

# Découvertes Récentes en physique : fabriquer et mesurer à l'échelle du nanomètre

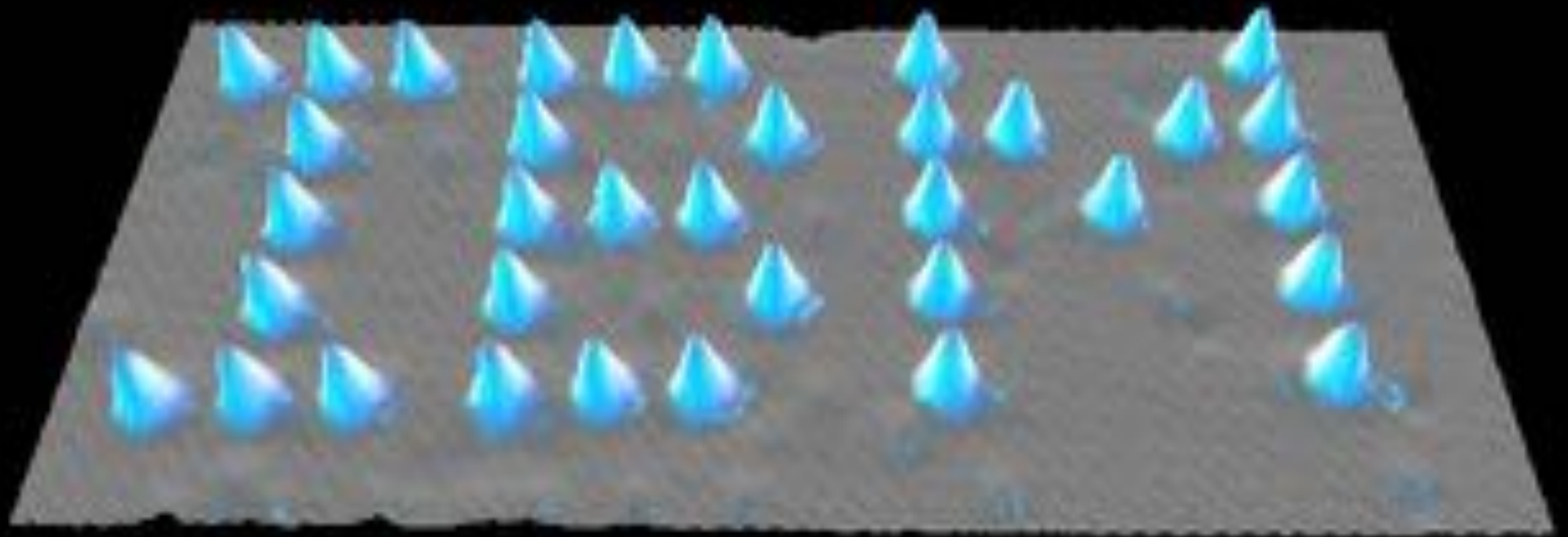
J. Bobroff, Univ. Paris-Sud

# Comment fabriquer ?

- atome par atome
- en gravant
- en évaporant
- à partir de matière existante

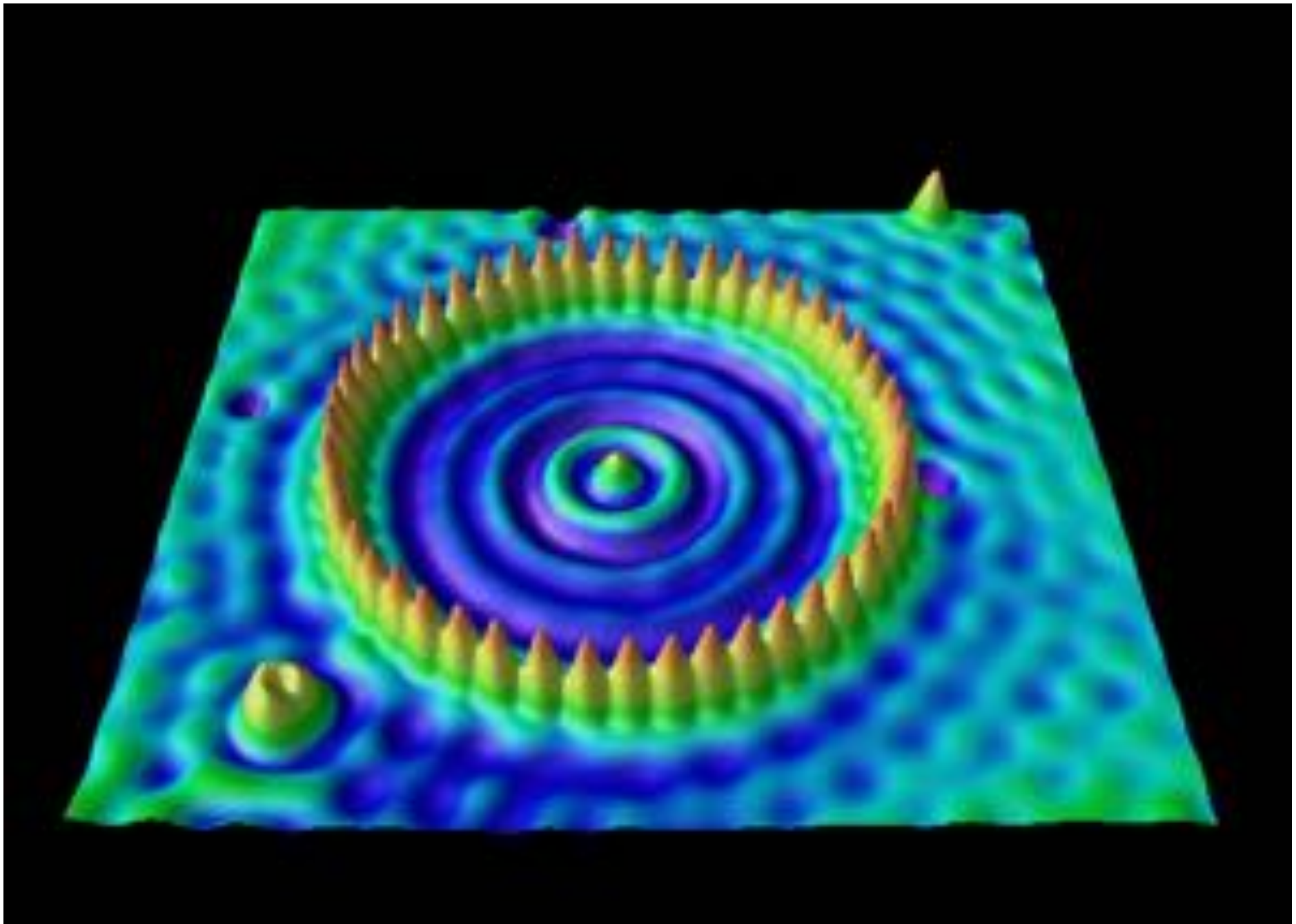
# Fabriquer atome par atome

Avec un microscope à effet tunnel, on peut déplacer des atomes, donc fabriquer à l'échelle du nanomètre des motifs et des structures

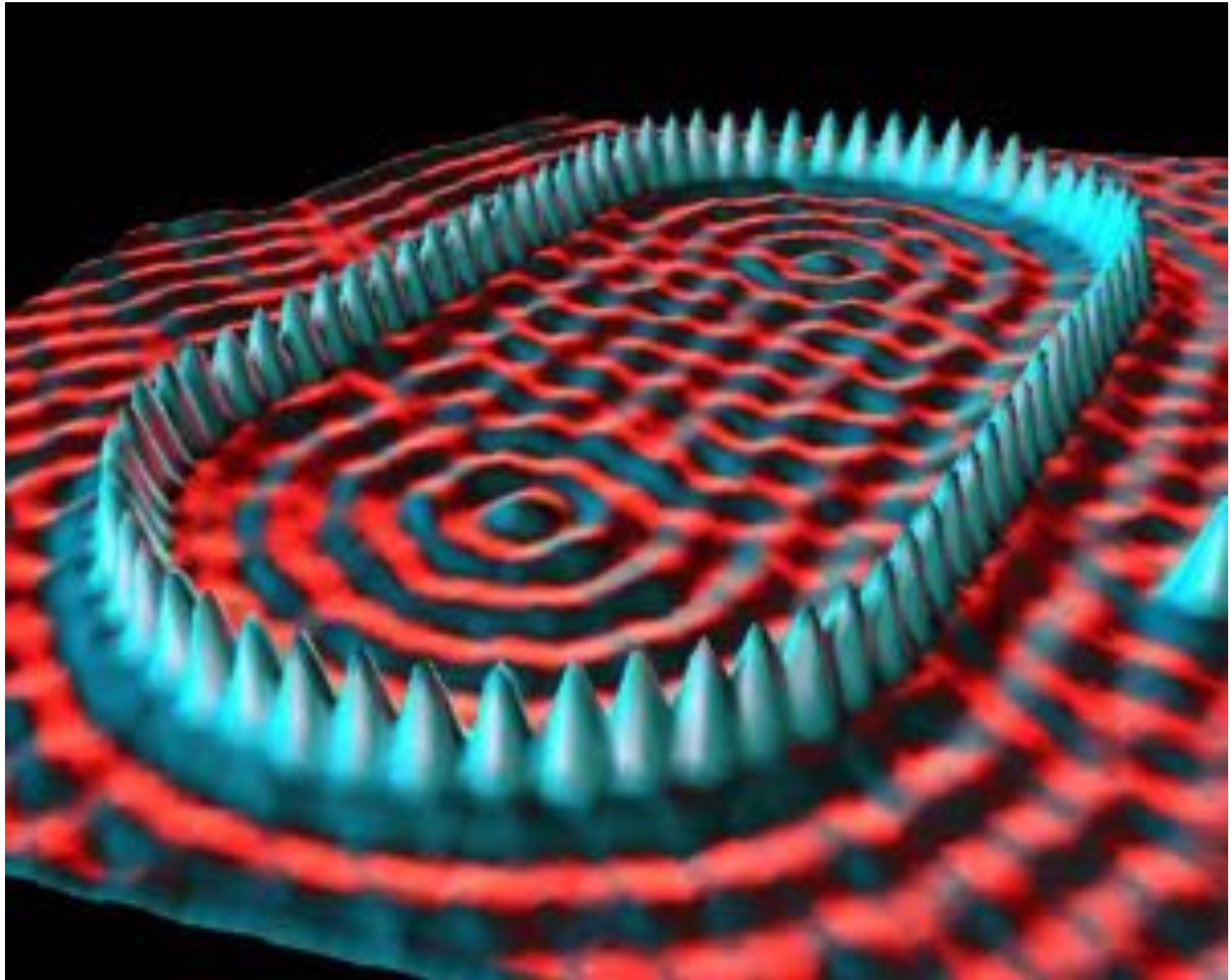


*Xenon sur Nickel (Don Eigler et al.)*

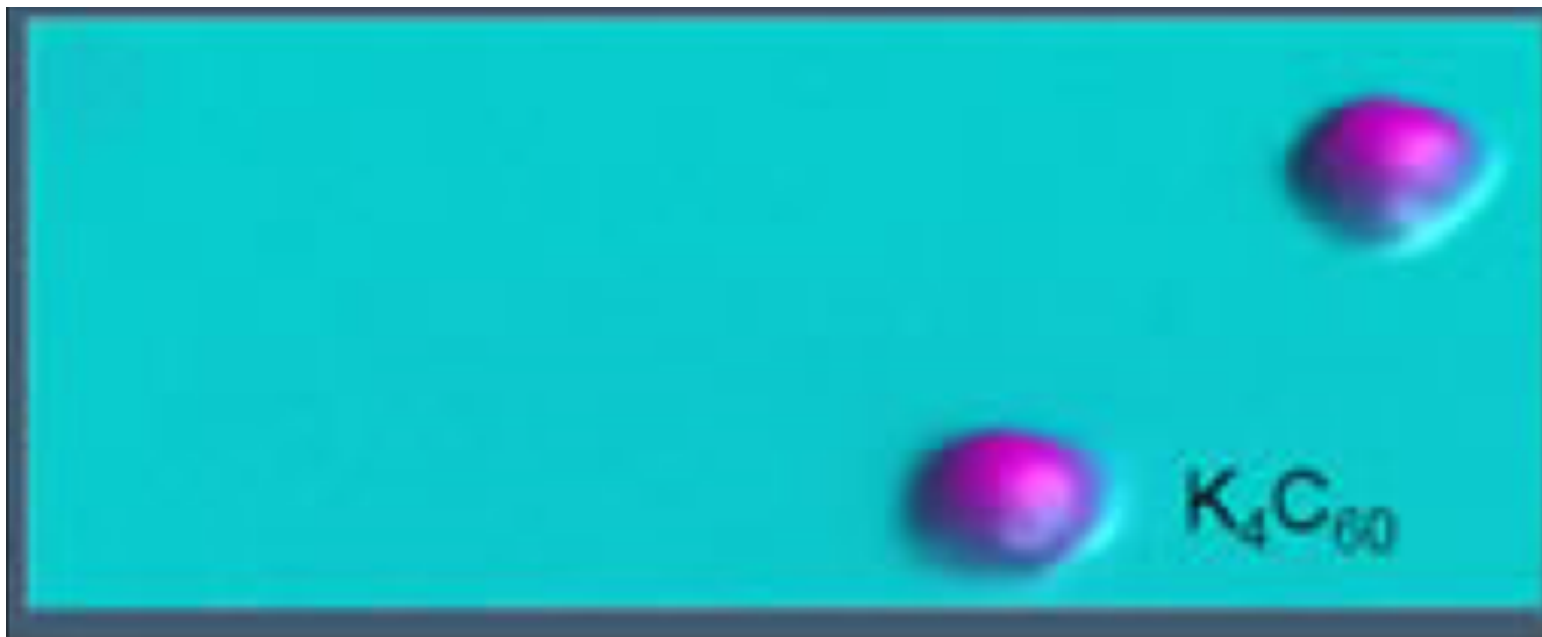




Fer sur cuivre (IBM)

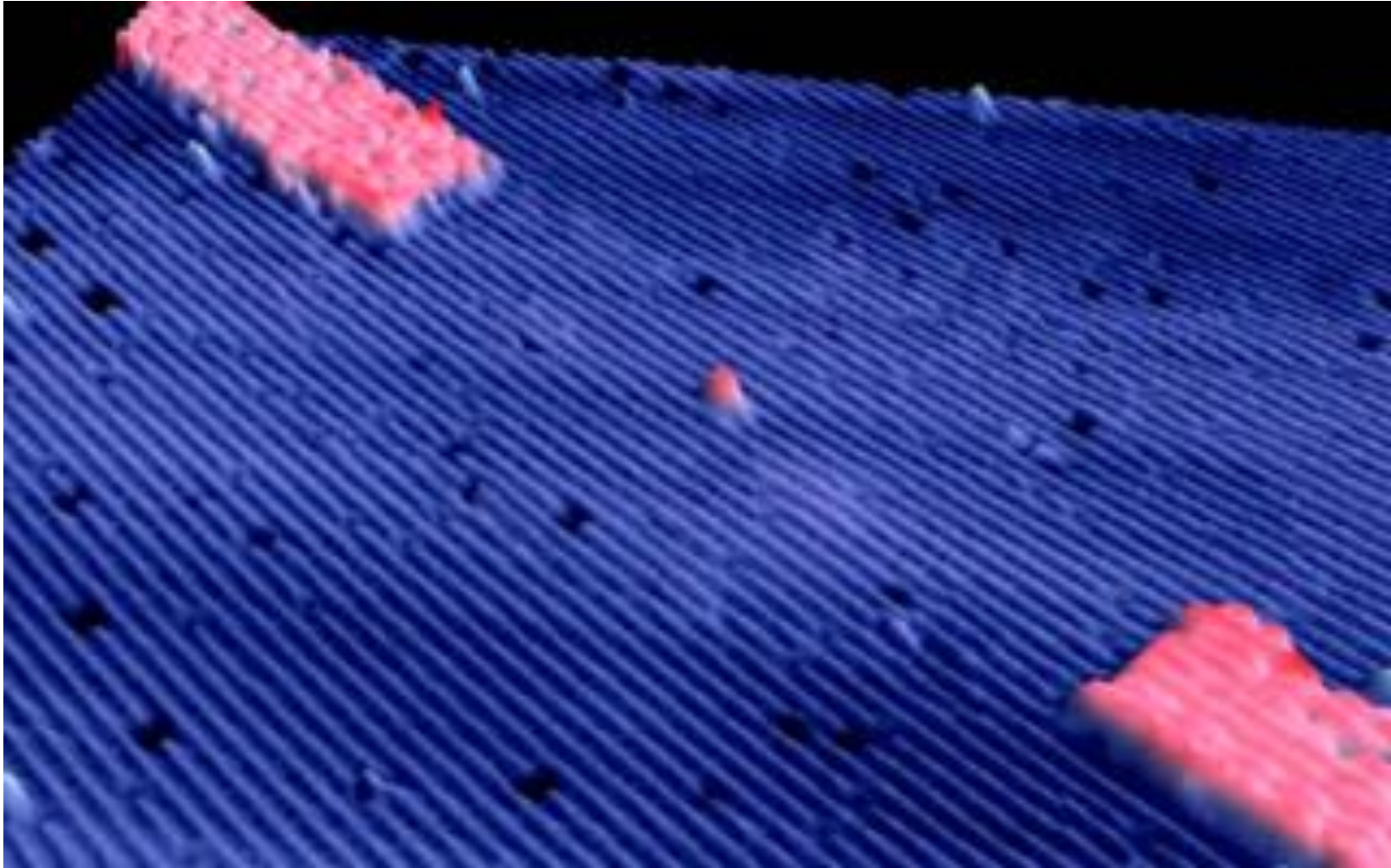


Fer sur cuivre (IBM)



*Michael Crommie, Berkeley*





transistor à un atome

une recherche récente  
stocker et lire de l'information  
sur un seul atome



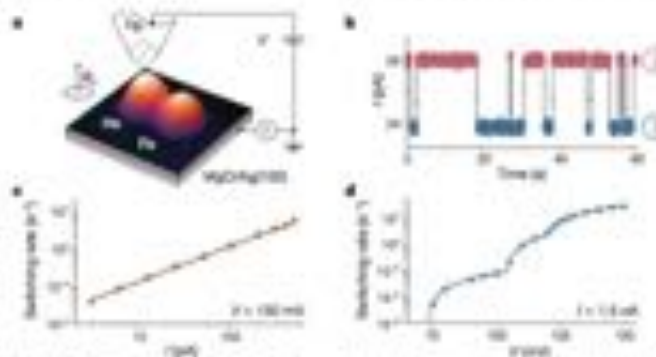
## Reading and writing single-atom magnets

Fabian D. Natterer<sup>1,2</sup>, Kai Yang<sup>1,2</sup>, William Paul<sup>1</sup>, Philip Willke<sup>1,2</sup>, Taryoung Choi<sup>1</sup>, Thomas Costler<sup>1,2</sup>, Andreas J. Heinrich<sup>1,2</sup> & Christopher F. Lutz<sup>1</sup>

The single-atom bit represents the ultimate limit of the classical approach to high-density magnetic storage media. So far, the smallest individually addressable bistable magnetic bits have consisted of 3–12 atoms<sup>1–3</sup>. Long magnetic relaxation times have been demonstrated for single lanthanide atoms in molecular magnets<sup>4–7</sup>, for lanthanide-doped in bulk crystals<sup>8</sup>, and recently for ensembles of helium (He) atoms supported on magnesium oxide (MgO)<sup>9</sup>. These experiments suggest a path towards data storage at the atomic limit, but the way in which individual magnetic centres are accessed remains unclear. Here we demonstrate the reading and writing of the magnetism of individual He atoms on MgO, and show that they independently retain their magnetic information over many hours. We read the He states using tunnel magnetoresistance<sup>10,11</sup> and write the states with current pulses using a scanning tunnelling microscope. The magnetic origin of the long-lived states is confirmed by single-atom electron spin resonance<sup>12</sup> on a nearby iron atom, which also shows that He has a large out-of-plane moment of  $10.2 \pm 8.1$  Bohr magnetons on this surface. To demonstrate independent reading and writing, we built an atomic-scale structure with two He bits, to which we write the four possible states and which we read out both magnetoresistively and resonantly by electron spin resonance. The high magnetic stability combined with electrical reading and writing shows that single-atom magnetic memory is indeed possible.

The demonstration of magnetic bistability in single-molecule magnets containing one rare-earth atom<sup>13,14</sup> illustrated the potential of single-atom spin centres in future storage media<sup>15,16,17</sup>. A ligand field that provides a barrier against magnetization reversal by lifting the Kraml degeneracies in single-molecule magnets<sup>18–21</sup> can also be realized for atoms bound to a surface<sup>22,23</sup>. While a break junction probes the quantum states of one isolated molecule<sup>24</sup>, a surface enables preparation of and access to numerous spin centres. Magnetic lifetimes in the range of milliseconds were accordingly obtained for single 3d atoms on MgO (ref. 25), but a recent report of magnetic bistability for He atoms on a platinum surface is debated<sup>26,27</sup>. A major advance of observing magnetic resonances was recently achieved with an ensemble of isolated He atoms on MgO (ref. 14), yet the question remained whether electrical probing of the highly localized f-orbitals of individual rare-earth atoms is possible<sup>27,28</sup>.

