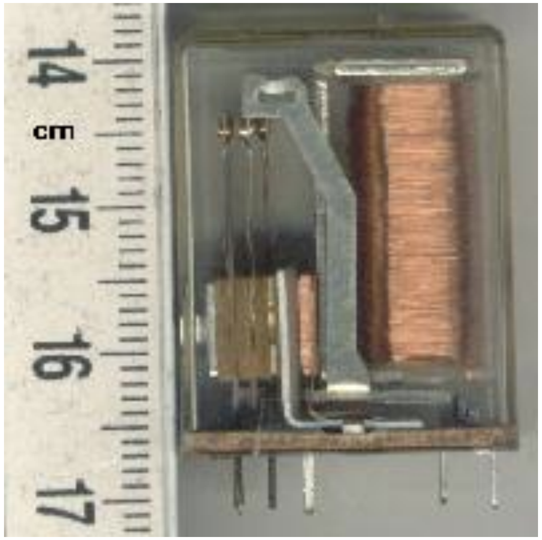


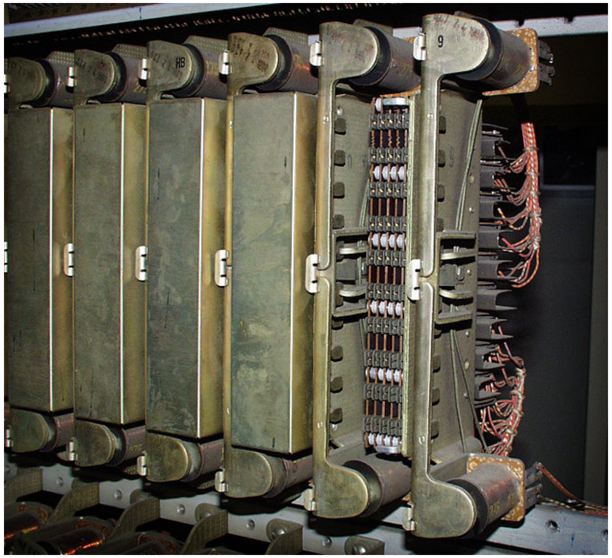
- Actuation mechanisms
  - Electromagnetic (issues: area consumption, insufficient E efficiency)
  - Electrothermal (issues: insufficient E efficiency)
  - Electrostatic (issues: challenging fabrication, limited speed)
  - Piezoelectric (issues: materials/fabrication challenging)
  - Piezoresistive (issues: uncertain scalability, challenging fabrication)

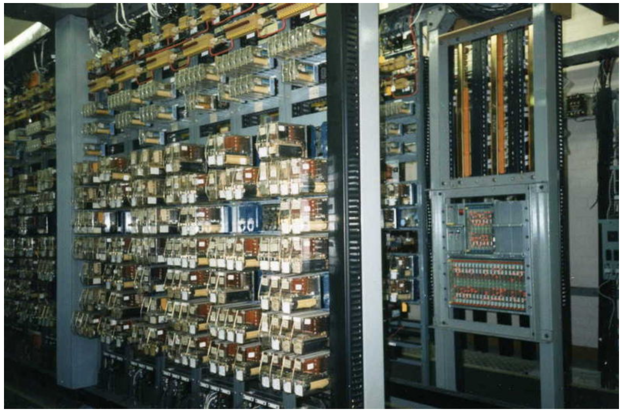
Contenders for digital computing devices (Electrostatic, Piezoelectric, Piezoresistive)

M/NEMS (Micro/NanoElectroMechanical System) basics

- NEMS, also called ‘relays’ because of their history







→ Originally invented in ~1830’s to improve the electrical telegraph

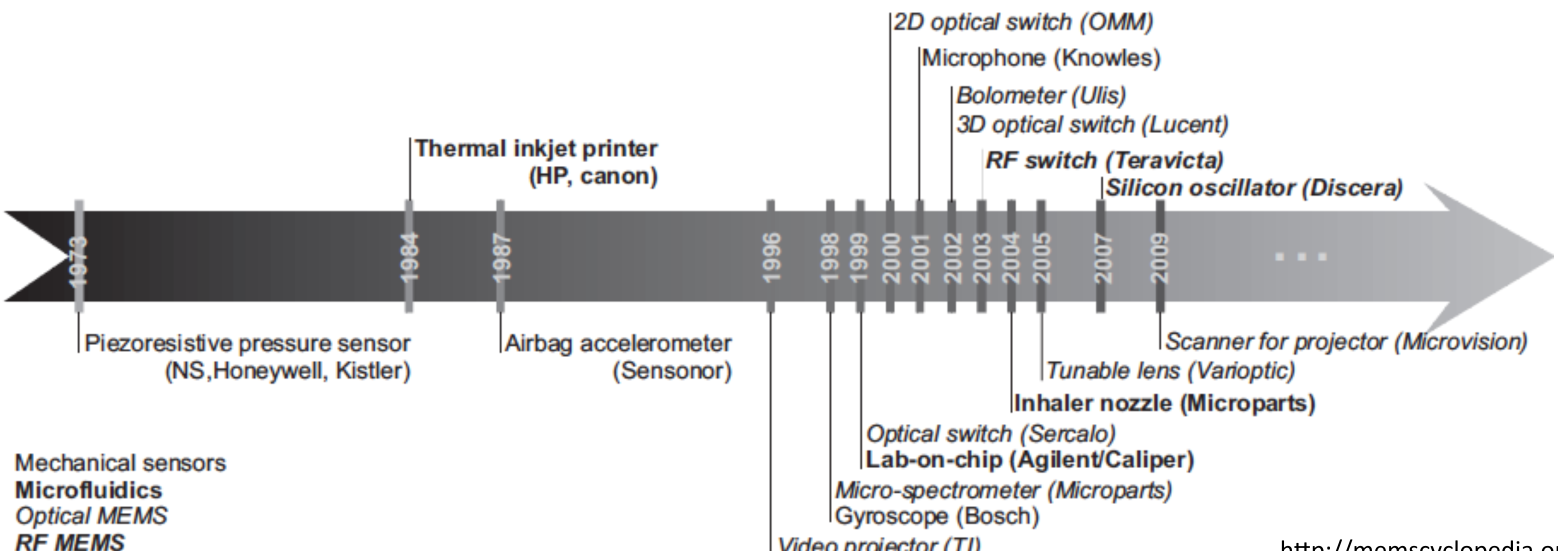
→ Found use in early logic operations before being overrun by vacuum tubes

→ Still major components of large machinery

M/NEMS (Micro/NanoElectroMechanical System) basics

- M/NEMS is not just about switches, but is a field with a myriad of applications/products
  - RF-MEMS
  - Accelerometers
  - Pressure/mass sensors
  - Microfluidics
  - etc.

