Sustainable Electronics for IoT

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Electronic is pervasive ...

- ✔ … it's around us
- ✔ … vocabulary

An exciting past (1/2) ...

1800: A. Volta
electrical battery

1830

1836: S.F.B. Morse
1st telegraph transmission
Washington - Baltimore

1864: J.C. Maxwell
electro-magnetism

1870: A. Meucci
invention of
Telephone

1886: H.R. Hertz
discovery of
radio waves

1895: G. Marconi
tirst wireless radio
transmission (1.5 km)

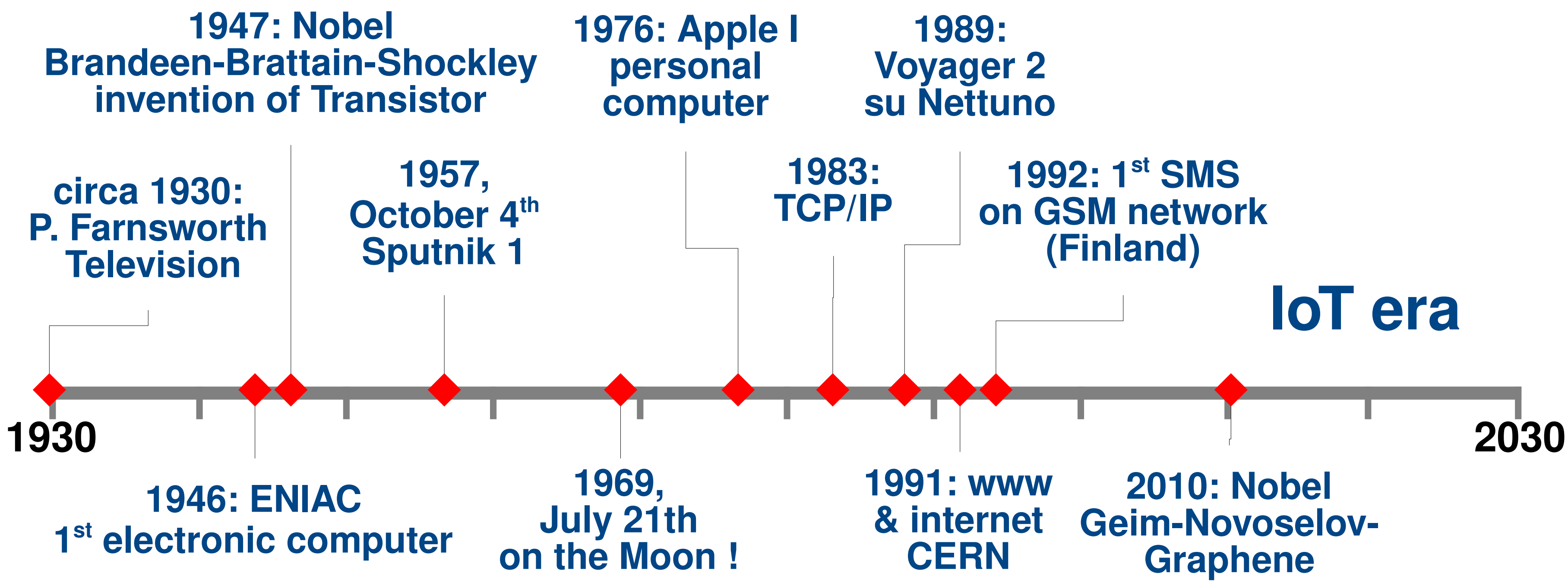
1901: G. Marconi
1st transoceanic
radio transmission

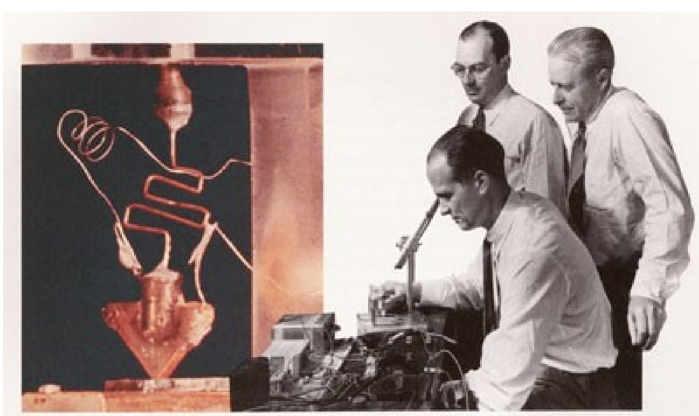
1904: J.A. Fleming
1908: L. de Forest
diode e del triode

1928, June 3rd,
SOS from Italia
Airship (Nobile)

1930

An exciting past (2/2) ...



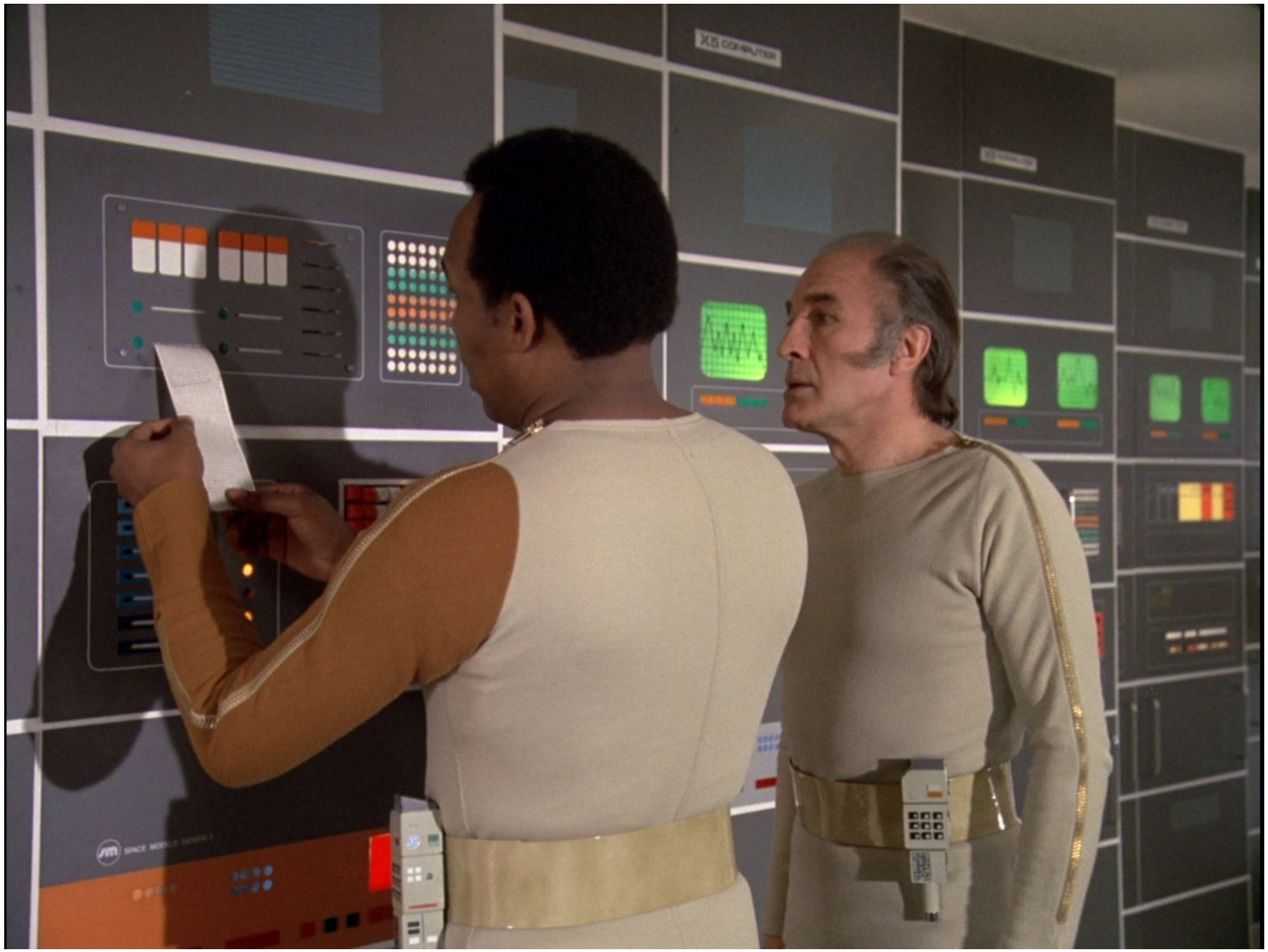


An amazing future (1/6) ...

Star Trek
(1966-1969)

Space 1999
(1975-1977)

An amazing future (2/6) ...



Space 1999 (super) Computer

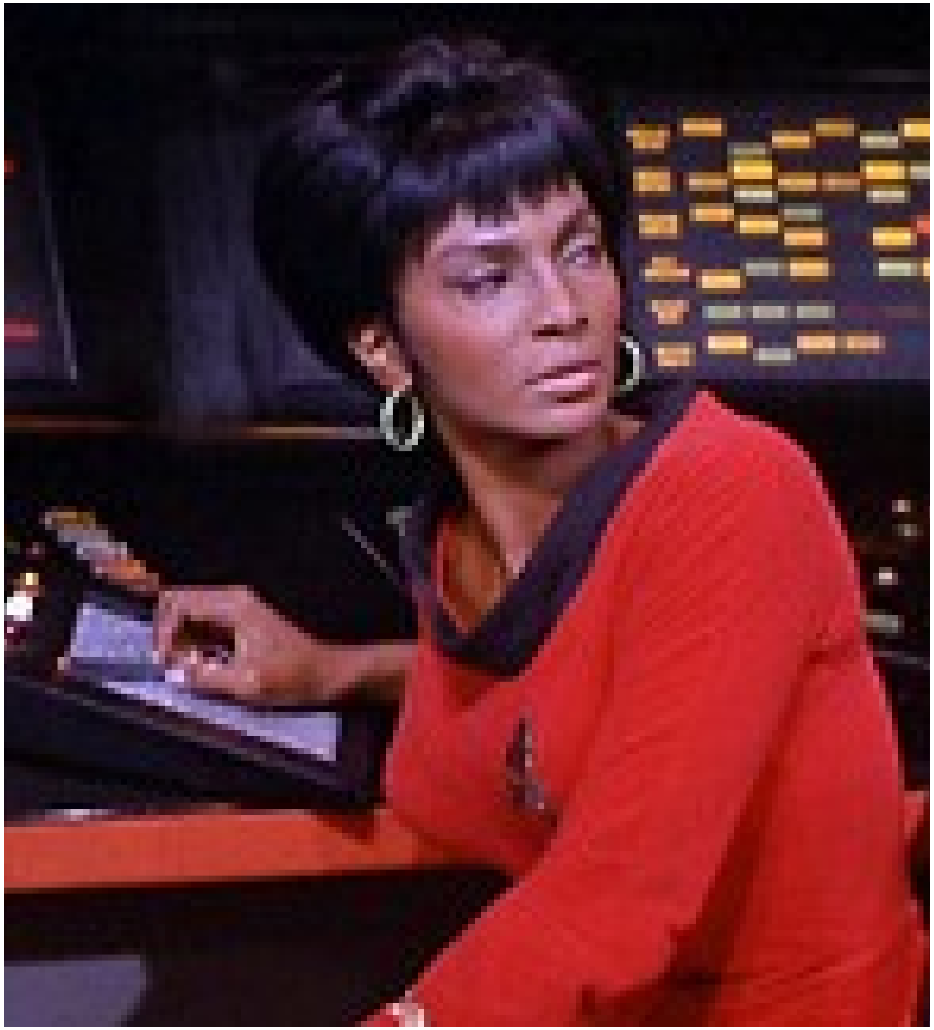
An amazing future (3/6) ...

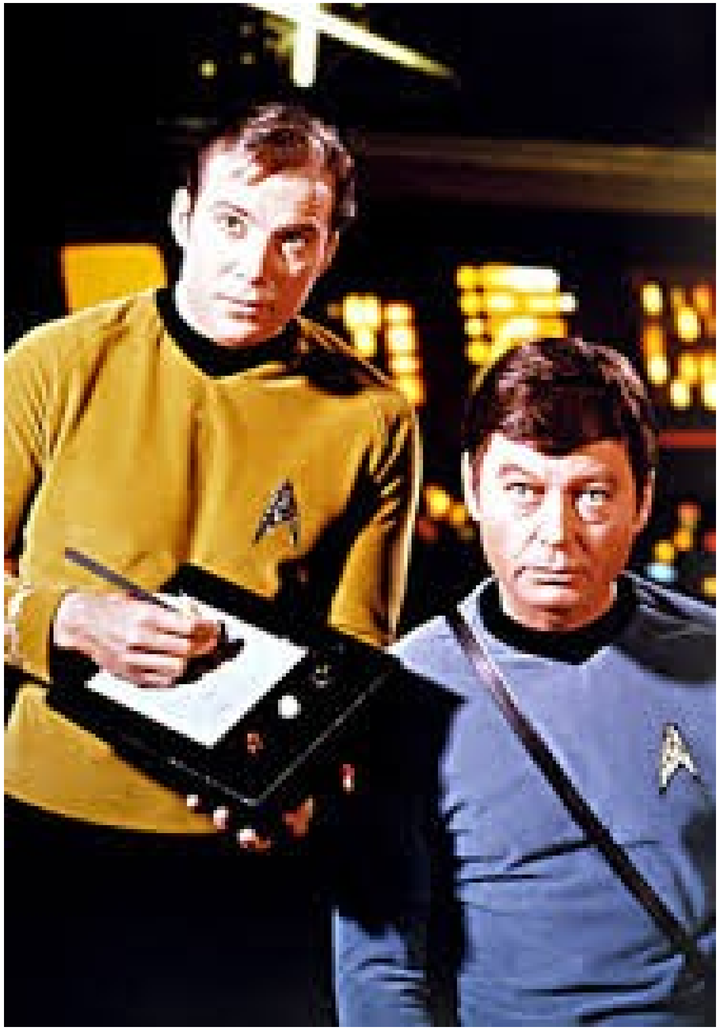
Star Trek Mobile (Smart) Phone

An amazing future (4/6) ...

Space 1999 Mobile (Smart) Phone

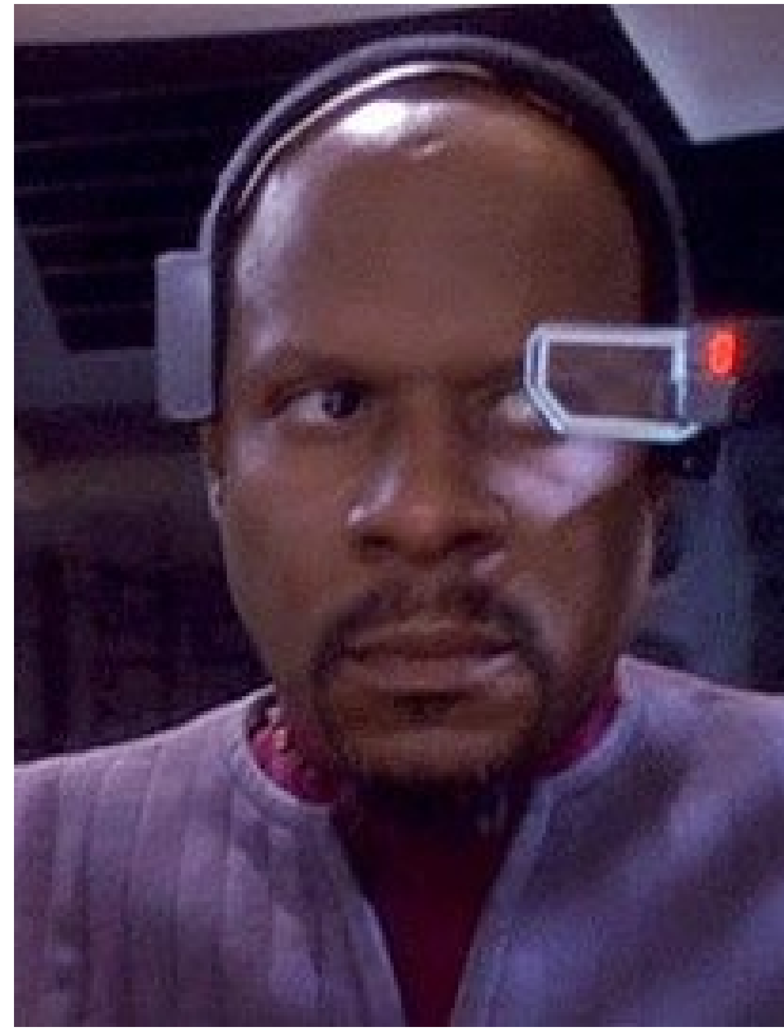
An amazing future (5/6) ...