Here we address the magnetic bistability of individual He atoms on MgO, which we switch using current pulses and detect through the tunnel magnetoresistance using a spin-polarized scanning tunnelling microscope (STM)<sup>29</sup>. We unambiguously prove the magnetic origin of the switching in the tunnelling resonance using STM-enabled single-atom electron spin resonance (ESR) on an adjacent iron (Fe) atom. Additionally, we determine by this method the out-of-plane component of the He magnetic moment, and use the long lifetime to store two bits of information in an array of two He atoms

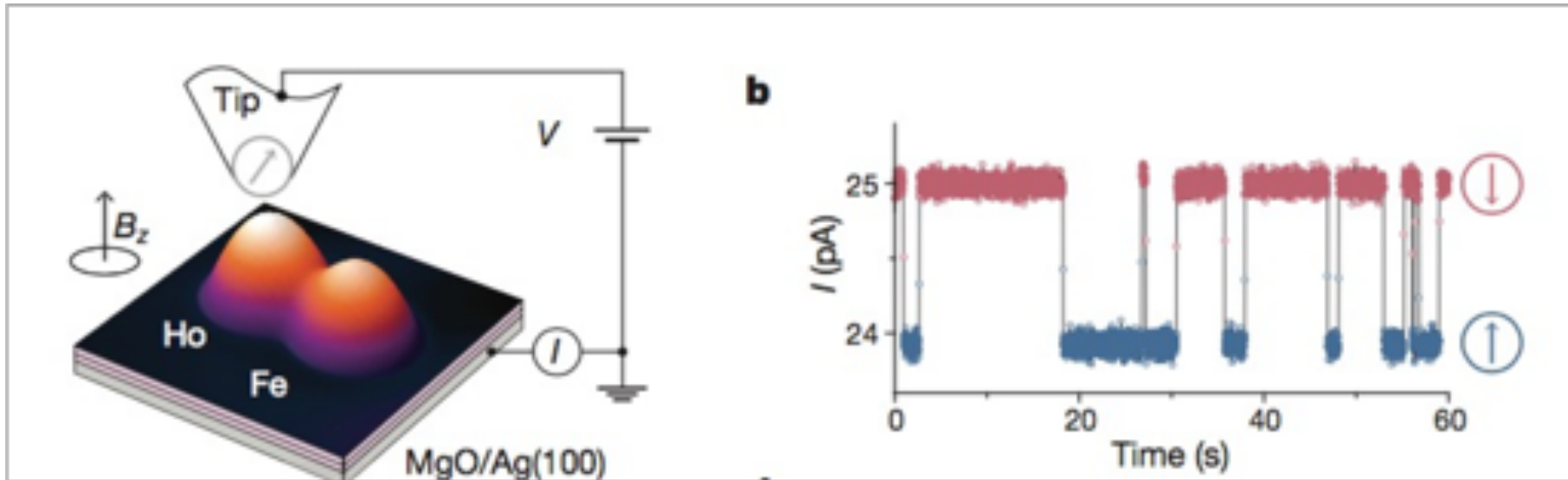


**Figure 1 | Experimental set-up and magnetic switching of helium.** **a**, Topographic image of a He atom on He atoms on helium (MgO). The magnetic states of He are controlled and probed with an STM using spin-polarized tunnelling ( $V = 100$  mV,  $I = 10$  pA,  $3.30$  nm,  $n = 1.14$  nm,  $T = 0.2$  K,  $B_z = 100$  mT). **b**, The magnetoresistive based current  $I$  recorded atop a He atom (STM image in **a**) shows switching between two magnetic states (red, down; blue, up) of long residence time ( $V = 100$  mV, current set point  $I = 10$  pA). At these tunnelling conditions, switching is induced

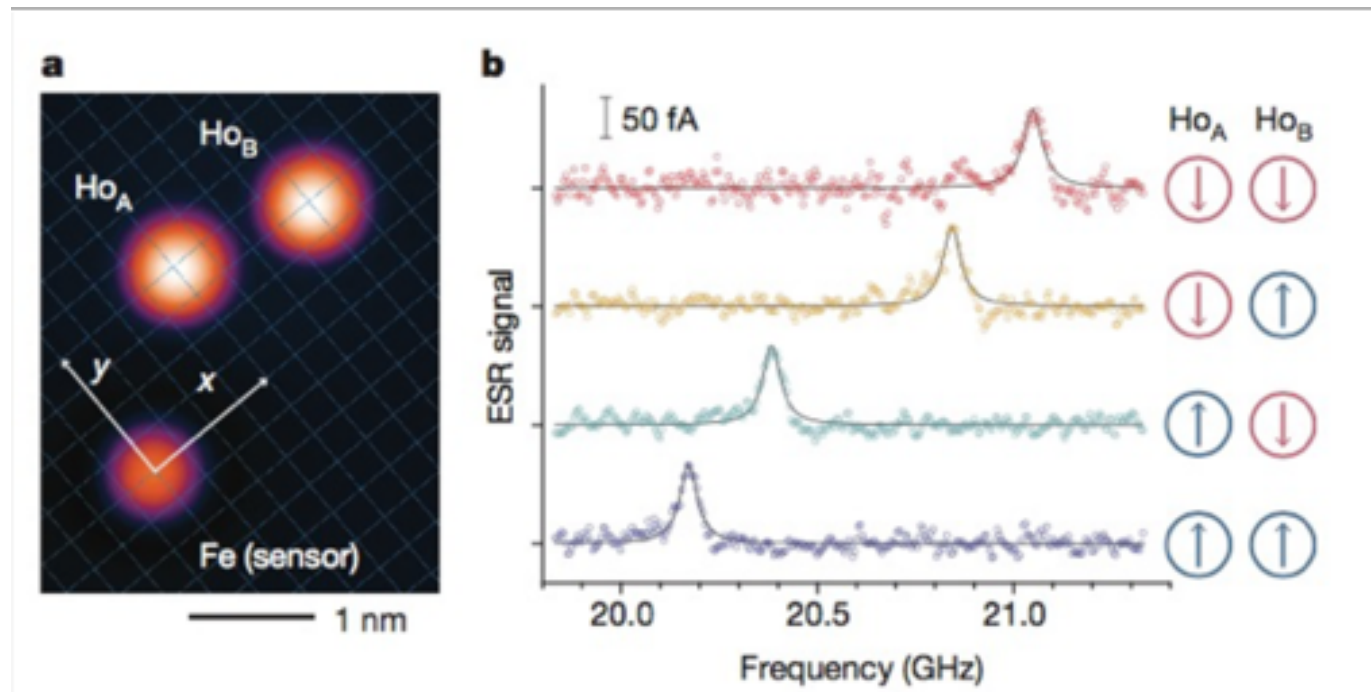
by tunnelling electrons. The switching rate  $\Gamma$  at  $B_z = 100$  mT scales as  $\Gamma = \alpha I^2 / \mu_0$ , where  $\mu_0$  is close to unity and  $\alpha$  is a switching coefficient (see Methods,  $V = 100$  mV,  $I_A = 1$  pA). **c**, The voltage dependence at  $B_z = 100$  mT of  $\Gamma$  at constant current ( $I = 10$  pA) reveals three rate-increasing thresholds at  $V_1 = 73 \pm 3$  mV,  $V_2 = 100 \pm 1$  mV and  $V_3 = 118 \pm 1$  mV. The solid line is a three-segment piecewise linear fit. The uncertainty of the fits in **a** and **c** indicates the standard deviation on the least-squares fit parameters.

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On change l'aimantation de l'atome de Ho via un courant dans la pointe :



On lit l'aimantation de chaque atome de Ho via un atome de Fer voisin :



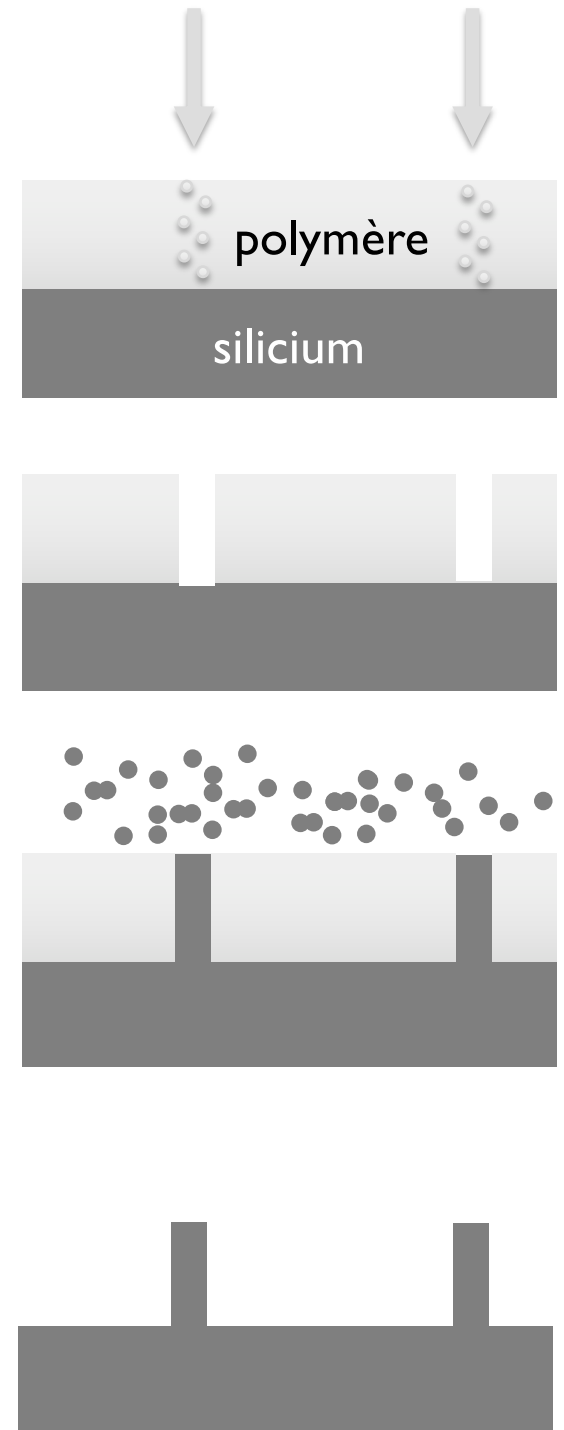
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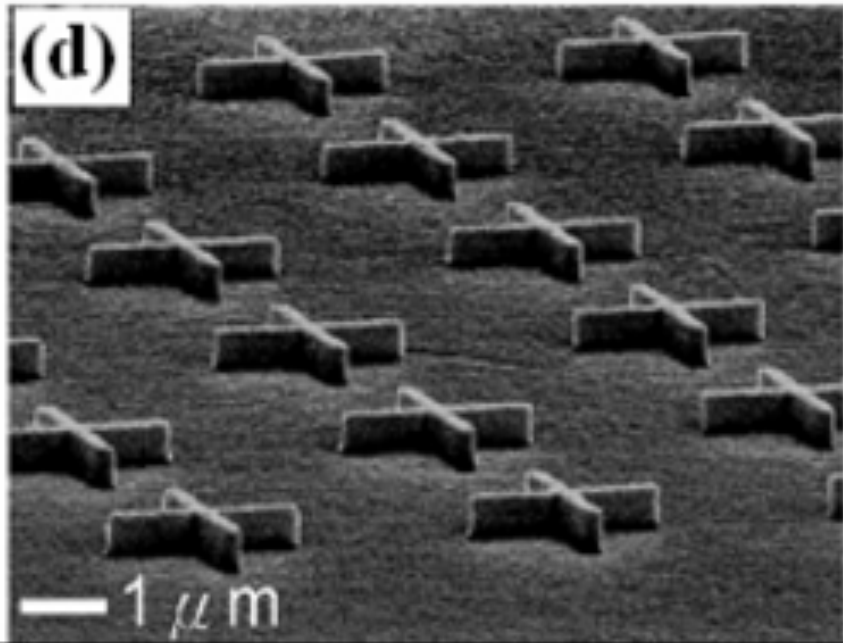
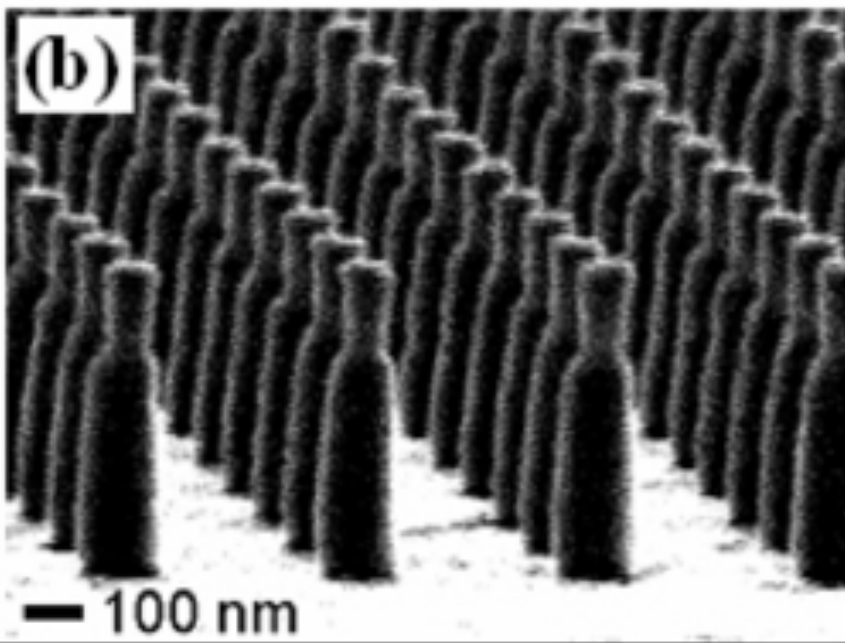
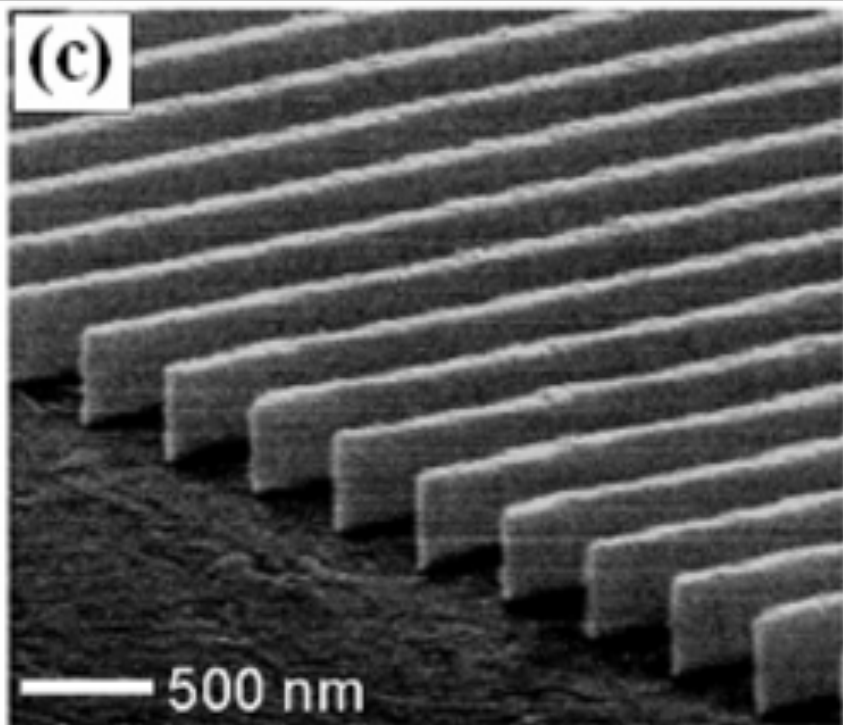
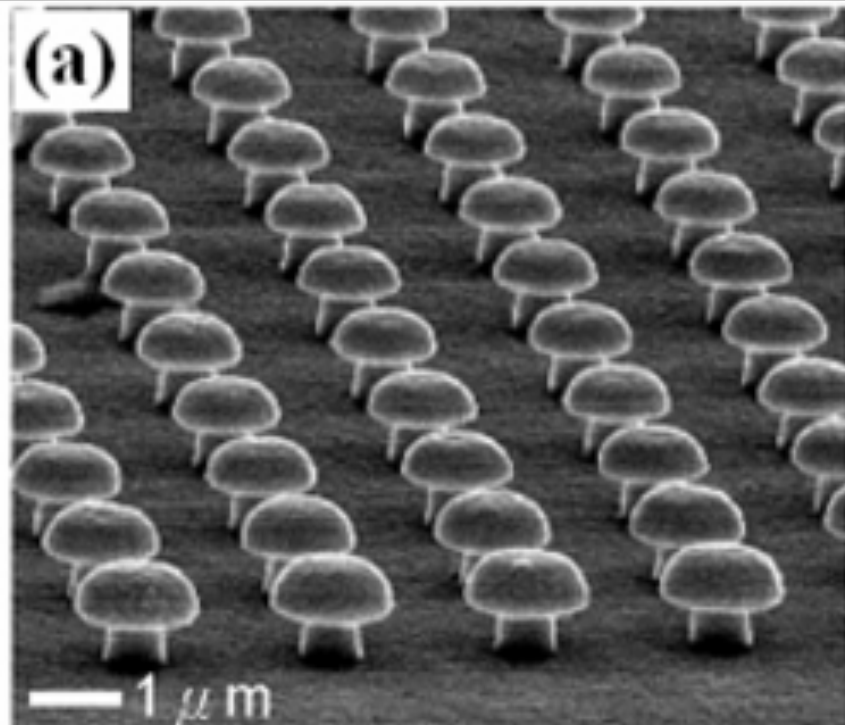
- atome par atome
- en gravant
- en évaporant
- à partir de matière existante



# la lithographie électronique

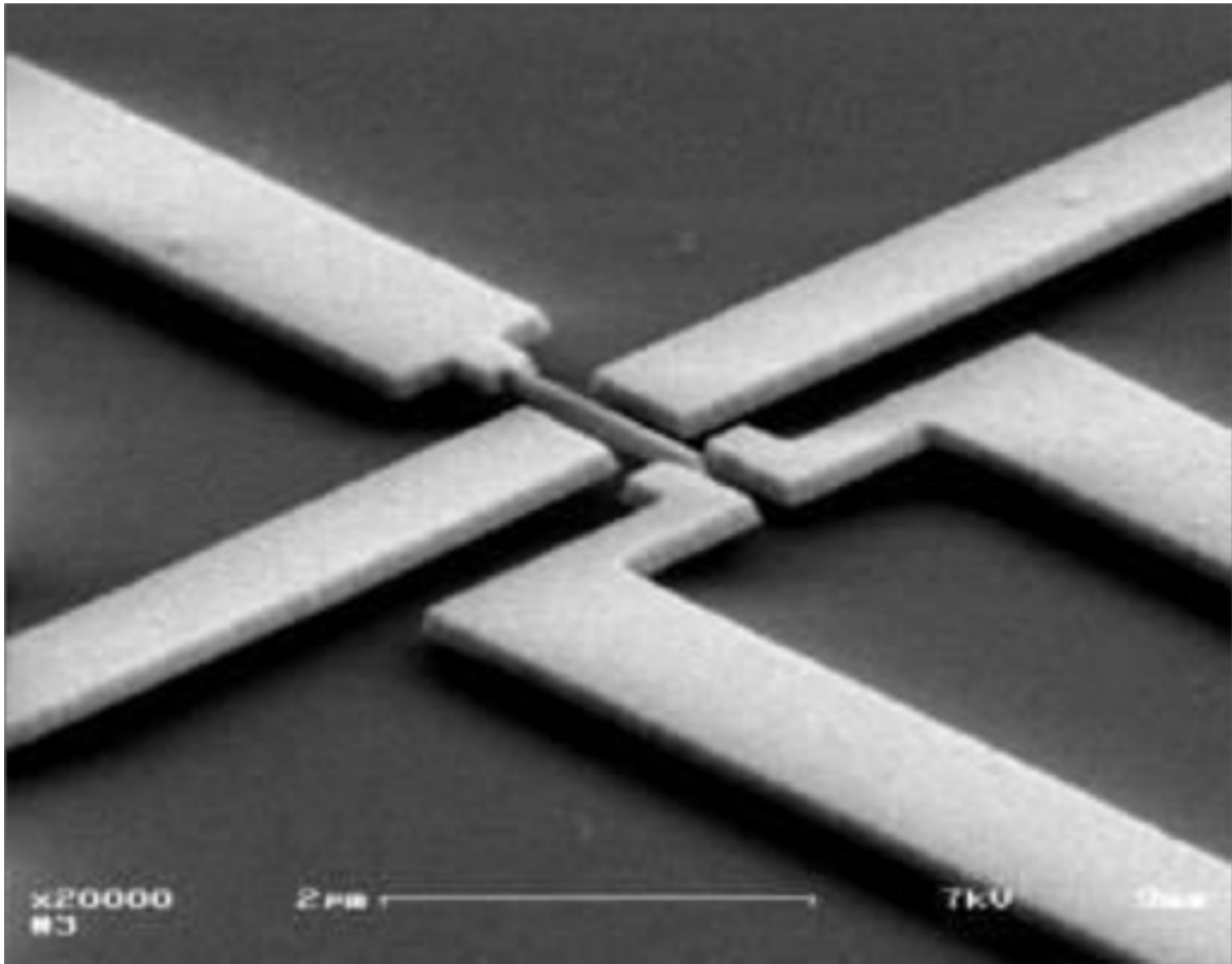
- 1) on grave avec un faisceau d'électrons une surface fine de polymère (résine). Ca casse les chaînes de polymères.
- 2) on applique un solvant qui enlève les régions irradiées seulement.
- 3) on évapore un métal sur le polymère gravé – ça remplit les trous.
- 4) on enlève le polymère : il reste un motif gravé.





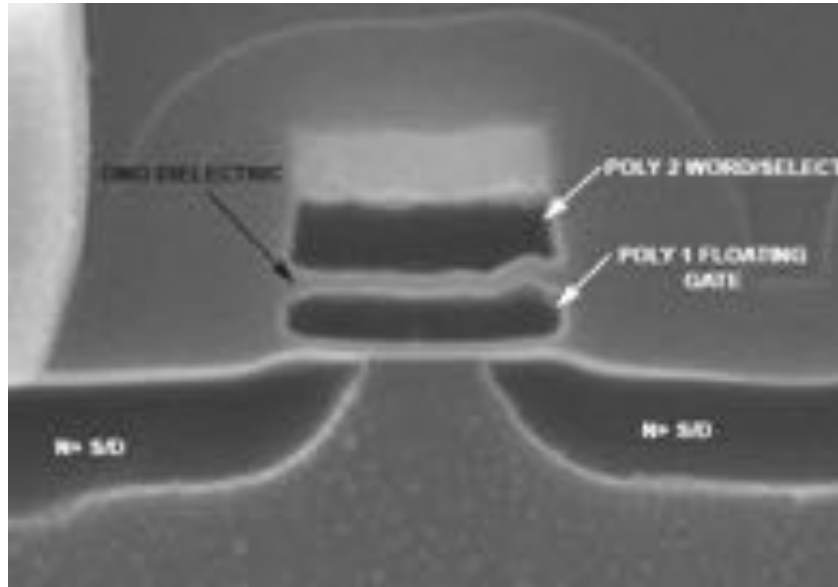
Utilisation principale :  
des composants petits pour l'électronique



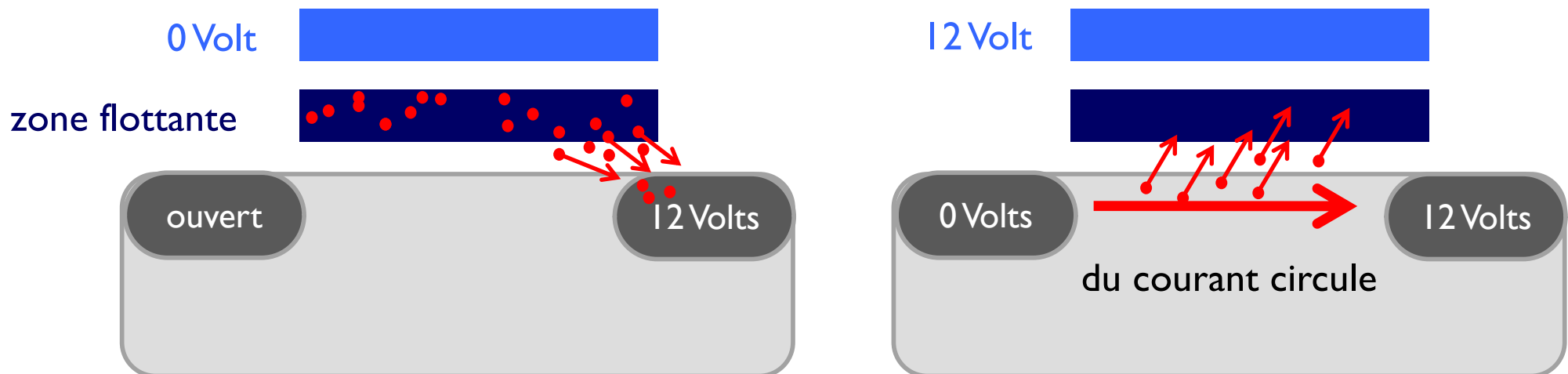


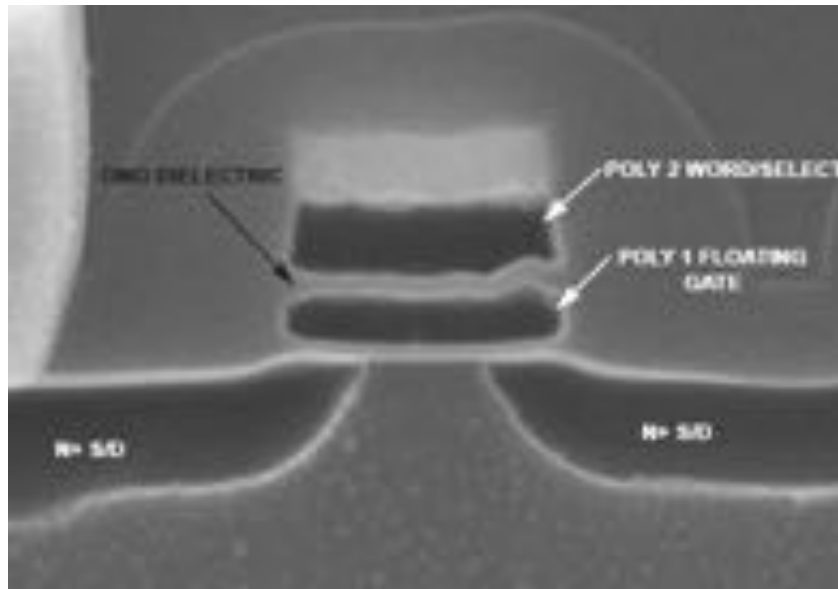
Un exemple de composant nano :  
la mémoire flash (par exple dans une clé USB)