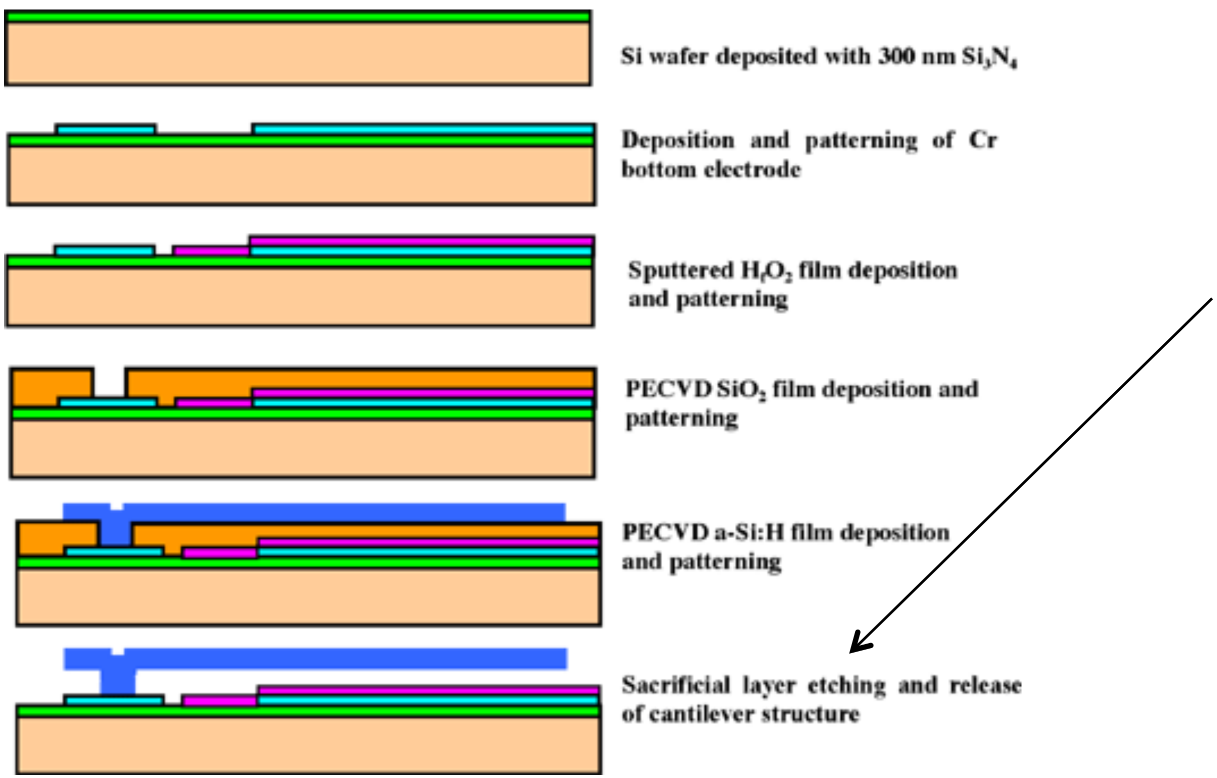
Product type	Examples
Pressure sensor	Manifold pressure (MAP), tire pressure, blood pressure..
Inertia sensor	Accelerometer, gyroscope, crash sensor...
Microfluidics / bioMEMS	Inkjet printer nozzle, micro-bio-analysis systems, DNA chips...
Optical MEMS / MOEMS	Micro-mirror array for projection (DLP), micro-grating array for projection (GLV), optical fiber switch, adaptive optics...
RF MEMS	High Q-inductor, switches, antenna, filter..
Others	Relays, microphone, data storage, toys...



http://memscyclopedia.org/Document/introMEMS.pdf

M/NEMS fabrication

- "Micromachining" and "MEMS fabrication" are coined terms related to making M/NEMS devices
- Key step: release

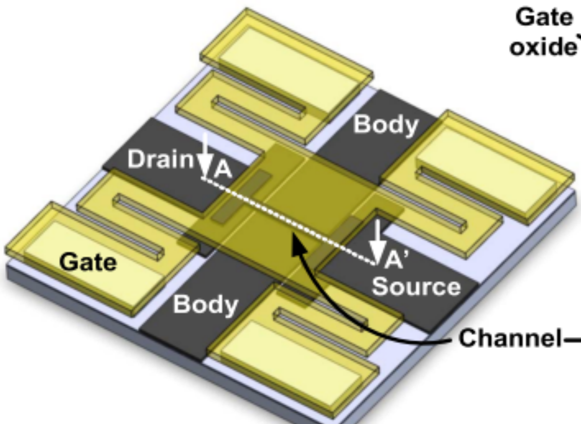


Potential collapse of cantilever, or overetch of sacrificial layer, damage to cantilever or substrate, etc.