Star Trek Electronic Tablet

An amazing future (6/6) ...

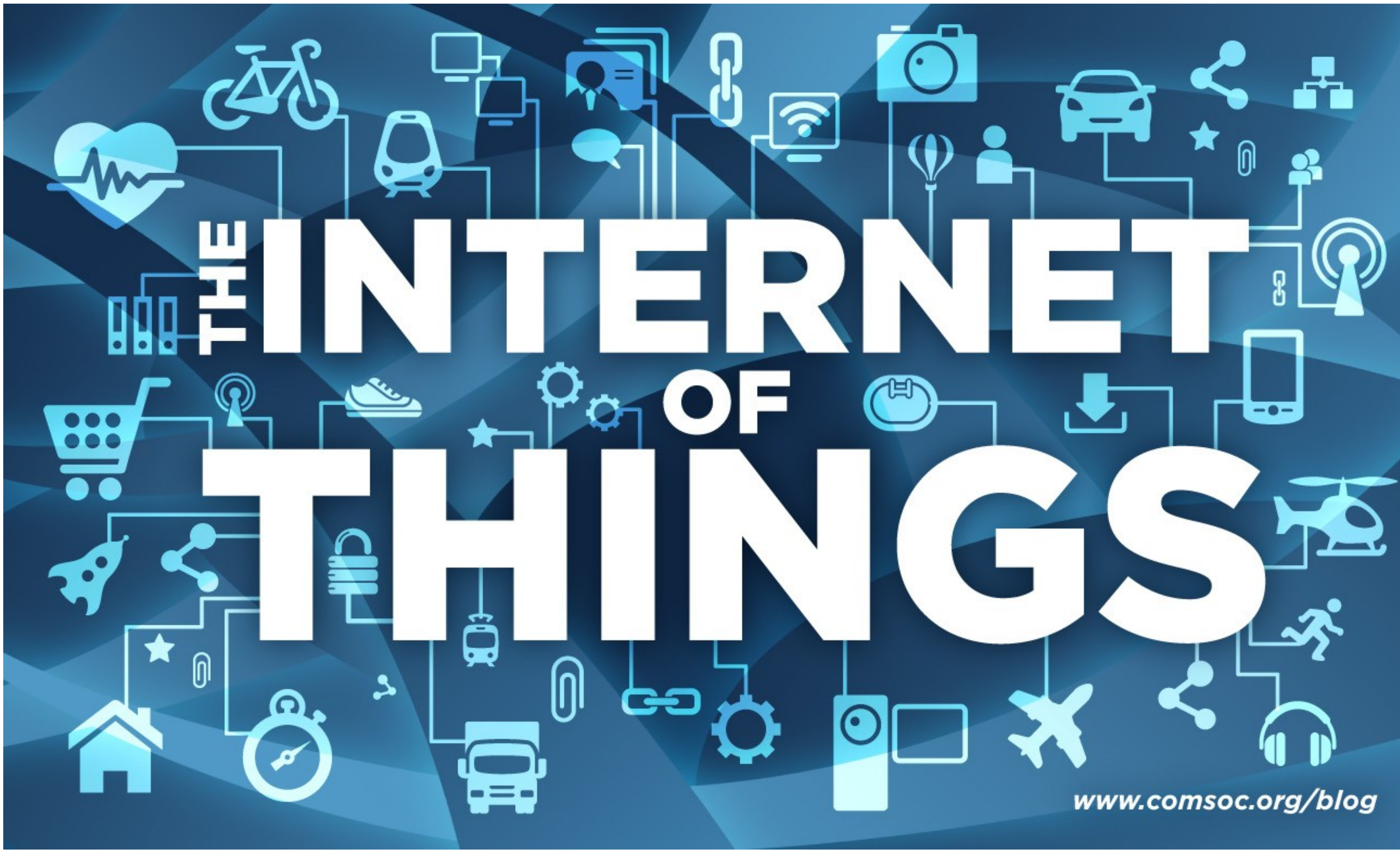


Star Trek Electronic Glasses

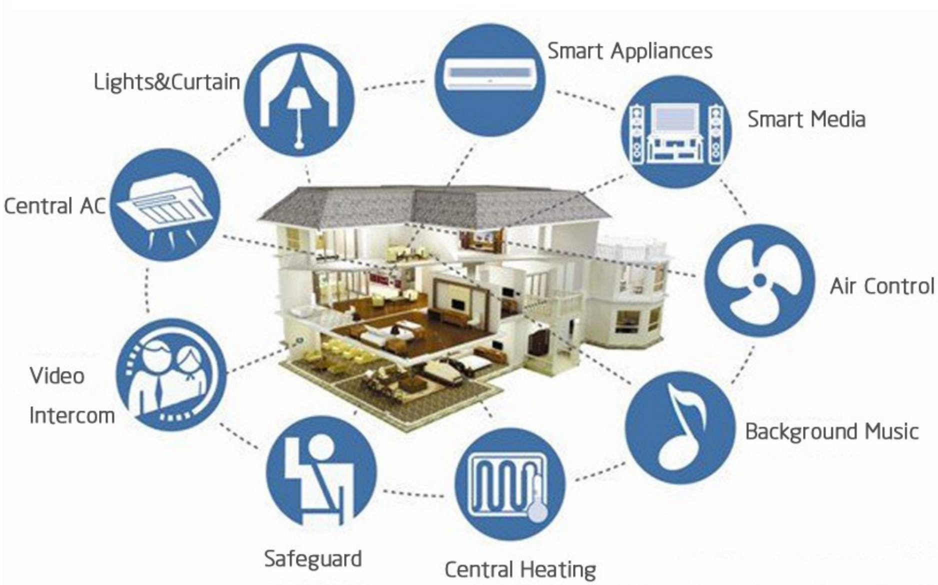
A future … that is already here !

>> What's Next ?

The vision (1/3) ...

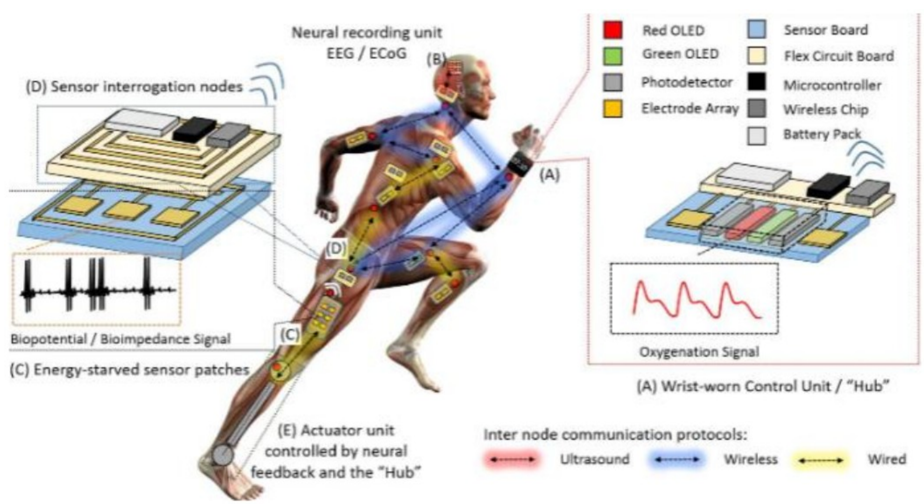


The vision (2/3) ...

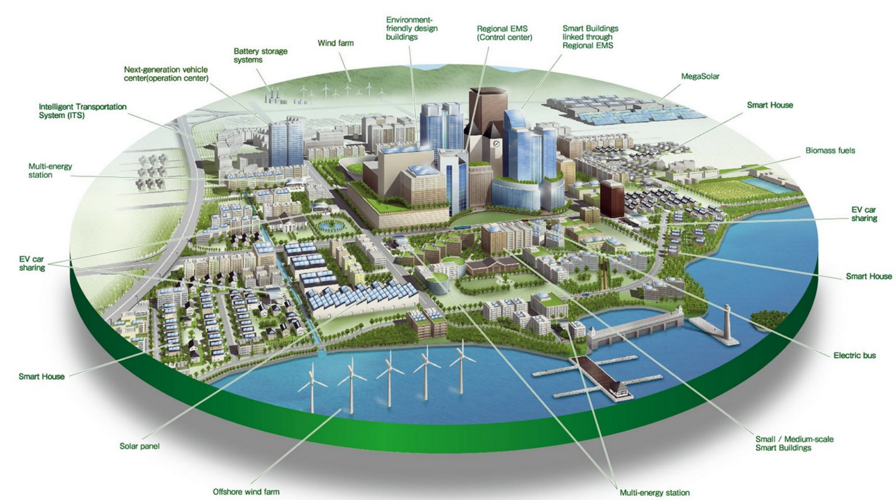


Smart Home

Smart Mobility



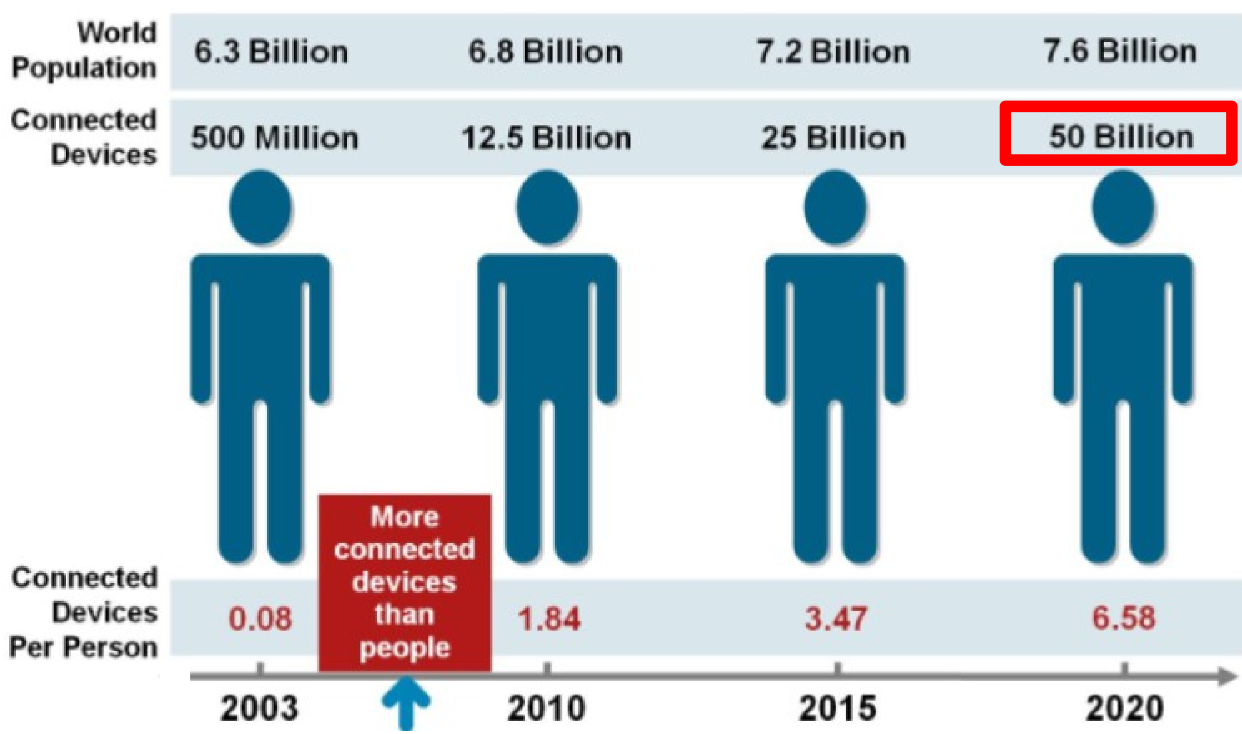
Smart Life



Smart City

The vision (3/3) ...

- ✔ **Internet of Things (IoT) = autonomous** sensors and actuators connected to the Internet: **Big-Data !**
- ✔ "**Things**" will be "**intelligent**" **like a space probe or a rover (same approach !!)**



Source: Cisco IBSG, April 2011

IoT: solution or problem ?

Electronic Waste (1/2)

50 million
metric tons per year

9 Cheops Pyramids !

Electronic Waste (2/2)

electronics spread all over the planet
(billions of disposable devices and sensors)

pollution caused by electronic circuits
(brominated bisphenol-A BPA epoxy resins in PCBs)

Green Electronic ?

Green Electronic (1/2)

Two main objectives:

- ✔ Environment saving
- ✔ Cost reduction

A new design approach:

- ✔ Reduce
- ✔ Recycle
- ✔ Reuse

Green Electronic (2/2)

✔ 4 action lines !

Green Electronic

- **Energy Autonomy** → Low Power No Batteries
- **Wireless Connection** → RFID technology
- **Integrate & Miniaturize** → Systems on Chip (SoC)
- **New Materials** → Recyclabe & Biodegrabable

Low Power
No Batteries

Low Power & No Batteries (1/3) !

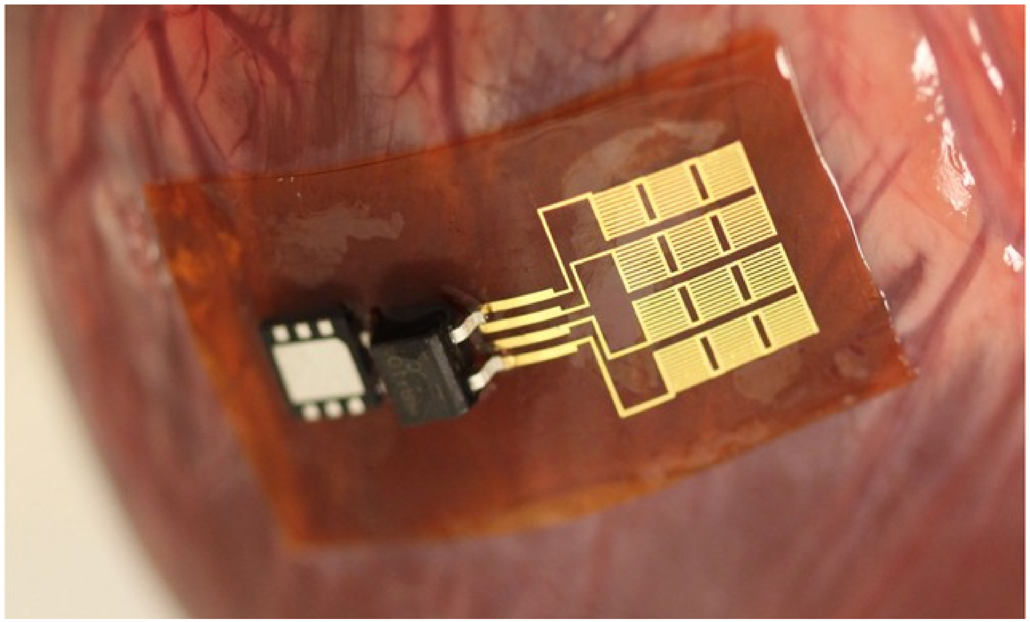
- ✔ The Nature knows how to do it …
- ✔ Energy Harvesting !

