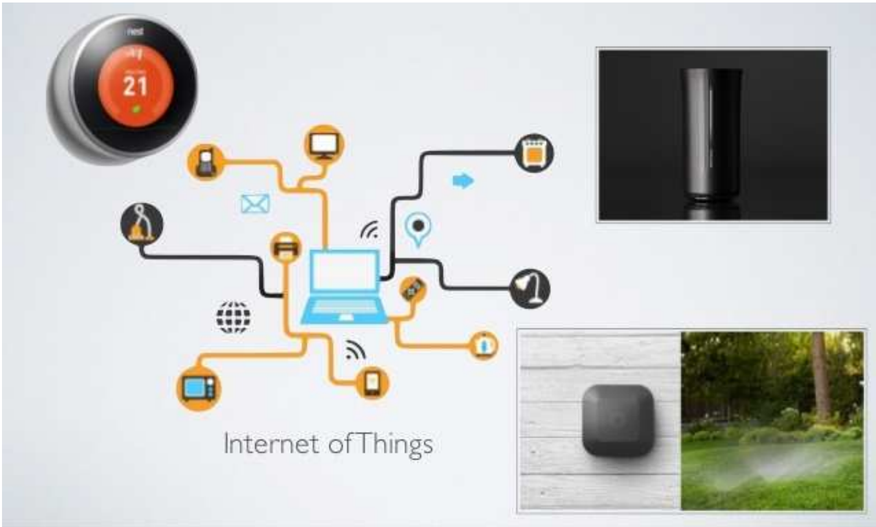
Université de Toulouse

DU CAPTEUR AU BANC DE TEST EN OPEN SOURCE HARDWARE



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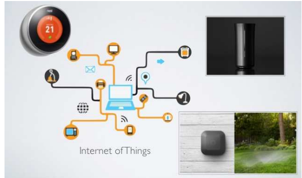
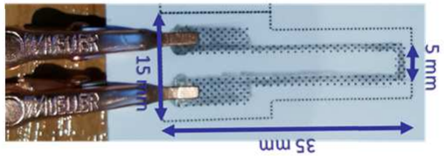
Laboratoire de Physique & Chimie des Nano-Objets

https://moodle.insa-toulouse.fr/course/view.php?id=1663

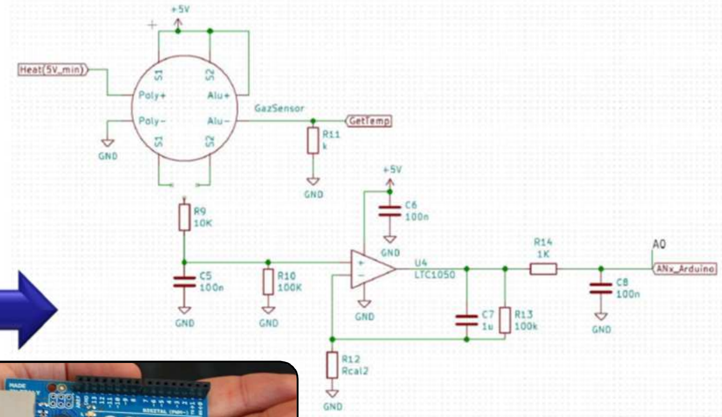
1. INTRODUCTION TO SENSOR AND MEASUREMENT CHAIN



2. GRAPHITE STRAIN SENSOR

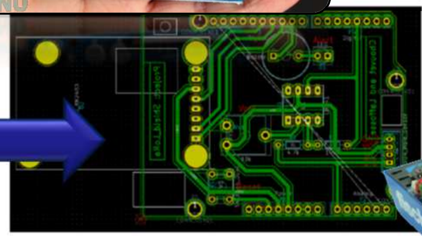


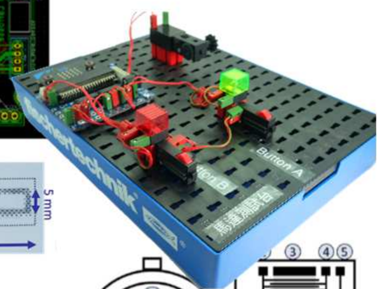
3. ANALOG ELECTRONIC CIRCUIT



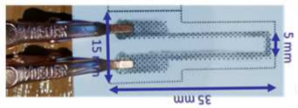
4. MICROCONTROLERS & OPEN SOURCE HARDWARE

5. PCB SHIELD ELABORATION (KICAD)

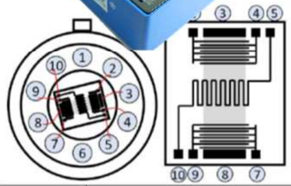




6. TEST BENCH



7. SENSOR DATASHEET



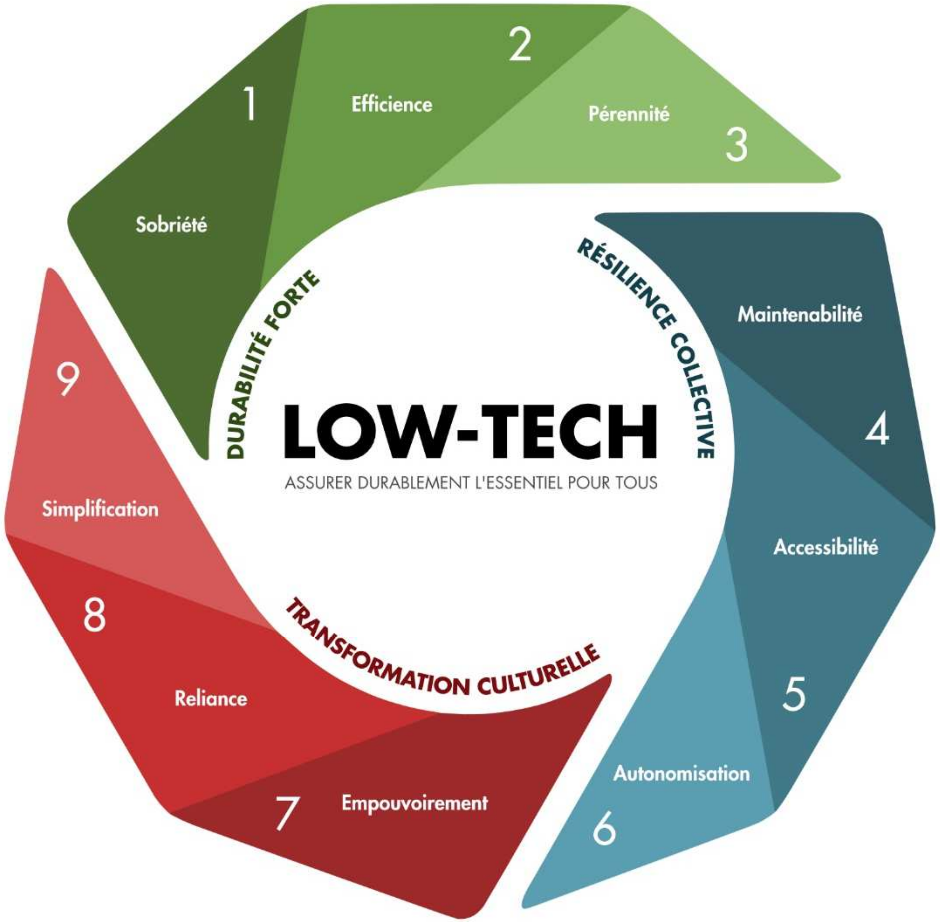
Pin number	Description
2, 4	Sensitive gas layer (WO_3 nanoparticles integrated on aluminium interdigitated combs)
3, 8	Heater polysilicon resistor

8. GITHUB

Github

https://moodle.insa-toulouse.fr/course/view.php?id=1663

VERS LA LOW-TECH…



LES CRITÈRES DE TOUTE DÉMARCHE D'INNOVATION LOW-TECH :

DURABILITÉ FORTE

1 Sobriété
Recentre sur l'essentiel et tend vers l'optimum technologique : plus basse intensité et plus grande simplicité technologiques permettant d'assurer les besoins avec un haut niveau de fiabilité

2 Efficience
Minimise la consommation d'énergie et de ressources, depuis l'extraction des matières premières jusqu'à la fin de vie en passant par la production, la distribution et l'utilisation

3 Pérennité
Présente une viabilité technique, fonctionnelle, écologique et humaine maximale à court, moyen et long terme

RÉSILIENCE COLLECTIVE

4 Maintenabilité
Peut être entretenu et réparé par les utilisateurs eux-mêmes autant que possible, avec des pièces et matériaux standards

5 Accessibilité
Offre une simplicité d'utilisation maximum

6 Autonomisation
Est fabriqué à partir de ressources exploitées et transformées le plus localement possible

TRANSFORMATION CULTURELLE

7 Empouvoirement
Facilite l'appropriation par le plus grand nombre, confère du pouvoir aux citoyens et aux territoires

8 Reliance
Favorise le partage de savoirs et de savoir-faire, la coopération, la solidarité, la cohésion sociale et les liens entre collectivités

9 Simplification
Décomplexifie la société aux niveaux socio-économique et organisationnel à partir d'une réflexion sur les besoins et les vulnérabilités

Conception et réalisation : Arthur Keller et Émilien Bournigal

Paper-based electronic sensors

Paper-based electronics have garnered significant attention due to the potential to produce:

flexible, thin, low-cost, portable, and environmentally-friendly products including:

- antennae[1],
- touch pads[2],
- microfluidic devices[3],
- displays[4]
- sound sources[5],
- printed circuit boards[6],
- and sensors[7,8].

example

Pencil Drawn Strain Gauges and Chemiresistors on Paper

Cheng-Wei Lin*, Zhibo Zhao*, Jaemyung Kim & Jiaxing Huang
Department of Materials Science and Engineering,
Northwestern University 2220 Campus Drive, Evanston, IL, 60208, USA.

