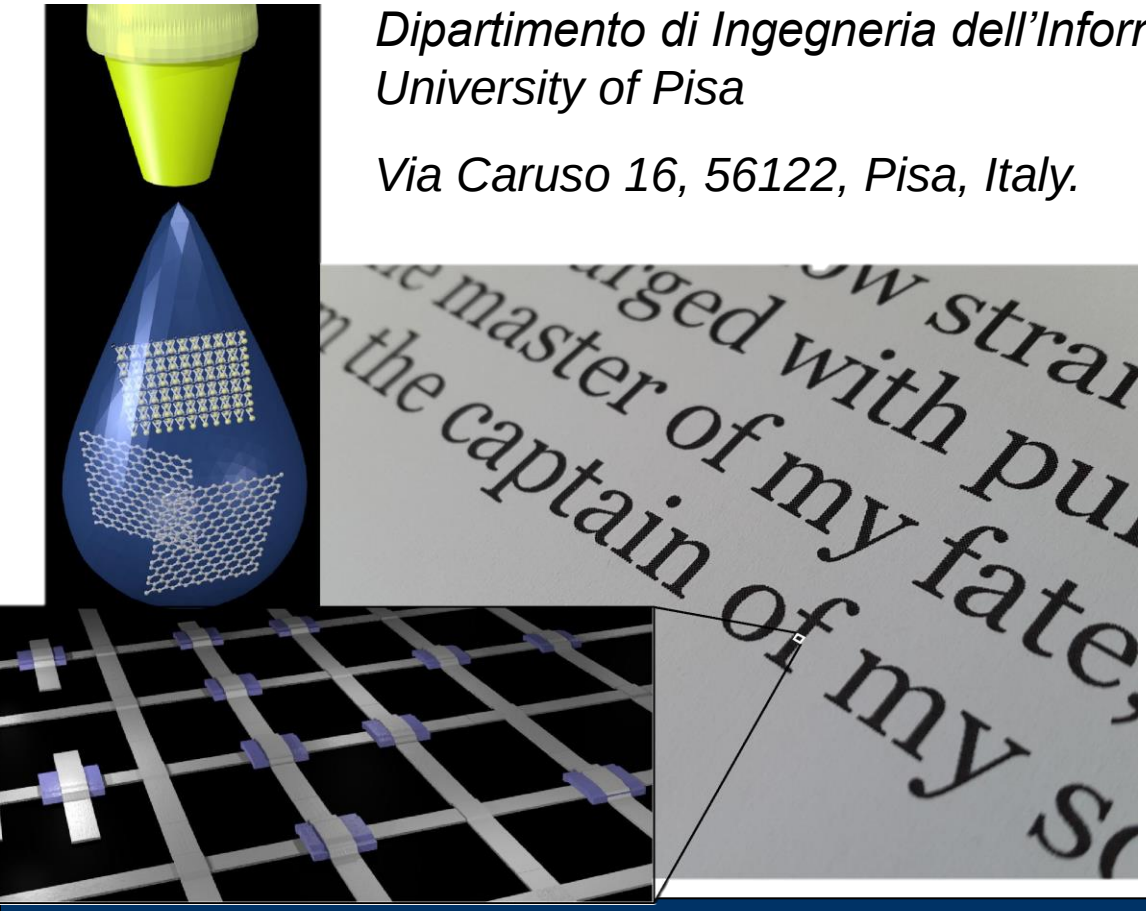
Nanomaterials for breakthrough innovations

G. Fiori



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University of Pisa

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gfiori@mercurio.iet.unipi.it

http://gianlucafiori.org

http://vides.nanotcad.com

Nanomaterials for breakthrough innovations ..... in electronics .....

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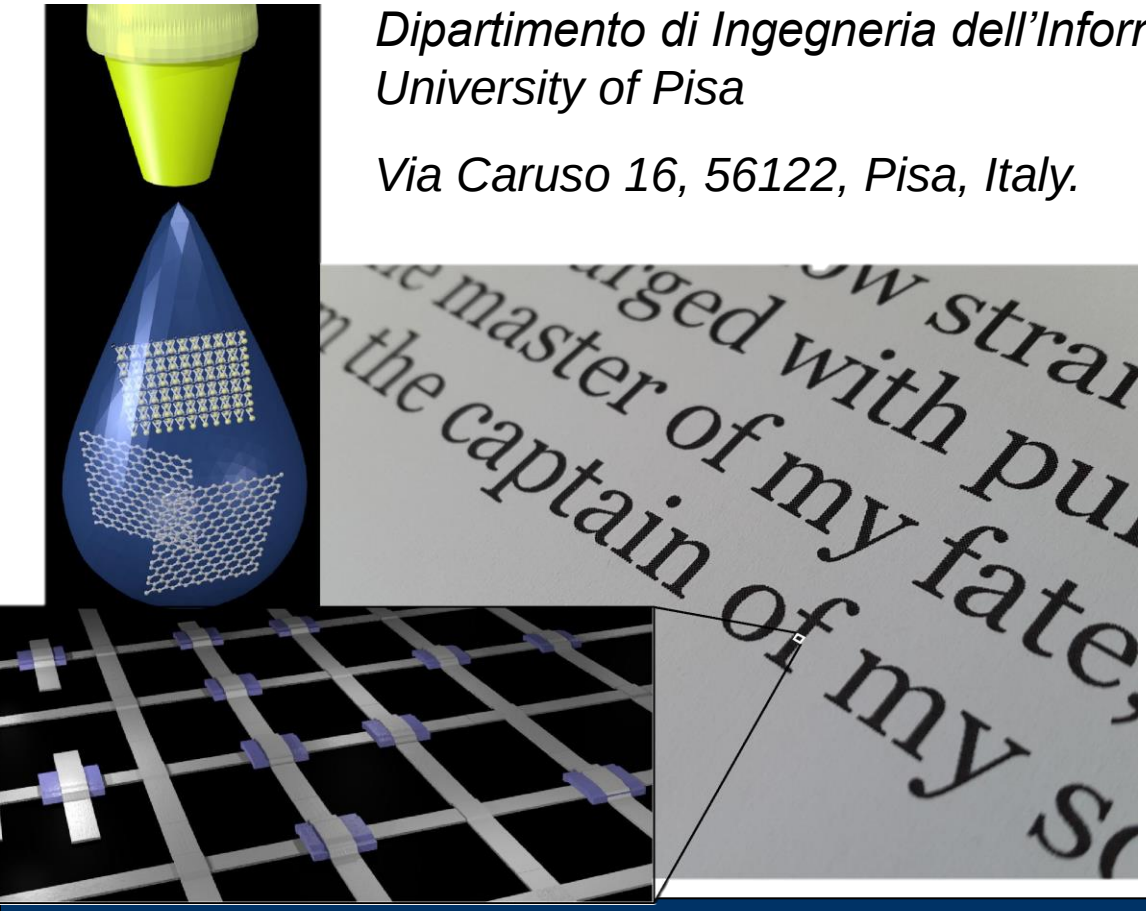

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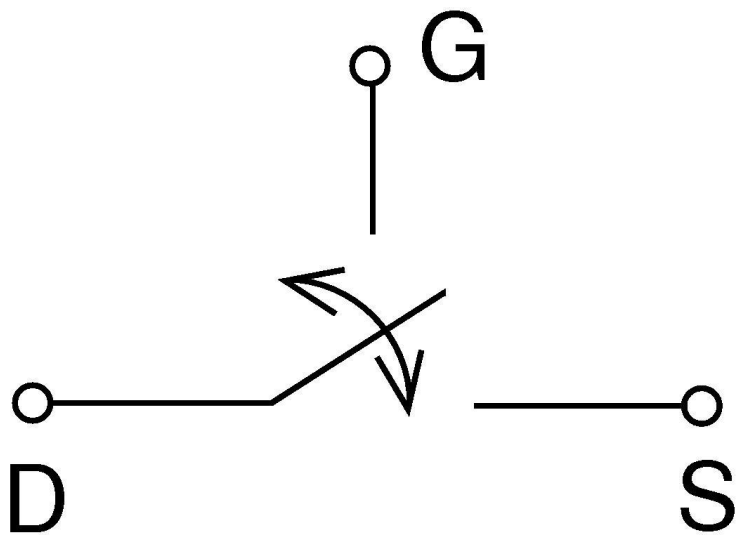
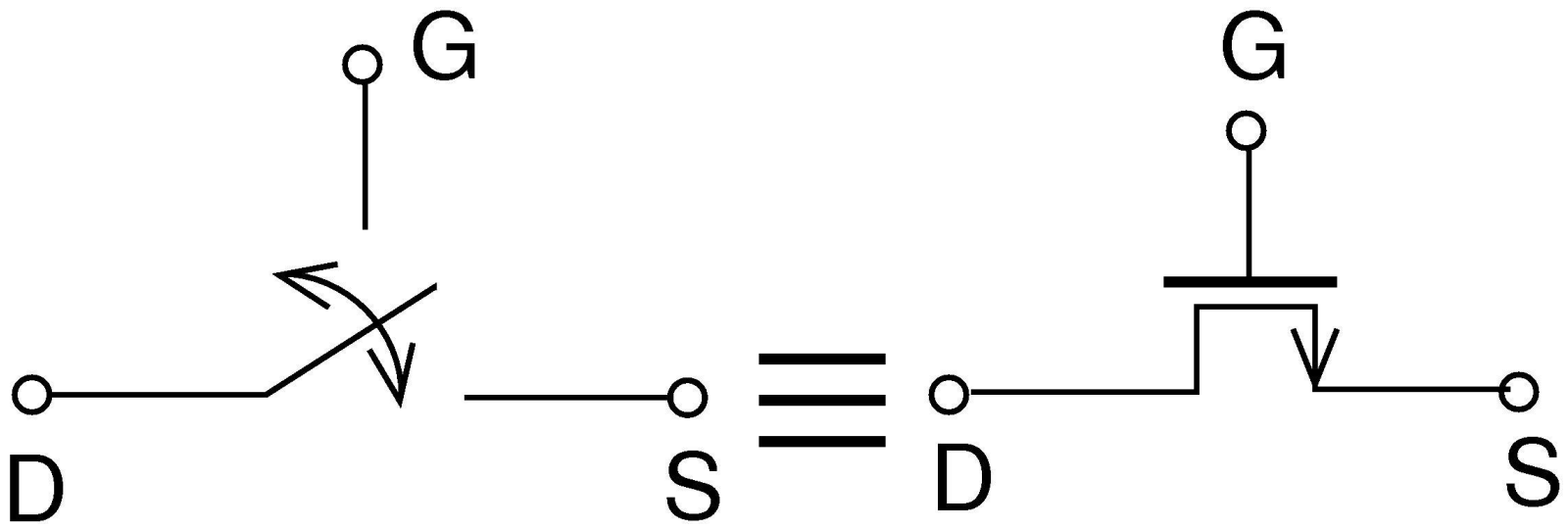
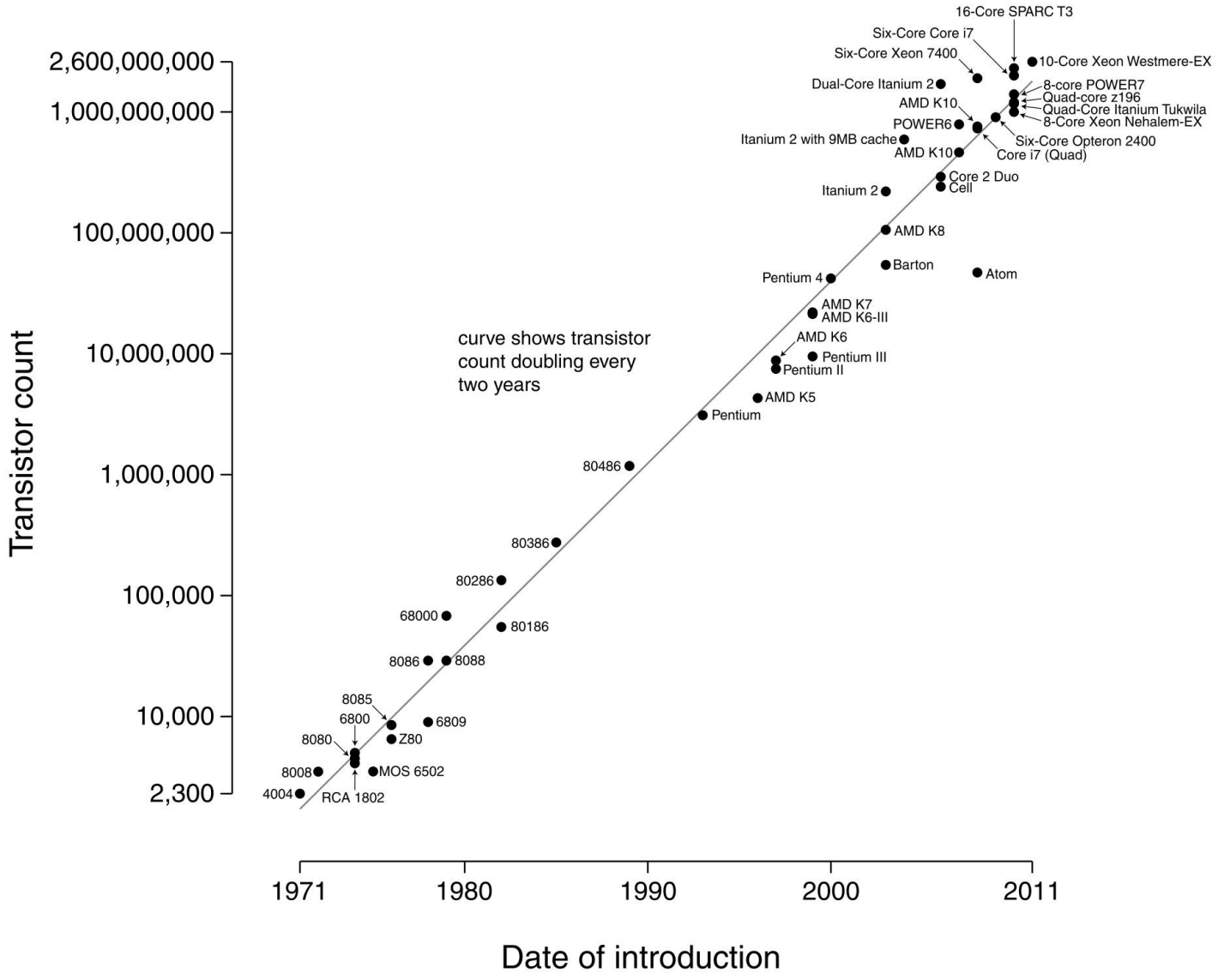
Main building block: the transistor



