The elusive Smart Dust: the way forward

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Cnam Paris

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future networks

Smart Dust turns 20

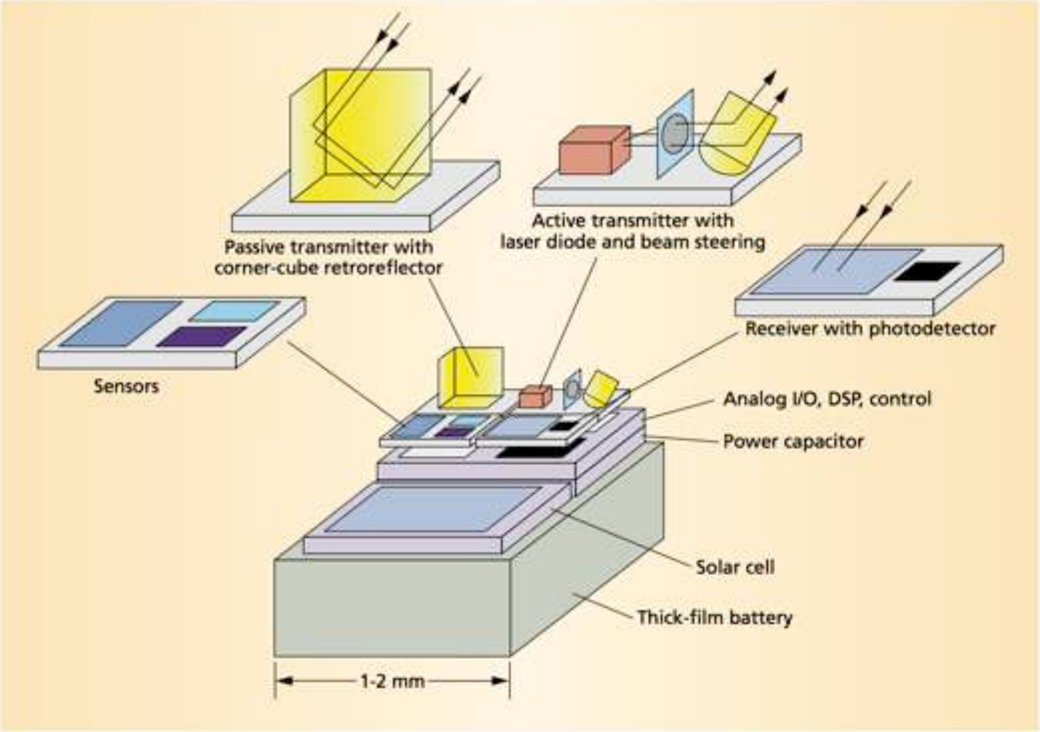

COVER FEATURE

Smart Dust: Communicating with a Cubic-Millimeter Computer

The Smart Dust project is probing microfabrication technology's limitations to determine whether an autonomous sensing, computing, and communication system can be packed into a cubic-millimeter mote to form the basis of integrated, massively distributed sensor networks.

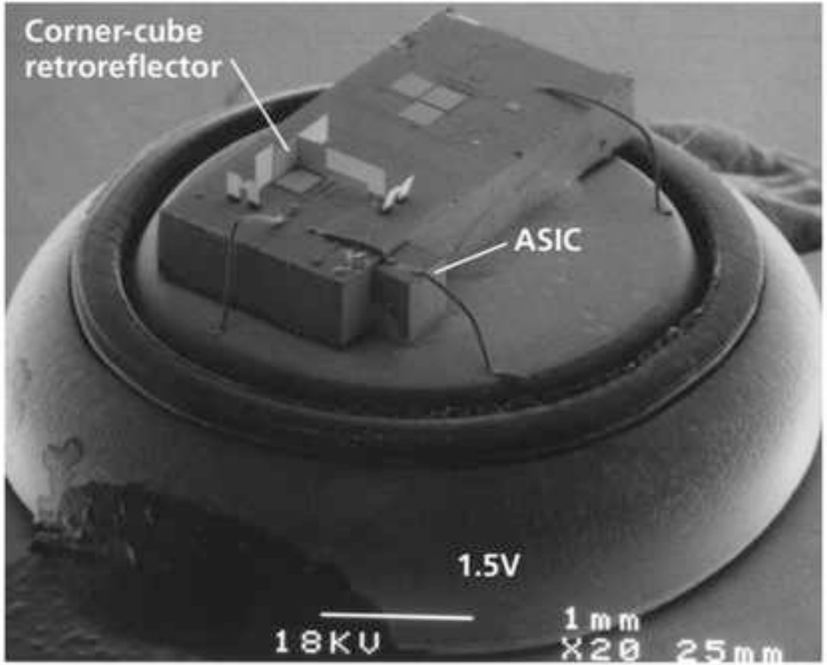
Brett Warneke
Matt Last
Brian Liebowitz
Kristofer S.J. Pister

SMART DUST REQUIREMENTS

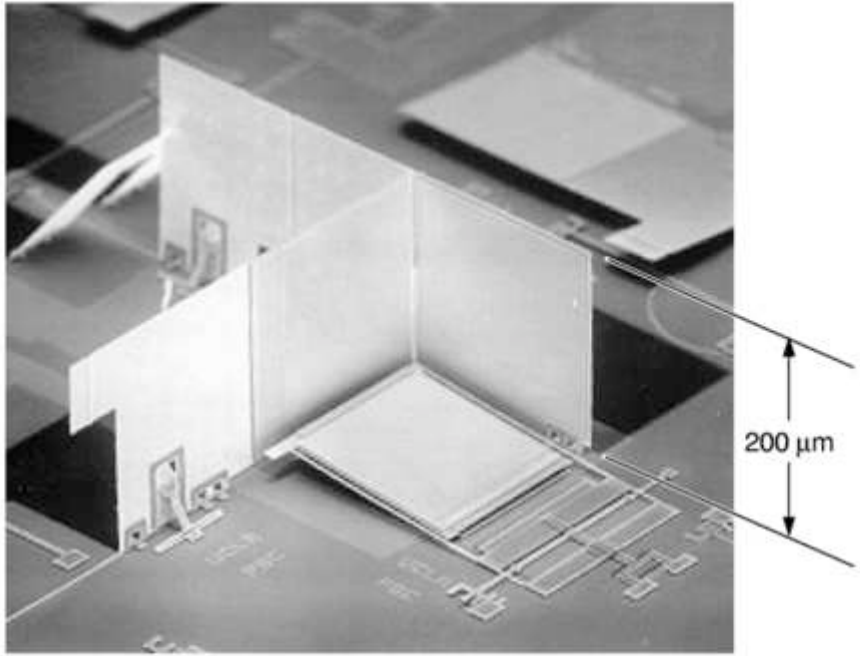


[Warneke2001]

Actual 1999 prototype



[Warneke01]



[Chu97]