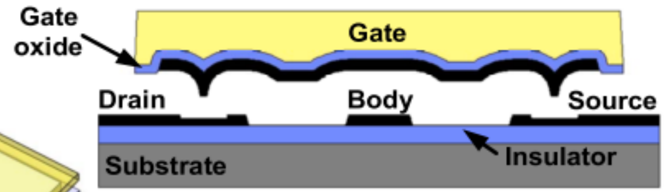
http://www.silvaco.com/tech_lib_TCAD/simulationstandard/2005/aug/a3/a3.html

NEMS (electrostatic) digital logic example

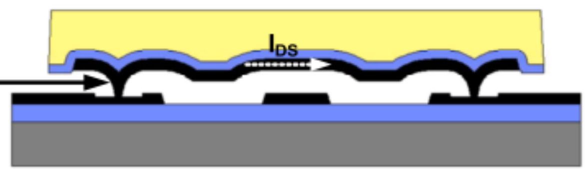
- 4-terminal device using a body bias to tune polarity



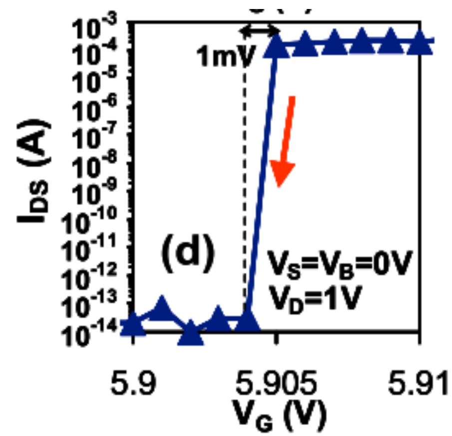
(a) Relay schematic



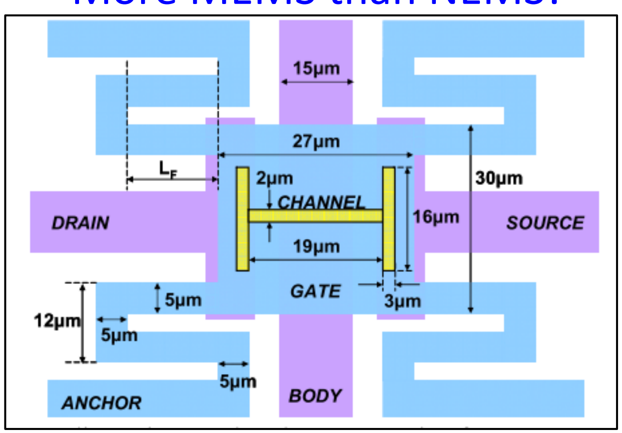
(b) AA' cross-section: OFF-state

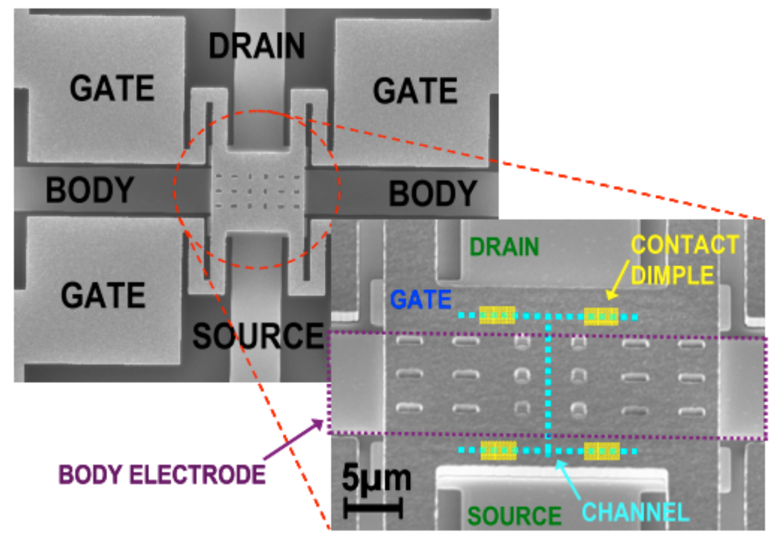


(c) AA' cross-section: ON-state



More MEMS than NEMS!