Main building block: the transistor

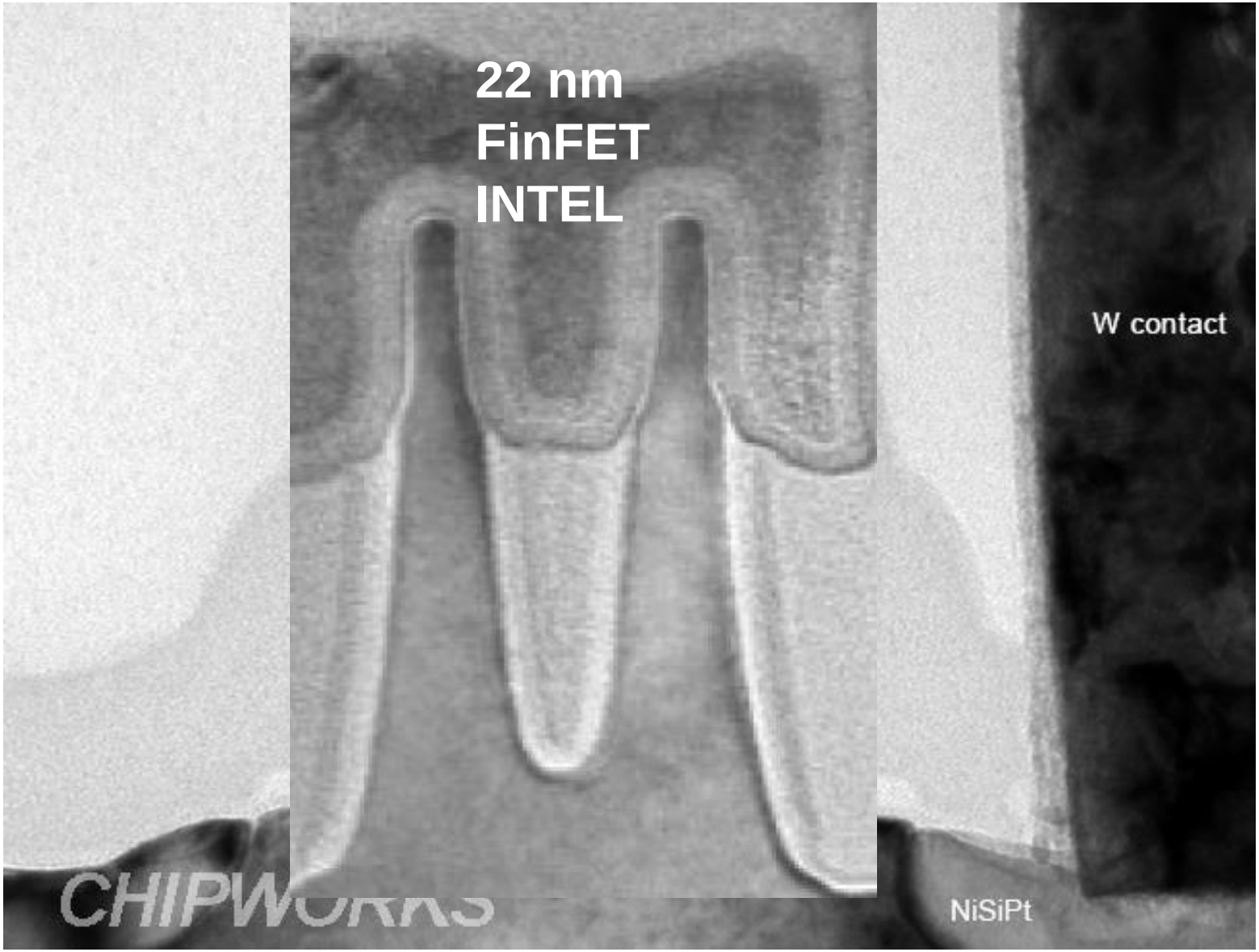


Microprocessor Transistor Counts 1971-2011 & Moore's Law

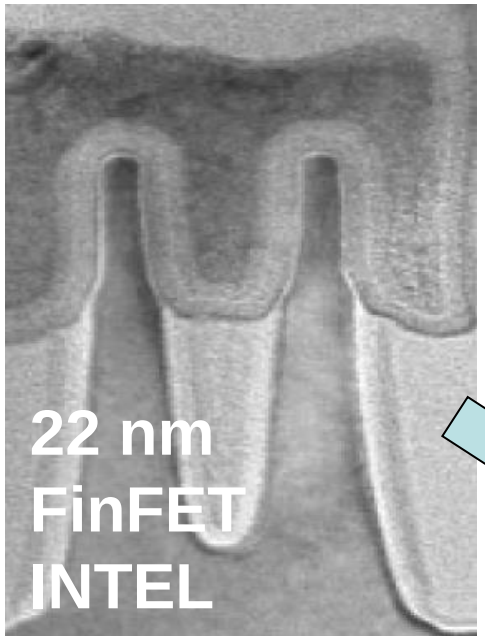


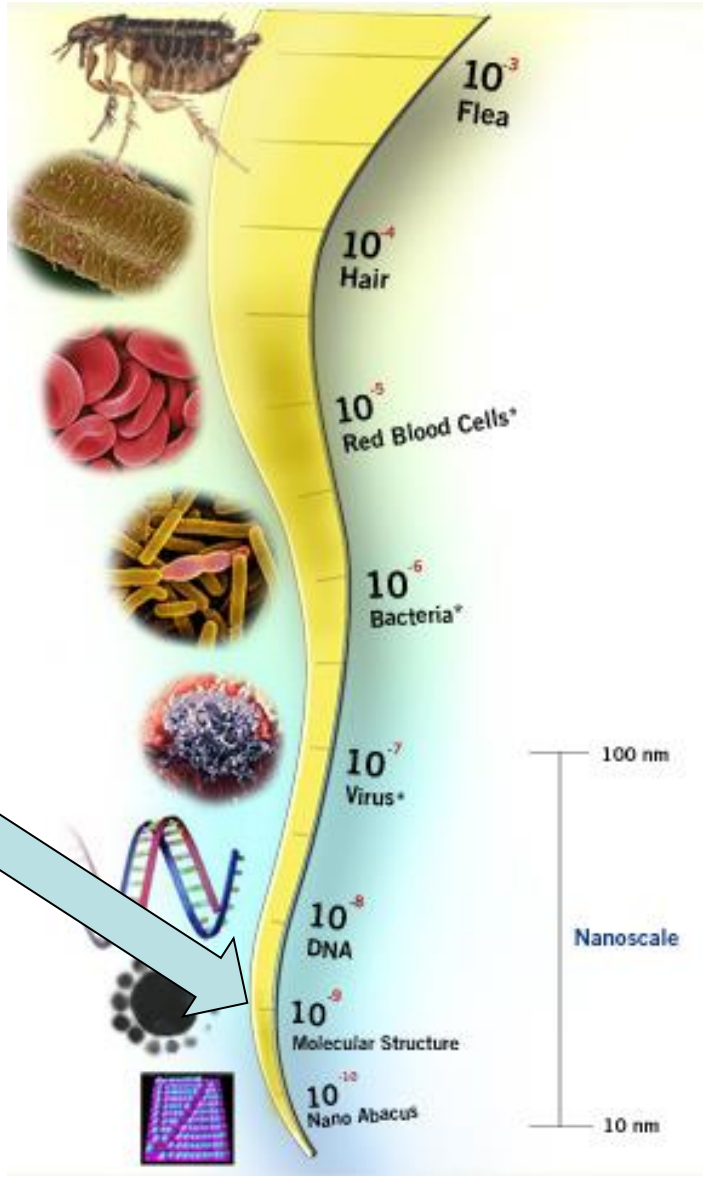
First Transistor Bardeen, Schockley, Brattain (1947)

Into the small

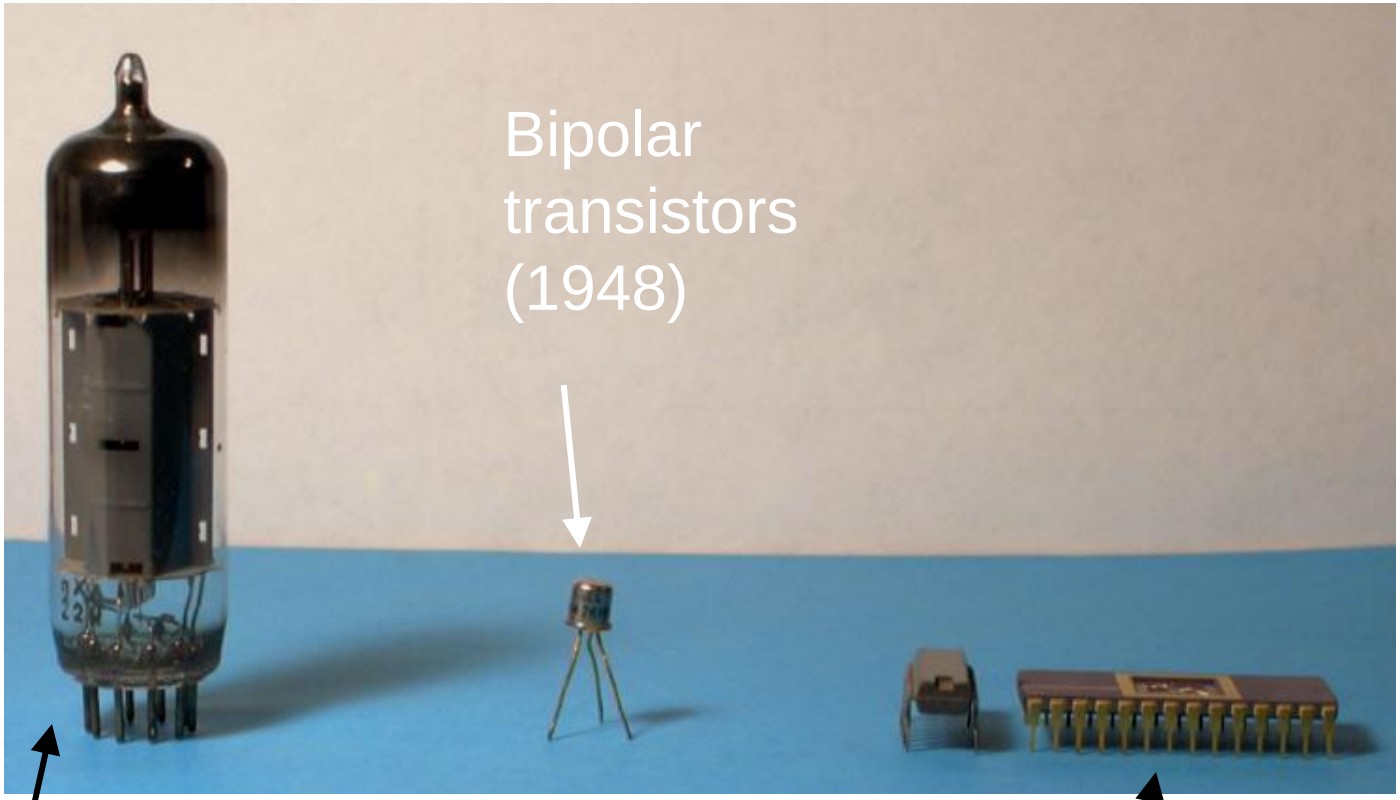


Nanometer scale





A long history.....