Low Power & No Batteries (2/3) !

Energy Source	Characteristics	Harvested Power
Light	Outdoor Indoor	100 mW/cm^2 100 μW/cm^2
Thermal	Human Industrial	60 μW/cm^2 ~1-10 mW/cm^2
Vibration	~Hz–human ~kHz–machines	~4 μW/cm^3 ~800 μW/cm^3
RF	GSM 900 MHz WiFi	0.1 μW/cm^2 0.001 μW/cm^2

Source: Texas Instruments

Low Power & No Batteries (3/3) !



Piezoelectric energy harvester on a bovine heart, after **University of Illinois & University of Arizona** – USA

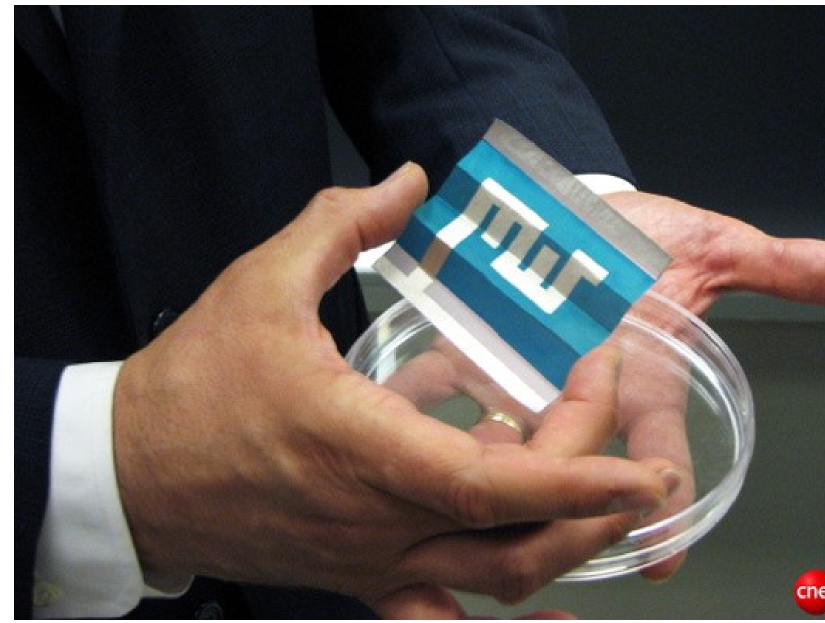


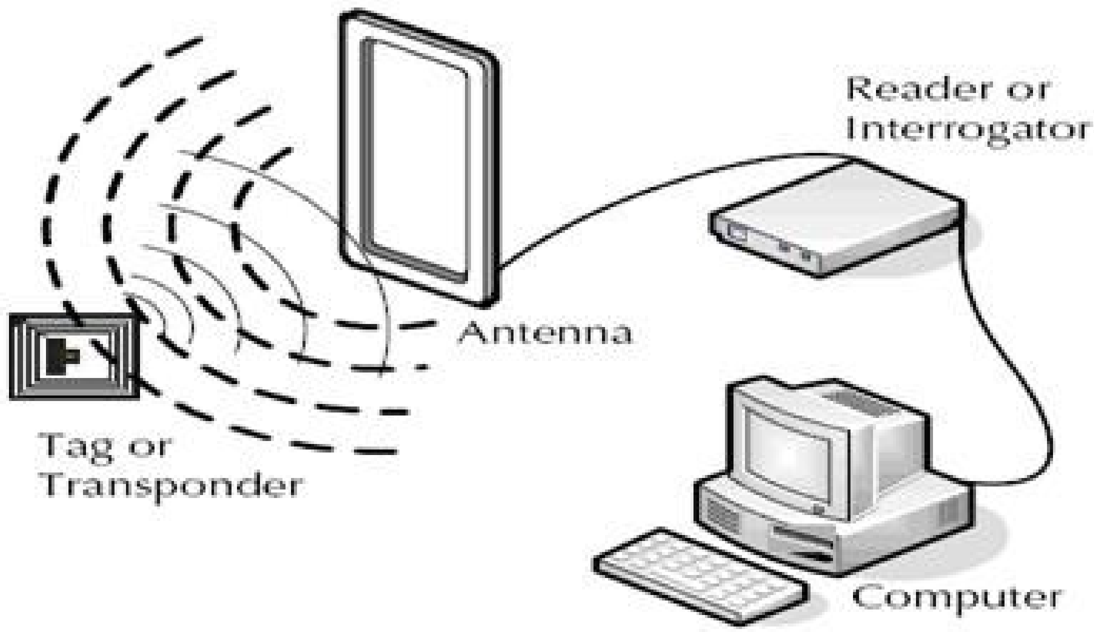
Photo-voltaic cell on paper, after **MIT** – Cambridge MA, USA

Other Approaches:

- ✔ **Wireless Power Transfer (WPT)**

RFID technology

RFID technology (1/2)



- ✔ **Information of demand** implies **low-power**.
- ✔ **No Battery**: the power comes from the interrogation (RF) signal.
- ✔ **Short** communication **range** (cm to meters).

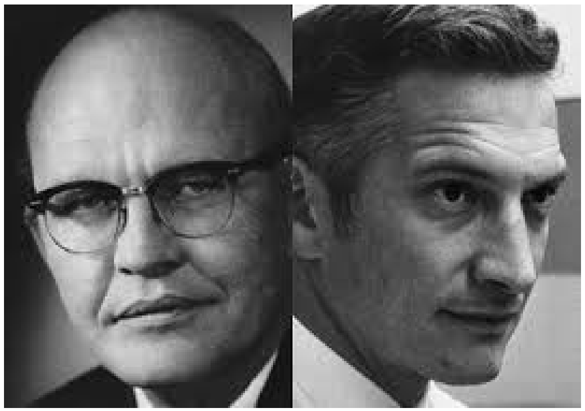
RFID technology (2/2)

✔ **RFID tags already in everyday life ...**

… but in a near future they will be **equipped with sensors !**

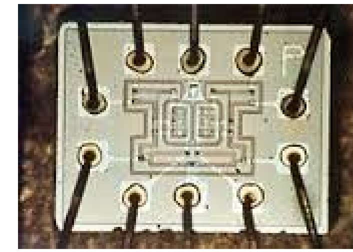
Systems on Chip (SoC)

Systems on Chip (1/4)

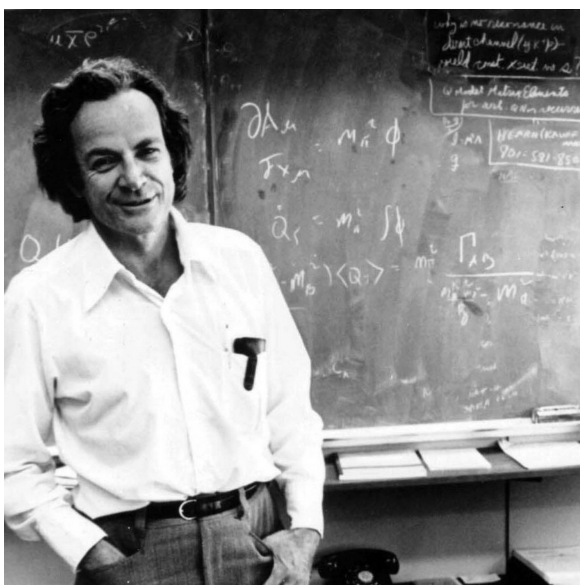


Jack Kilby (Nobel 2000) & Robert Noyce

- ✔ **1958 – invention of the integrated circuit**



NOR gate
Apollo Guidance Computer



Richard Feynman (Nobel 1965)

- ✔ **1959 – top-down nanotechnology**

There's Plenty of Room at the Bottom

Richard P. Feynman

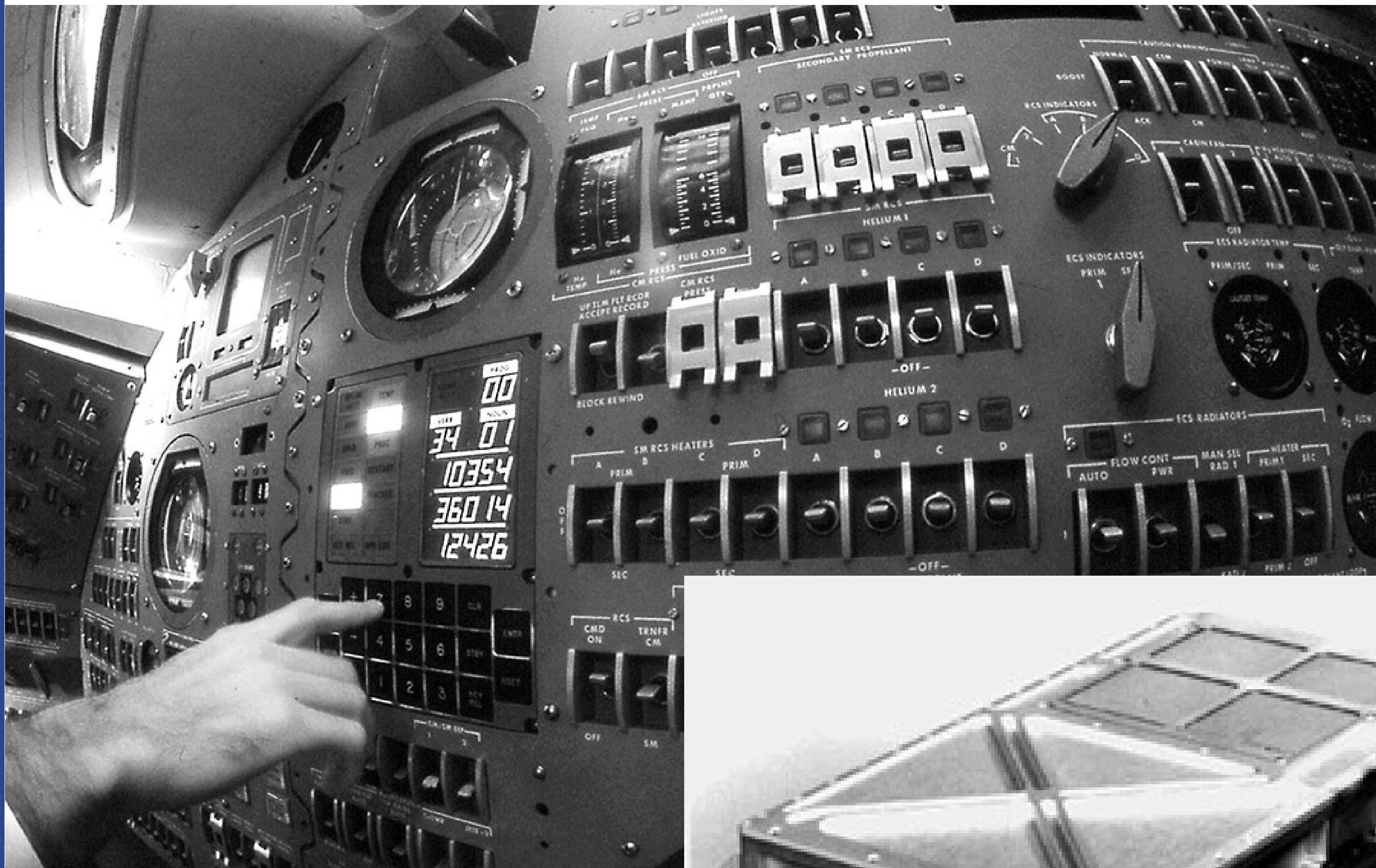
I imagine experimental physicists must often look with envy at men like Kamerlingh Onnes, who discovered a field like low temperature, which seems to be bottomless and in which one can go down and down. Such a man is then a leader and has some temporary monopoly in a scientific adventure. Percy Bridgman, in designing a way to obtain higher pressures, opened up another new field and was able to move into it and to lead us all along. The development of ever higher vacuum was a continuing development of the same kind.

dots on the fine half-tone reproductions in the Encyclopaedia. This, when you demagnify it by 25 000 times, is still 80 angstroms in diameter—32 atoms across, in an ordinary metal. In other words, one of those dots still would contain in its area 1000 atoms. So, each dot can easily be adjusted in size as required by the photoengraving, and there is no question that there is enough room on the head of a pin to put all of the Encyclopaedia Britannica.

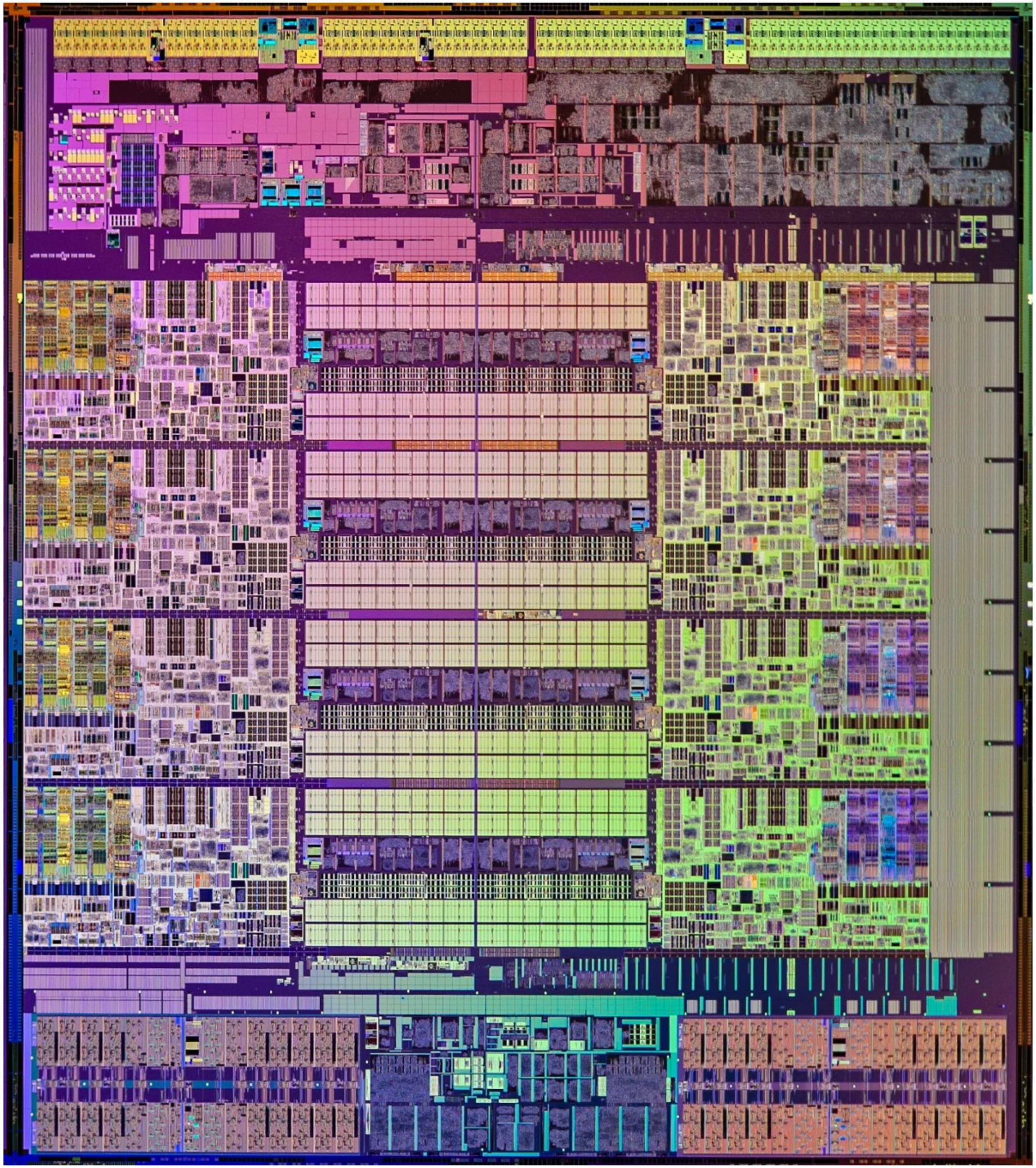
Furthermore, it can be read if it is so written. Let's imagine that it is written in raised letters of metal; that is,