SCIENTIFIC REPORTS | 4 : 3812 | DOI: 10.1038/srep03812

Pencil traces can function:

- as strain gauges to detect compressive and tensile deflections,
- but also as chemiresistors sensitive to volatile chemical vapors.

Moreover, complete devices can be fabricated **without the need for metallic electrodes using only pencil traces drawn** from a single type of pencil or a combination of different types of pencils in an all-pencil fabrication process.

The pencil-on-paper approach offers a unique method to develop sensing platforms where devices can be fabricated in minutes using nothing more than common office supplies.

HOW ? : Standard pencil leads are composed of fine graphite particles bound together by clay binders (liant argileux).

ULTRAFINE GRAPHITE PARTICLES ON PAPER

When pencil traces are drawn on paper, friction between the pencil lead and the paper rubs off graphite particles which in turn adhere to the paper fibers:

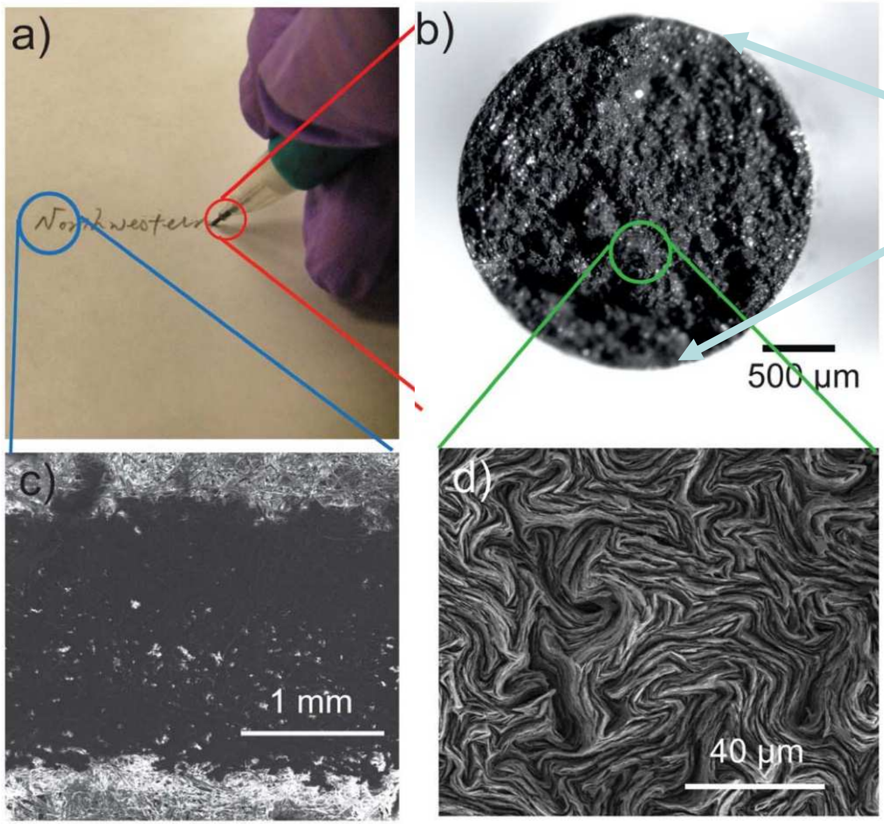


Figure 1 | (a) Optical image of a propelling pencil loaded with HB leads, writing on paper substrates. (b) Stereomicrograph of a pencil lead. (c) SEM image of a 2B pencil trace on paper showing that a continuous carbon particle film was deposited on paper. (d) SEM image of a propelling pencil lead.

Thus pencils can be viewed as an easily deployable form of ultrafine graphite particles.

Also, pencil traces can be regarded as conductive thin films made of percolated graphite particle network on paper (SEM, Figure 1b), which can take on arbitrary shapes and patterns.

DIFFERENT TYPE OF PENCILS

1 - The difference in color arises from the different relative fractions of graphite between harder and softer pencil leads (from 9H to 9B).

2 - The normalized EDS spectra confirm that harder pencil leads contain a higher proportion of clay binders while softer leads contain a higher proportion of graphite particles.

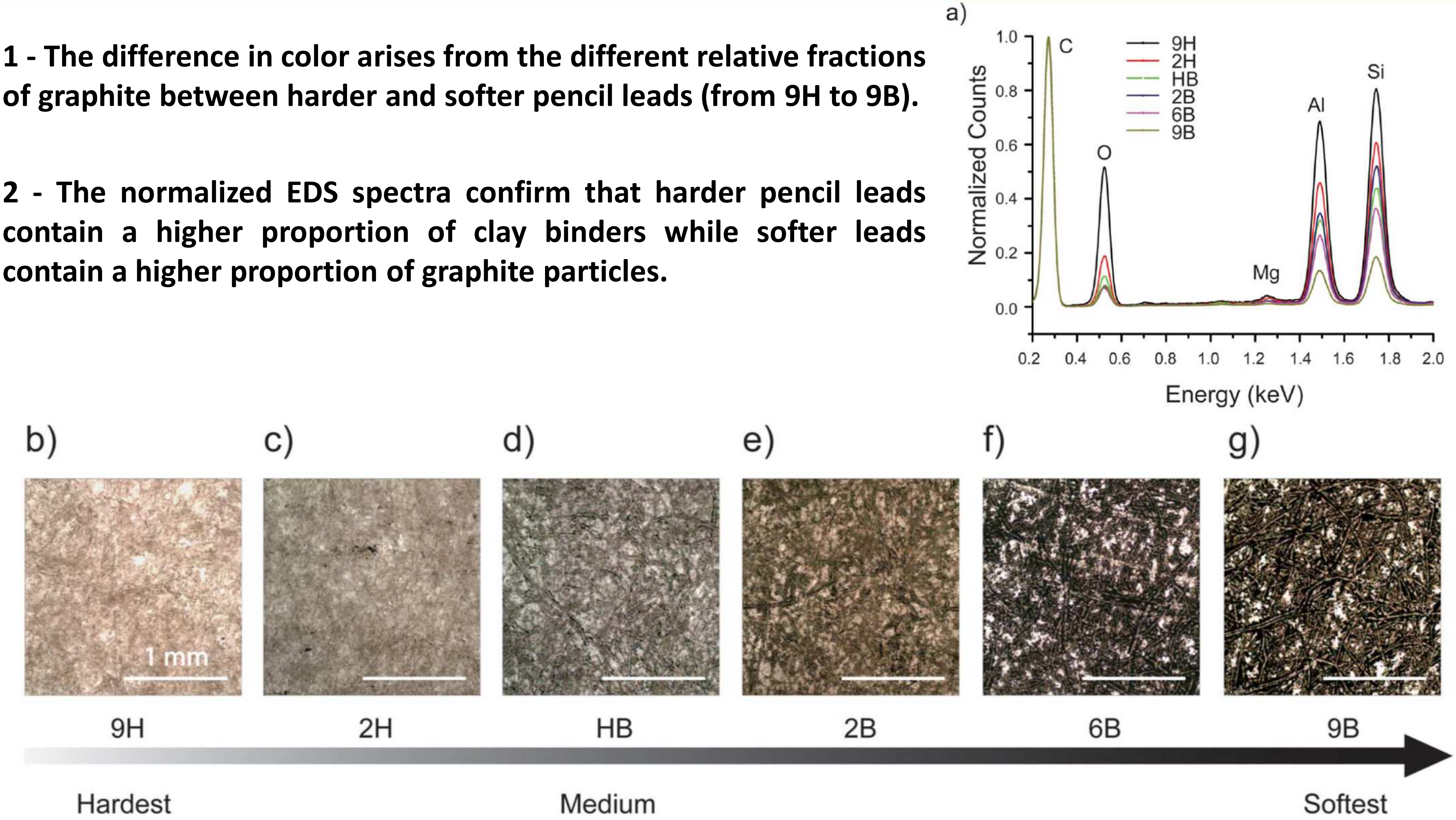
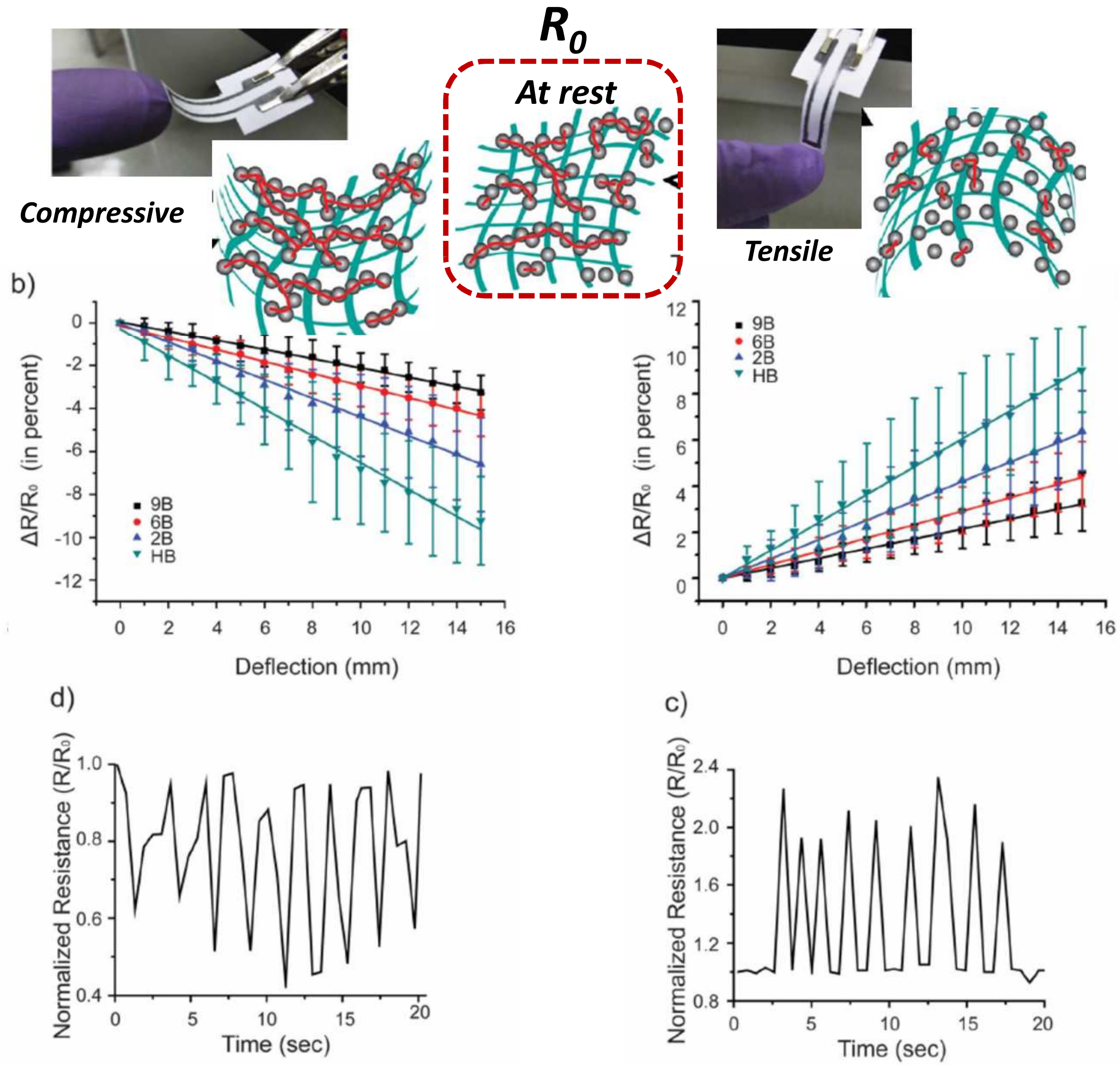


