Trends in Analog/Mixed-Signal Products & Technology and Challenges for Design

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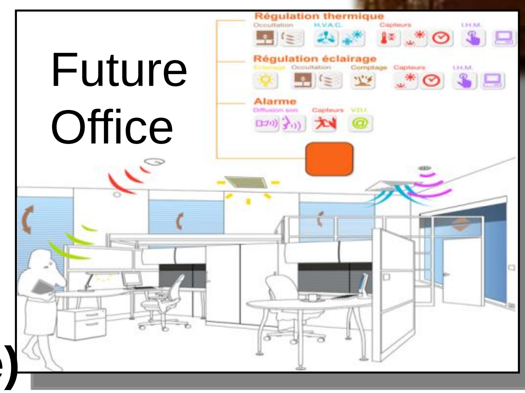
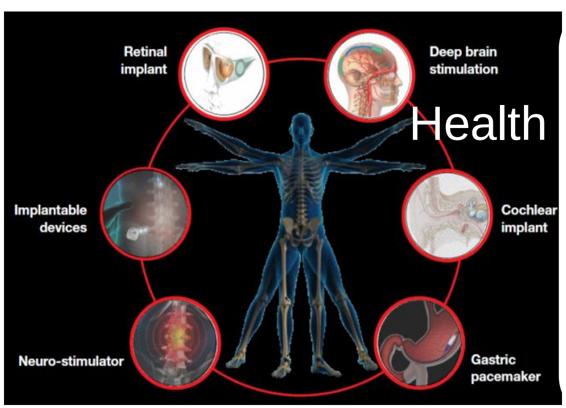
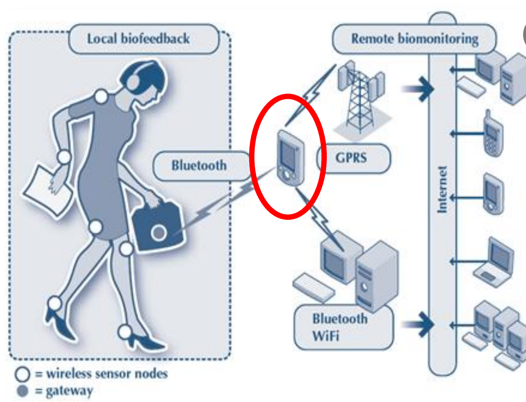
October 2012

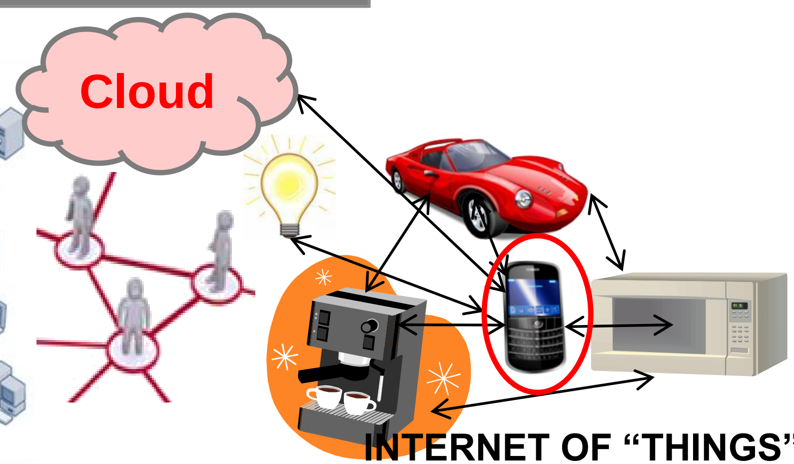
Symbiotic Society Drivers For The Future

- Personal and Health Technology
- Smart Buildings and Infrastructure
- Energy Efficiency
  - Generation (Solar, Distributed Sources)
  - Consumption and Management
    - (Lighting, Motor Control)
- Safety and Security
  - Transportation
- Tied together by the Cloud
  - Mobile is the Personal Hub (maybe)

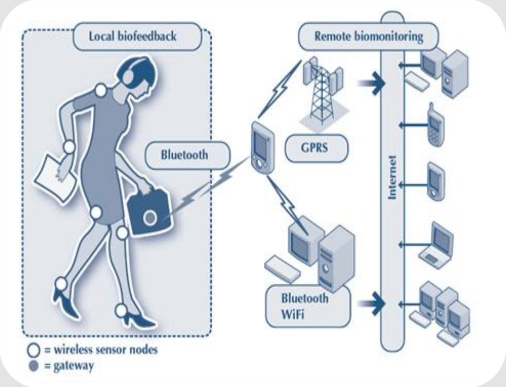


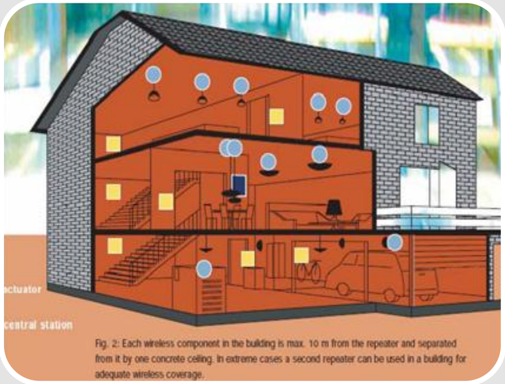






What is needed?





Personal/Health Technology

- Body Area Network
- Low Power Sensors
- Analog
- Gbps Data Comms
  - RF
- Data Analysis
- Energy Harvesting
- Implantables

Structure & Environment monitoring

- Low Power Sensors
  - MEMs/NEMs
- ULP Analog
- ULP Signal analysis
- Data Comms
  - RF
- Energy Harvesting

Smart building

- Intelligent Ambient Low Power Sensors
- Data Comms
  - RF and wired
- Energy Harvesting

Wireless is pervasive .. Today
Some Proprietary RF links & Many use Standards

Alarm and Security

Sub 1 GHz

CC1110/11

Sub 1 GHz SoC
32KB Flash, USB 2.0
0.3 uA sleep current

CC1101

Sub 1 GHz Transceiver
+ MSP430 MCU,
Up to 500 Kbps
-112dBm sensitivity

Remote Controls

CC2.4 GHz

CC2530/33

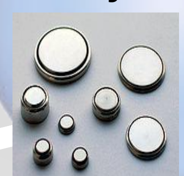
RF4CE
IEEE 802.15.4 compliant
System on Chip
RemoTI SW

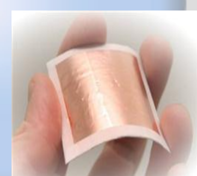
CC2510/11

2.4 GHz Radio
8051 MCU,
32 KB Flash, USB
Proprietary solution

Low Power RF

Battery: 30-100mAh





Smart Metering

CC2530

ZigBee
System on Chip
IEEE 802.15.4 compliant
+ CC259x Range Extenders

CC1020

Narrowband
12.5 KHz channel spacing
-118dBm sensitivity

Wireless Audio

CC8520

PurePath™ Wireless
Just Released
High Quality
Wireless Audio

CC2590

2.4 GHz Range Extender

Home Automation & Lighting

CC2530

ZigBee
System on Chip
IEEE 802.15.4 compliant
+ CC259x Range Extenders

CC1101

Sub 1 GHz Transceiver
+ MSP430 MCU,
Up to 500 Kbps
-112dBm sensitivity

Sport & HID

CC2540

Bluetooth Low Energy
Coming Soon
BTLE compliant

CC2500

2.4 GHz Transceiver
+MSP430 MCU

Elements of a Wireless Sensor Node

Easy to Deploy:

- ❑Cost of deployment(or change battery) > cost of sensor
- ❑inter-operability with existing "wireless networks"
  - ❑Multi- Standard Support
- ❑Multi-Modal Sensor support with "unified" interface mechanisms
- ❑Secure - fast friend handshake, fast drop of foe
- ❑Configurable: Master, Slave or Both
- ❑Cost - $ ❑Volume ~ cm3 ❑ Lifetime ~decade

Self Sustaining Energy

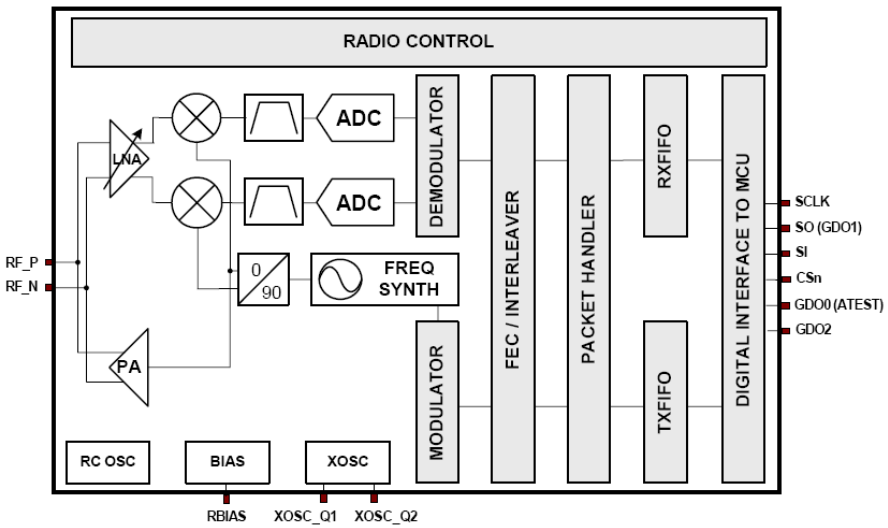
- ❑ Multiple Sources of Energy:
  - ❑ Fixed: Primary Battery
  - ❑ Harvesting
  - ❑High density Storage:
    - ❑Chargeable Battery,
    - ❑Super Caps
- ❑Re-claiming