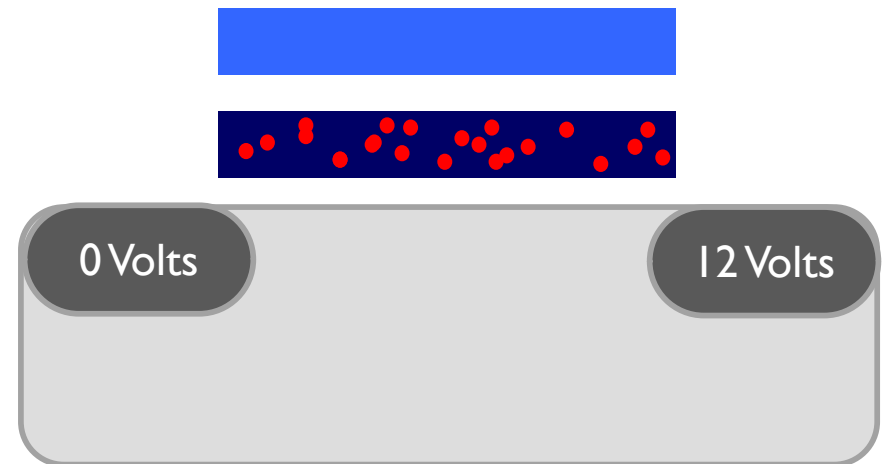
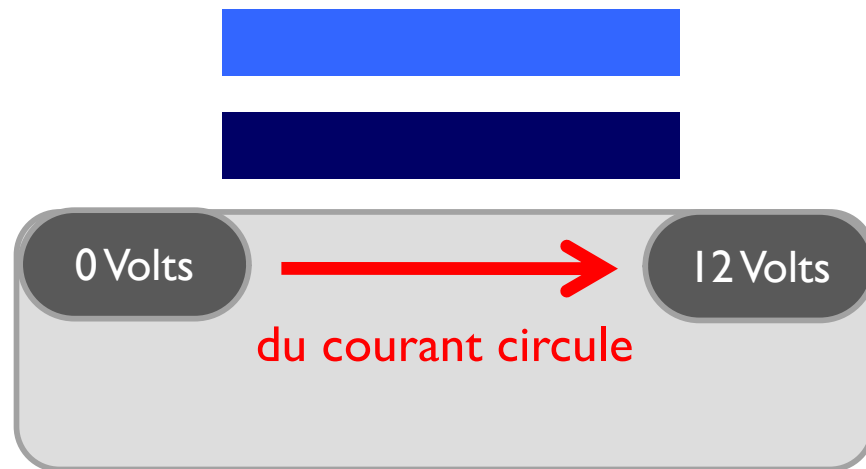


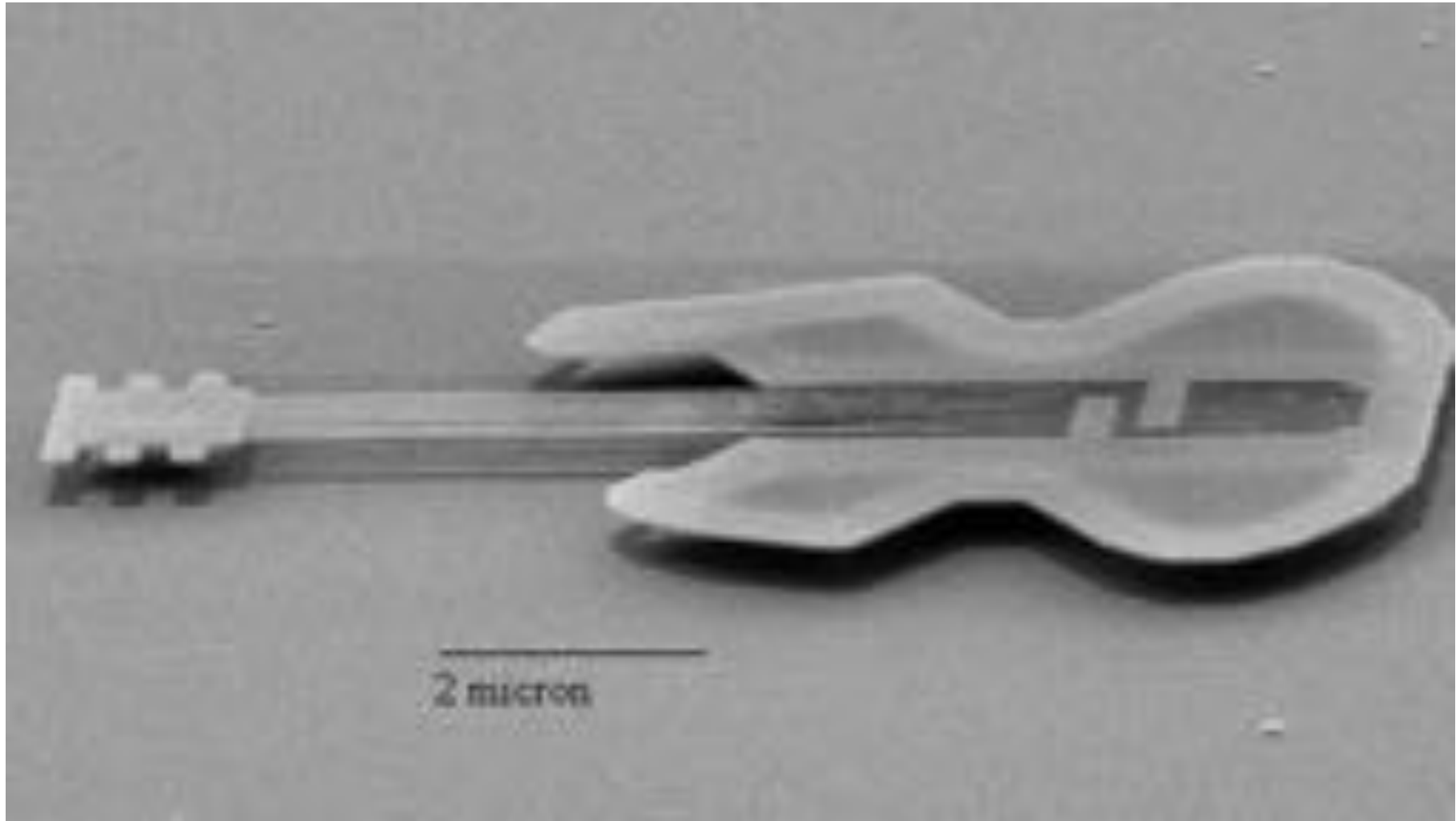
Écriture : on peut arracher ou injecter des électrons par effet tunnel dans la zone flottante





Lecture : si il y a des électrons stockés, ça bloque le courant électrique.





nanoguitare



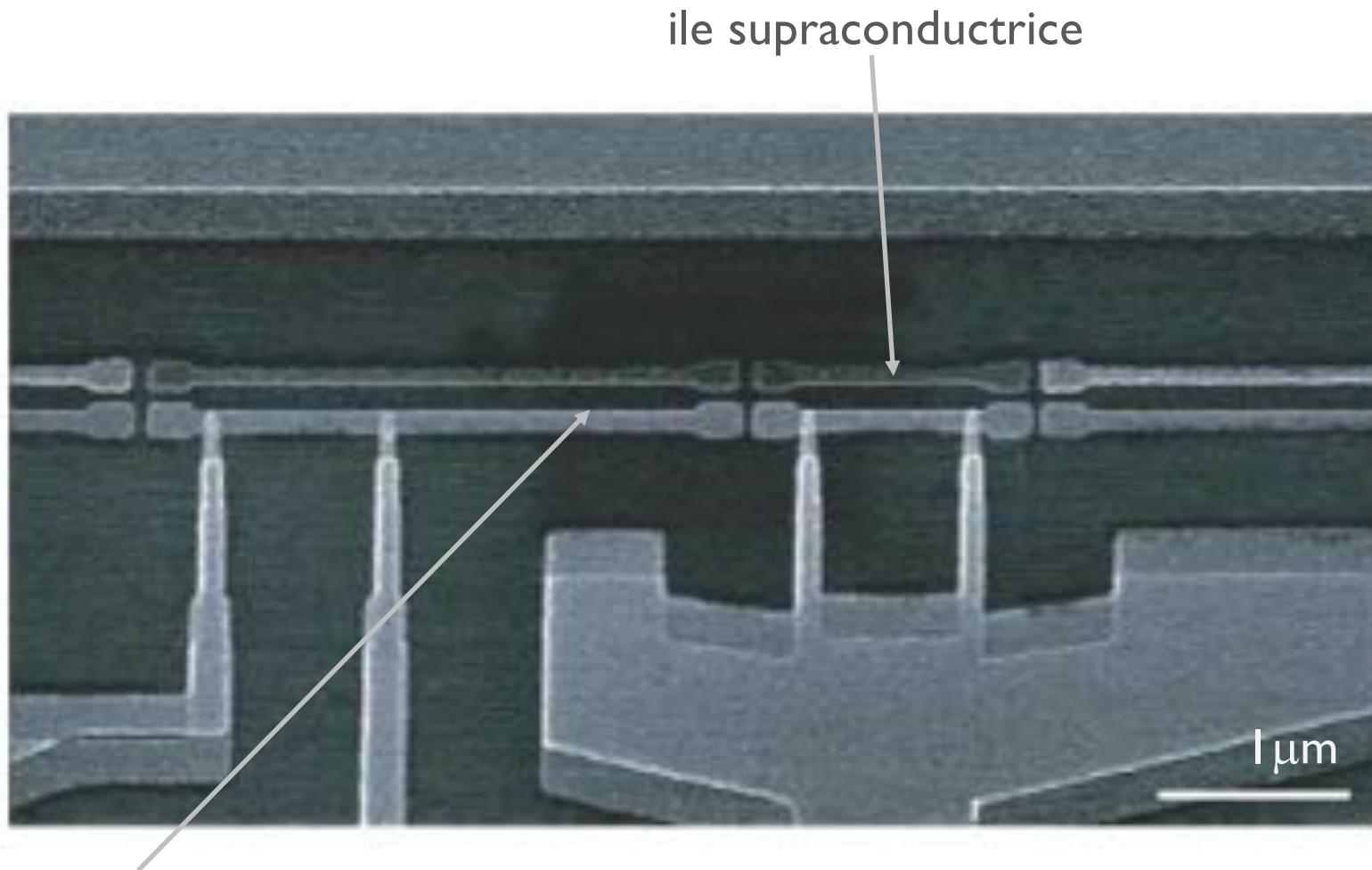
**une recherche récente:**

graver des composants utilisant  
des supraconducteurs

pour des ordinateurs quantiques

## exemple : un qubit de charge supraconducteur

On peut placer  $N$  et  $N+1$  paires d'électrons dans une île supraconductrice via des jonctions Josephson.



mesure via un transistor  
à un électron

# mais...

- problème de décohérence
- problème pour trouver le bon algorithme
- problème d'erreurs qui croît exponentiellement

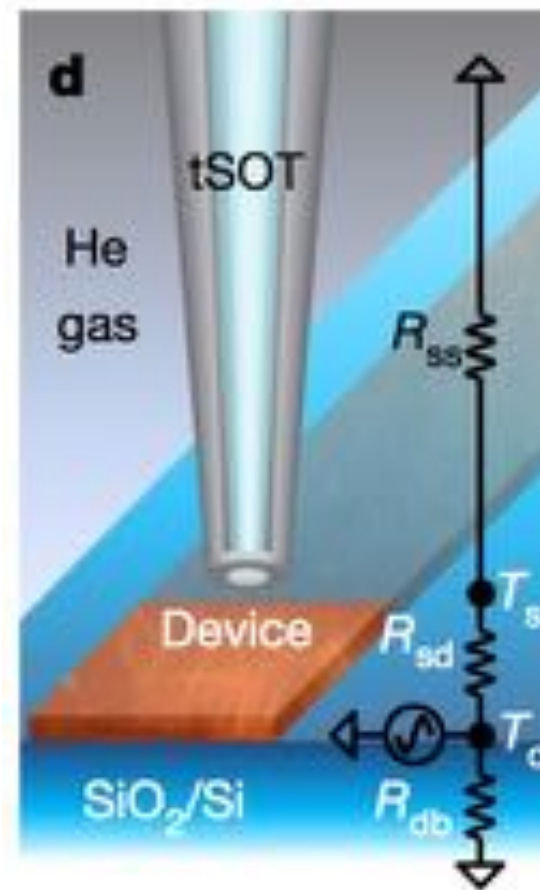
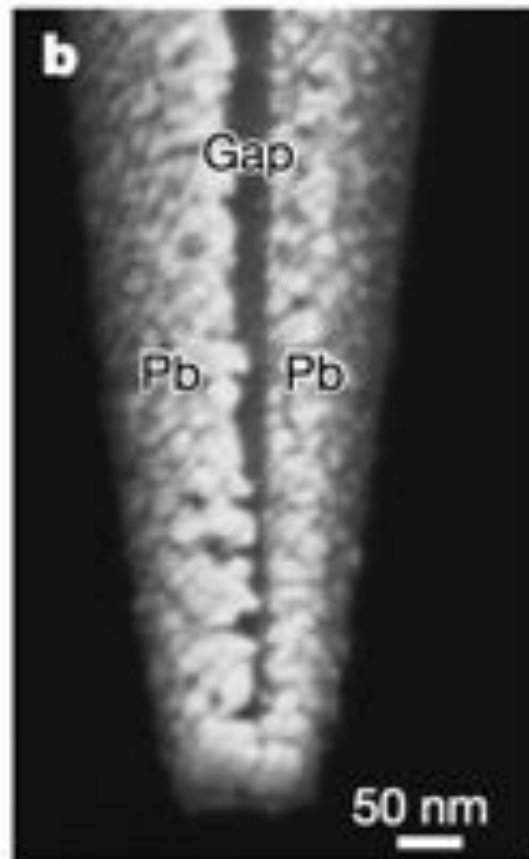
**une recherche récente:**  
graver des composants utilisant  
des supraconducteurs  
pour un nano-thermomètre

# Nanoscale thermal imaging of dissipation in quantum systems

D. Halbertal<sup>1</sup>, J. Cuppens<sup>1,2</sup>, M. Ben Shalom<sup>3,4</sup>, L. Embon<sup>1†</sup>, N. Shadmi<sup>5</sup>, Y. Anahory<sup>1</sup>, H. R. Naren<sup>1</sup>, J. Sarkar<sup>1</sup>, A. Uri<sup>1</sup>, Y. Ronen<sup>1</sup>, Y. Myasoedov<sup>1</sup>, L. S. Levitov<sup>6</sup>, E. Joselevich<sup>5</sup>, A. K. Geim<sup>3,4</sup> & E. Zeldov<sup>1</sup>



Composant SQUID (supraconducteur-isolant-supraconducteur) au bout d'une pipette.  
Le courant critique du SQUID varie avec la température :  $I_c(T) \approx I_0(1 - T/T_c)$ .  
→ Sensibilité :  $1 \mu\text{K} \cdot \text{Hz}^{-1/2}$  et possibilité de déplacer le thermomètre



# Nanoscale thermal imaging of dissipation in quantum systems

D. Halbertal<sup>1</sup>, J. Cuppens<sup>1,2</sup>, M. Ben Shalom<sup>3,4</sup>, L. Embon<sup>1†</sup>, N. Shadmi<sup>5</sup>, Y. Anahory<sup>1</sup>, H. R. Naren<sup>1</sup>, J. Sarkar<sup>1</sup>, A. Uri<sup>1</sup>, Y. Ronen<sup>1</sup>, Y. Myasoedov<sup>1</sup>, L. S. Levitov<sup>6</sup>, E. Joselevich<sup>5</sup>, A. K. Geim<sup>3,4</sup> & E. Zeldov<sup>1</sup> Nature 2016

on fait circuler 12 nA dans un nanotube : ça le chauffe et on le détecte.

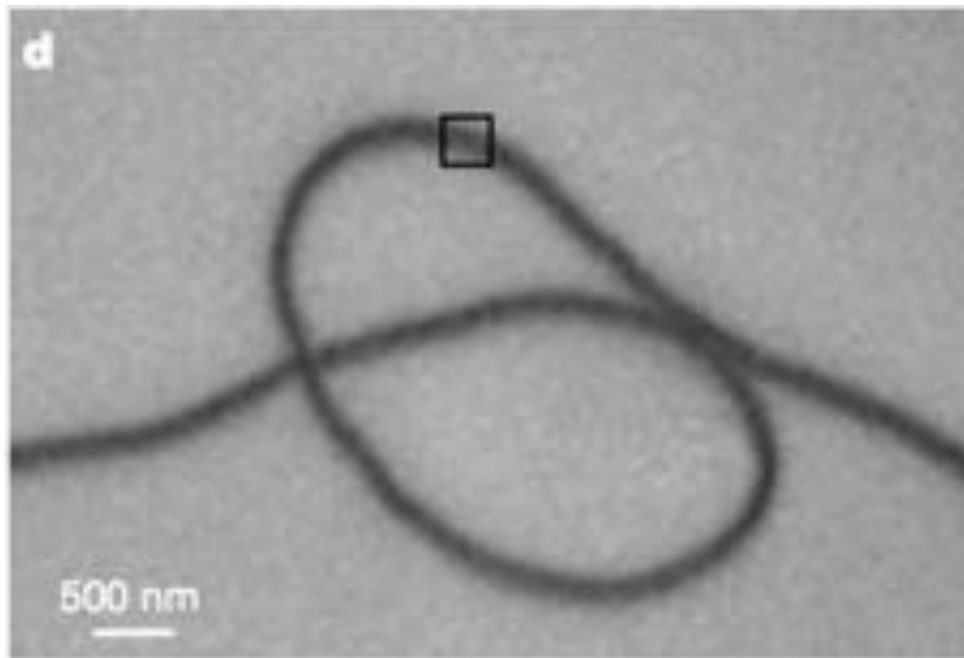


image par microscopie électronique

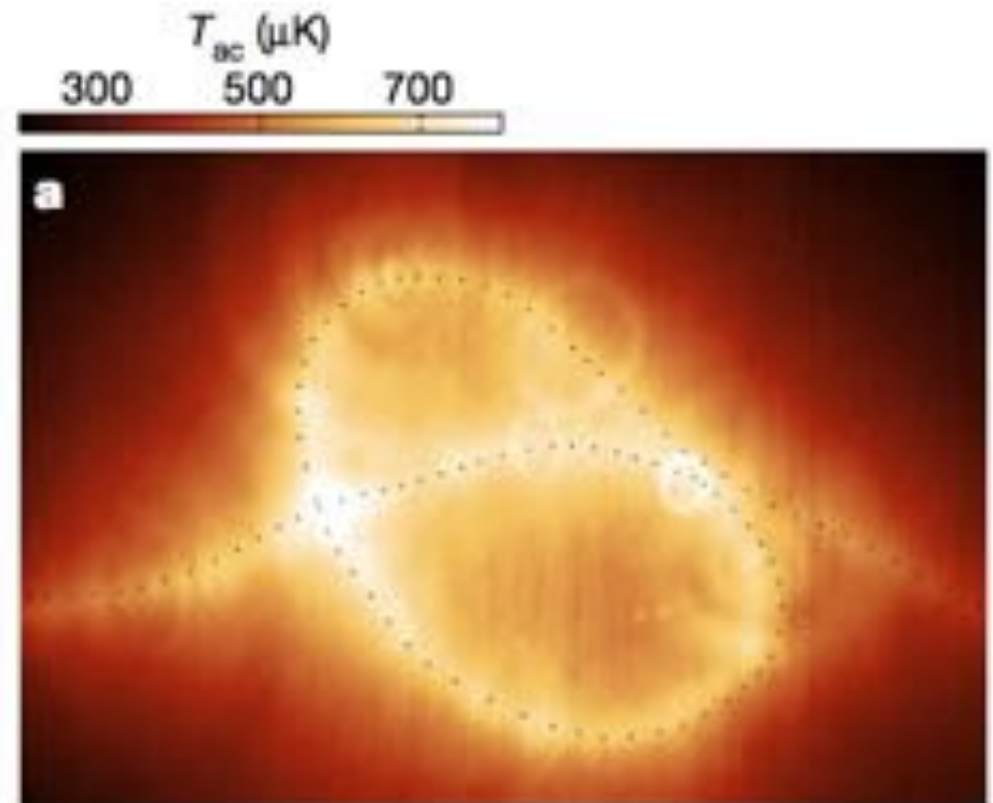


image thermique

# Nanoscale thermal imaging of dissipation in quantum systems

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expérience avec une autre boucle de nanotube et un courant de 3nA