Figure 2 | (a) EDS spectra of pencil leads correlating hardness with the fraction of carbon. Intensities of all of the spectra were normalized based on the carbon peak. (b–g) Optical microscopy images of traces drawn on the paper substrates from pencils of decreasing hardness.

=> The higher carbon content, in the softer leads (9B), results in darker traces on paper

PENCIL DRAWN GRAPHITE SENSOR CHARACTERISATION

Expansion and contraction of THIS GRAPHITE PARTICLE NETWORK, induced by either mechanical stress or chemical interactions, should greatly affect the quality of inter-particle contacts and thus the overall electrical conductivity.



1 - The base resistances of the unstrained devices drawn by **9B, 6B, 2B, and HB** pencils were measured to be **200 kΩ, 500 kΩ, 2MΩ, 20 MΩ,** respectively.

As expected, the softer pencil leads with higher graphite content exhibited lower resistances.

CAUTION

The base resistances of traces drawn with 2H and harder pencils were too high to be measured.

2 - Within the measured range of deflections, the mean resistance changes were linearly correlated to the mean magnitudes of deflection within around 1% deviations.

Rem: the rectangular contact patterns were fixed on a glass slide so that the deflection only bends the beam.

3 – The most sensitives are HB, 2B, 6B, 9B respectively ie. the less charged with graphite nanopartcicles

CAUTION

=> HOW TO EXPLAIN THIS BEHAVIOR ?

Figure 4 | (a–b) Change in normalized resistance vs. deflections for devices drawn with four different types of pencils during compressive and tensile mode of deflections, respectively. (c–d) Repetitive responses under repeated tensile and compressive cycles, respectively.

PENCIL DRAWN STRAIN SENSORS

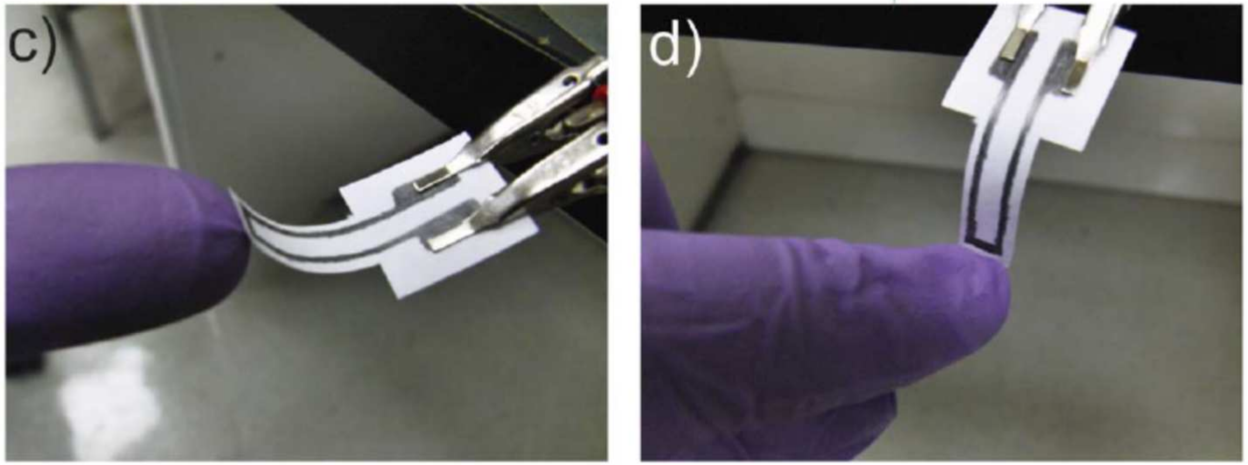
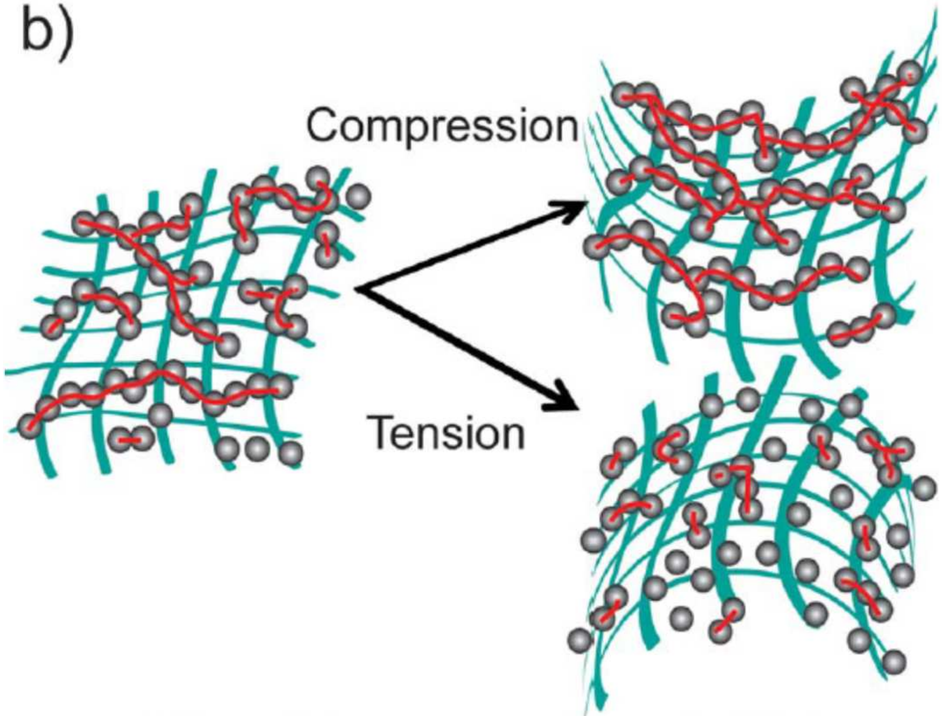
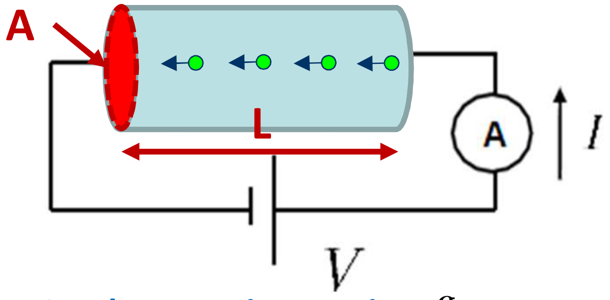


Figure 3 | (a) A photograph showing the U-shaped pencil trace drawn on a paper beam functioning as a strain gauge. (b) Schematic drawing shows that the number of connected graphite particle chains varies depending on the types of deformation. (c–d) Photograph of the gauge deformed by a single finger in compression and tension, respectively.