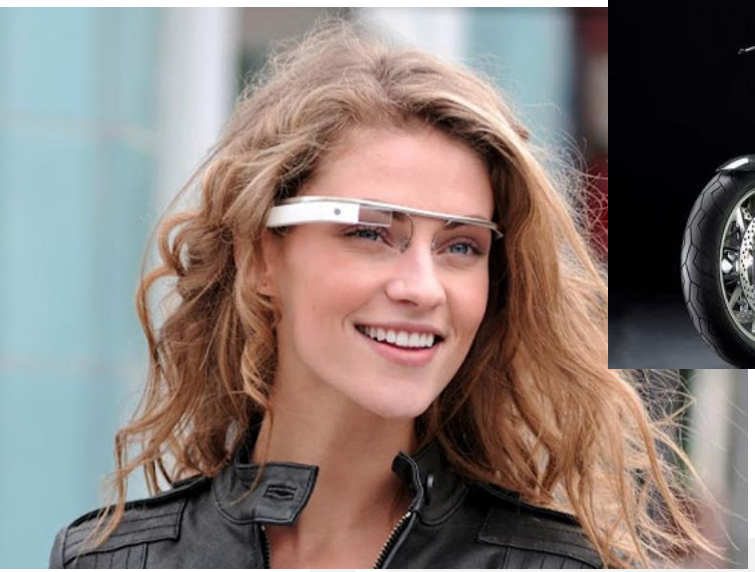


Vacuum
tube(1907)

Integrated
circuits

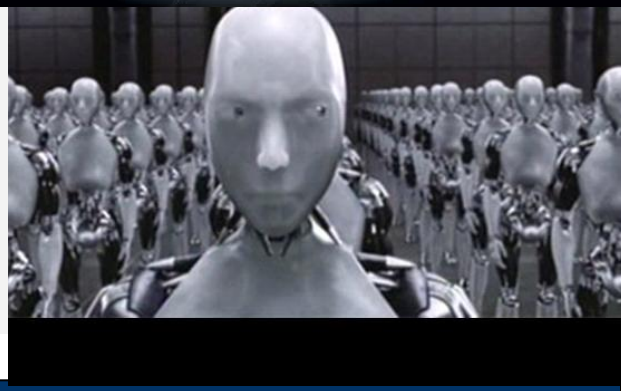
(1959)

A lot of applications



iPad Air

The power of



Power Density Issue

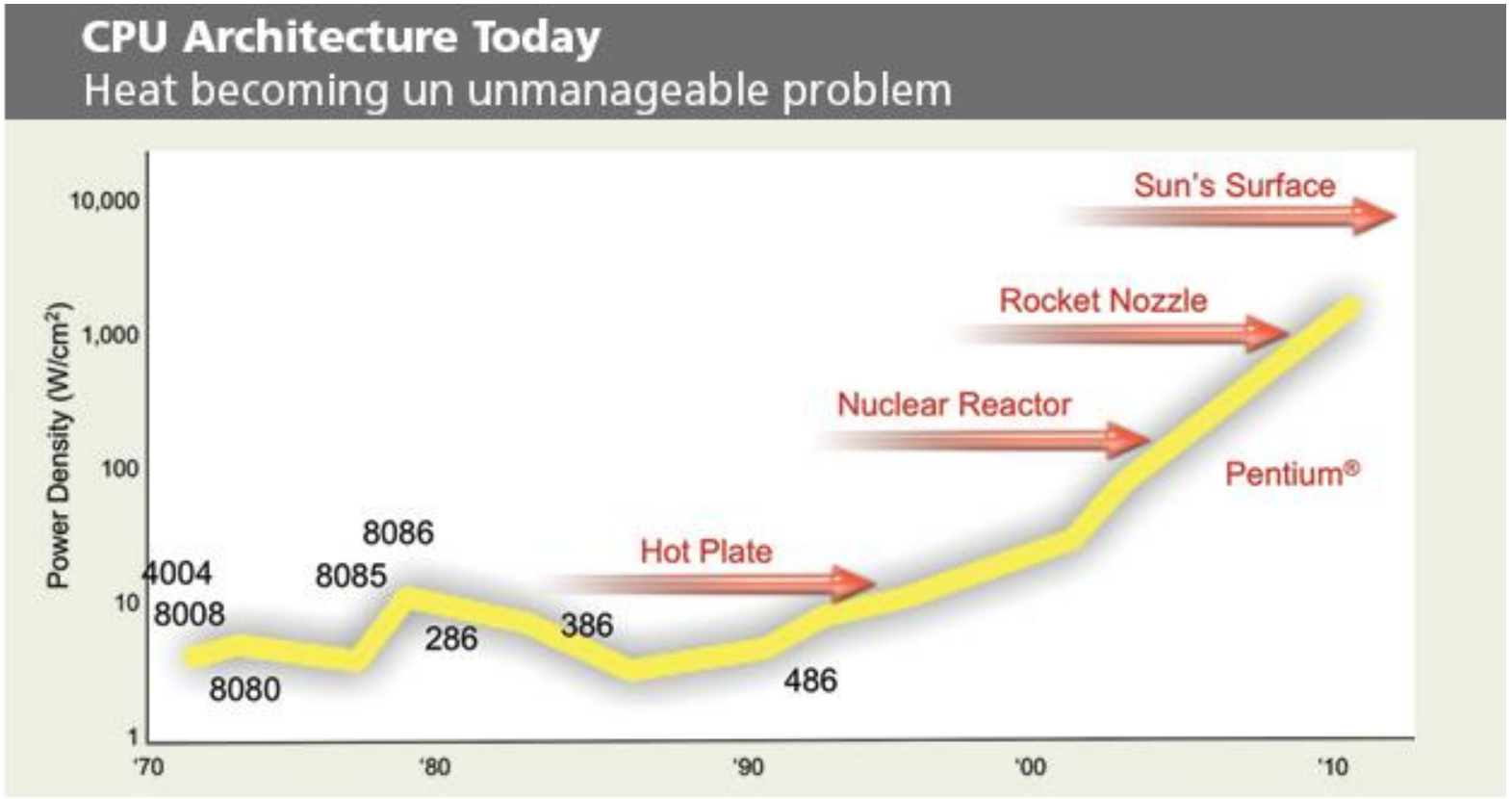
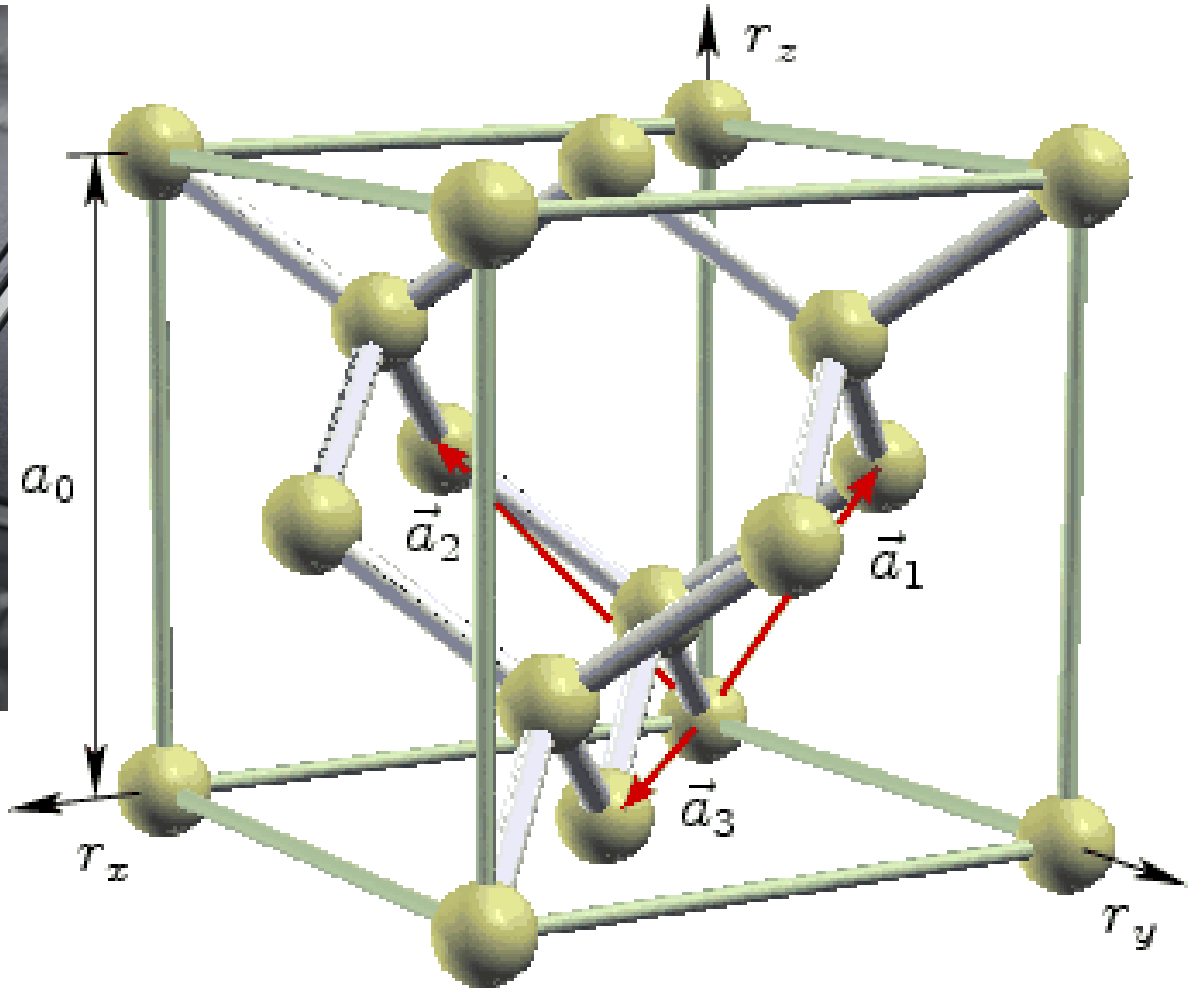


Figure 1. In CPU architecture today, heat is becoming an unmanageable problem. (Courtesy of Pat Gelsinger, Intel Developer Forum, Spring 2004)

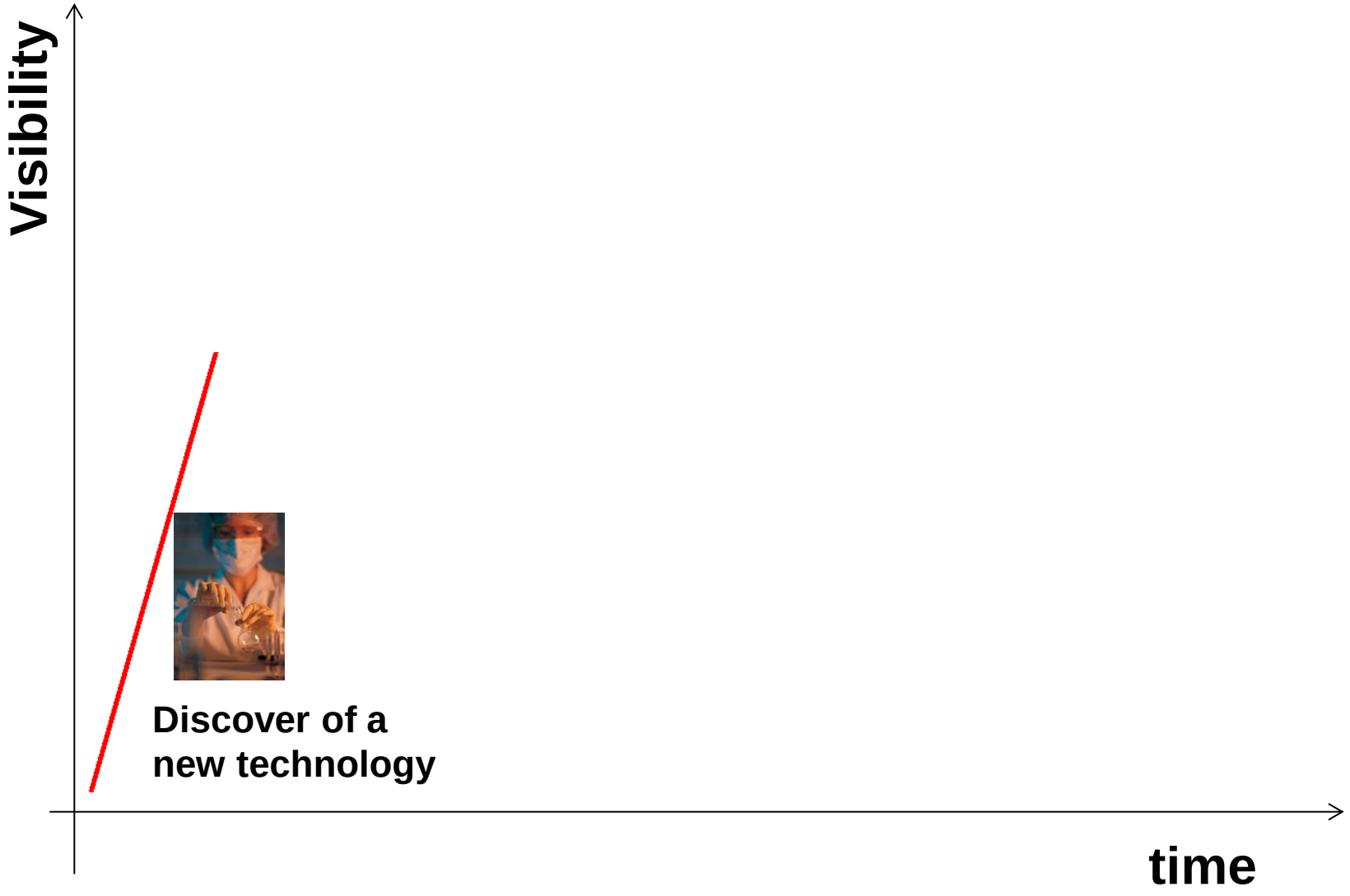
- **From:**http://www.cadalyst.com/hardware/workstation-performance-tomorrow039s-possibilities-viewpoint-column-6351

Q: How to keep on producing devices with improved performances?