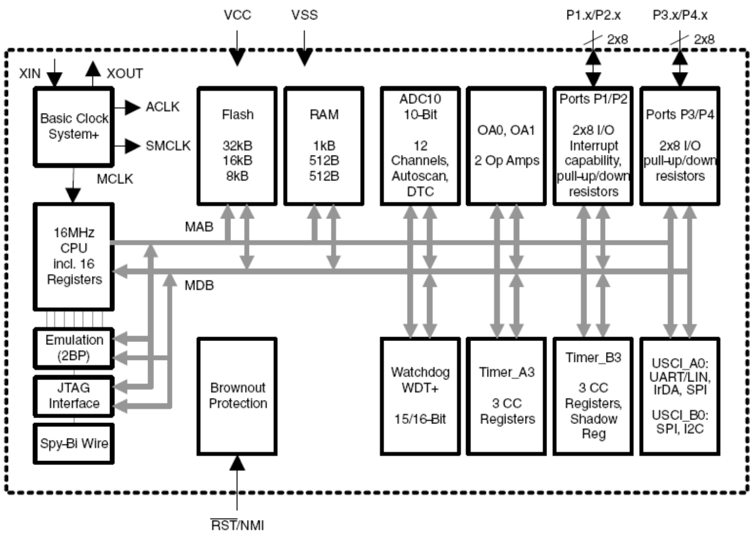
Always on & Always Aware

- ❑Energy efficient
  - ❑ Sensing and Sense signal conditioning
  - ❑ Smart "Communicator":
    - ❑ Connects when deemed necessary
    - ❑Terse : Compressed Data
      - ❑ "assessment" computation
      - ❑ Complex signal computation
- ❑Can Hibernate
  - ❑retain "history" at Full Power Loss

Power Consumption: Example

The Challenge of Powering a LPRF System





CC2500 Typicals:
Vcc Range: 1.8V to 3.6V
WOR Sleep Current: 900nA
Idle Current: 1.5mA
FSTXon Current: 7.4mA
Rx Current: 15mA @ 2.4kB/s
Tx Current: 21mA @ 0dB

MSP430F2274 Typicals:
Vcc Range: 1.8V to 3.6V
Sleep Current: 0.1uA @ 3V
32kOsc Current: 0.9uA @ 3V
CPU off Current: 90uA @ 3V
Active Current: 390uA @ 3V

Present Performance

Sensing Rate	10	100	1000	Hz
Average Sensing Power	33	303	3000	uW
Average uC Power	2	7	60	uW
Average Radio Power	2	2	2	uW
Total Average Power	37	312	3062	uW
Estimated Battery Lifetime*	4.61	0.55	0.06	Years
* 500mA-Hr 3V Battery				

-- Reporting results once/day with 1kB per node and 20 nodes transmitted --

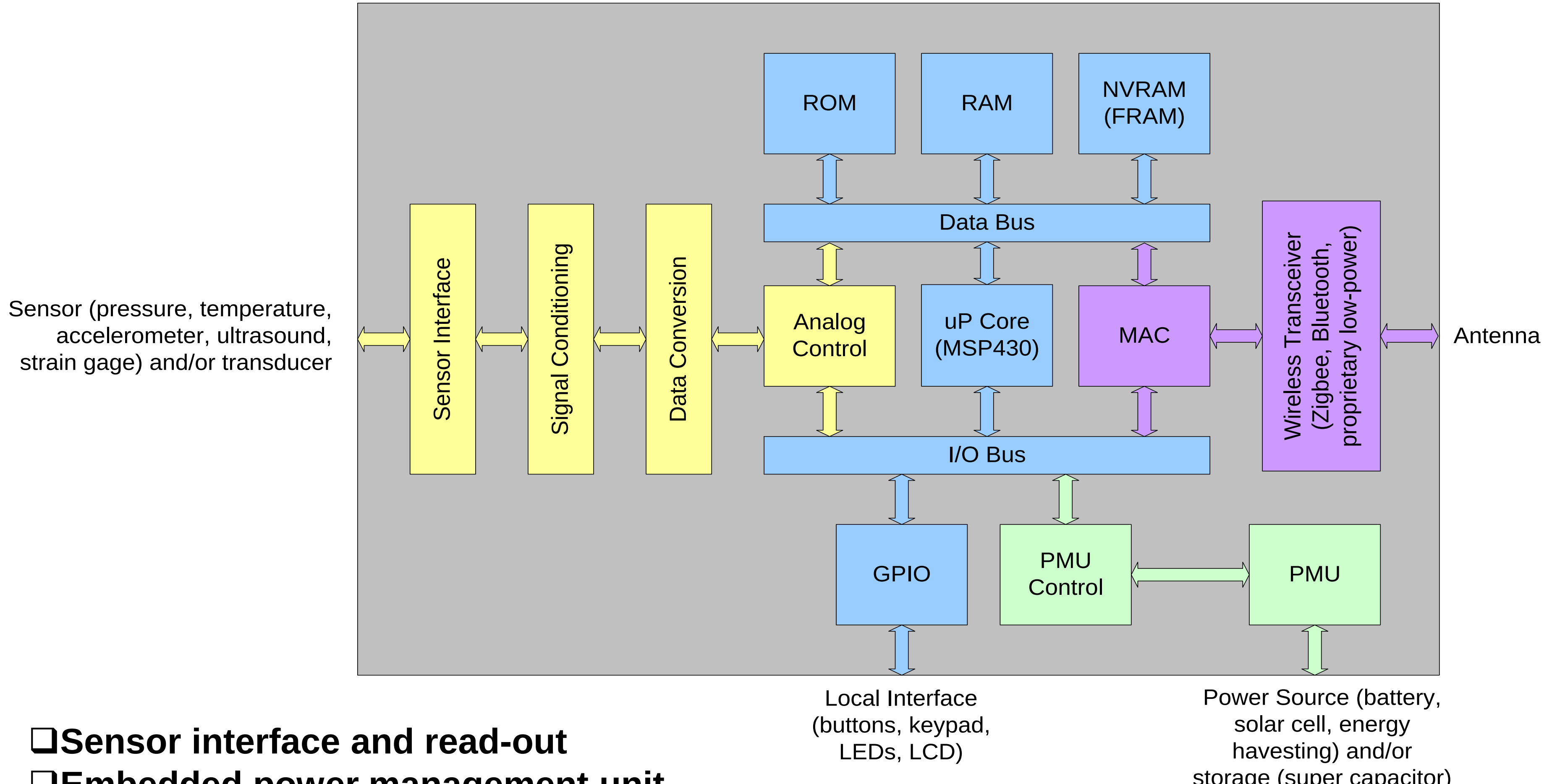
Target Performance

Sensing Rate	10	100	1000	Hz
Average Sensing Power	2	16	150	uW
Average uC Power	1	4	30	uW
Average Radio Power	2	2	2	uW
Total Average Power	5	21	182	uW
Estimated Battery Lifetime*	31.64	7.97	0.94	Years
* 500mA-Hr 3V Battery				

-- Reporting results once/day with 1kB per node and 20 nodes transmitted --

➔ Power will be low enough to use energy harvesting in a small "box"

