Toward adiabatic computation

July 10, 2015

NiPS Summer School 2015
ICT-Energy: Energy consumption in future ICT devices
Outline

• Performance of NEMS switches: reality vs. necessity
• Adiabatic NEMS-based logic circuits
• Adiabatic MEMS logic gate
• Adiabatic NEMS memory device
Electrostatic NEMS Switches (back to basics)

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High switching frequency ($> 1 \text{ GHz}$)
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High switching frequency ( > 1 GHz)

Low series resistance (~ 1 MΩ)
What do Logic circuit designers look for in a switch

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Long lifetime ( > $10^{15} - 10^{18}$ operations)
What do Logic circuit designers look for in a switch

No leakage current
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Low $V_T$ ( $< 1 \text{V}$)
High switching frequency ( $> 1 \text{ GHz}$)
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Long lifetime ( $> 10^{15} - 10^{18}$ operations)
Small Footprint area ( $< 1 \text{ \mu m}^2$)
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Electrostatic NEMS Switches (back to basics)

Scaling of NEMS Switches (in real life)

Slope = -1.5

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Scaling of NEMS Switches \textit{(in real life)}

Fabrication limitation

Casimir and vdW Force

Scaling of NEMS Switches \textit{(in real life)}

![Graph showing scaling of NEMS Switches](image)

- Fabrication limitation
- Casimir and vdW Force
- Tunneling currents

Scaling of NEMS Switches (in real life)

- Fabrication limitation
- Casimir and vdW Force
- Tunneling currents
- Adhesion Forces

Remember the end of Moore’s law
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Technological and engineering work-arounds may always be found

Some possible solutions
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- Apply pre-bias (explored in literature): problem with adhesion forces!!
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J-O Lee et al., "3-Terminal Nanoelectromechanical Switching Device in Insulating Liquid Media for Low Voltage Operation and Reliability Improvement", IEDM 2009
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- Apply pre-bias (explored in literature): problem with adhesion forces!!
- Dual gate structures
- Immerse in liquid dielectric
- Innovative fabrication process
- Explore new materials and modes of operation
NEMS-Based Adiabatic Logic Circuits
A Match Made in Heaven?
NEMS-Based Adiabatic Logic

Circuit Level Approach

- Sub-threshold
- Parallelism
- Power Gating
- Asynchronous
- Adiabatic

Device Level Approach

- SOI/ FDSOI
- FinFET
- TFET
- III-V FET
- NWFET
- CNTFET
- NEMS

Classical Logic (quick reminder)

\[ E_{\text{Dissipated}} = \frac{1}{2} CV_{dd}^2 \]
Adiabatic Charging of Capacitors


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\[ E_{\text{adiabatic}} \approx \frac{RC}{T} CV^2 \]


Adiabatic Charging of Capacitors

\[ E_{\text{adiabatic}} \cong \frac{RC}{T} CV^2 \]

\[ ESF \cong \frac{T}{2RC} \]


Adiabatic Charging of Capacitors

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REMEMBER
REMEMBER

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Adiabatic Logic

Adiabatic Logic

CMOS Adiabatic Logic

P. Teichmann, 2012

Inverter circuit in the (a) PFAL and (b) ECRL family
CMOS Adiabatic Logic

P. Teichmann, 2012

Inverter circuit in the (a) PFAL and (b) ECRL family

\[
E_{\text{dissipated}} \cong \frac{RC}{T} CV^2 + \frac{1}{2} CV_T^2 + I_{\text{leakage}} V_{dd} T
\]

Adiabatic

Non-Adiabatic

Static

CMOS Adiabatic Logic

P. Teichmann, 2012

**CMOS Voltage Scaling**

Voltage vs. Technology Generation

- $V_{DD}$
- $V_{TH}$

Gate Overdrive: $V_{DD} - V_{TH}$

**Power Density vs. Gate Length**

Source: P. Packan (Intel), 2007 IEDM Short Course

Source: B. Meyerson (IBM), Semico Conf., January 2004

$E_{dissipated} \approx \frac{CV^2}{T} + \frac{CV^2}{2T} + I_{leakage} V_{dd}$
CMOS Adiabatic Logic

Why NEMS-Based Adiabatic Logic?
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3. Adiabatic circuit => Reduce losses associated with high voltage

4. NO LEAKAGE
NEMS Adiabatic Logic

Unconventional computing
Soldier crabs *Mictyris guinotae* exhibit pronounced swarming behavior. Swarms of the crabs are tolerant of perturbations. In computer models and laboratory experiments we demonstrate that swarms of soldier crabs can implement logical gates when placed in a geometrically constrained environment.
Robust Soldier Crab Ball Gate

OR gate
Robust Soldier Crab Ball Gate

AND gate
Robust Soldier Crab Ball Gate
Robust Soldier Crab Ball Gate

- How much energy?
Robust Soldier Crab Ball Gate

• How much energy?