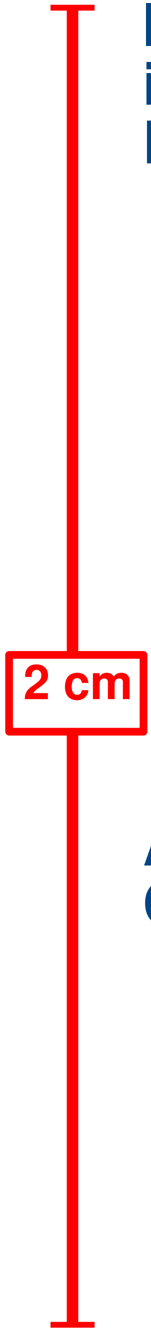
talk given at the APS meeting, December 29^{th} 1959

Apollo Guidance Computer (AGC)



Systems on Chip (2/4)





Intel® Core i7-5960X Processor (2014)

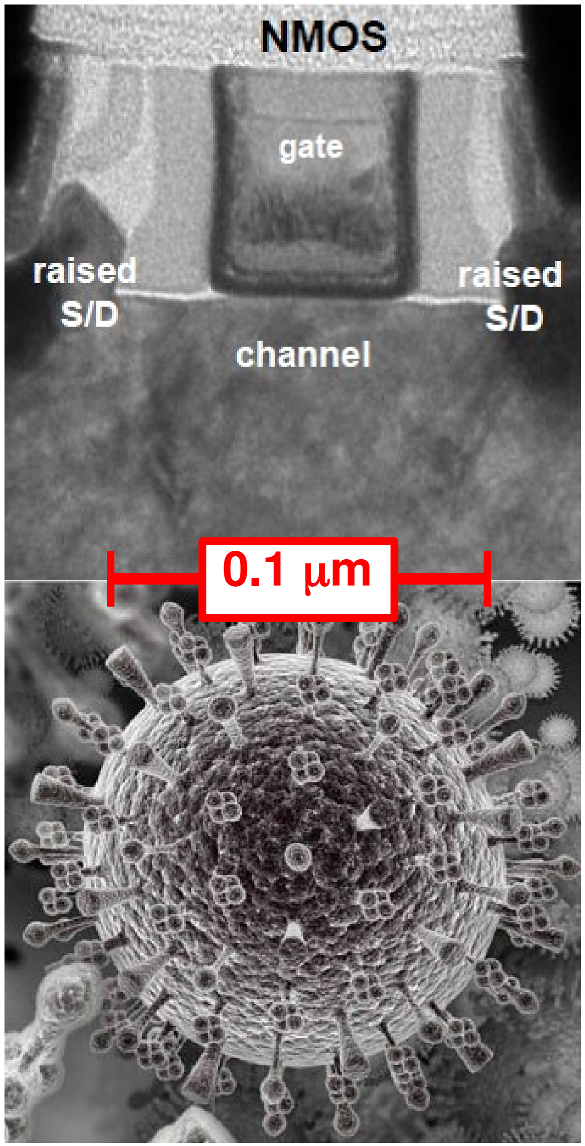
- ✔ 8 cores, 64 bit
- ✔ 3 GHz clock
- ✔ 64 GB RAM
- ✔ **2.6 billions transistors**
- ✔ **354 G-flops**

Apollo Guidance Computer (1965)

- ✔ **16800 transistors**
- ✔ **26 k-flops**
- ✔ **16.6 million less than I7 !**

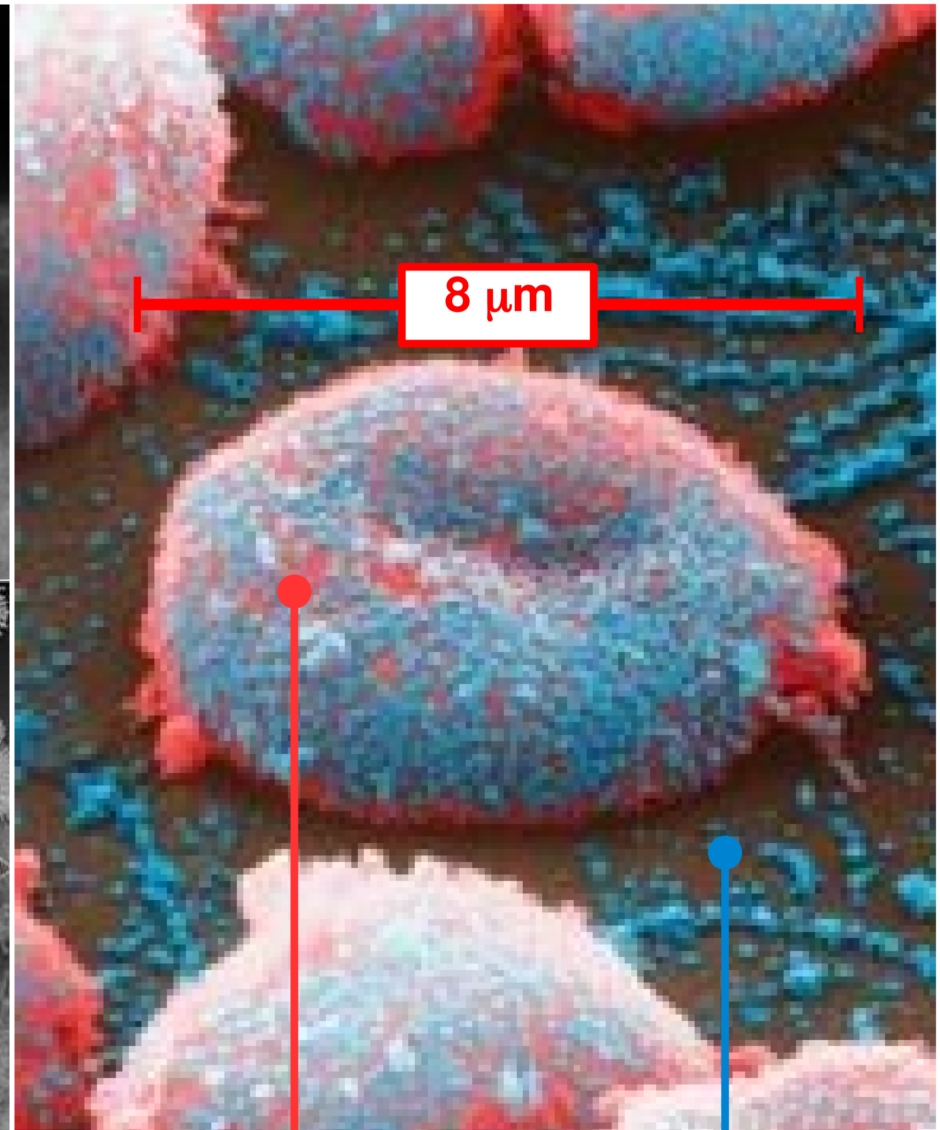
Systems on Chip (3/4)

32 nm transistor



avian flu virus (H1N1)

red blood cell under H1N1 attack

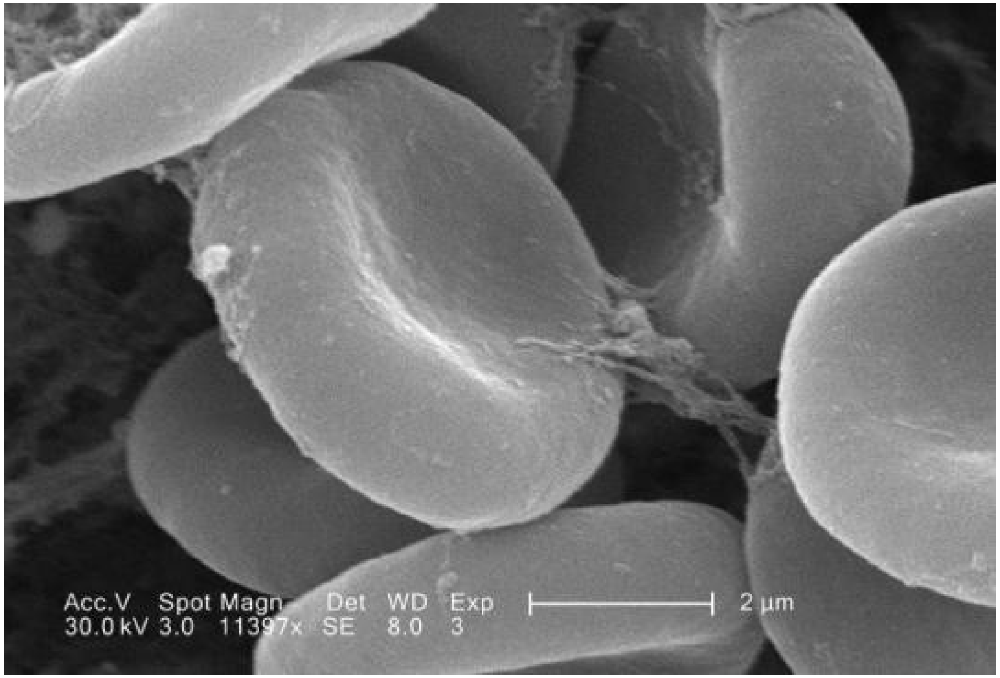


red blood cell

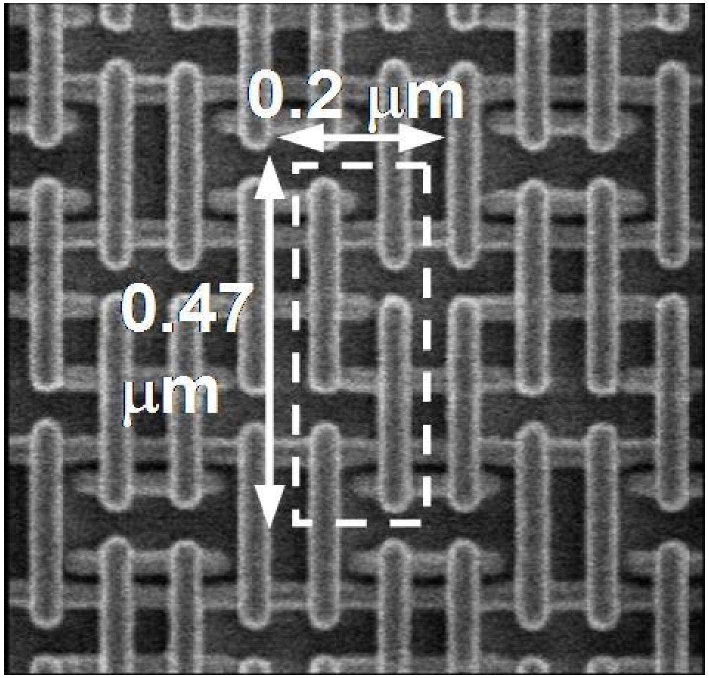
H1N1 virus

Systems on Chip (4/4)

human red blood cells

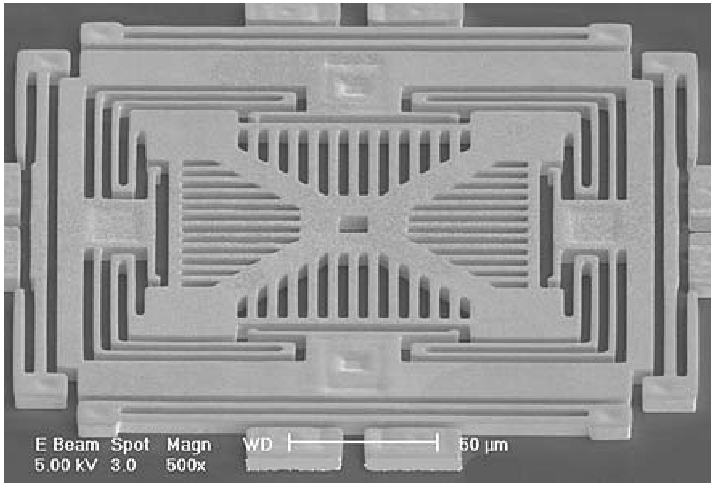


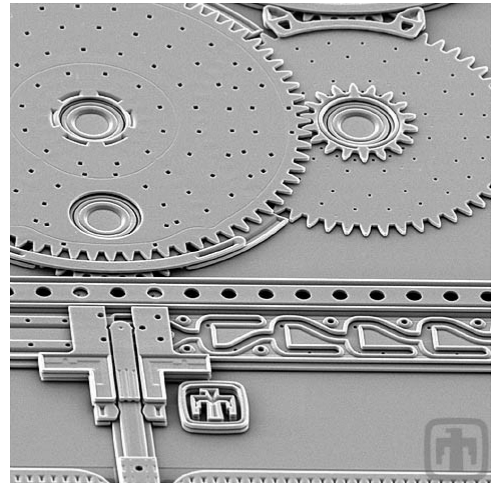
1-bit of RAM (22 nm CMOS)

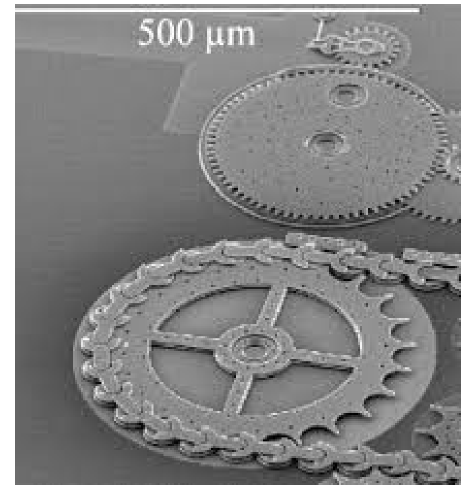


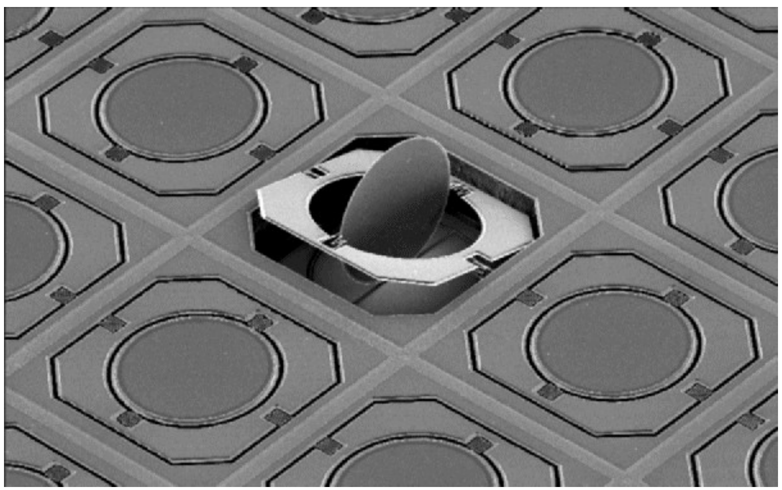
- ✔ **512 = bit of RAM (CMOS 22 nm) on a red blood cell !**
- ✔ **2 red blood cells ≈ a Twitter message !**