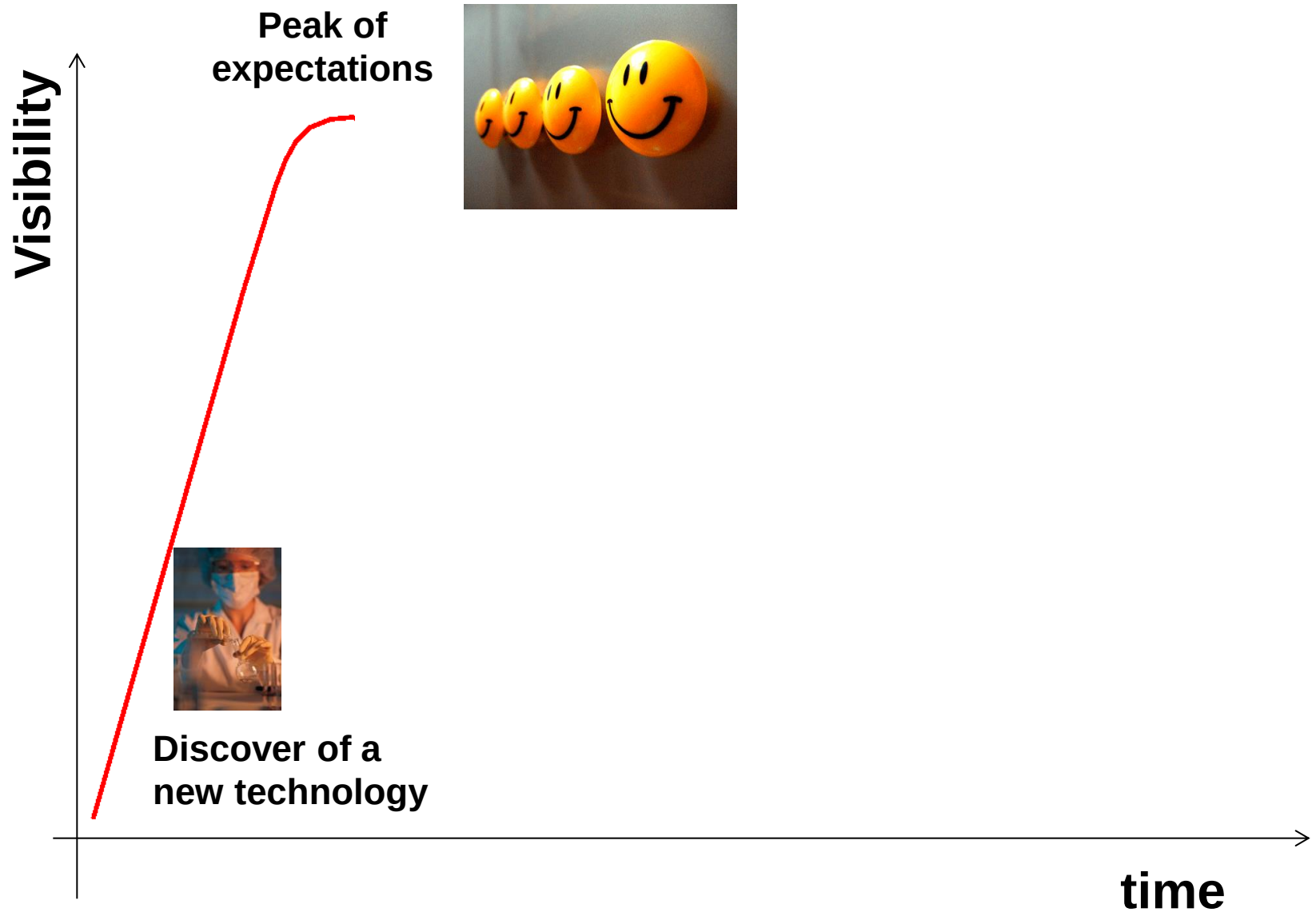
Silicon



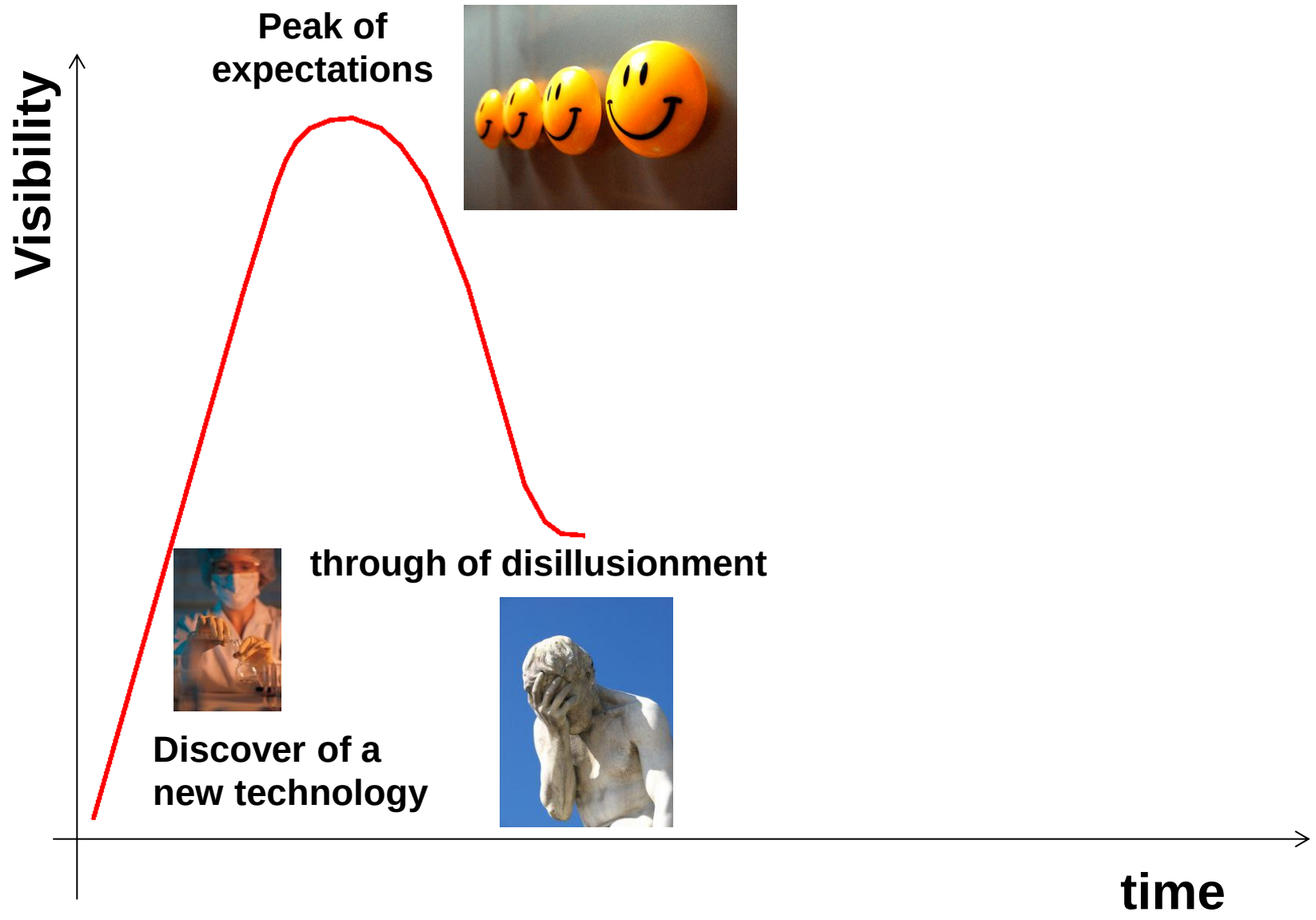
hypes/hopes curve



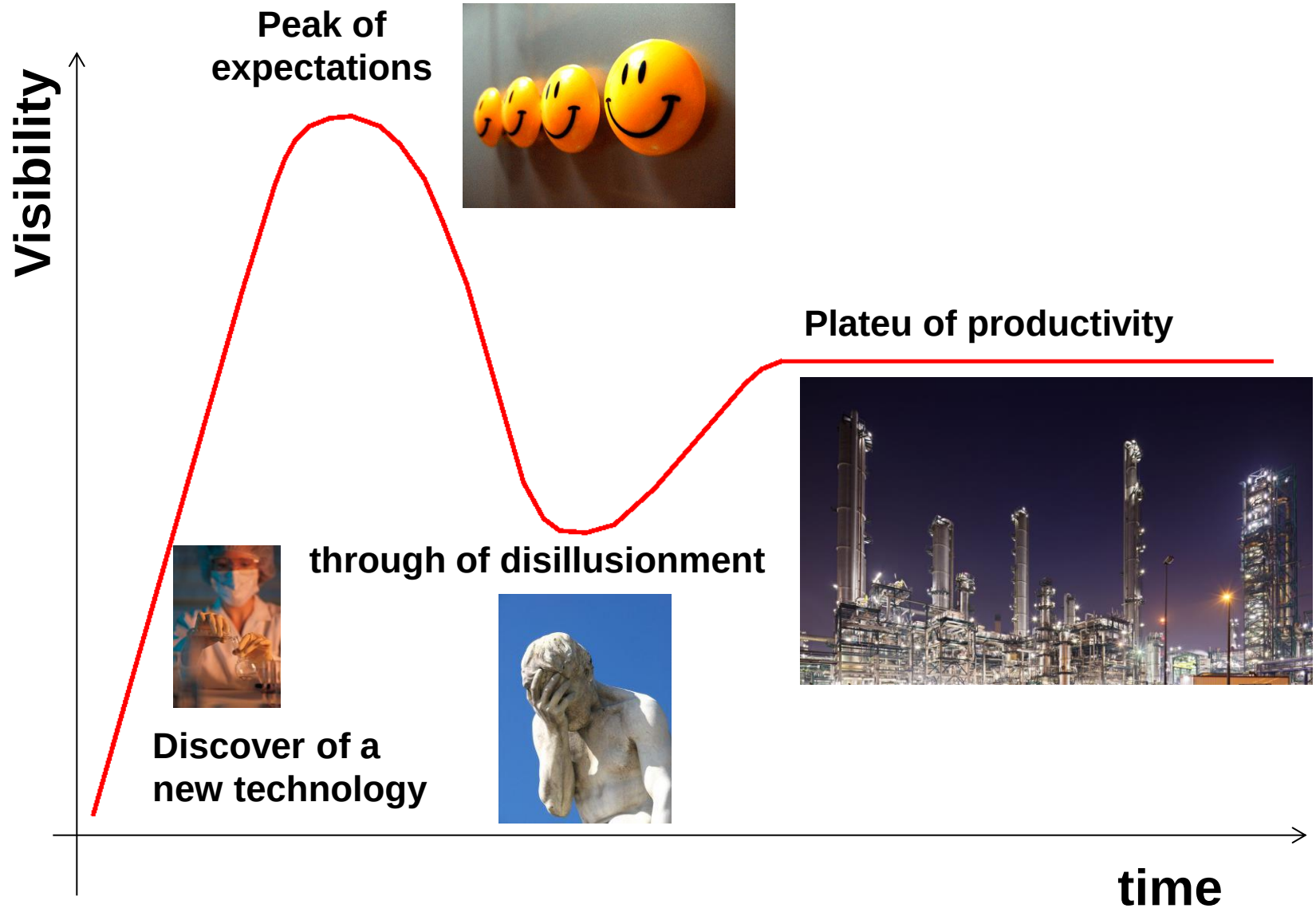
hypes/hopes curve

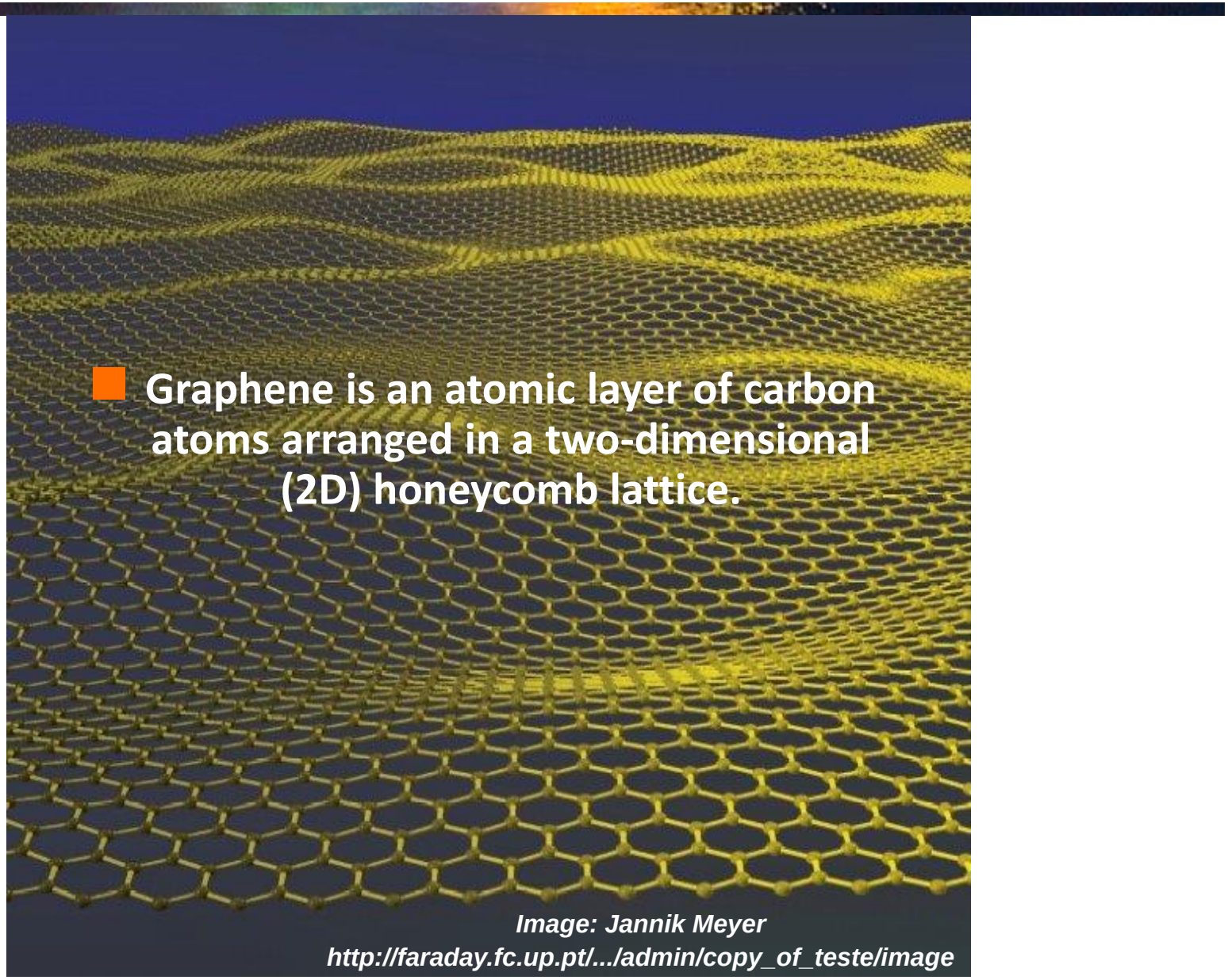


hypes/hopes curve

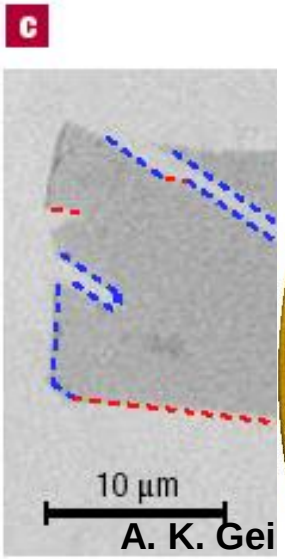


hypes/hopes curve




Graphene is an atomic layer of carbon atoms arranged in a two-dimensional (2D) honeycomb lattice.
Image: Jannik Meyer
http://faraday.fc.up.pt/.../admin/copy_of_teste/image

- **2D Allot Novosel**



A. K. Gei

ect in Atomically
bon Films

ı,[1]* S. V. Morozov,[2] D. Jiang,[1]
. V. Grigorieva,[1] A. A. Firsov[2]

- K.
- K.
- K.