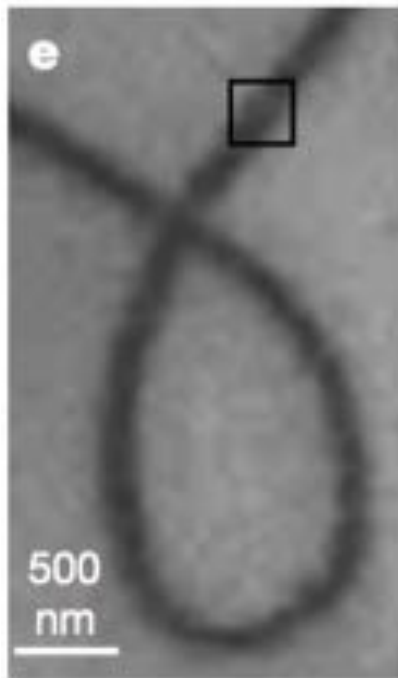


image par microscopie électronique

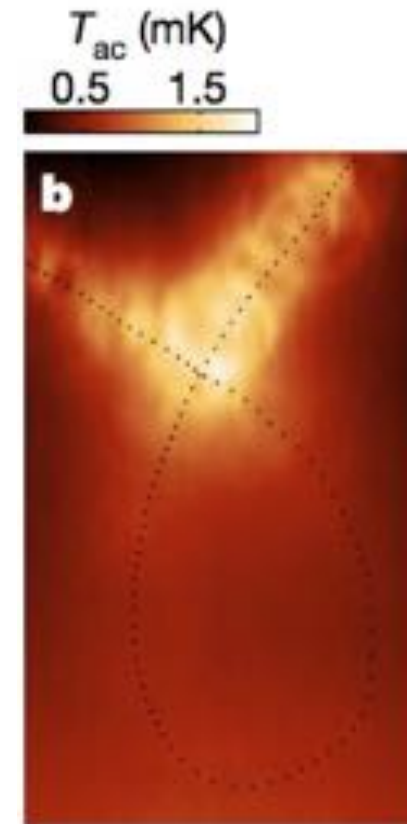


image thermique

Il n'y a plus de courant dans la boucle  
On vient de détecter un court-circuit

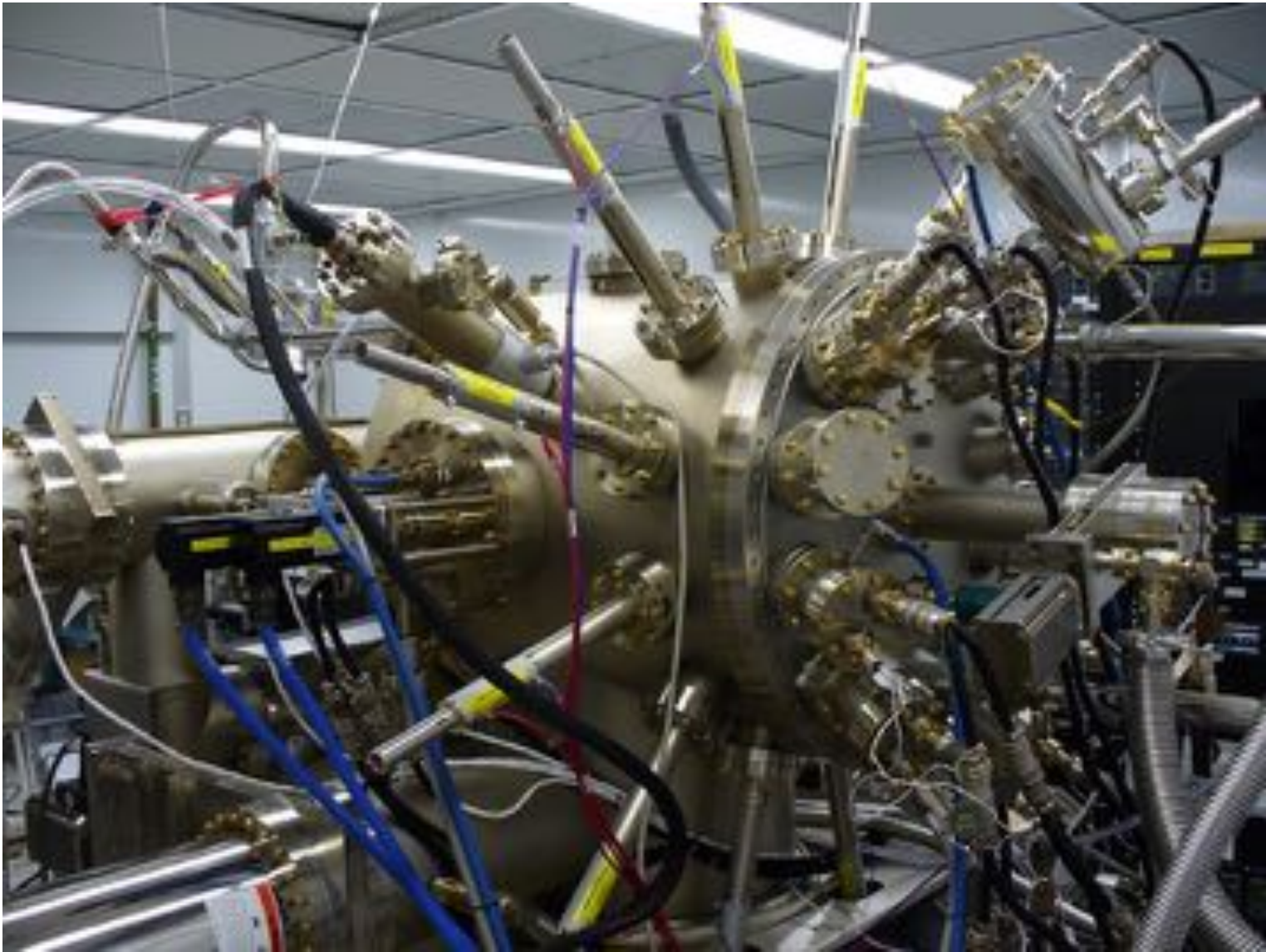
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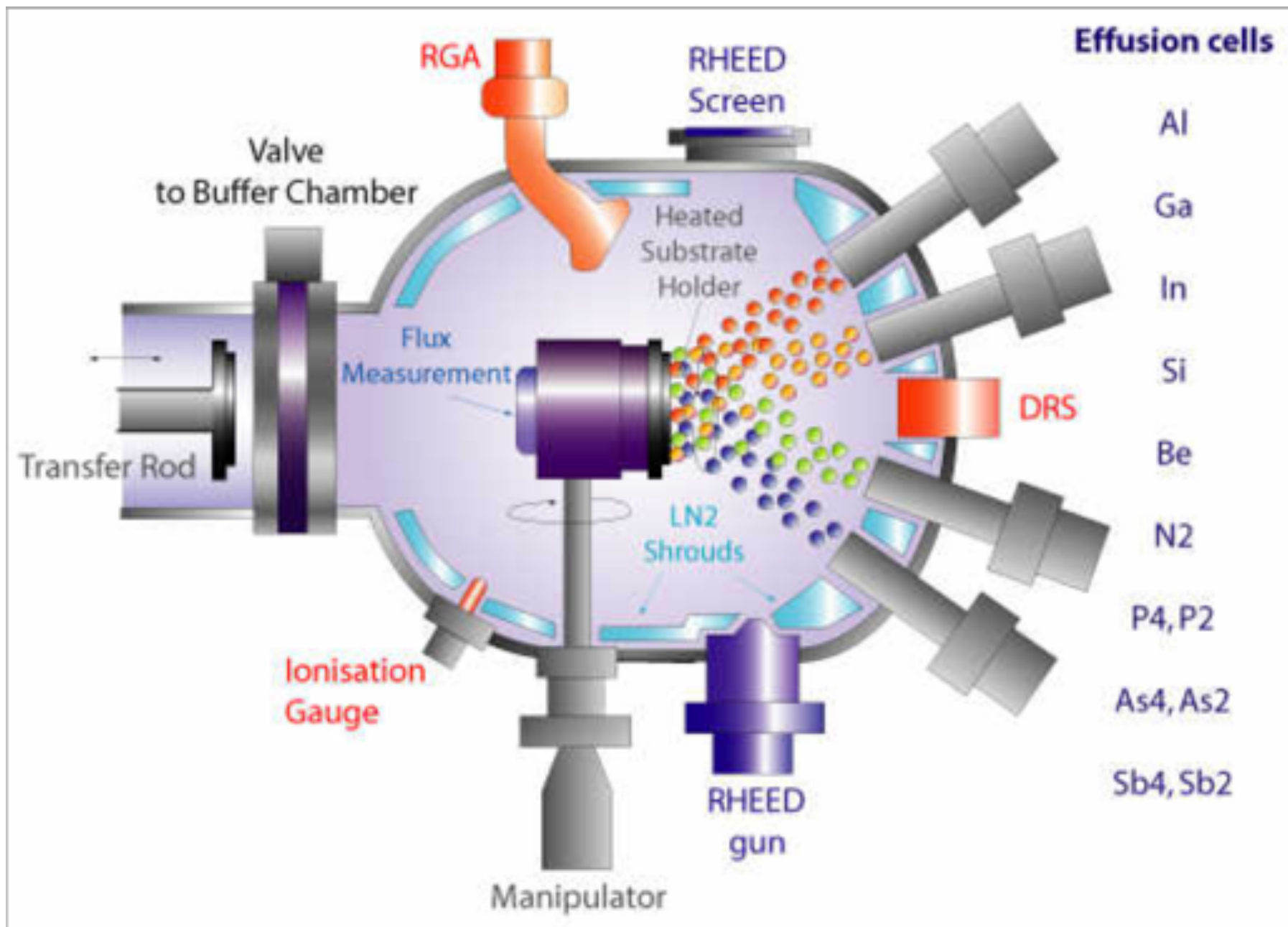


Fabriquer en évaporant

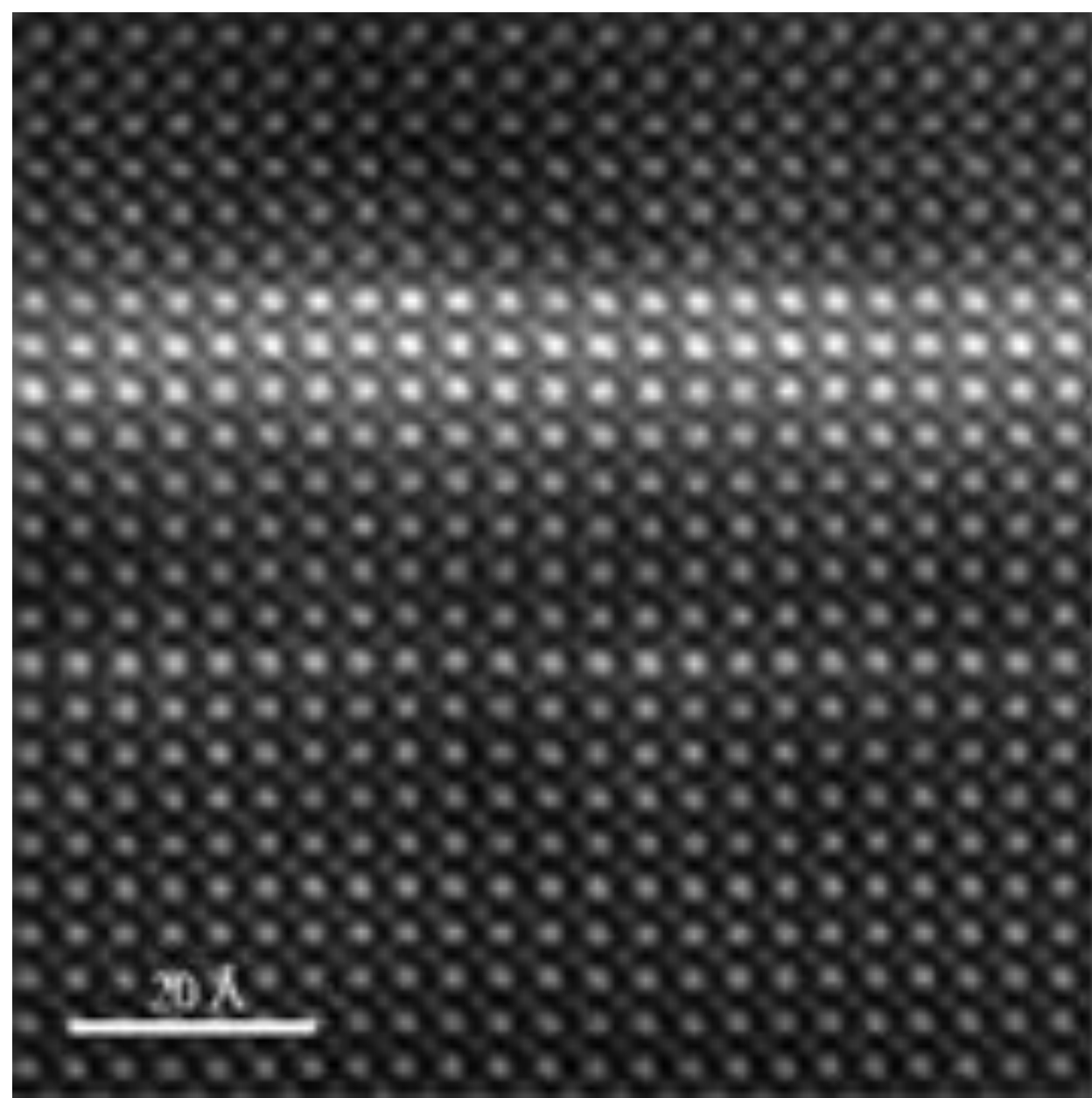
on évapore des vapeurs contrôlées sur  
une surface pour qu'elles s'y déposent  
couche par couche



Epitaxie par jets moléculaires



Epitaxie par jets moléculaires



STO Capping Layer  
←  
3 Unit Cells of LSMO  
←  
5 Unit Cells of STO  
←  
1 Unit Cell of LSMO  
←  
STO Substrate

20 Å

# des multicouches magnétiques



P. Grunberg, A. Fert



une recherche récente:  
simuler un neurone  
avec des couches minces  
magnétiques



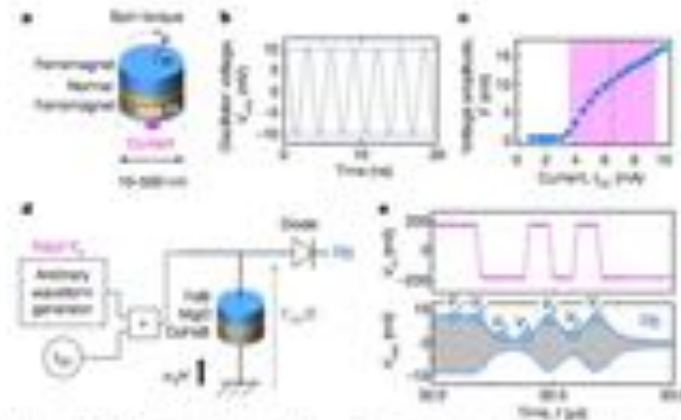
# Neuromorphic computing with nanoscale spintronic oscillators

Jacobs Dreier<sup>1</sup>, Mathias Klum<sup>1</sup>, Flavio Alessi-Araujo<sup>1</sup>, Sumati Dhanraj<sup>1</sup>, Gary Khalsa<sup>1,2</sup>, Damien Querlioz<sup>1</sup>, Paolo Bernini<sup>1</sup>, Vincent Couv<sup>1</sup>, Kay Yakushiji<sup>1</sup>, Akira Fukushima<sup>1</sup>, Shiroh Kubota<sup>1</sup>, Shing Yuasa<sup>1</sup>, Mark D. Stiles<sup>3</sup> & Jude Crosser<sup>1</sup>

Neurons in the brain behave as nonlinear oscillators, which develop rhythmic activity and interact to process information<sup>1</sup>. Taking inspiration from this behaviour to realise high-density, low-power neuromorphic computing will require very large numbers of nanoscale nonlinear oscillators. A simple estimation indicates that to fit  $10^7$  oscillators organised in a two-dimensional array inside a chip the size of a thumb, the lateral dimension of each oscillator must be smaller than one micronometre. However, nanoscale devices tend to be noisy and to lack the stability that is required to process data in a reliable way. For this reason, despite multiple theoretical proposals<sup>2–7</sup> and several candidates, including monolayers<sup>8</sup> and superconducting<sup>9</sup> oscillators, a proof of concept of neuromorphic computing using nanoscale oscillators has yet to be demonstrated. Here we show experimentally that a nanoscale spintronic oscillator (a magnetic tunnel junction)<sup>10</sup> can be used to achieve spike-like

oscillations with an accuracy similar to that of state-of-the-art neural networks. We also determine the regime of magnetisation dynamics that leads to the greatest performance. These results, combined with the ability of the spintronic oscillators to interact with each other, and their long lifetimes and low energy consumption, open up a path to fast, parallel, on-chip computation based on networks of oscillators.

Nanoscale spintronic oscillators (or spin-torque nano-oscillators) are nanoscale pillars composed of two ferromagnetic layers separated by a non-magnetic spacer (Fig. 1a). Charge currents become spin-polarised when they flow through these junctions and generate torques on the magnetisations<sup>11,12</sup> that lead to sustained magnetisation precession at frequencies of hundreds of megahertz to several tens of gigahertz. Magnetisation oscillations are converted into voltage oscillations through magnetic resistance. The resulting radio-frequency oscillations, of up to tens of millivolts (ref. 13), can be detected by measuring



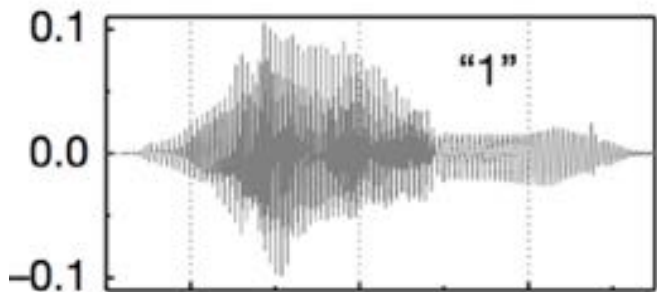
**Figure 1 | Spin-torque nano-oscillator for neuromorphic computing.** **a**, Schematic of a spin-torque nano-oscillator, consisting of a non-magnetic spacer (NM) between two ferromagnetic layers with magnetisations  $M_1$  for the first layer (blue) and  $M_2$  for the second layer (red). A current injected into the oscillator induces magnetisation precession of  $M_1$ . For our experiments we used a nano-oscillator with a diameter of 200 nm; however, diameters of 10–500 nm are possible. **b**, Measured AC voltage amplitude by the oscillator as a function of current  $I_{DC}$  at  $\mu_0 H = 430$  mT for a steady current injection of 7 mA at an external magnetic field  $\mu_0 H = 430$  mT. The dotted blue lines highlight the amplitude  $V_rms$ , voltage amplitude  $V$  as a function of  $I_{DC}$  current  $I_{DC}$  at  $\mu_0 H = 430$  mT (blue square). The purple shaded area highlights the typical excursions in the

voltage amplitude that results when an input signal of  $V_{in} = 4$  (20) mV is injected (here for  $I_{DC} = 4$  (2) mA (vertical dotted line) and  $\mu_0 H = 430$  mT). **c**, Schematic of the experimental set-up. **d–f**, Current  $I_{DC}$  and a rapidly varying waveform that encodes the input  $V_{in}$  are injected into the spin-torque nano-oscillator. The measured voltage  $V_rms$  emitted by the oscillator in response to the excitation is measured with an oscilloscope. For computing the amplitude  $V$  of the oscillator in real time, measured directly with a microwave diode  $d$ , a super  $V_{in}$  (top, magenta) and measured microwave voltage  $V_rms$  (bottom, grey) emitted by the oscillator as a function of time. Here  $I_{DC} = 4$  mA and  $\mu_0 H = 430$  mT. The voltage  $V$  of the oscillator signal is highlighted in blue. For computing it is sampled periodically, as shown by the blue circle labelled  $V_s$ .

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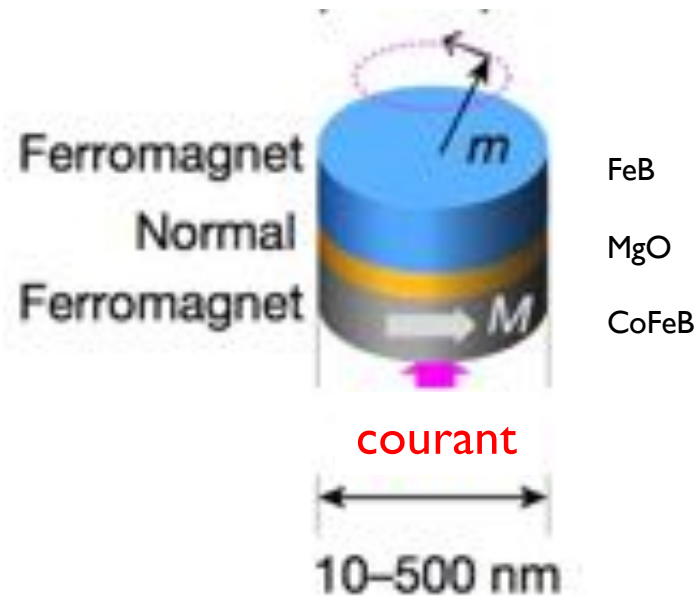


le son pour « 1 », « 2 », « 3 »...



courant

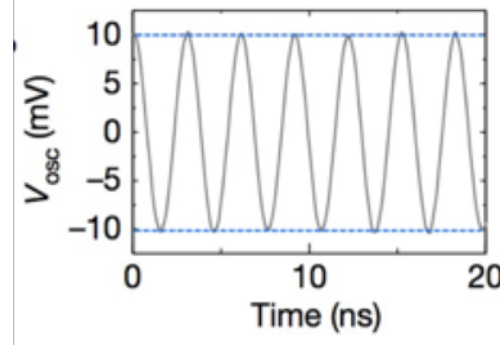
le courant fait tourner l'aimantation qui fait osciller la magnétoresistance



courant

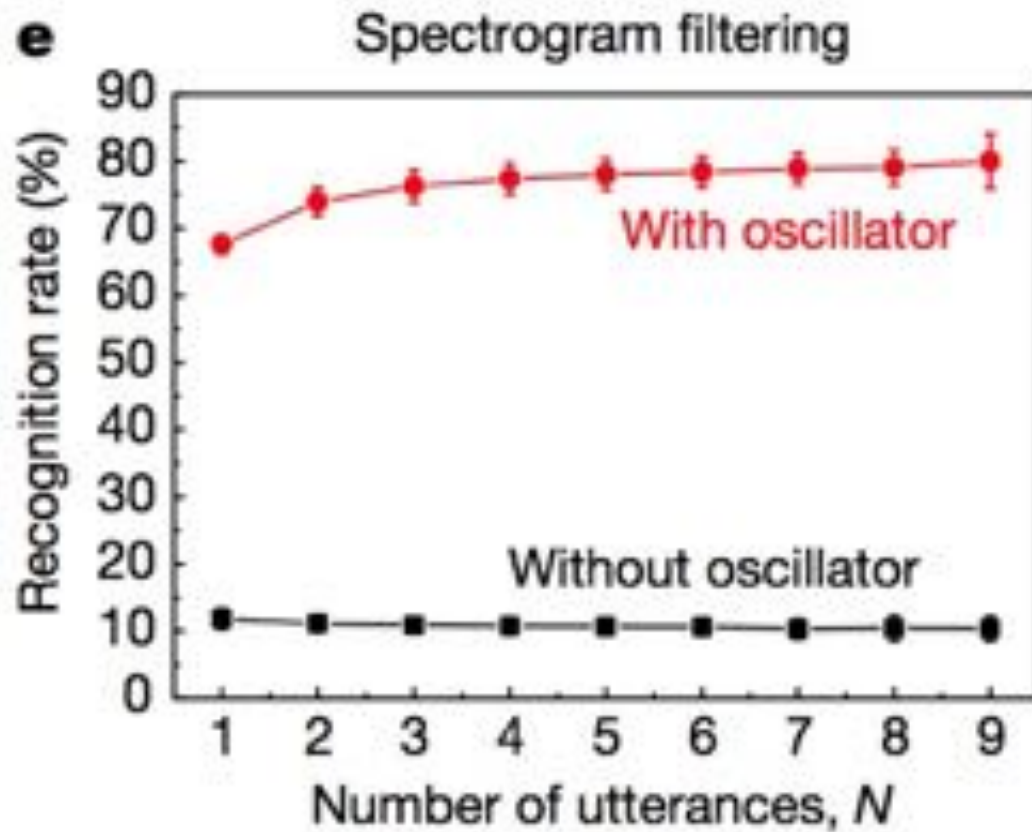
10-500 nm

tension oscillante



machine learning





reconnaissance des sons  
avec le « spin torque oscillator »

