ITRS 2004 Updateに見る今後のLSI技術の方向性

特別講演
ユビキタス･エレクトロニクスに向けた低消費電力設計技術と有機トランジスタ回路

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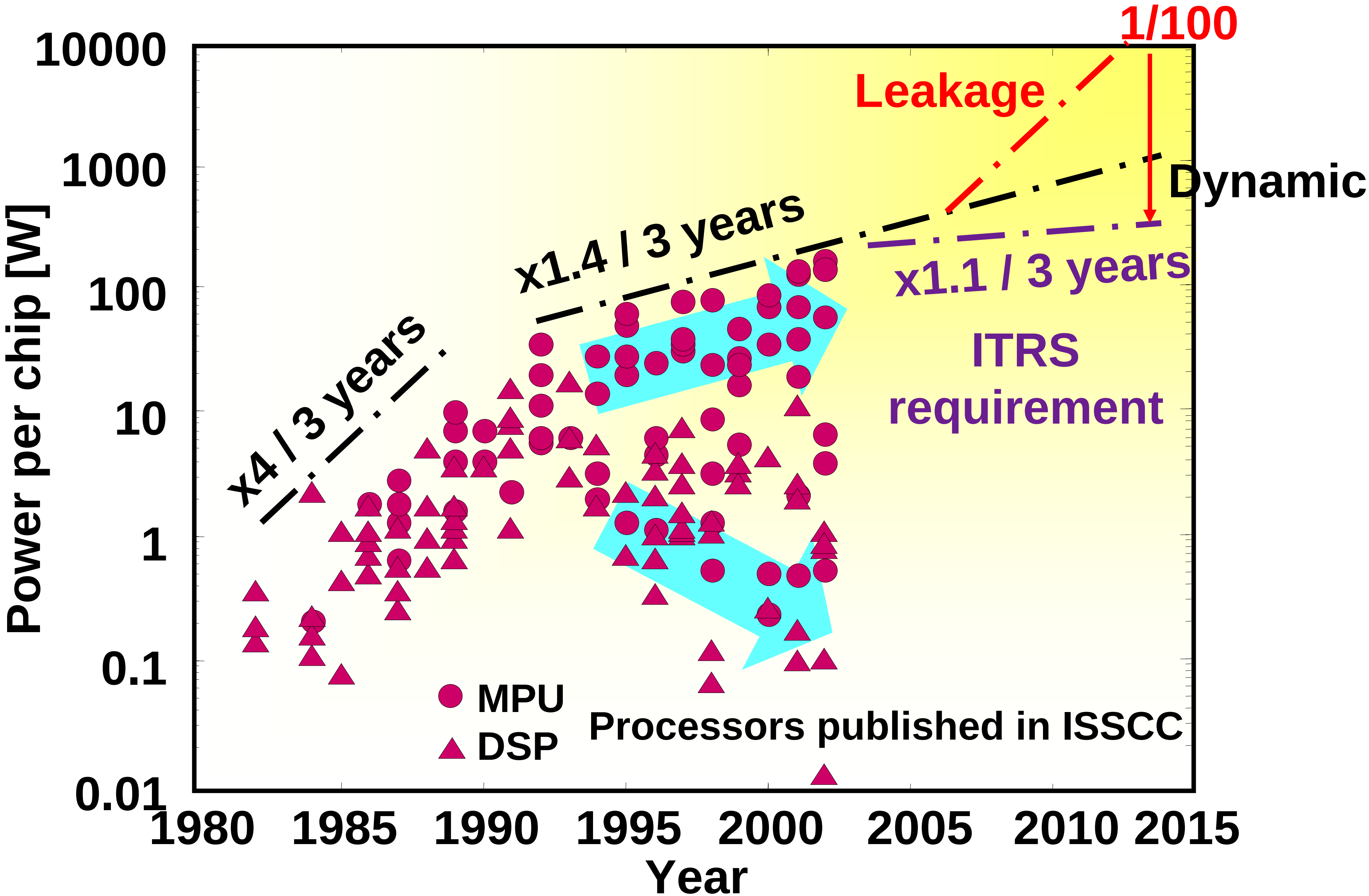
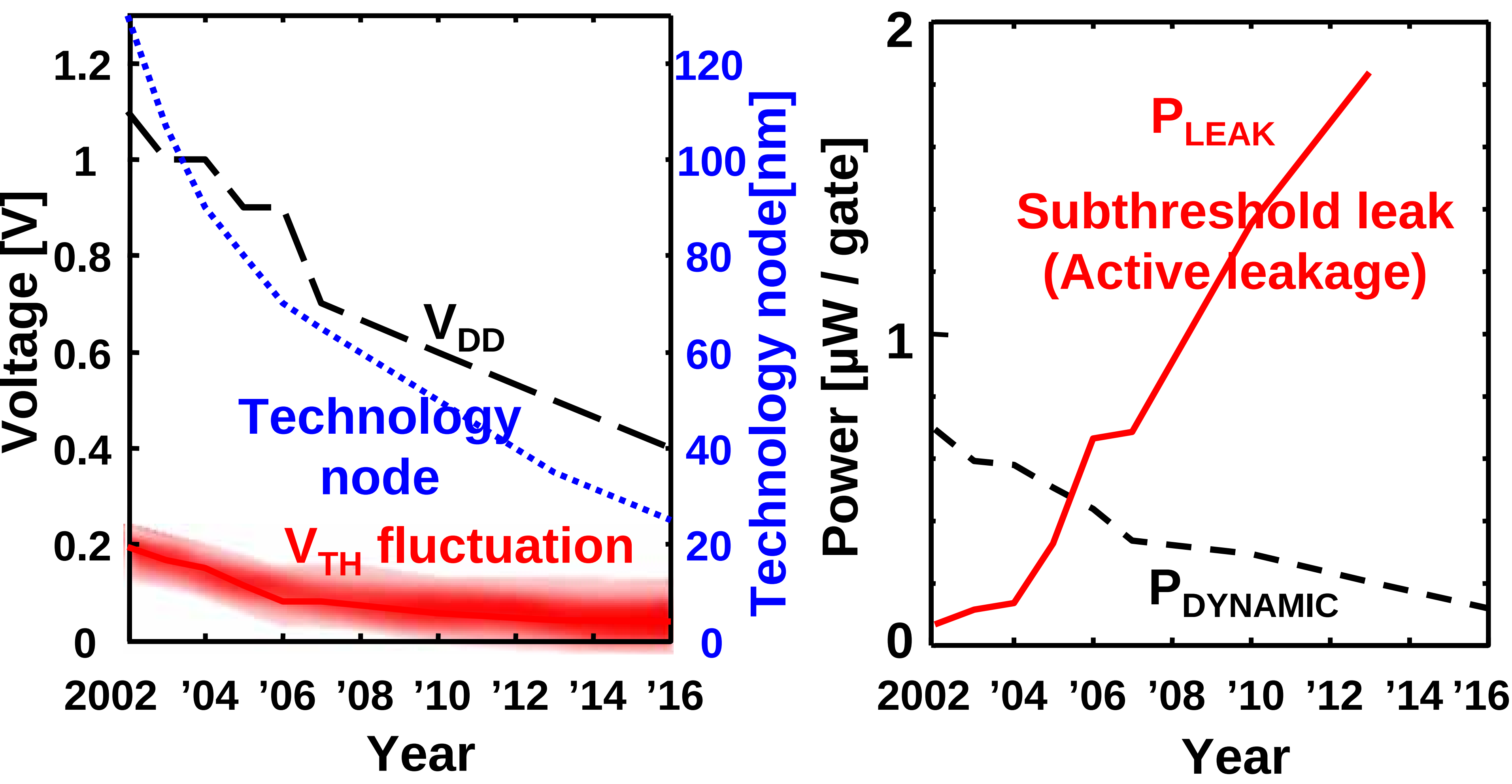
http://lowpower.iis.u-tokyo.ac.jp/

Power is a stumbling block to Moore's law



Active leakage makes things more challenging

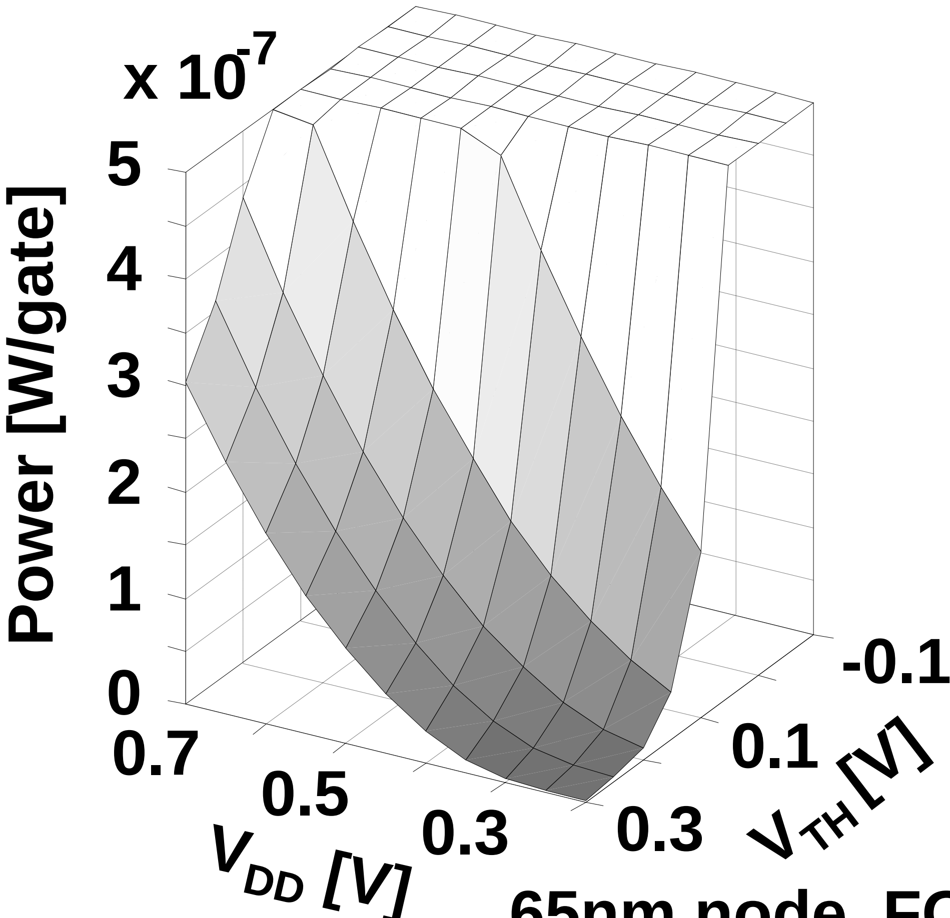


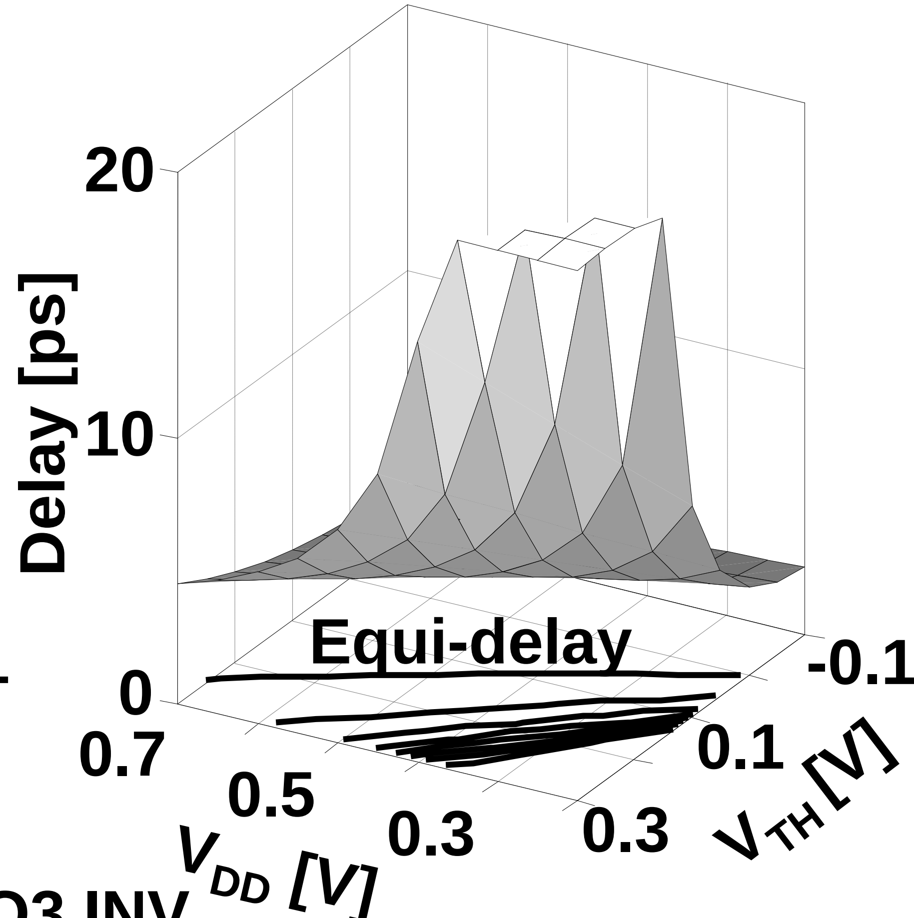
Trade-off between power and delay

$$Power = a \cdot f \cdot C \cdot V_{DD}^2 + I_0 \cdot 10^{-\frac{V_{TH}}{s}} \cdot V_{DD}$$