Agenda

Silicon roadmap

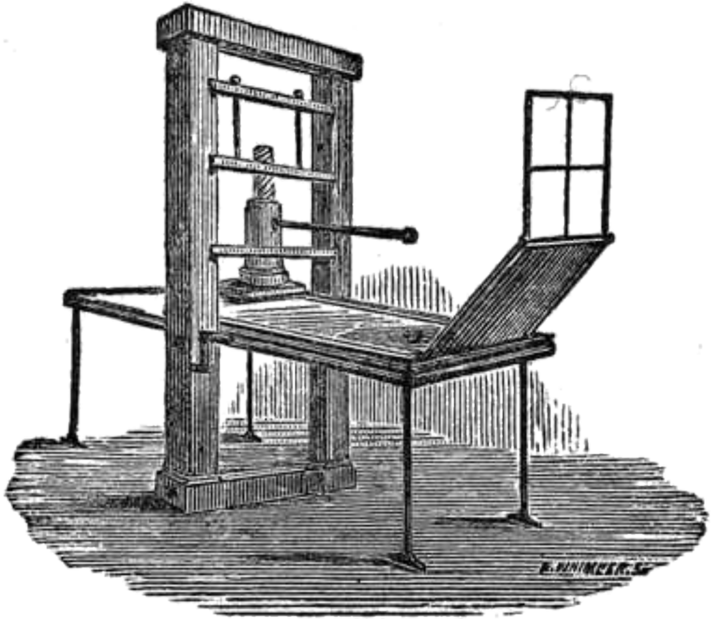
Power source

Computation

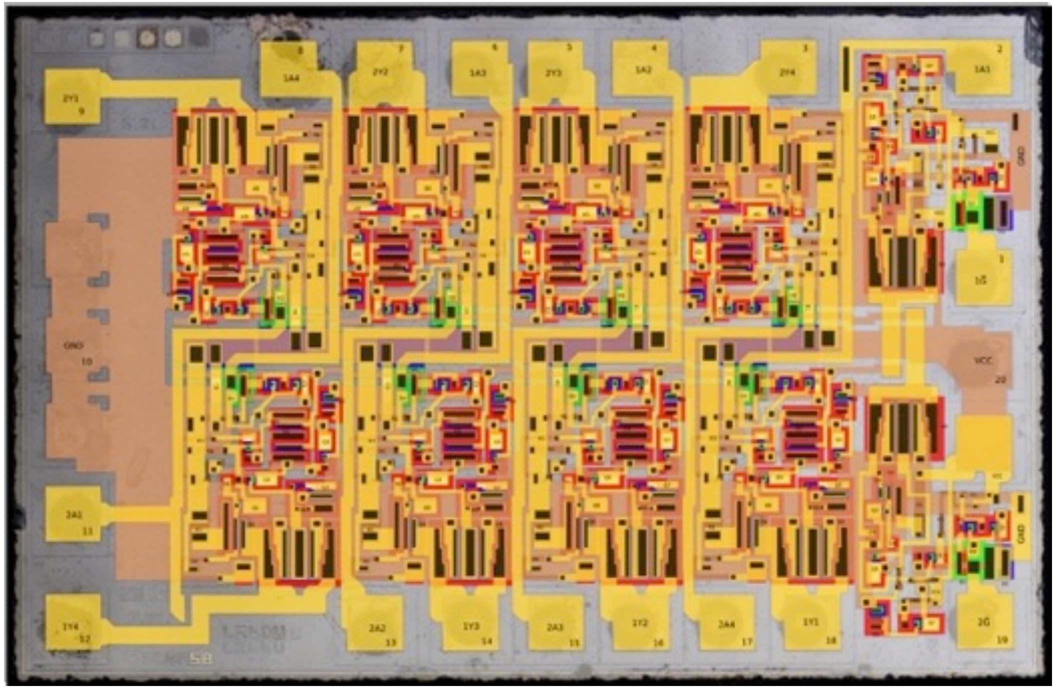
Communication

Integration

Planar manufacturing



Planar semiconductors



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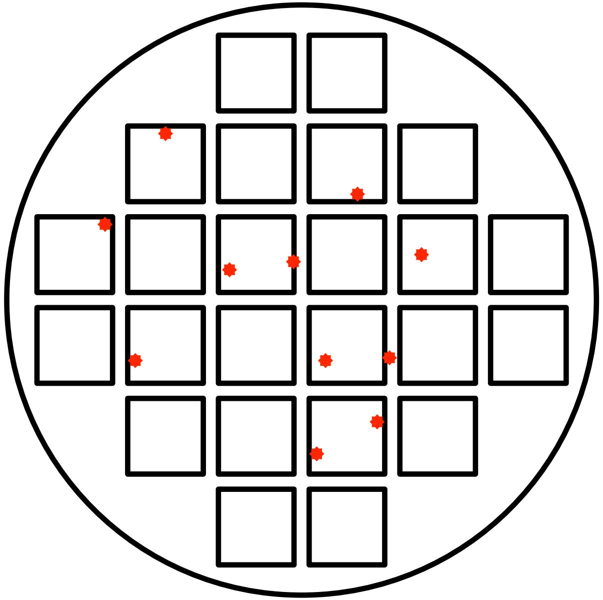
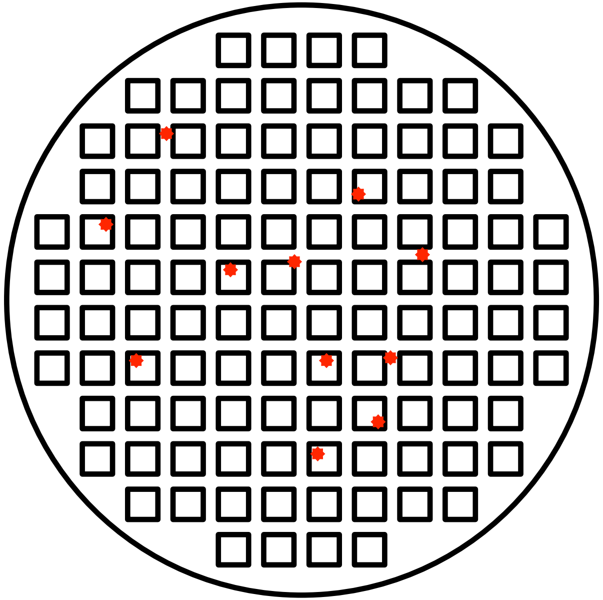
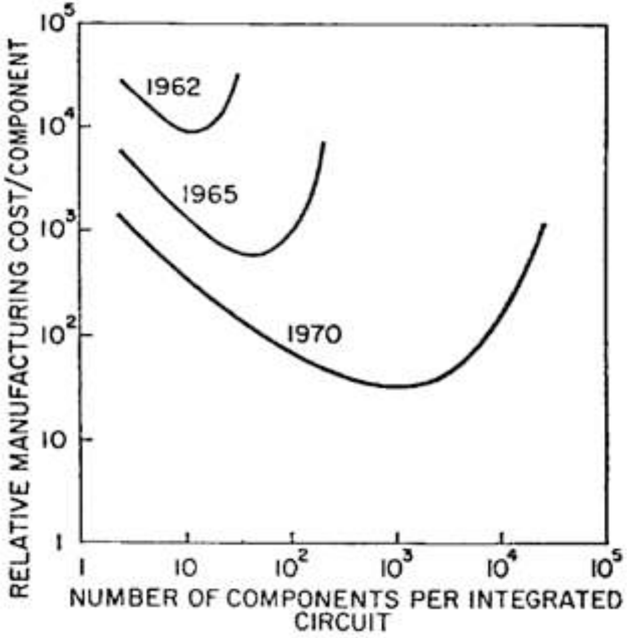
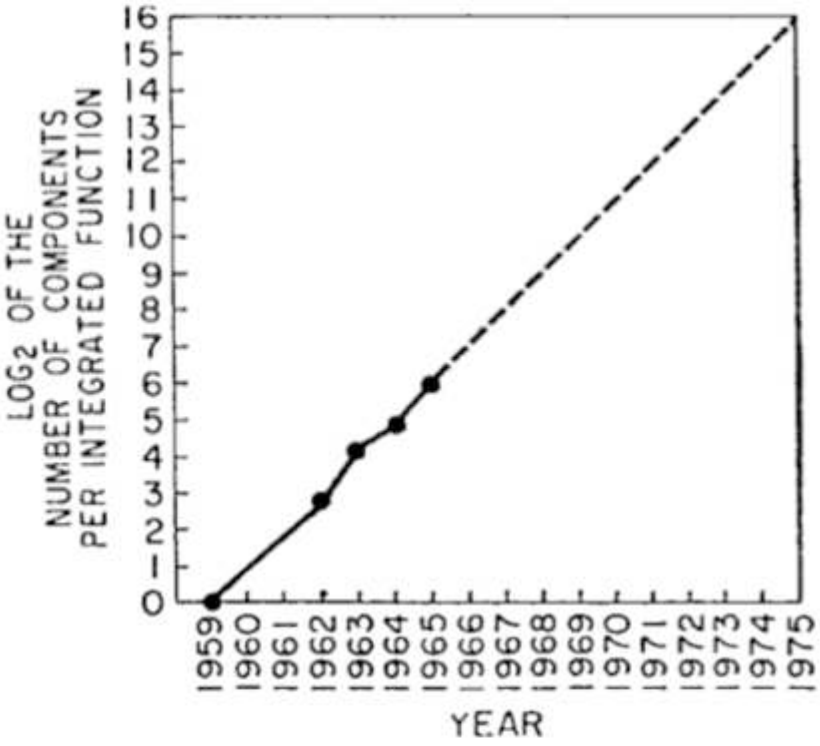
Silicon real estate





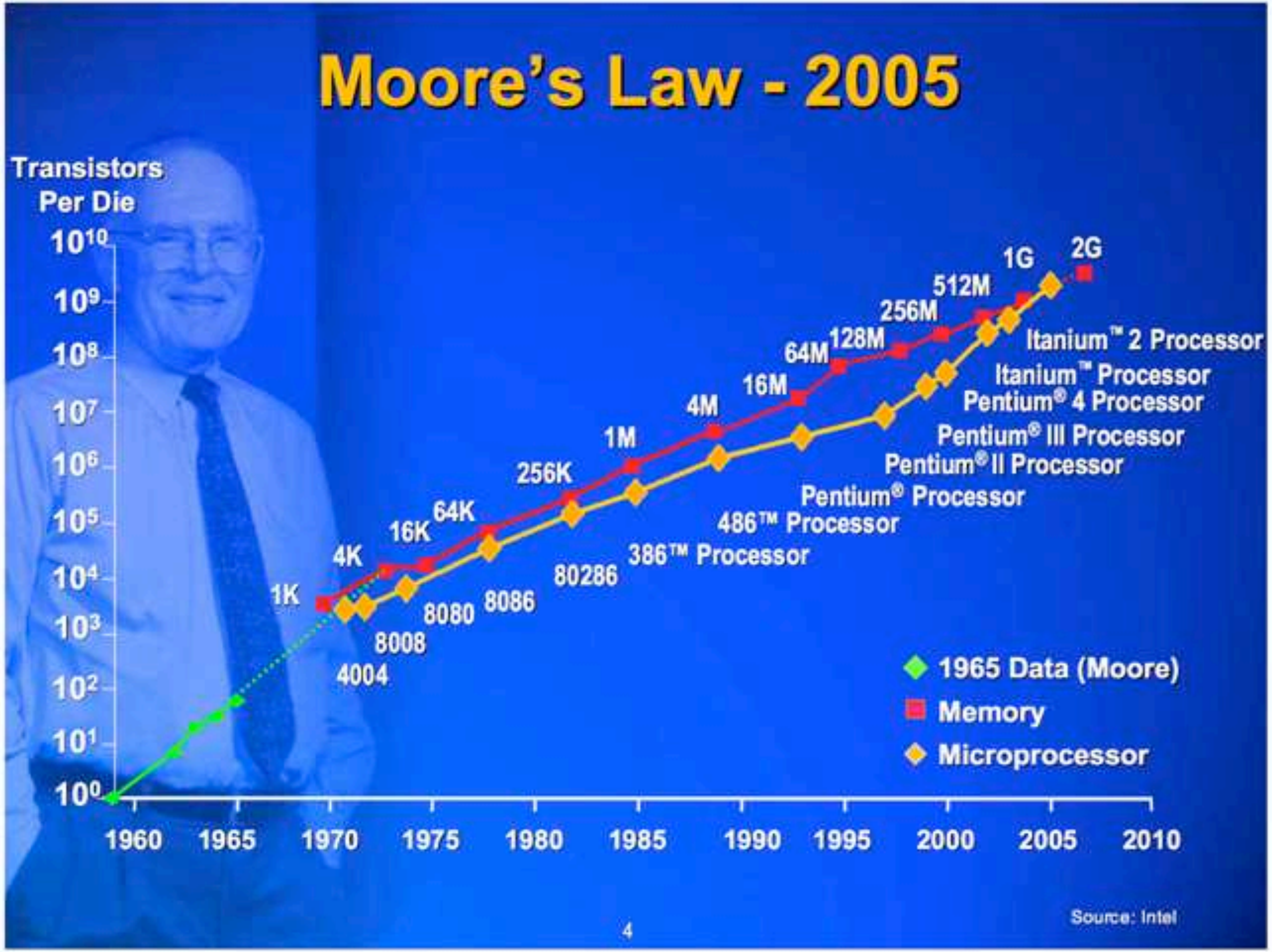
Moore's law





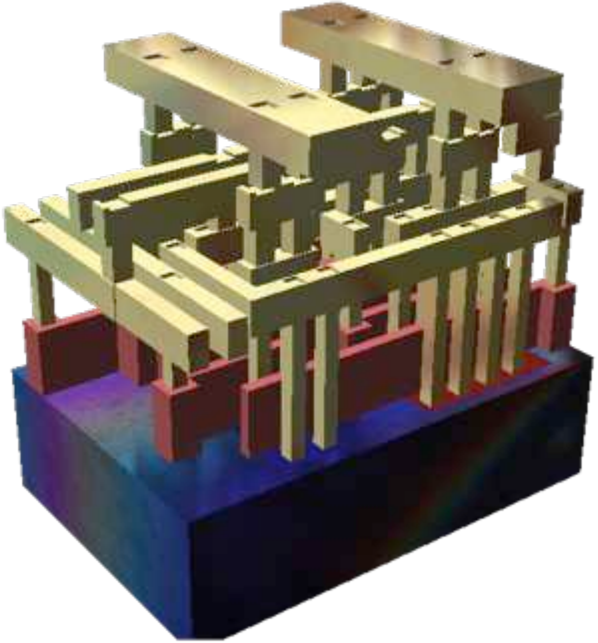
[Moore65]

Moore’s law

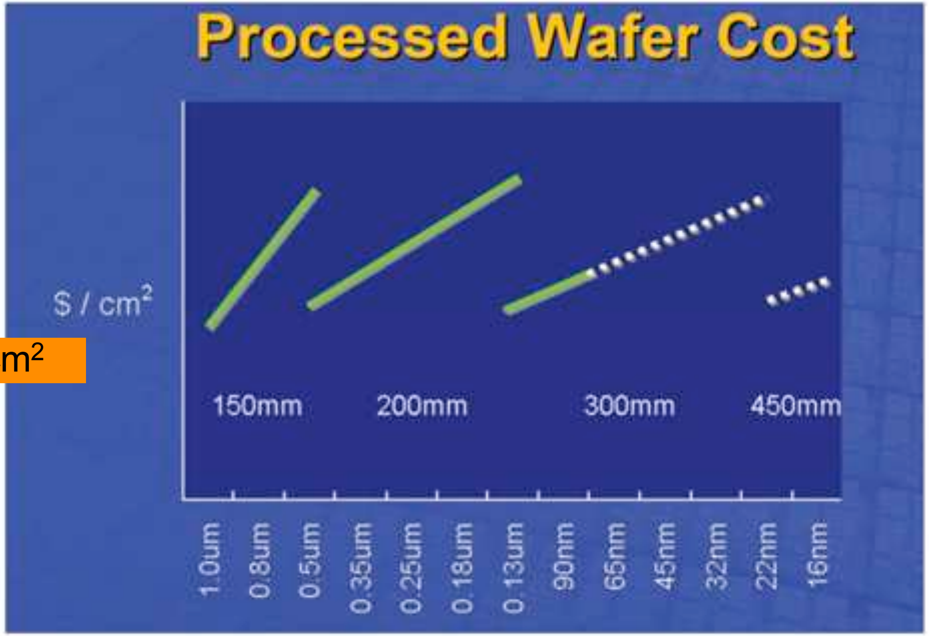


[Holt05]

