

Ultra-Low Power, Sub-threshold Design - From Watch Microelectronics to IoT Integrated Circuits

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Abstract—In the era of battery operated devices, in particular booming wearables and Internet-of-Things (IoT) objects, ultra-low energy consumption is becoming the most important challenge in the electronic design. Supply-voltage scaling is an efficient way to reduce energy by lowering the operating voltage. The reported Minimum Energy Point (MEP), in i.e. modern CMOS 65nm, can be as low as 0.35V. To achieve such low voltage operation, sub-threshold circuit design needs to be considered. Swiss watch microelectronics was exploring this approach since 1970. An overview of the principles and challenges of today’s sub-threshold design will be given in this paper. The paper depicts also the 50 years of the Swiss “Quest for the Holy Grail” in ultra low-power wearable electronics, started with the world’s first electronic quartz wrist watch BETA1 (1967) developed by the Centre Electronique Horloger (CEH) in Neuchâtel, toward autonomous, batteryless IoT objects of tomorrow.

Index Terms—Sub-threshold design; Watch microelectronics; Integrated circuits; IoT

I. THE FIRST ELECTRONIC QUARTZ WATCH

50 years ago ...

- 1967
 - The first integrated electronic quartz watch
 - Beta 1, Beta 2
 - **The quartz watch is born!**
 - Beta 21
 - The industrial prototype
- Precision :
 - The Beta 21 watch is **10 x more precise** than the mechanical watch of the 60s!
- Volume :
 - Its movement is **300 x smaller** than that of the best quartz marine chronometer of that time!
- Autonomy :
 - The Beta 21 watch has an autonomy **200 x more** important than the mechanical watch (2 days), i.e. about **400 days!**
(Total chip power consumption <18µA at 1.3 V)



[1-2]

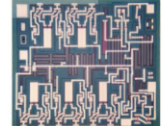
Key elements [1]



Module of the first commercial watch developed at CEH.

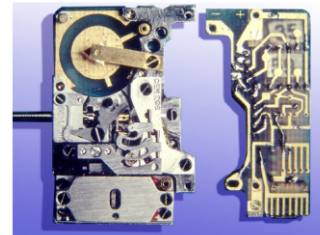


Miniaturized quartz resonator
First prototype of 8192Hz small size resonator developed at CEH.



First LSI circuit developed for a wristwatch (110 components, 8.7mm², 12µA at 1.3V)

Module illustration



on the left: electromechanical part

on the right: the printed circuit with the IC and the quartz

First electronic quartz watch - Realizations

- The miniaturized quartz resonator
 - The geometry of the resonator must assure an ideal mechanical vibration of the quartz. Designed to avoid loss of energy and assure a resistance to shocks.
- The electronic circuit
 - 3 functions : maintenance of the vibrations of the quartz, division of the frequency and command of the display.
- The microelectronic technology
 - New technology of integrated circuits born in the USA in 1958, adapted.
 - Later, new microelectronic technology (CMOS) exploited allowing a drastic reduction of electrical consumption.
- Secret project

Wristwatch - A first electronic wearable device?

wearable technology

Examples

noun

1. a small computer or advanced electronic device that is worn or carried on the body:
the trendiest wearable technologies.

from Dictionary.com

Characteristics:

- Battery operated, miniaturized electronic device, worn or carried on the body
 - Integrated low-power electronics

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The CEH prototype [2]

CEH (since 1962) -> CSEM (since 1984)
 Centre Electronique Horloger (CEH)
 Centre Suisse d'Electronique et de Microtechnique (CSEM)

II. FROM BATTERY-LIGHT TO BATTERY-LESS

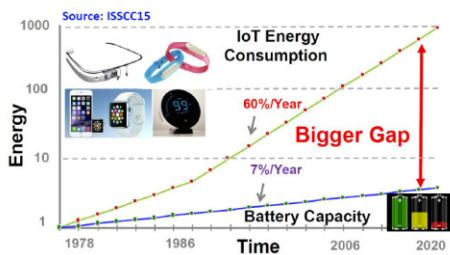
And today?

50 years later ...

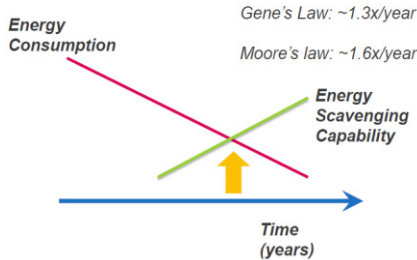
Power and miniaturization challenge remains!