Granular system



1 - Conductance G d'un barreau métallique de grandes dimensions:

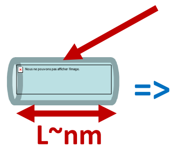


I = G. V

où G = σ.(A/L)

Si L~λ_{e-}

e^- wave



=> « ~Quantum mechanical waveguide »

Quantum conductance: $g_Q = \frac{e^2}{h}$

Resistance correspondante: $R_Q \approx 26k\Omega$

2 – Conductance intragrain: g_0

Dans un système diffusif: on relie la conductance d'un grain élémentaire à l'énergie de Thouless:

$$g_0 = E_{Th}/\delta \quad \text{où} \quad E_{Th} = D_0/a^2 \quad \text{et} \quad D_0 = v_F^2\tau/d$$

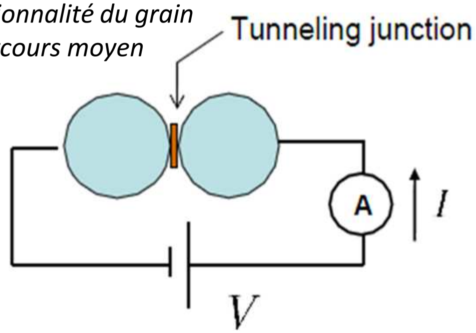
$l = v_F\tau$ ou $l = 2a$

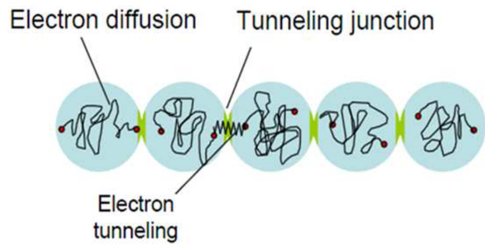
diffusif **balistique**

δ: espacement moyen des niveaux énergétiques
D_0: coefficient de diffusion classique
a: taille linéaire du grain (e.g. rayon)
v_F : vitesse de Fermi
τ: temps de diffusion élastique dans le grain
d: dimensionnalité du grain
l: libre parcours moyen

Généralement:
$E_{th} > \delta$ => $g_0 >> 1$

3 - Conductance tunnel à travers la jonction intergrain g_t:





I_t Tunneling current $$g_t = \frac{I_t}{V}$$

Conductance tunnel sans dimension:

$$g = \frac{g_t}{g_Q}$$

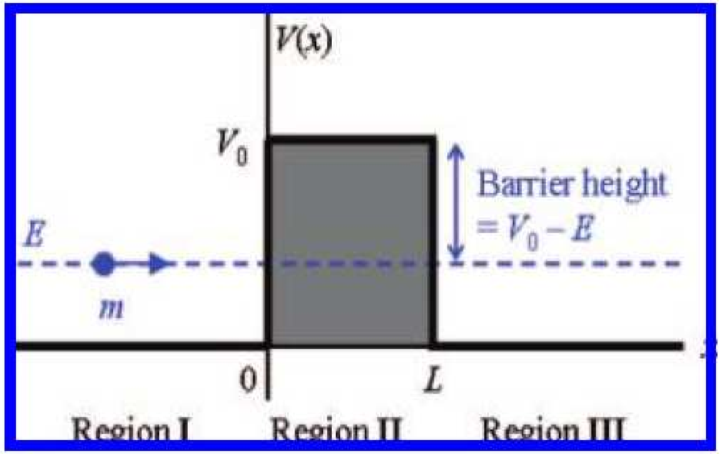
⇒Indication du régime de conductance :

- **g>>1 => The effects of the quantification of the charge are exponentially small : Régime métallique**
- **g<<1 => Quantification of the charge : Régime isolant**

$\Rightarrow$ $\boxed{\textbf{Système granulaire ssi } g_t << g_0}$

1 – IDEAL CASE: Potential V_0 barrier and width L:

$$\begin{cases} -\dfrac{\hbar^2}{2m}\dfrac{d^2\psi(x)}{dx^2} + V_0\psi(x) = E\psi(x) & 0 \le x \le L, \\ -\dfrac{\hbar^2}{2m}\dfrac{d^2\psi(x)}{dx^2} = E\psi(x) & \text{otherwise} \end{cases}$$



$$\psi_{\mathrm{I}}(x) = A\,e^{i\alpha x} + B\,e^{-i\alpha x}$$ **Incident part + Reflected part**

$$\psi_{\mathrm{II}}(x) = C\,e^{\kappa x} + D\,e^{-\kappa x}$$

$$\psi_{\mathrm{III}}(x) = F\,e^{i\alpha x}$$ **Transmitted part**

$\Rightarrow$ ***Probabilité de transmission*** $|T|^2 = \left|\dfrac{F}{A}\right|^2$

Thick barrier: κL>>1

$$|T|^2 \approx \left|\frac{4i\alpha\kappa\,e^{-i\alpha L}}{(i\alpha-\kappa)^2\,e^{\kappa L}}\right|^2 = \frac{16\alpha^2\kappa^2}{(\alpha^2+\kappa^2)^2}\,e^{-2\kappa L} = 16.\left(\frac{E}{V_0}\right)\left(1-\frac{E}{V_0}\right).e^{-2\kappa L}$$

$$|T|^2 \approx e^{-2\kappa L}$$

$$\alpha = \sqrt{2mE}/\hbar$$

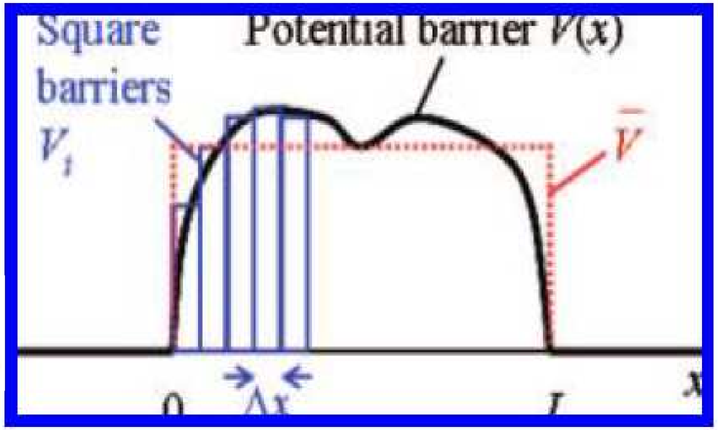
$$\kappa = \sqrt{2m(V_0-E)}/\hbar$$

Tunnel cste $\beta = 2\kappa$

2 – PARTICULAR CASE: Slowly varying arbitrary shape:

$$|T|^2 \approx \exp\left(-\frac{2\sqrt{2m(\bar{V}-E)}L}{\hbar}\right) = e^{-2\bar{\kappa}L}$$

$$\bar{\kappa} = \sqrt{2m(\bar{V}-E)}/\hbar$$

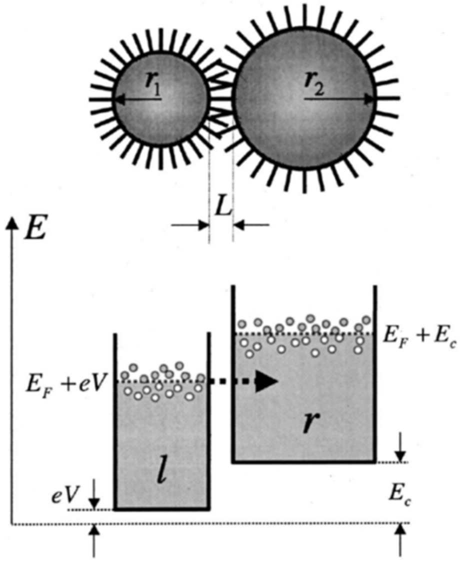


To develop formulas for the conductance of a nanoparticle film:

Let's first consider two neighboring normal metal nanoparticles with electrostatic potential difference *V*.

The nanoparticles are separated by a gap *L* formed by organic linker molecules which surround the nanoparticles.

Rem: when an electron tunnels from the left (l) to the right (r) nanoparticle it has to overcome the Coulomb charging energy Ec.



Energy diagram illustrating the transition of an electron moving from the left l metal nanoparticle to its neighbor nanoparticle on the right r.

Rem: in the case of small nanoparticles (e.g. ~10nm in diameter) the electron level spacing is negligibly small.

Using scattering theory, the electron current I which flows between the two metal nanoparticles is given by[9]:

$$I=\frac{4\pi e}{\hbar}\sum_{r,l}\{\underbrace{f(E_l-eV)[1-f(E_r-E_c)]}_{\text{Electrons from left to right}}-\underbrace{f(E_r)[1-f(E_l-eV-E_c)]}_{\text{Electrons from right to left}}\}|T_{lr}|^2\delta(E_r-E_l)$$

e is the electron charge and
f is the Fermi-Dirac distribution
The quantities T_{lr} are the transition matrix elements and
E_l and E_r are the energy levels of electrons in the nanoparticles.
E_C is the Coulomb charging energy (Coulomb blockade energy) required to move an electron from one nanoparticle to a neighboring one. which in this case can be well described by the Abeles formula

$$E_C=\frac{e^2}{2\pi\varepsilon_0\varepsilon_r}\frac{L}{D(D+2L)}$$

where *D* is the diameter of a nanoparticle and ε_r the relative dielectric constant of the molecules that surround the nanoparticles and L interdistance.

The sum is over all the single electron states *l* and *r* of the left and right nanoparticle, respectively.

If $eV \ll E_F$ as well as $E_C \ll E_F$, this equation can be written in the form :

$$I=\frac{4\pi e}{\hbar}|T(E_F)|^2\rho^2(E_F)\int_{-\infty}^{\infty}dE\{f(E-eV)[1-f(E-E_c)]-f(E)[1-f(E-eV-E_c)]\}.$$

$\rho(E_F)$ is the electron density of states at the Fermi level.

If $kT \ll E_F$, the integral can be evaluated analytically resulting in:

$$I = \frac{4\pi e}{\hbar} |T(E_F)|^2 \rho^2(E_F) \left[\frac{E_c + eV}{1 - e^{(E_c+eV)/kT}} - \frac{E_c - eV}{1 - e^{(E_c-eV)/kT}} \right].$$

If we only consider electrical conduction in nanoparticle films for small applied voltages where $eV \ll E_C$:

$$I = \underbrace{\frac{8\pi e^2}{\hbar} |T(E_F)|^2 \rho^2(E_F) \frac{1 - (1 - E_c/kT)e^{E_c/kT}}{(1 - e^{E_c/kT})^2}}_{= G_{12}} V.$$

$$|T(E_F)|^2 \sim e^{-\beta L}$$

$$\beta = (8 m U_0 / \hbar^2)^{1/2}.$$

Here, m is the effective mass of the electrons in the nanoparticles.