Next Generation Wireless Sensor Node

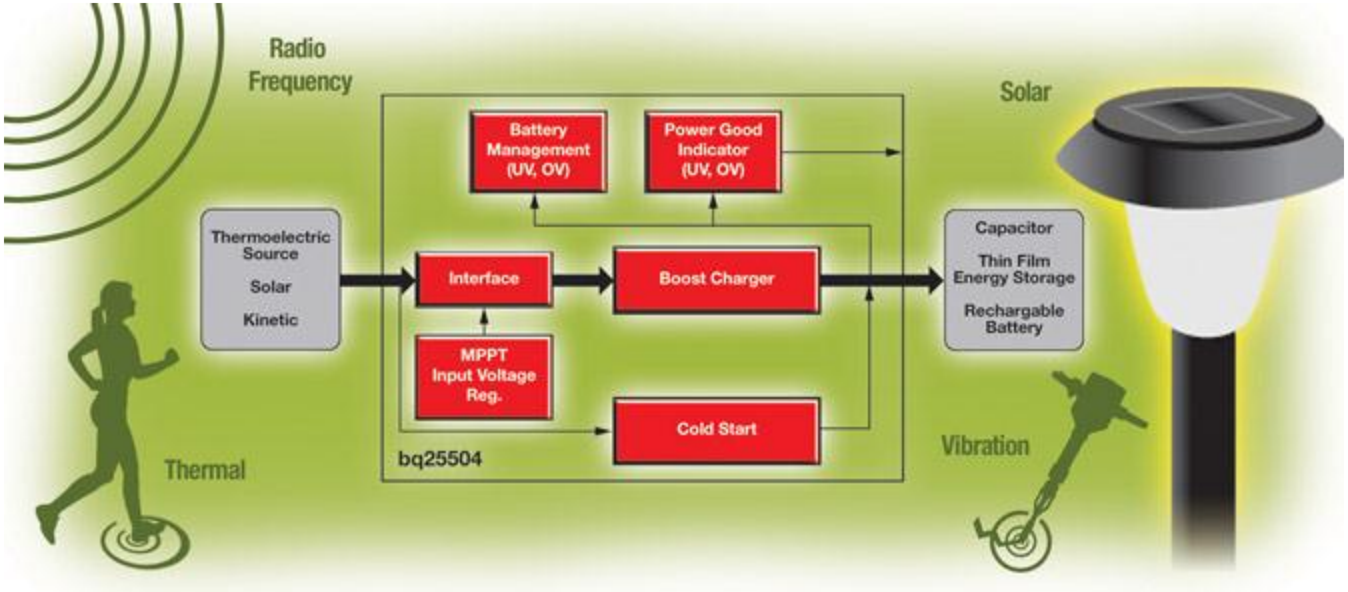


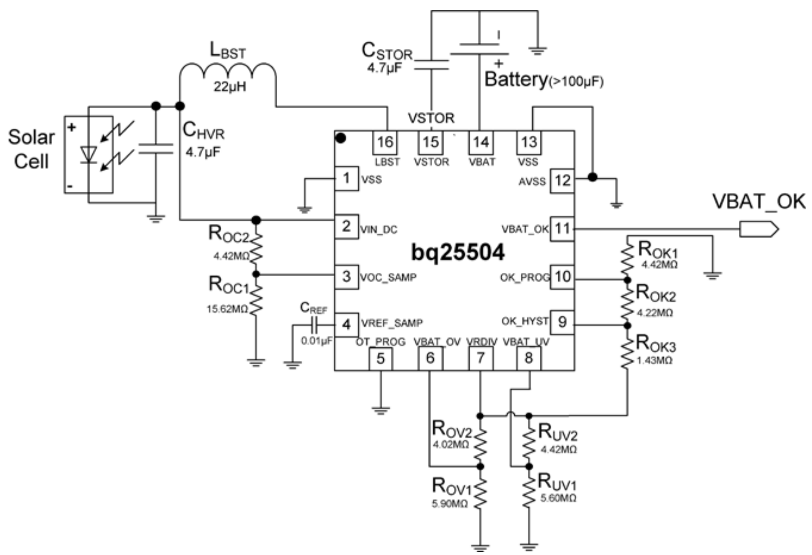
- ❑**Sensor interface and read-out**
- ❑**Embedded power management unit**
- ❑**Communications: Low power wireless Interface**
- ❑**Low-power embedded processor subsystem**

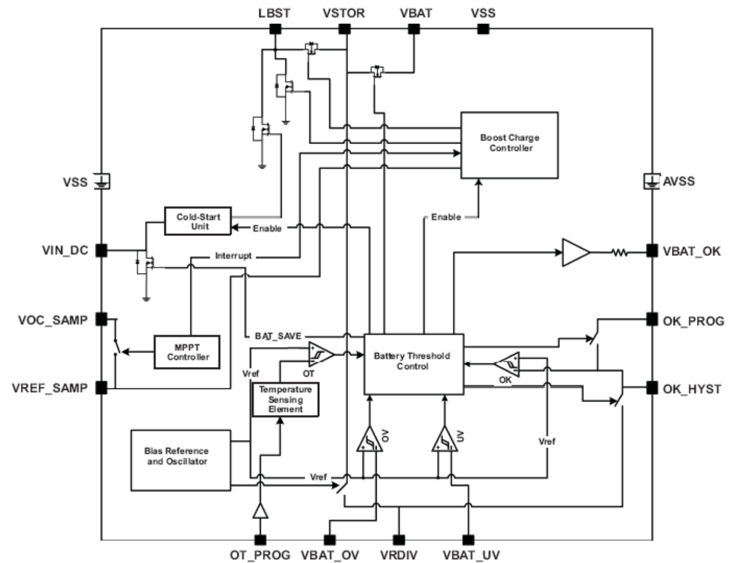
Energy Harvesting: Sources and Technology

Energy Source		Harvested Power
Vibration/Motion		
Human	**High-Q needs to be resonant with vibration (Wide Band ?)**	4 μW/cm²
Industry		100 μW/cm²
Temperature Difference		
Human	**Needs good contact with body and high Delta-T.**	25 μW/cm²
Industry		1–10 mW/cm²
Light		
Indoor	**Shading and "dirt" coverage "on demand light possible"**	10 μW/cm²
Outdoor		10 mW/cm²
RF		
GSM	**Only useful in very close proximity to source**	0.1 μW/cm²
WiFi		0.001 mW/cm²

Energy Harvesting



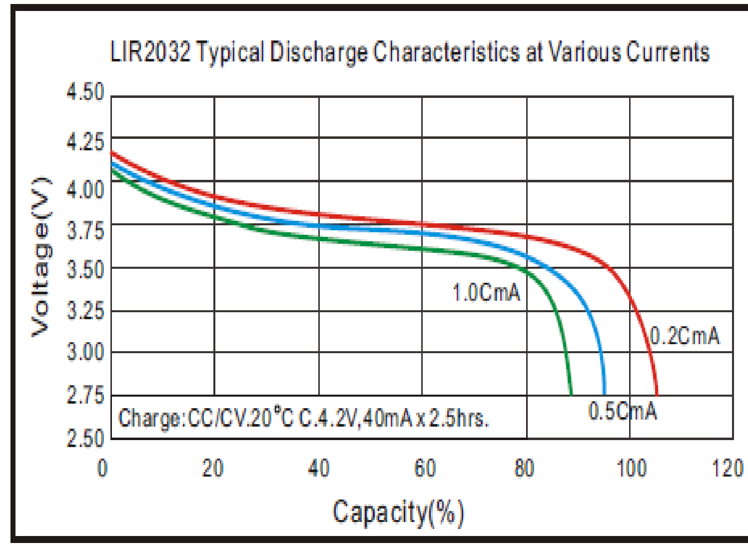




Rechargeable Li-ion Battery Example

2032: 1 cm^3
Li-ion : 40mAh
Chargeable

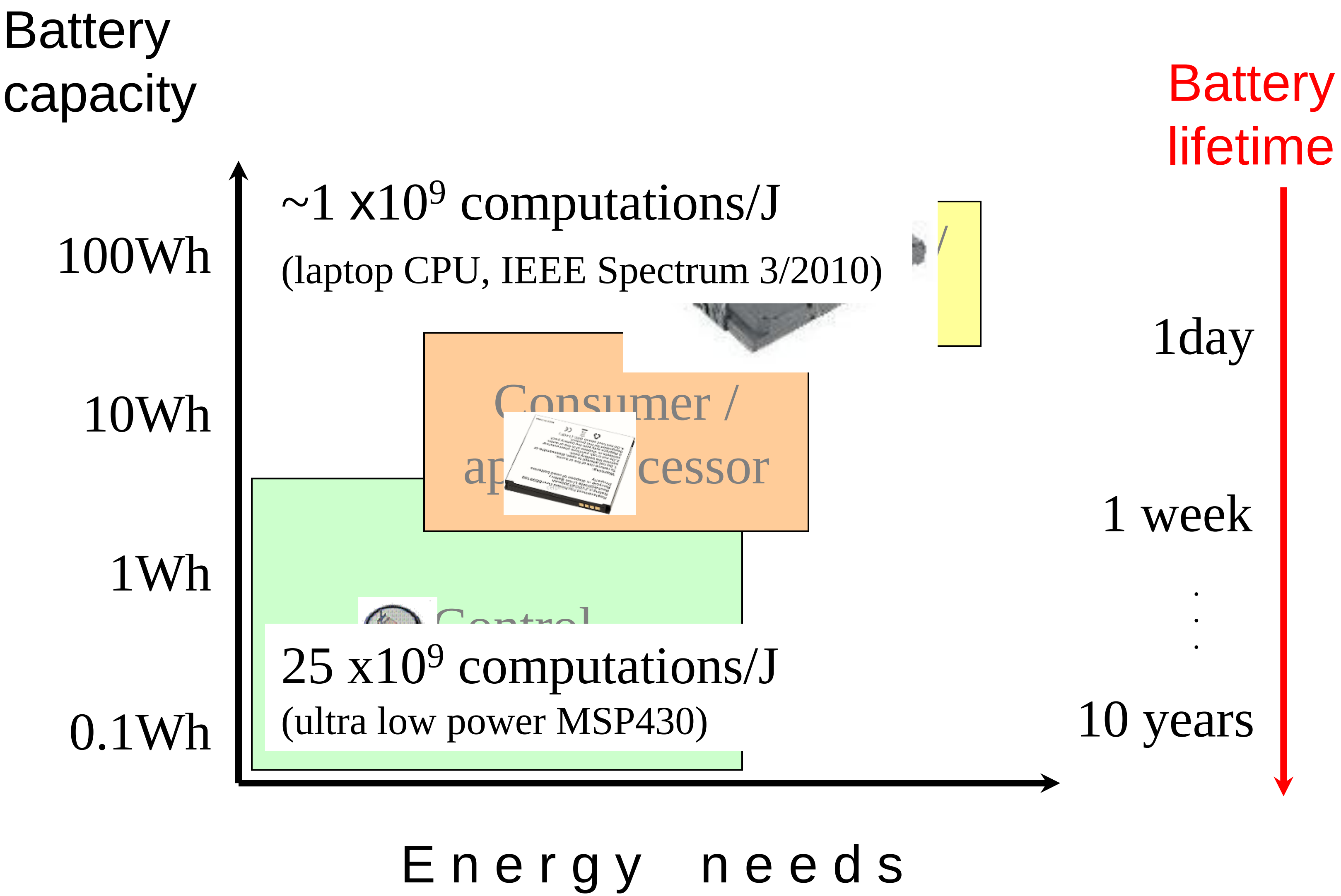
Discharge cut-off voltage	2.75V
Internal Impedance	≤600 mΩ
Cycle life	>500cycles(≥80% capacity)
Nominal Weight	2.8±0. 3g