... from battery-light to battery-less

Power challenge for Internet of Things (IoT)



CSEM Vision : From wireless to batteryless

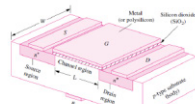
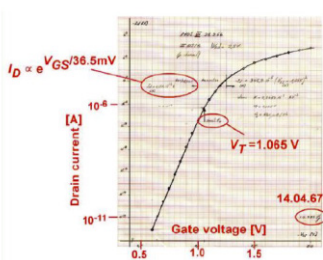


Ultra-low energy consumption

- becoming the most important challenge in the electronic design
- supply-voltage scaling (an efficient way to reduce energy)
 - extreme low supply operation – below MOS threshold voltage
 - > "sub-threshold" / "week inversion" circuit design techniques!
- Swiss watch microelectronics was exploring this approach since the end of '60s
- hundred of millions of week inversion ICs been produced for watch applications

III. SUB-THRESHOLD DESIGN

Pioneering weak inversion for analog CMOS [1]



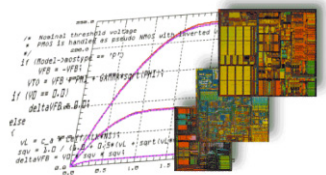
- First measurement of a MOS transistor at very low current (1967, by Eric Vittoz)
- Sub-threshold voltage experiments

EKV Model (Low Power MOSFET Model) [3]

- Advanced MOSFET model for low-voltage low-current circuit design
- As supply voltage of circuits decreases to reduce power consumption
 - analog designs require a more physical, accurate and continuous compact MOS model.

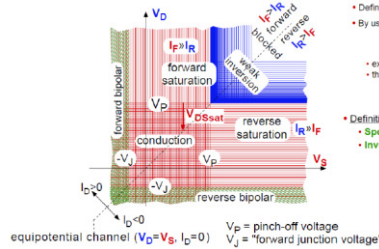
=> Enz-Krummenacher-Vittoz (EKV) model

(http://ekv.epfl.ch/)

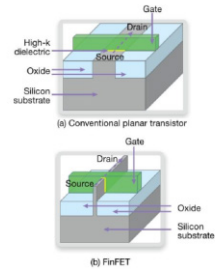
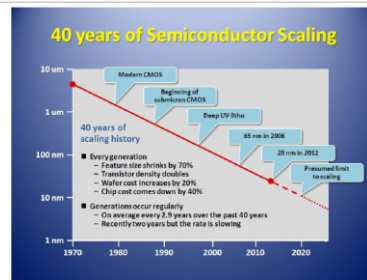


Modeling [3]

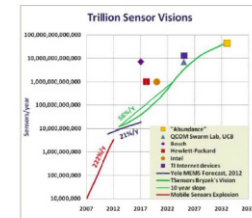
MOS TRANSISTOR: MODES OF OPERATION



CMOS technology scaling



CMOS supply voltage scaling: Challenge to operate at 0.4V!



Category	Year	2005	2007	2008	2010	2011	2015	2020	2027	2030
Energy	Energy source	0	0	0	0	0	0	0	0	0
	Energy source (Energy harvesting)	0	0	0	0	0	0	0	0	0
	Lowest VDD Used by Components (V)	0.8	0.75	0.7	0.65	0.65	0.55	0.45	0.4	0.4
	Deep voltage current of CMOS (pA)	100	72	52	38	27	19	14	10	7
Power	Transistor density of CMOS (transistors/cm²)	88%	82%	80%	88%	89%	90%	98%	99%	99%
	Typical power density of CMOS (mW/cm²)	1	1.17	1.38	1.91	1.95	2.88	3.92	5.64	6.14
	Peak current (consumed by connectivity interface (mA)	50	19.2	7.66	2.97	1.11	0.40	0.20	0.06	0.04
	Transmission Power per bit (pJ/bit)	2.88	1.07	0.38	0.14	0.05	0.02	0.005	0.001	0.0005
Form factor	Mobile footprint (mm²)	500	20	1	0.5	0.3	0.1	0.05	0.02	0.01
	Mobile footprint (mm)	1	1	1	1	1	1	1	1	1
	Mobile footprint (mm)	1	1	1	1	1	1	1	1	1
	Mobile footprint (mm)	1	1	1	1	1	1	1	1	1
Performance	Mobile Current / Operation frequency (fA/Hz)	20	25.7	25.7	11.3	6.9	3.7	6.7	5.8	5.8
	Max. Mobile frequency (MHz)	200	270	277	300	350	500	1000	1000	1000
	Mobile throughput (Mbps)	1014	1014	1014	1014	1014	1014	1014	1014	1014
	Mobile throughput (Mbps)	1014	1014	1014	1014	1014	1014	1014	1014	1014
Peripheral	Number of sensors integrated in systems	4	8	16	32	64	128	256	512	1024
	Max. Sensor Power (pW)	2000	1000	500	250	125	62.5	31.25	15.625	7.8125

Opportunity: Sensors will populate the world of IoT

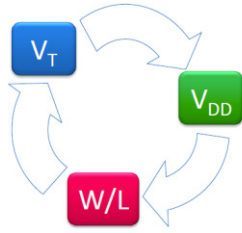
Source: 2015 ITRS "IoT" roadmap [4]

Design considerations in week inversion [5-7]

- Exponential I-V characteristics in week inversion
 - PVT variations – Not only an issue for analog!
 - Small variation on process (i.e. Vt)
 - exponential variation on the bias current
 - Temperature effects
 - Matching
 - Current matching degraded
 - Voltage matching improved