Rem: this equation is equivalent to the results obtained from the so-called orthodox theory of single-electron tunneling[11] which is valid if the resistance R_T of all the tunnel barriers in the system is much greater than the quantum resistance $R_Q = h/e^2 \sim 26\ k\Omega$.

For $eV \ll E_C$ this leads to a resistance between nanoparticles $R_{12} = V_{12} / I_{12}$ of the form:

$$R_{12} = G_{12}^{-1}$$

$$R_{12} \propto e^{\beta L} \frac{(1 - e^{E_C/k_B T})^2}{1 - (1 - E_c/k_B T)\, e^{E_C/k_B T}}$$

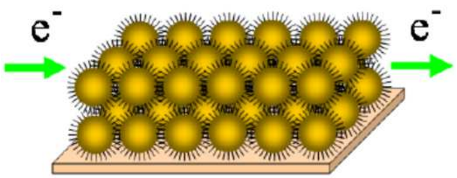
. The first term $e^{\beta L}$ represents the electron tunneling
. The second term $f(E_C, T)$ arises from the scattering of electrons from occupied single electron states of one metal nanoparticle into unoccupied states of the neighboring nanoparticle.

Rem: $eV_{12} \ll E_C$ is valid because typically $eV < 10^{-2}$ meV (using a V distributed over a huge number of NPs) and typically $E_C > 1$ meV

PERCOLATION MODEL FOR ELECTRON CONDUCTION IN GRANULAR SYSTEMS

1 – IN A ORDERED NETWORK, e.g. REGULAR CUBIC LATTICE :

The total resistance *R* along the length *l* of a nanoparticle film on a regular cubic lattice is given by :



where the film consists of metal nanoparticles placed :
- *l* length of the NP film
- *a is the* lattice spacing,
- *w* is the width and
- *d* the thickness of the film.

$$\boxed{R_{tot} = \frac{l.a}{w.d} R_{12}} \Leftrightarrow \boxed{G_{tot} = \frac{w.d}{l.a} G_{12}}$$

e.g. for gold NPs films: l~50µm, a~1nm, w~5µm, d~50nm,

***Characteristics of NPs: diameter** d~10 nm, interdistance L~1 nm and β=10 nm^{-1}, at room temperature typical values of $E_C/L.k_BT$~0.2 nm^{-1}<< β,*

A nanoparticle film of adjacent nanoparticles can be viewed as being connected by local conductances *G* :

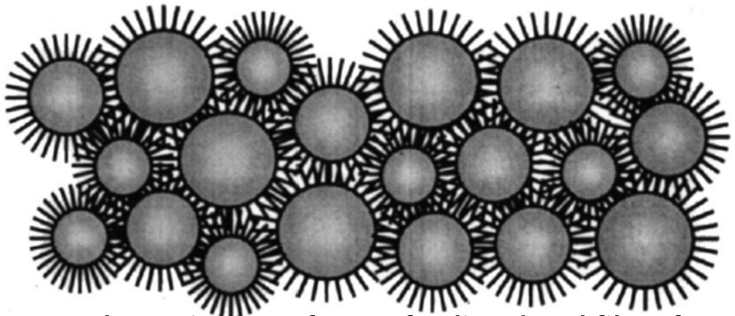
$$\begin{cases} I \sim e^{-[\beta L + g(E_c/kT)]} V, \\ g(E_c/kT) = -\ln \dfrac{1-(1-E_c/kT)e^{E_c/kT}}{(1-e^{E_c/kT})^2}. \\ \beta = (8mU_0/\hbar^2)^{1/2}. \end{cases}$$

$$\boxed{G \sim e^{-\xi} \quad \text{where} \quad \xi = \beta L + g(E_c/kT)}$$

The conductance of the granular system is a function of :
L : the internanoparticule distance
β : the tunneling constant
E_C: the Coulomb charging energy
And temperature !!!

What happens if the system is a HIGHLY DISORDERED NETWORK (like the pencil trace) ?

2 – IN A HIGHLY DISORDERED NETWORK :



Schematic view of part of a disordered film of nanoparticles linked by organic molecules.

9B

The electrical conductivity of a pencil trace depends on the quality of the contact between graphite particles in **the percolating network.**

In percolation theory, the total conductance G_{tot} of a highly disordered conductor network is given by :

$$G \sim e^{-\xi}$$

where $\xi = \beta L + g(E_c / kT)$

$$\boxed{G_{tot} = G_0 e^{-\xi_c}}$$

Rem: depending on the system, the estimation of the analytical form of the temperature independent prefactor G_0 can be quite difficult !

Here, **ξ_c is the value of ξ at the percolation threshold**, which is the point where, in a thought experiment, **an infinitely large connected cluster starts to emerge when randomly chosen pairs of neighboring nanoparticles are connected by conductors in a descending order of *G* values.**

$$\xi_c = \begin{cases} \left(\dfrac{2 f_c \Delta\lambda \Delta\epsilon}{1-f_v}\right)^{1/2} + \lambda_M - \Delta\lambda/2 + \epsilon_M - \Delta\epsilon/2 & \text{if } -\Delta\lambda/2 \leq \xi_c - \lambda_M - \epsilon_M + \Delta\epsilon/2 \leq \Delta\lambda/2, \\ \lambda_M + \epsilon_M - \left(\dfrac{1}{2} - \dfrac{f_c}{1-f_v}\right)\Delta\epsilon & \text{if } \Delta\lambda/2 - \Delta\epsilon/2 \leq \xi_M - \lambda_M - \epsilon_M \leq \Delta\epsilon/2 - \Delta\lambda/2. \end{cases}$$

f_c *and* f_v are the fraction of conductors and voids, respectively
$\lambda_M = \beta L_M$ and $\varepsilon_M = E_{CM} / kT$ are the mean values of the distributions and
$\Delta\lambda$ and $\Delta\varepsilon$ are the widths of the distributions.

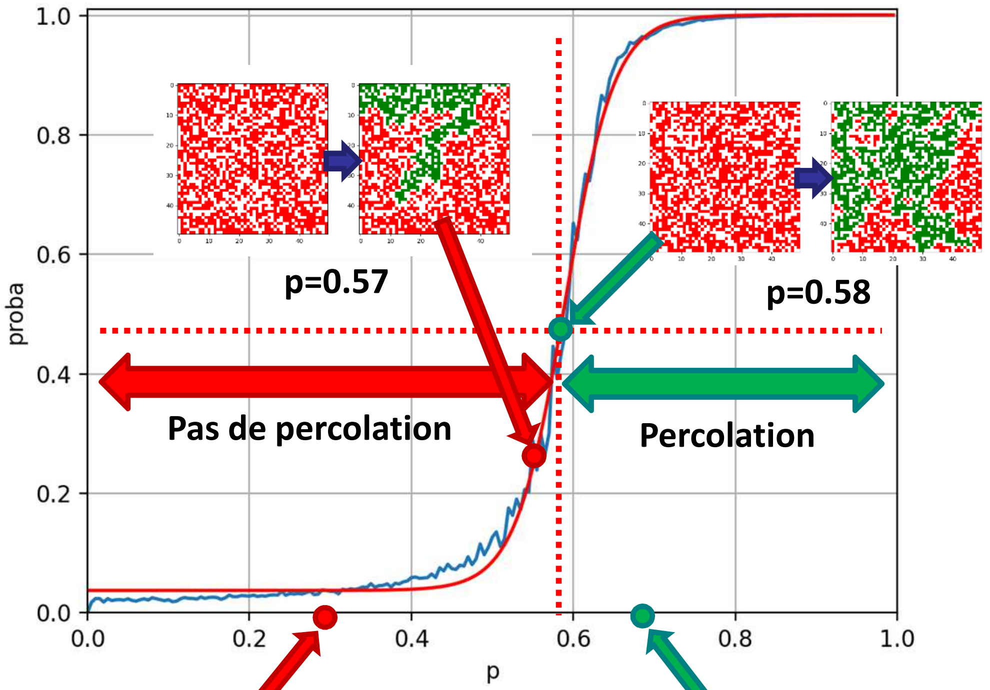
L_M is the average gap (excluding voids) separating neighboring nanoparticles and
E_{CM} is the average Coulomb charging energy.