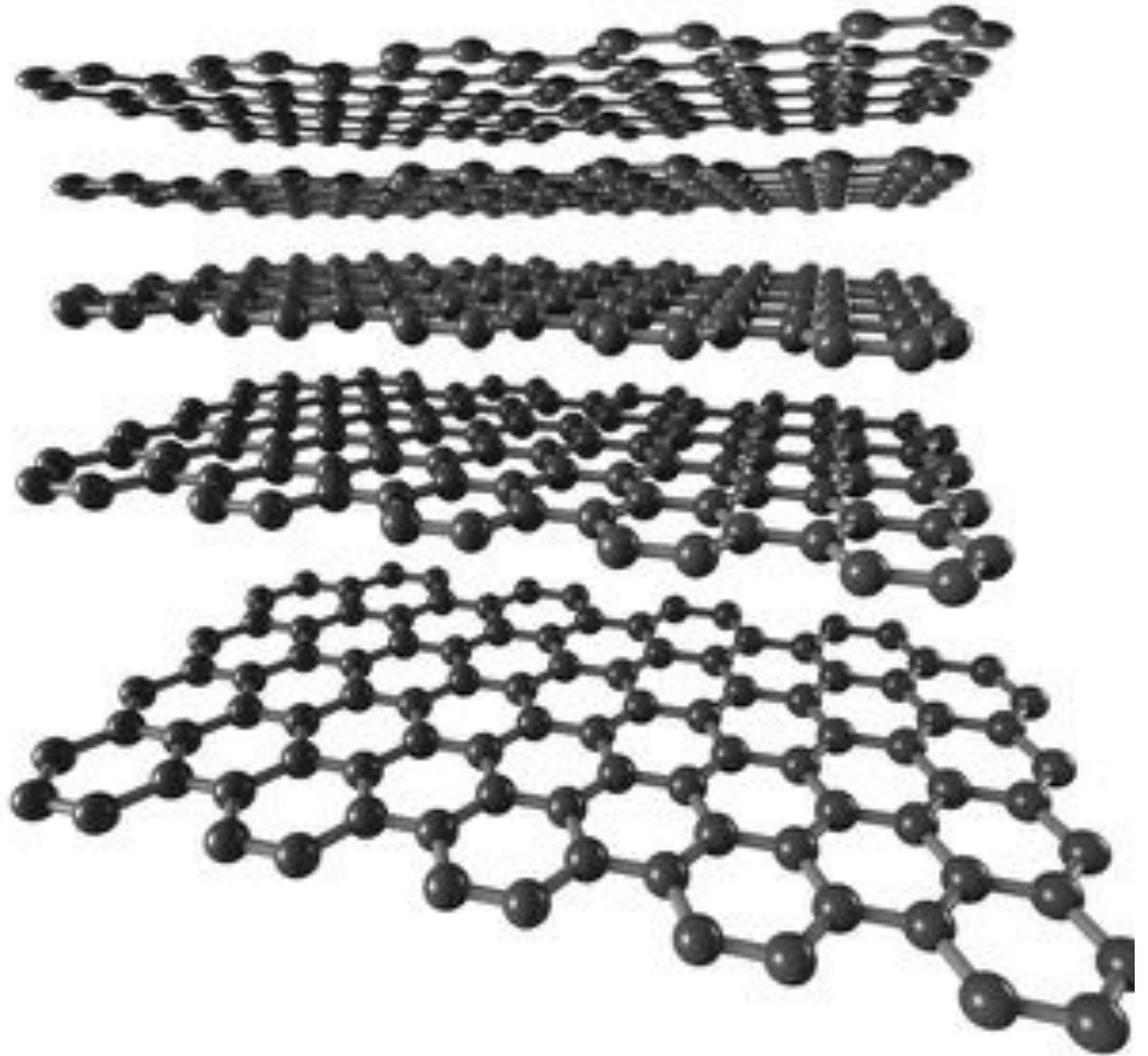
sans le « spin torque oscillator »

↑  
nombre d'itérations d'apprentissage

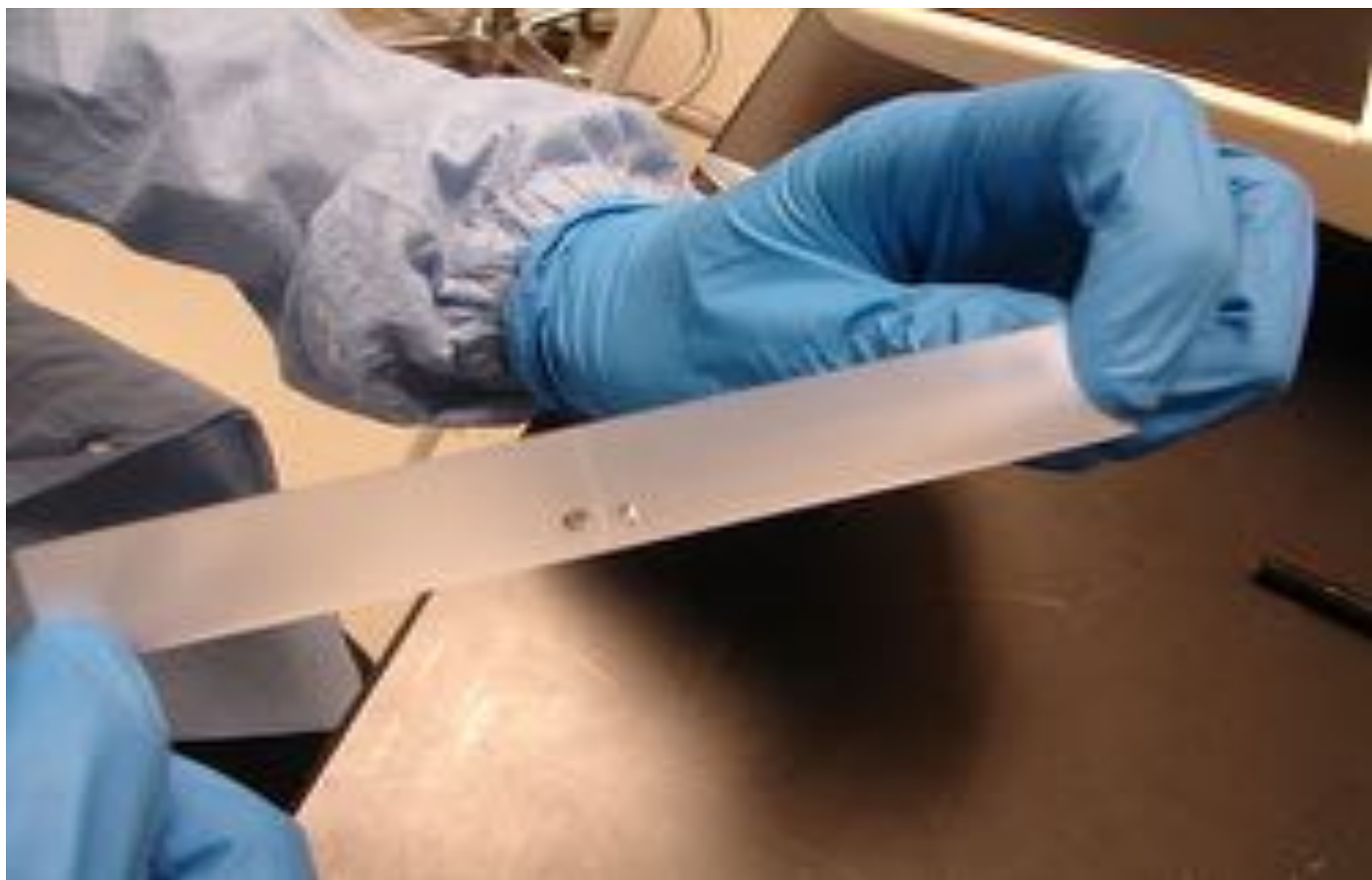
# Comment fabriquer ?

- atome par atome
- en gravant
- en évaporant
- à partir de matière existante

du charbon (le graphite) :





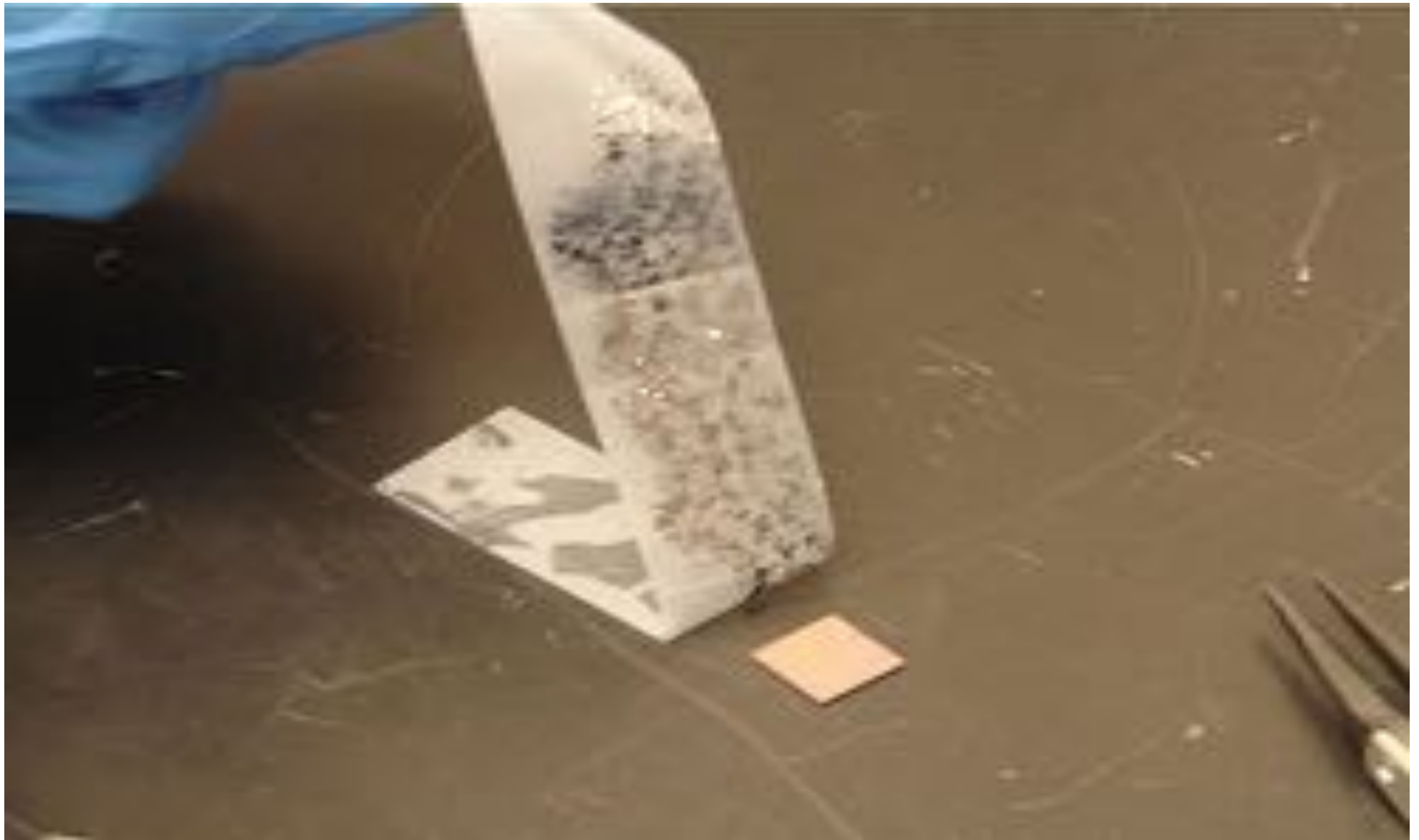








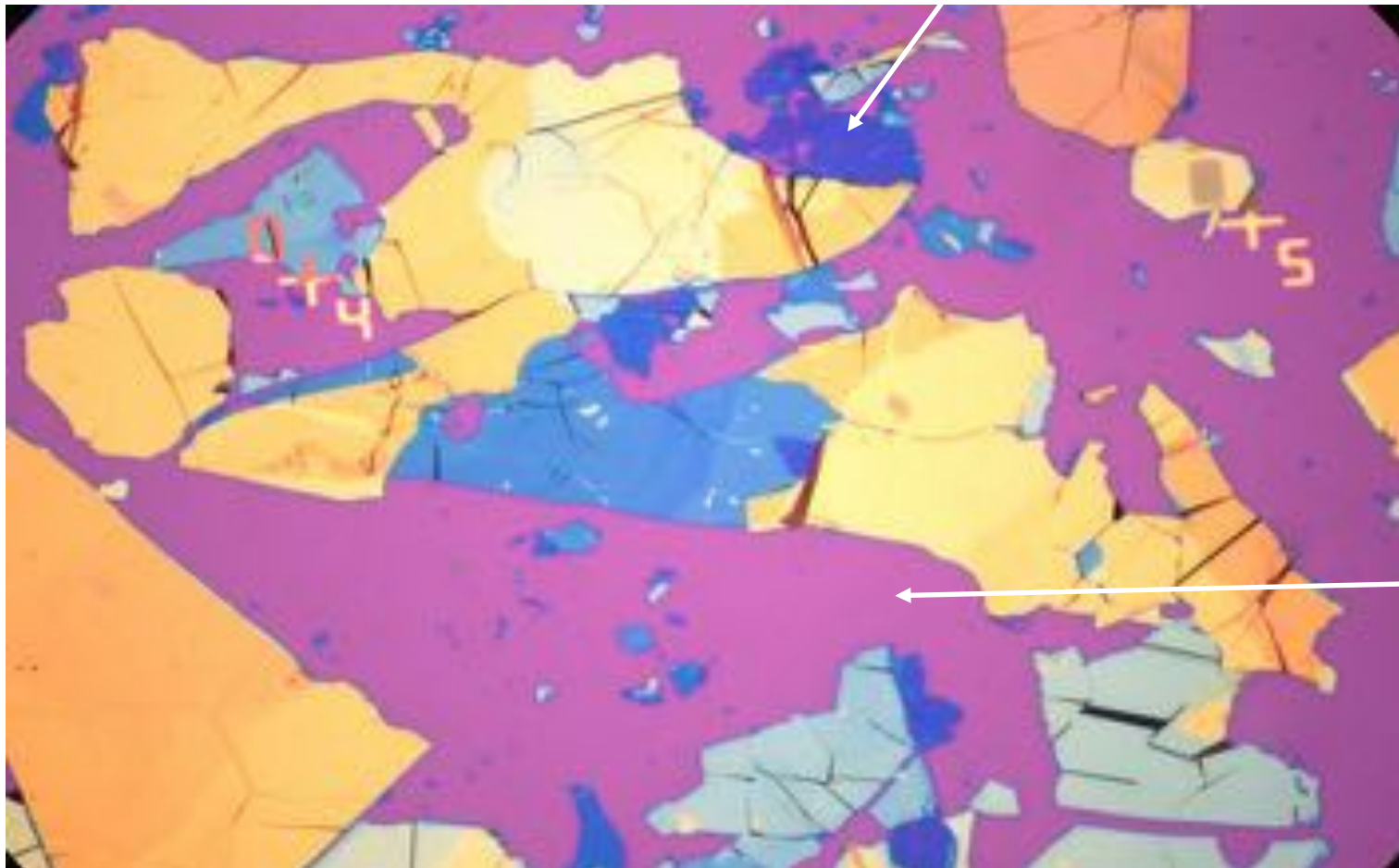




# Faire du graphène et le reconnaître

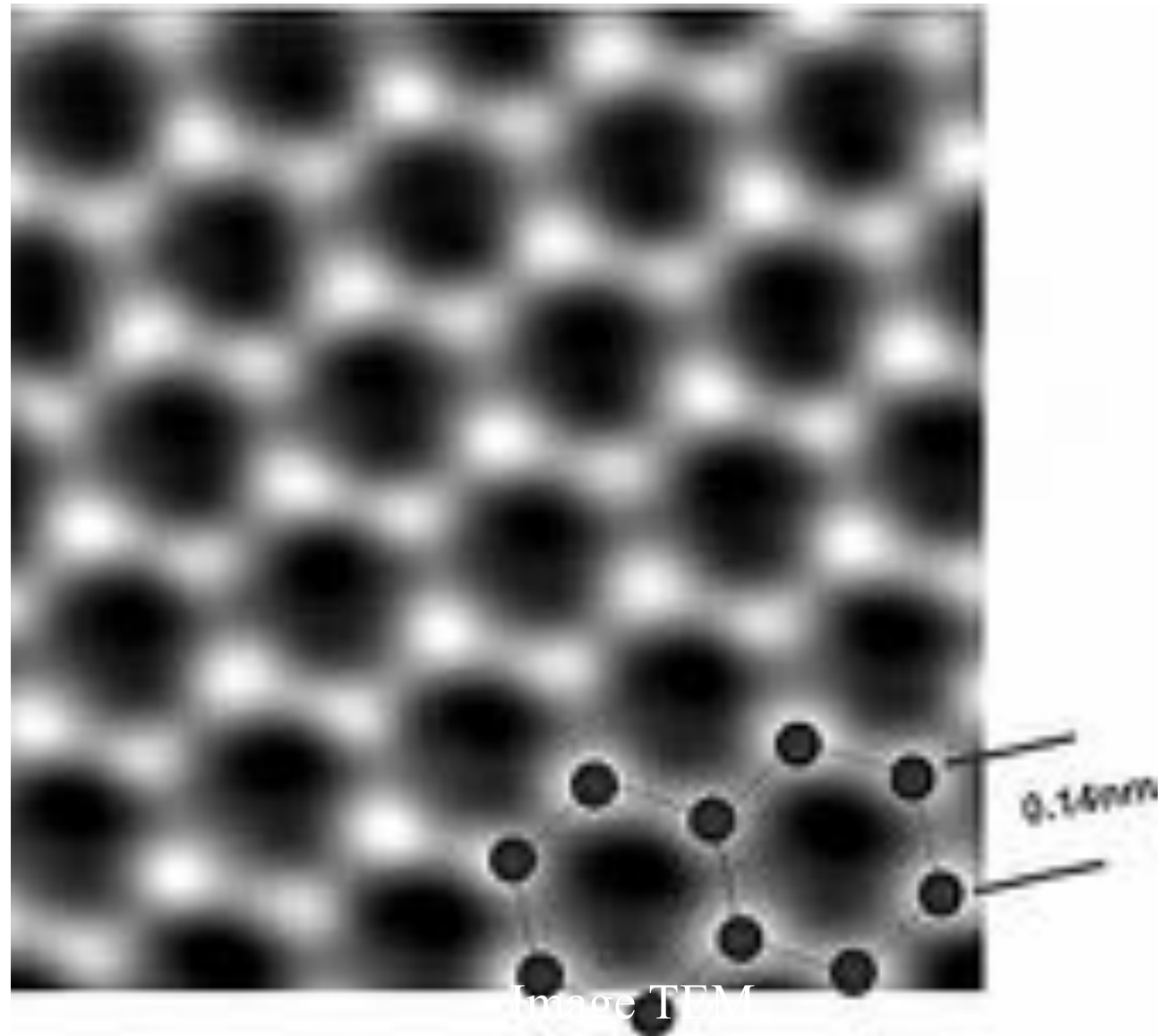
Repérer le graphène par sa couleur, grâce aux interférences optiques  
fonction de l'épaisseur

Couleur très claire légèrement teintée = graphène  
Couleur brillante = graphite (métal)

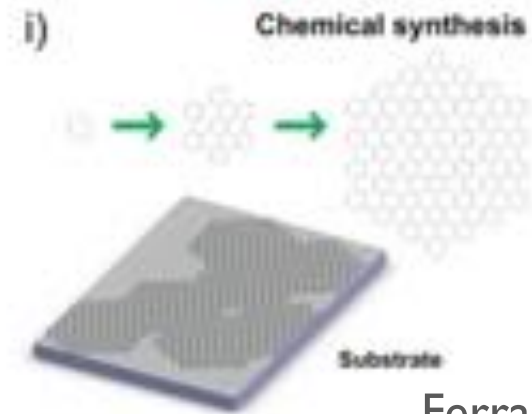
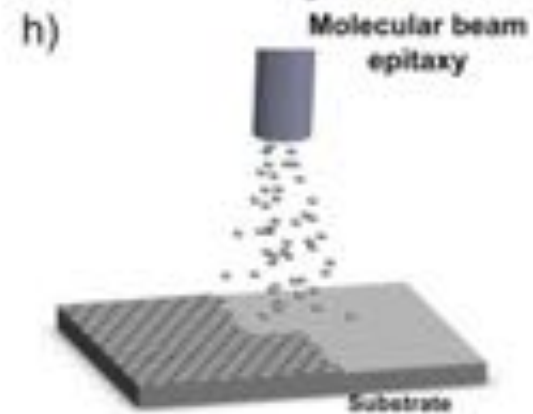
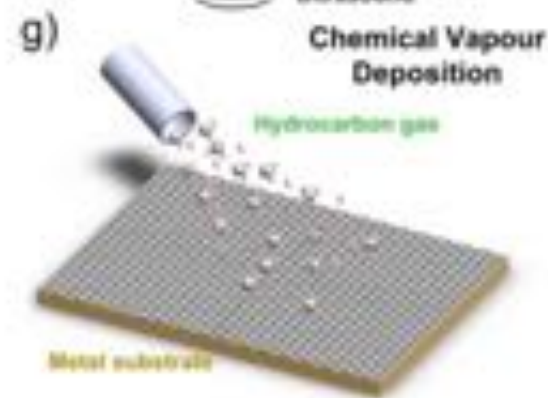
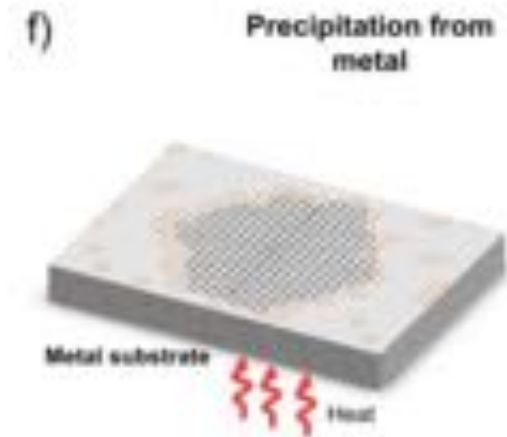
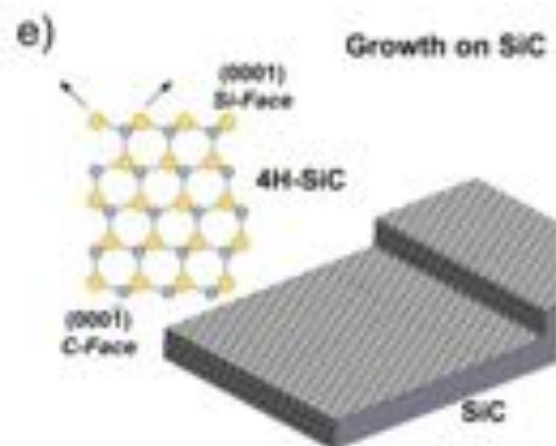
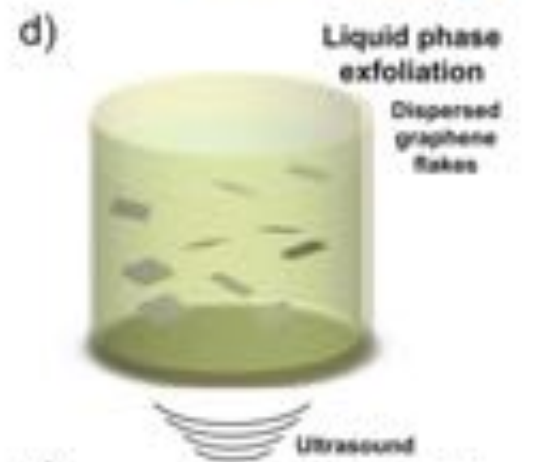
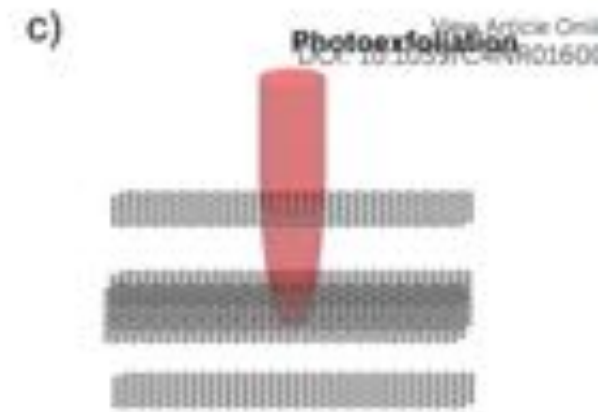
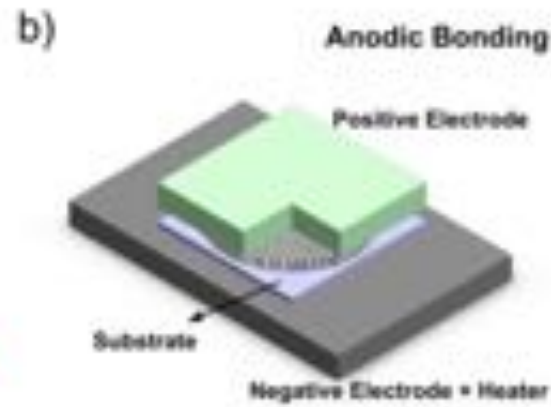
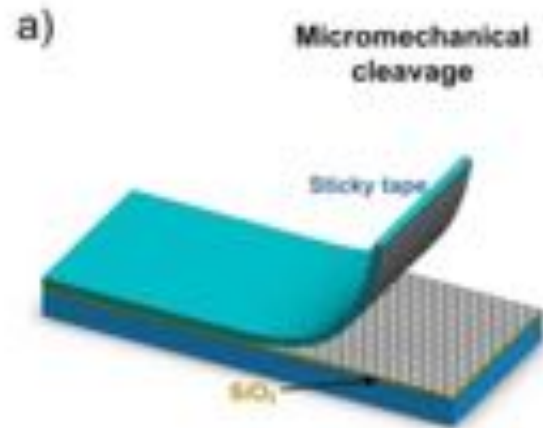


SiO<sub>2</sub>  
(285nm = rose)  
sur Si

graphène mesuré par microscope à effet tunnel



# Autres moyens de production du graphène



# Propriétés mécaniques du graphène

le graphène est très dur et stable et 2D  
→ utilisable comme outil de choix à l'échelle  
du nanomètre.