(+ other leakage)

$$Delay \propto \frac{C \cdot V_{DD}}{(V_{DD} - V_{TH})^{1.3}}$$

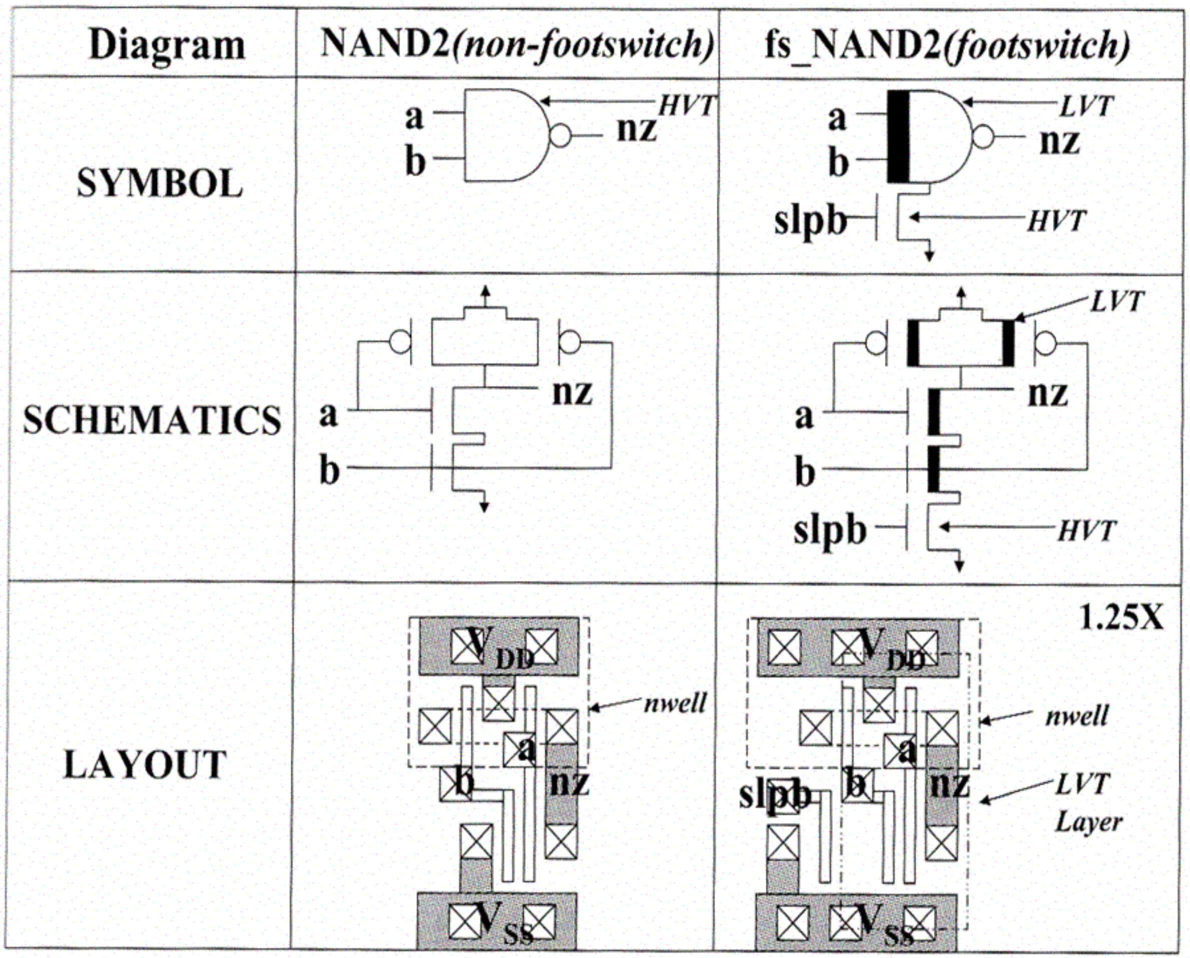


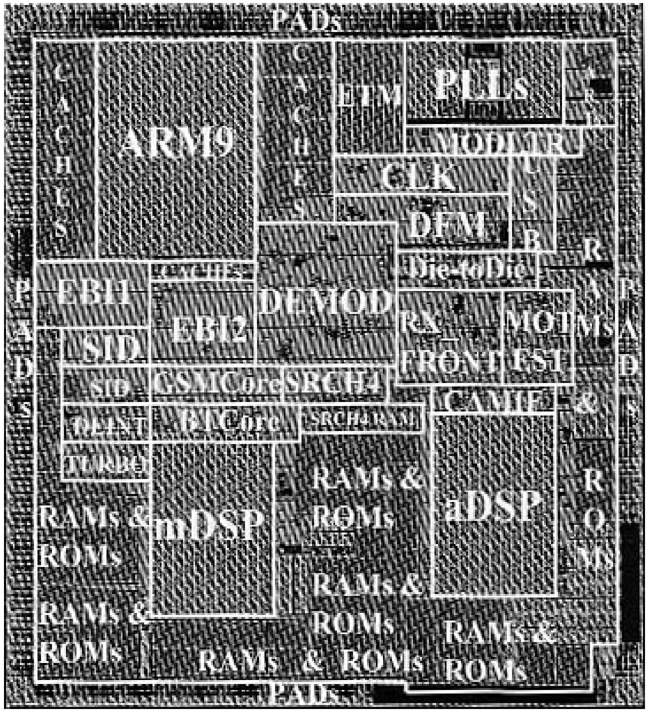


65nm node, FO3 INV

More generally, trade-off exists between power and QoS.

Leakage-aware design from Qualcomm





Multi-V_{DD}: Seven V_{DD}'s

Dual-V_{TH}: Two V_{TH}'s for PMOS and NMOS each

Power gating: Selective MTCMOS reduced standby to 1/3~1/4.

G. Uvieghara, et al., "A Highly-Integrated 3G CDMA2000 1X Cellular-Baseband Chip with GSM/AMPS/GPS/Bluetooth/Multimedia Capabilities and ZIF RF Support," ISSCC paper#23.3, Feb. 2004.

Adaptive control basics

- **What to monitor**

  Leakage current, Speed, Workload, Temperature, Error rate, Quality of Service (QoS)

- **How to monitor**

  Replica (critical path), Representative, Actual

- **What to control**

  Frequency, V_{DD}, V_{TH}, V_{SWING}, Activity, W, Gate bias of switches, Power-gating

- **How to control**

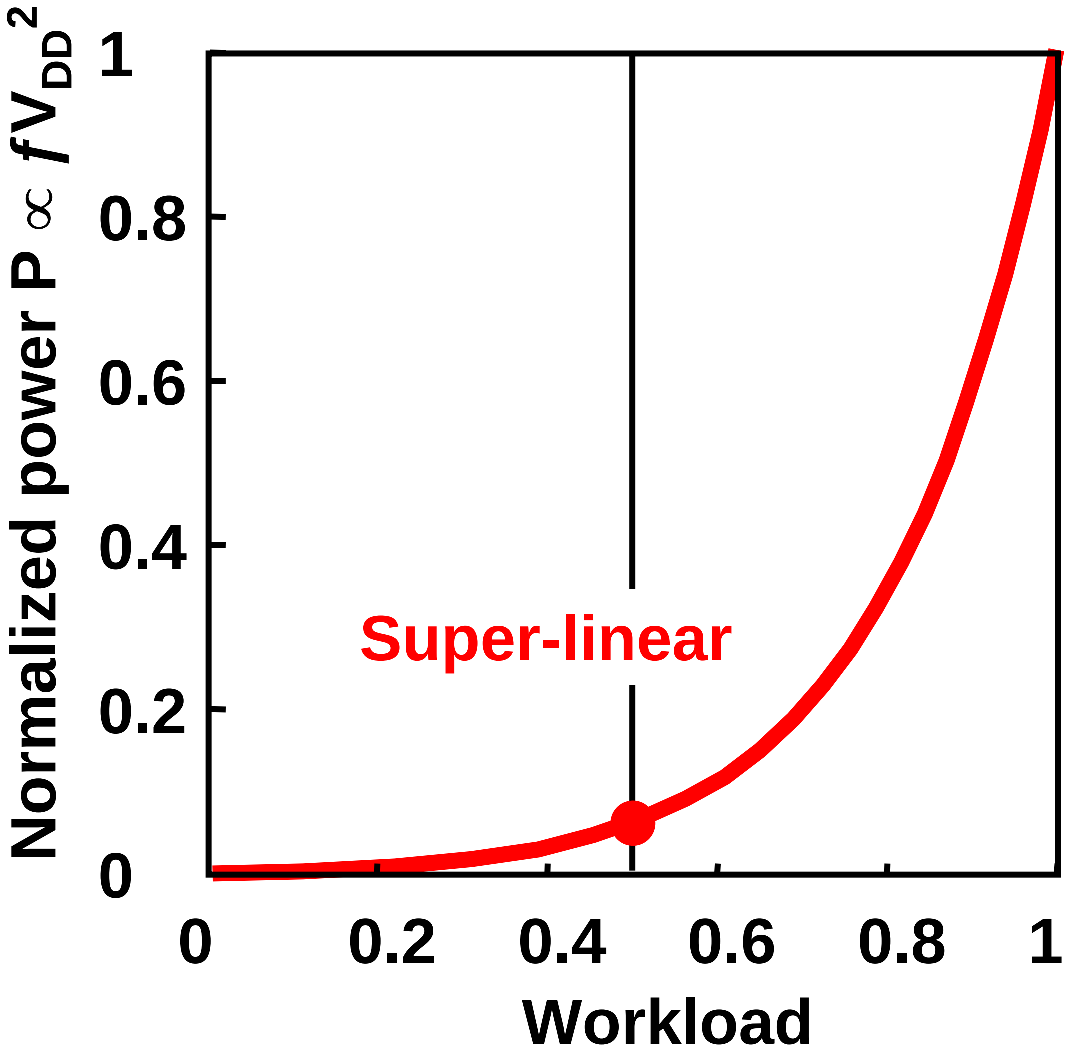
  Analog, Digital, Software

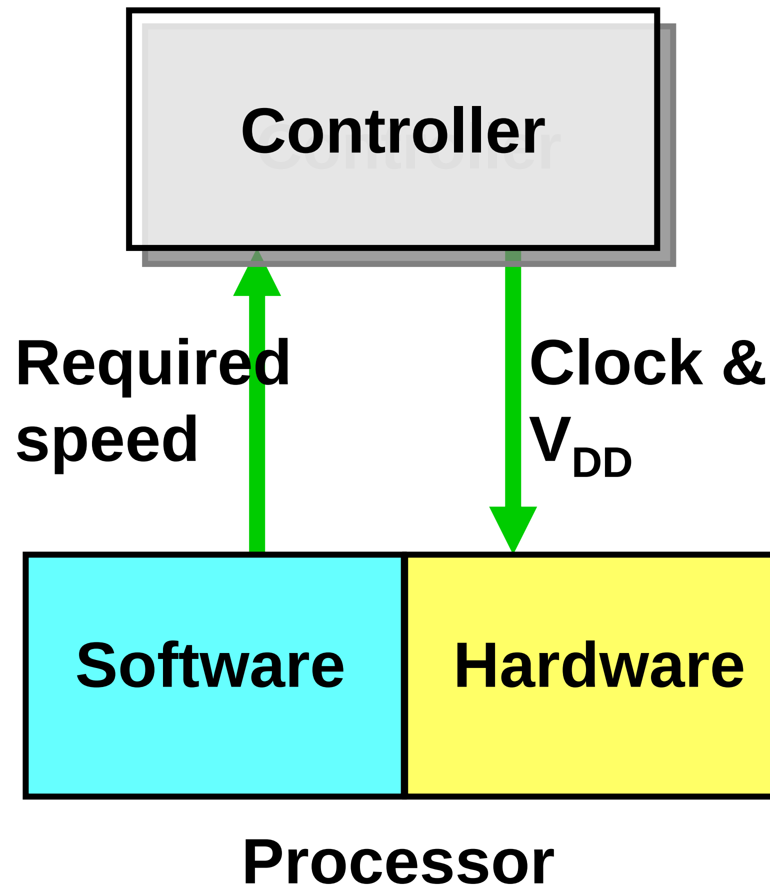
- **Granularity of control**

  Chip level , Block level, Gate level, Transistor level

Adaptive V_{DD} (& *f*) control

Changing V_{DD} and f adaptive to workload

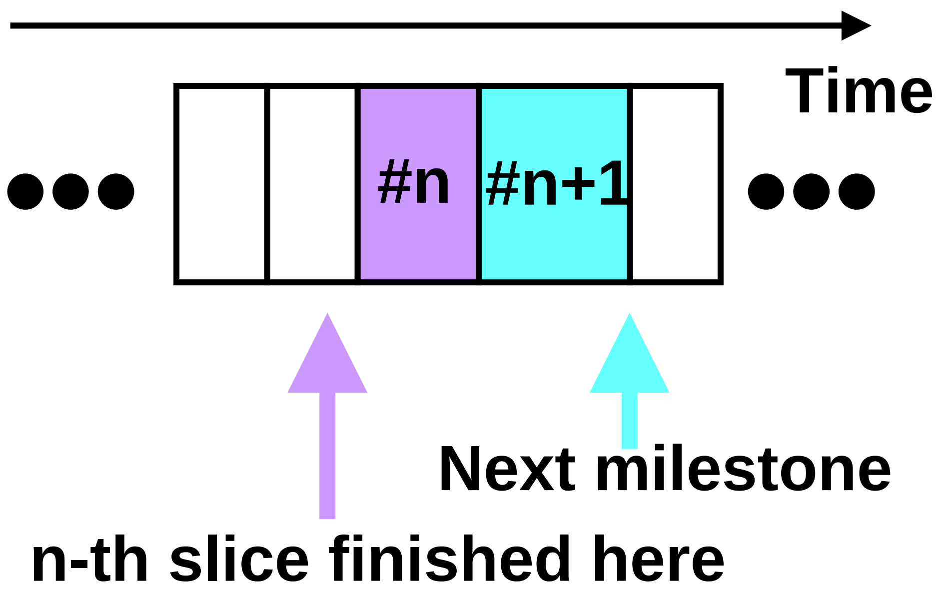


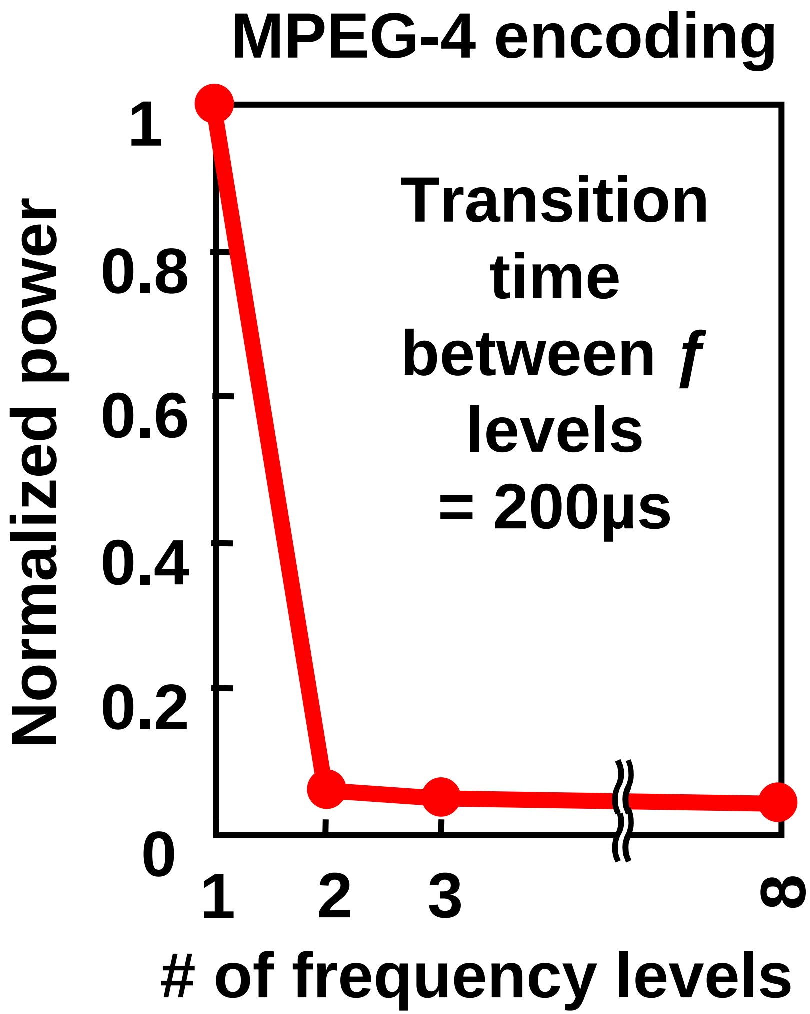


S. Lee et al, DAC, June 2000

Applicable to real-time application

V_{DD}-hopping





Application slicing and software feedback guarantee real-time operation.