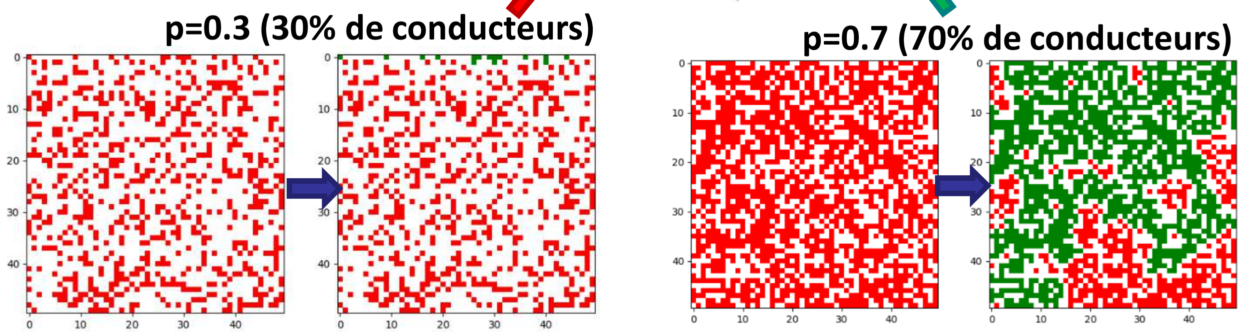
```python
from numpy import zeros
from numpy.random import rand
import matplotlib.pyplot as plt
from matplotlib.colors import ListedColormap
import random

"""
Simulateur de percolation isolant/conducteur
"""

# Définition des paramêtres de la simulation
ISOLANT = 0.0       # en blanc
CONDUCTEUR = 1.0    # en rouge
PERCO = 0.5         # en vert
N = 50

# fonction de création de la matrice de simulation.
def Grid(n,p):
    grid = zeros((n,n))
    for i in range(n):
        for j in range(n):
            if random.random() < p:
                grid[i][j] = CONDUCTEUR
    return grid

# Algorithme de percolation isolant/conducteur
def Percolate(grid):
    pgrid = grid.copy()
    n,n = pgrid.shape
    chemin = []
    # recherche des particules conductrices en haut de la matrice
    for j in range(n):
        if pgrid[0][j] == CONDUCTEUR:
            chemin.append((0,j))
            pgrid[0][j] = PERCO
    # recherche d'un chemin percolant
    while len(chemin) > 0:
        (i,j) = chemin.pop()
        pgrid[i][j] = PERCO
        if i > 0 and pgrid[i-1][j] == CONDUCTEUR:
            chemin.append((i-1,j))
            pgrid[i-1][j] = PERCO
        if i < n-1 and pgrid[i+1][j] == CONDUCTEUR:
            chemin.append((i+1,j))
            pgrid[i+1][j] = PERCO
        if j > 0 and pgrid[i][j-1] == CONDUCTEUR:
            chemin.append((i,j-1))
            pgrid[i][j-1] = PERCO
        if j < n-1 and pgrid[i][j+1] == CONDUCTEUR:
            chemin.append((i,j+1))
            pgrid[i][j+1] = PERCO
    return pgrid

# Fonction de détermination de la percolation
def IfPercolate(grid):
    n,n = grid.shape
    for j in range(n):
        if grid[n-1][j] == PERCO:
            return True
    return False

# choisir une répartition conducteur/isolant
p = input('Choisissez une repartition conducteur/isolant : ')
p = float(p)
# création de la grille de percolation
mat = Grid(N,p)
# essai de percolation
pmat = Percolate(mat)
# détermine si la percolation a eu lieu
if IfPercolate(pmat):
    print ('Percolation')
else:
    print ('Pas de percolation')

# tracé des grilles
fig = plt.figure(figsize=(10,10))
fg_color = 'blue'
bg_color = 'white'
axe1 = fig.add_subplot(2,2,1)
#axe1.set_title('Grille initiale', color=fg_color)
axe1.imshow(mat, origin='upper', interpolation='nearest',cmap=ListedColormap(['white','green','red']))
axe2 = fig.add_subplot(2,2,2)
#axe2.set_title('Grille Percolée ?', color=fg_color)
axe2.imshow(pmat, origin='upper', interpolation='nearest',cmap=ListedColormap(['white','green','red']))

plt.show()
```

ISOLANT => en blanc

CONDUCTEUR => en rouge

PERCOLATION => en vert





C'est une magnifique sigmoïde, qui montre bien l'effet de seuil autour de p_c

$$f_\lambda(x) = f(\lambda x) = \frac{1}{1 + e^{-\lambda x}}$$

Rem: comme Fermi-Dirac qui donne la probabilité de répartition de deux populations e^- et trous sur les niveaux d'énergie d'un semiconducteur

MODULE OBJECTIVES

Pencil Drawn Strain Gauges and Chemiresistors on Paper

Cheng-Wei Lin*, Zhibo Zhao*, Jaemyung Kim & Jiaxing Huang
Department of Materials Science and Engineering,
Northwestern University 2220 Campus Drive, Evanston, IL, 60208, USA.

SCIENTIFIC REPORTS | 4 : 3812 | DOI: 10.1038/srep03812 - 2014

1 - The base resistances of traces drawn with 2H and harder pencils were too high to be measured.

Since traces from HB pencil demonstrated the largest response while 2H pencil traces were nonconductive, the carbon content of the HB pencil traces may coincidentally **<u>lie just above the percolation threshold.</u>**

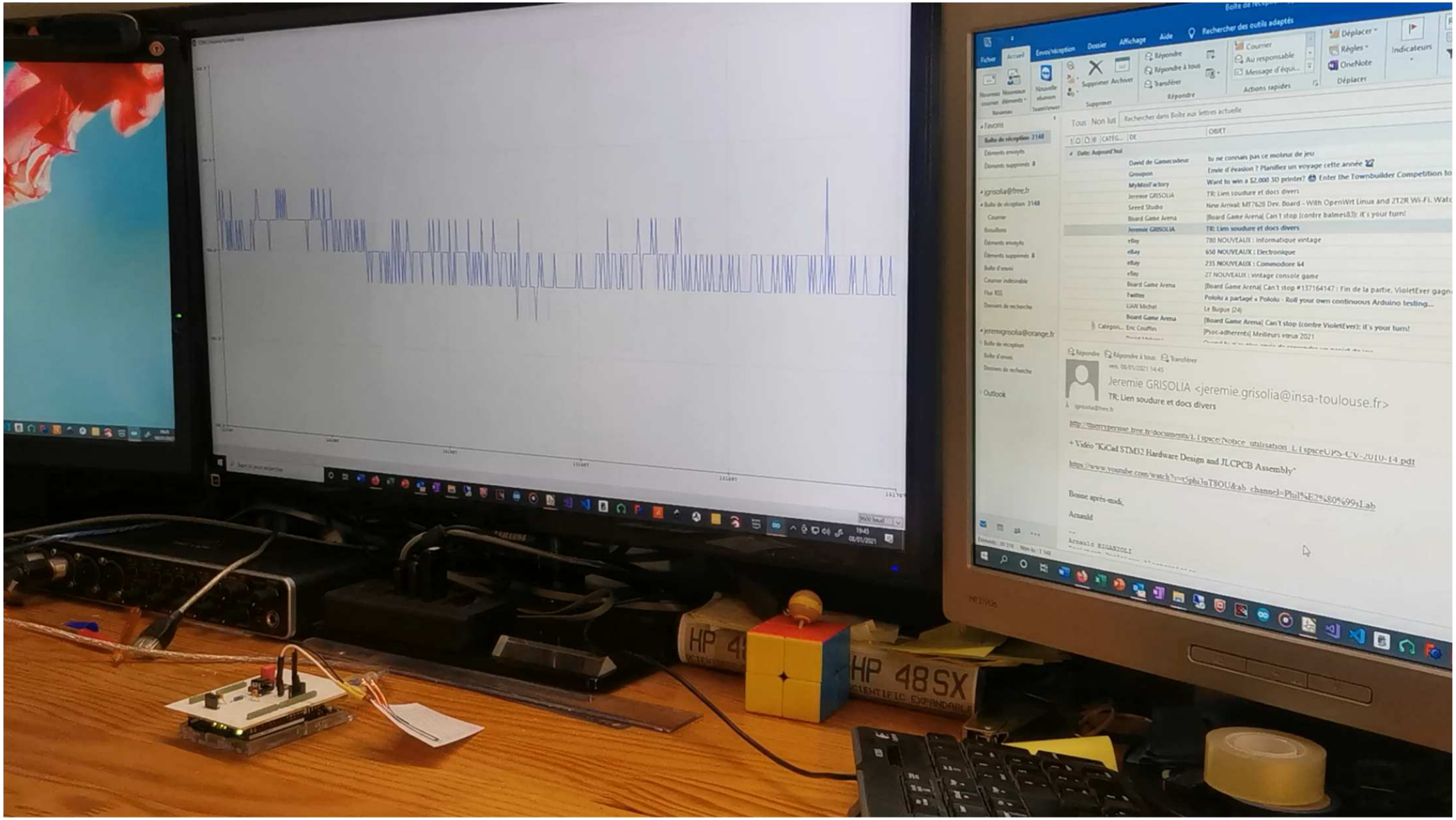
NDLR: and then 2H is just under percolation threshold ??????

2 - Changes of electrical resistance along the Ushaped trace were monitored using a Keithley 2400 source meter connected to the electrodes by toothless alligator clips.

Resistance measurements over time were recorded:
using a Labview program interfaced with a Keithley 2400 source meter.

DEFI: Serez-vous meilleurs que ces chercheurs ????
1 - en faisant une électronique qui permette de mesurer le 2H
2 - avec un dispositif bas-coût
3 - et transportable !!!

PLACE À LA DÉMONSTRATION !!!



QUE FAUT-IL RETENIR ?

1 – Comment developer des capteurs low-tech très compétitifs ?

2 – Comment fonctionne, à grands traits, un capteur à base d'un système granulaire ?

3 – Ce qu'est un système granulaire

4 – A grands traits, le calcul du courant et l'expression de la conductance dans un reseau régulier de nanoparticules.

5 – De quoi depend la conductance d'un système granulaire (constante de barrière tunnel, interdistance, énergie de chargement…)

6 – L'expression de la conductance dans un système granulaire fortement désordonné et ses dépendances (moyenne de distribution de taille de nanoparticules, moyenne de distribution des interdistances, distribution Moyenne des énergies de chargement…)

7 – Une première réflexion sur la difference entre SCIENCE et RECHERCHE

et maintenant, passons à la réalisation de ces capteurs, du banc de test et de leur exploitation !