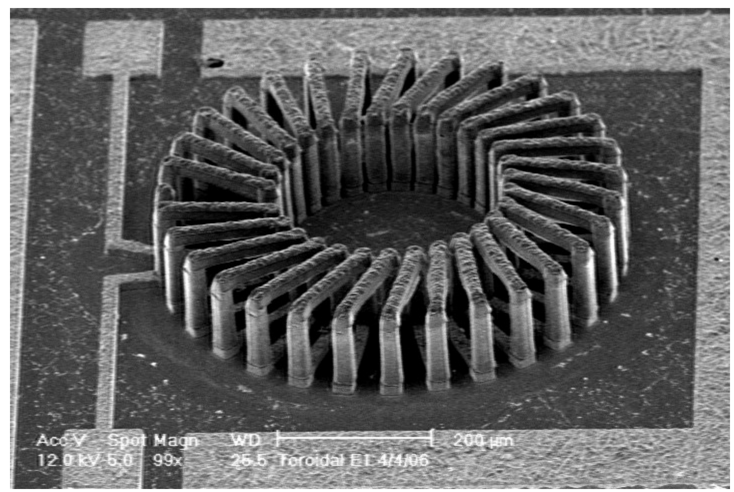
Micro Electro-Mechanical Systems

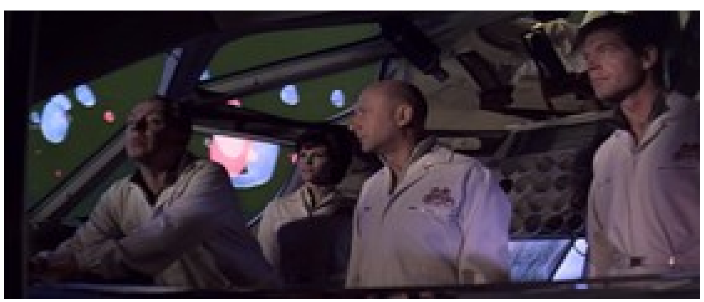












- ✔ **Fantastic Voyage ?** (Viaggio Allucinante) 1966. Otto Klement, Jerome Bixby, Isaac Asimov.

Recyclable & Biodegradable

What a material ?

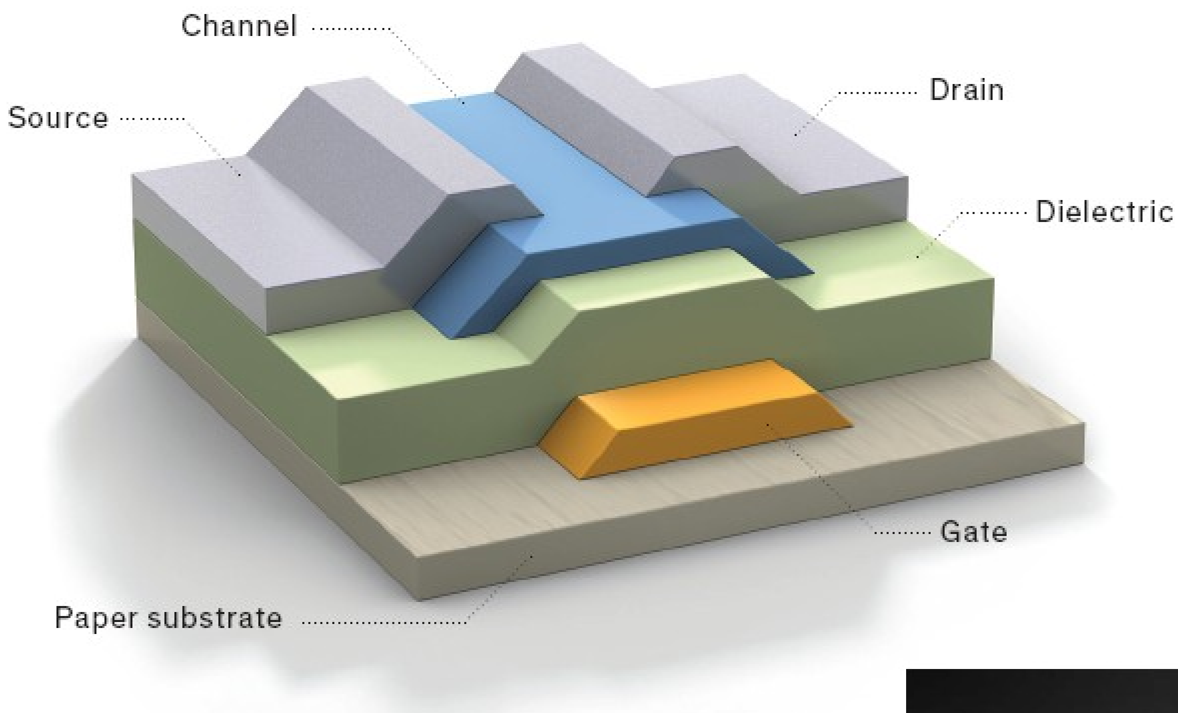
Paper Bridge
(cardboard tube)

Shigeru Ban

Cellulose (paper) is:

- ✔ the most common natural polymer
- ✔ practically inexpensive
- ✔ recyclable
- ✔ biodegradable

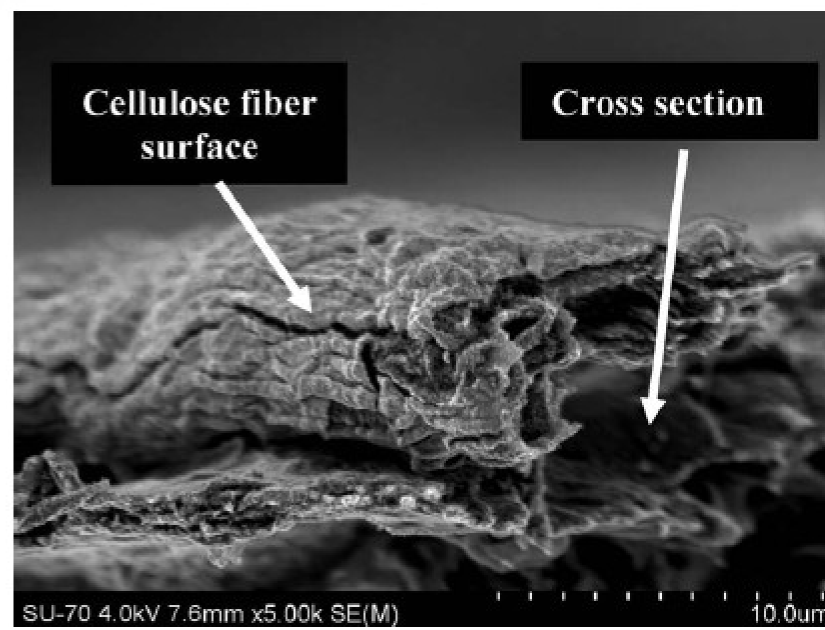
Cellulose transistors



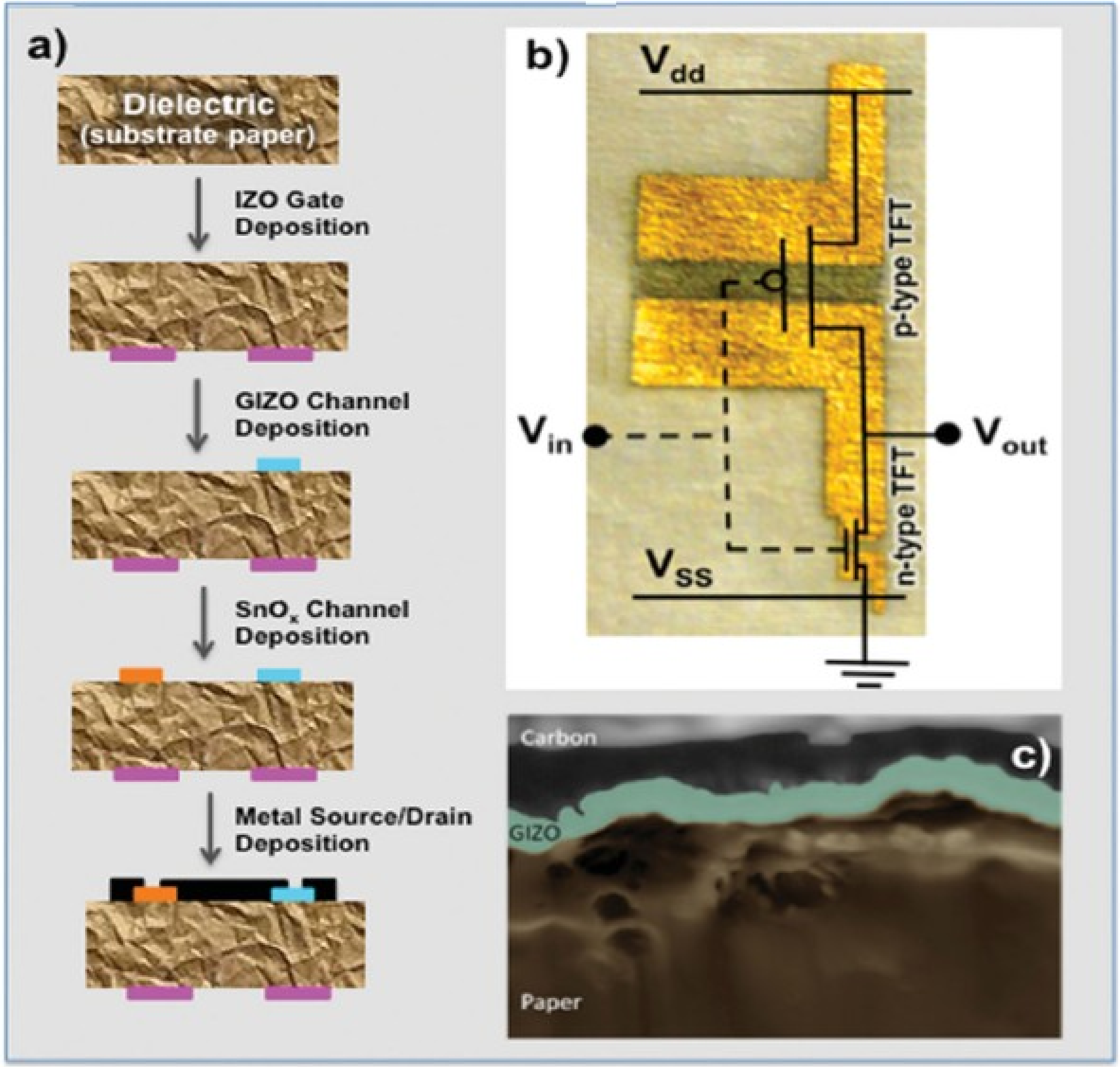
After **A.J. Steck**, in IEEE Spectrum, Feb. 2013.

After **E. Fortunato** *et al.*, in IEEE Electronic Device Letters, Sep. 2008.

- ✔ Thin Film Transistor (TFT) structure with back-gate.
- ✔ Paper used as substrate or as gate dielectric.
- ✔ Organic or inorganic semiconductor materials.
- ✔ Roughness is a problem ...



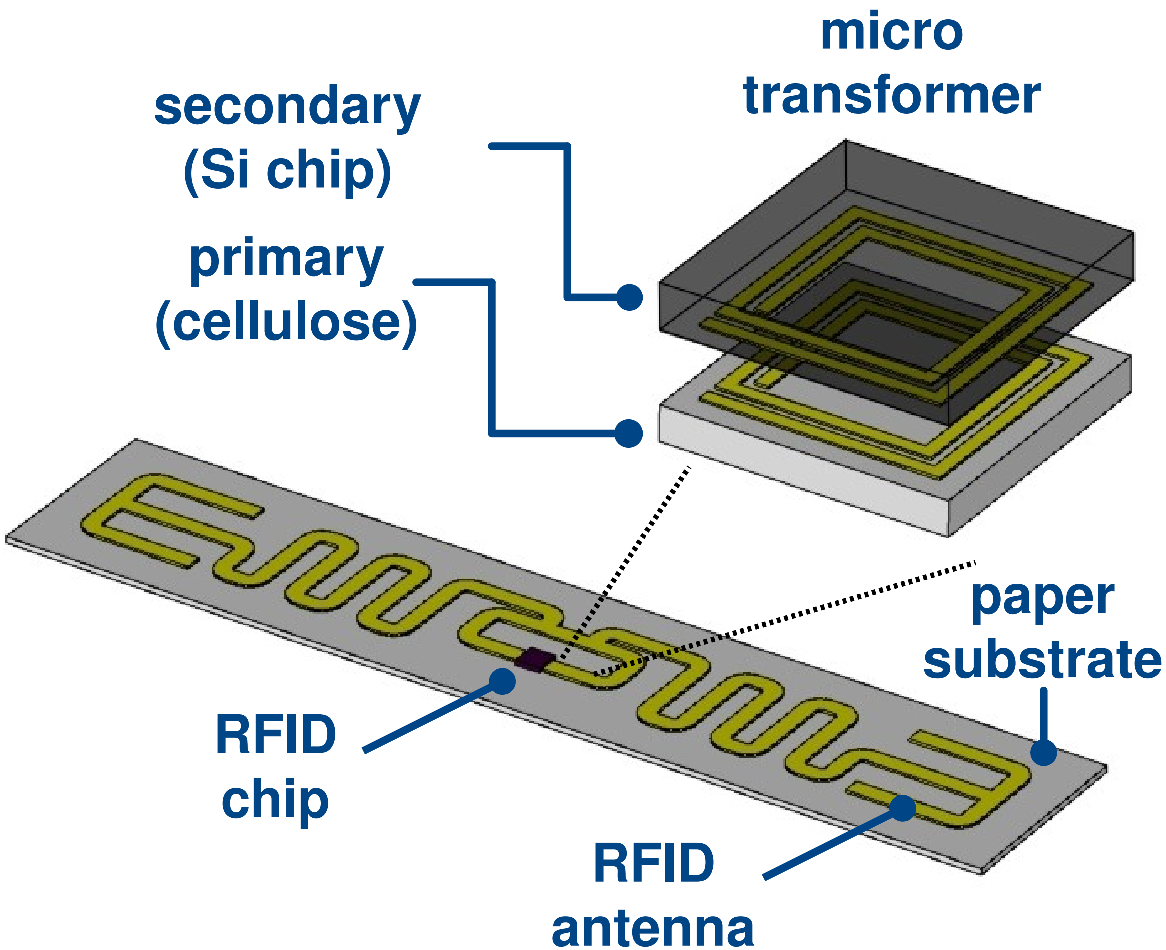
Cellulose logic gates



- ✔ First CMOS inverter on paper.
- ✔ Low-speed (in the kHz range).
- ✔ Suitable for static memory and for the processing of slow signals.

After **E. Fortunato** *et al.*, in Advanced Materials, May 2012.