Module d'Young = 1 TeraPa :

matériau le plus solide jamais mesuré  
(200 fois plus que l'acier)

Mais mesure sur des surfaces de qq  $\mu\text{m}$  donc pas de  
défauts

donc pas de rupture facile -

pas pareil pour de grandes surfaces

recherche récente :  
plier et découper du graphène



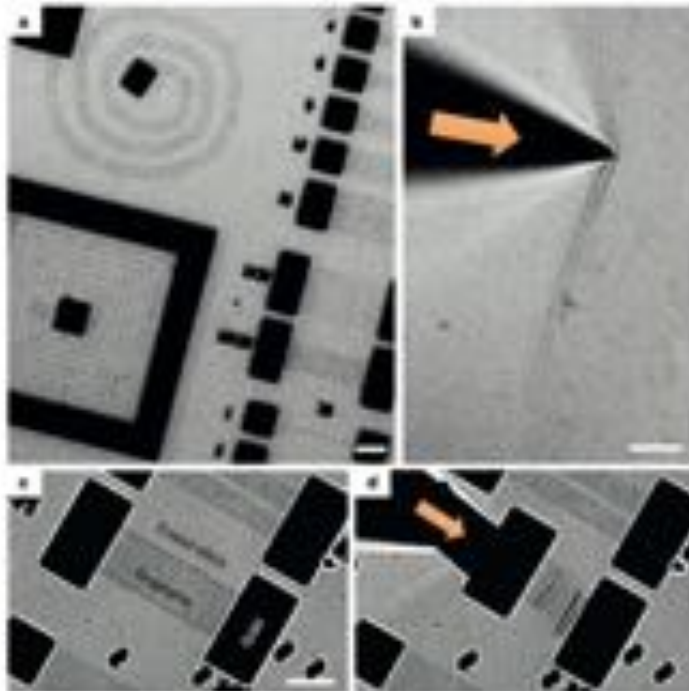
## Graphene kirigami

Melina E. Blew<sup>1</sup>, Arthur W. Bernard<sup>1</sup>, Peter A. Ross<sup>1</sup>, Samantha P. Roberts<sup>1</sup>, Kathryn L. McGill<sup>1</sup>, Pinshun Y. Huang<sup>2</sup>, Alexander R. Royack<sup>2</sup>, Joshua W. Koo<sup>2</sup>, Bryce Robert<sup>1</sup>, David A. Muller<sup>1,2</sup> & Paul L. McEuen<sup>1,2</sup>

For centuries, practitioners of origami (折紙, *ami*, paper) and kirigami (折紙, *ami*) have lashed sheets of paper into beautiful and complex three-dimensional structures. Both techniques are scalable, and scientists and engineers are adopting them to different two-dimensional starting materials to create structures from the macro- to the microscale<sup>1–3</sup>. Here we show that graphene<sup>4,5</sup> is well suited for kirigami, allowing us to build robust microscale structures with tunable mechanical properties. The material parameter crucial for kirigami is the Poisson–von Kármán number<sup>6,7</sup>  $\gamma$ ; an indication of the ratio between in-plane stiffness and out-of-plane bending stiffness, with high numbers corresponding to membranes that more easily bend and crumple than they stretch and shear. To determine  $\gamma$ , we measure the bending stiffness of graphene monolayers that are 10–100 micrometres in size and obtain a value that is thousands of times higher than the predicted atomic-scale bending stiffness. Interferometric imaging attributes this finding to ripples in the membranes<sup>8,9</sup> that stiffen the graphene sheets considerably, to the extent that

$\gamma$  is comparable to that of a standard piece of paper. We may therefore apply ideas from kirigami to graphene sheets to build mechanical metamaterials such as stretchable electrodes, springs, and hinges. These results establish graphene kirigami as a simple yet powerful and customizable approach for lashing atom-thick graphene sheets into resilient and movable parts with microscale dimensions.

Devices such as those shown in Fig. 1a, c, d are made from polycrystalline monolayer graphene that is grown on copper by chemical vapour deposition<sup>10</sup>, and then transferred to fused silica wafers that are coated with an aluminium release layer. We use optical lithography to pattern both the graphene and the 30-nm-thick gold pads that are deposited on top of the graphene to act as handles. Finally, we release the graphene from the surface by etching away the aluminium in mild acid. The devices remain in aqueous solution with added salts or surfactants as desired. An inverted white-light microscope with a video camera is used to image the sheets, and micromanipulators are used to probe them.



**Figure 1 | Fabricating and manipulating graphene.** **a**, Transmission white light image showing completed devices: a spiral spring, a kirigami pyramid, and a variety of cantilevers. **b**, Manipulating a large sheet of graphene with a micromanipulator. The sheet folds and crumples like soft paper, and returns to its original shape. **c, d**, Manipulating devices with gold pads. The devices can be lifted entirely off the surface (see Supplementary Video 1, S1a) and return to their original shape. All images and videos have undergone linear contrast adjustments.

<sup>1</sup>Department of Physics and Center for Quantum Imaging, Princeton University, Princeton, New York 08542, USA. <sup>2</sup>Department of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853, USA. <sup>3</sup>Department of Mechanical and Computer Engineering, Cornell University, Ithaca, New York 14853, USA. <sup>4</sup>Department of Materials Science and Engineering, Princeton University, Princeton, New York 08542, USA. <sup>5</sup>Department of Chemistry, Princeton University, Princeton, New York 08542, USA.



kirigami :  
couper + papier





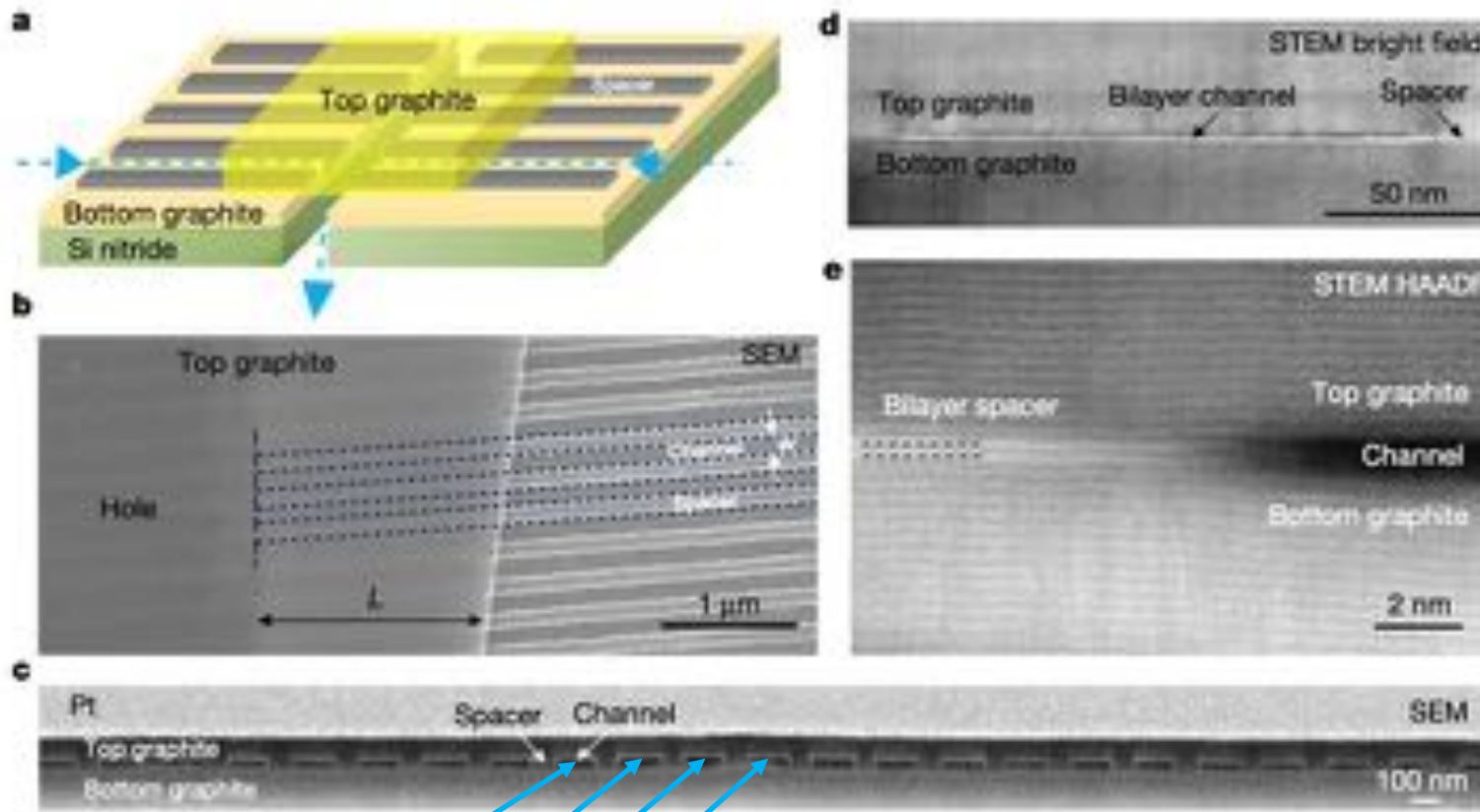
<https://youtu.be/PslqicBrsQQ>

recherche récente :  
filtrer l'eau

# le graphène comme tamis

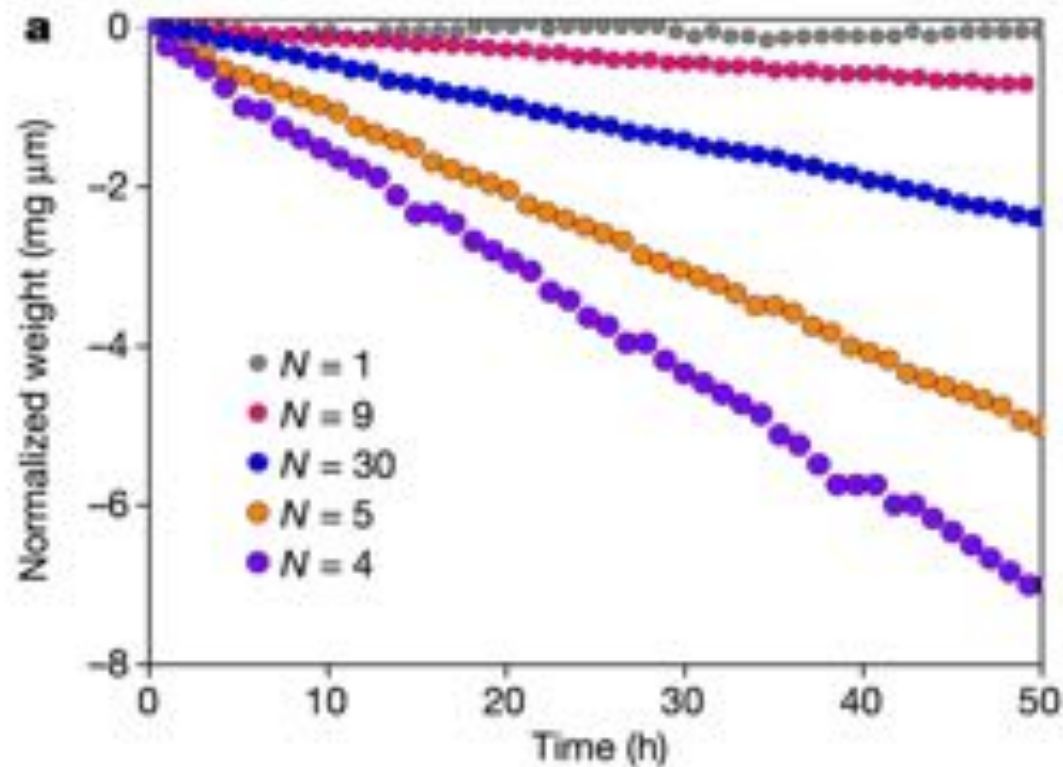
## Molecular transport through capillaries made with atomic-scale precision

B. Radha<sup>1</sup>, A. Esfandiari<sup>1</sup>, F. C. Wang<sup>2</sup>, A. P. Rooney<sup>3</sup>, K. Gopinadhan<sup>1</sup>, A. Keerthi<sup>1</sup>, A. Mishchenko<sup>1</sup>, A. Janardanan<sup>1</sup>, P. Blake<sup>4</sup>, L. Fumagalli<sup>1,4</sup>, M. Lozada-Hidalgo<sup>1</sup>, S. Garaj<sup>5</sup>, S. J. Haigh<sup>3</sup>, I. V. Grigorieva<sup>1</sup>, H. A. Wu<sup>2</sup> & A. K. Geim<sup>1</sup>



ça peut passer par là: largeur 130 nm

graphite  
-----  
qq plans de graphene  
-----  
graphite



**Figure 3 | Water flow through channels of different height. a,** Examples of gravimetric measurements for various  $N$  (the number of graphene layers used as spacers). They were carried out at 21 °C in near zero humidity, and the curves are normalized for the effective length of the devices,  $\tilde{L}$ .

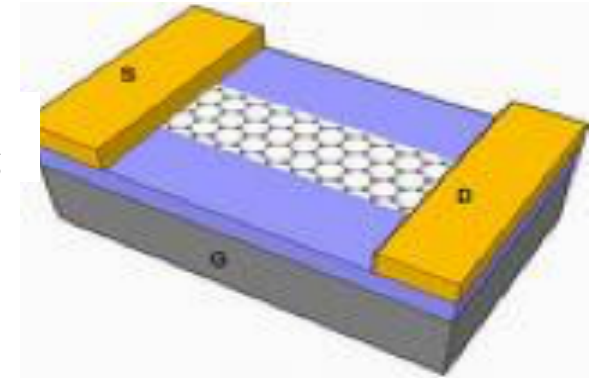
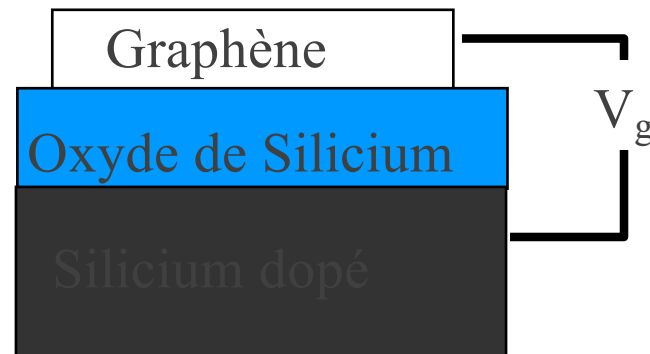
largeur du capillaire :  $N \times 0.34 \text{ nm}$

vitesse d'écoulement  $j_q \text{ l m/sec}$

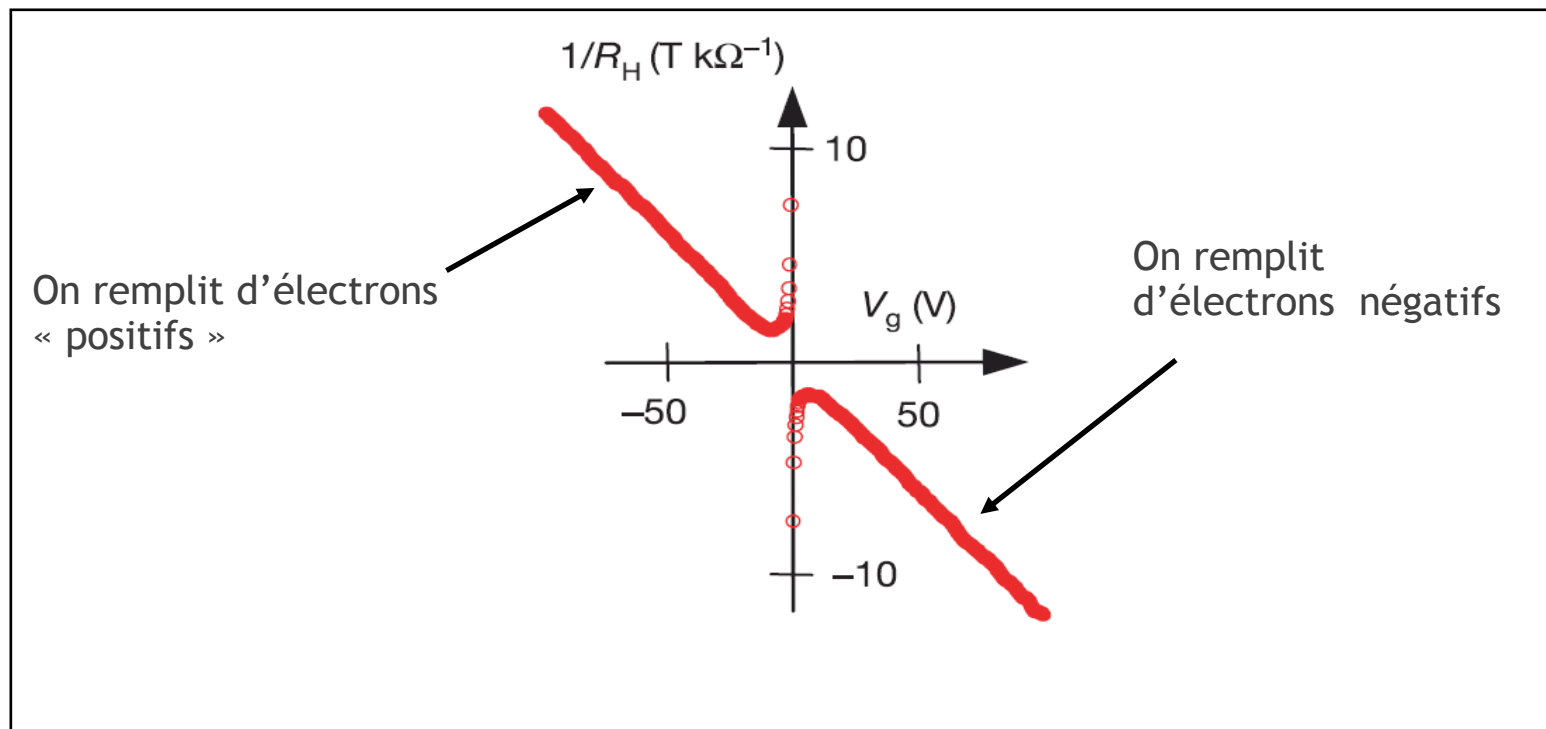
Ouvre la voie au contrôle de capillaires de diamètres nanométriques pour filtrer des molécules selon leur taille

# Propriétés électriques du graphène

On peut contrôler son nombre d'électrons et le doper énormément: on introduit ou on arrache des électrons via une grille et une tension



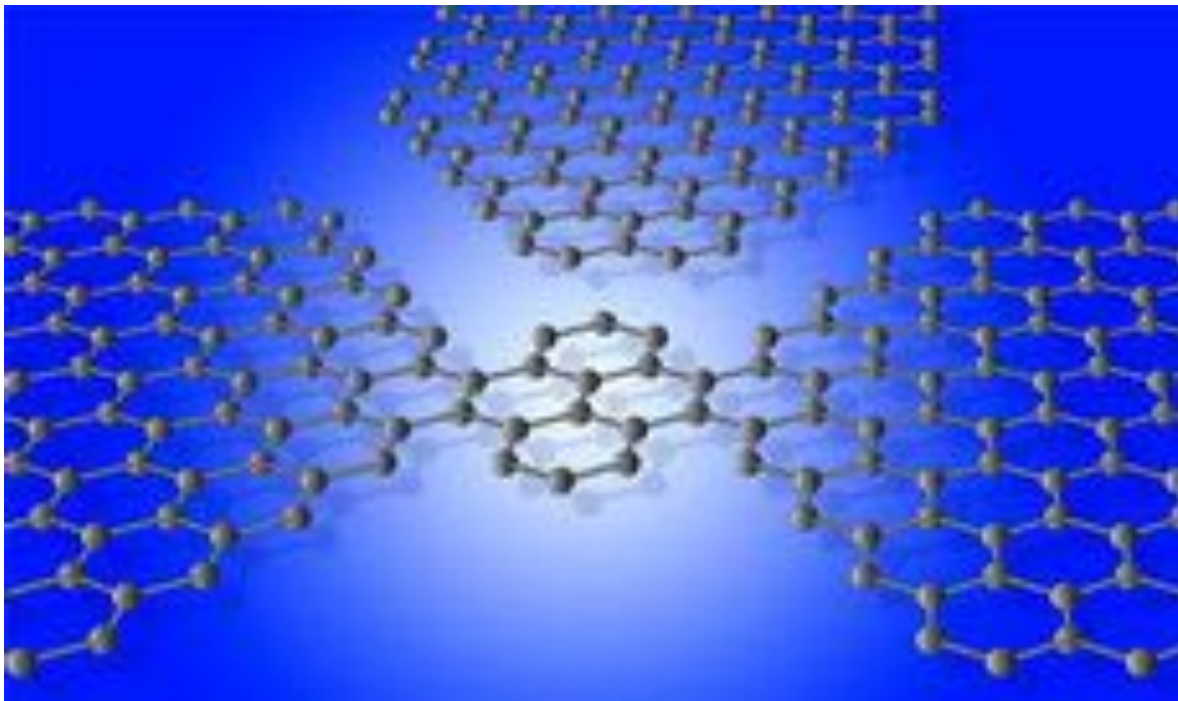
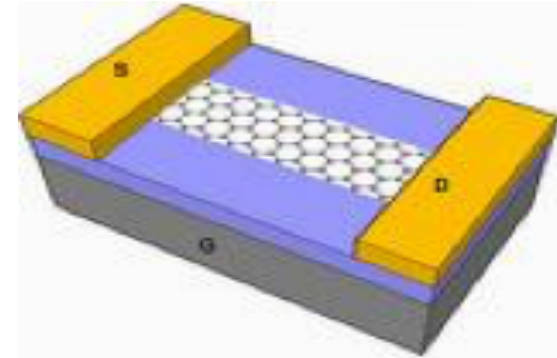
Effet Hall :  $R_H = B / (nb \text{ porteur} * \text{charge})$