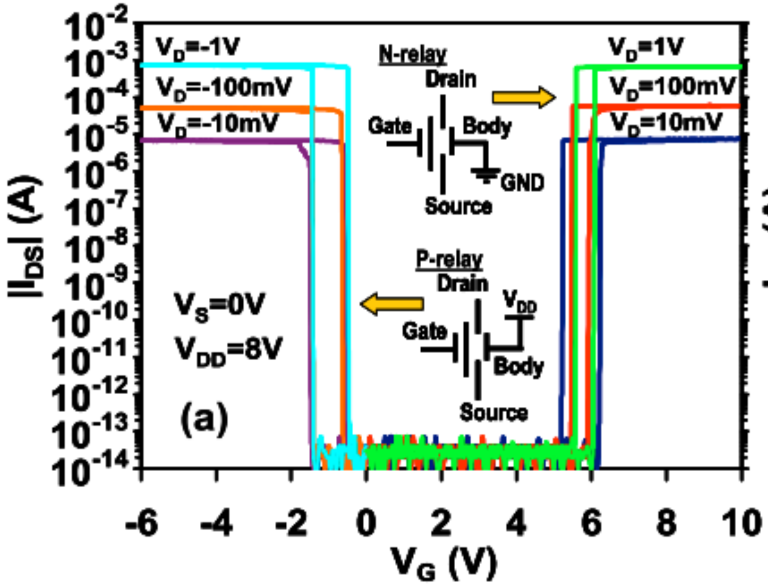


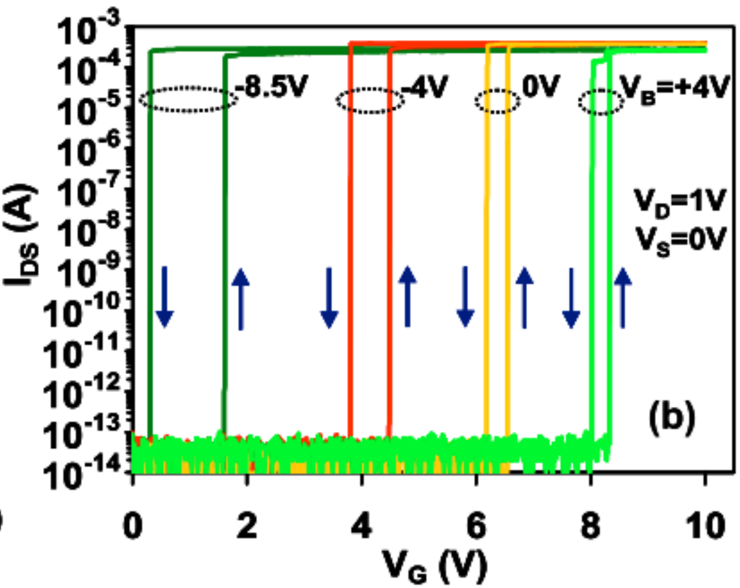


R. Nathanael *et al., IEDM Technical Digest,* pp. 9.4.1-4, 2009.

NEMS (electrostatic) digital logic example

- Mimic n- and p-type operation by adjusting body bias



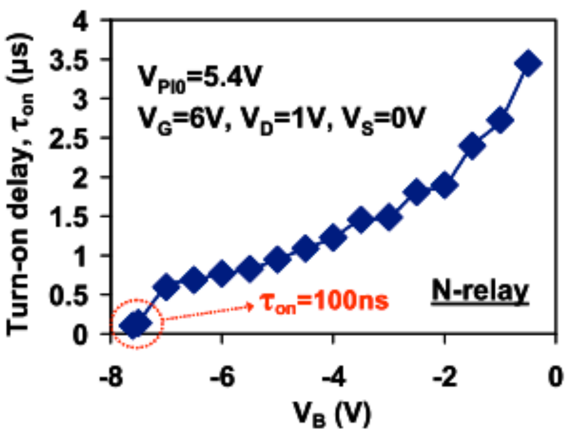


→ Larger the body bias, larger the hysteresis

→ Surface adhesion forces causing hysteresis

→ Contact resistance challenging to control

→ Logic demonstrated



R. Nathanael *et al., IEDM Technical Digest,* pp. 9.4.1-4, 2009.

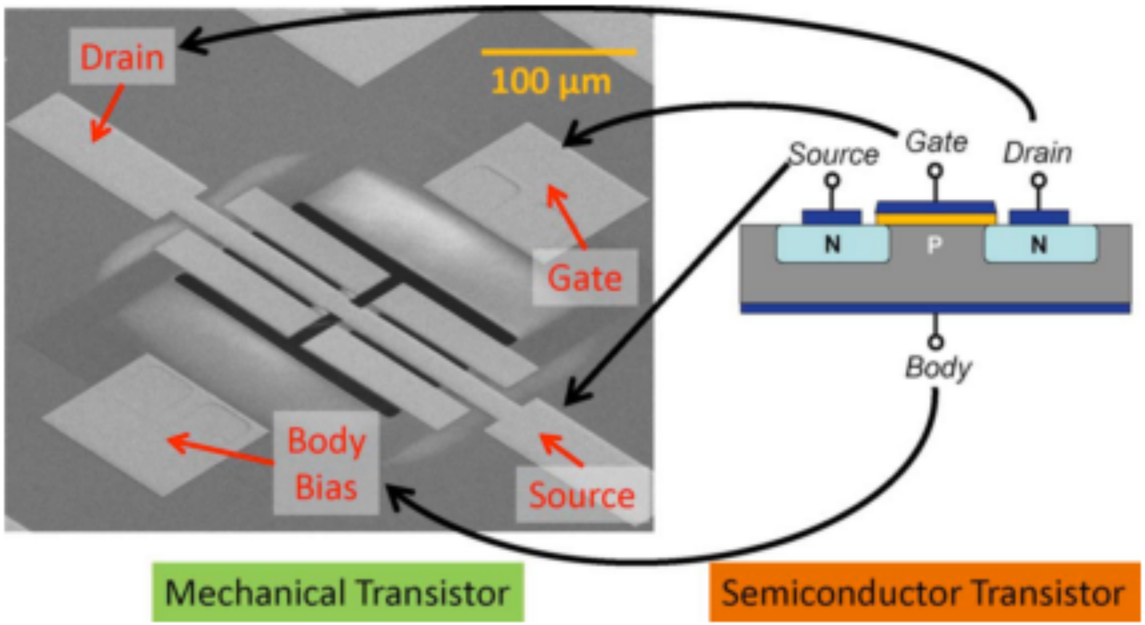
NEMS (electrostatic) digital logic example

- Advantages
  - Excellent low energy option demonstrated
  - Ability to yield complementary logic function
  - Potentially reduce needed buffers in logic to offset larger device size compared to CMOS
  - High current

- Challenges
  - Fabrication is challenging, especially to scale
  - Contact resistance effects –surface deformation, adhesion forces, uniformity, etc.
  - Slow switching speed (not RC-delay, but mechanical delay limited)
    - ~100s ns vs. ~1 ps for CMOS
  - Hysteresis ("pull-in operation")
  - Reliability (how many times can you switch these things?)

NEMS (piezoelectric) digital logic example

- Compare device to MOSFET:

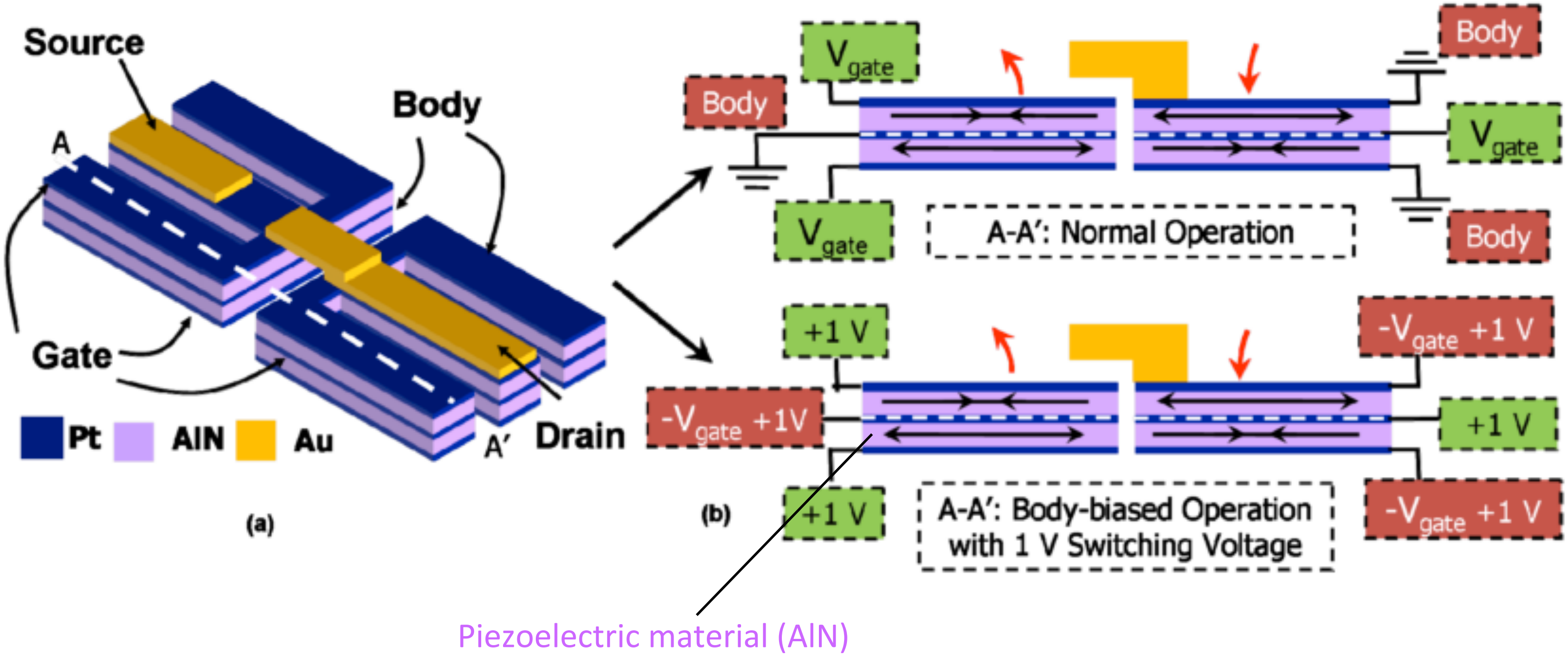


→ Effort to increase device community comfort with NEMS

→ Huge difference in <u>scale</u>

N. Sinha *et al., J. Microelectromechanical Sys.,* vol. 21, pp.484-496, 2012.

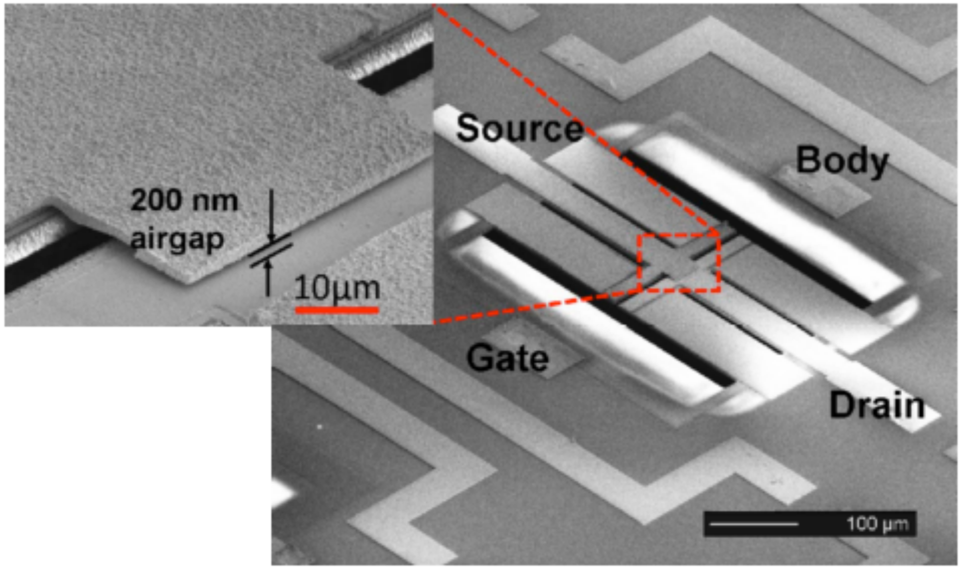
- Inverse piezoelectric effect
  - Material deformation in response to electric field

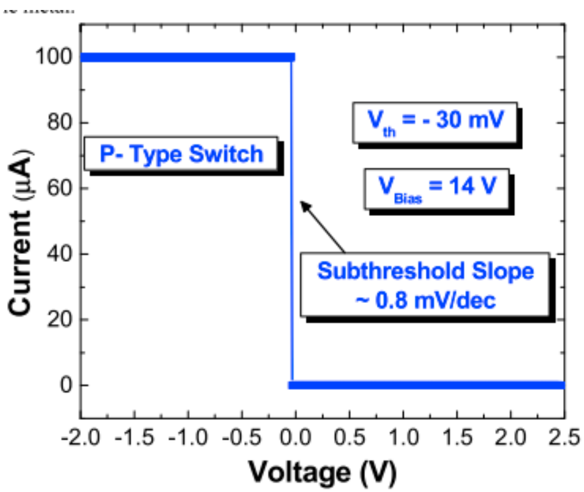


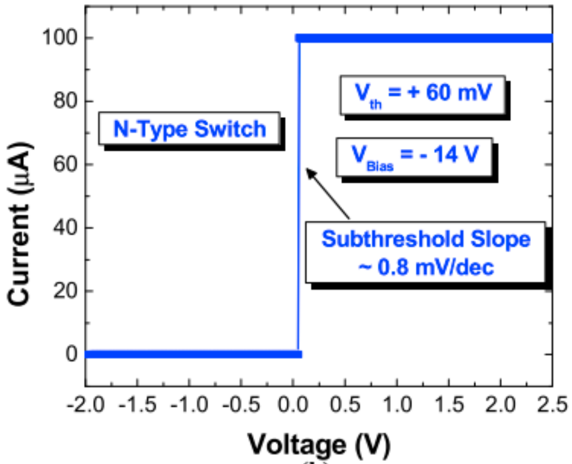
→ Applying a gate voltage creates an electric field between the gate plates and the body plates, causing the PE material between the plates to expand/retract, causing the drain cantilever to contact the source region.