Two hopping levels are sufficient.

V_{DD}-hopping with RTOS saves 2/3 of power

H. Kawaguchi et al, RTAS Workshop, May 2001

Adaptive V_{TH} control

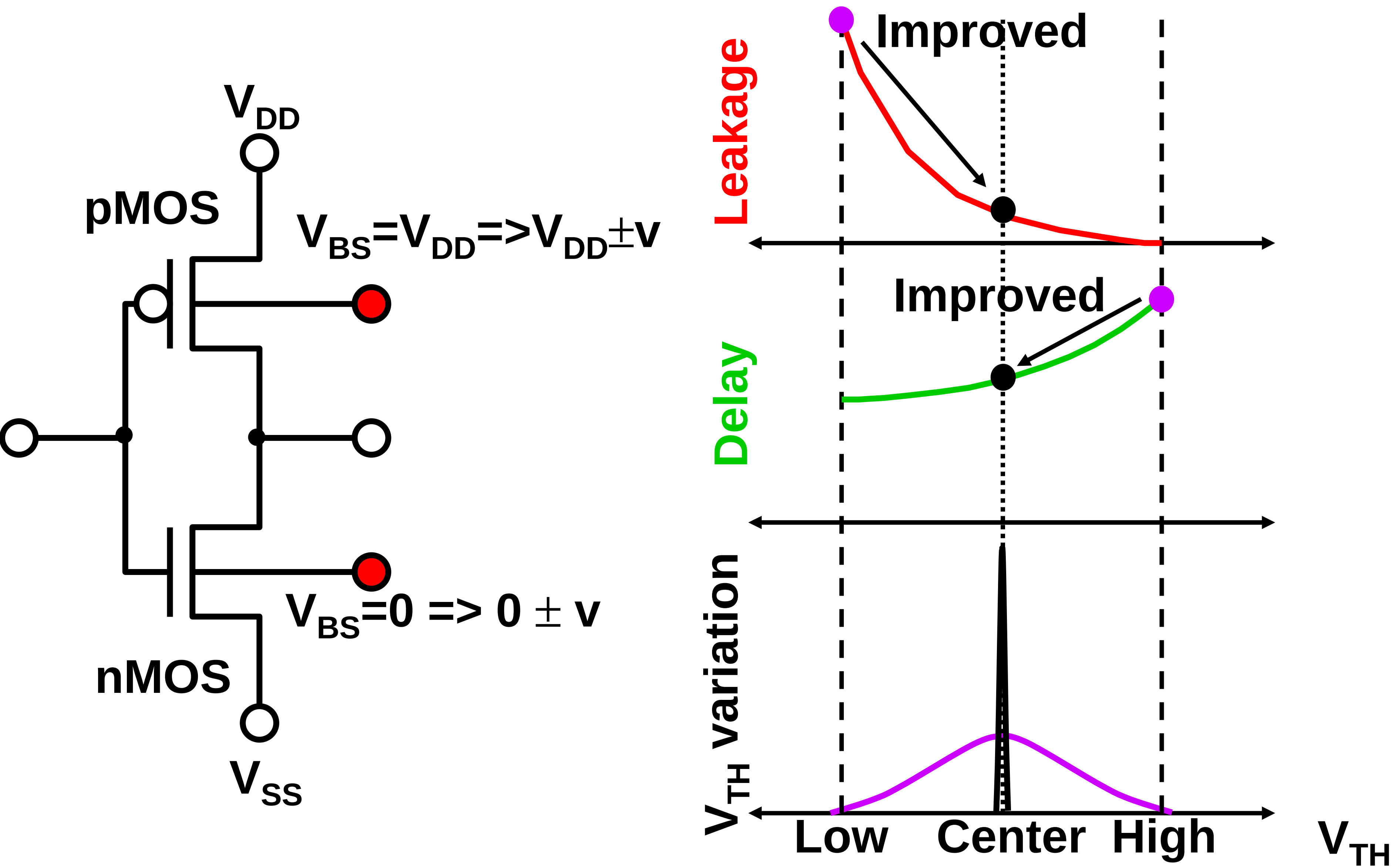
1. Changing V_{TH} adaptive to process/temp. variability

2. Changing V_{TH} adaptive to required performance

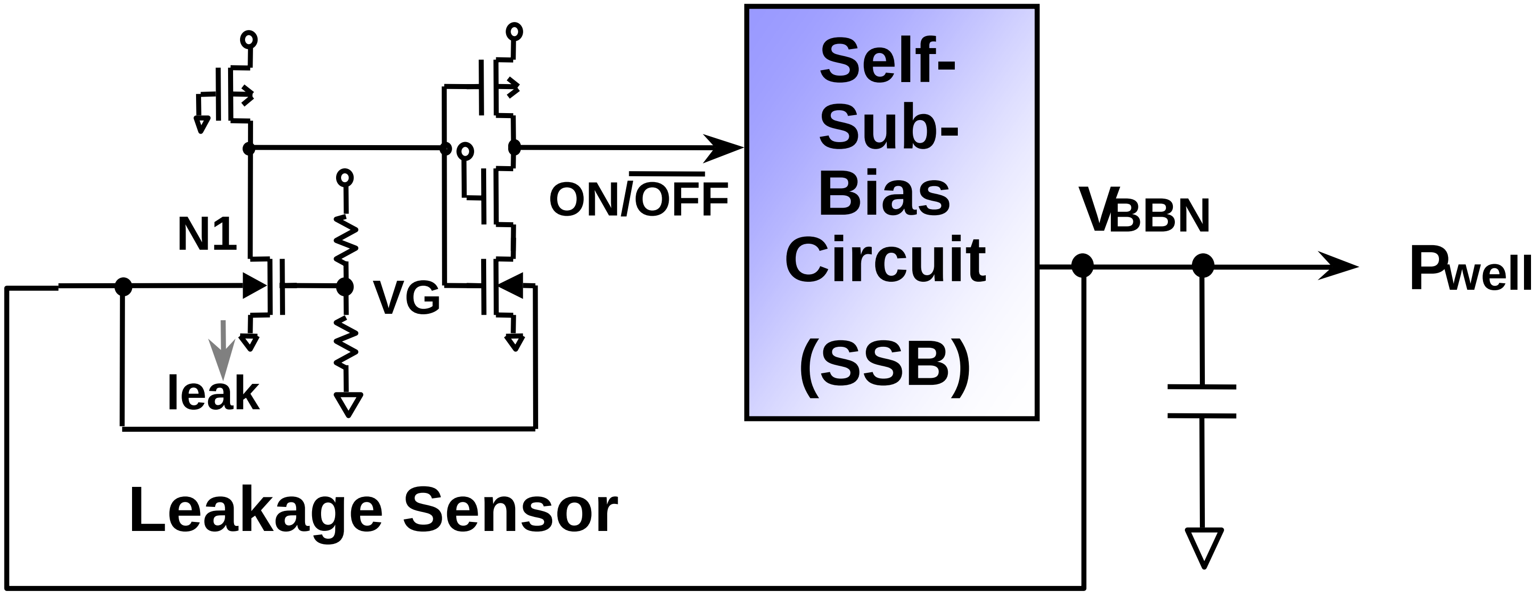
3. Applying extremely high V_{TH} in standby

4. Applying high V_{TH} in burn-in and I_{DDQ} test

Adaptive V_{TH} for variation control



Adaptive V_{TH} in early days (VTCMOS)



low Vth → large leakage → SSB ON → deepVBB → high Vth

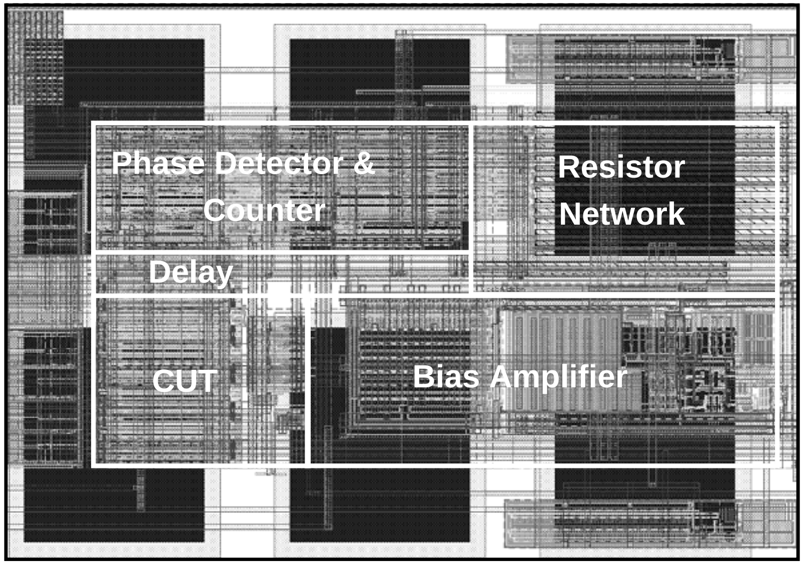
high Vth→ little leakage → SSB OFF → shallow VBB → low Vth

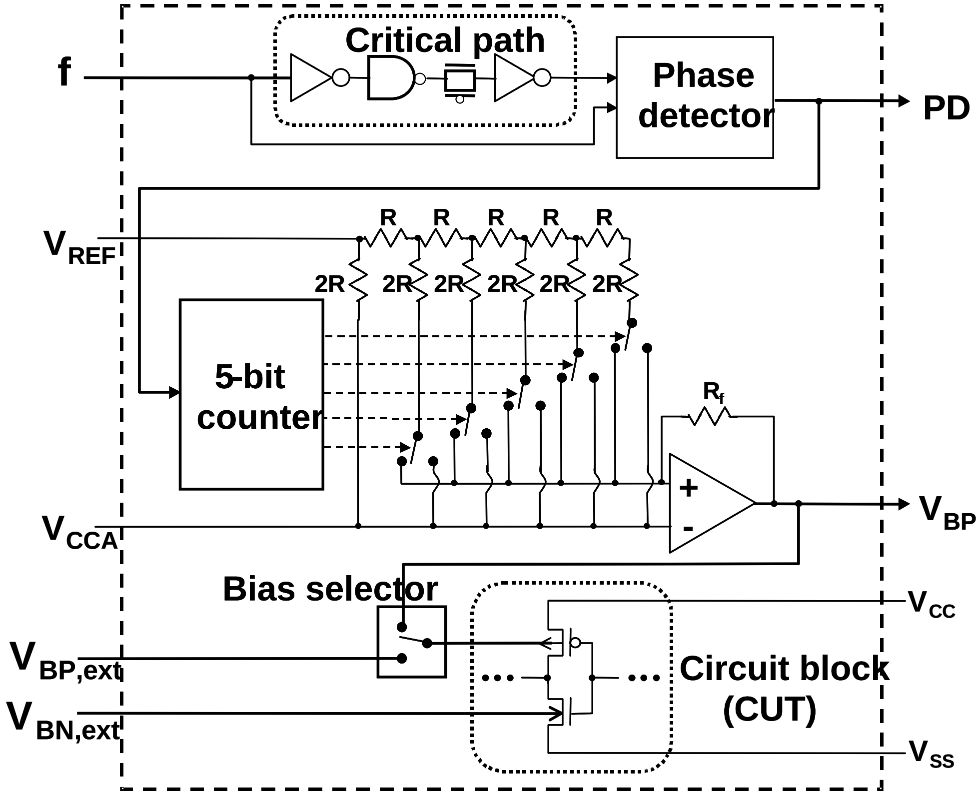
- control V_{TH} to adjust leakage current
- compensate V_{TH} fluctuation

Leakage, Replica, Reverse body bias, Analog, Chip level

T. Kobayashi, and T. Sakurai, "Self-Adjusting Threshold-Voltage Scheme (SATS) for Low-Voltage High-Speed Operation," in Proc. IEEE 1994 CICC, pp.271-274, May 1994.

Adaptive V_{TH} in finer granularity





21 sub-sites with separate body bias for each sub-site

Speed, Replica, Body bias, Digital, Block level

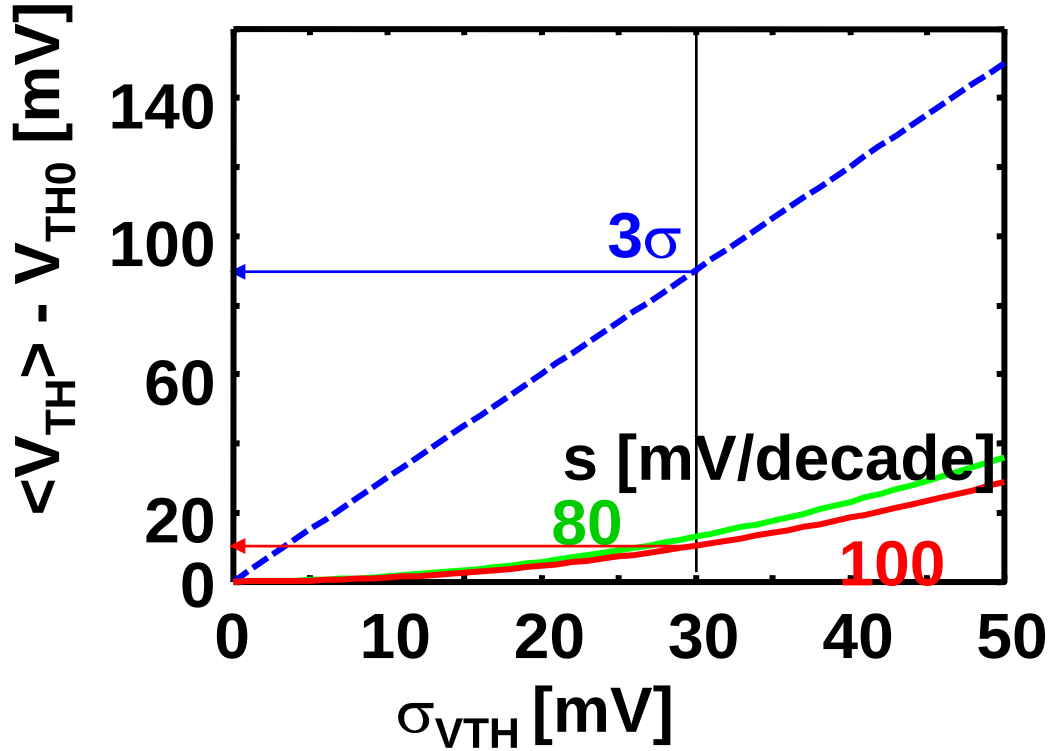
J. Tschanz, J. Kao, S. Narendra, R. Nair, D. Antoniadis, A. Chandrakasan, and V. De, "Adaptive Body Bias for Reducing Impacts of Die-to-Die and Within-Die Parameter Variations on Microprocessor Frequency and Leakage," ISSCC, Paper 25.7, 2002.