Silicon economics

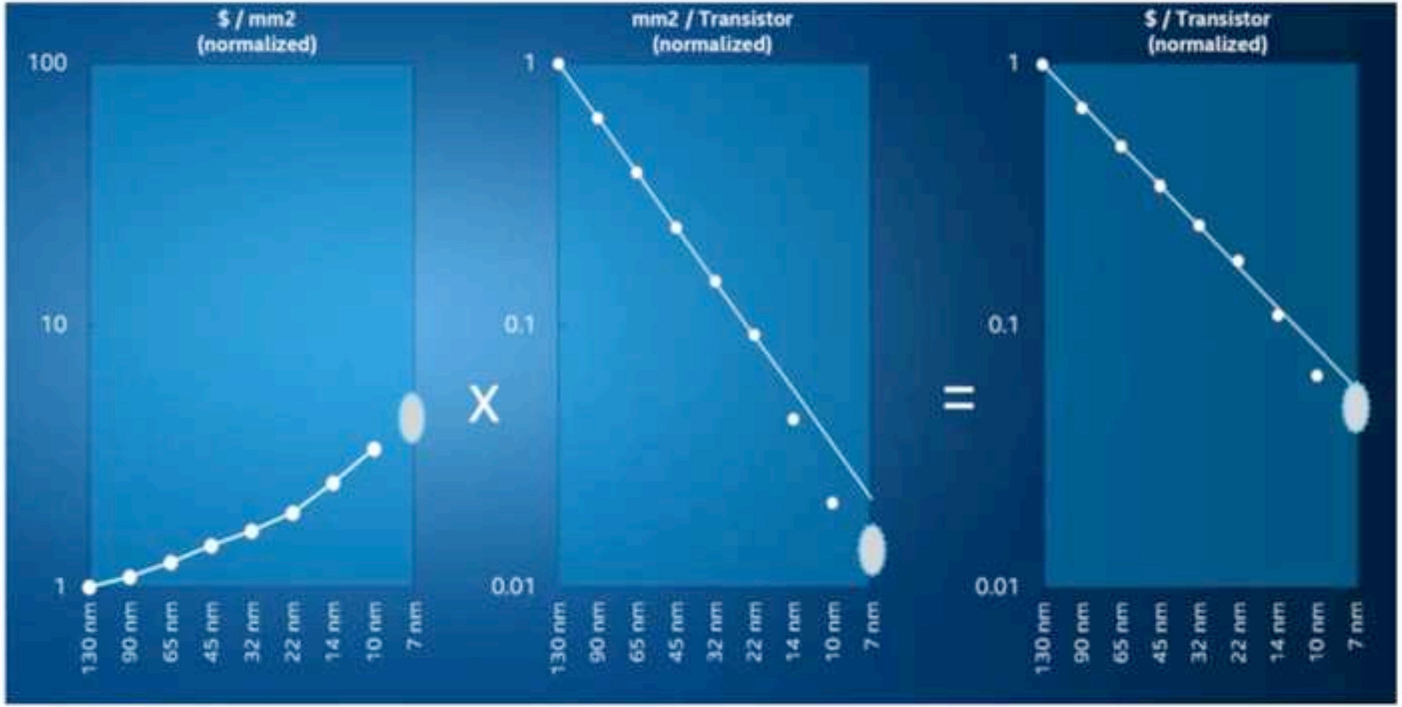


$\$1/cm^2$



[Holt05]

Ride Moore's law!



[Holt15]

Silicon roadmap

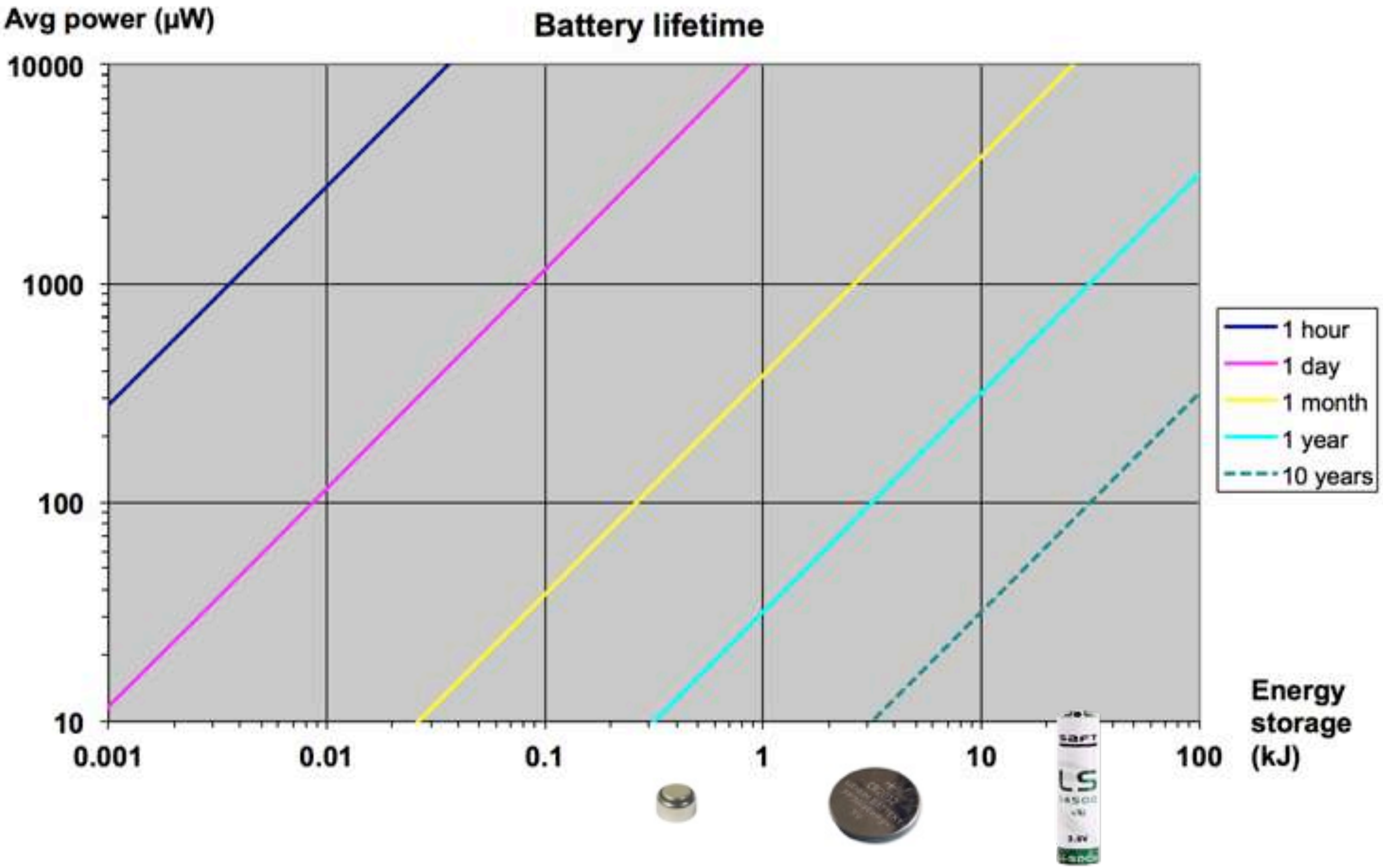
Power source

Computation

Communication

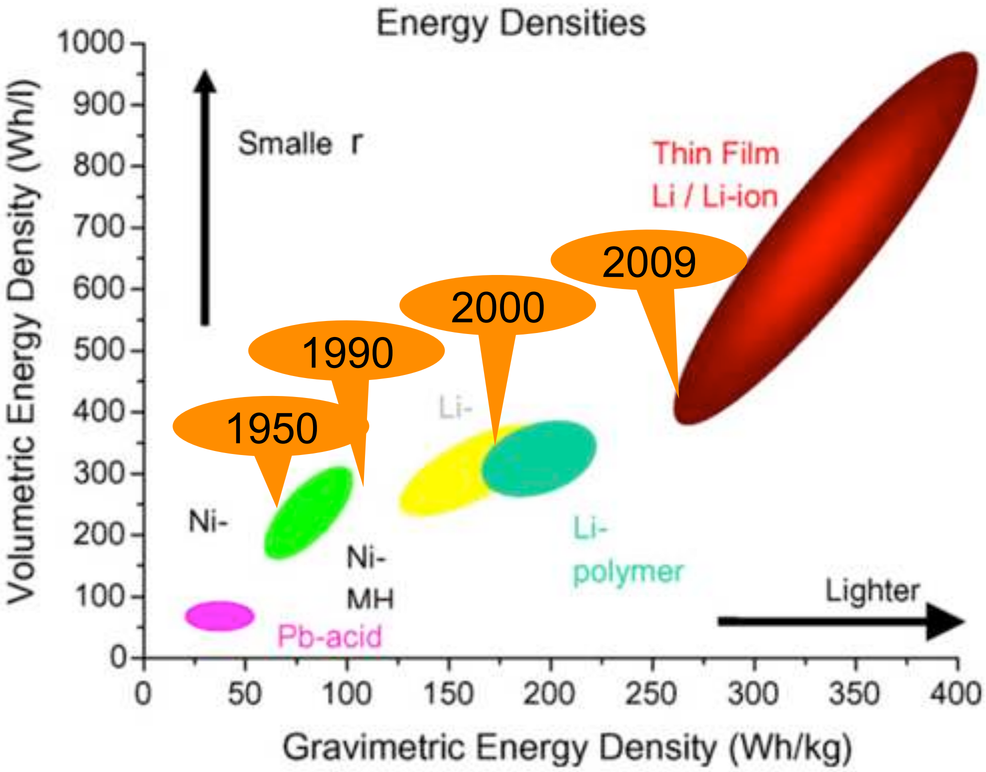
Integration

Power budget



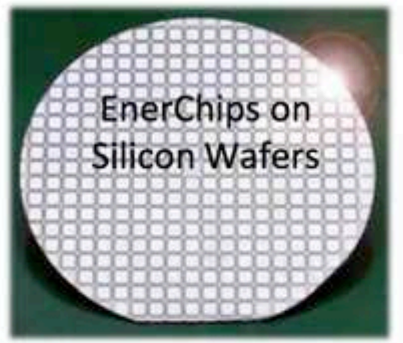
Battery performance over time

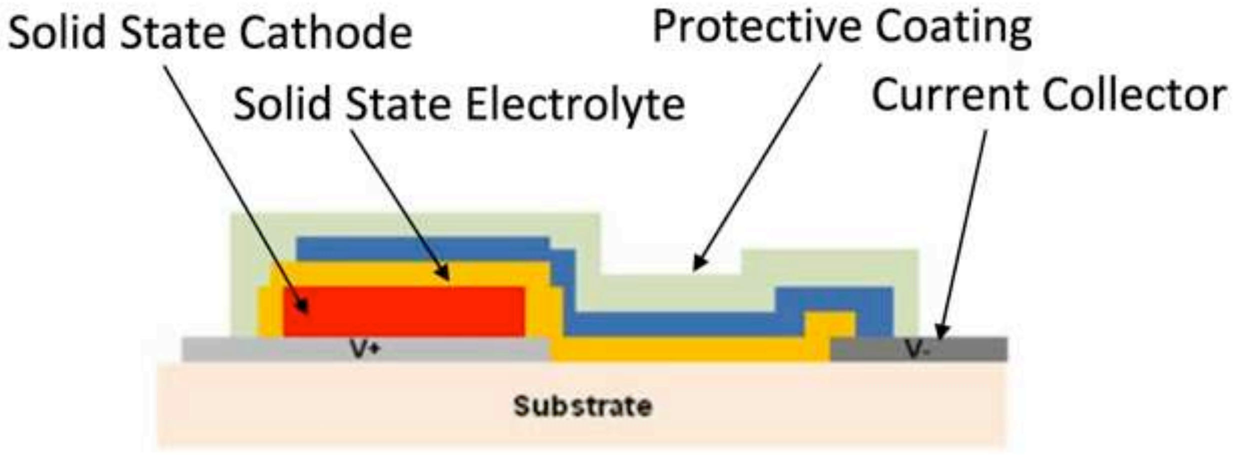
Over 1990 – 2010,
performance has approx. doubled



[Patil08]