N. Sinha *et al.*, *J. Microelectromechanical Sys.*, vol. 21, pp.484-496, 2012.

- Compare device to MOSFET:







→ Body bias enables n- and p-type operation

→ Switching time: ~220 ns

N. Sinha *et al., J. Microelectromechanical Sys.,* vol. 21, pp.484-496, 2012.

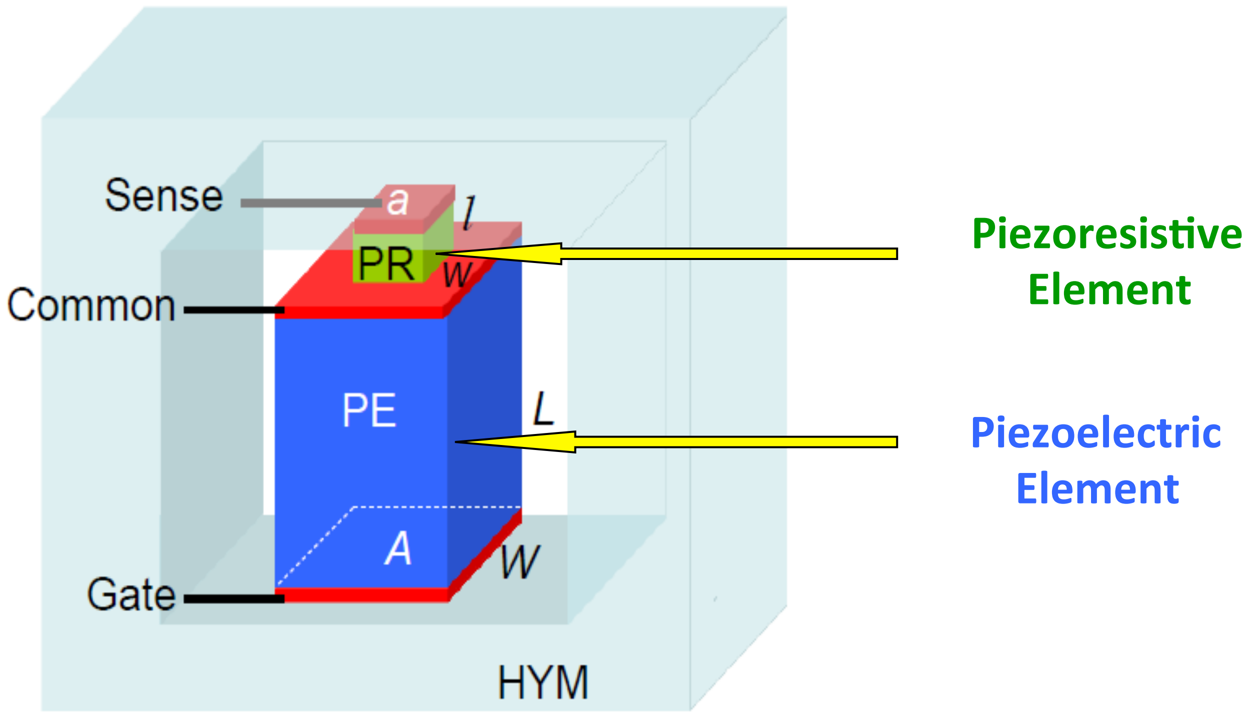
NEMS (piezoelectric) digital logic example

- Advantages
  - Excellent low energy option demonstrated
  - Ability to yield complementary logic function
  - Potentially reduce needed buffers in logic to offset larger device size compared to CMOS
  - High current
  - No hysteresis

- Challenges
  - Fabrication is challenging, especially to scale
  - Contact resistance effects –surface deformation, uniformity, etc.
  - Slow switching speed (not RC-delay, but mechanical delay limited)
    - ~200s ns vs. ~1 ps for CMOS
  - Reliability (how many times can you switch these things?)

NEMS (piezoresistive) digital logic example

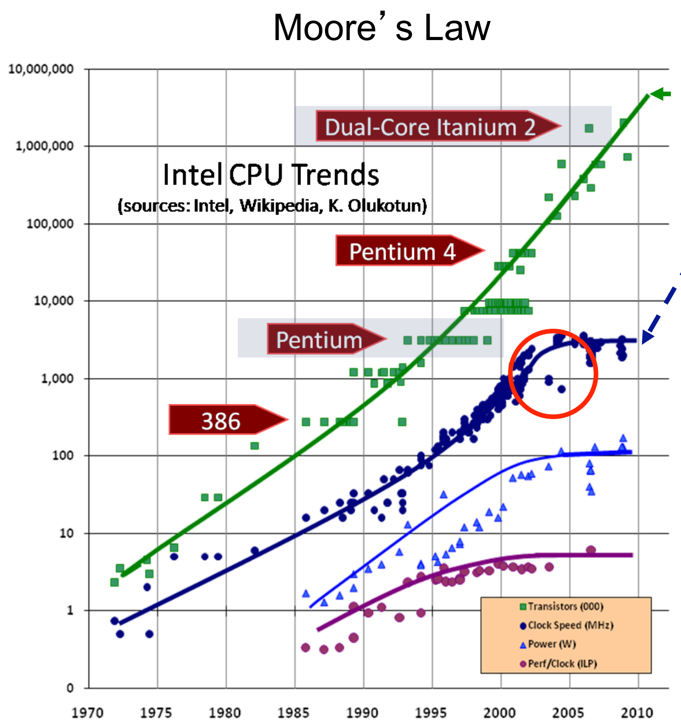
- IBM has a sizable effort towards a piezoelectronic transistor (PET)
  - DARPA funded with U-Wisconsin and Penn State



Slides courtesy of D. Newns (IBM)

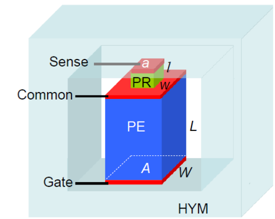
NEMS (piezoresistive) digital logic example

- Motivation – Overcome CMOS speed block
  - THIS LOOK FAMILIAR??? SEEN SEVERAL TIMES IN CLASS NOW AND THEY USE IT TO MOTIVATE NEMS!