Si to cellulose interface

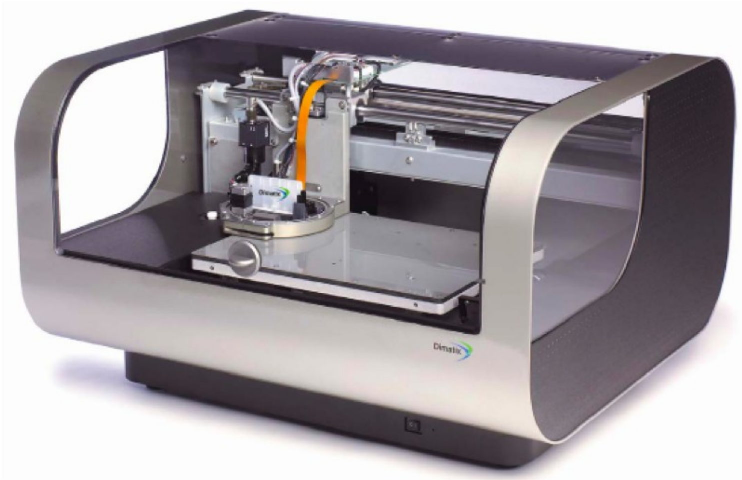


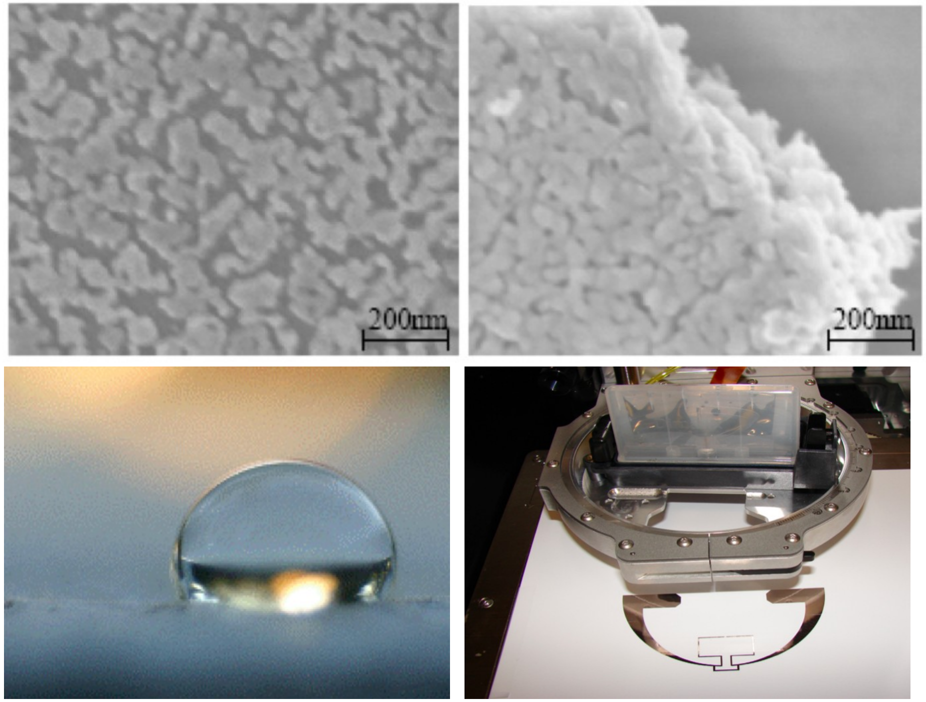
Circuits on cellulose can be interfaced with CMOS chips !

After **F. Alimenti** *et al.*, in IEEE MTT Transactions, Mar. 2011.

- ✔ interface achieved via **magnetic coupling**.
- ✔ place and glue: **no galvanic contacts !**

Circuits technologies (1/2)

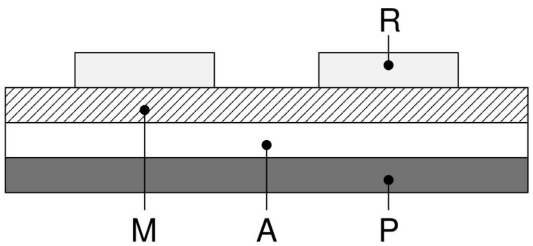




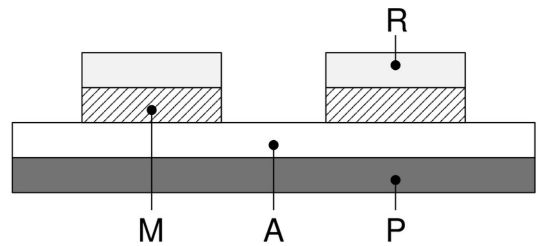
Viable technologies:

- ✔ ink-jet printing;
- ✔ screen printing;
- ✔ adhesive laminate;
- ✔ mix of the above ...

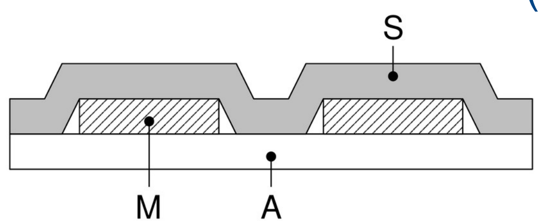
Circuit technologies (2/2)



(a)

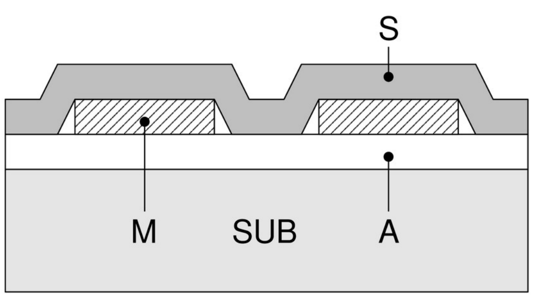


(b)

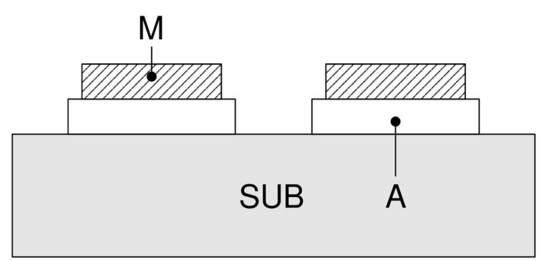


(c)

After **F. Alimenti** *et al.*, in IEEE Microwave and Wireless Component Letters, Dec. 2012.



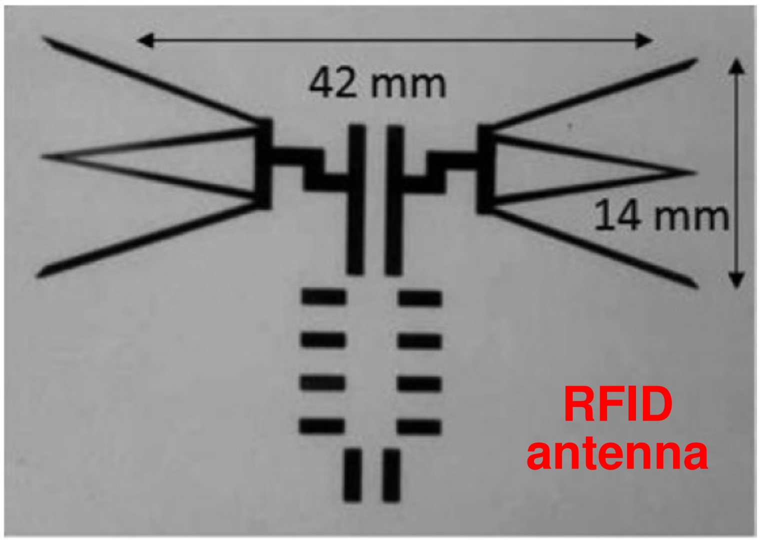
(d)

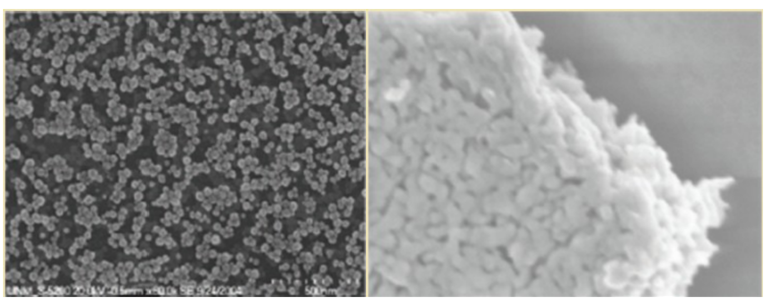


(e)

- ✔ The adhesive copper tape is **etched by photo-lithography**.
- ✔ Layout **transferred** to the host substrate **via sacrificial layer**.
- ✔ **The circuit can be sticked on demand !**

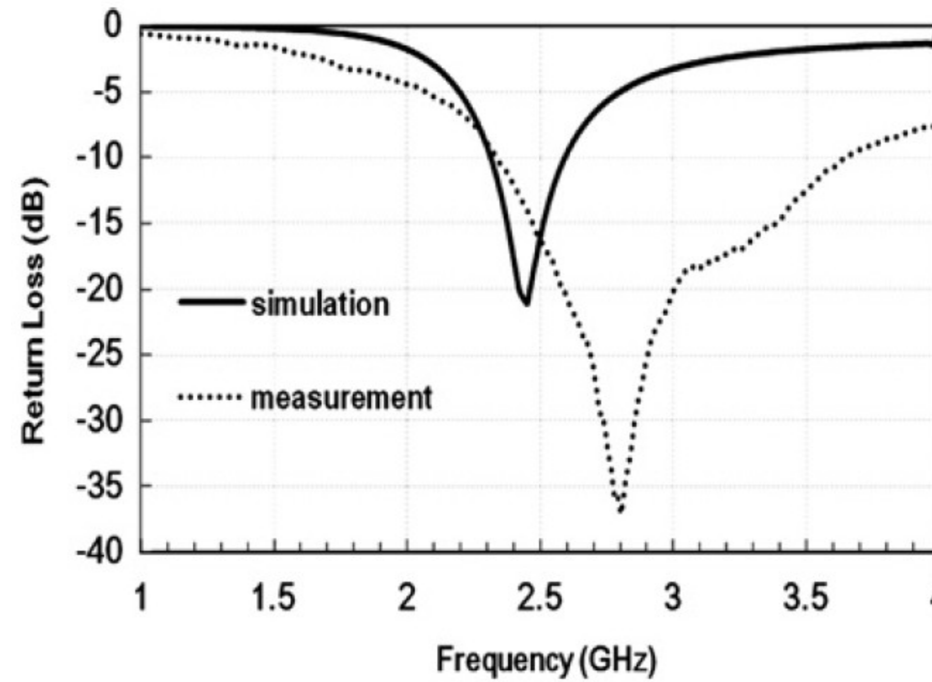
Circuit examples (1/3)





Ag Ink
before sintering

Ag Ink
after sintering



After **G. Orecchini** *et al.*, in IET Microwave Antennas and Propagation, N. 8, Aug. 2011.

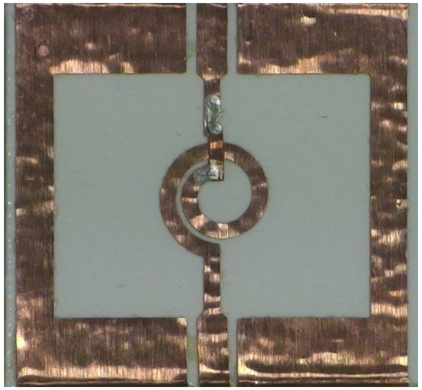
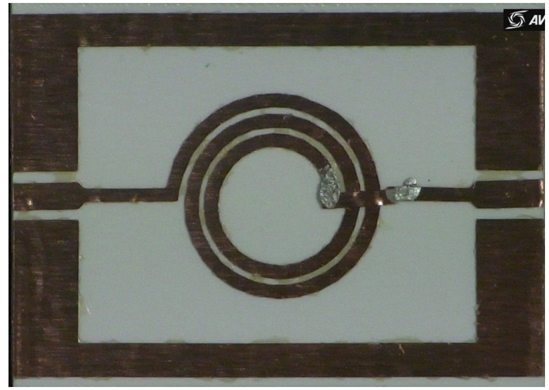
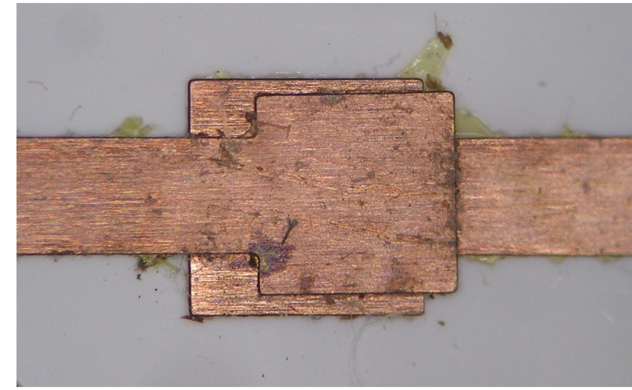
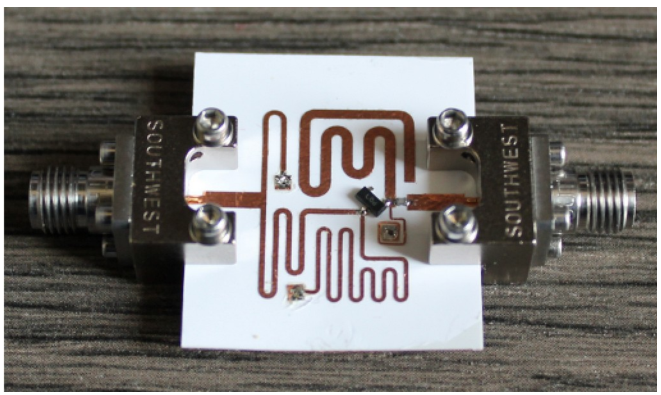
IET Premium (Best Paper) Award, Year 2013

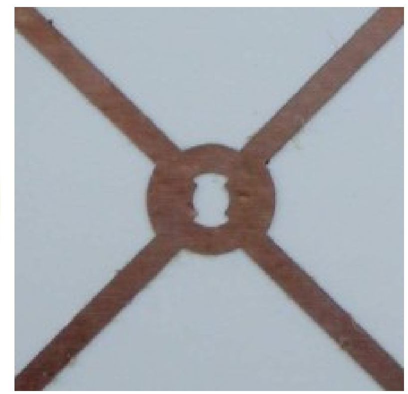
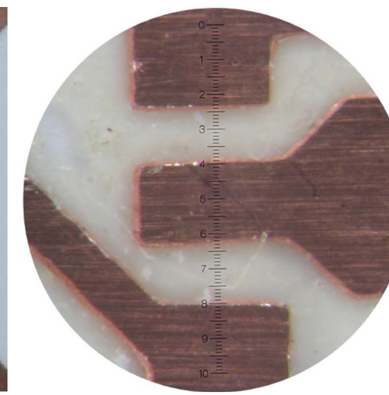
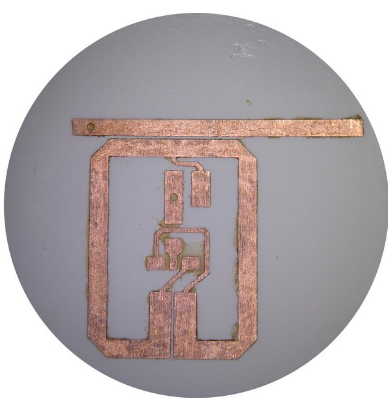
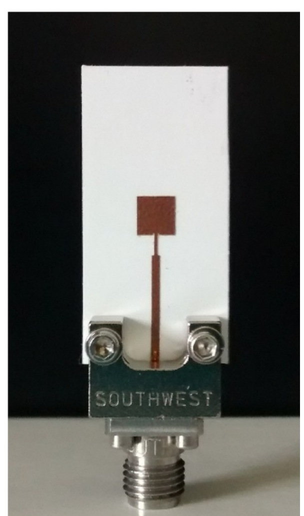
- ✔ Ag ink needs sintering at 150 °C for 15 minutes.
- ✔ Cured **Ag ink conductivity only 1/5 of bulk copper**.
- ✔ **How to reduce conductor loss (relevant for printed antennas)?**