Random V_{TH} variation affects I_{LEAK} little

$$\langle I_{OFF}\rangle = \int_{-\infty}^{\infty} I_{OFF}(V_{TH}) f(V_{TH}) dV_{TH} = \int_{-\infty}^{\infty} I_{OFF0} e^{-\ln 10 \frac{V_{TH}}{s}} \frac{1}{\sqrt{2\pi}\sigma_{VTH}} e^{-\frac{(V_{TH}-V_{TH0})^2}{2\sigma_{VTH}^2}} dV_{TH}$$

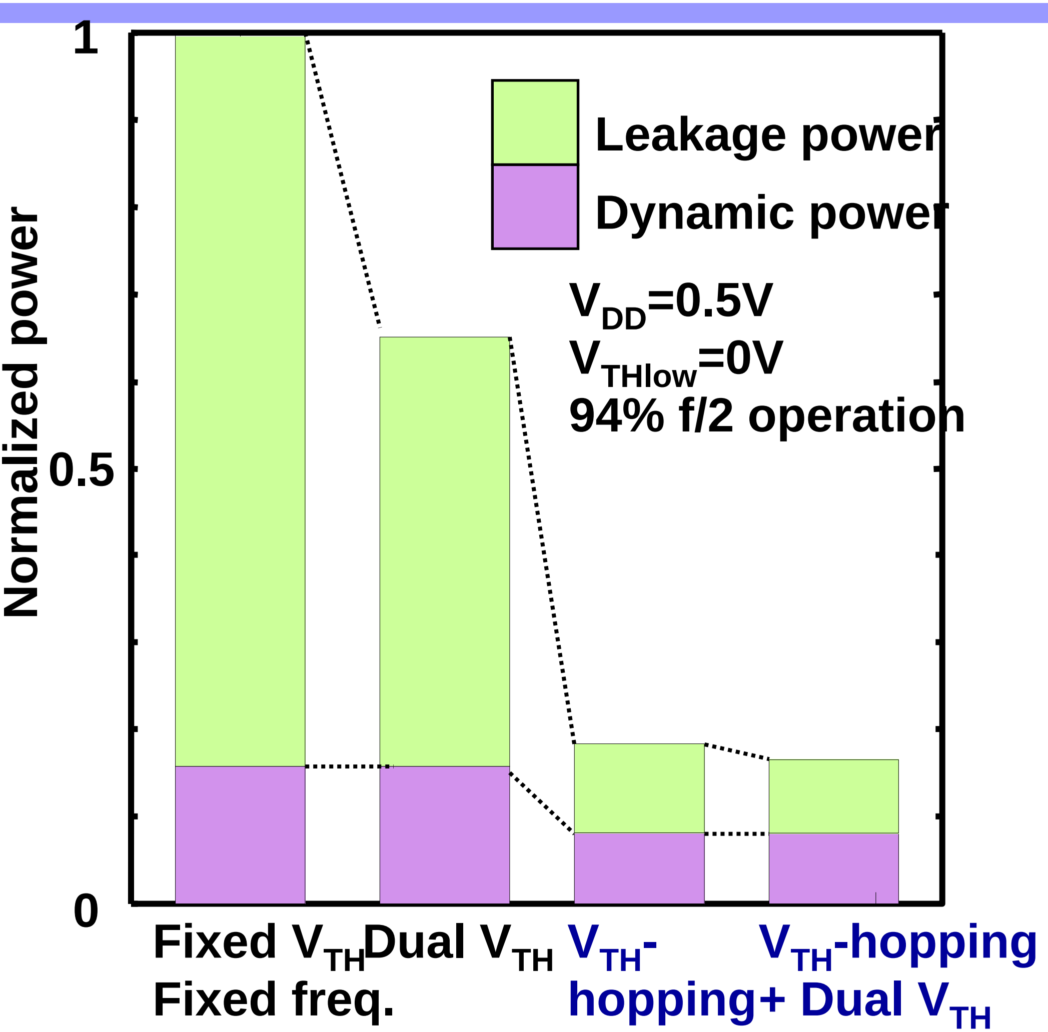
$$= I_{OFF0} e^{\frac{1}{2}\left(\sigma_{VTH}\frac{\ln 10}{s}\right)^2}$$

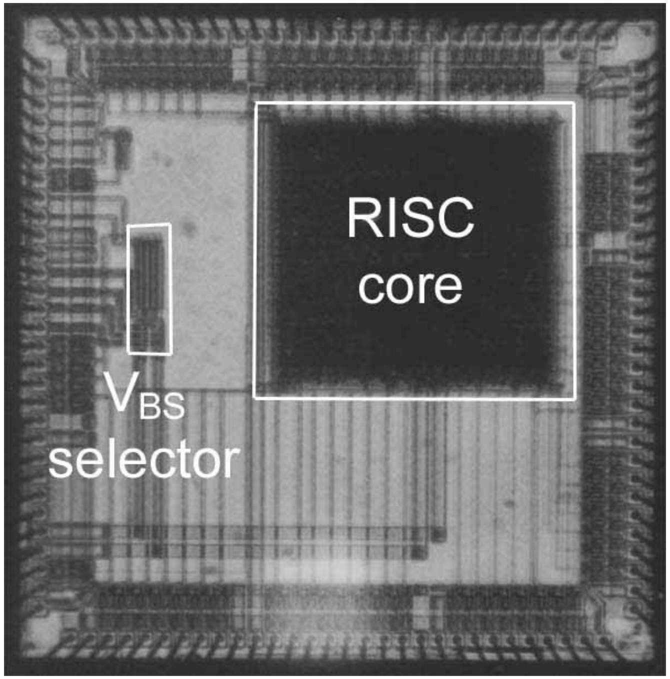
Equivalent V_{TH} shift $<V_{TH}> - V_{TH0} = -\sigma_{VTH}^2 \frac{\ln 10}{2s}$



Systematic V_{TH} variation (inter-, intra-chip) is important.

Software control of V_{TH} adaptive to workload





0.6μm process
Overhead of V_{TH}-hopping : 14%
RISC core : 2.1mm x 2.0mm
V_{BS} selector : 0.2mm x 0.6mm

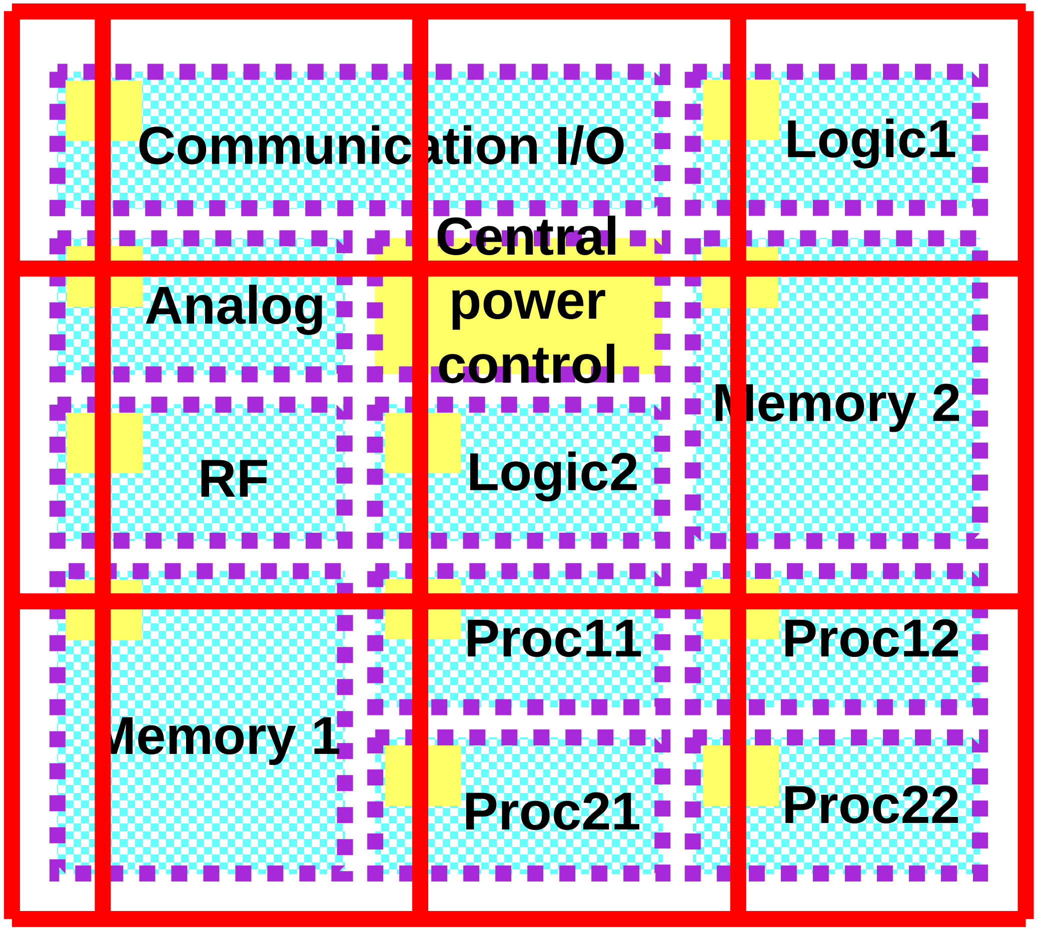
Workload, Actual, reverse body bias, Software, Chip level

Waste is more in time than space. Time adaptive control

K.Nose, M.Hirabayashi, H.Kawaguchi, S.Lee and T.Sakurai, "VTH-Hopping Scheme to Reduce Subthreshold Leakage for Low-Power Processors," JSSC, pp.413-419, Mar. 2002.

Perspectives

Finer grain adaptive V_{DD} & V_{TH}



Adaptive V_{TH} doesn't need shifters.

High voltage distribution

Power delivery circuit
Voltage regulation
Voltage hopping
Power-gating

Chips or blocks
Lower voltage
Variable V_{DD} / V_{TH}
Multiple V_{DD} / V_{TH}

Data voltage converters
Clock domain conversion

History and perspective of adaptive control

Assign proper V_{DD} and V_{TH} in time & space

Once upon a time on a peaceful chip of VLSI before the notorious power war …

We were using single V_{DD} and single V_{TH} for an entire chip.

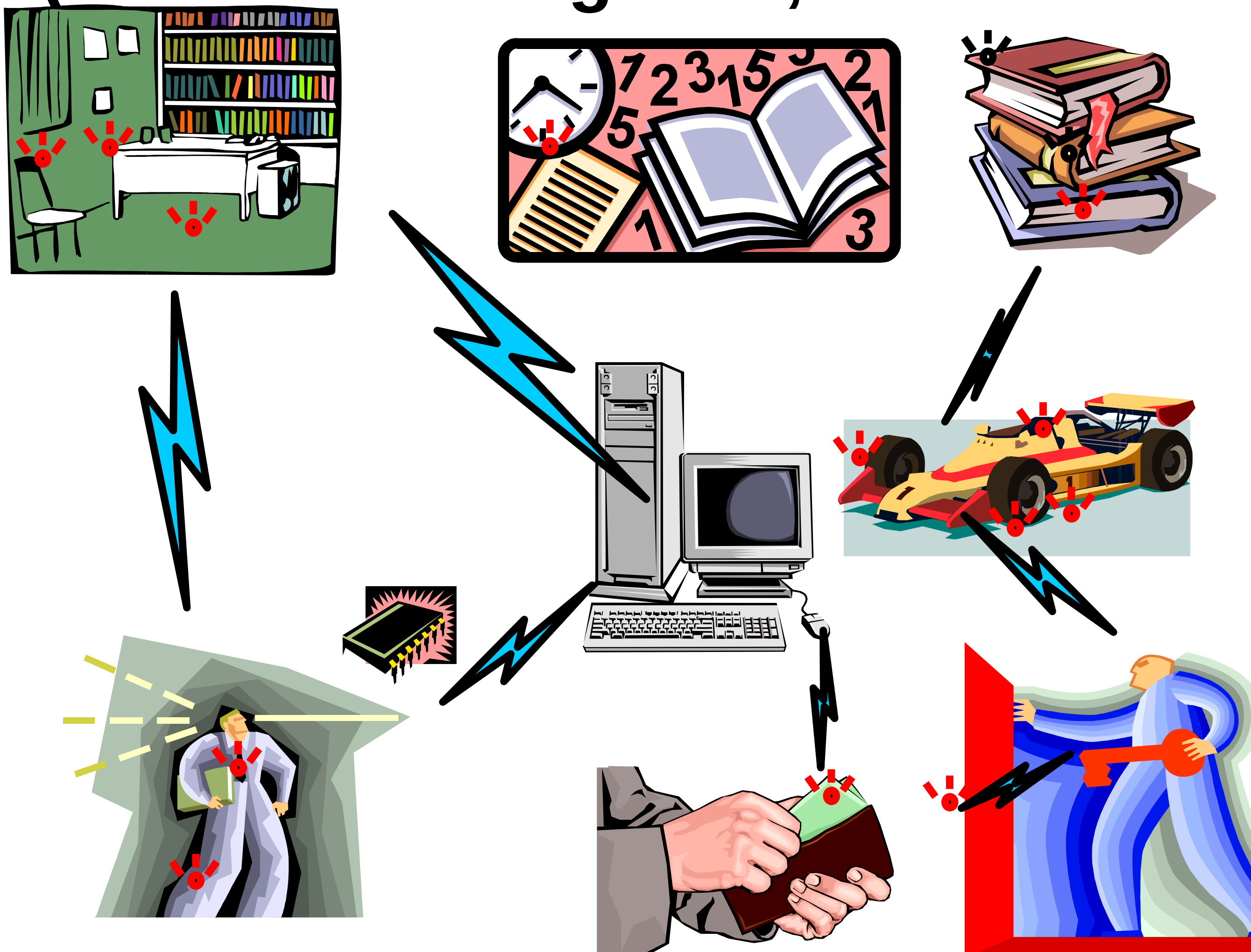
Then, the power war began and we started using multiple V_{TH} and V_{DD} depending on the location on a chip.