REFERENCES & REMERCIEMENTS

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Department of Materials Science and Engineering,
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Electron transport in nanoparticle assemblies
K.-H. Müller[1], J. Herrmann[2], G. Wei[1], B. Raguse[1], and L. Wieczorek[1]
[1]Future Manufacturing Flagship, 1CSIRO Materials Science and Engineering
Lindfield NSW 2070, Australia
[2]National Measurement Institute, Lindfield NSW 2070, Australia
978-1-4244-5262-0/10/$26.00 © 2010 IEEE - ICONN 2010

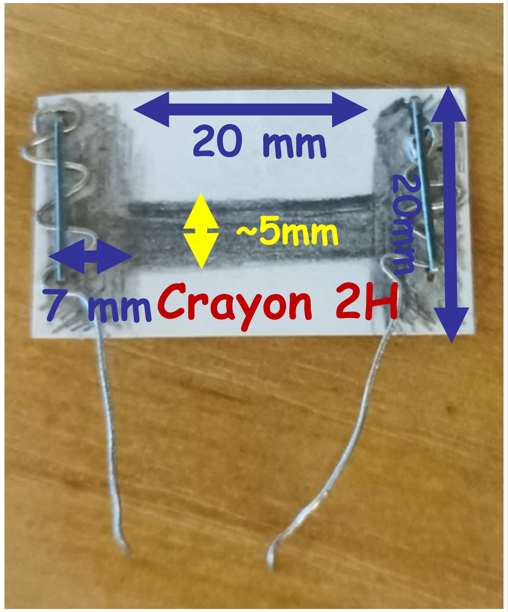
Percolation model for electron conduction in films of metal nanoparticles linked by organic molecules
K.-H. Müller,* J. Herrmann, B. Raguse, G. Baxter, and T. Reda
Commonwealth Scientific and Industrial Research Organization, Telecommunications and Industrial Physics, Sydney 2070, Australia
PHYSICAL REVIEW B 66, 075417 (2002)

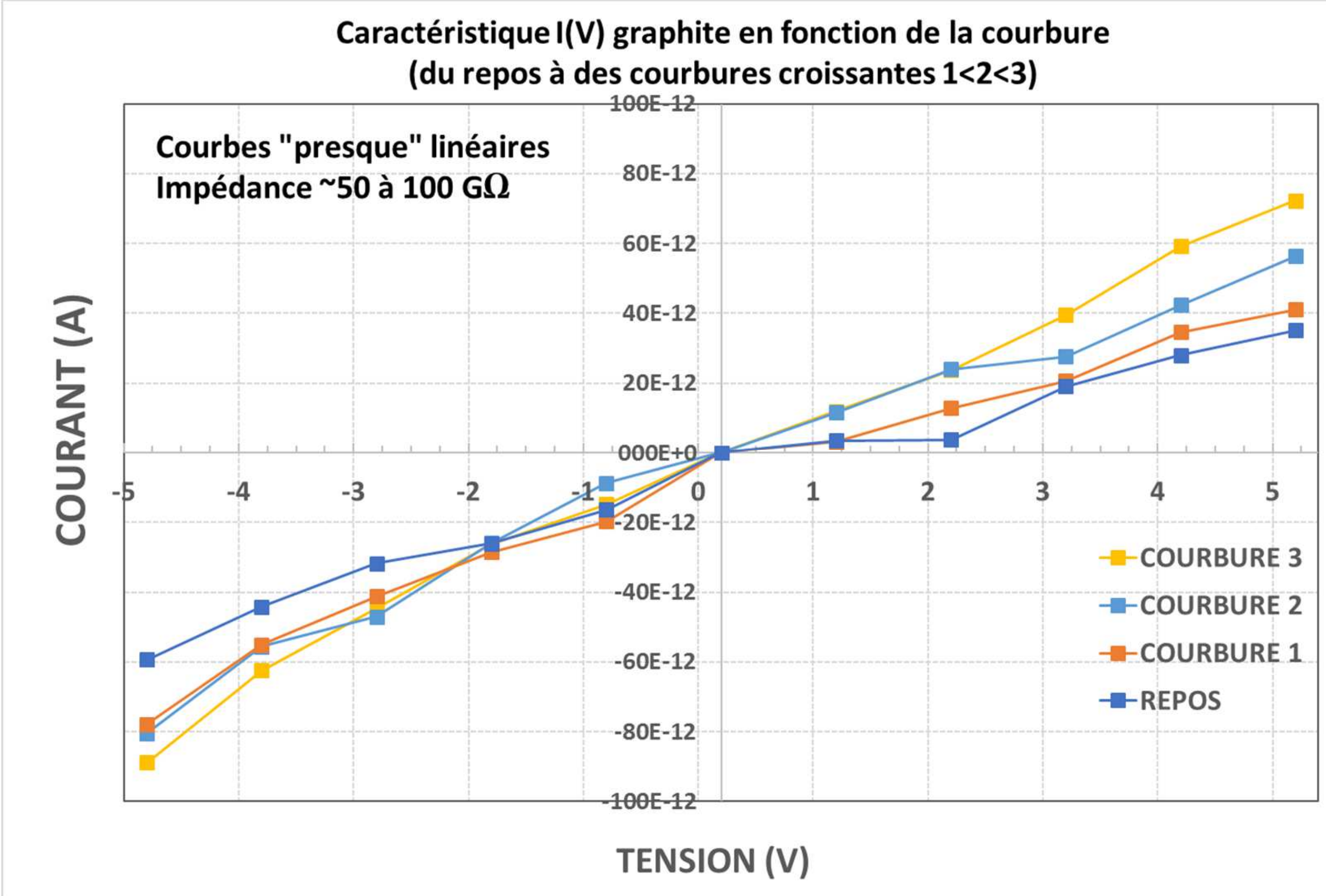
Python code for percolation simulation
(www.tangenteX.com)

Remerciements à l'équipe de l'AIME: Frédéric Gessinn, Reasmey Tan, Marc Respaud…

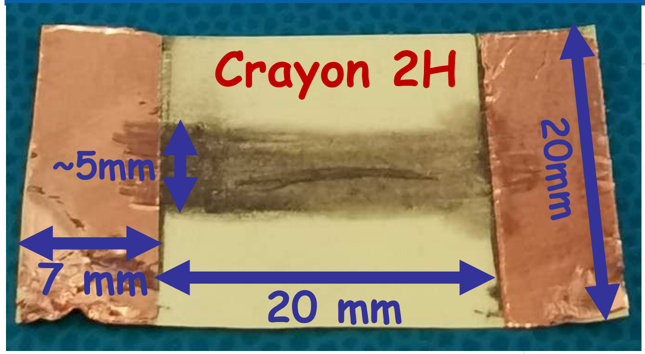
BONUS

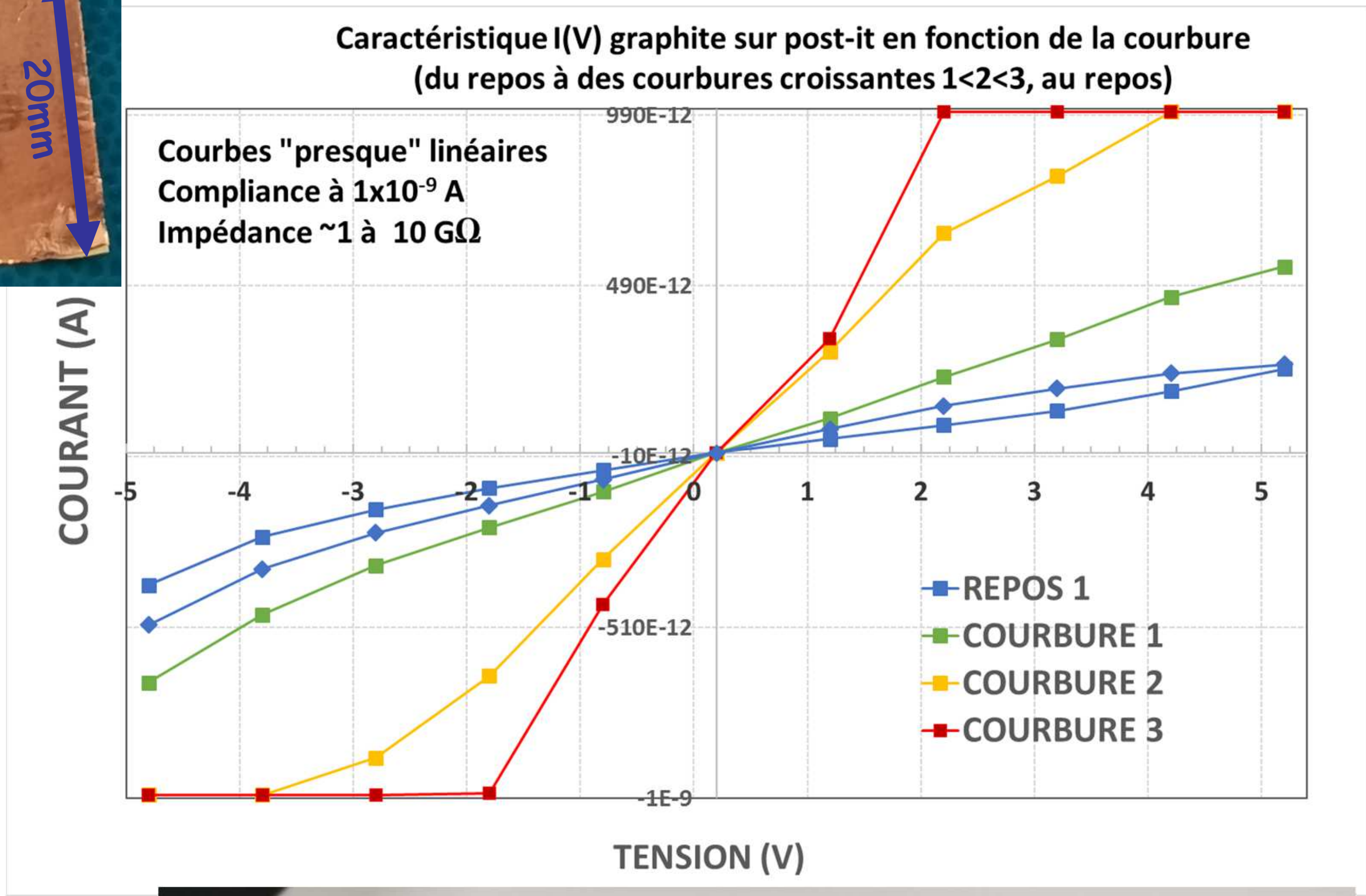
JAUGE DE CONTRAINTE AVEC UN CAPTEUR A BASE DE GRAPHITE