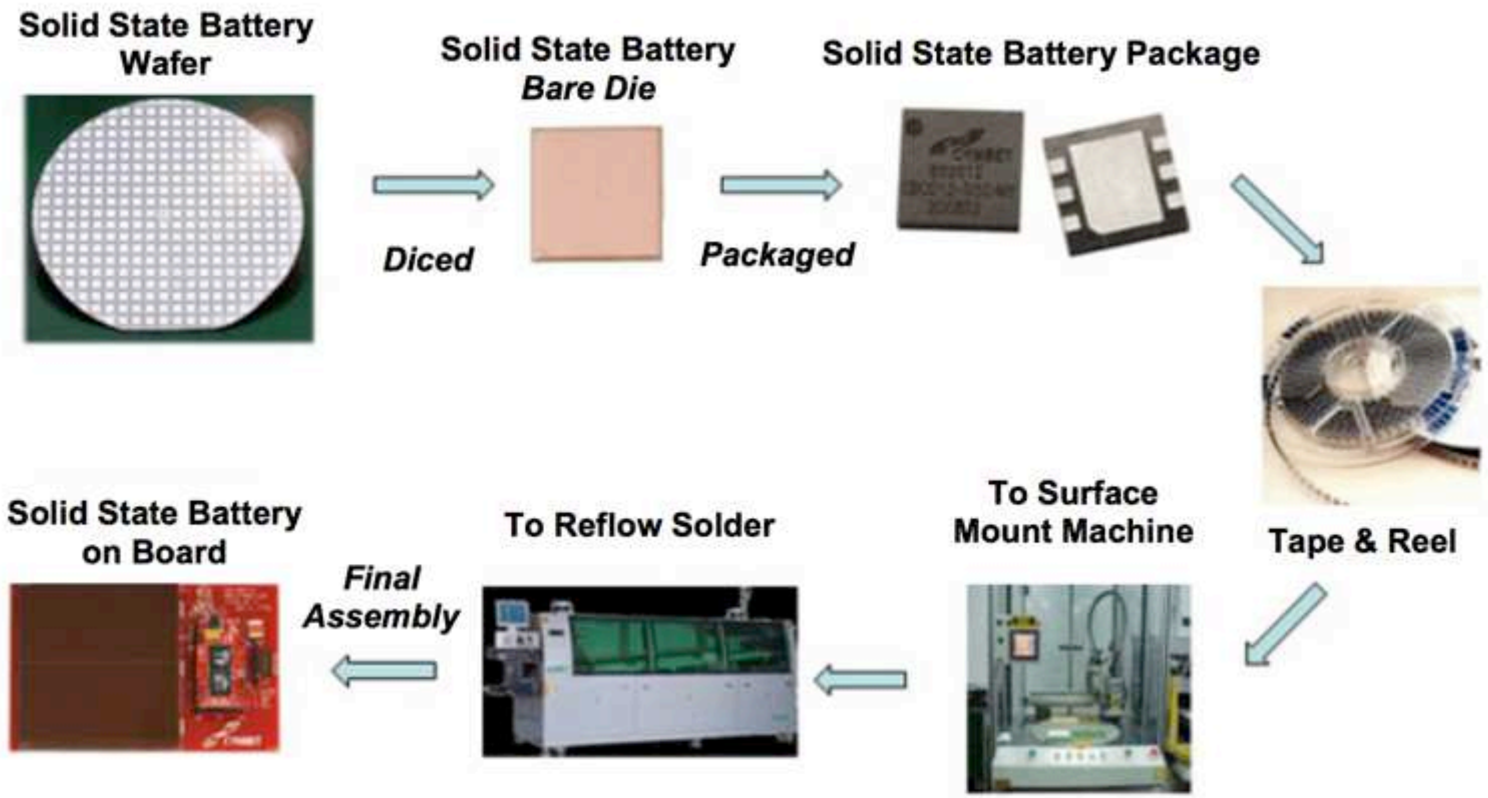
Thin Film Li batteries can be built on silicon die





[Cymbet13]

Battery chips used as any other silicon chips



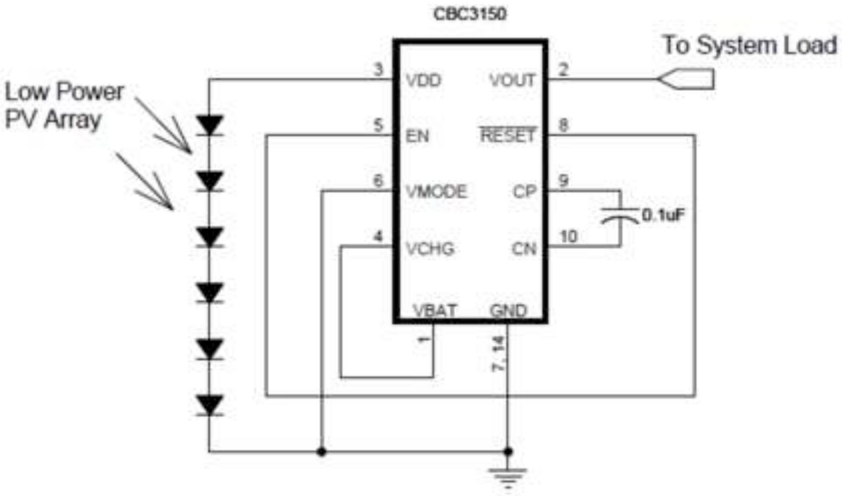
[Grady14]

Battery chip can be integrated with other dice in one package

[Cymbet13]

CBC3150

- 0.2 J, 1 kohm
- 3.3 V, 10 uA typ output current
- 2.5 – 5.5 V input
- $3



Solar energy harvesting

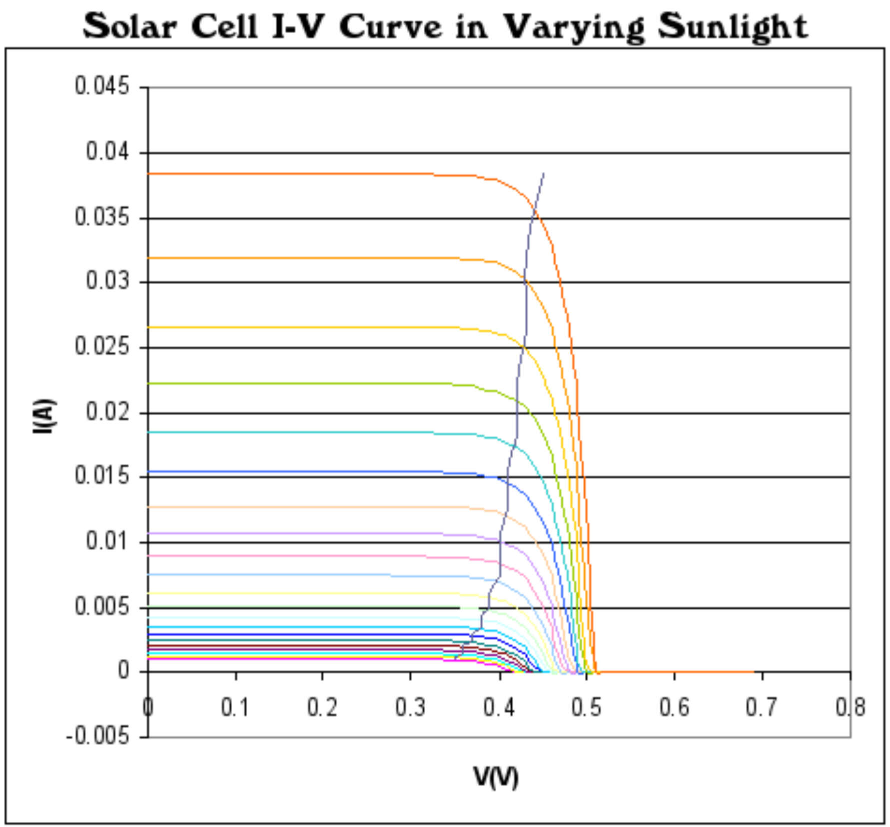
Power available

- 1 – 10 mW / cm^2 outdoor
- 10 – 100 uW indoor daylight

Photovoltaic cell efficiency

- Silicon : 12-18%
- Organic : 8-10%
  – perovskites: 20%
- Research: 40%

Max Power Point tracking



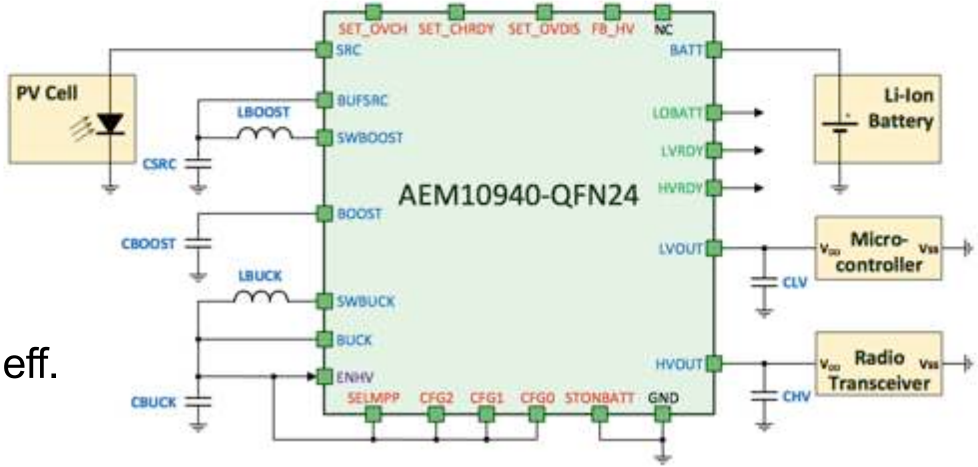
Energy harvester chip

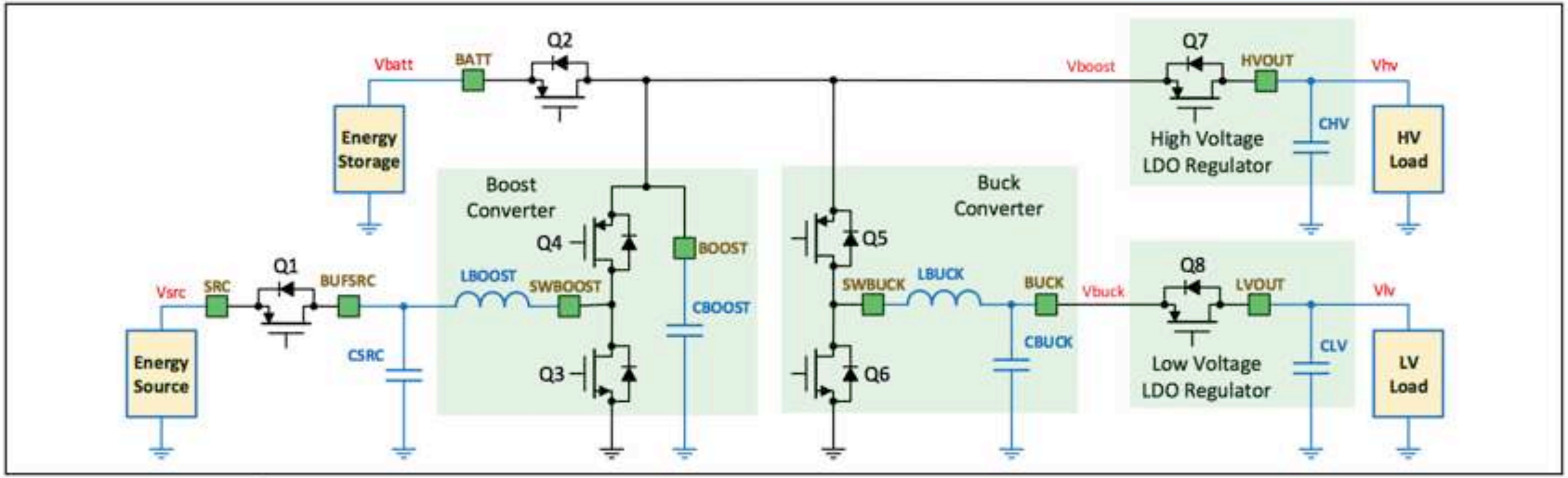
Deals with variable source

- voltage, power: MPP Tracking

Example : AEM10940 (2016)

- Cold start at 0.38 V and 11 uW source
- Sustained operation at 0.1 V source, 40% eff.
- 500 mW output





Vibration energy harvesting

Piezoelectric converters	Electromagnetic converters	Electrostatic converters
Use of piezoelectric materials	Use of Lenz's law	Use of a variable capacitor structure

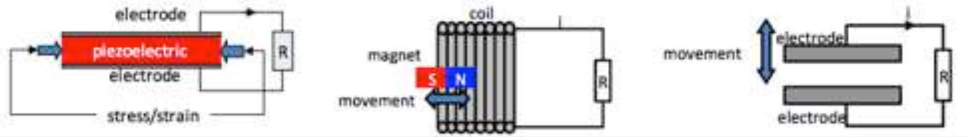


Table 5. Electret-free electrostatic vibration energy harvesters from the state of the art