Still, the power war gets severer and we started to vary V_{TH} and V_{DD} in time adaptively.

In finer granularity in time and space … with a help from circuit and software.

Ubiquitous electronics

Emerging app.: ubiquitous electronics (ambient intelligence, wireless sensor network)



RFID node
Sensor node
Storage node
Computing node
Networking node
Actuator node
Display node

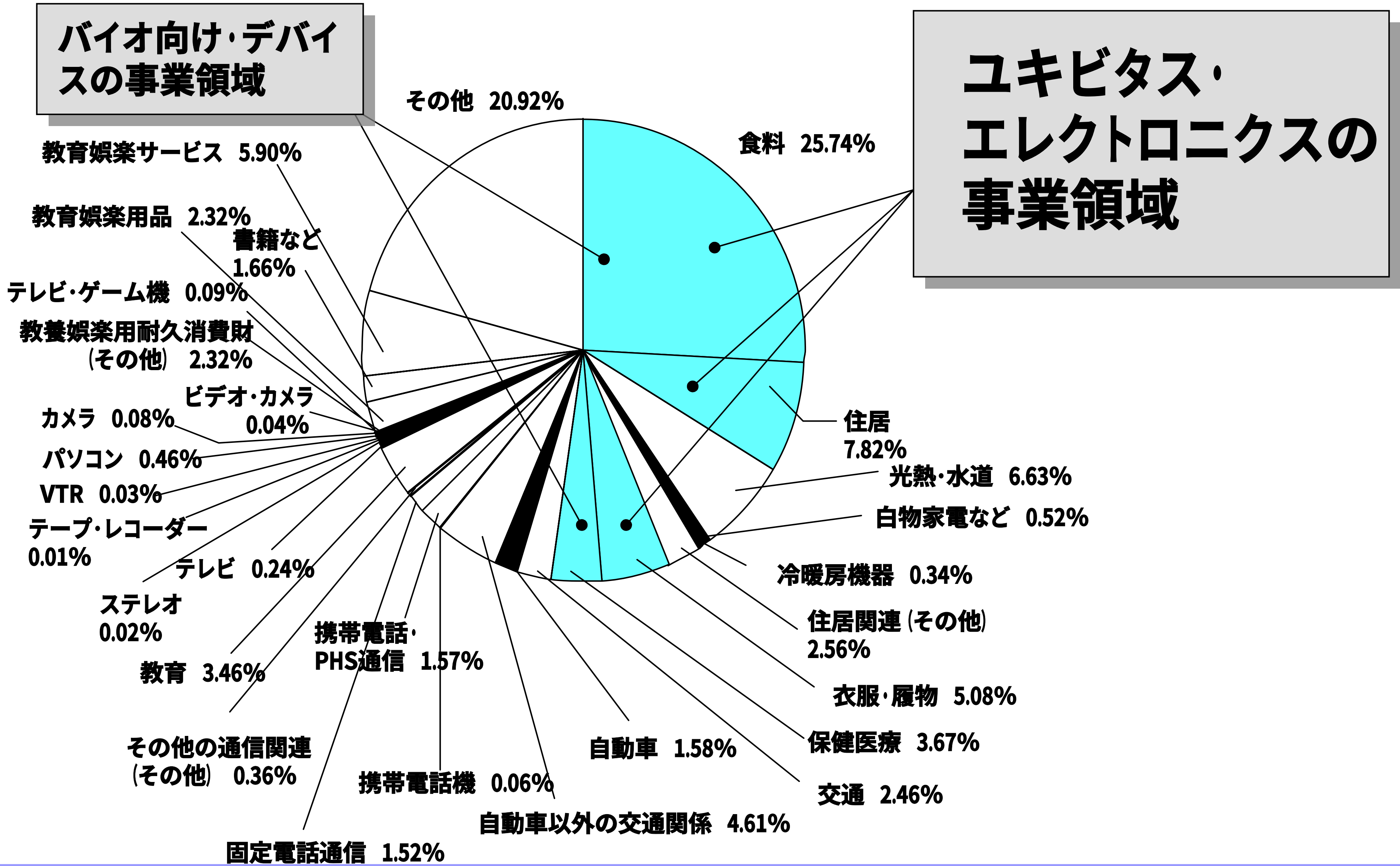
センサ・ネットワーク技術に取り組むことで，すぐに収益を得られるわけではない。ただその将来性は大きい。当社の組み込みマイコン製品が持つ年間数十億米ドルという収益規模を，センサ・ネットワーク関連製品ははるかにしのぐことになるだろう。だからこそ取り組んでいる。

Forming infrastructures

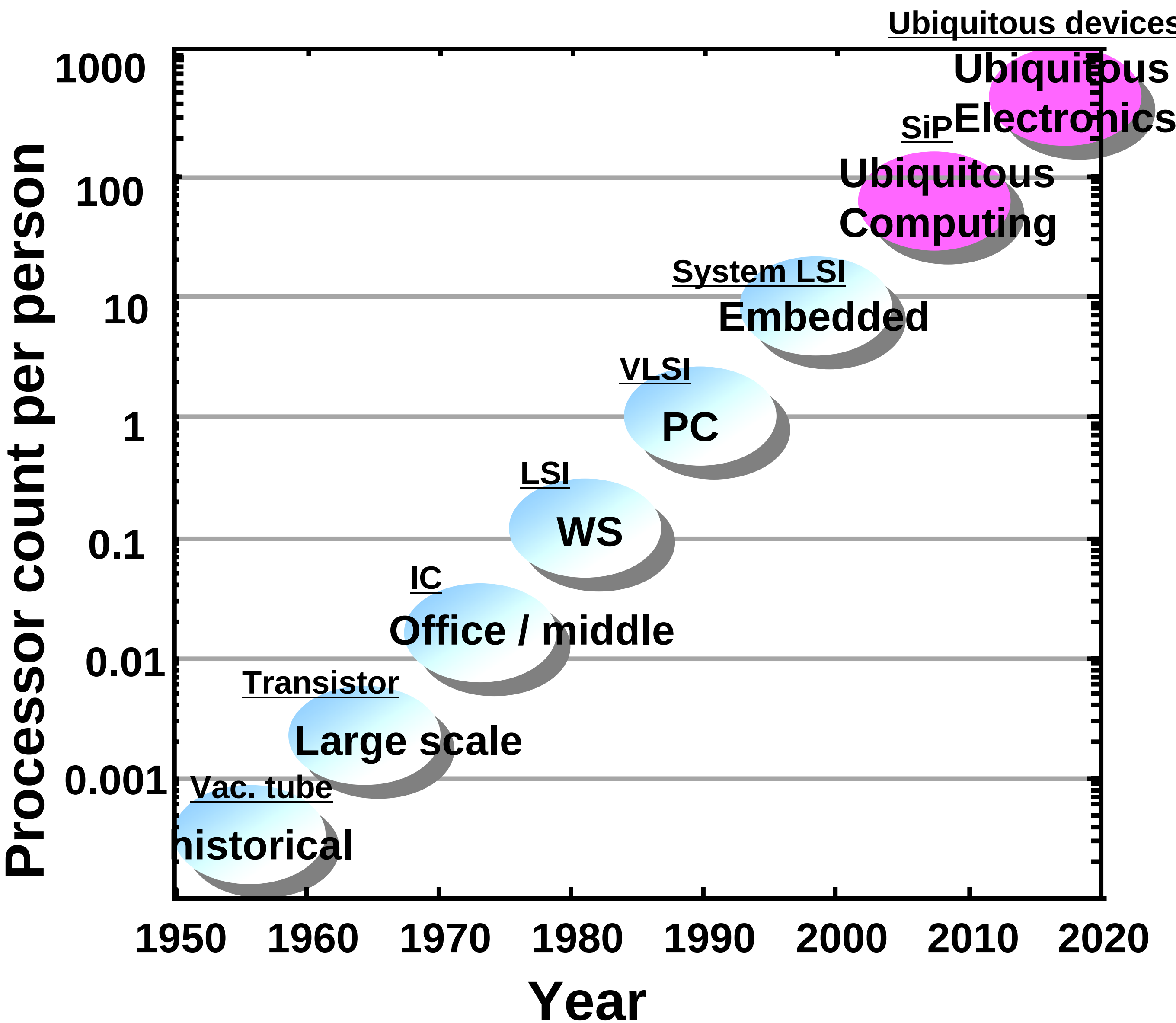
http://bwrc.eecs.berkeley.edu/Research/Pico_Radio/NAMP/

日経エレクトロニクス2002.5.20 p.192

日本の世帯の出費分布


バイオ向け·デバイスの事業領域
ユキビタス·エレクトロニクスの事業領域
その他 20.92%
食料 25.74%
教育娯楽サービス 5.90%
教育娯楽用品 2.32%
書籍など 1.66%
テレビ·ゲーム機 0.09%
教養娯楽用耐久消費財（その他） 2.32%
ビデオ·カメラ 0.04%
カメラ 0.08%
パソコン 0.46%
VTR 0.03%
テープ·レコーダー 0.01%
テレビ 0.24%
ステレオ 0.02%
教育 3.46%
携帯電話·PHS通信 1.57%
その他の通信関連（その他） 0.36%
携帯電話機 0.06%
固定電話通信 1.52%
自動車以外の交通関係 4.61%
自動車 1.58%
交通 2.46%
保健医療 3.67%
衣服·履物 5.08%
住居関連（その他） 2.56%
冷暖房機器 0.34%
白物家電など 0.52%
光熱·水道 6.63%
住居 7.82%

Ubiquitous electronics is natural extension



Electronics is part of environments enhancing convenience and security of daily life.

People use electronics consciously.

Emerging applications and key technologies

Key applications

Physical needs

Bio-electronics, tissue engineering, environmental eng.

Robot
Elderly care, household, emergency

Wireless sensor network
Ambient intelligence
Ubiquitous electronics

IT, PC,
Digital consumer,
Comm.

Spiritual needs

Key technologies

Power-aware electronics

Wireless

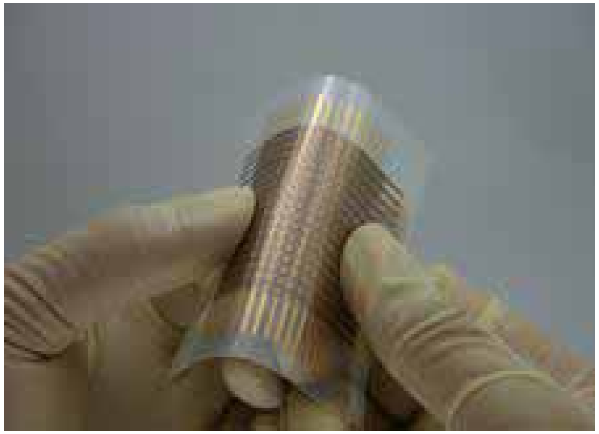
Sensors

Assembly

Large-area electronics

Organic integrated circuits

Frequently-mentioned features of organic IC's



- **Advantages**

  Low-cost manufacturing
  Mechanical flexibility

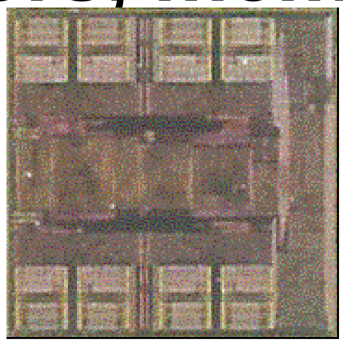
- **Disadvantages**

  Low speed (<10^{-3} of Si VLSI)
  Low density (<10^{-4} of Si VLSI)

Cost consideration

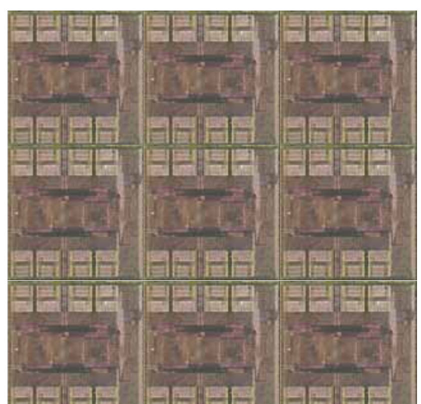
- **Cost per function**
  (processors, memories, analog, …)

Organic



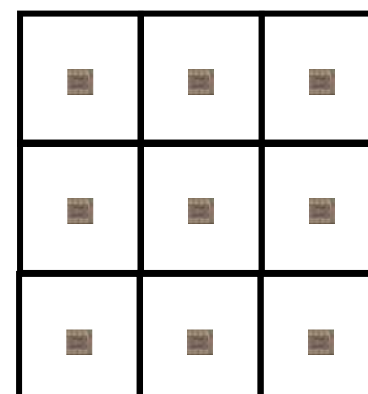
Si

- **Cost per area**
  (sensors, display, actuators, …)