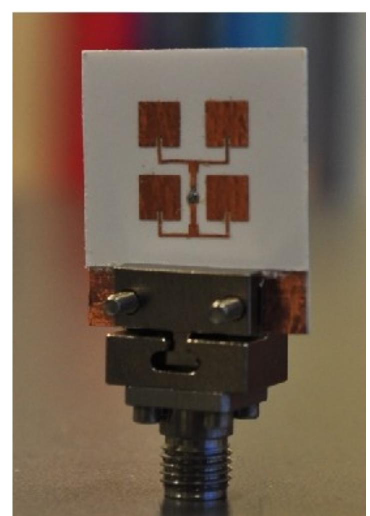
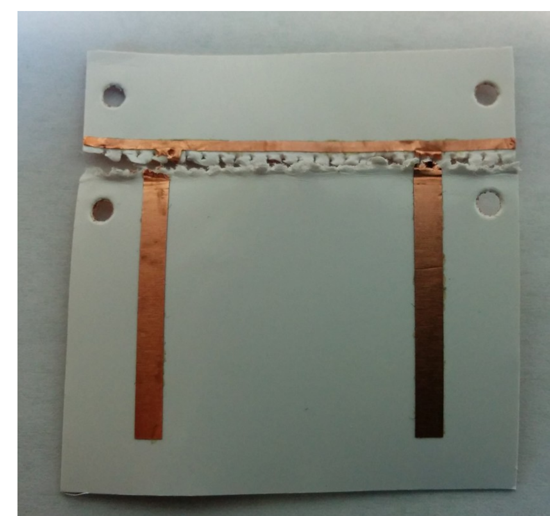
Circuit examples (2/3)

Cooperation with **Prof. M. Tentzeris** *et al.*, Georgia Institute of Technology, Atlanta (GA), USA

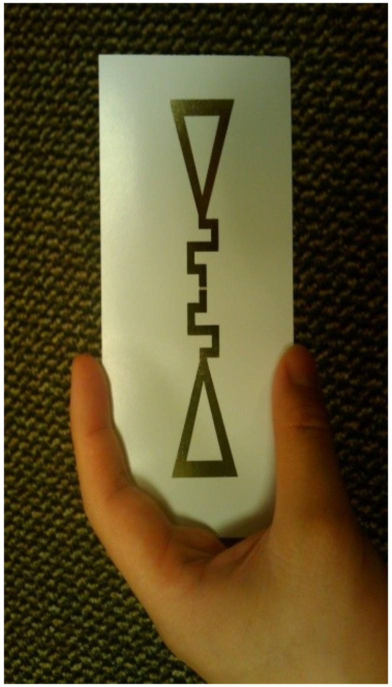
Circuit examples (3/3)

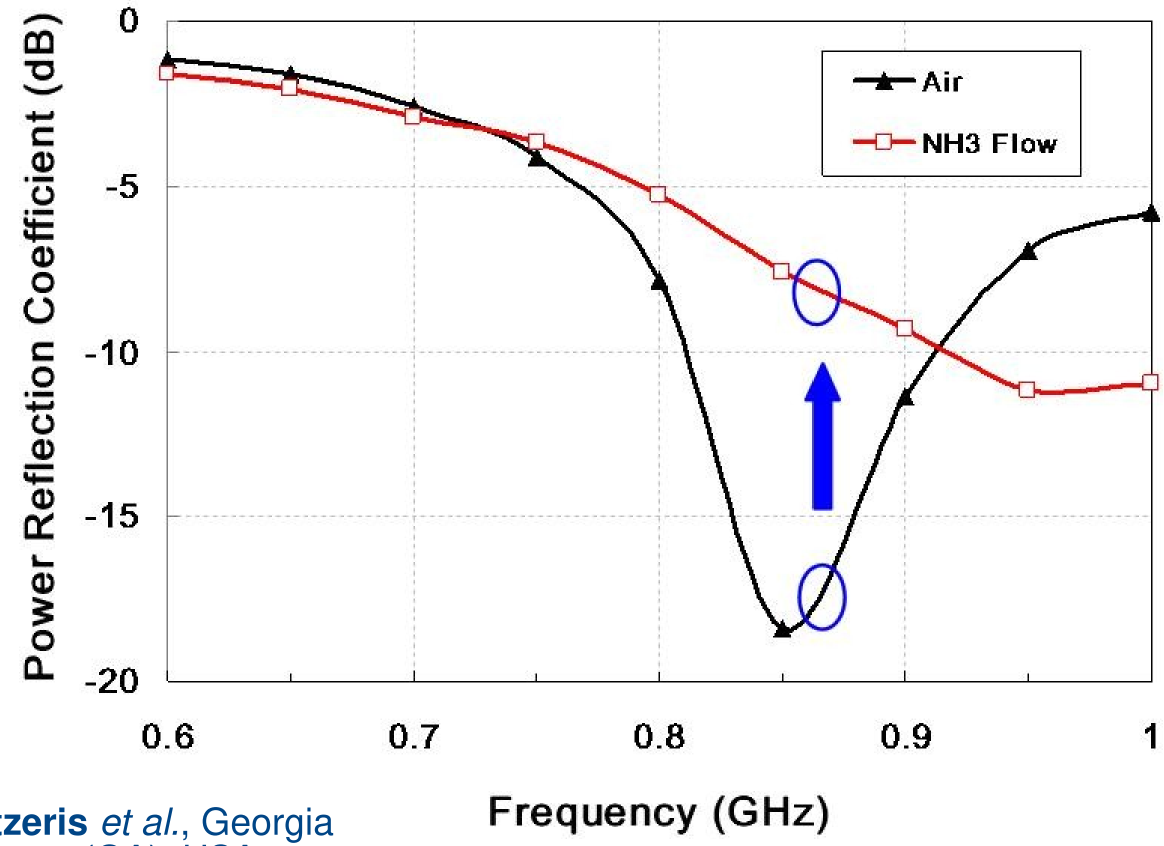





Cellulose sensors ?

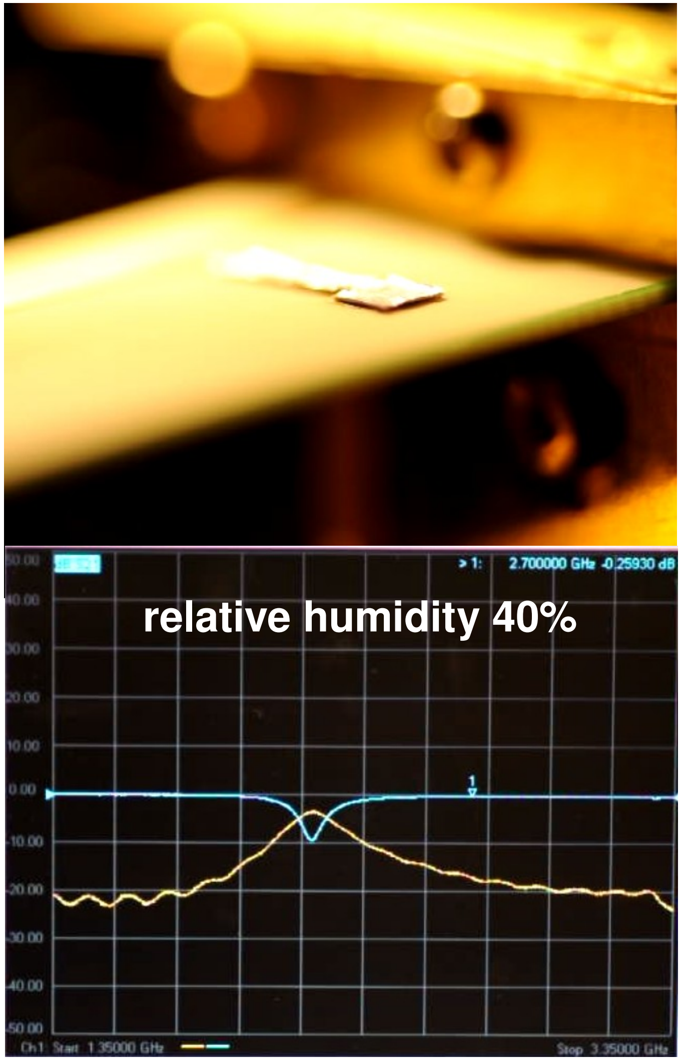


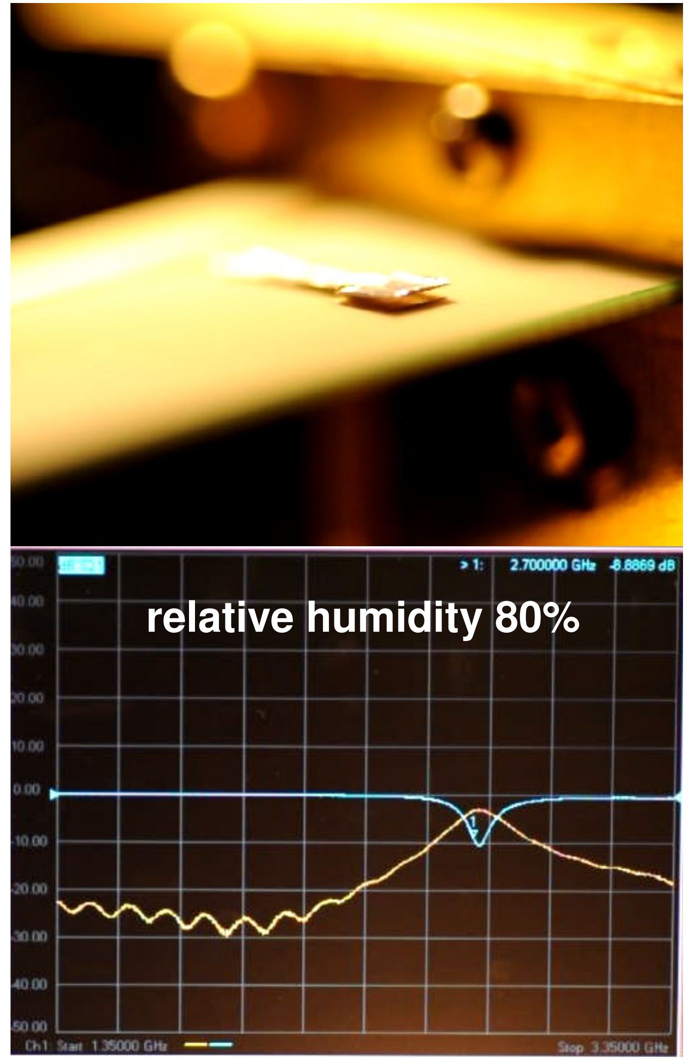


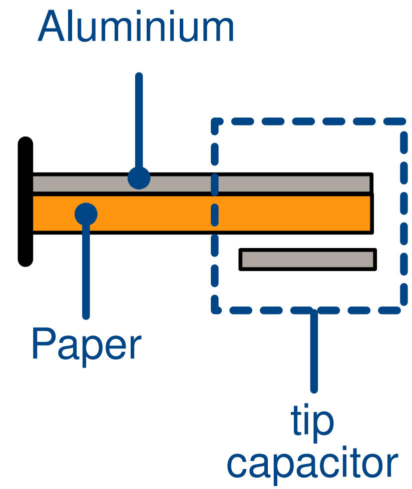
Cooperation with **Prof. M. Tentzeris** *et al.*, Georgia Institute of Technology, Atlanta (GA), USA

- ✔ **RFID chip-less tag**: antenna on cellulose loaded with a CNT layer.
- ✔ The **CNT** layer acts as a resistor sensitive to the **NH3** concentration.
- ✔ **The impedance changes are detected as a variation of the backscattered power level.**

Cellulose micro machines ?



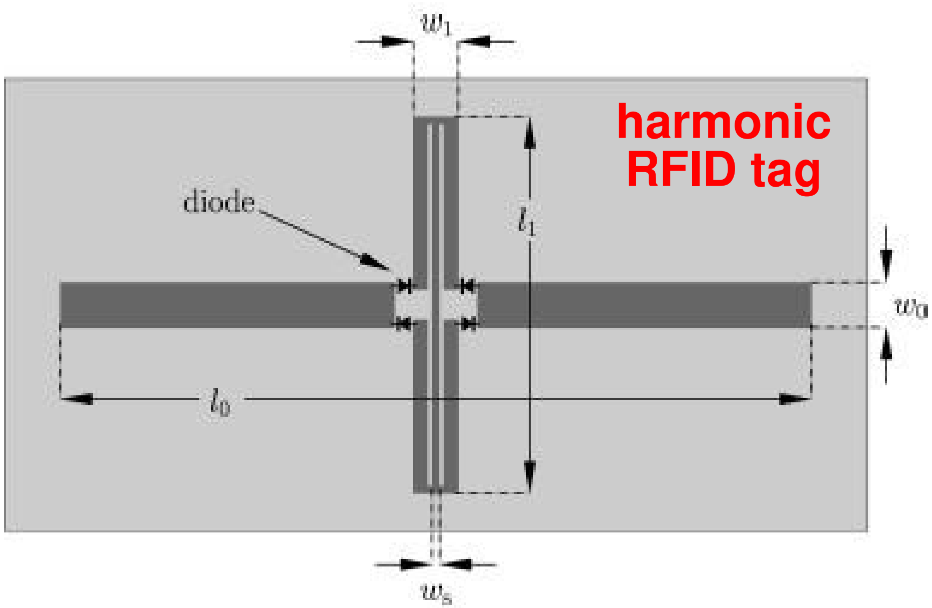


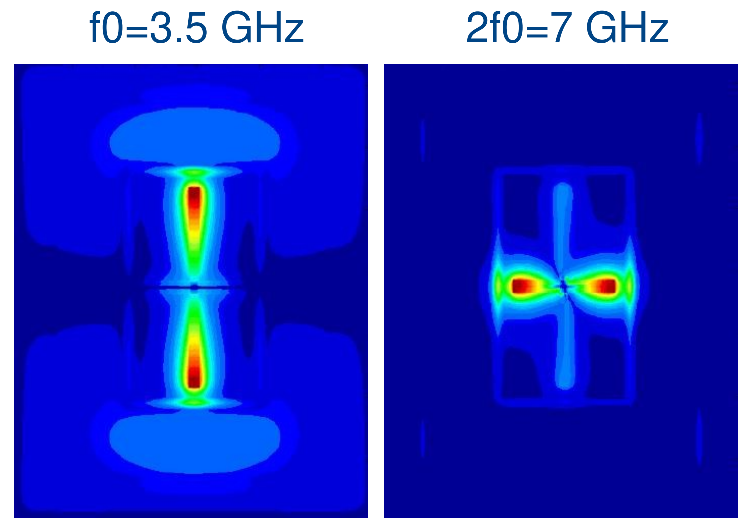


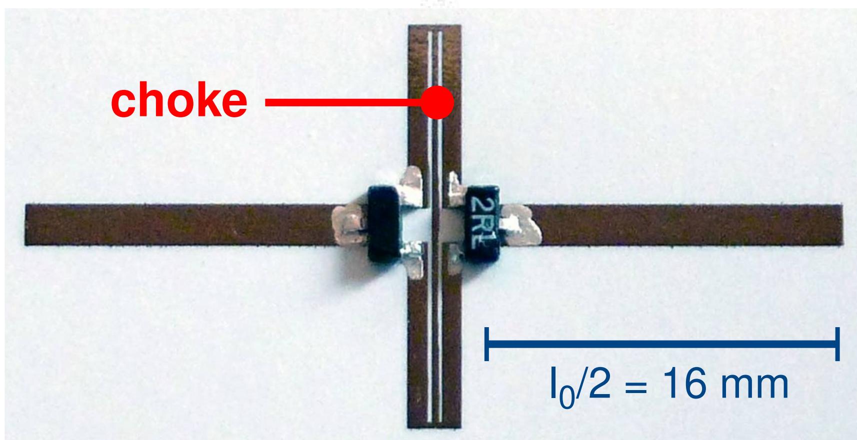
✔ **Sensor structure: bi-material strip !**