http://eemb.com/pdf/Li-ion/LIR2032.pdf

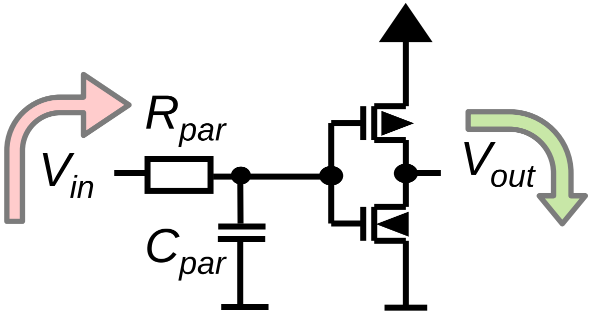
Greater than 1mA for 0.2 x Capacity to 1x Capacity

MCU Energy Awareness



Digital CMOS Power Contributors - Active

- Active power is determined by
  - the delta voltage between in- and output
  - the charging capacitance
  - the frequency and the amount of gates switching



- Dynamic power consumption:

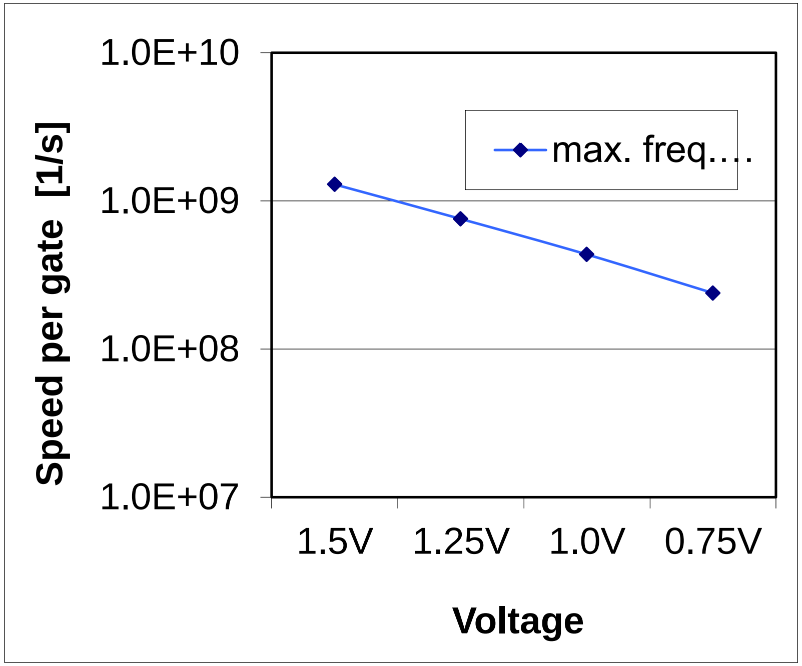
$$P_{dynamic} = p_{switch} \cdot V_{dd}^2 \cdot f_{clock} \cdot C_{load} \cdot N$$

Total power versus V_{dd} for min. cap. cells

- Dynamic power consumption:

$$P_{dynamic} = p_{switch} \cdot V_{dd}^2 \cdot f_{clock} \cdot C_{load} \cdot N$$

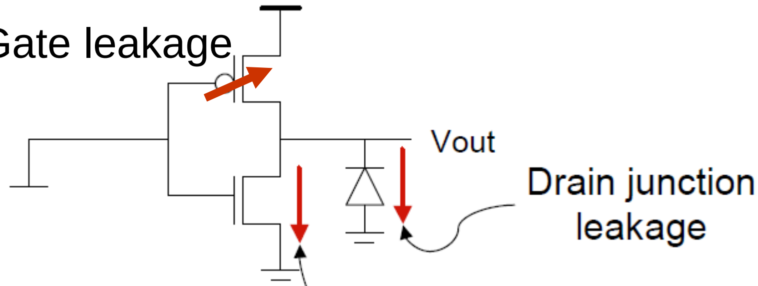
- Speed: $f_{max} \propto \frac{I_{on}}{V_{dd} \cdot C_{load}}$



→ Since C_{load} needs to be minimal for minimal dynamic power, the energy optimal approch to speed is to set supply voltage according to maximal desired speed of a gate without adding to its drive strength (input capacitiance to the previous gate)

→ In this way also leakage per gate scales with supply voltage ...

Digital CMOS Power Contributors - Leakage



- Leakage power has several sources:
  - Historically dominated by sub-threshold and junction leakage (FOM: V_{th}, V_{dd})
  - Gate leakage is more critical with advanced process nodes (FOM: t_{ox} and V_{dd})
- Static power consumption:

$$P_{static} = V_{dd} \cdot \left(I_{leakage,junction} + I_{leakage,gate}\right) \cdot N$$
$$\propto V_{dd} \cdot N \cdot \left(e^{-q \cdot V_{th}/kT} + e^{-F \cdot t_{ox}/V_{dd}}\right)$$

  - All gates are affected – also those who are not active

Power Dissipation and Device Characteristic

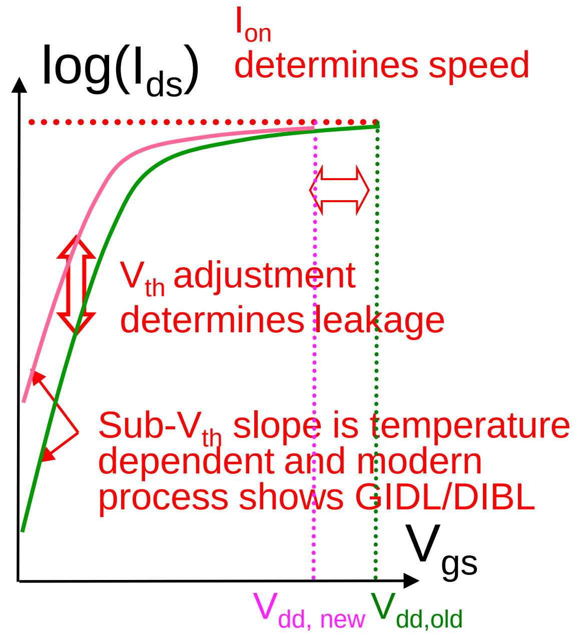
- Dynamic power consumption:

$$P_{dynamic} = p_{switch} \cdot V_{dd}^2 \cdot f_{clock} \cdot C_{load} \cdot N$$

- Static power consumption:

$$P_{static} = V_{dd} \cdot \left(I_{leakage,junction} + I_{leakage,gate} \right) \cdot N$$

$$\propto V_{dd} \cdot N \cdot \left(e^{-q \cdot V_{th} / kT} + e^{-F \cdot t_{ox} / V_{dd}} \right)$$