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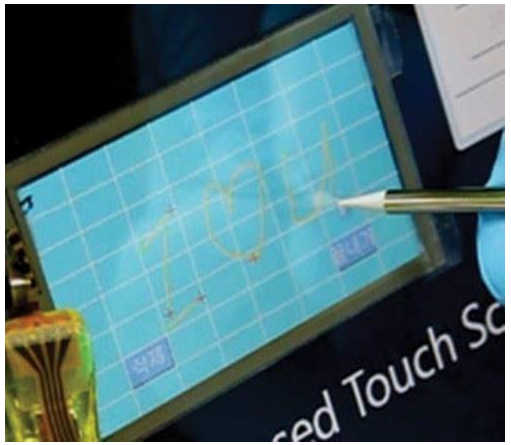
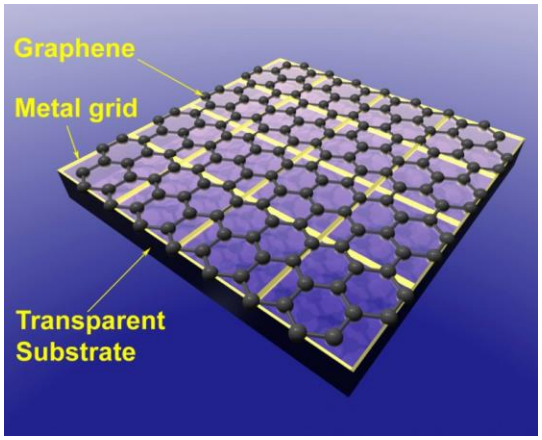
The wonder material

- Large mobility (>10^5 cm^2/Vsec)
- Transparent (>90% transparency for a single monolayer)
- Large ther y
- Mechanica
  properties:



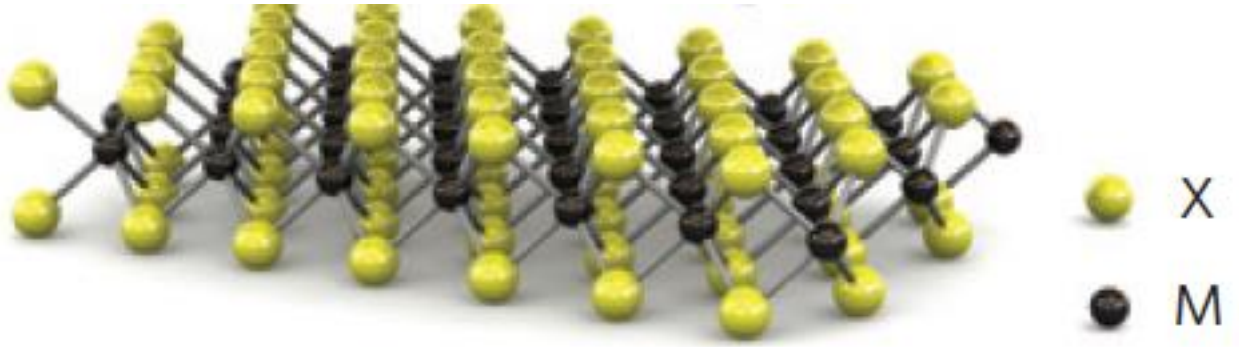


“Killer Application”

Transition metal dichalgogenides (TMDCs)