Moore's Law: transistor density is *still increasing*

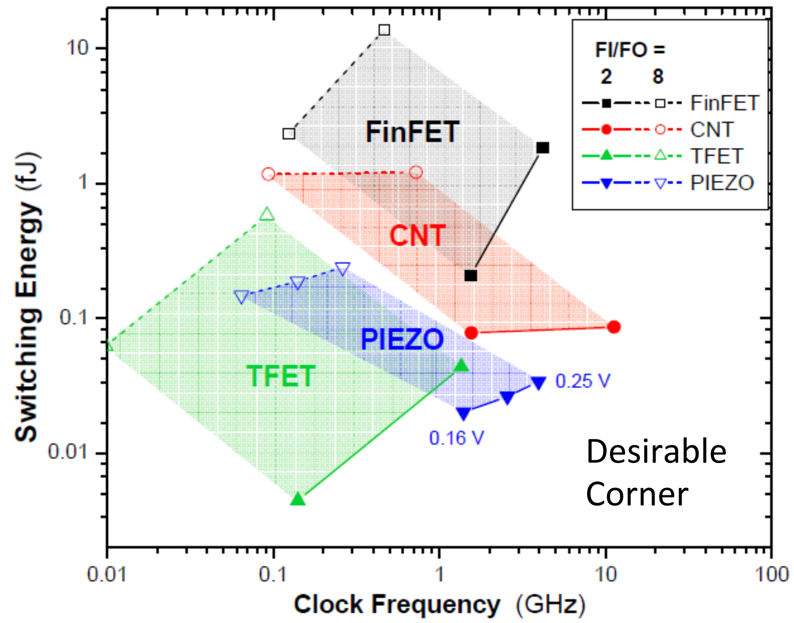
- But CMOS clock speed has **not increased** since 2003– limiting processor compute power
- Line voltage V_{DD} has **stopped decreasing** so power rises unacceptably if speed increases.
- Invent a new type of fast switch with novel physics operable at **low voltage/power**
- Our PiezoElectronic Transistor (PET) is shown by simulation and theory (based on bulk material properties) to achieve this goal.



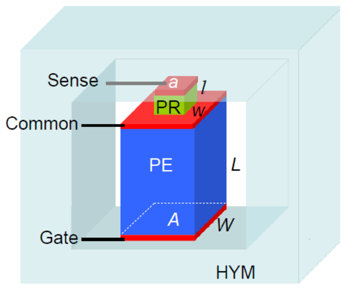
Slides courtesy of D. Newns (IBM)

Reduce *server farm, supercomputer, hand-held device* power consumption.

- PET performance comparison



11nm Technology study:
The PET has impressive advantages!



PET low power, high speed, performance compares favorably with other Switching devices. Fanout supported.

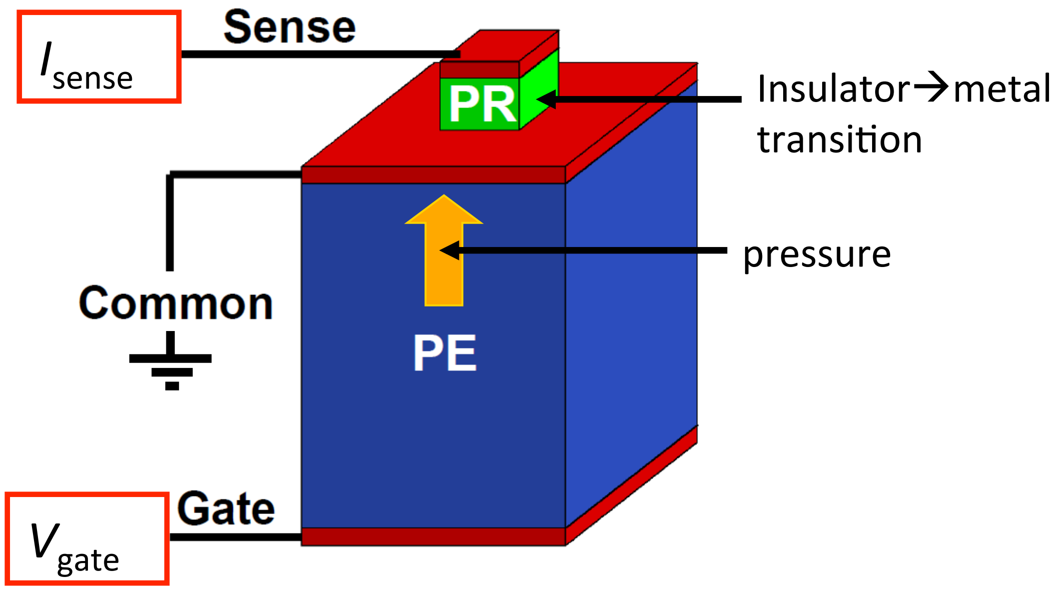
Power up to factor of 50 saved over the FinFET.

Slides courtesy of D. Newns (IBM)

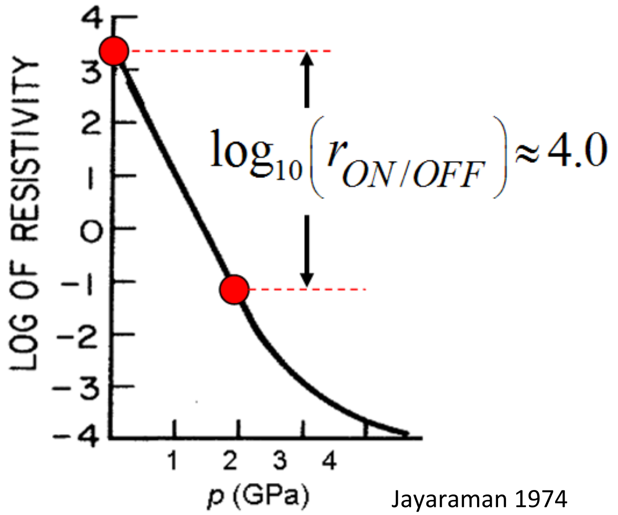
NEMS (piezoresistive) digital logic example

- Piezotronics – Electrical viewpoint

A ***gate*** voltage on a ***piezoelectric*** (PE) applies ***pressure*** to a ***piezoresistive*** (PR) material which induces a **insulator→metal transition**, turning on the current through ***sense***.