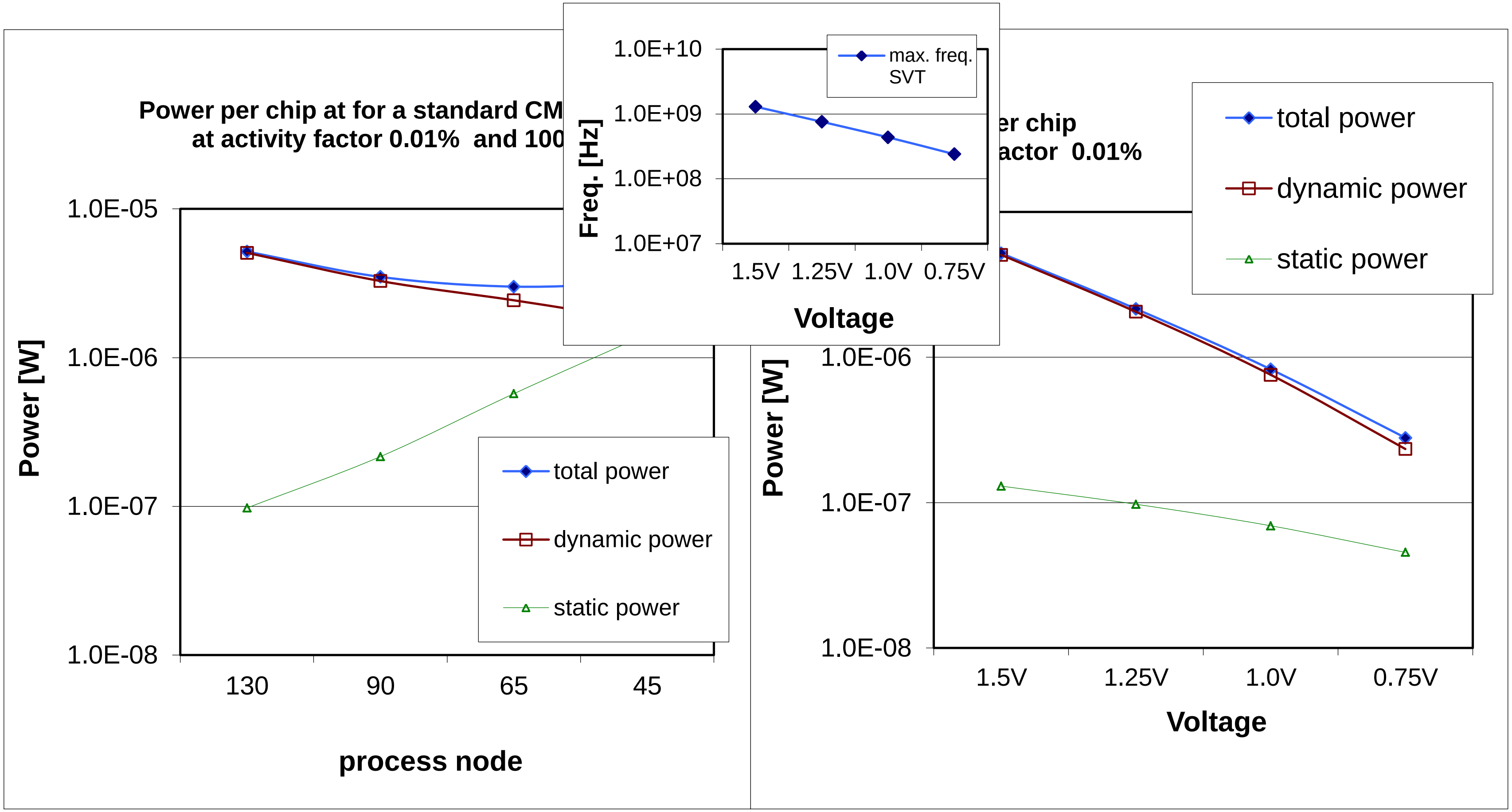
⇨ Historically processes have been optimized for speed

⇨ Thinner oxide increases tunneling leakage currents

⇨ Higher temperatures degrade sub-threshold slope (S) and therefore also leakage currents

⇨ As long as no digital circuit is completely shut-off, increasing functionality and speed (~ more current) will increase leakage currents

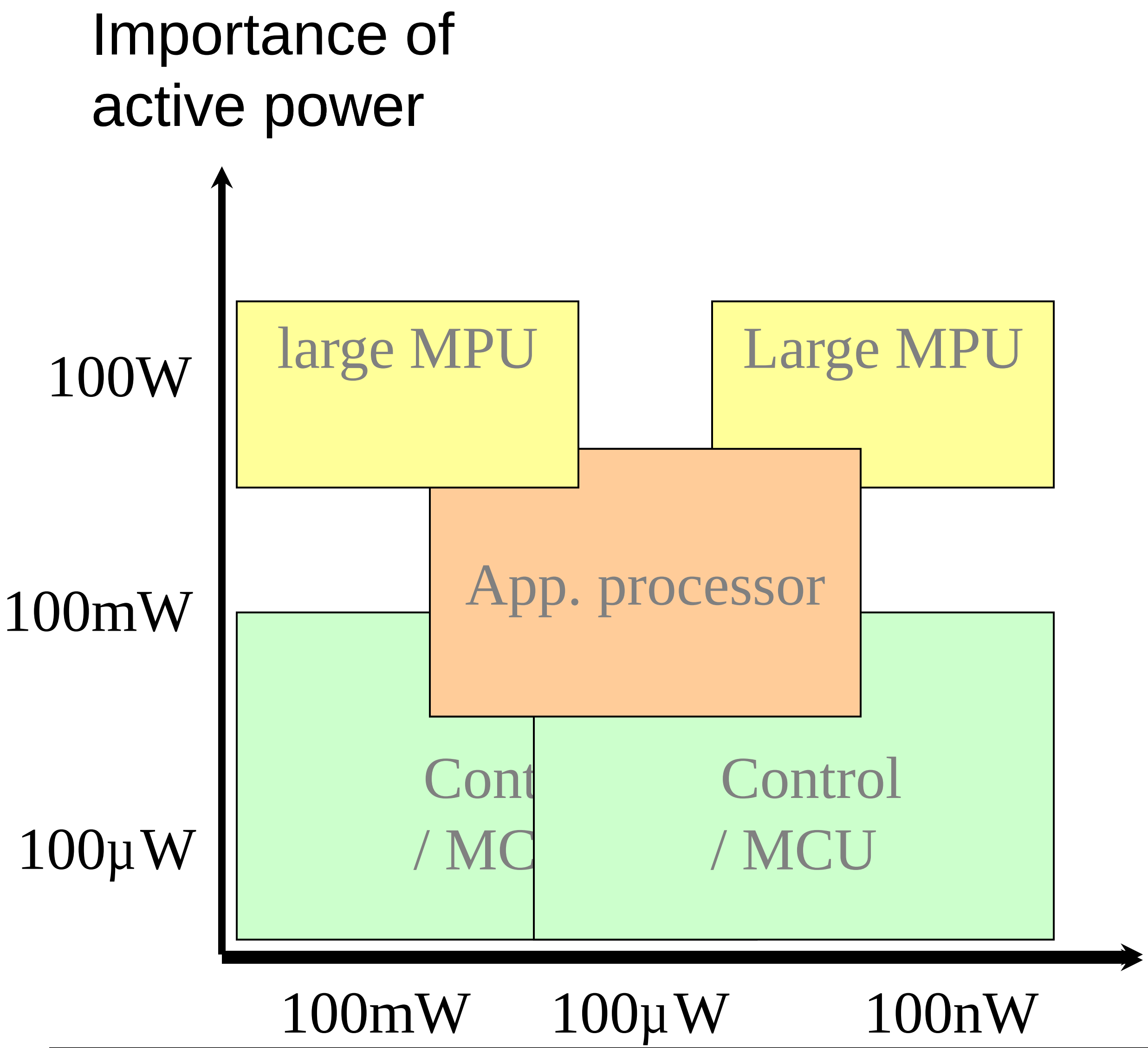
Logic Power Dissipation vs. technology and V_{dd}



→ Leakage currents cause severe problems in advanced technologies becoming dominant power contributor

→ Supply voltage lowering helps for power saving, but at cost of speed

Active / Leakage Power



- Dynamic power scales with 1/node^x
- Leakage power gets worse per node *(without design tricks …)*

Power and Scaling

With *decreasing* V_{dd} (at even increasing number of transistors N) the leakage can only be constant when V_{th} does not increase:

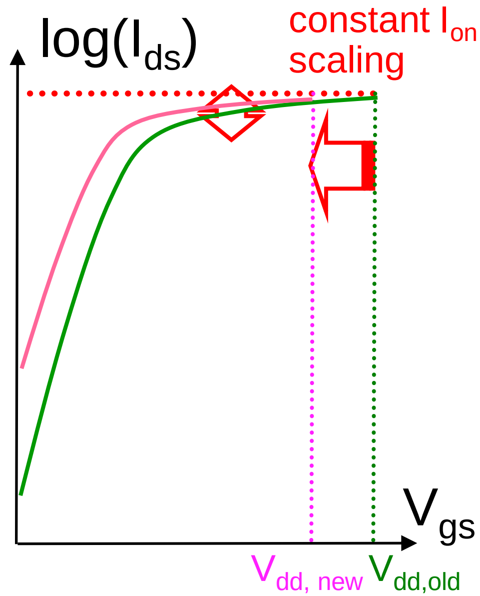
- Static power consumption:

$$P_{static} = V_{dd} \times \left(I_{leakage,junction} + I_{leakage,gate} \right) \times N$$

$$\propto V_{dd} \times N \times \left(e^{-q\,V_{th}/kT} + e^{-T\,t_{ox}/V_{dd}} \right)$$

- Speed:

$$f_{\max} \propto \frac{I_{on}}{V_{dd} \cdot C_{load}}$$



⇨ Scaling V_{dd} and keeping C_{load} constant is necessary for smaller area

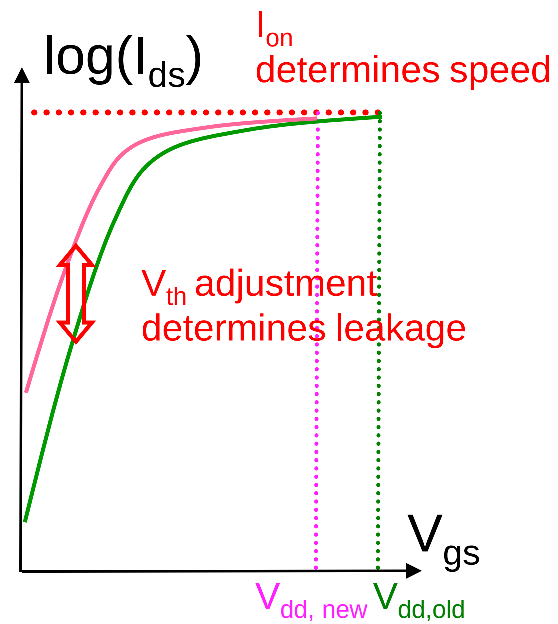
⇨ To compensate sub-V_{th} leakage, V_{th} has to increase resulting in lower I_{on} (reduced speed)