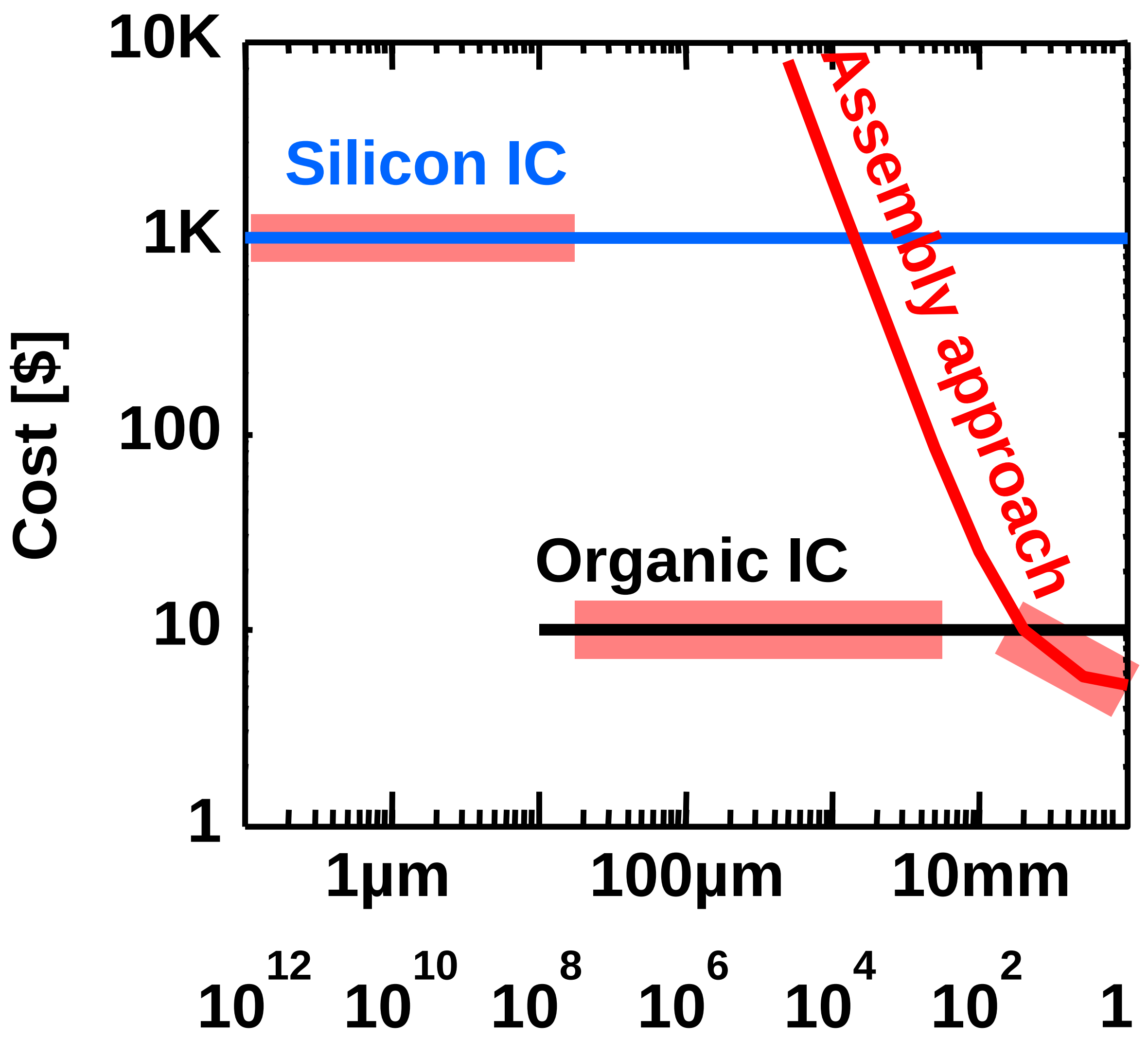


Organic

Si



Cost in each technology for large area



Area:
100mm x 100mm

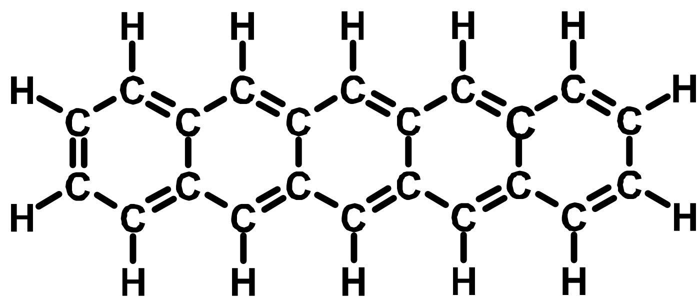
Assembly approach:
($ of organic IC)/2
+
20¢ x (# of devices)

← Resolution

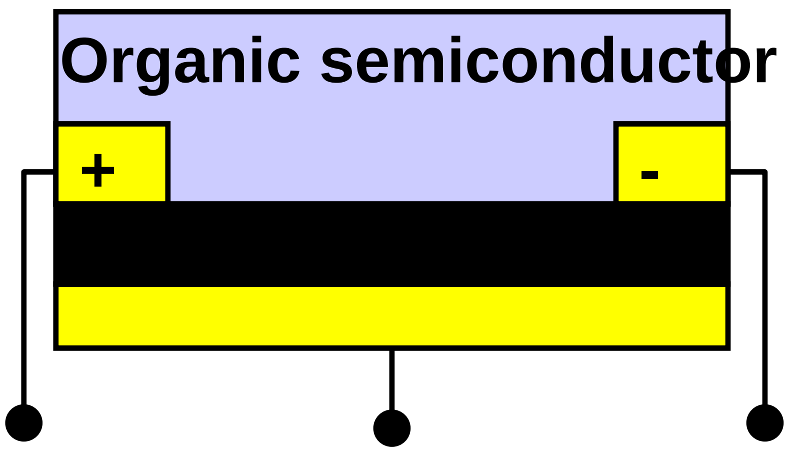
← # of devices

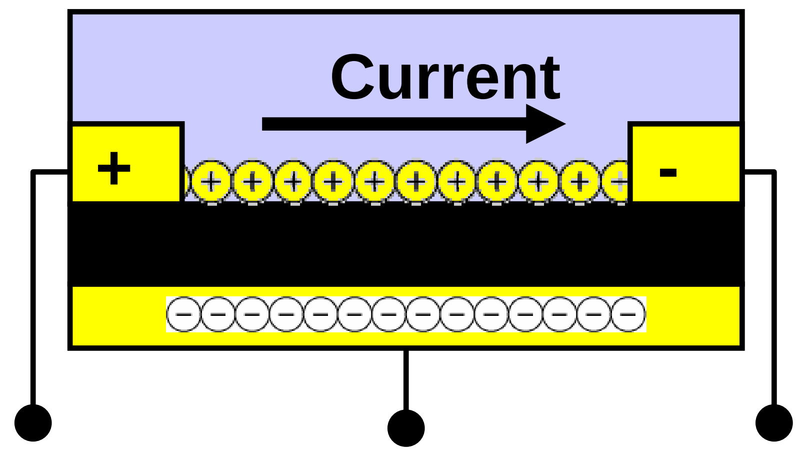
Organic transistors

Organic semiconductors: main elements --- C & H



Pentacene





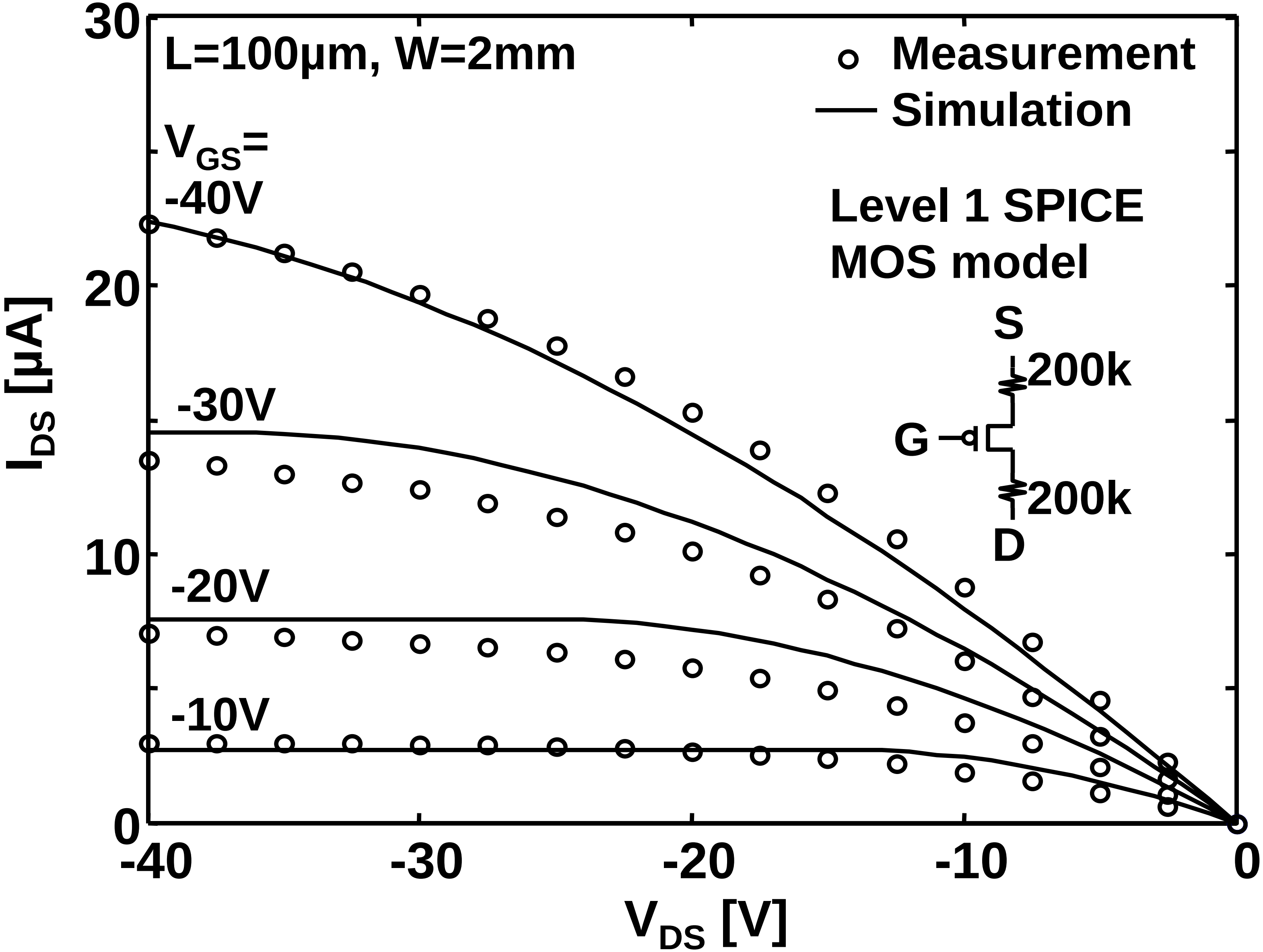
Source Gate Drain

Voltage

OFF

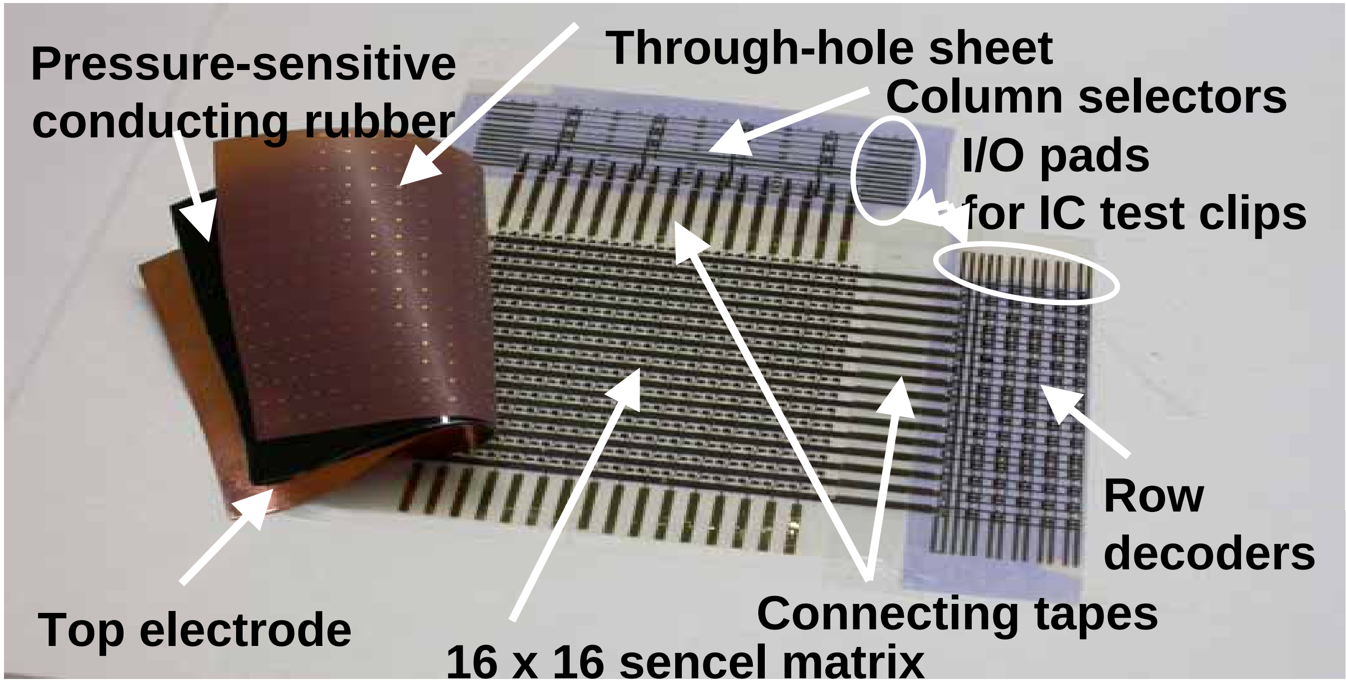
ON

Modeling by SPICE level1



E-skin: large-area pressure sensor

Large-area low-power electronics by organic IC's



Less than 1mW

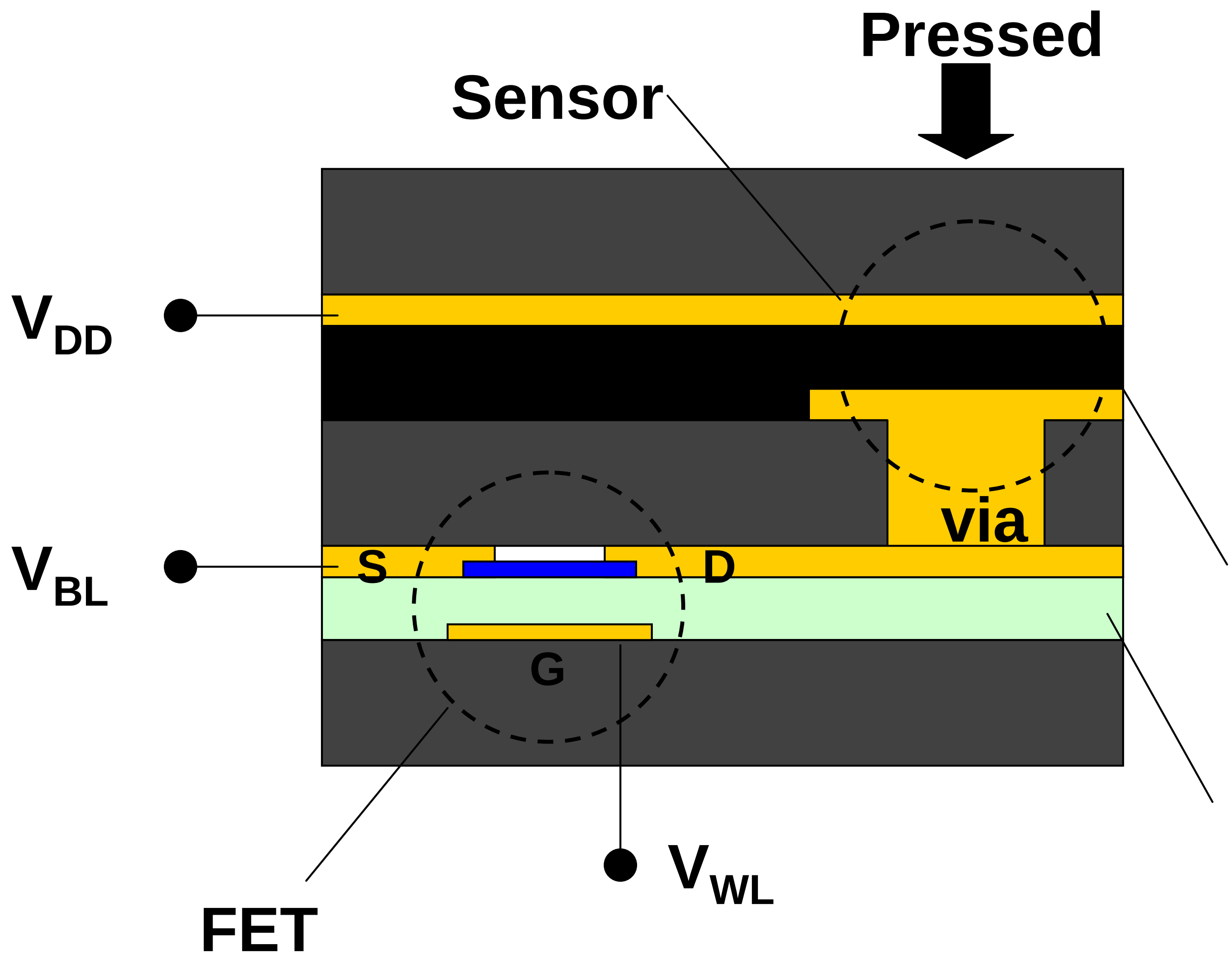
E-skin: Large-area low-power pressure sensor