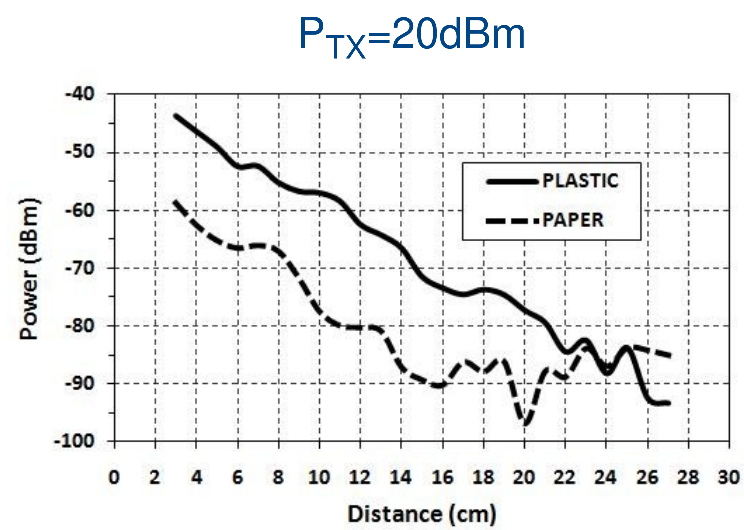
- ✔ **MEMS** on cellulose are feasible !
- ✔ **Humidity sensor** on paper

Harmonic RFID system



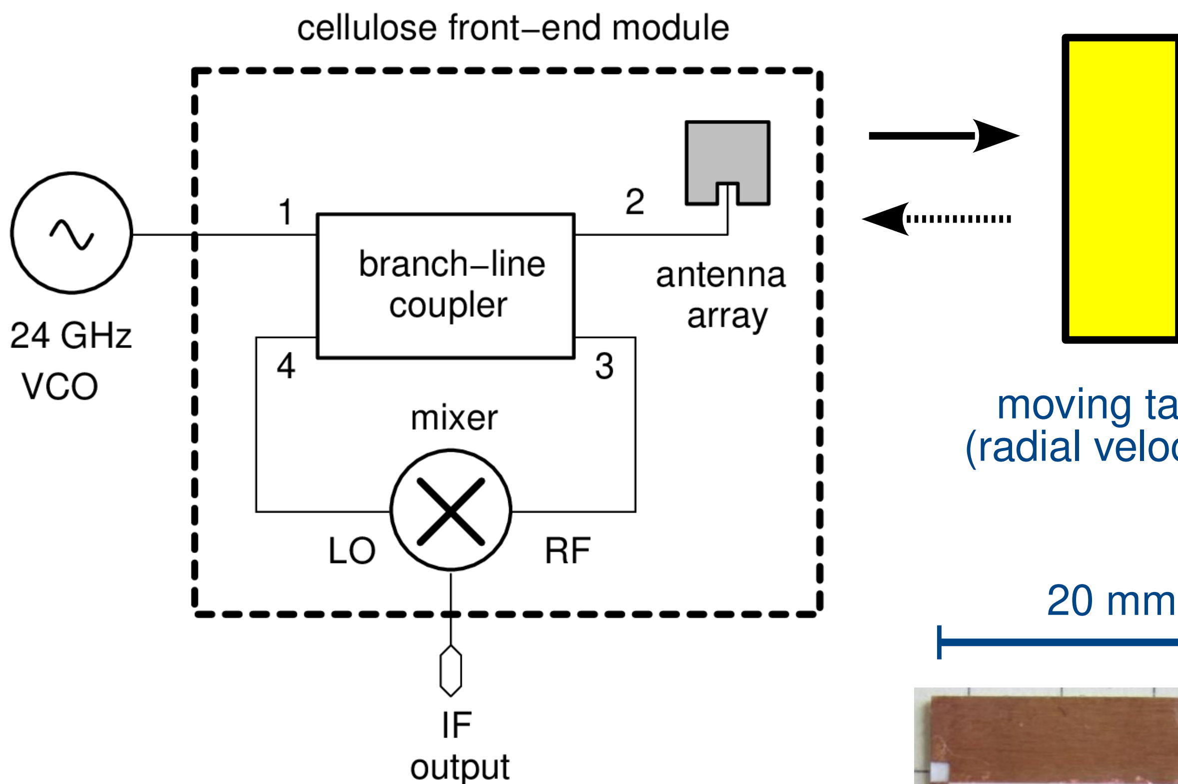






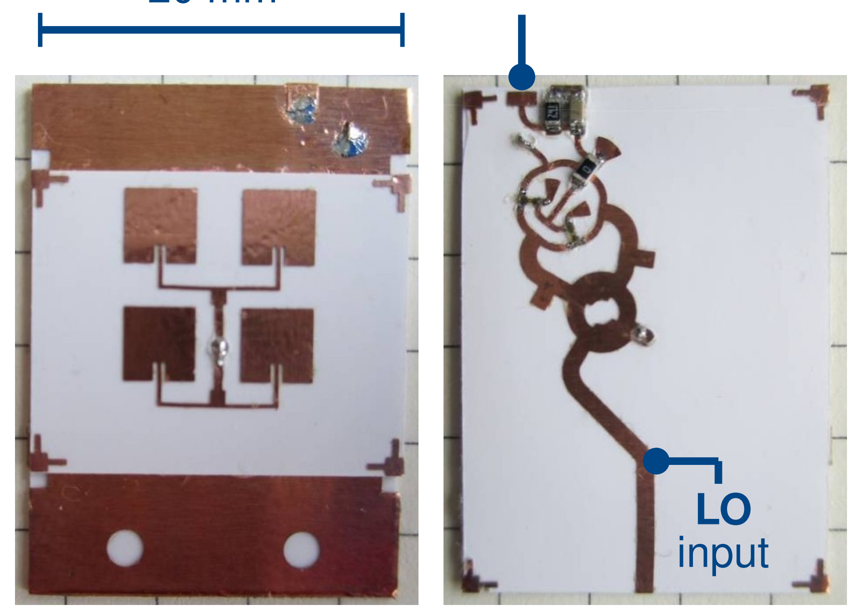
- ✔ **Longest dipole**: receives the carrier at f0.
- ✔ **Schottky diode bridge**: generates the second harmonic (2f0).
- ✔ **Shortest dipole**: irradiate 2f0 in an orthogonal polarization.

24-GHz Doppler radar (1/2)



$$f_\delta = 2 f_0 \frac{v}{c_0}$$

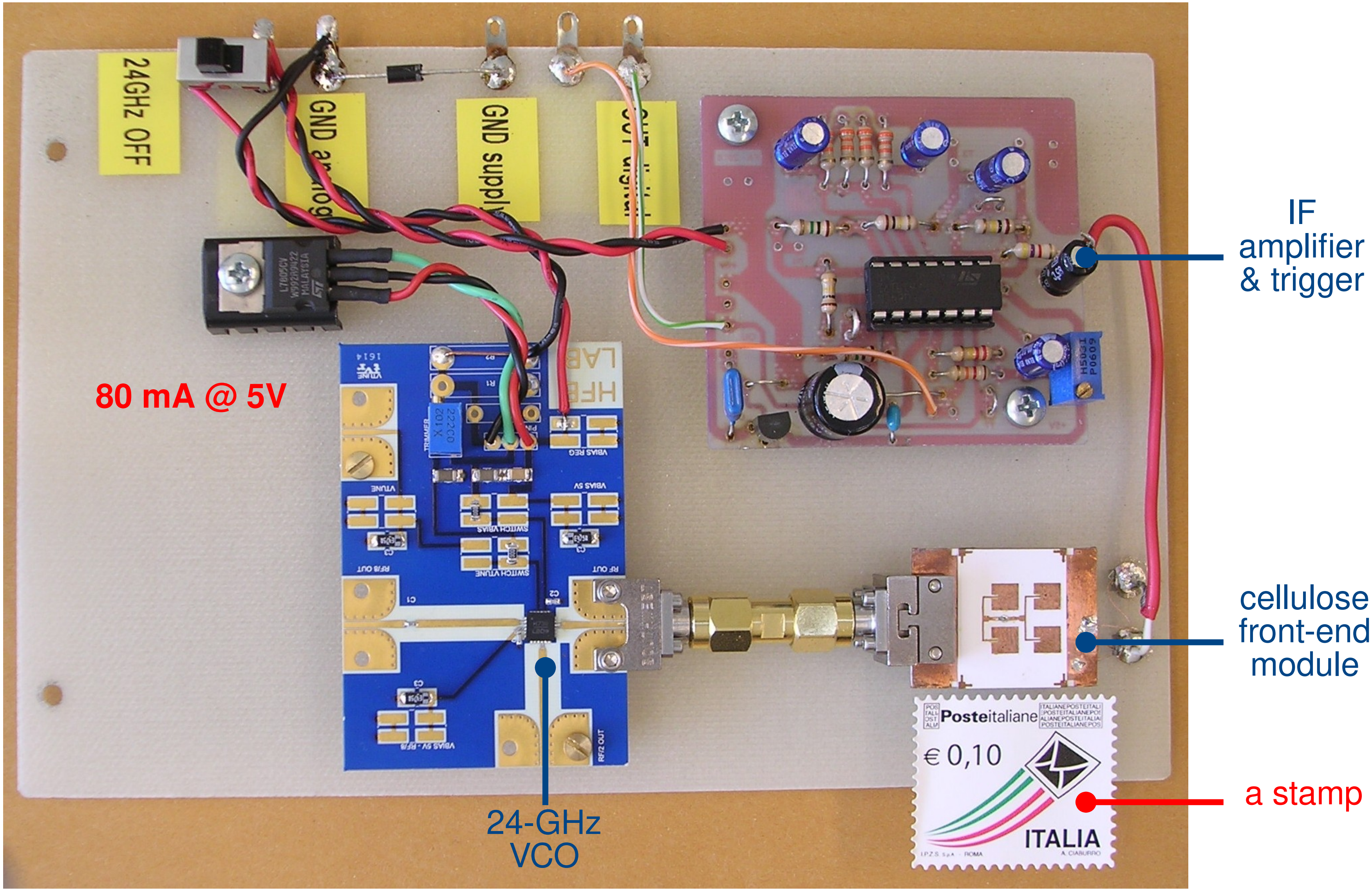
Doppler shift
160 Hz per m/s
@ 24 GHz



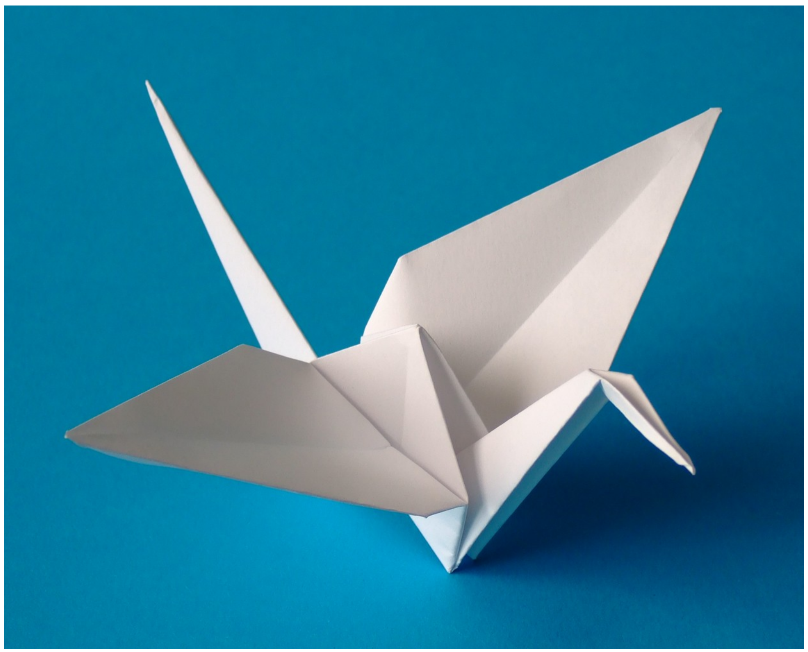
top side   bottom side

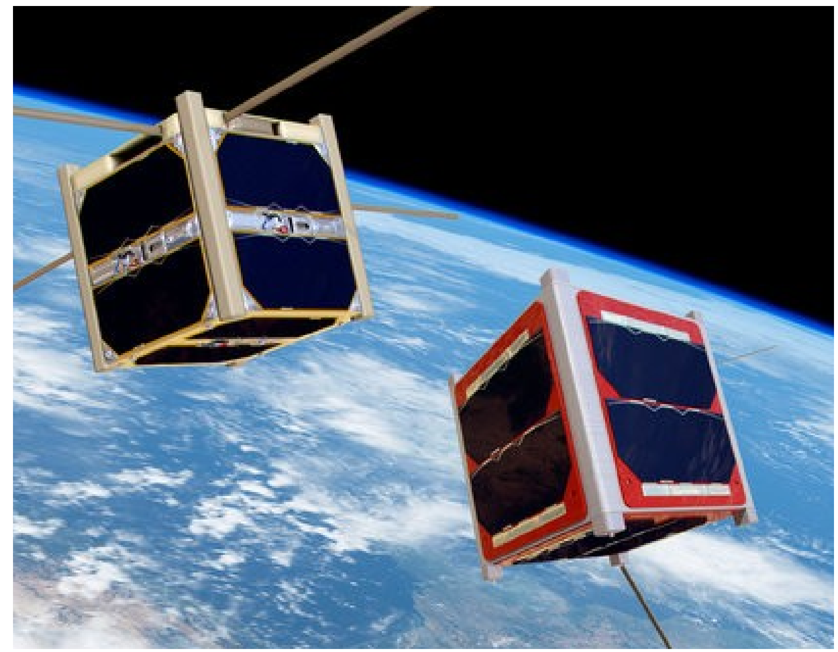
- ✔ **Applications**: movement sensor, intelligent lighting systems, etc.
- ✔ **True 24-GHz multi-layer circuit on cellulose !**

24-GHz Doppler radar (2/2)



Looking at the future ...





- ✔ "**Paper**" has flown in space missions since sixties !
- ✔ **Why not building "origami" Cubesats on paper?**

Conclusion

Apollo 8, December 1968

Voyager 1, February 1990

To really solve our problems we have ...
To really change our point of view