• Crabs usually eat algae. Crabs are omnivorous, meaning that they will eat both plants and other animals for sustenance.
Robust Soldier Crab Ball Gate

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• Energy Content of Algae: 5kcal for 3g
Robust Soldier Crab Ball Gate

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- Energy Content of Algae: 5kcal for 3g
- Average weight of the crabs was 42g
Robust Soldier Crab Ball Gate

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• Crabs usually eat algae. Crabs are omnivorous, meaning that they will eat both plants and other animals for sustenance.

• Energy Content of Algae: 5kcal for 3g

• Average weight of the crabs was 42g

• Suppose daily need is 50% of its weight: 21g of algae and thus 35kcal
Robust Soldier Crab Ball Gate

• How much energy?

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• Energy Content of Algae: 5kcal for 3g

• Average weight of the crabs was 42g

• Suppose daily need is 50% of its weight: 21g of algae and thus 35kcal

• 146440J of energy for daily operating a crab logic gate or 1.7W of power
What about the memory?
NEMS system
NEMS system

$Z > 0: \Omega_1$

$Z < 0: \Omega_0$

6x1 nm$^2$ - 240 atoms

$a = 2.42$ Å

$Y = 0.85$ TPa

$T = 10$ K
Heat production evaluation

\[ H(P, R, t) = H_{\text{kin}}(P) + H_{\text{int}}(R) + H_{\text{ext}}(R, t) \]
Heat production evaluation

\[
H(P, R, t) = H_{kin}(P) + H_{int}(R) + H_{ext}(R, t)
\]

\[
H_{ext}(R, t) = \sum_{i=1}^{n} \theta \left( x_i - \frac{1}{2} \right) \left( \frac{f_{UL}(t)}{g - z_i} - \frac{f_{DL}(t)}{g + z_i} \right) + \\
+ \theta \left( \frac{1}{2} - x_i \right) \left( \frac{f_{UR}(t)}{g - z_i} - \frac{f_{DR}(t)}{g + z_i} \right)
\]
Heat production evaluation

\[ H(P, R, t) = H_{kin}(P) + H_{int}(R) + H_{ext}(R, t) \]

\[ H_{ext}(R, t) = \sum_{i=1}^{n} \left[ \theta \left( x_i - \frac{l}{2} \right) \left( \frac{f_{UL}(t)}{(g - z_i)} - \frac{f_{DL}(t)}{(g + z_i)} \right) + \right. \]
\[ \left. \theta \left( \frac{l}{2} - x_i \right) \left( \frac{f_{UR}(t)}{(g - z_i)} - \frac{f_{DR}(t)}{(g + z_i)} \right) \right] \]

\[ W = \left\langle \int_{t_0}^{t_{end}} \frac{\partial H_{ext}(R, t)}{\partial t} dt \right\rangle \]
Heat production evaluation

\[ H(\mathbf{P}, \mathbf{R}, t) = H_{\text{kin}}(\mathbf{P}) + H_{\text{int}}(\mathbf{R}) + H_{\text{ext}}(\mathbf{R}, t) \]

\[ H_{\text{ext}}(\mathbf{R}, t) = \sum_{i=1}^{n} \left[ \theta \left( x_i - \frac{1}{2} \right) \left( \frac{f_{UL}(t)}{(g - z_i)} - \frac{f_{DL}(t)}{(g + z_i)} \right) + \theta \left( \frac{1}{2} - x_i \right) \left( \frac{f_{UR}(t)}{(g - z_i)} - \frac{f_{DR}(t)}{(g + z_i)} \right) \right] \]

\[ W = \left\langle \int_{t_0}^{t_{\text{end}}} \frac{\partial H_{\text{ext}}(\mathbf{R}, t)}{\partial t} dt \right\rangle \quad \Delta H = 0 \quad Q = W \]
2-DOF potential landscape
Reset protocol

- Objective: move the system from an unknown state to known state
- $\Delta S = k_B \log(2)$
- $Q_{\text{min}} = k_B T \log(2)$
Reset protocol

Quick and dirty: apply a positive force along Z on all atoms
Reset protocol

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WRONG: it is not possible to control the velocity!
Reset protocol

Quick and dirty: apply a positive force along Z on all atoms
Reset protocol

Controlled way: apply a set of forces in to gently put the system in the desired configuration
Reset protocol

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\[ \frac{Q}{k_B T} = k_B T \ln 2 \]

\[ \tau_p = 110 \text{ ns} \]

\[ Q_L = k_B T \ln 2 \]
Switch protocol

- Objective: move the system from a known state to another known state
- $\Delta S = 0$
- $Q_{\text{min}} = 0$
Switch protocol

Controlled way: apply a set of forces in to gently put the system in the desired configuration
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\[ \frac{Q}{k_B T} \]

\[ \tau_p = 210 \text{ ns} \]
Switch protocol

Wrong way: apply the switch protocol from the wrong initial state
Switch protocol

Wrong way: apply the switch protocol from the wrong initial state
Switch protocol

Wrong way: apply the switch protocol from the wrong initial state

\[ Q_{\text{min}} > 2Q_L \]
Thank you for your attention!

igor.neri@nipslab.org