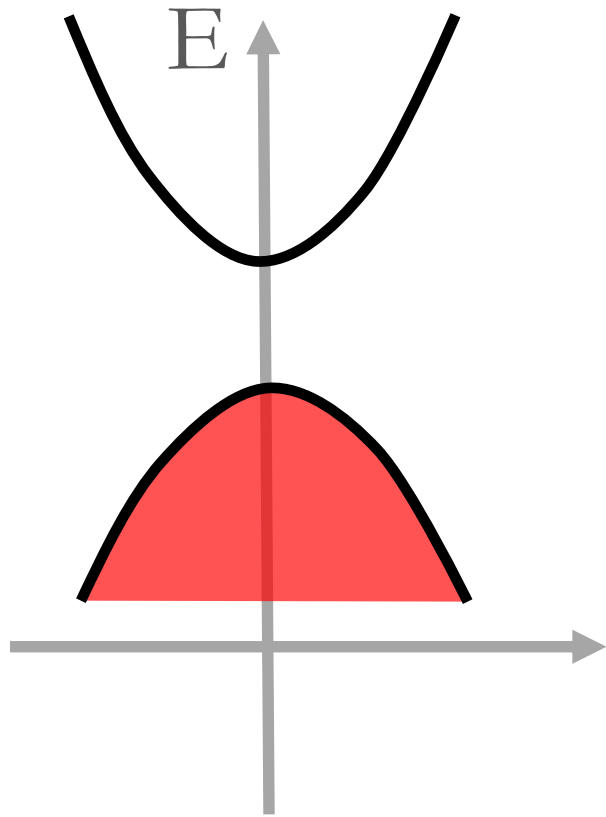
# Propriétés électriques du graphène

Très bonne mobilité des électrons, contrôle de leur charge, et miniaturisation : possibilité de faire des transistors de 10 nm (limite pour les transistors actuels = 50nm)

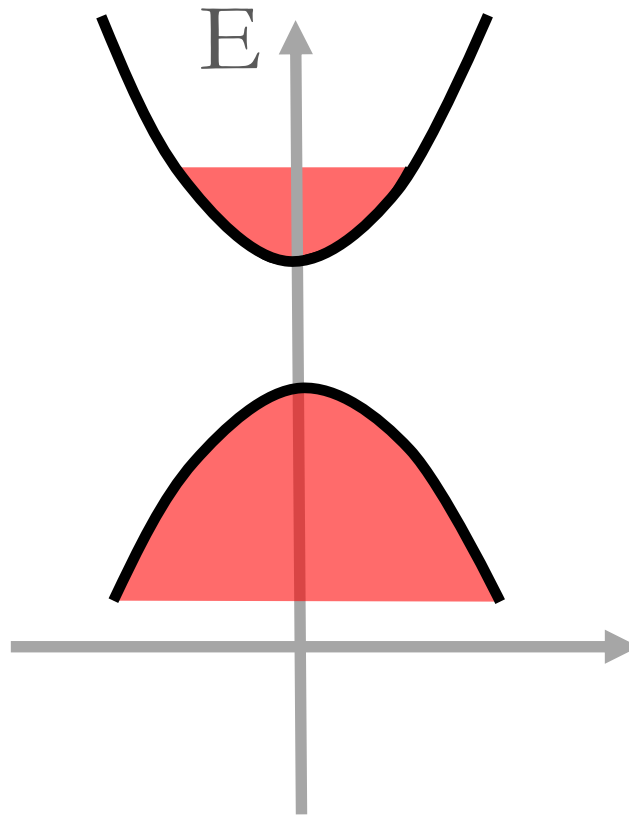
Possibilité de lignes très fines  
(mais comment bien couper les bords ?)



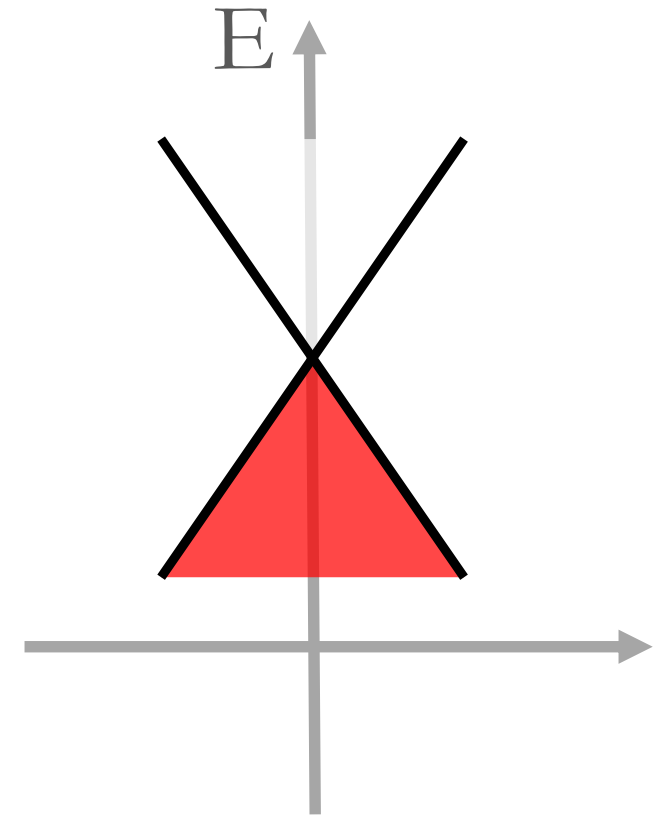
# Propriétés électriques du graphène



isolant



métal



cônes de Dirac



# Propriétés électriques du graphène

Cas pathologique :

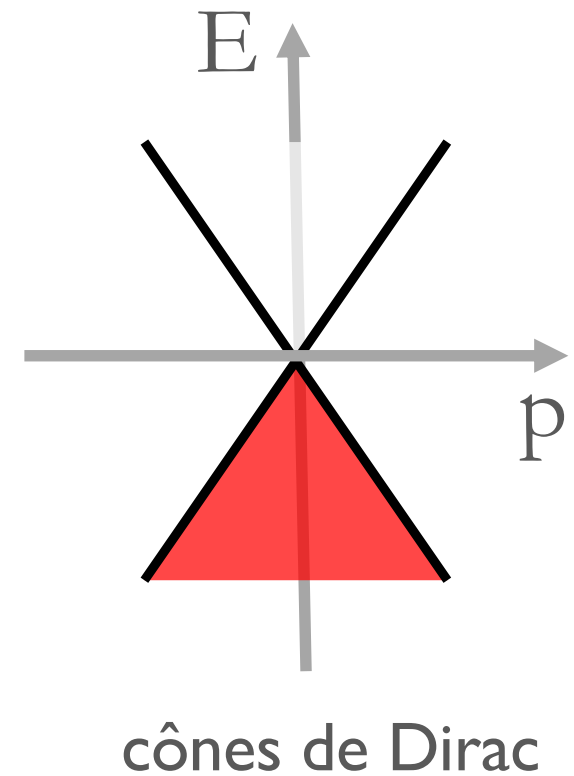
pas de bande interdite, mais pas d'électrons  
au niveau de Fermi : ni métal ni isolant !

Energie linéaire avec  $p$  :

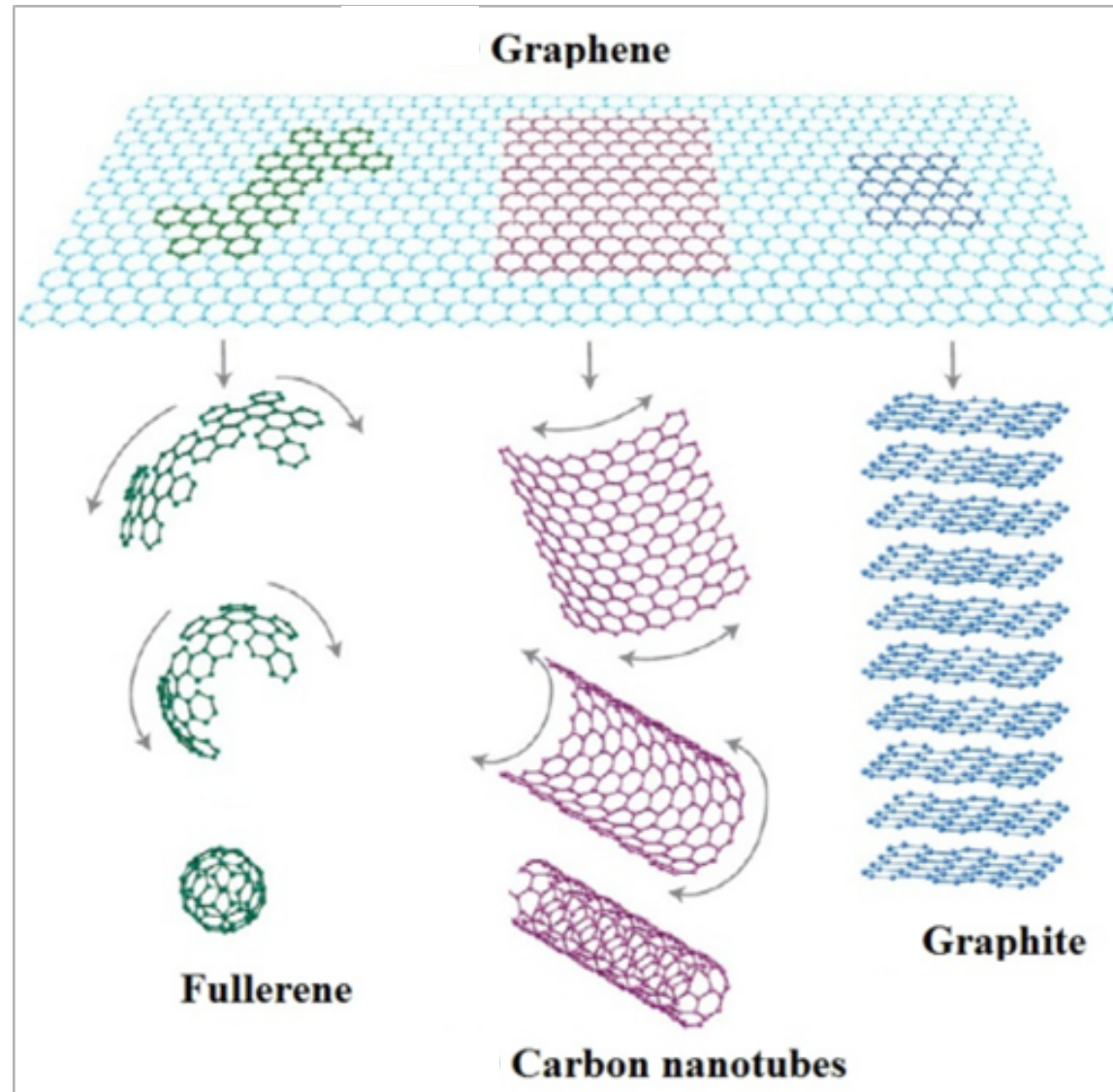
comme des électrons relativistes

sans masse  $\varepsilon = \pm \sqrt{p^2 c^2 + m^2 c^4} = \pm c * p$

Nouvelle physique des cônes de Dirac :  
nouveau transport des électrons,  
nouveaux effets quantiques, ...

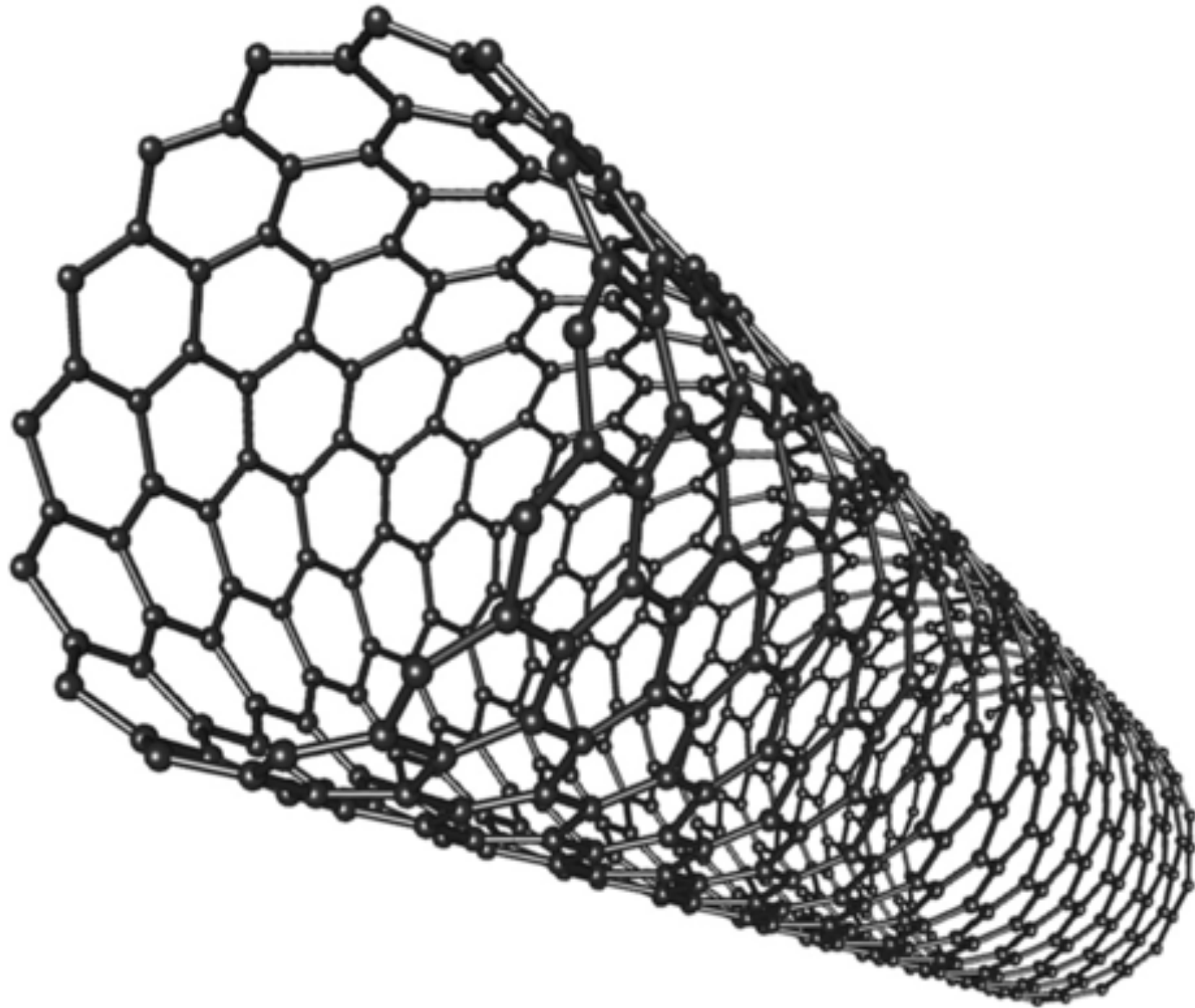


# d'autres formes de nano-objets à partir du graphite :



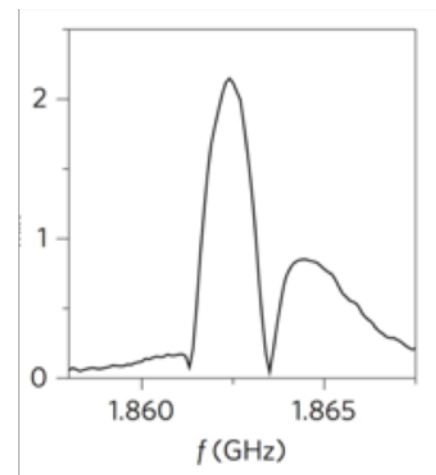
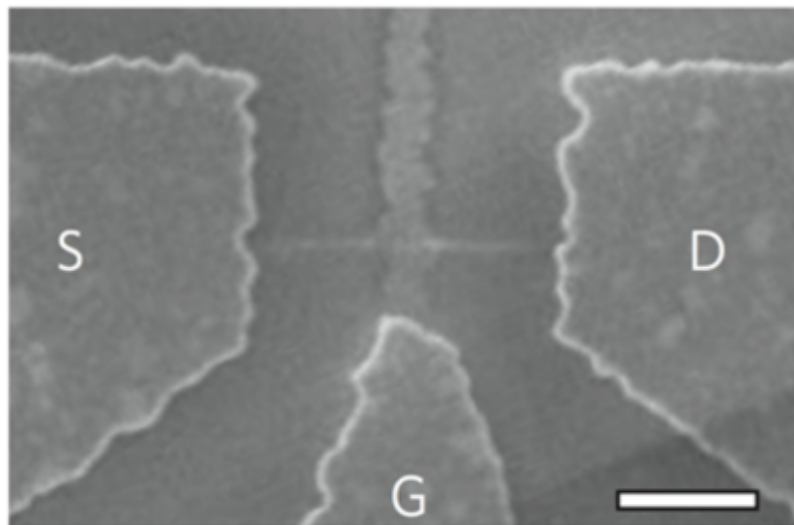
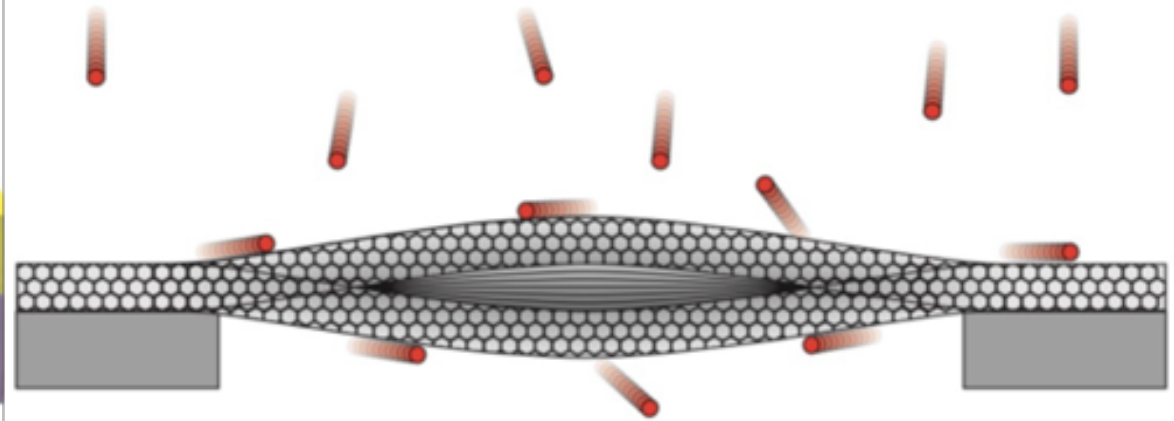
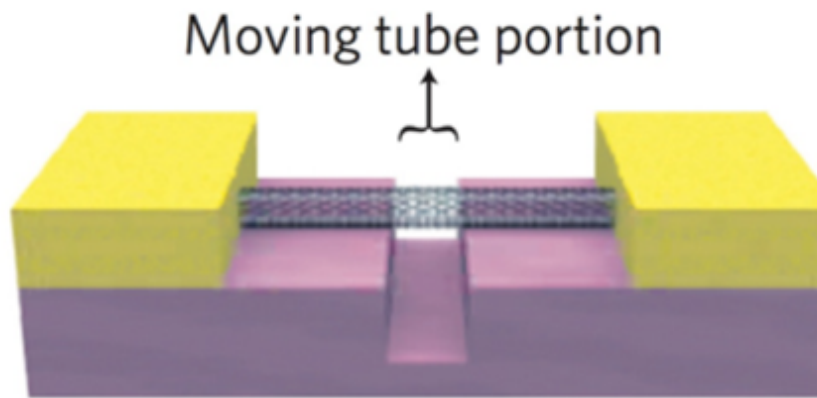
une recherche récente :  
peser un atome avec un nanotube

un nanotube de carbone :

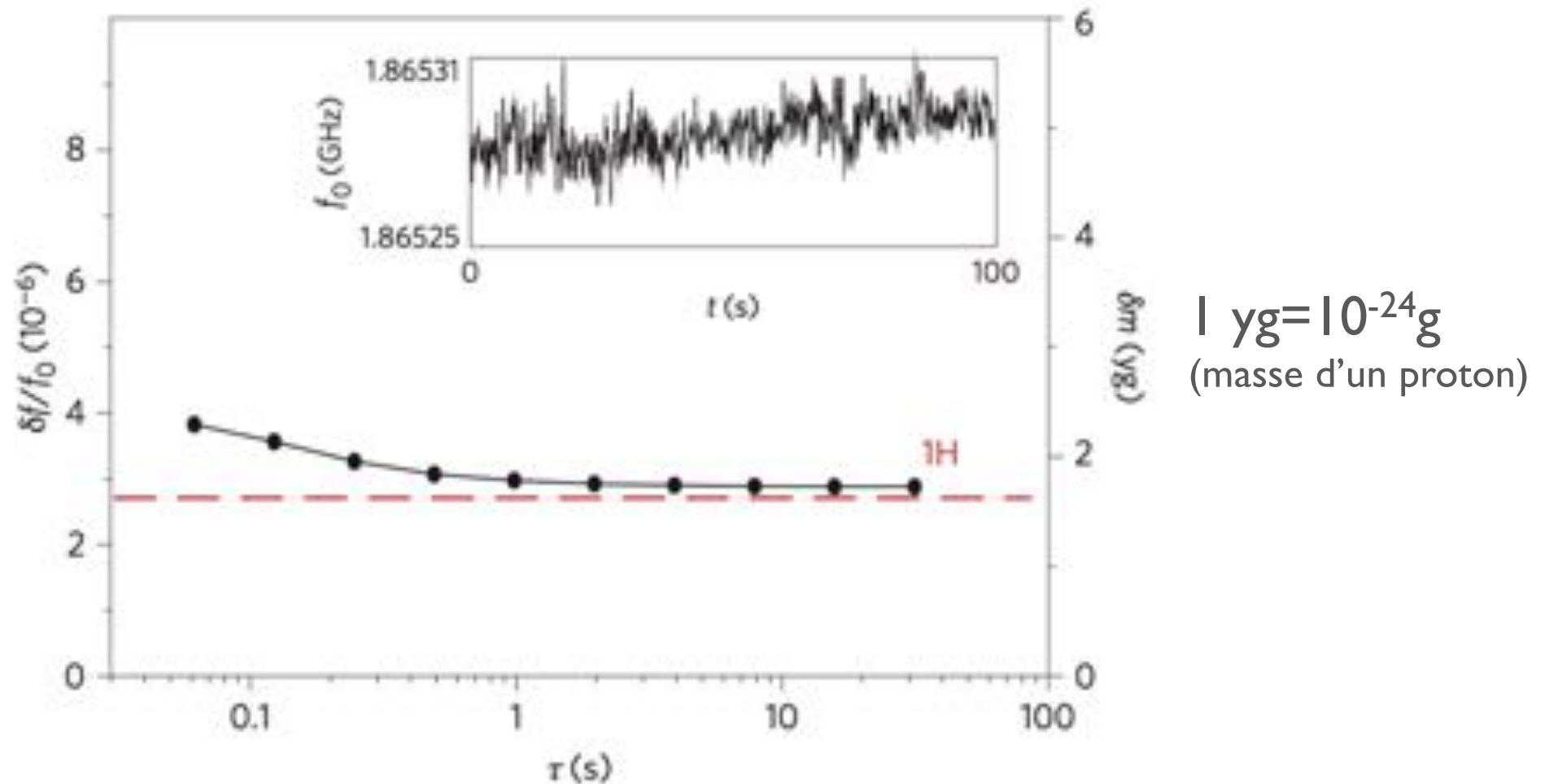


# A nanomechanical mass sensor with yoctogram resolution

J. Chaste<sup>1</sup>, A. Eichler<sup>1</sup>, J. Moser<sup>1</sup>, G. Ceballos<sup>1</sup>, R. Rurali<sup>2</sup> and A. Bachtold<sup>1\*</sup>