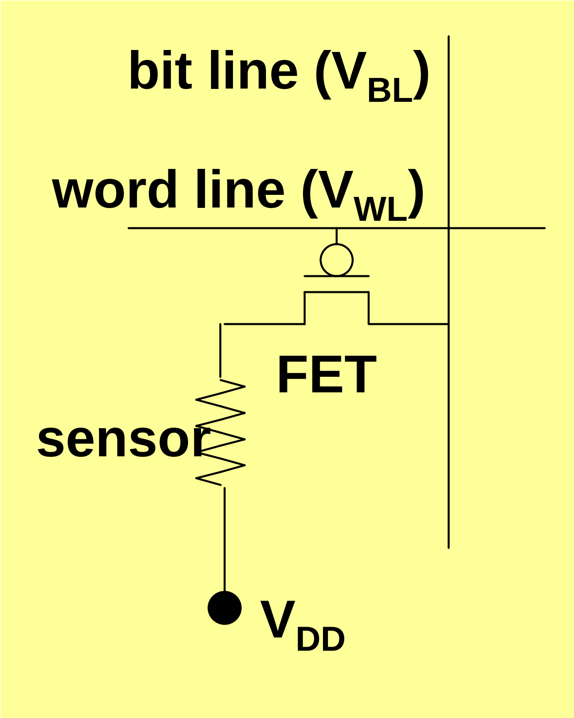
T.Someya, "Integration of Organic Filed-Effect Transistors and Rubbery Presssure Senso for Artificial Skin Applications," IEDM, 8.4.1-8.4.4, Sep. 2003.

T.Someya, H.Kawaguchi, T.Sakurai, "Cut-and-Paste Organic FET Customized ICs for Application to Artificial Skin," ISSCC'05, paper#16.2, Feb. 2004.

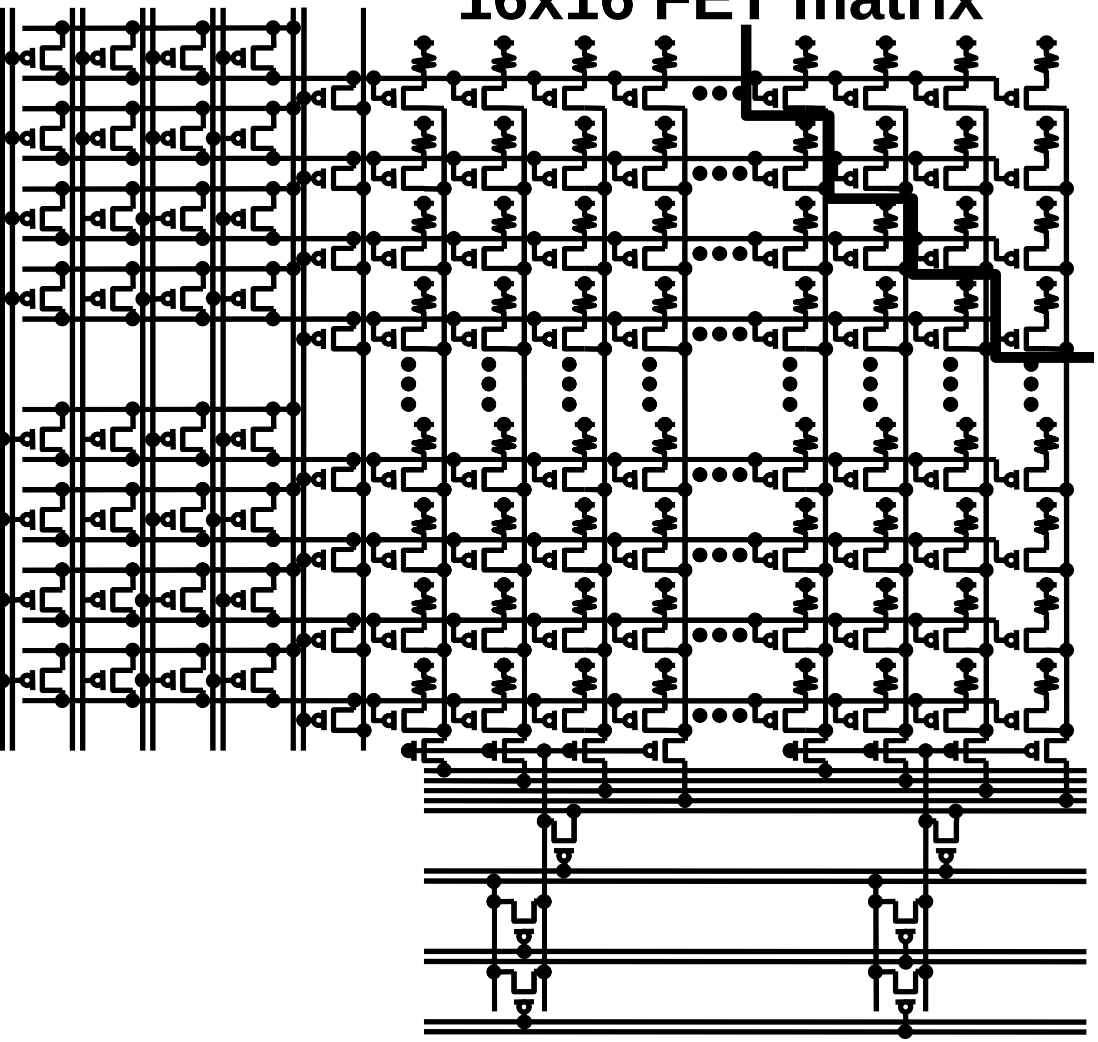
Electronic artificial skin (E-skin)

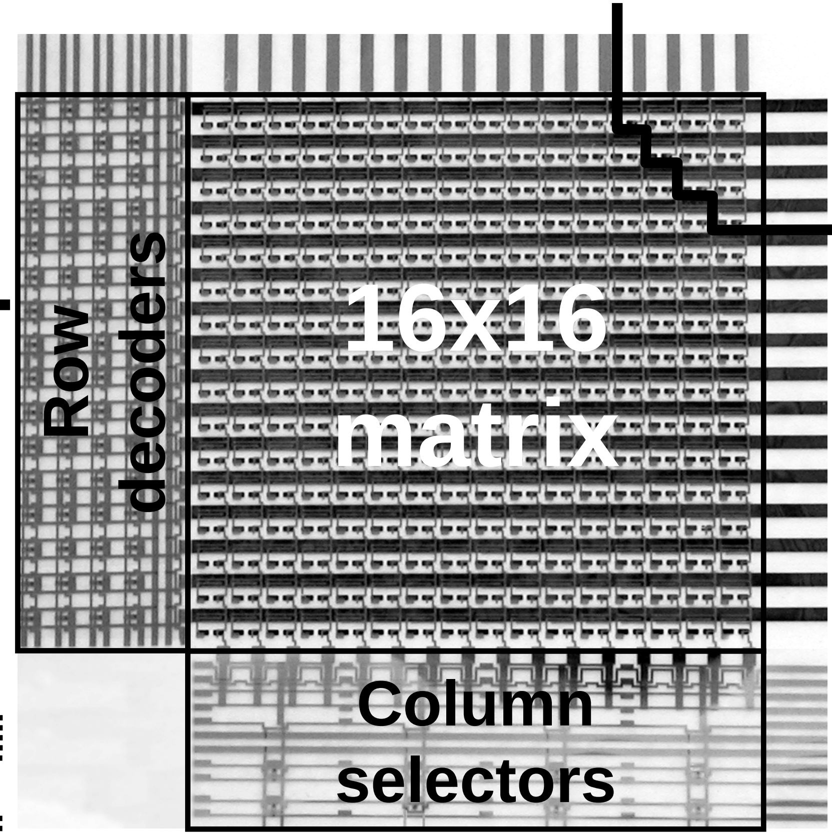
Simply laminating four different sheets……



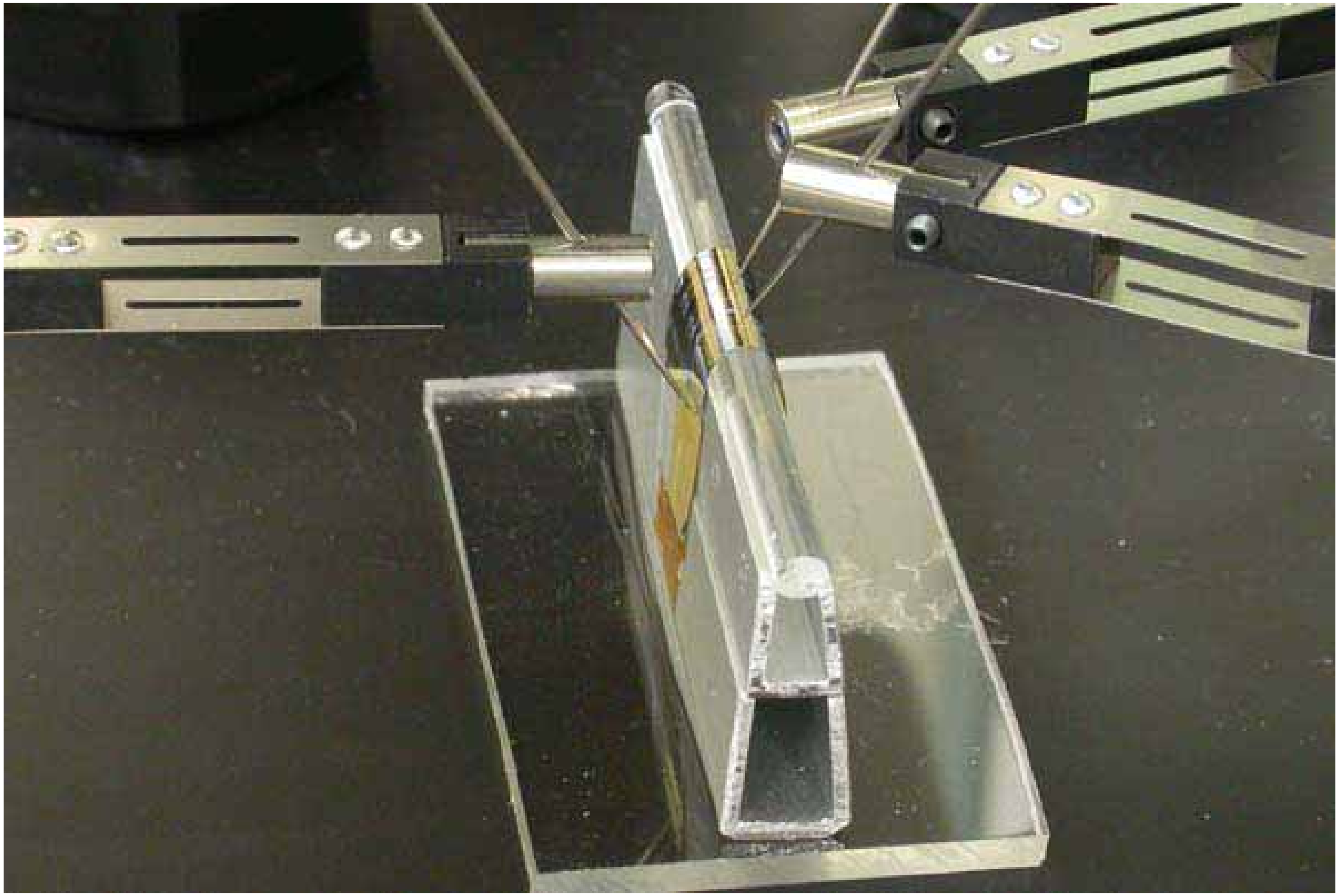


Cut-and-paste feature (16x16 sencels)