Author	Ref	Output power	Surface	Volume	Polarization voltage	Vibrations
Tashiro	[19]	36 μW		15000 mm^3	45V	1,2G@6Hz
Roundy	[24]	11 μW	100 mm^2	100 mm^3		0.23G@100Hz
Mitcheson	[25]	24 μW	784 mm^2	1568 mm^3	2300 V	0.4G@10Hz
Yen	[26]	1,8 μW	4356 mm^2	21780 mm^3	6 V	1560Hz
Despesse	[21]	1050 μW	1800 mm^2	18000 mm^3	3 V	0.3G@50Hz
Hoffmann	[23]	3.5 μW	30 mm^2		50 V	13G@1300-1500Hz
Basset	[22]	61nW[1]	66 mm^2	61.49mm^3	8 V	0.25G@250Hz

$C = \varepsilon.S/d$; $Q = CV$; $dE = V.dQ$

[Boisseau12]

Silicon roadmap

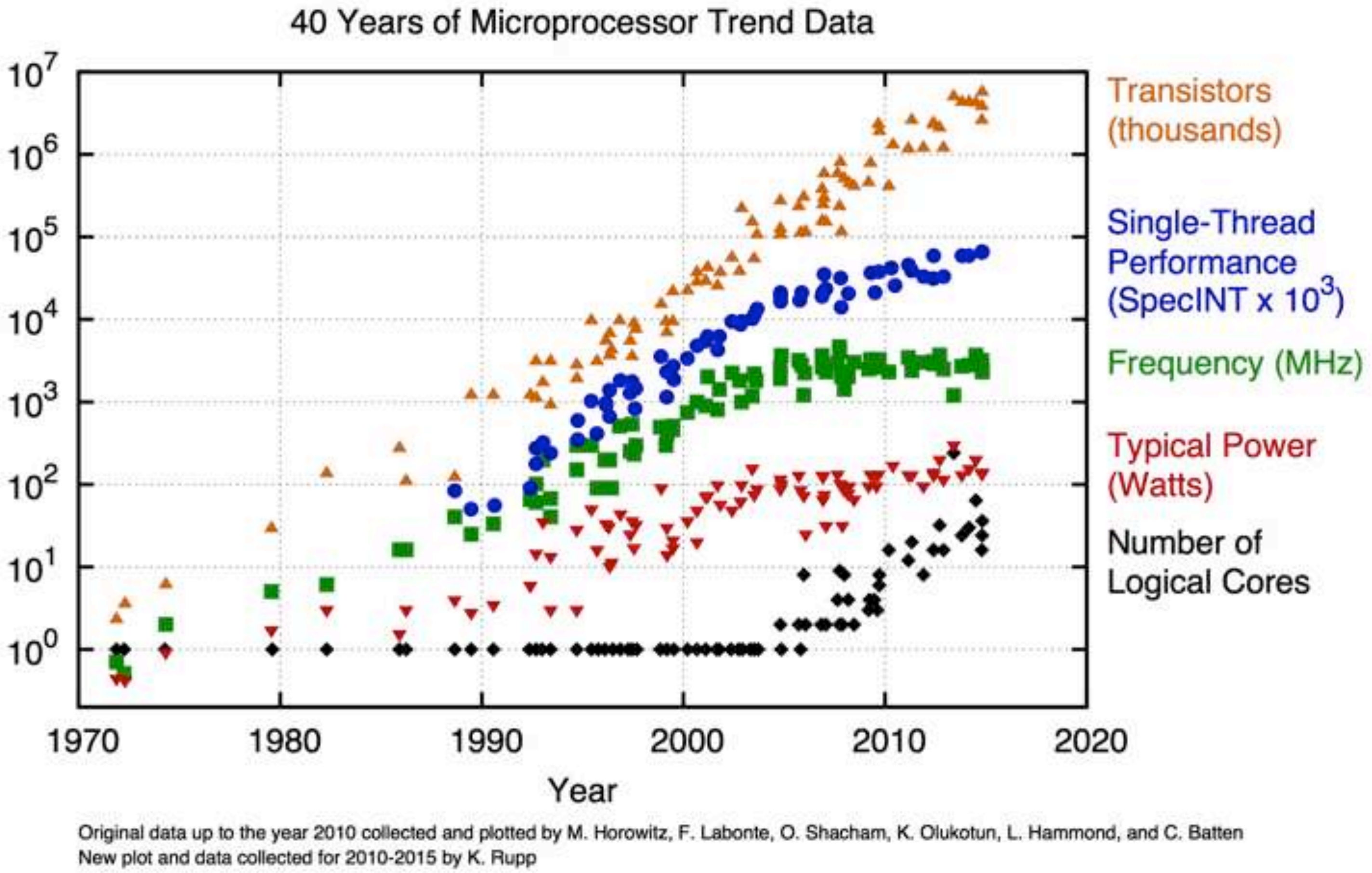
Power source

Computation

Communication

Integration

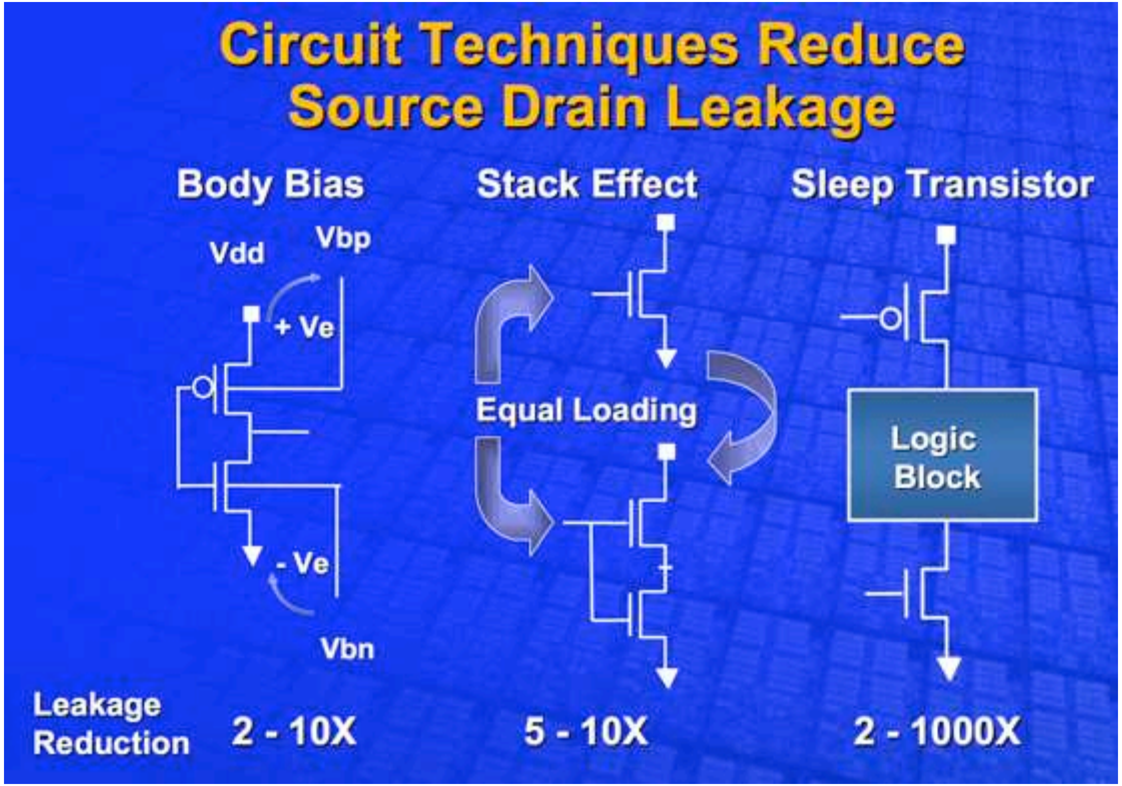
Microprocessor history



[Rupp15]

Techniques for low power computing

- Silicon technology
- Clock gating
- Power gating
- Multiple power domains
- Dedicated hardware functions
- Circuit design



[Holt05]

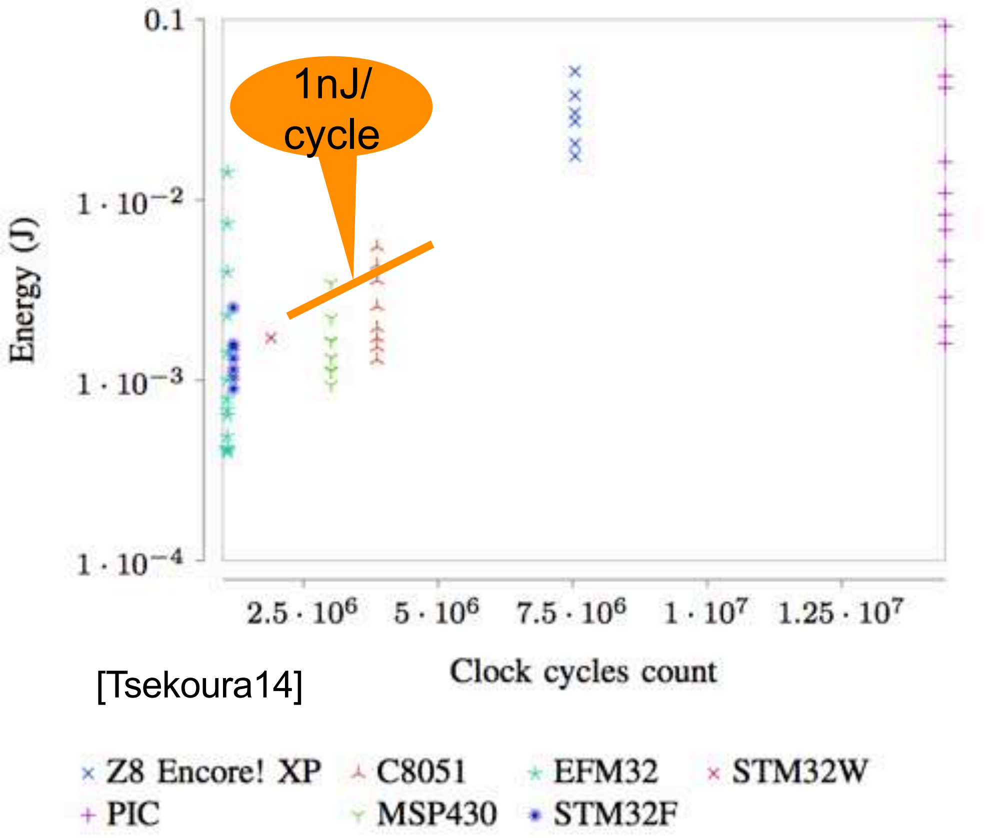
Energy cost of computation (energy efficient micro-controllers)

Energy-efficient processors

- ~ 1 nJ per instruction

Hardwired-logic

- ~ 10 pJ per 8 bit ALU operation



[Tsekoura14]

Silicon roadmap

Power source

Computation

Communication

Integration

RF communication, radio chip

	Band	Std	Rx current	Sensitivity	Tx current @ 0dBm
TR1001	868 MHz	OOK, ASK	2 – 4 mA	~ -100 dBm	12 mA @ +1.5dBm
CC1021 (2003)	868 MHz	FSK, GSK, OOK	18 mA	~ -110 dBm	22 mA
CC1201 (2013)	868 MHz	FSK, GSK, MSK, OOK	19 – 23 mA	~ -115 dBm	28 mA
MC13192 (2003)	2.4 GHz	IEEE 802.15.4	37 mA	-92 dBm	34 mA
CC2538 (2012)	2.4 GHz	IEEE 802.15.4	20 mA	-97 dBm	24 mA
LTC5800 (2013)	2.4 GHz	IEEE 802.15.4	4.6 mA	-93 dBm	5.5 mA

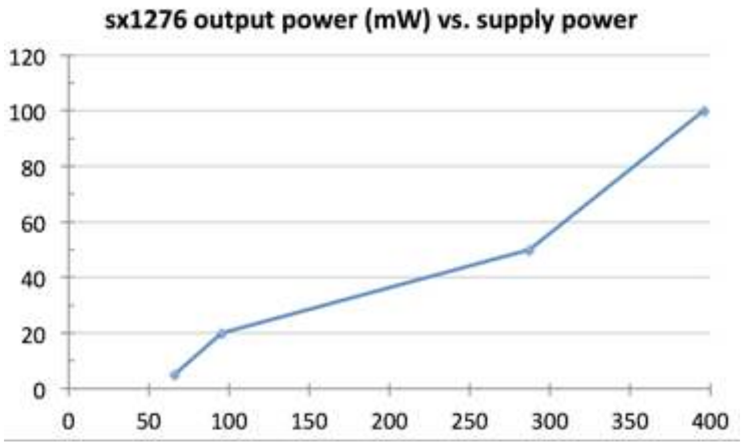
Duty-cycling these radios is mandatory. 100 – 250 nJ/bit at highest datarate.