Piezoelectronic Transistor (PET)

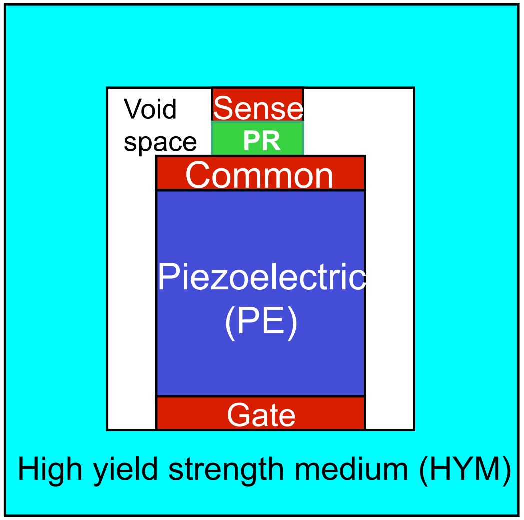


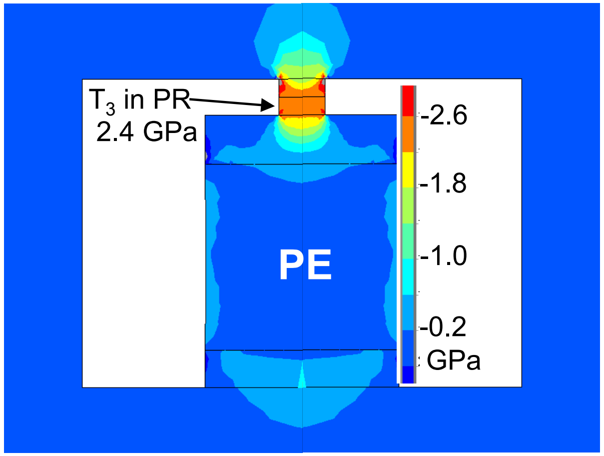
Jayaraman 1974

Slides courtesy of D. Newns (IBM)

NEMS (piezoresistive) digital logic example

- Piezotronics – Mechanical viewpoint





The Gate/PE/Common/PR/Sense sandwich is embedded in a **high yield strength medium** (HYM; e.g., SiN), to hold the Sense-Drive physical distance constant.

The area ratio $Area_{PR} << Area_{PE}$ (a/A) steps up the pressure in the PR – the **hammer and nail principle.**

A void space allows unconstrained motion of the components.

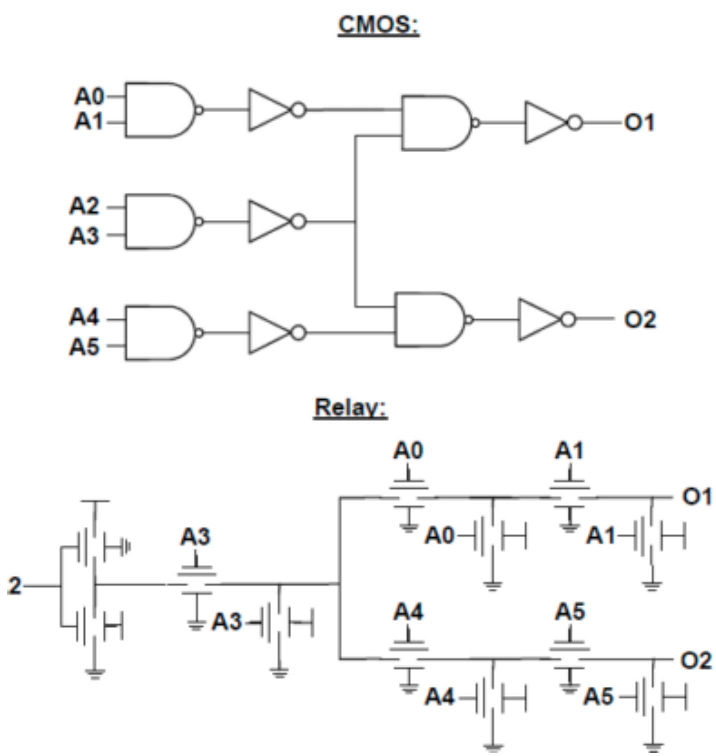
Slides courtesy of D. Newns (IBM)

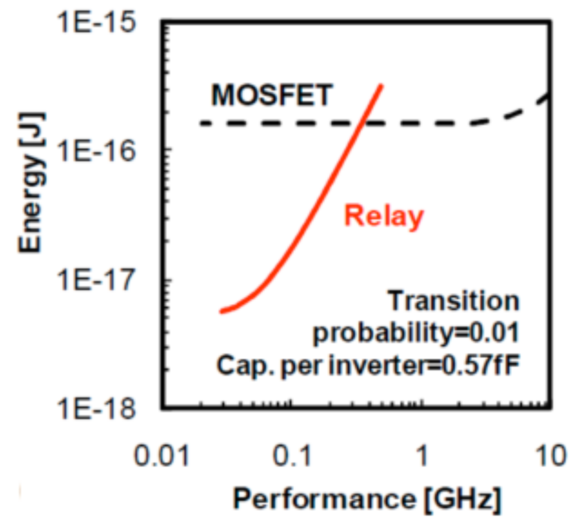
NEMS (piezoresistive) digital logic example

- Advantages
  - Excellent low energy option demonstrated
  - Ability to yield complementary logic function
  - Potentially reduce needed buffers in logic to offset larger device size compared to CMOS
  - High current
  - No hysteresis
  - Switching speed comparable to CMOS (theoretical)

- Challenges
  - Fabrication is challenging, especially to scale
  - Material quality/uniformity effects
  - Reliability (how many times can you switch these things?)

- Most demonstrations of NEMS provides a demo of a logic function (at least inverter), often more advanced
  - V_{pi} (which is V_t) is well-defined and can thus yield logic function, even though it is very SLOW logic!





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