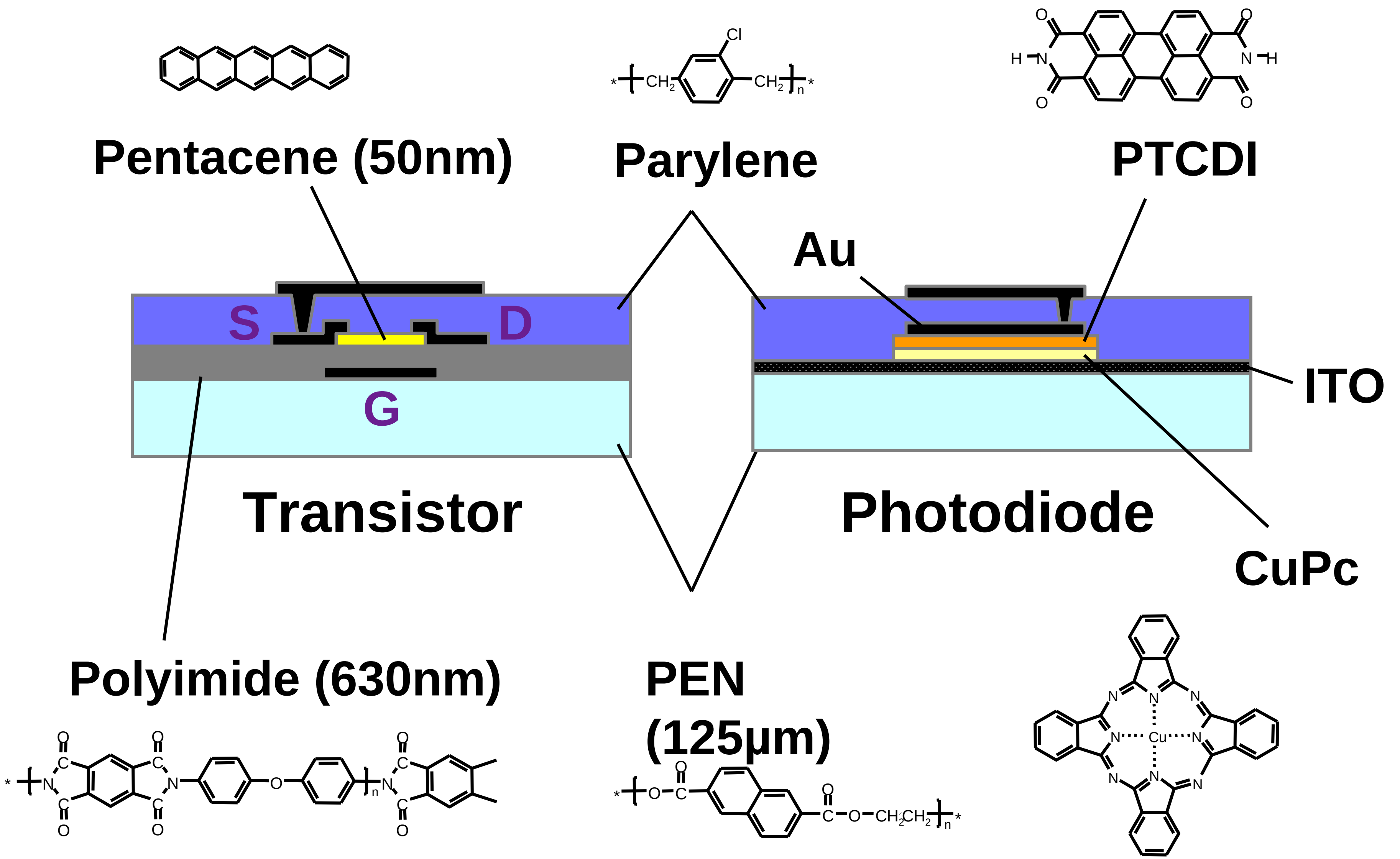
Bend-proof



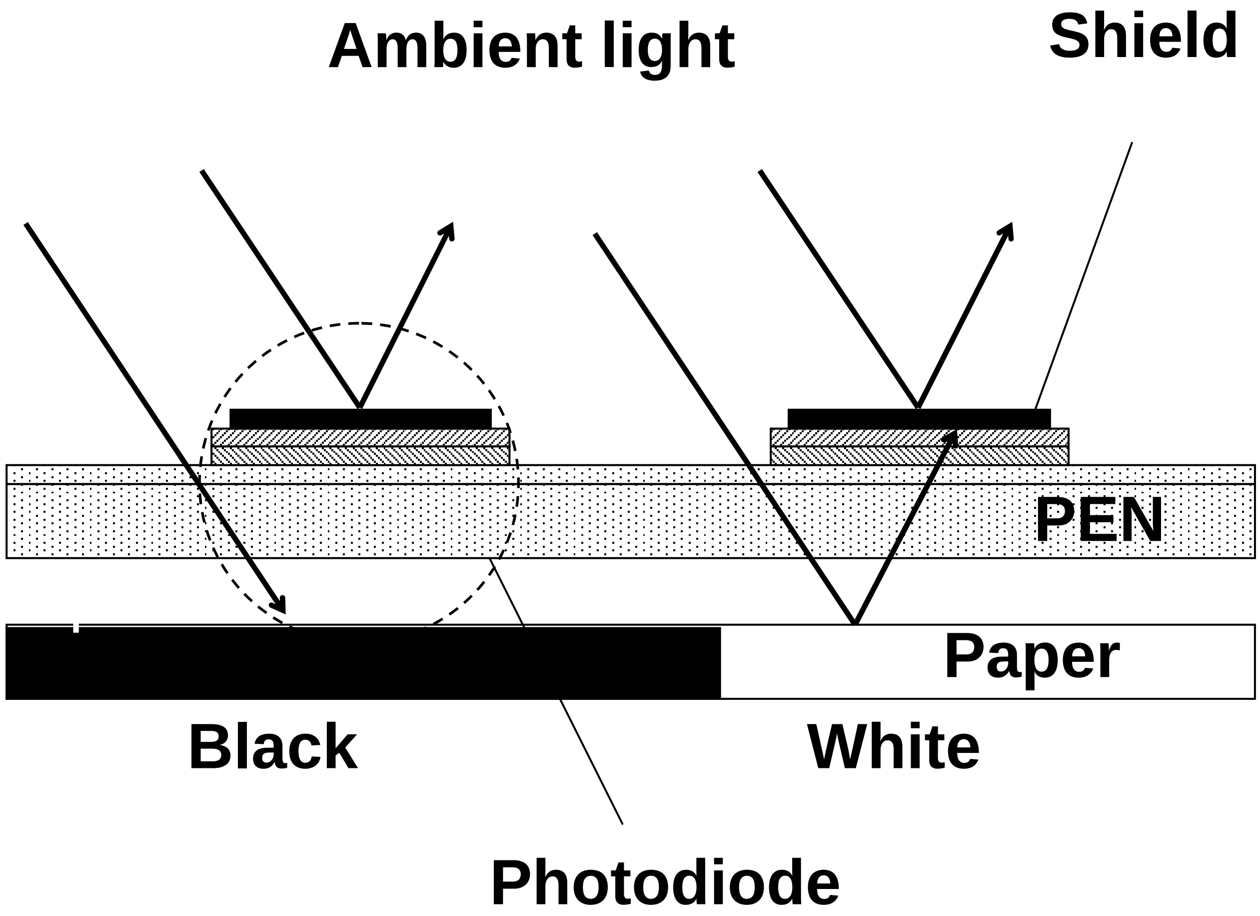
With bending down to 5mm in radius, Current is decreases less than 3%.

Sheet-type scanner by organic FETs

Manufacturing process flow

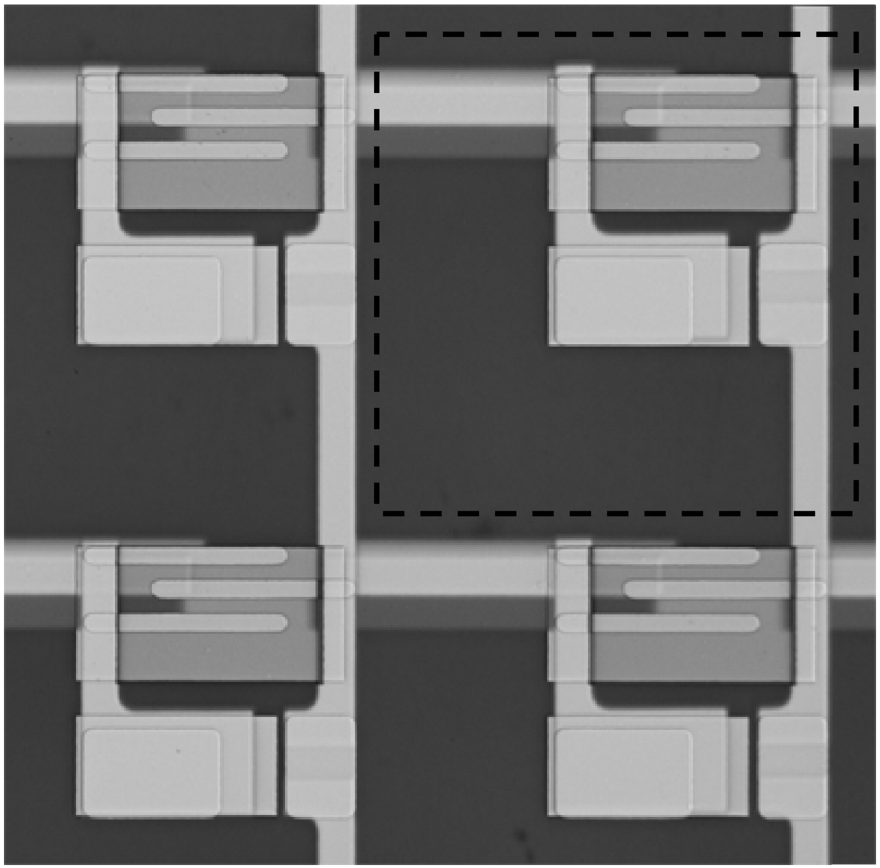


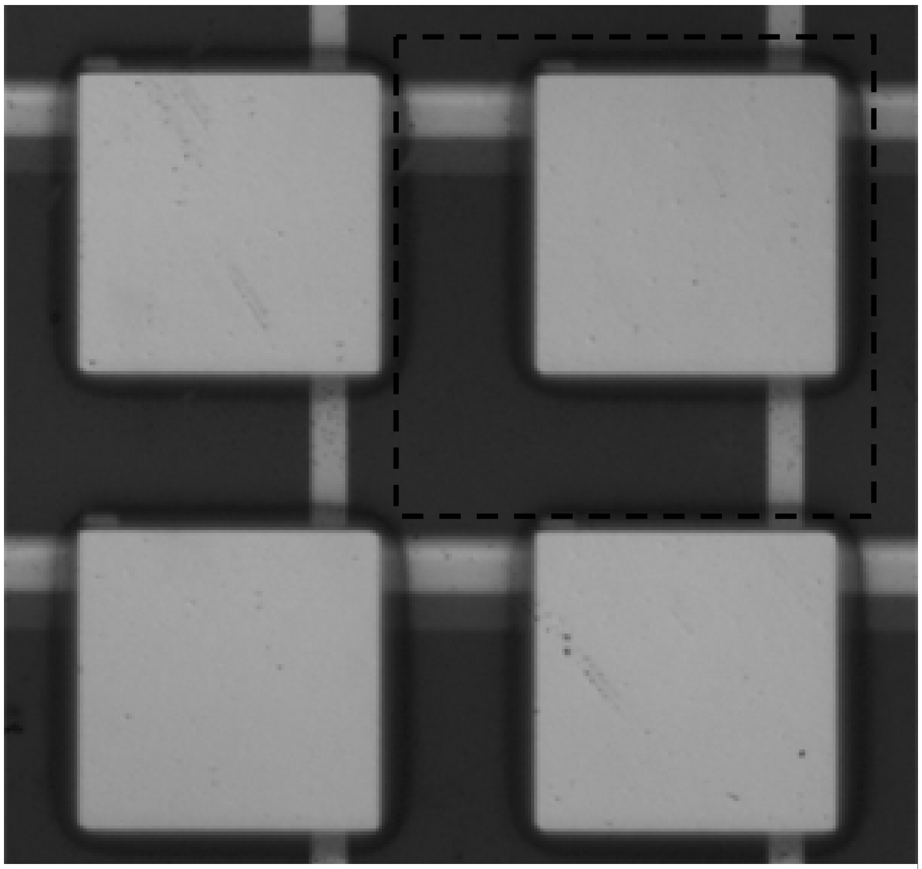
Principle



Magnified images of sensor cells

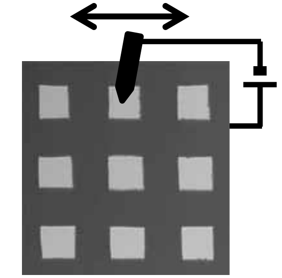
Transistors | Transistors & Diodes



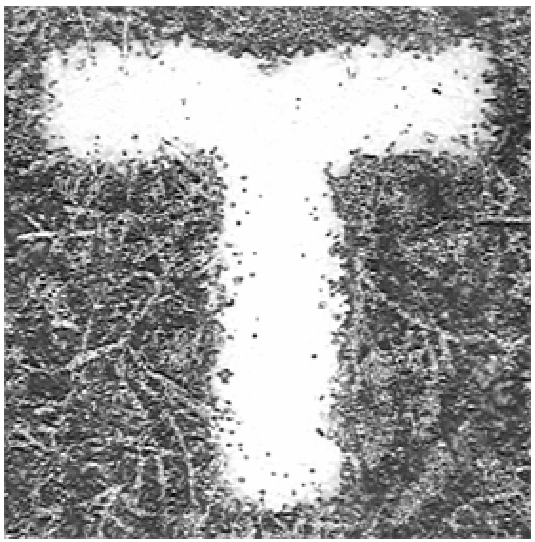


200 μm

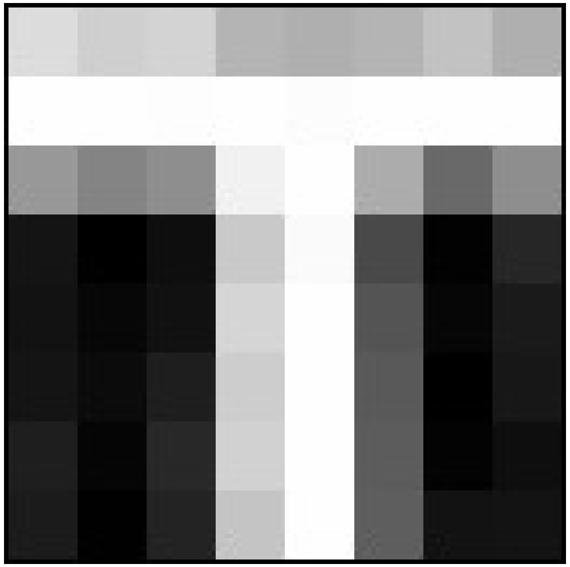
Scanned image

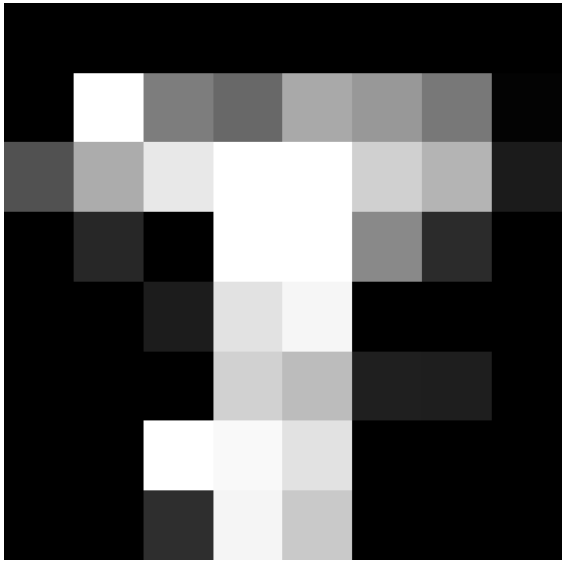


Target "T"	Commercial (250 dpi)	This study (250 dpi)



0.2 mm





Light intensity 80 mW/cm^2

A wine label can be scanned in without peeling it off.

Summary

- **Low-power design trend**
  - **Adaptive control with software**
  - **Parallel with in finer granularity**

- **Ubiquitous electronics**
  - **Low-power, large-area electronics**

- **Organic electronics**
  - **Large-area sensor applications**