LoRa radio chip

	Band	Std	Rx current	Sensitivity	Tx current @ 0dBm
SX1276	868 MHz	FSK, LoRa	11 mA	-136/-118 dBm @ 125kHz BW	20 mA @ +7 dBm

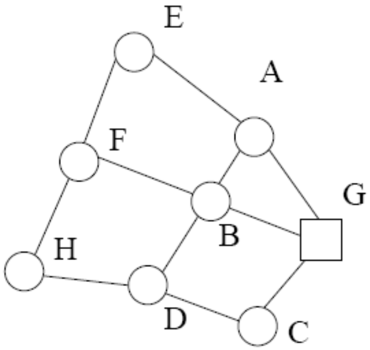
Receive
- Current consumed independent of Spreading Factor
- Energy per bit inversely proportional to Data Rate
- 3 – 100 uJ/bit for 125 kHz BW SF 7 – 12

Transmit
- Current consumed independent of SF, dependent of Tx power
- Energy per bit dependent on Data Rate and Tx power
- (7 .. 200) – (42 .. 1300) uJ/bit
  for SF 7 ..12, Tx power +7 – +20 dBm



Slow modulation is good for coverage, bad for energy expenditure

Schedule-based medium access



TDMA access provides inherent duty-cycling

Communication slots allocated based on flows requirements

Requires network-wide synchronisation

Multiple frequency channels used in same network

Rotating logical to frequency channel mapping

Example IEEE 802.15.4 TSCH

Synchronization provided by beacons and ACKs

Minimum comm. period based on **clock accuracy**

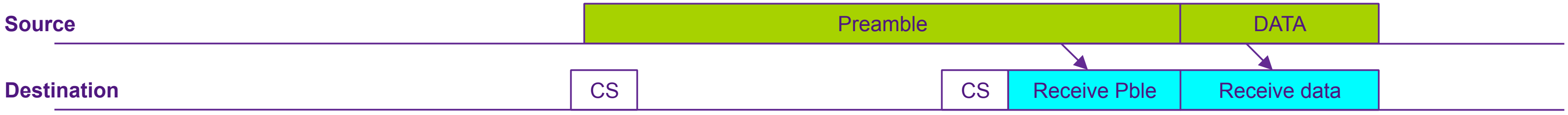
Latency vs. Energy trade-off.

Energy efficient channel sampling still useful.

	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10
ch.15									E->A	
ch.14	A->G			G->C						
ch.13						D->H				
ch.12		F->E					B->A			
ch.11					C->D					F->B
ch.10			G->B							
ch.9										
ch.8	E->F					G->A		B->G		
ch.7				D->B						A->E
ch.6					H->F					
ch.5		D->C					C->G			
ch.4									B->D	
ch.3										
ch.2	H->D					B->F				
ch.1			F->H							
ch.0					A->B					

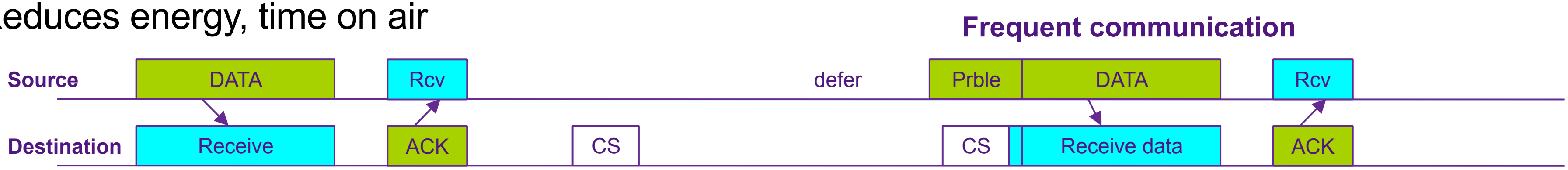
Preamble sampling

Transmitters adapt to receiver sampling period



Transmitters can learn receiver sampling phase

Reduces energy, time on air



Preambule length depends on **clock accuracy** and time elapsed since last communication

Latency vs. Energy trade-off.

Energy-efficient channel sampling is *key* to low power receiver.

Wake-up radios

Less consuming radio

- Can be left receiving continuously
- Latency shorter than sampling/duty-cycling

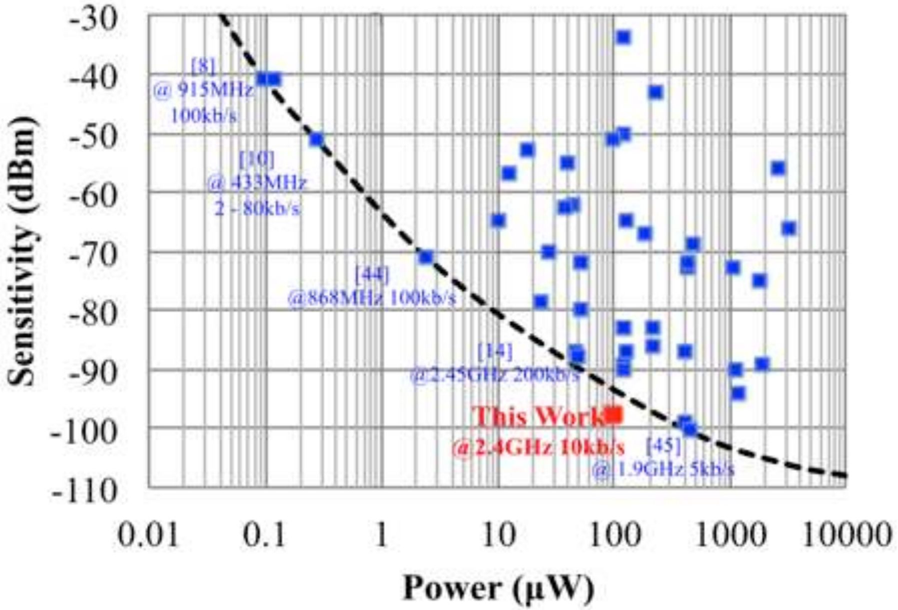
System integration issues

- Lower sensitivity, non-detection
- Interference, false positives
- Separate frequency, different propagation
- Same frequency, collision avoidance

IEEE 802.11ba

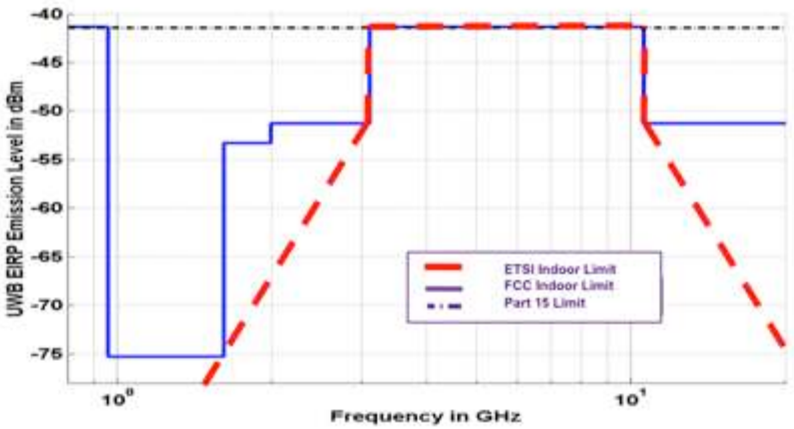
5G wake-up sequence

ANR Wake-Up ANR-17-CE25-0011



[Salazar16]

Ultra-Wide-Band radios (1/2)



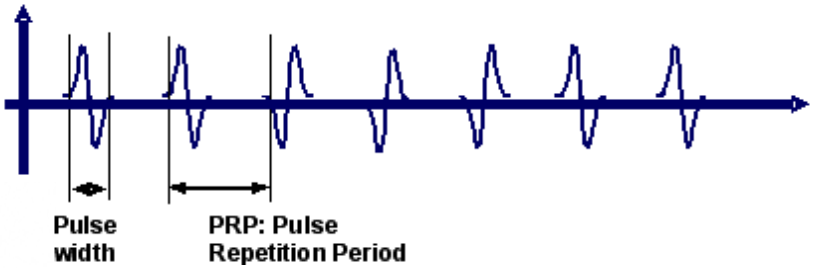
Low power density, wide spectrum

Legalized 2003 in the USA, then RoW

- 3.1 – 10.6 GHz, at -41,3 dBm/MHz max avg and 0 dBm/50 MHz max peak

Can use short pulses

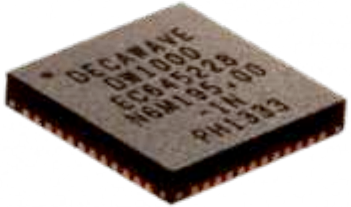
Good opportunity for accurate ranging



Standardized in IEEE 802.15.4a (Rev 2007)

- 110 kbps – 6,8 Mbps, 100 m.

Chips by BeSpoon, Decavawe.