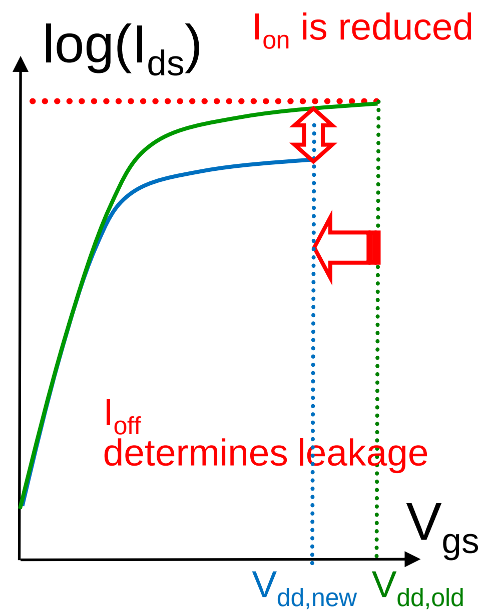
⇨ At small t_{ox}, gate and s/d tunneling leakage is a severe problem

⇨ While reducing speed (lower V_{dd}), tunneling leakage decreases as well (at reduced speed)

Technology Scaling for ULP

To optimize for leakage and speed/active power on technology and circuit level it is beneficial to have two types of transistors …

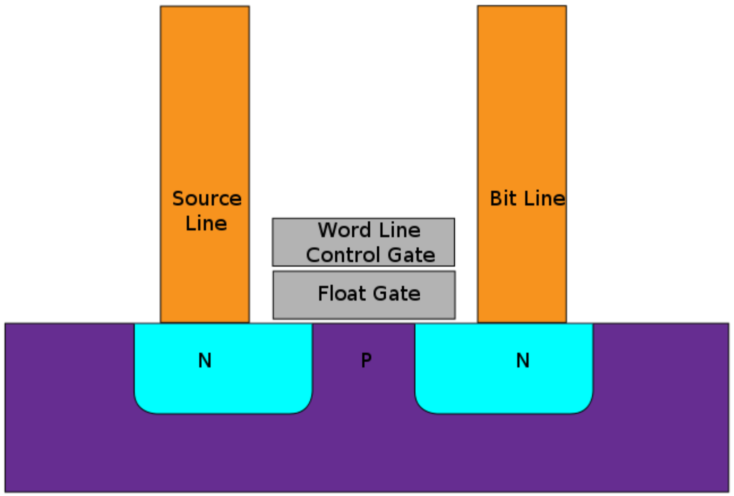




- ⇨ Scaling V_{dd} and keeping C_{load} constant is necessary to active power improvement of advanced CMOS
- ⇨ Gate and S/D leakage needs optimization from standard CMOS
- ⇨ To keep leakage low a second type of transistor is kept in the process

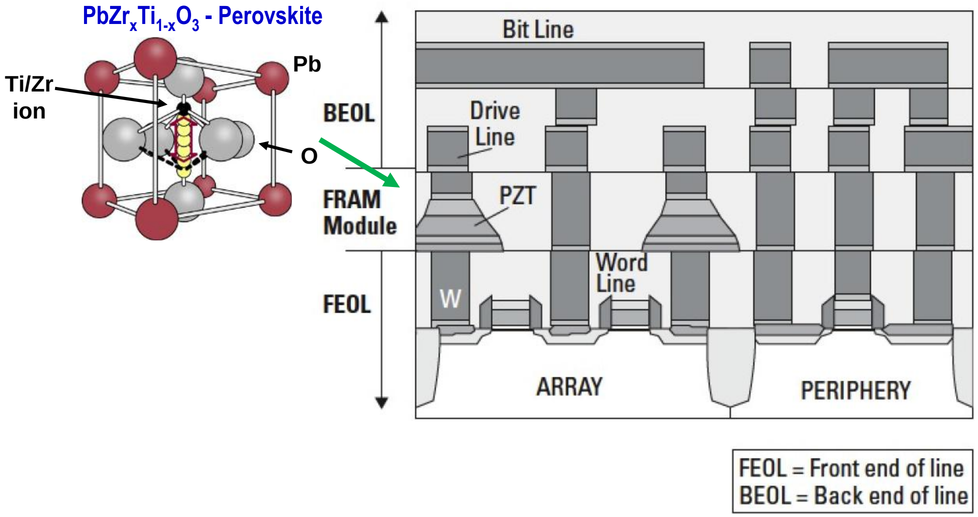
NVM Technology Comparison

Flash



- Good read speed (single tranistor)
- Very dense bit cell
- Floating gate memories need high voltages to write (>10 V)
- Exhibit slow writes/erase cycles
- Limited endurance due to oxide damage

FRAM



- Read speeds slightly lower than Flash
- Bit cell size larger than Flash
- No high voltage → only 2 mask adder, no high voltage needed
- Write current as low as read current
- Endurance (theoretically) infinite

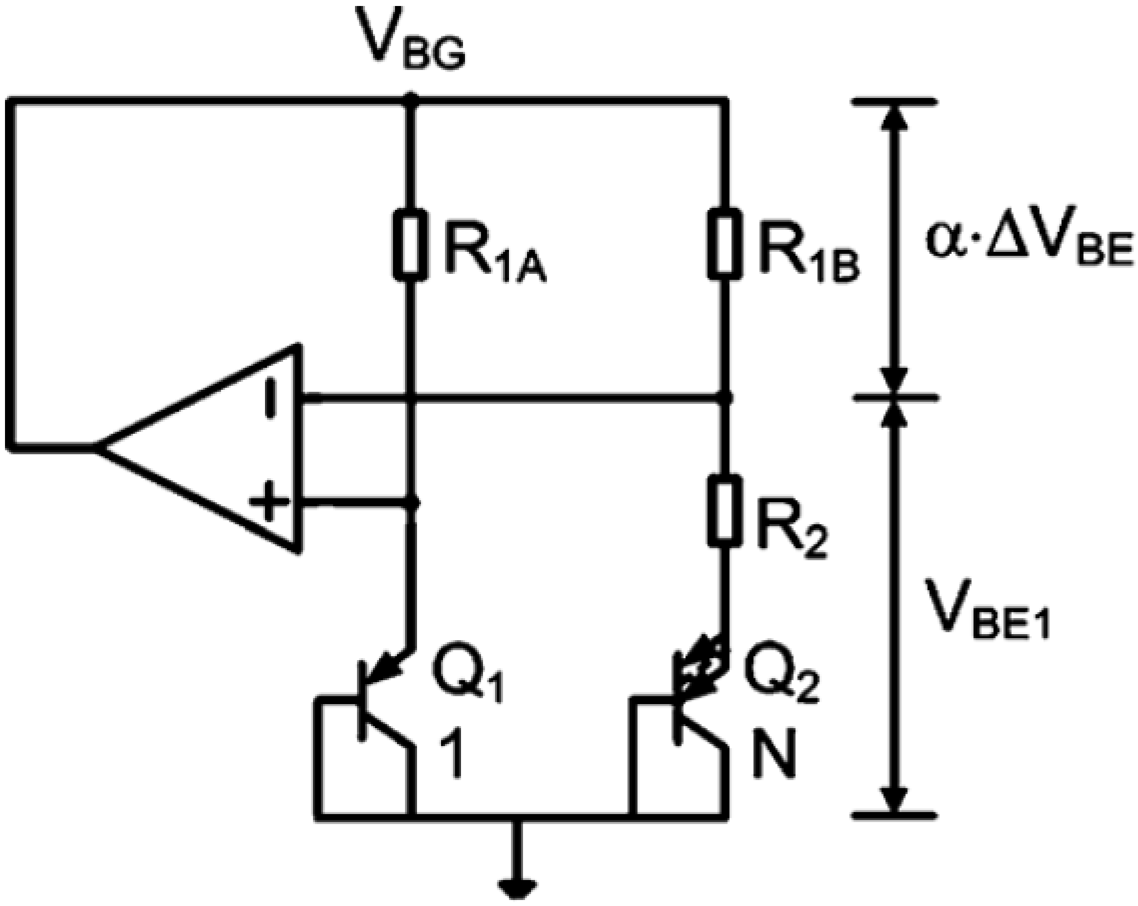
Key Memory Technology Comparison

	FRAM	SRAM	EEPROM	Flash
Nonvolatile Retains data without power	Yes	No	Yes	Yes
Write speed (13 KB)	10ms	<10ms	2 secs	1 sec
Average active Power [µA/MHz]	82	<60	Up to 10mA	260
Write endurance	1 million billions (10^{15})	Unlimited	~500,000	10,000
Dynamic Bit-wise programmable	Yes	Yes	No	No
Unified memory Flexible code and data partitioning	Yes	No	No	No