JAUGE DE CONTRAINTE AVEC UN CAPTEUR A BASE DE GRAPHITE





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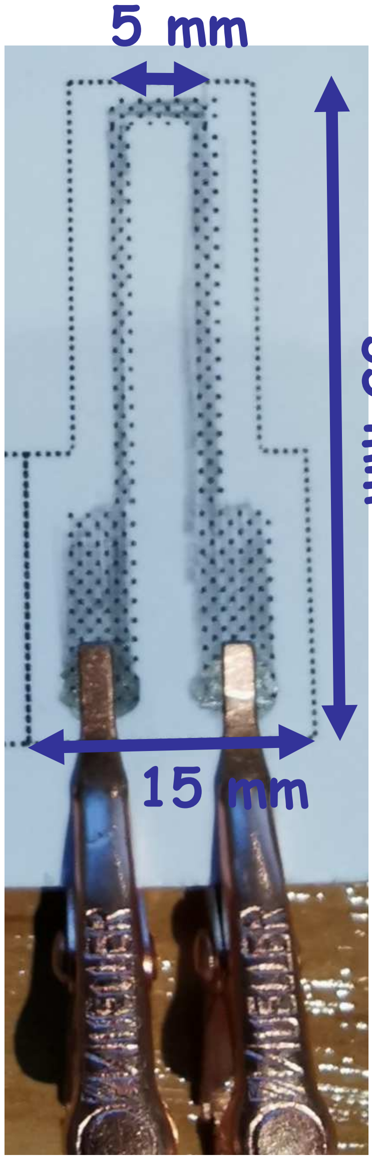

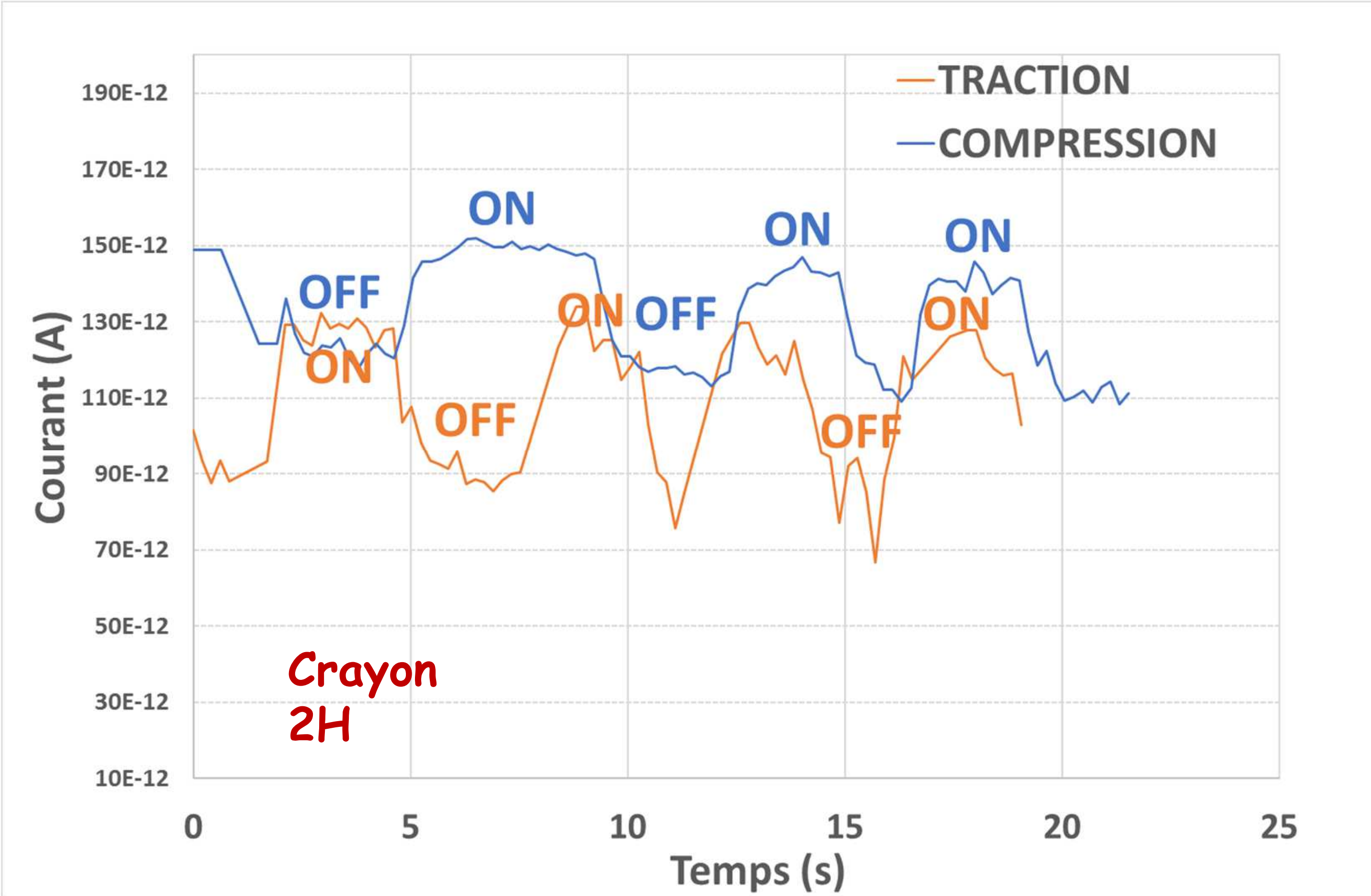

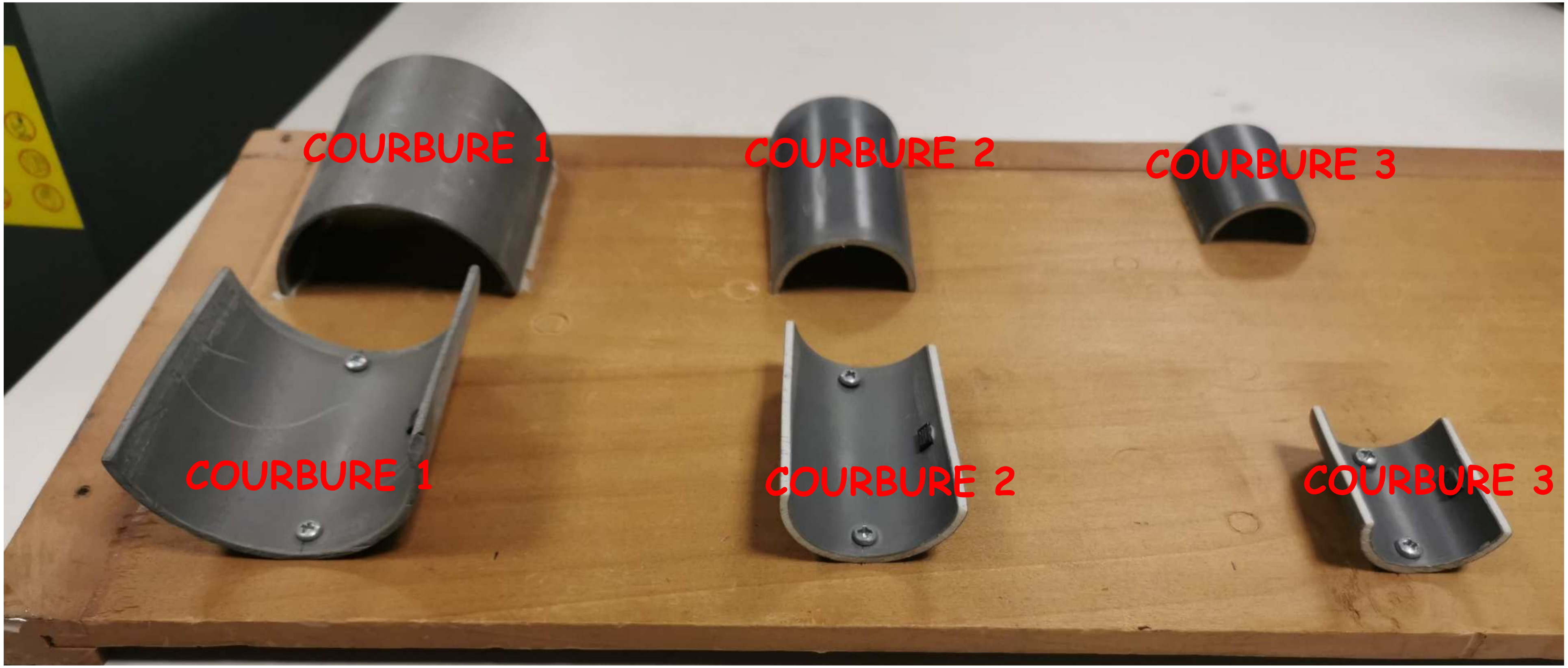
COURBURE 1
COURBURE 2
COURBURE 3
COURBURE 1
COURBURE 2
COURBURE 3