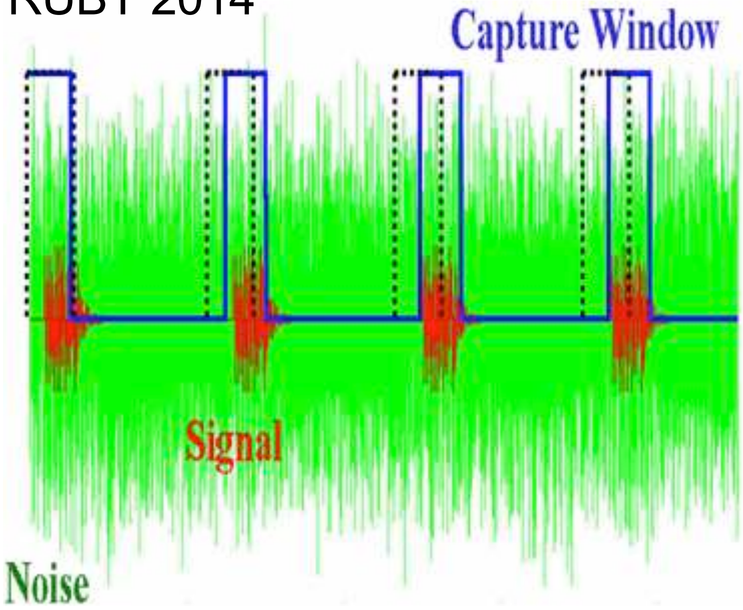


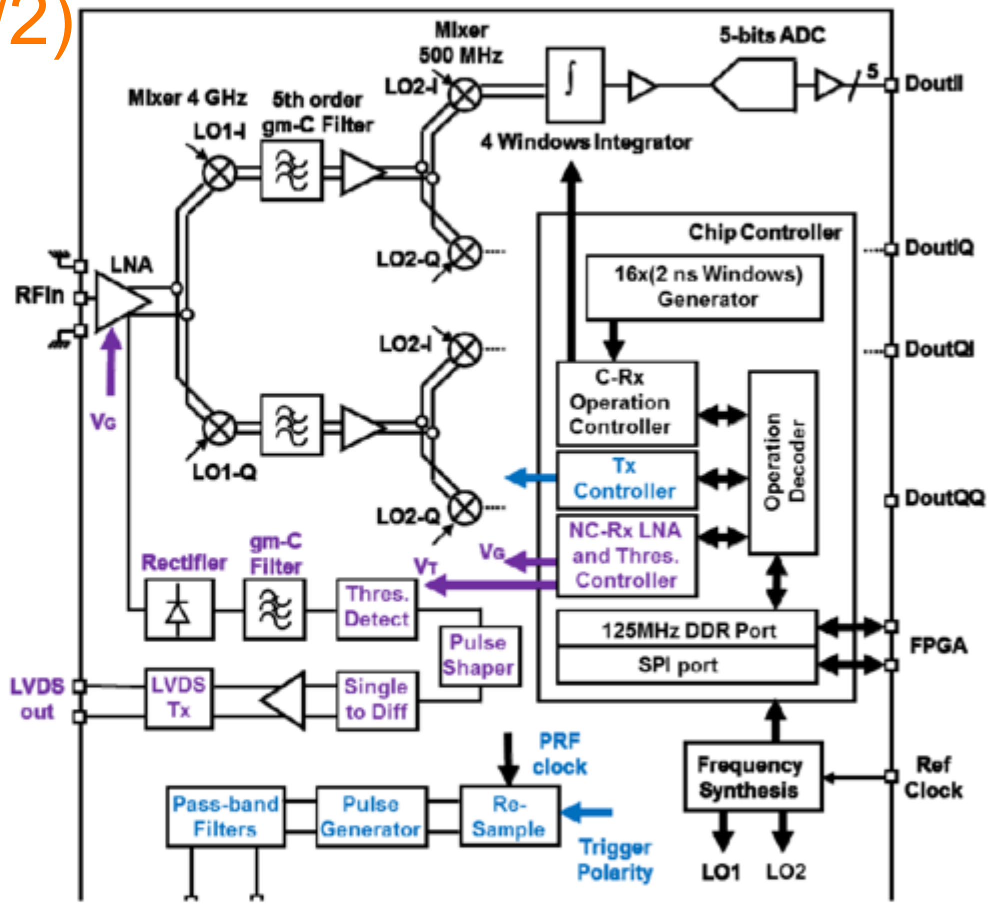
Ultra-Wide-Band radios (2/2)

Also opportunity for ultra-low-power radio

Wideband electronic circuits can be turned on fast.

ANR RUBY 2014



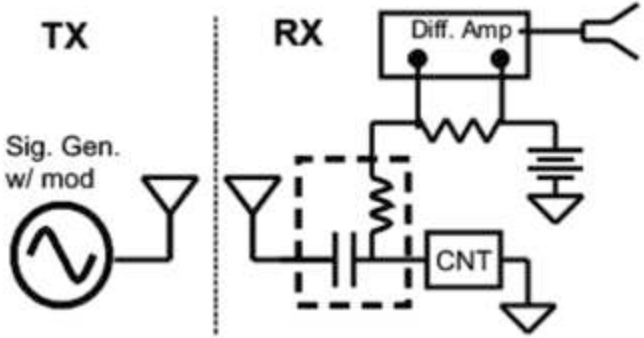


[Ouvry14]

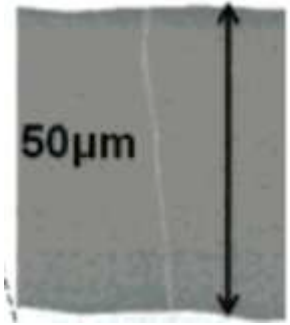
Passive radios (1/2)

Passive *receivers*

- Galena (lead-sulfite) receivers (1894, J. C. Bose)
- Single Carbon Nanotube receivers
- MEMS-based receivers
- Passive mixers



[Rutherglen07]



Passive radios (2/2)

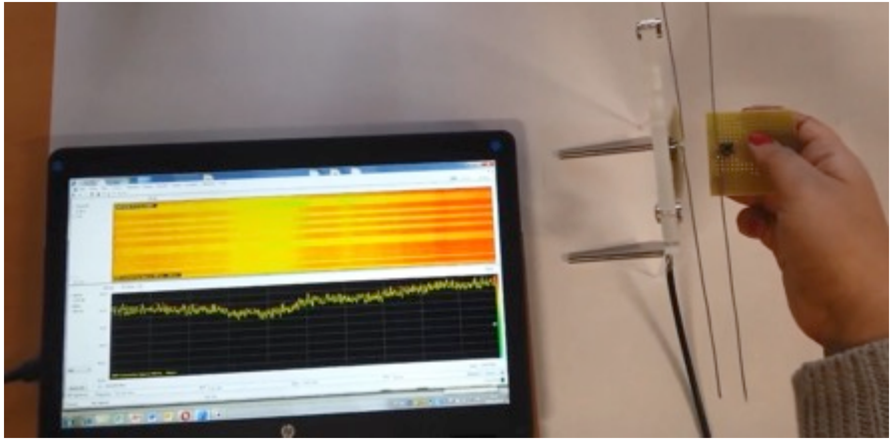
Passive *transmitters*

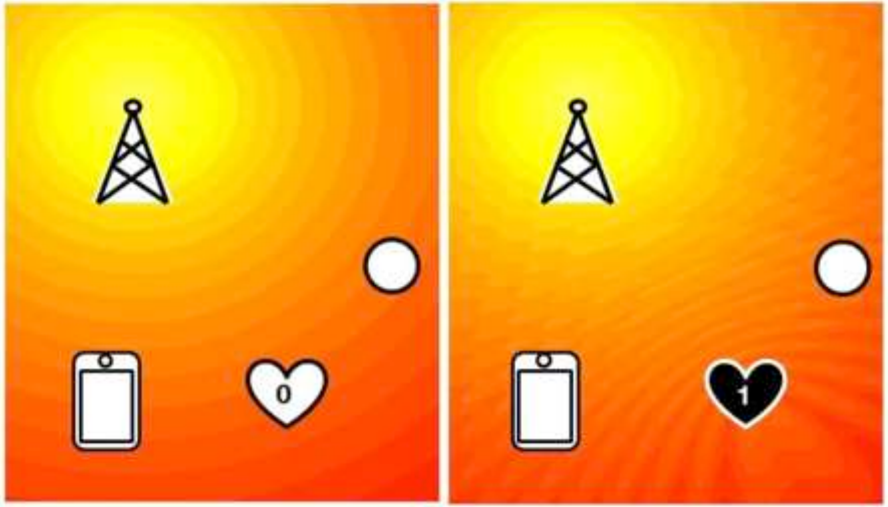
- Passive RFIDs
- Illumination source can be unknowing third party.

ANR project submitted at call 2019

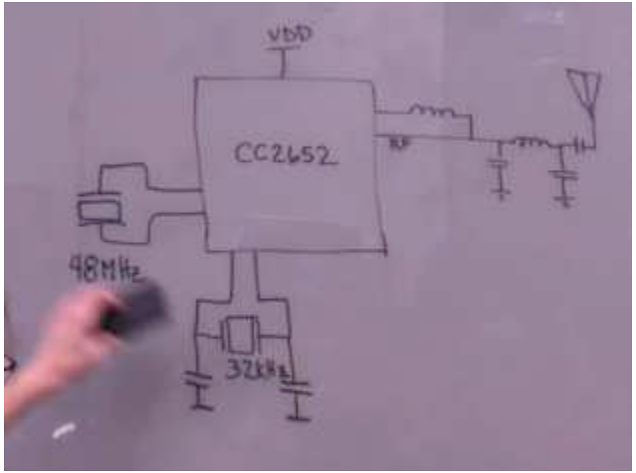
LoRaWAN passive transmitter [Talla17]

- 2.8 km range reported





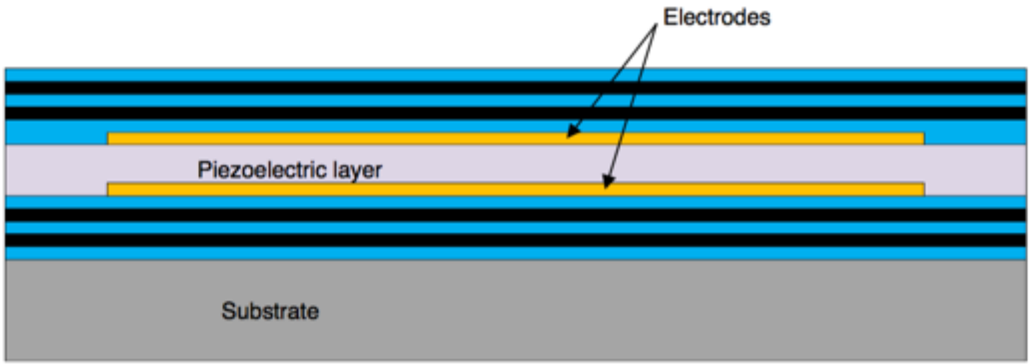
Cheaper radios (1/2)

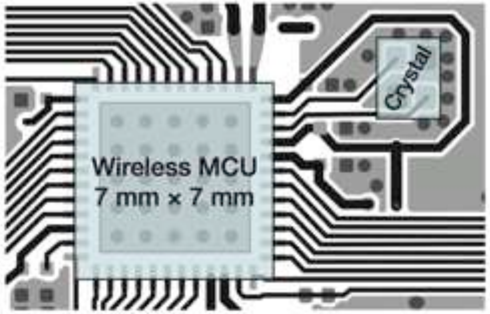


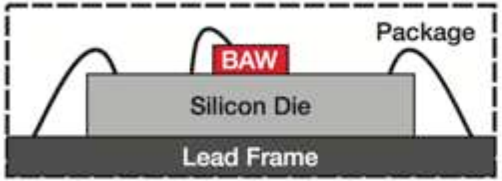
In-package Bulk Acoustic Wave (BAW) resonator.

Feb 27 2019, TI announced the CC2652RB

- Bluetooth and 15.4 radio, Zigbee and Thread stacks
- 48 MHz BAW with
  40 ppm accuracy over whole temp/voltage range







Cheaper radios (2/2)

Crystal-less radio

- E.g. [Wheeler17], LC oscillator
- Needs network-based synchronization

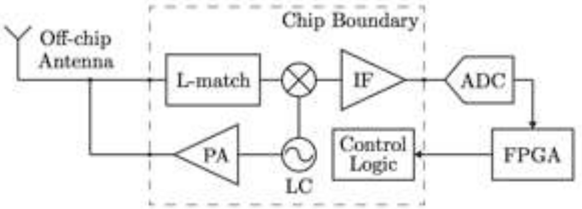


Fig. 1. System level block diagram of the transceiver.

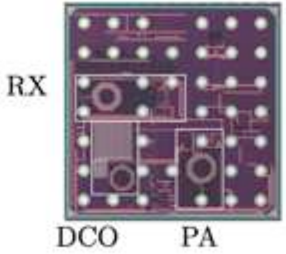
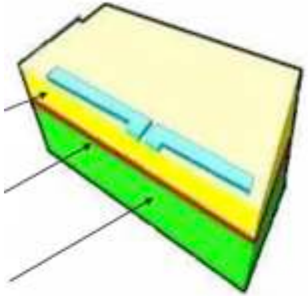
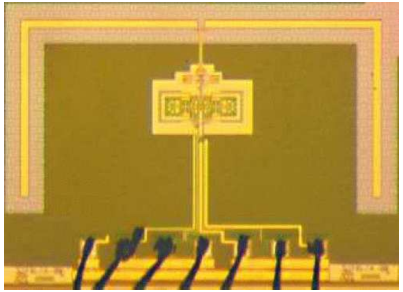


Fig. 2. Die photo of the 1.83 mm * 1.83 mm flip-chip IC, of which the radio occupies 1.2 mm^2.