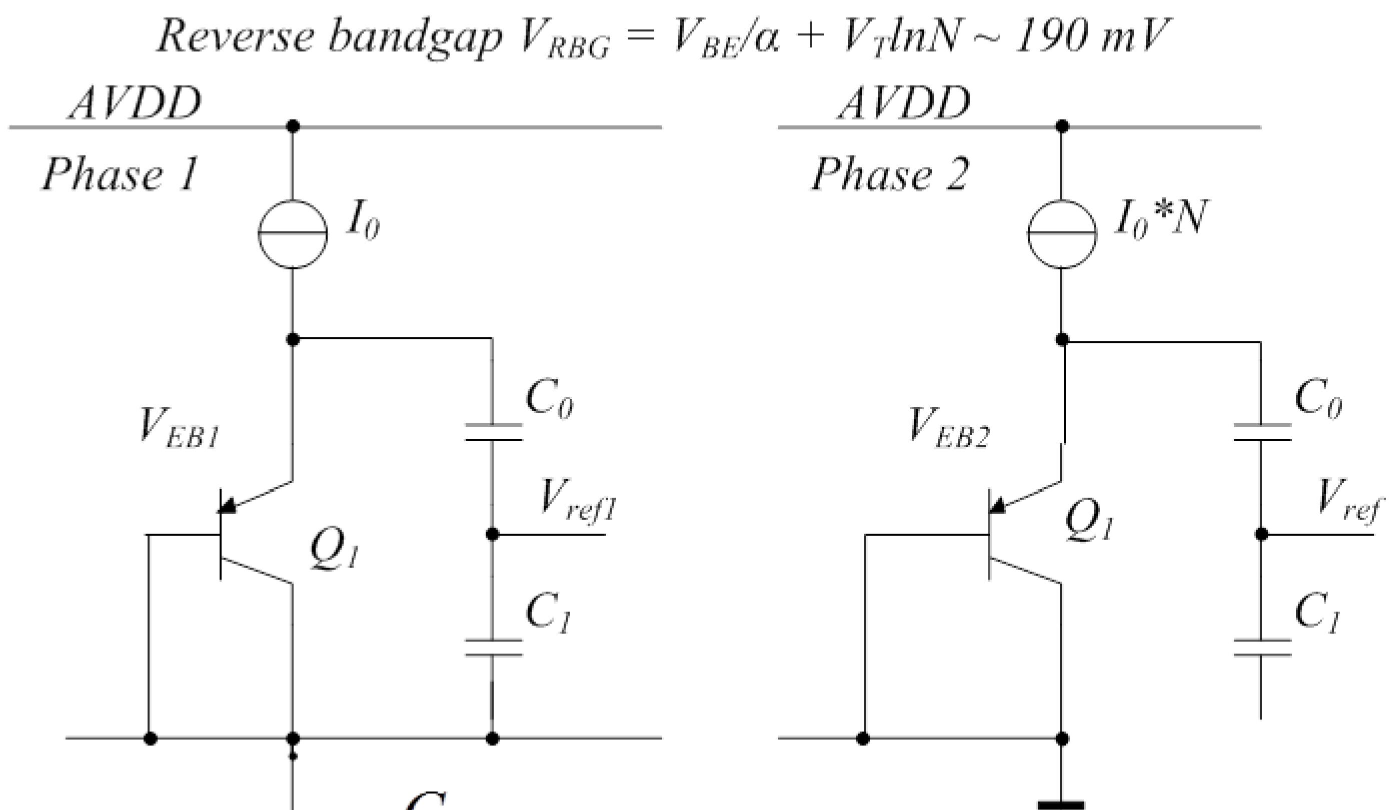
V.C. Kumar, Texas Instruments - August 20, 2012