- **Formula:**

MX_2



M: Transistion metal

group IV: Ti, Zr, Hf, …

group V: V, Nb, Ta, …

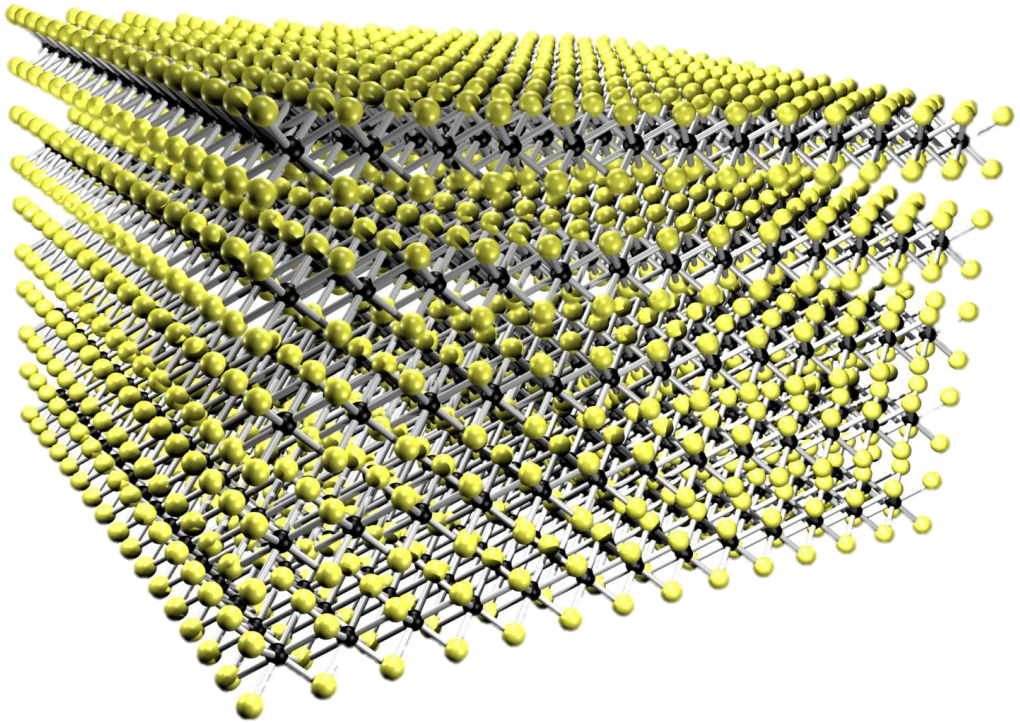
group VI: Mo, W,

X: chalgogenide: S, Se, Te

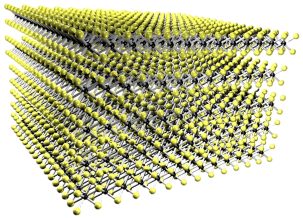
Energy gap 1-2 eV

Figure credits:
Wang et al. Nat Nano vol 7, 699, 2012

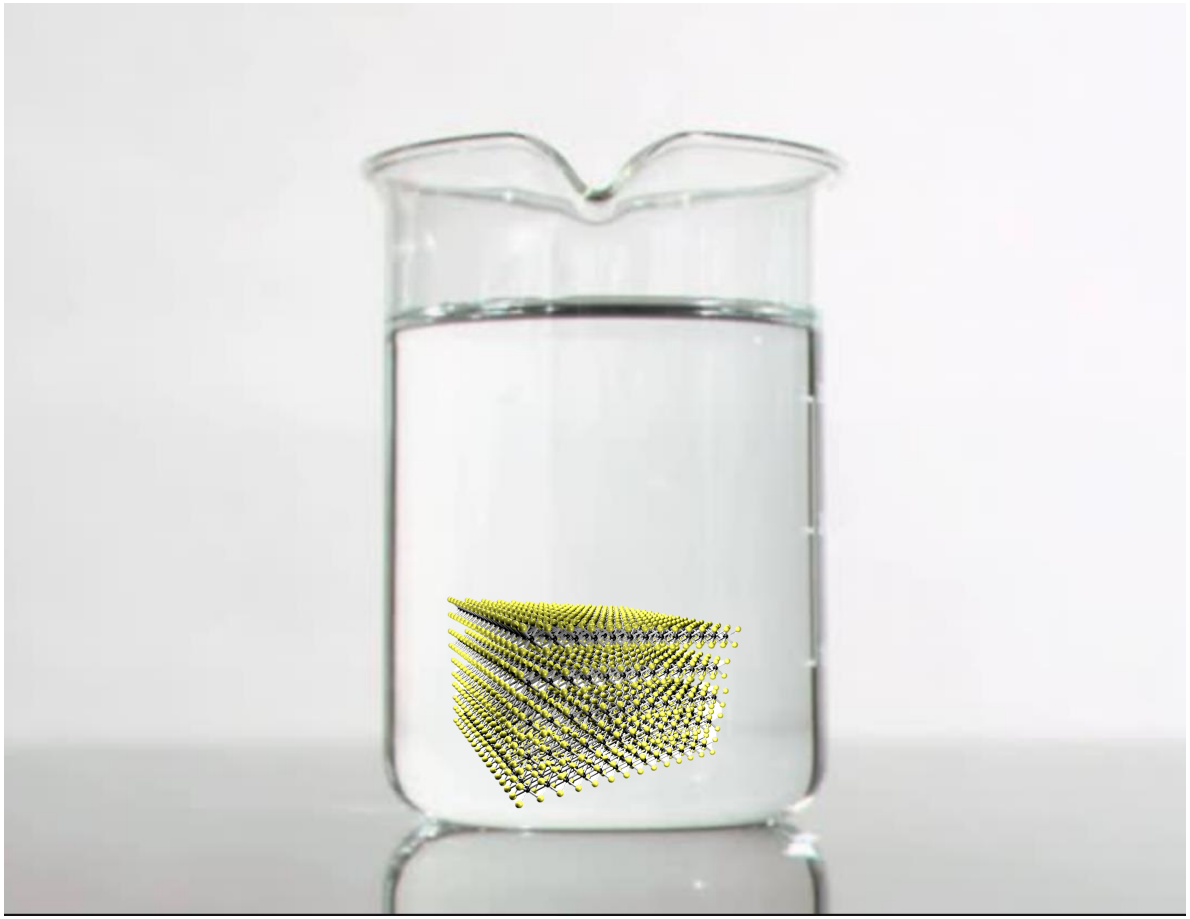
Layered Materials



Liquid Phase Exfoliation

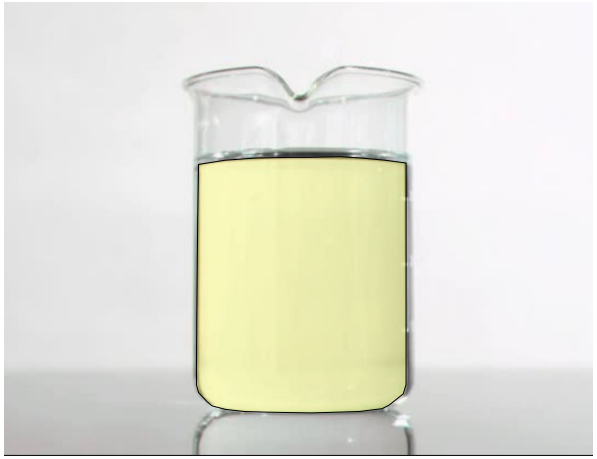


Liquid Phase Exfoliation



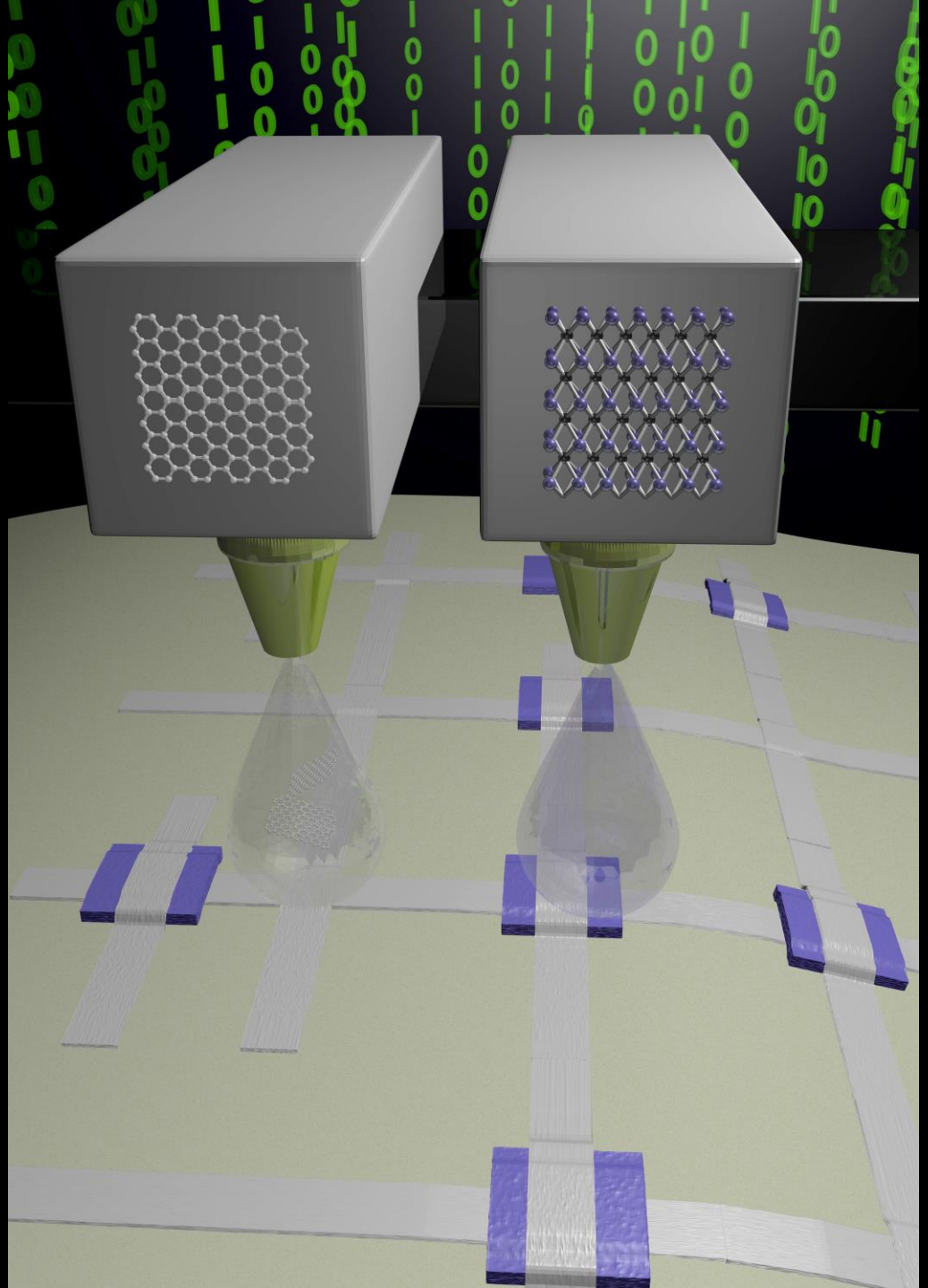
Liquid Phase Exfoliation

conducting



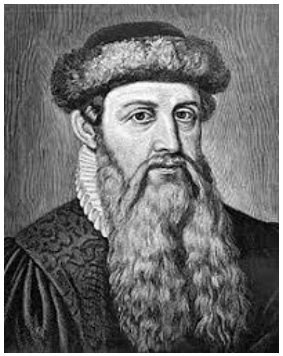
semi-conducting

insulating

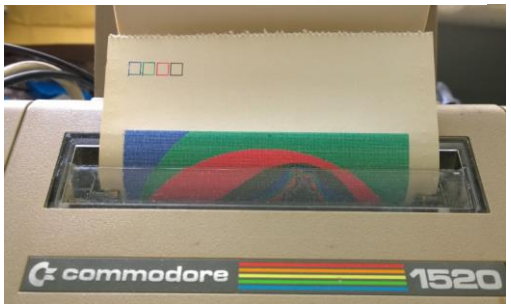


motivations

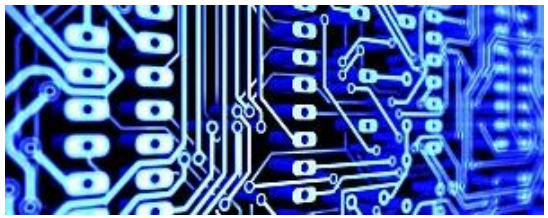
- The Development of printing techniques has paved the way towards mass production of books, leading to the ***democratization of knowledge.***



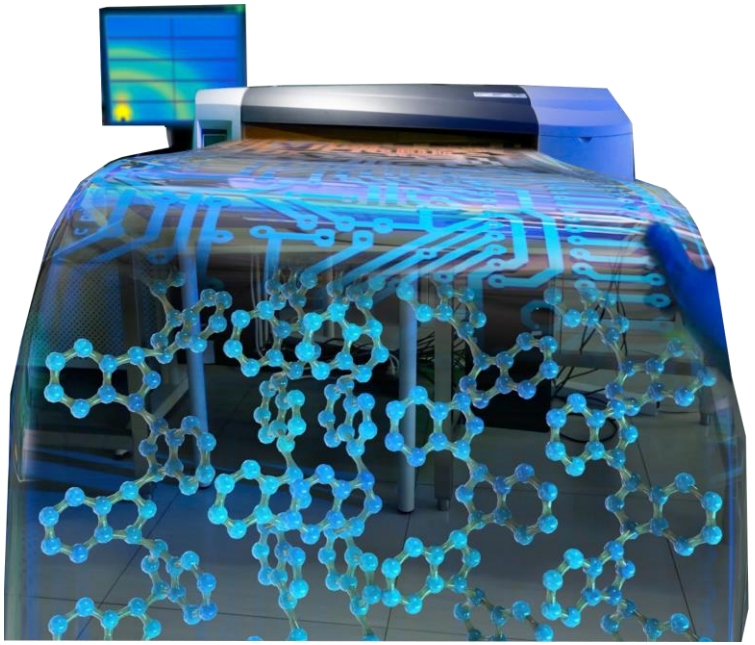
- **Desktop printing (early '80)** as a corner stone in the hystory of printing (*just-in-time*, wide-spread, i.e., offices not typographies)



- However, so far, this technology has mainly been limited to the printing of documents (books, magazines, etc.), but, ***what about if, in the ICT era, we managed to extend printing technologies also to fabricate electronic circuits?***



the vision



- from expensive, huge, specialized semiconductor fabs
- to cheaper, fully customizable, distributed desktop fabrication

the vision

- Today

Rigid, produced in series, not customizable (designed by somebody else than the user)

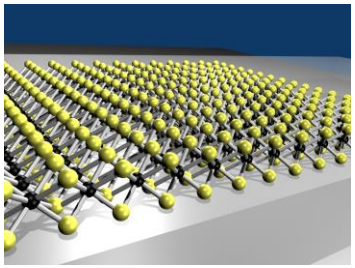
- Tomorrow

Flexible, foldable, fully customized, designed and fabricated by the user (and cheaper)

.... and on paper

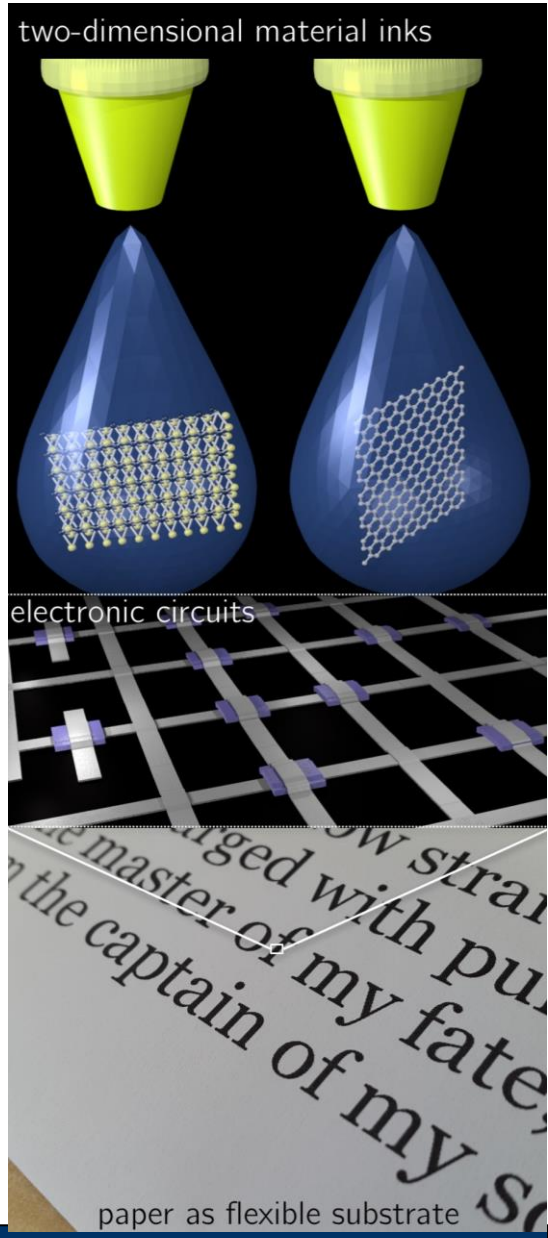
motivations

- **Why 2DMs?** current inks with limited mechanical (poor bendability, ε < 3%), electrical properties (μ <10 cm^2/Vs) and stability.



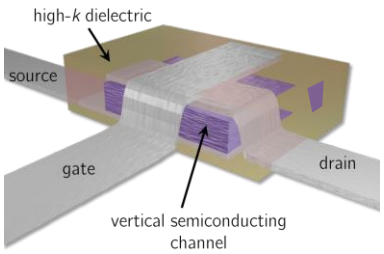
- **2DMs** can be the **"game changer":**
  - extraordinary mechanical (ε < 10%), electrical properties (μ >10 cm^2/Vs).
  - plethora of materials (i.e., semiconducting, conducting and insulating).
  - Heterostructures.

- **Why now?** Recently demonstration [Al. et G. Fiori, C. Casiraghi, Nature Nano., 2017] of water-based bio-compatible 2DMs inks, *enabling heterostructure fabrication*.

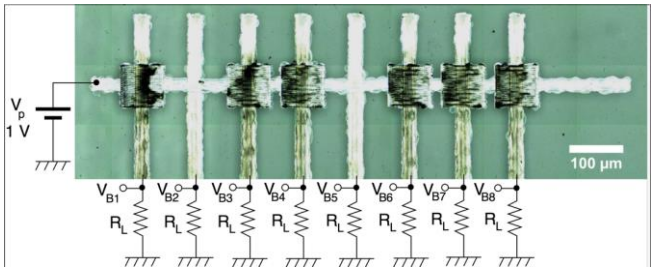


the vision *beyond* state-of-the-art

novel FET heterostructures

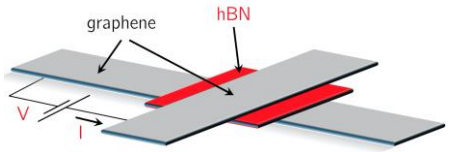


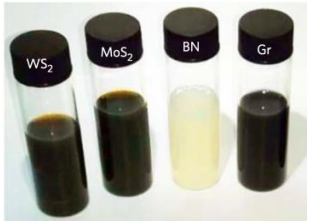
ROM memory



[Al. et G. Fiori, C. Casiraghi, Nat. Nano, 2017]

capacitor

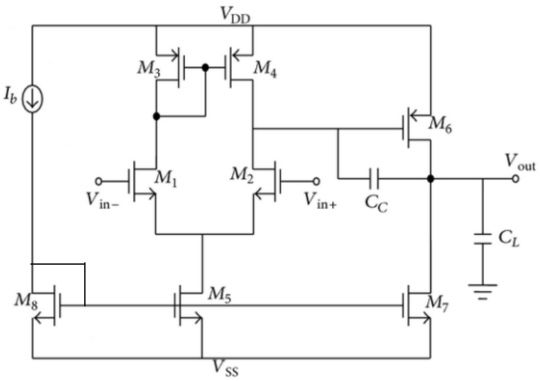




2DM inks

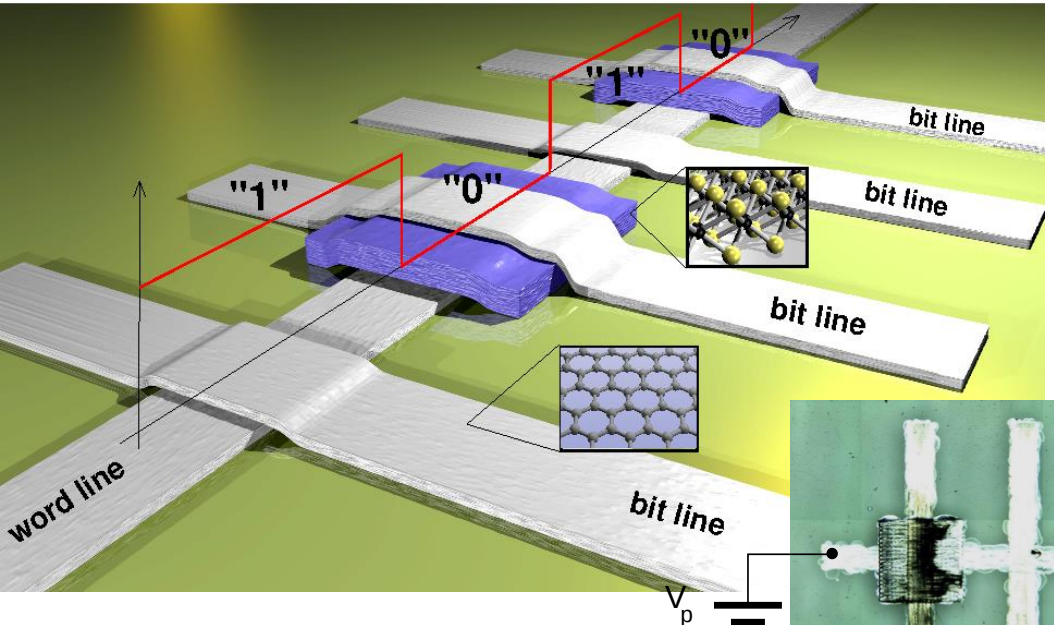
MANCHESTER 1824
The University of Manchester