Circuit building blocks to support sub-threshold digital design [8-9]

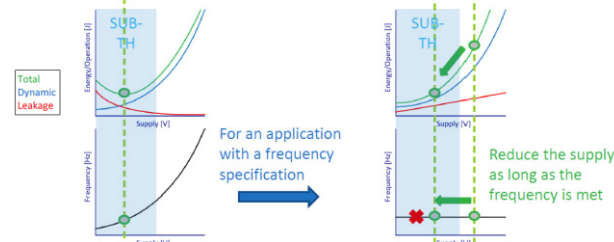
- These basic blocks:
 - ✓ Standard cell library
 - ✓ RAM
 - ✓ ROM
 - ✓ Level shifters
 - ✓ Pads
 - ✓ Power Management
- Libraries can be optimized for several criteria:
 - The lowest possible supply voltage
 - The lowest possible leakage while supporting a target frequency.



Sub-threshold design - Digital

Minimum energy per operation

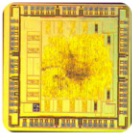
$$E = \alpha \cdot C \cdot V_{dd}^2 + \frac{I_{off} \cdot V_{dd}}{f}$$



→ Optimum supply in sub-threshold

→ Optimum supply is the lowest possible

Embedded Computation & Control: 0.4V μ -controller [10]



Operation over 3 decades of frequency demonstrated: from 20kHz to 20MHz

What it does

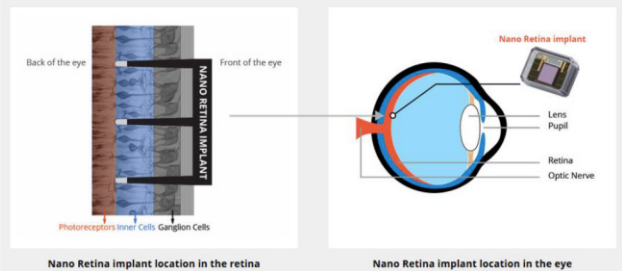
- ✓ 32b μ C with RAM/ROM
- ✓ Down to 0.4V, 5nW leakage
- ✓ As low as ~ 15 pJ/operation

Benefits for the users

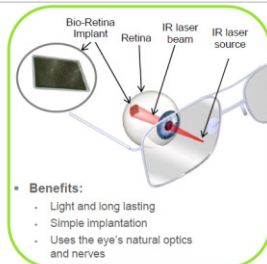
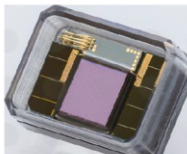
- ✓ High performance controller for zero-power nodes
- ✓ Scalable computing power

Sub-threshold design - Analog

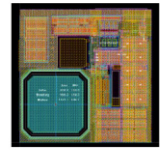
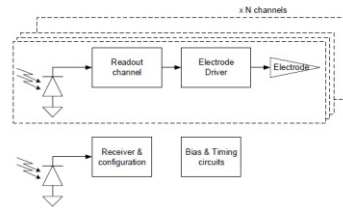
Battery-less implant [11]



Module and remote power



Weak inversion retina ASIC - block diagram & pixel layout [12]

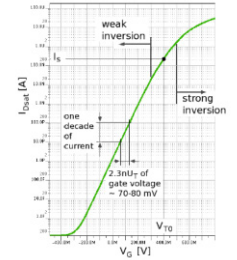


Using CMOS in weak Inversion

- To reach 100nA range of total IC power consumption:
 - All the functions of the retina built with MOS in weak inversion
 - All voltages scaled to in terms of $nU_T \sim 32$ mV
 - One decade of current corresponds to a gate voltage increase of $nU_T \ln(10) = 2.3 nU_T$

$$I_{Dsat} = I_s \exp\left(\frac{V_G - V_{T0}}{nU_T}\right)$$

$$U_T = \frac{kT}{q} = 26.7 \text{ mV at } T = 37^\circ\text{C}$$



IV. ULP IoT CONNECTIVITY

What about IoT?

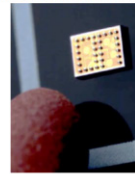
... is growing fastly (remember the ITRS Sensor roadmap)

... the sub-threshold activity (targeting IoT) becomes increasingly attractive

Amiqmicro, MIE Fujitsu Semiconductor with CSEM etc.

a 5mW Bluetooth Low Energy Transceiver

- The first **true 1V BT 5 LE silicon IP**, functional down to 0.9V



- Following the ULP design - watch microelectronics philosophy
- Toward today's connected objects and future IoT nodes

V. CONCLUSION

- **50 years of the Swiss "Quest for the Holy Grail" in ULP** wearable electronics, based on the **low-voltage, weak inversion and sub-threshold**
- From **the world's first electronic quartz wristwatch BETA 1** until today, several generations of researchers have built & evolved micro-power design techniques:
 - from 10 μ m to 28nm semiconductor process
 - from bipolar logic to RF CMOS
 - from 100 transistor LSI to multi million transistor SoCs
- Heading toward autonomous, **batteryless IoT objects of tomorrow.**

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