Traditional Bandgap Reference

$$Traditional\ bandgap\ V_{BG} = V_{BE} + \alpha V_T \ln N \sim 1.2V$$



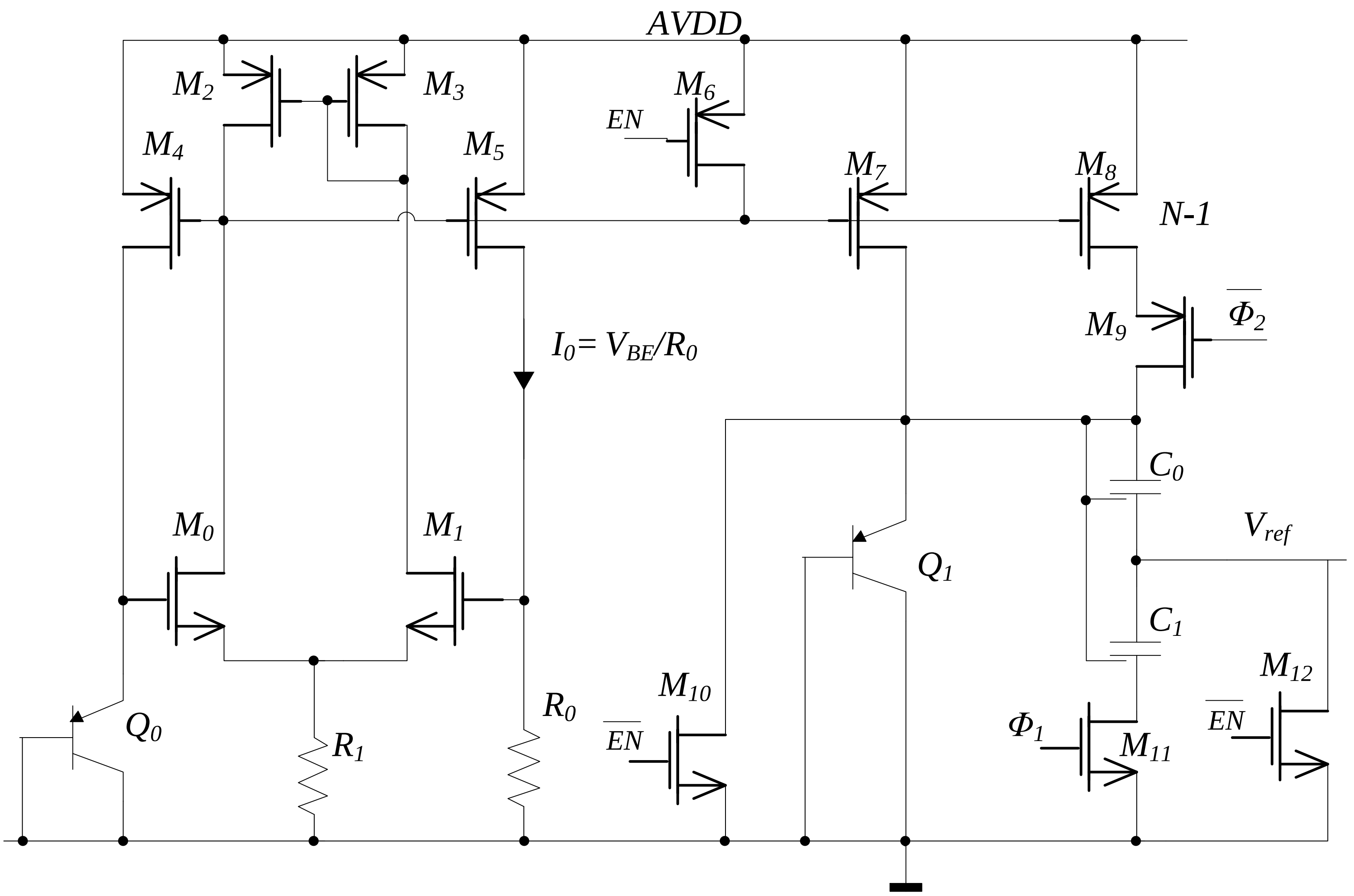
Switch Cap Reverse Bandgap Principle



$$V_{ref1} = \frac{C_0}{C_0 + C_1} V_{EB1}$$

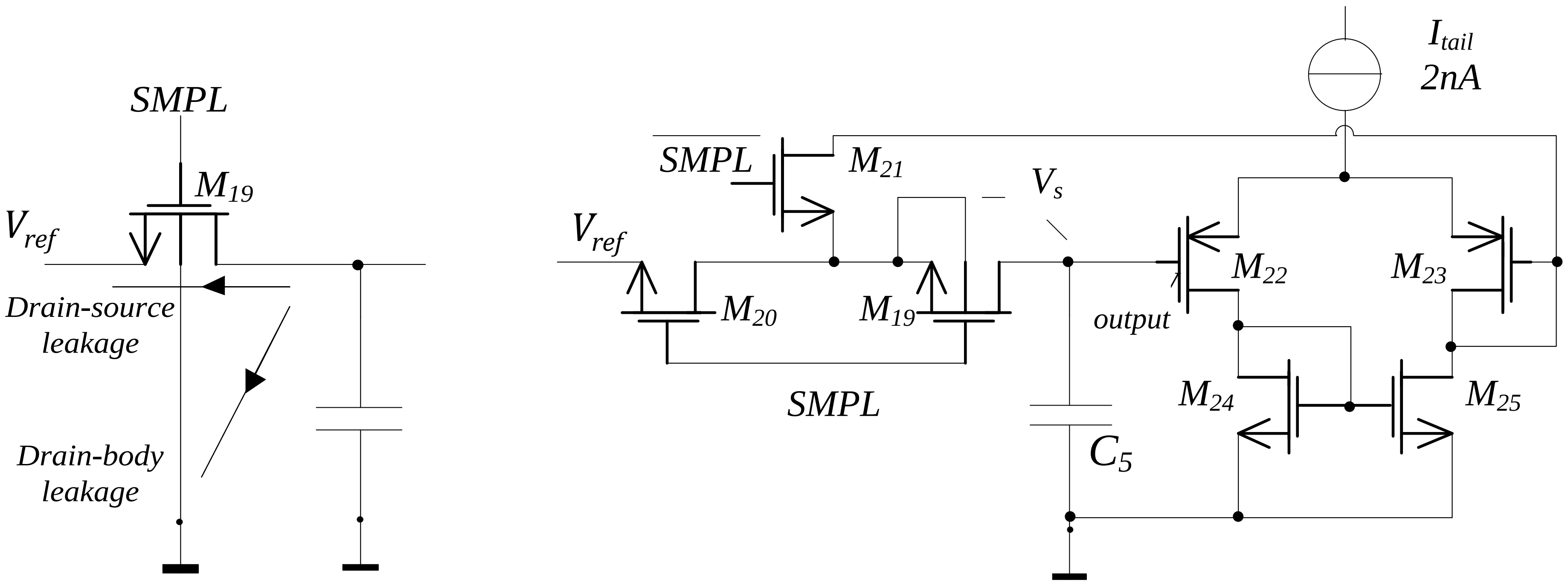
$$V_{ref} = V_{ref1} + V_T \ln N$$

Reference Core Schematic



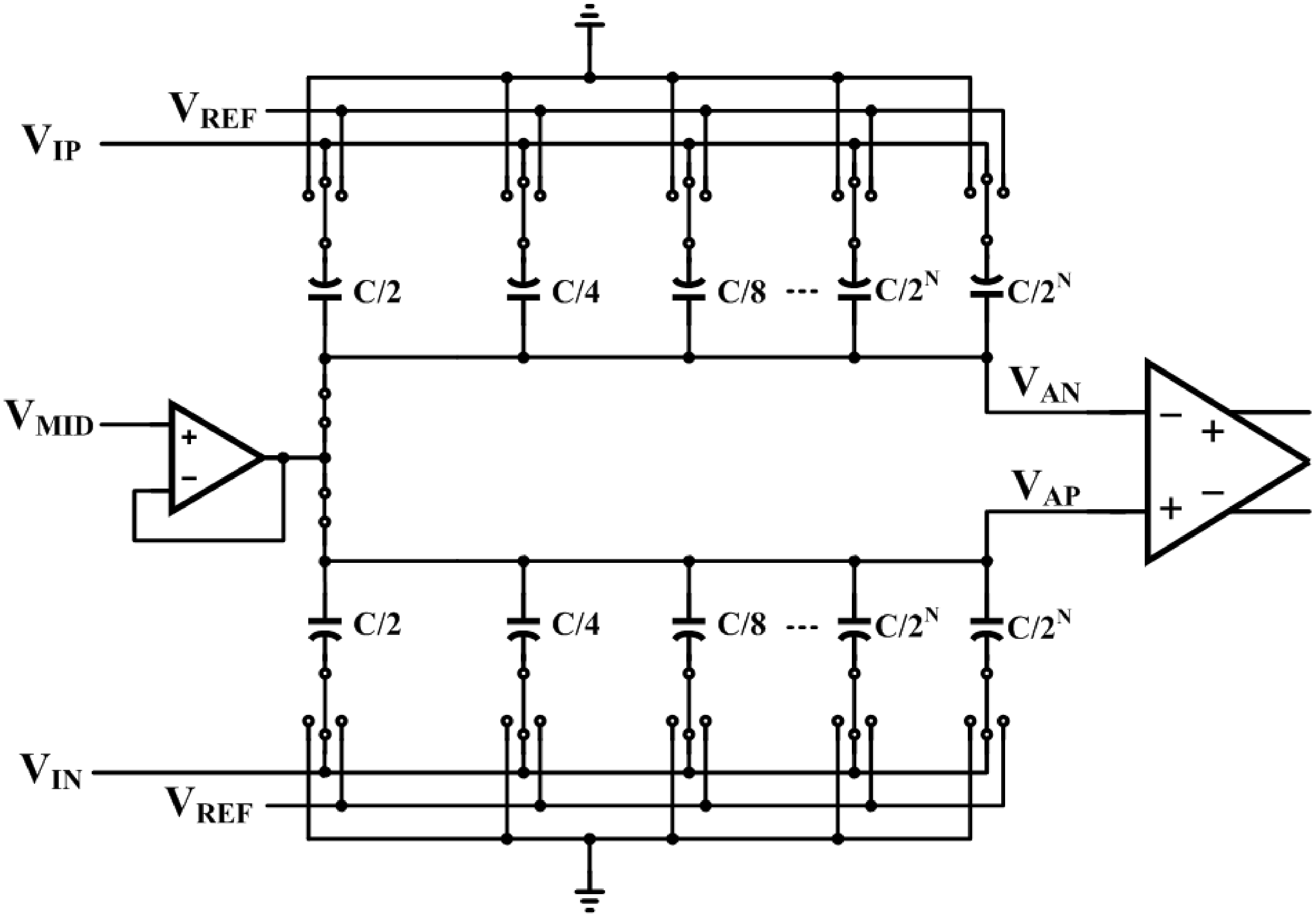
Parasitic part of C_0/C_1 is the main error source

Sample / Looooooong Hold

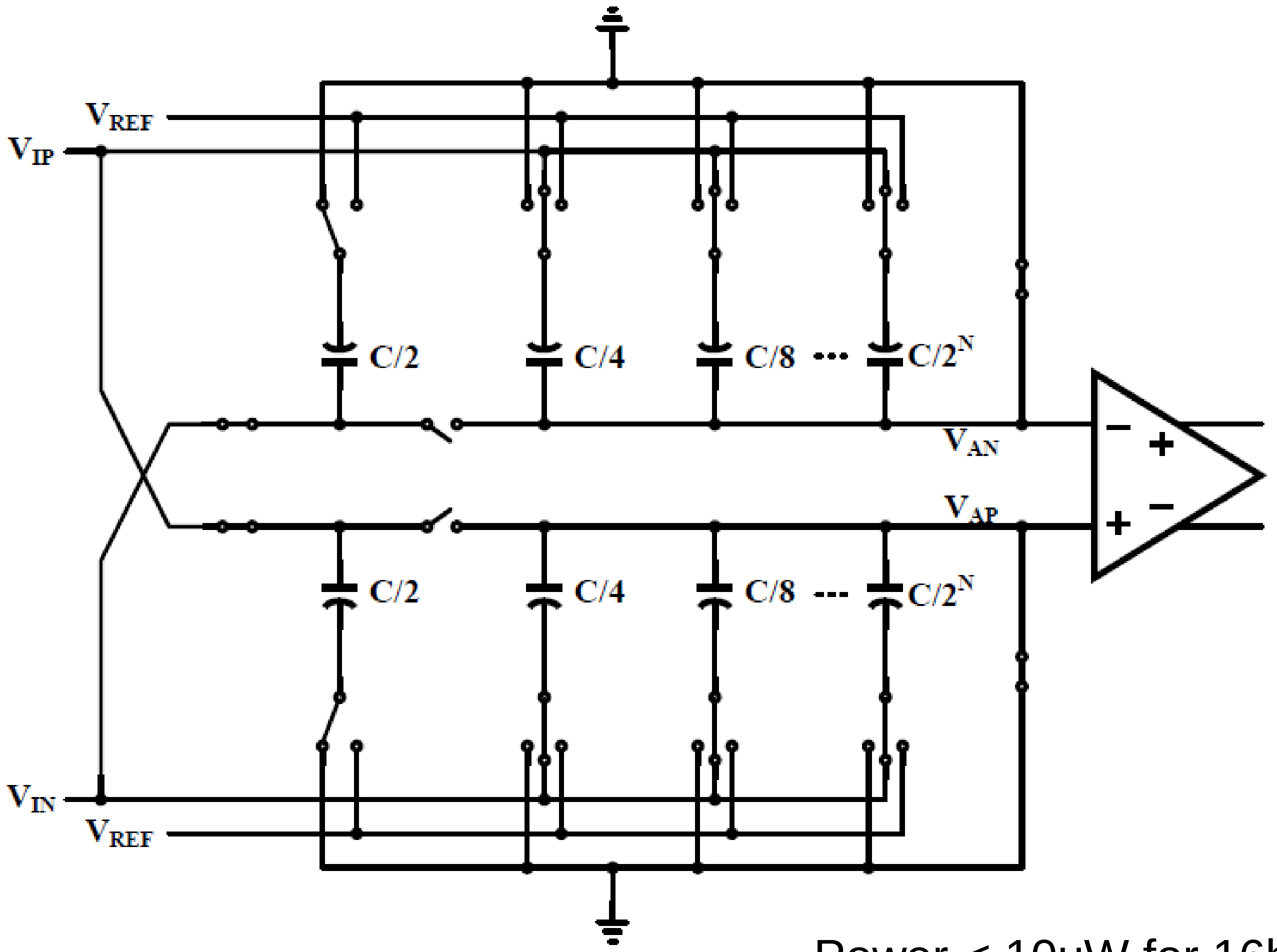


Power < 0.2uW

Conventional Fully-differential SAR ADC (Sampling Phase)



ADC Power Reduction. Moving Fully-differential ZPS SAR ADC (Sampling Phase)



Power < 10uW for 16b @ 1kHz

Summary

Easily accessible wireless sensor node capability is coming soon to fit across many applications

Solutions exist and near coming

- Low power uC
- Low power analog and mixed-signal
- Lower power RF
- Energy harvesting improving
- Process technology to support

Need to consider next level of integration – especially sensors

Need to plan infrastructure data connectivity

Thank you for your attention.

Acknowledgements

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