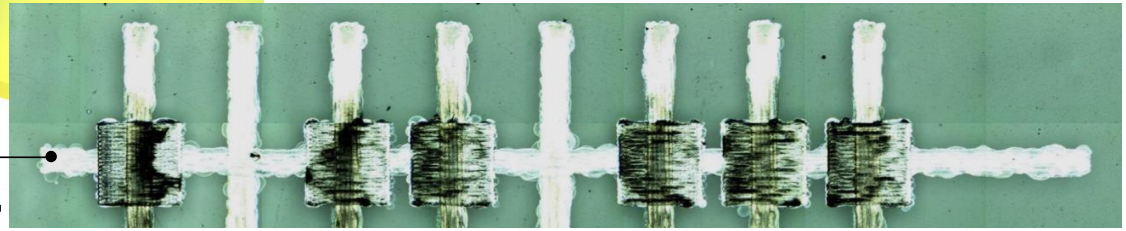
Printed electronic device toolbox

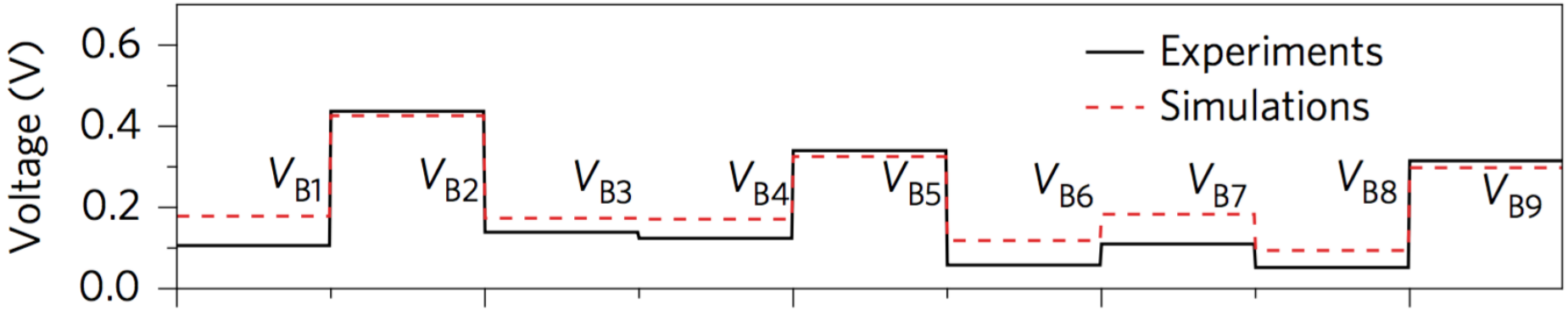


CMOS operational amplifier

First demo of Full-2D-based Ink-Jet ROM

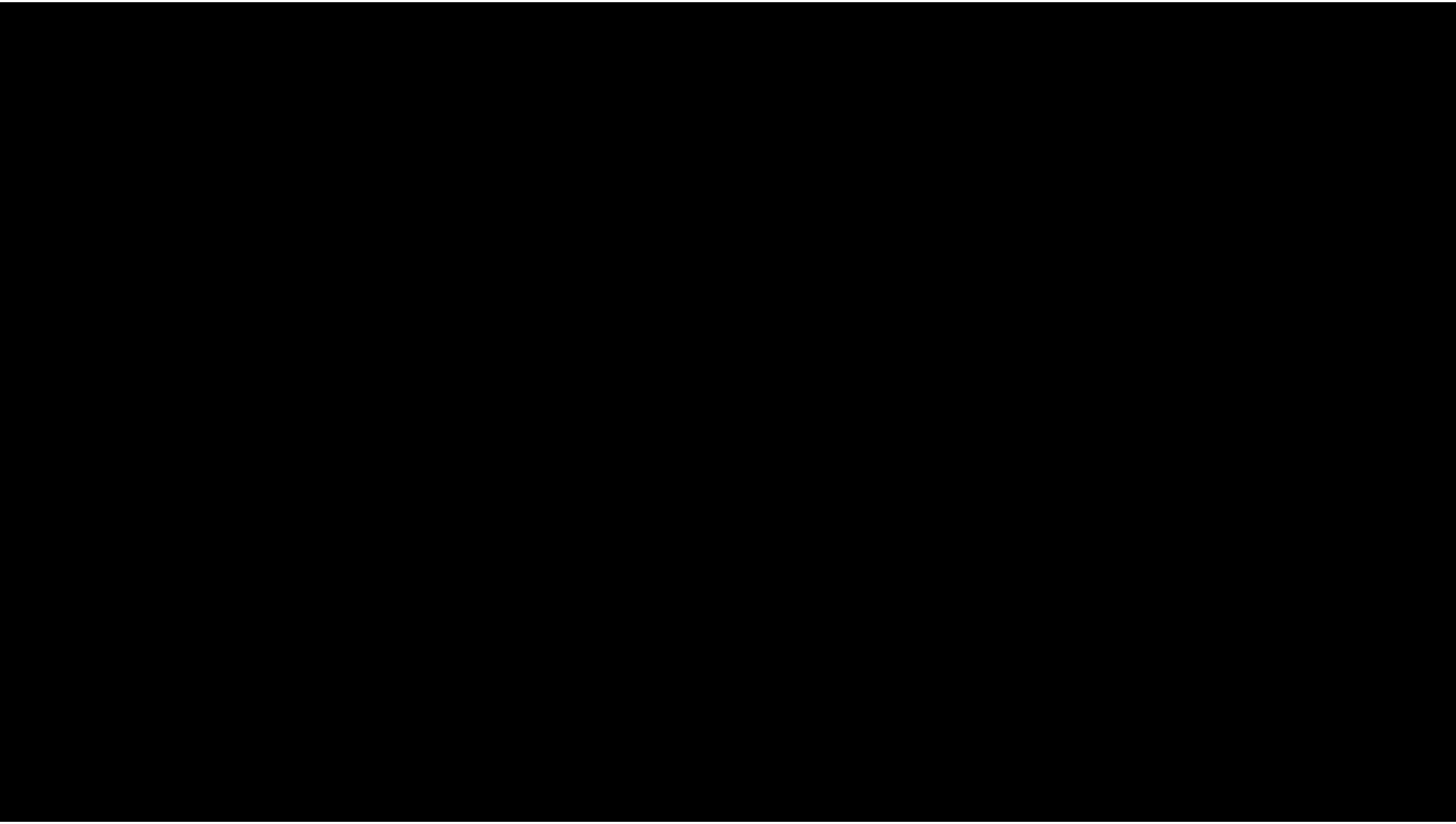






[D. McManus et al. Nat. Nanotechnology, 2017]

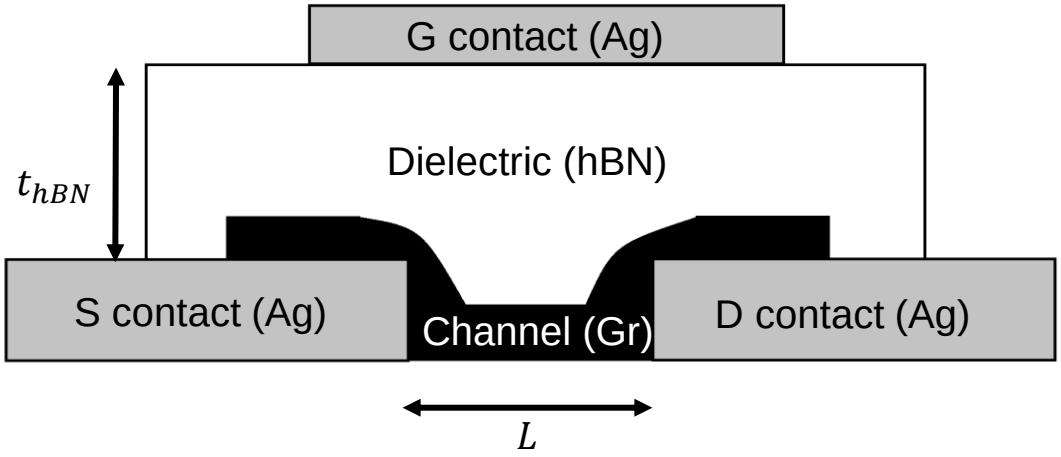
Proof of concept: 2D-based Inkjet ROM



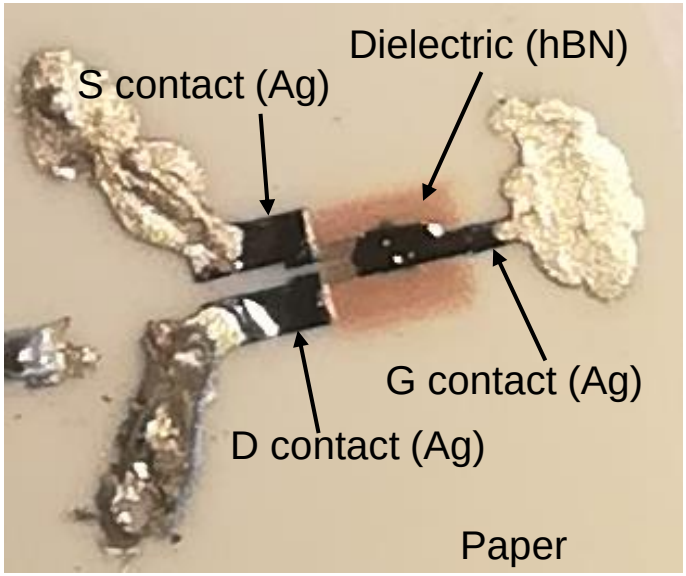
Joint collaboration between University of Manchester (C. Casiraghi) and University of Pisa

Fully inkjet graphene-FET on paper

- Printed on paper.
- Structure:
  1. S and D contacts (Ag);
  2. Channel (Gr);
  3. Dielectric (hBN);
  4. G contact (Ag).