On-chip antenna

- e.g. [Pons05]
- Deemed viable for frequencies > 10 GHz





Silicon roadmap

Power source

Computation

Communication

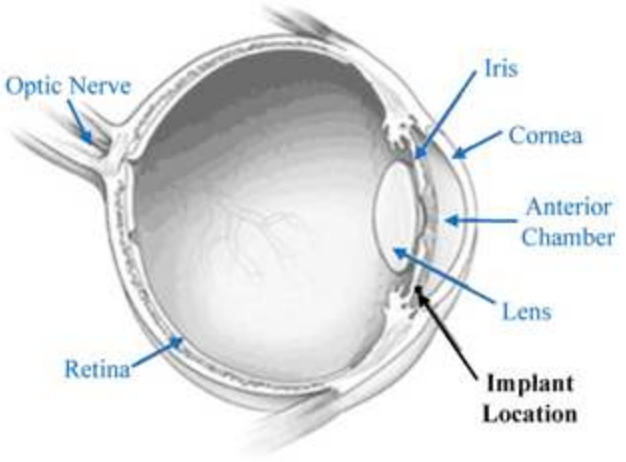
Integration

University of Michigan "Michigan Micro-Mote" (M3)

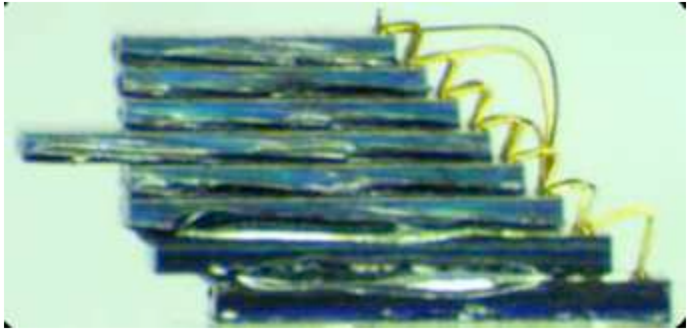
10 years of experience integrating micro-sensors

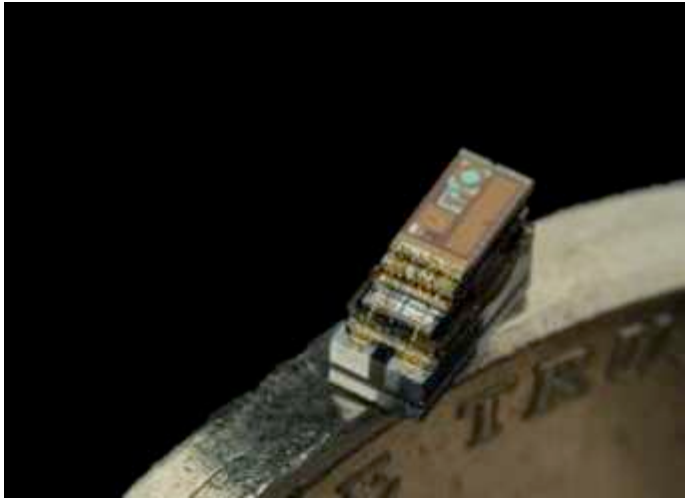
Complete methodology and sub-system library

Many sensors applied to medical use cases



[Ghaed13]



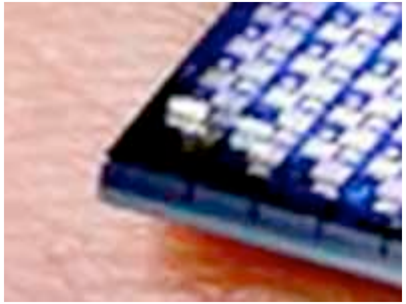


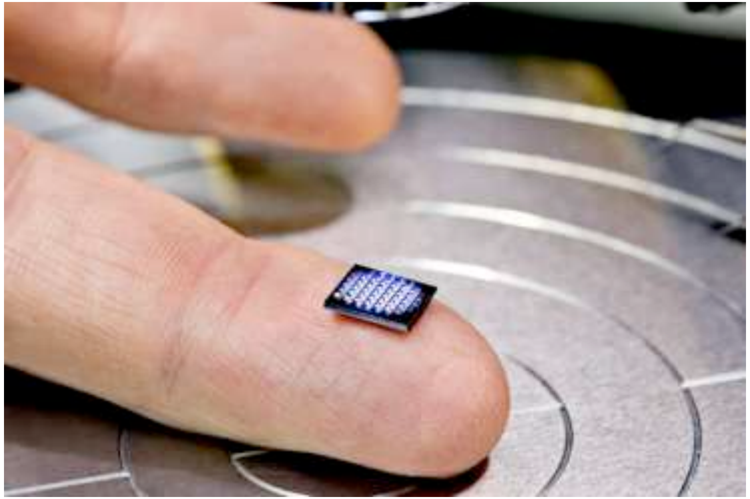
[Pannuto15]

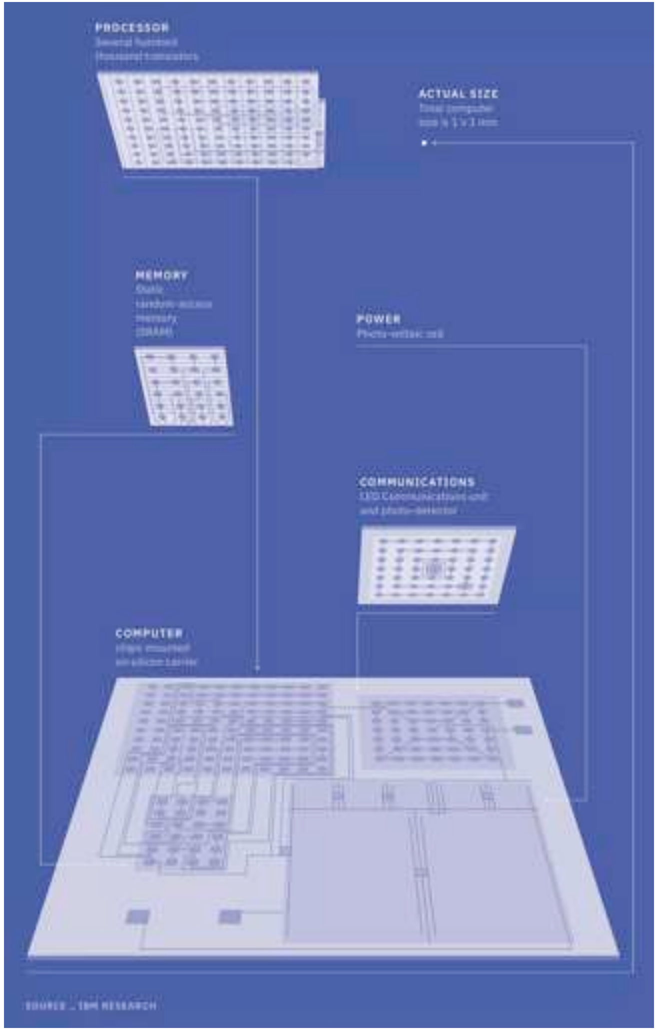
IBM “world’s smallest computer”

Unveiled at IBM Think 2018 conference, March 2018

- 1 mm * 1 mm silicon chip carrier
- CPU several 100 K’s transistors
- Optical communication
- Photovoltaic cell
- SRAM



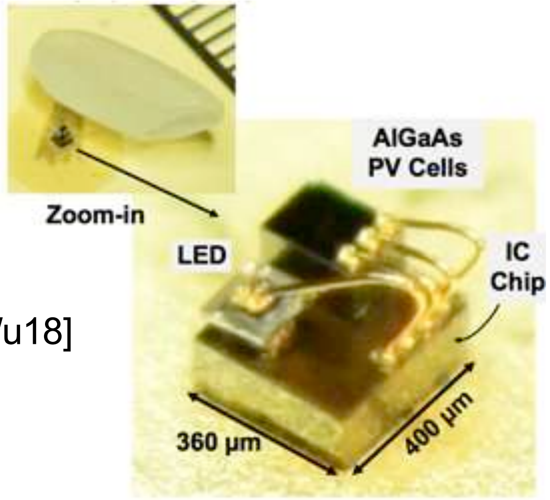




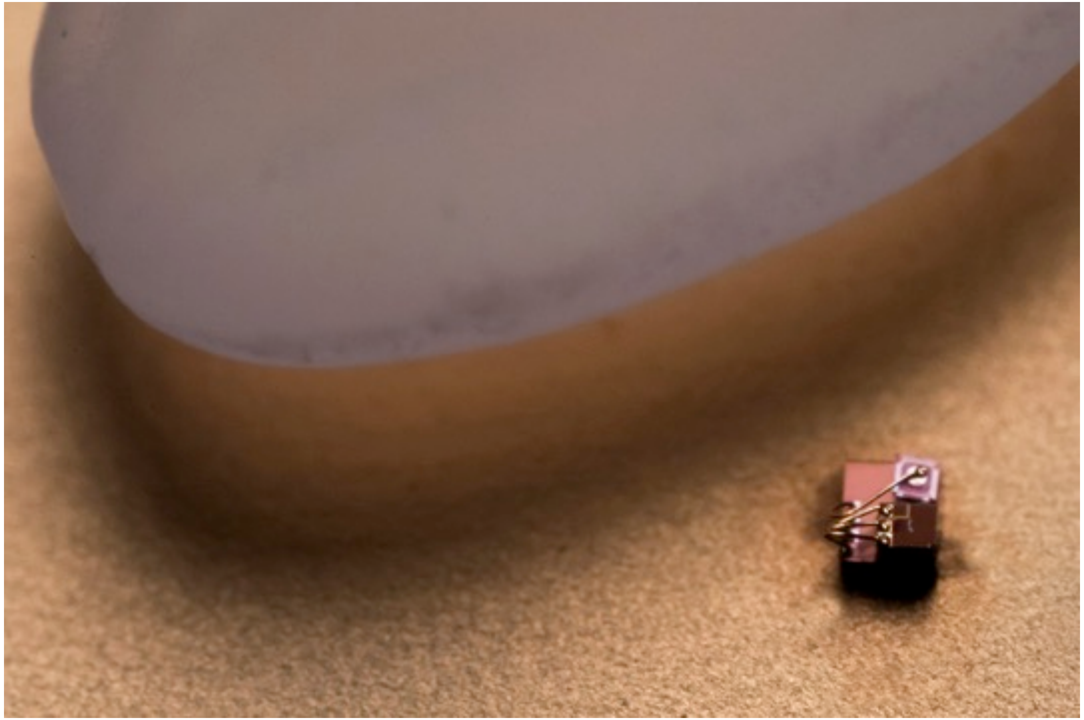
University of Michigan “Michigan Micro-Mote” (M3)

2018 Cell Temperature Sensing

- Cortex M0 processor
- Optical communication
- Photovoltaic supply



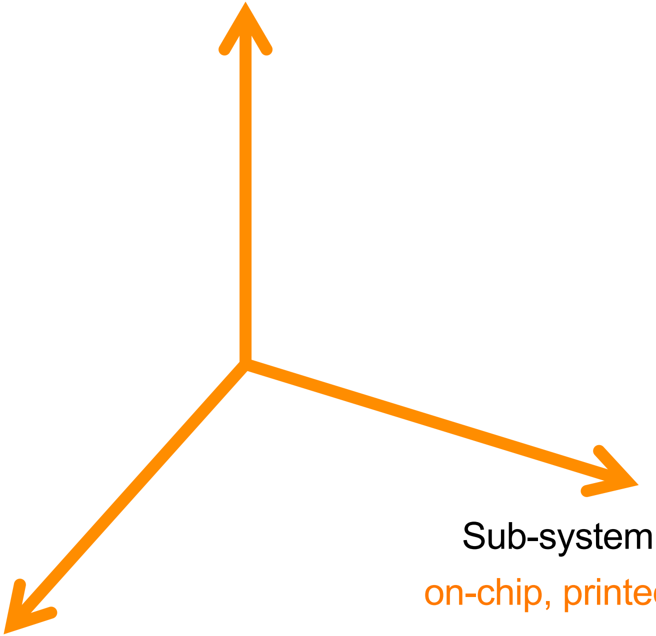
[Wu18]



[McAlpine18] Photo: Joseph Xu/Michigan Engineering

Conclusions

Work needed in all dimensions



Smart Dust, are you there?

Few-cm^3 autonomous commercial motes are *around the corner*

- CC2256RB, antenna, battery, solar cell + power mngt

Semi-autonomous 10 mm^3 motes *still in research phase*

- UCB Single Chip micro-Mote (SCuM), standards-compliant
- relies on frequency anchor node, needs 2.4 GHz antenna

1 mm^3 dependent nodes, *to be explored*

- optical or THz communication
- asymmetric architecture, close range communication
- useful knowledge for provisioning/debug of larger motes

Thanks

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