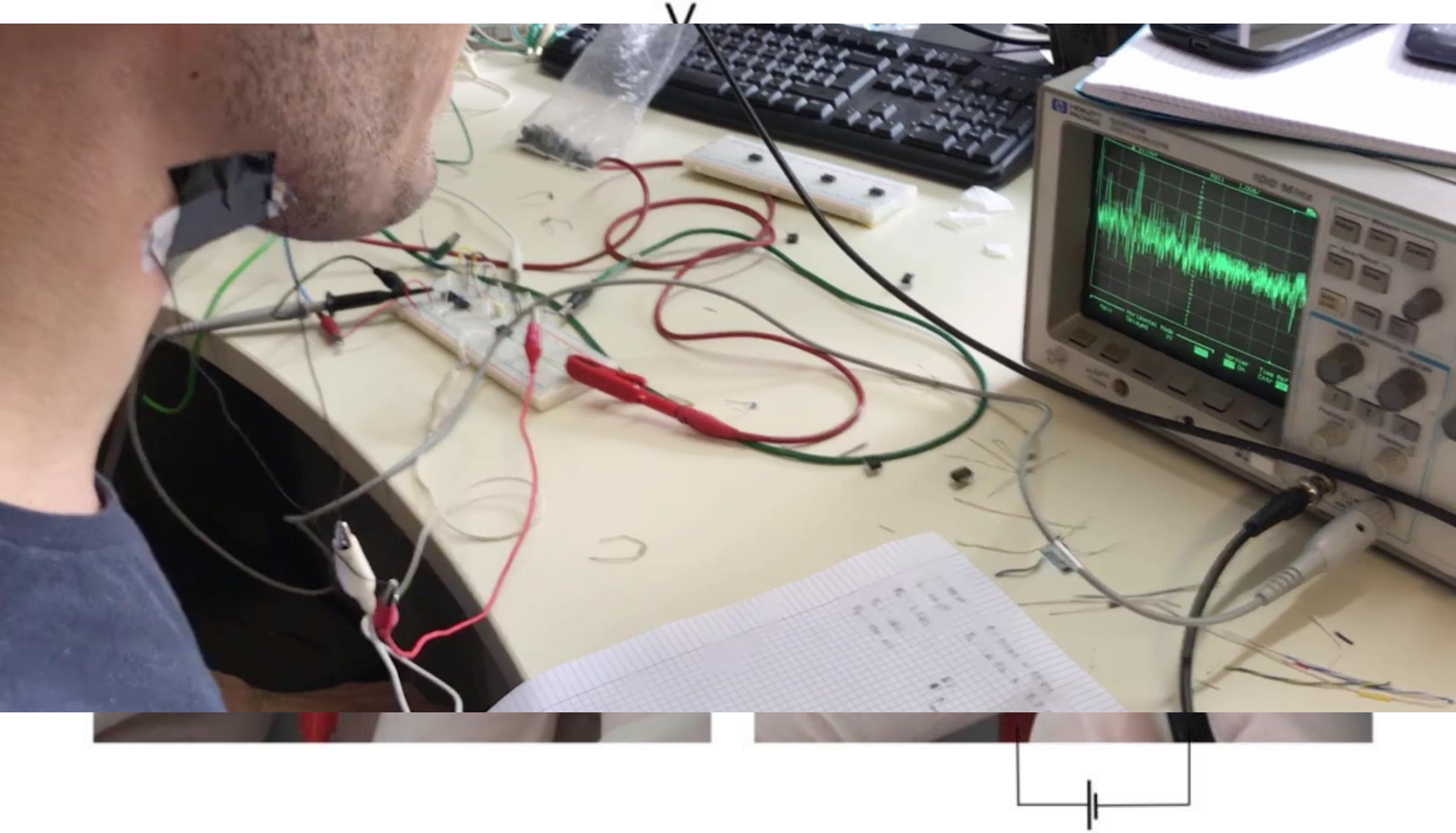


Schematic cross section

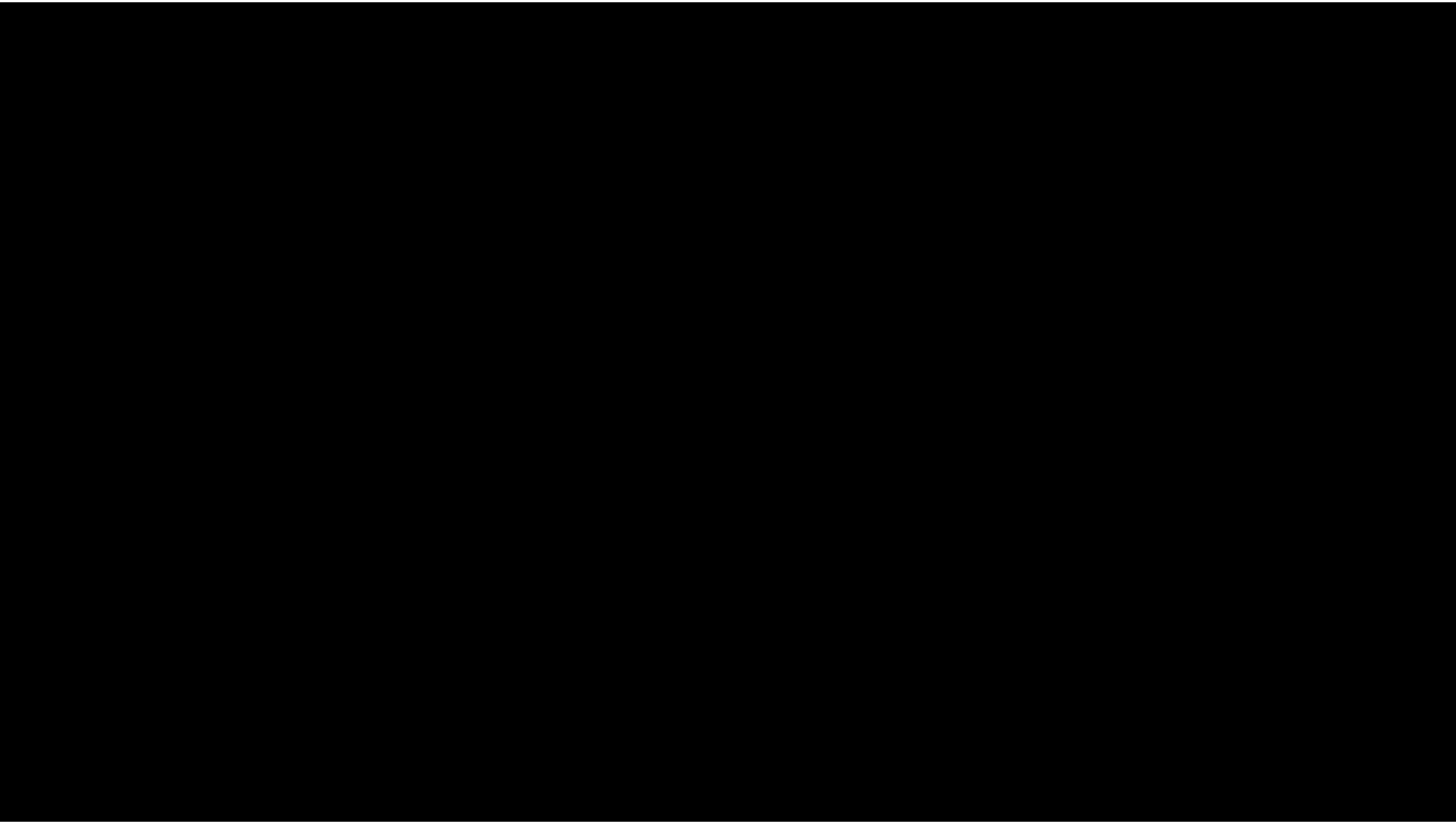


- Channel parameters: $\begin{cases} L \approx 70\ \mu m \\ W \approx 500 \mu m \\ R \approx 10K\Omega \end{cases}$

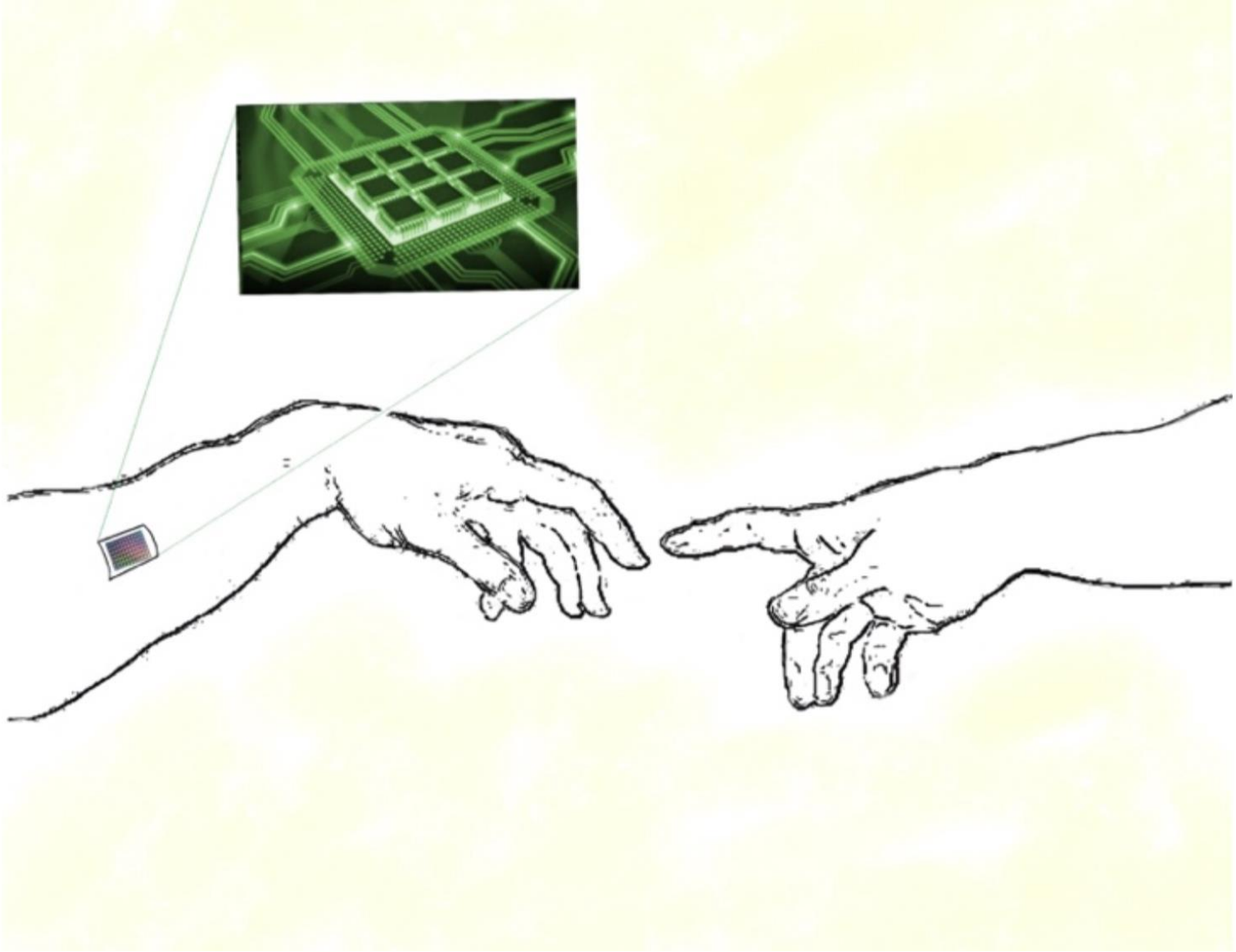
Strain gauge



Strain gauge



WASP Project



WASP Project

The University of Manchester
Ink preparation
Device printing
Sensor fabrication

Università di Roma Tor Vergata
Opto-electronic device simulations
Energy system fabrication

ICN2 Institut Català de Nanociència i Nanotecnologia
BioSensor Design, characterization and fabrication

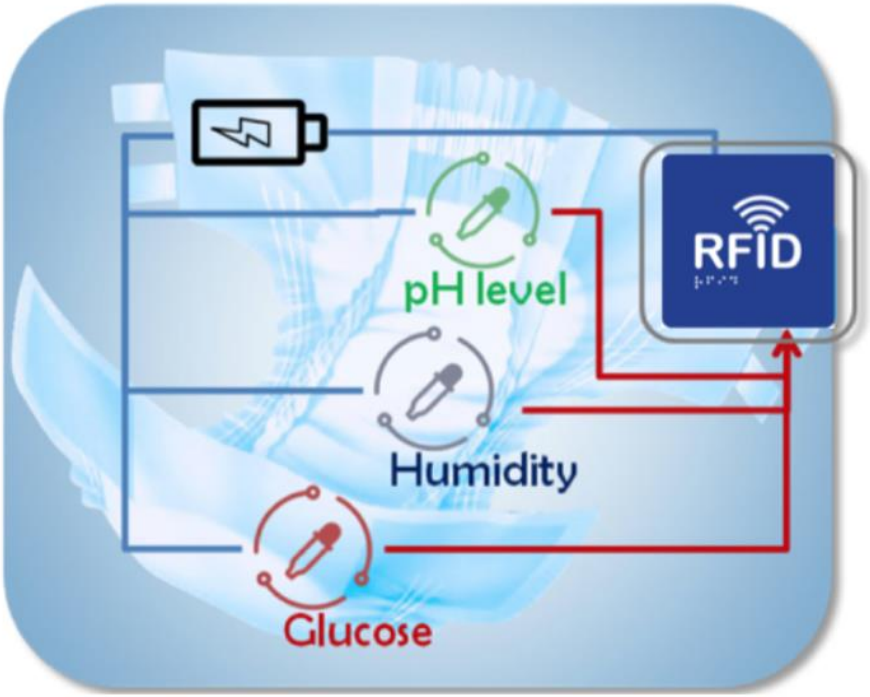
UNIVERSITÀ DI PISA
Multi-scale simulations of electronic devices and materials
Device printing and design

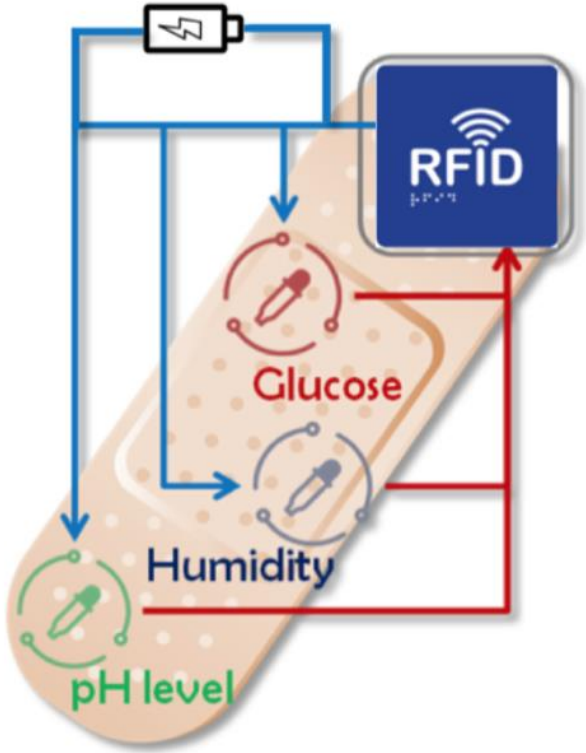
essity
SCA
Scalability assessement
Industrial Exploitation (end-user)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
Energy system fabrication

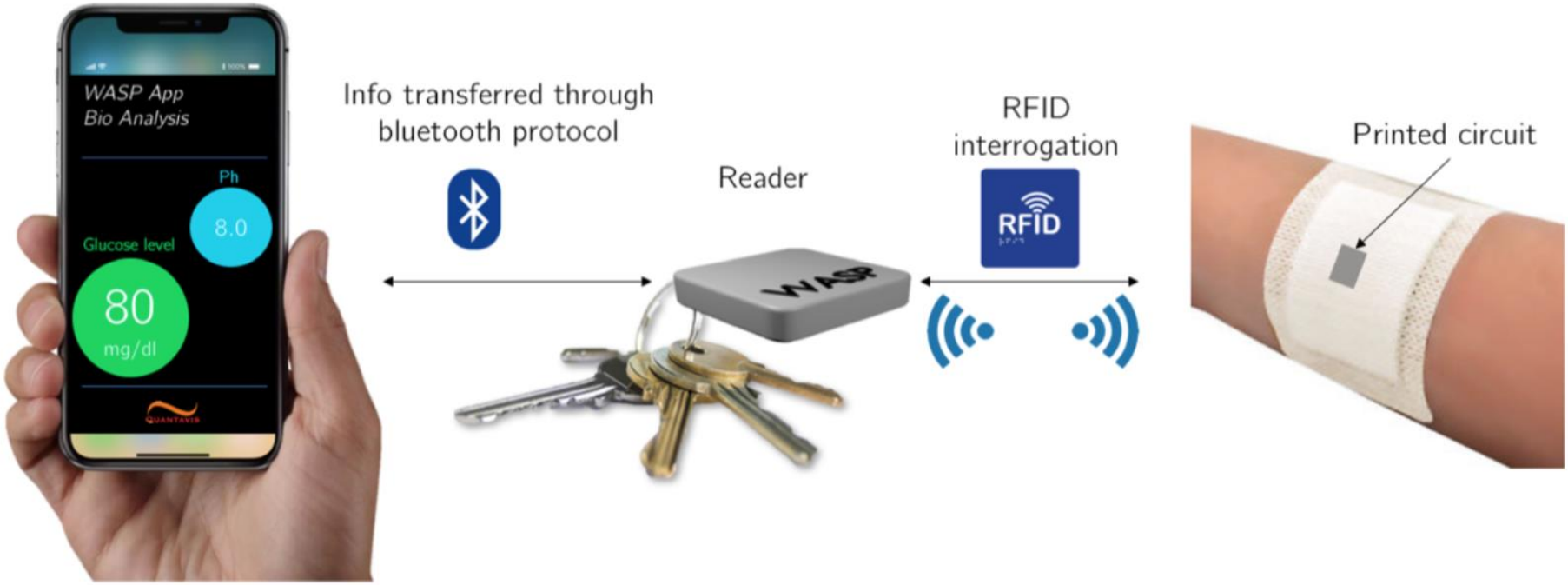
QUANTAVIS
Communication system design and realization
System integration

WASP Project





WASP Project



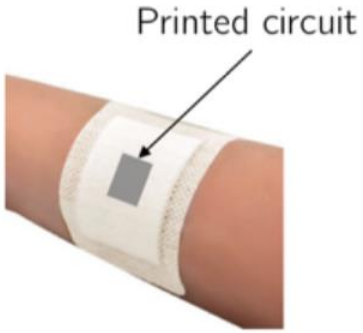
WASP Project

anti-counterfeating: 5 EUR
banknote prototype

anti-counterfeating of luxury goods

LABEL

Product Freshness Information (break of the cold chain, expired or not)



portable healthcare applications

Last Remark

Acknowledgements

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Graphene Flagship Core 2
(Co. # 785219)