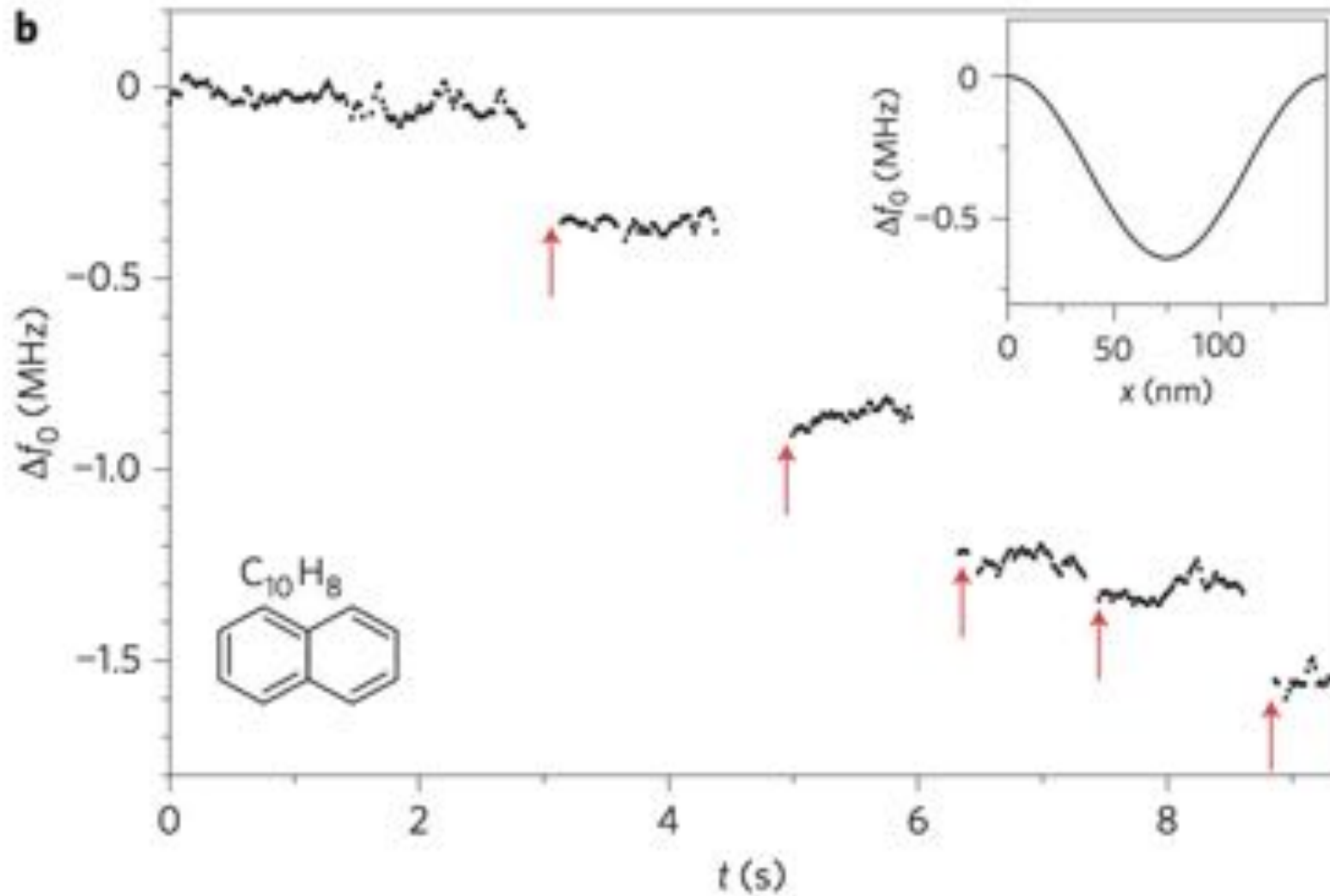


resonance mécanique



**Figure 2 | Measuring mass resolution.** Standard error of the resonance frequency (left axis) and corresponding mass resolution (right axis) as a function of averaging time at 5.5 K. The red dashed line corresponds to the

avec le nanotube, on peut mesurer un proton = 1 yottogramme =  $10^{-21} \text{ g}$



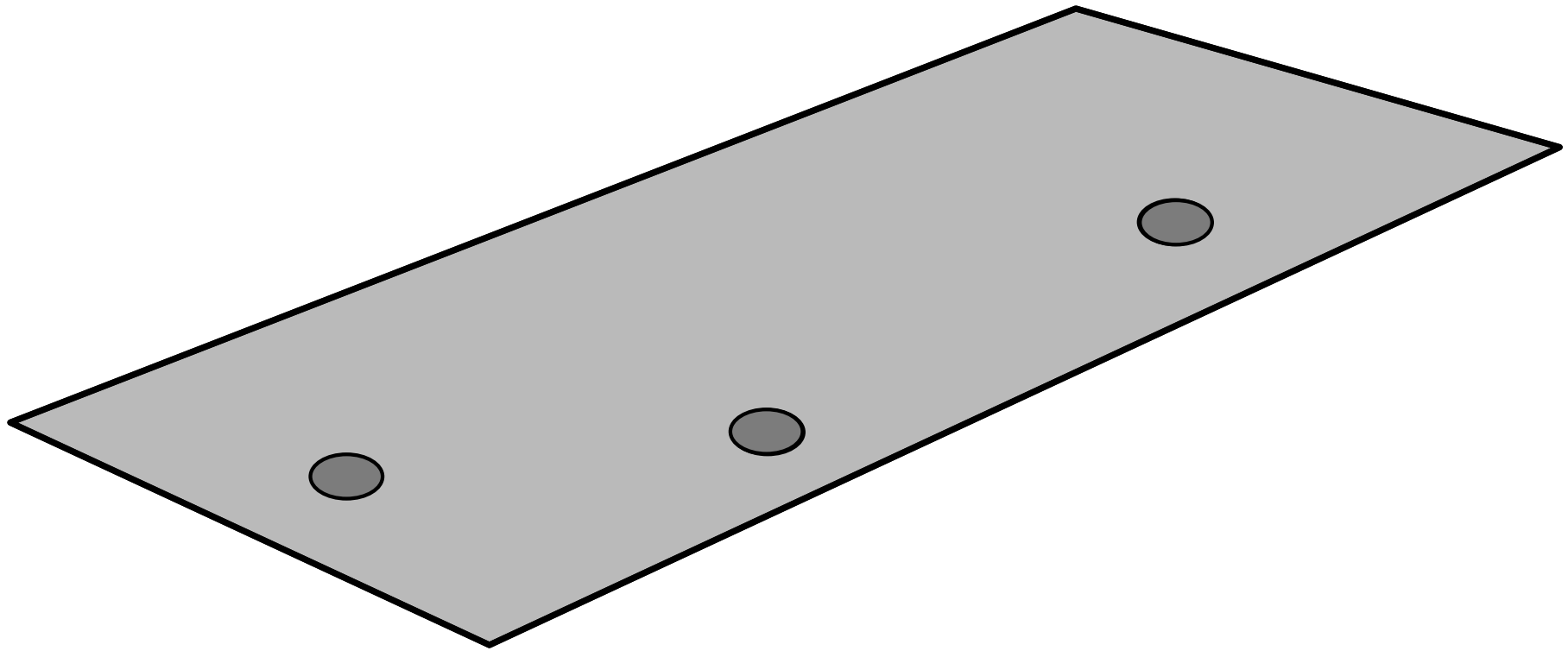
mesure à  $T=4.3$ K de l'absorption par le nanotube  
au cours du temps de molécules  $C_{10}H_8$

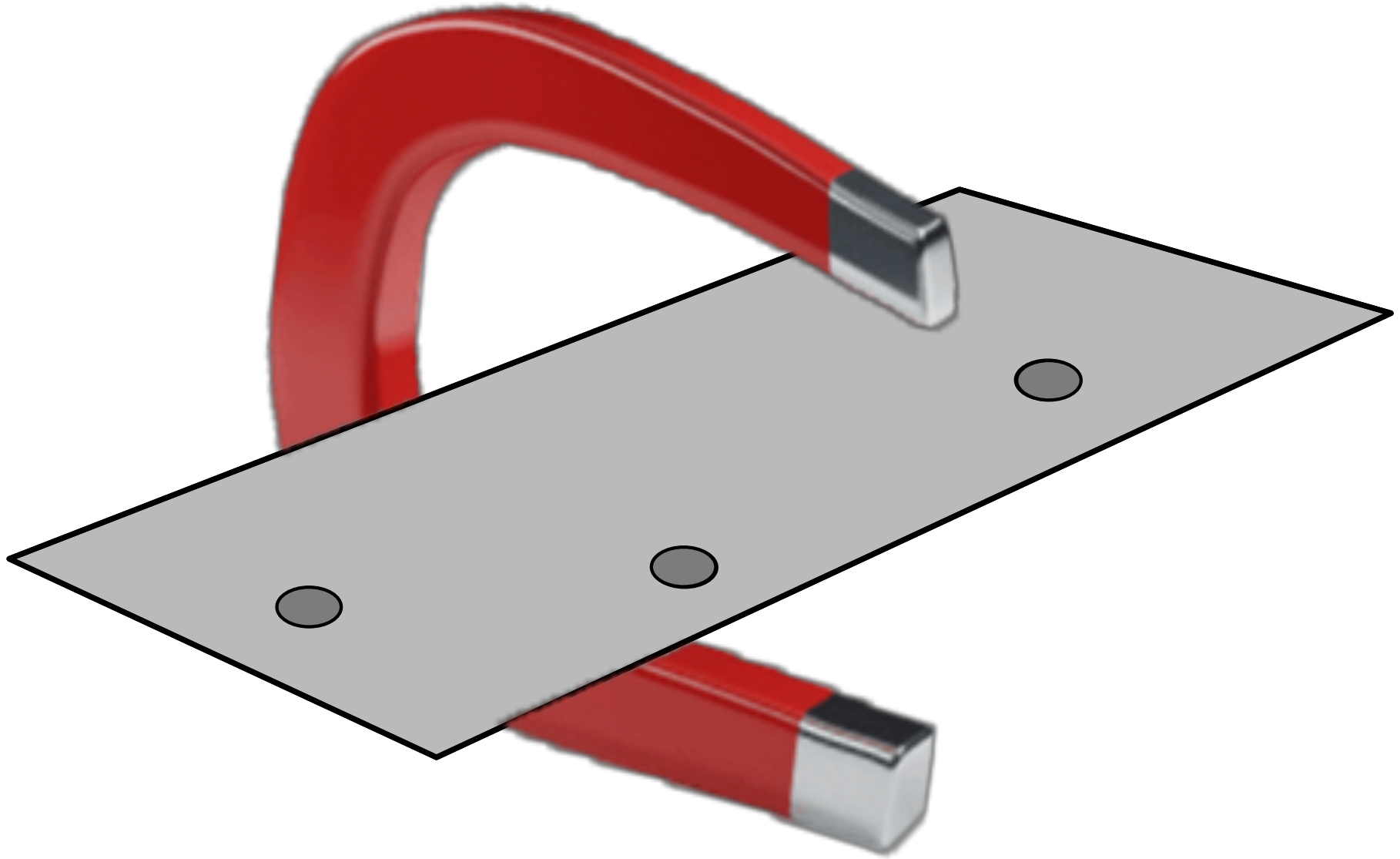
intérêt : mesurer sans ioniser

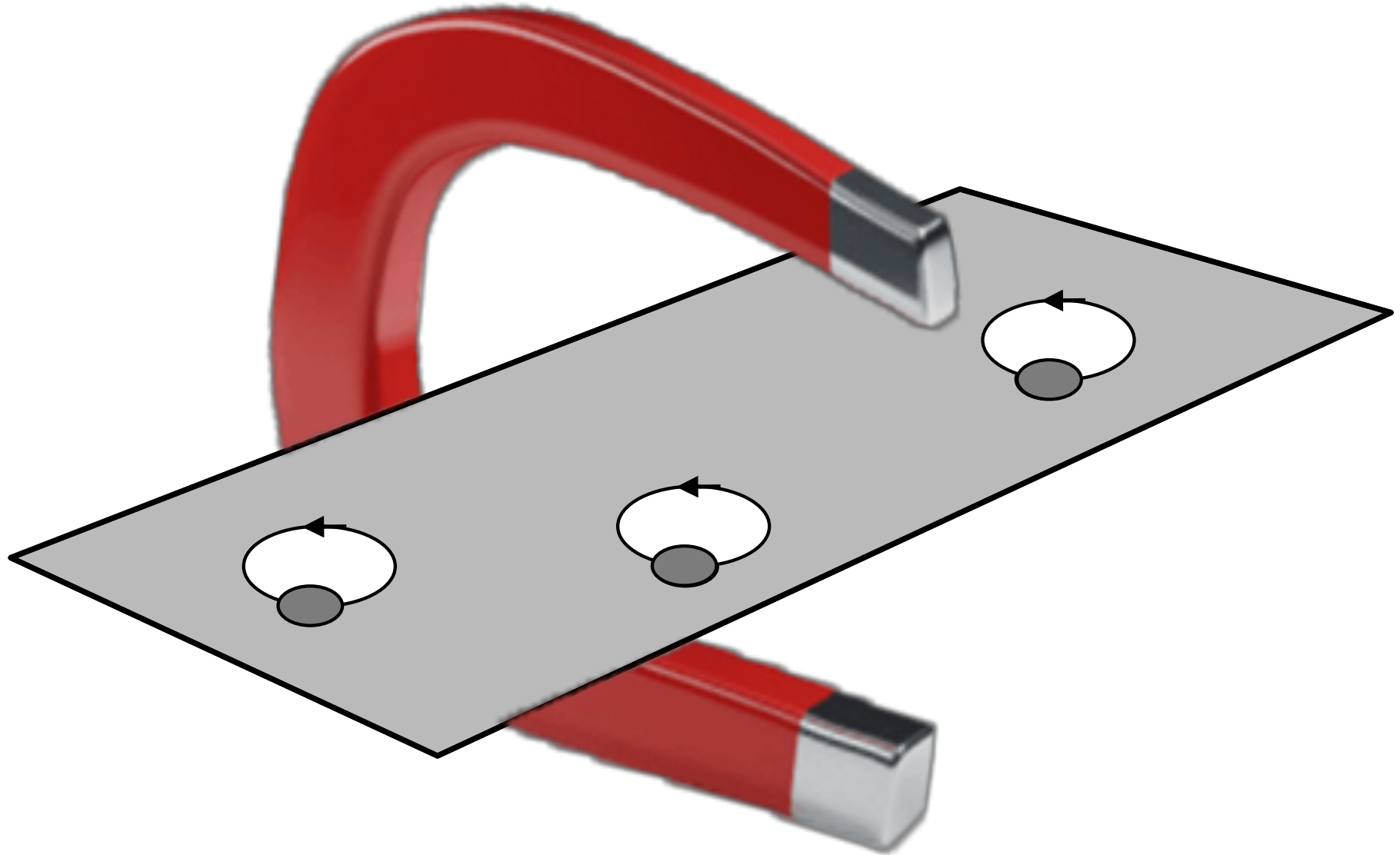
Chaste et al. 2012

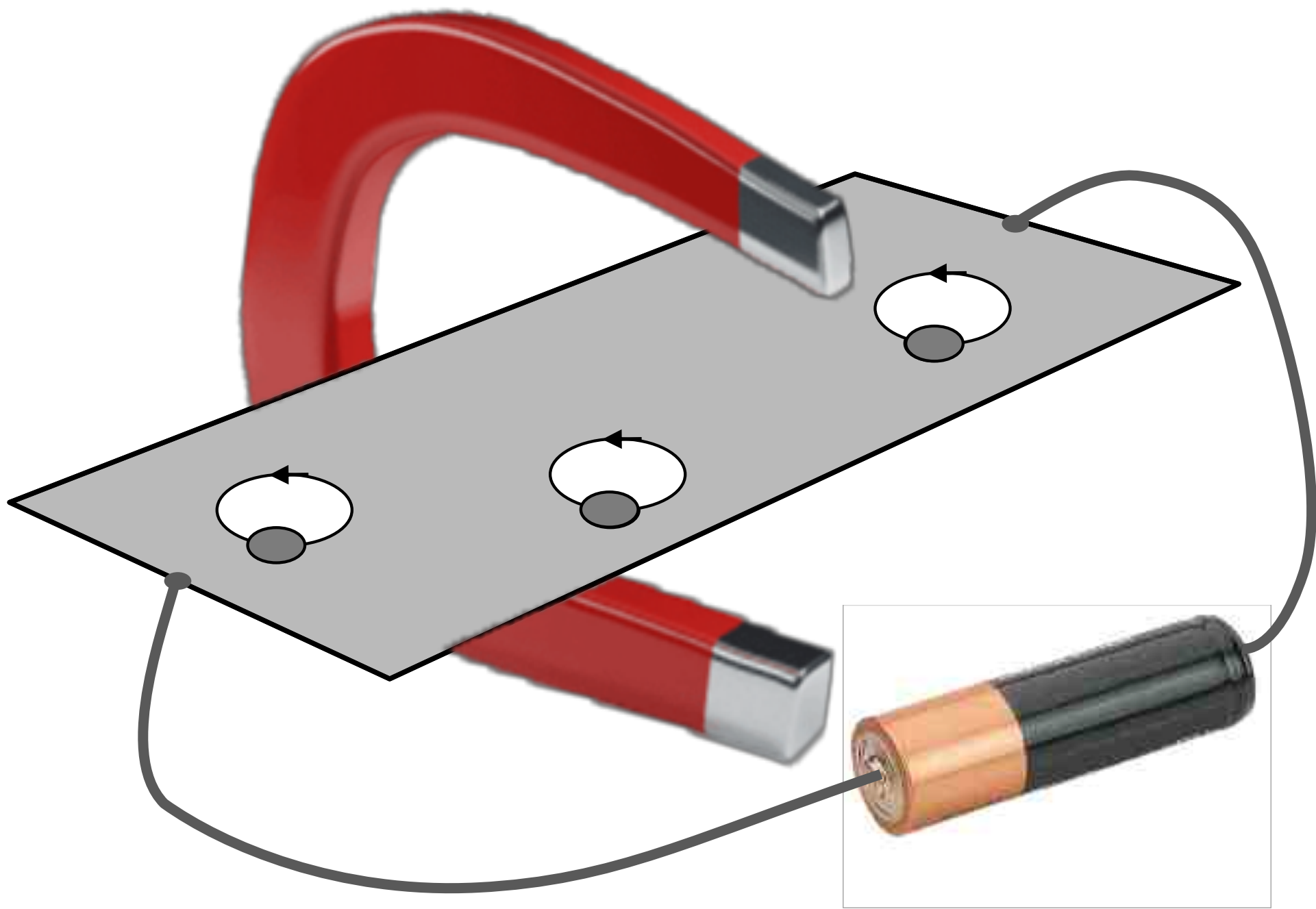


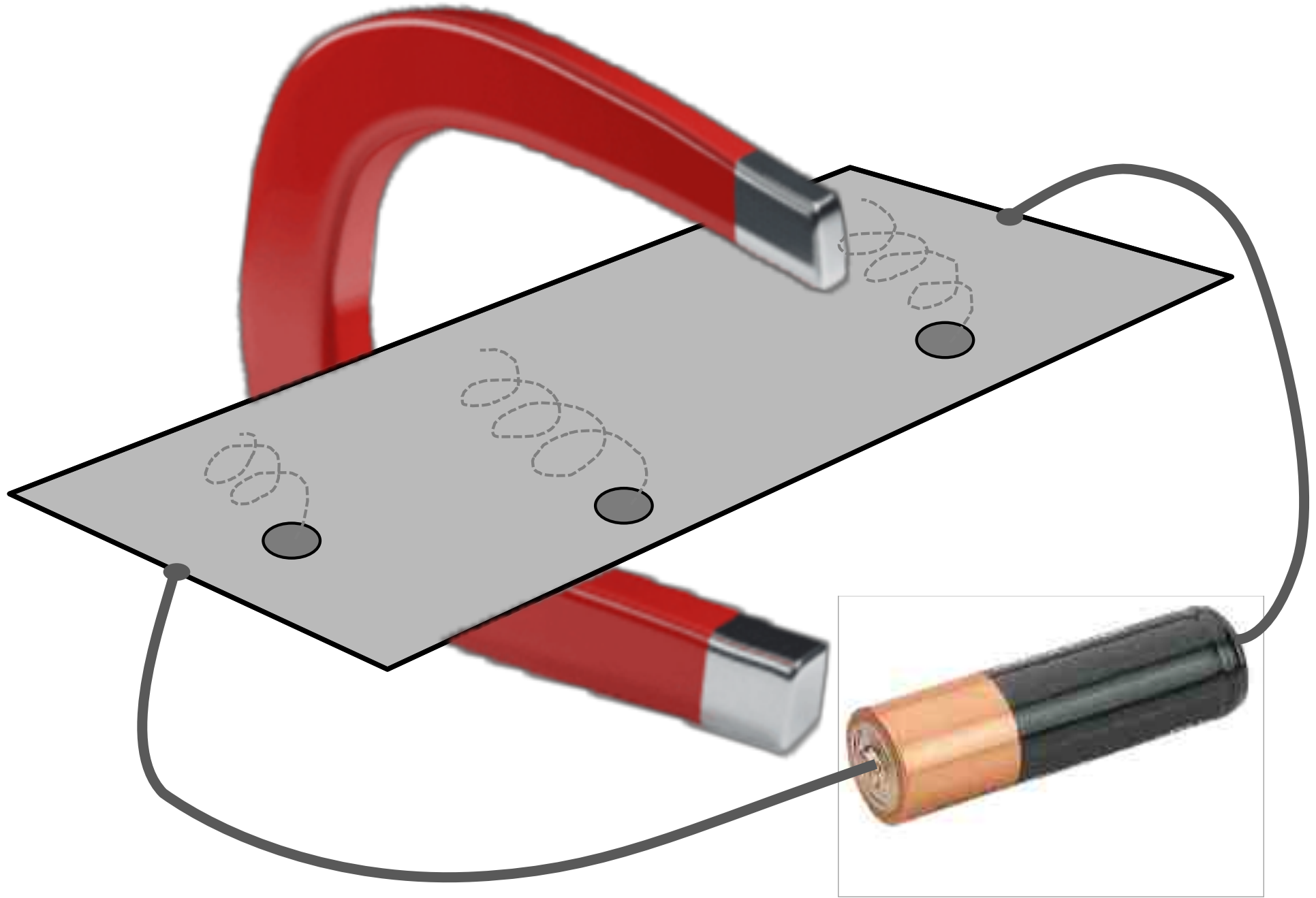
en bonus :  
l'effet Hall quantique  
et la topologie

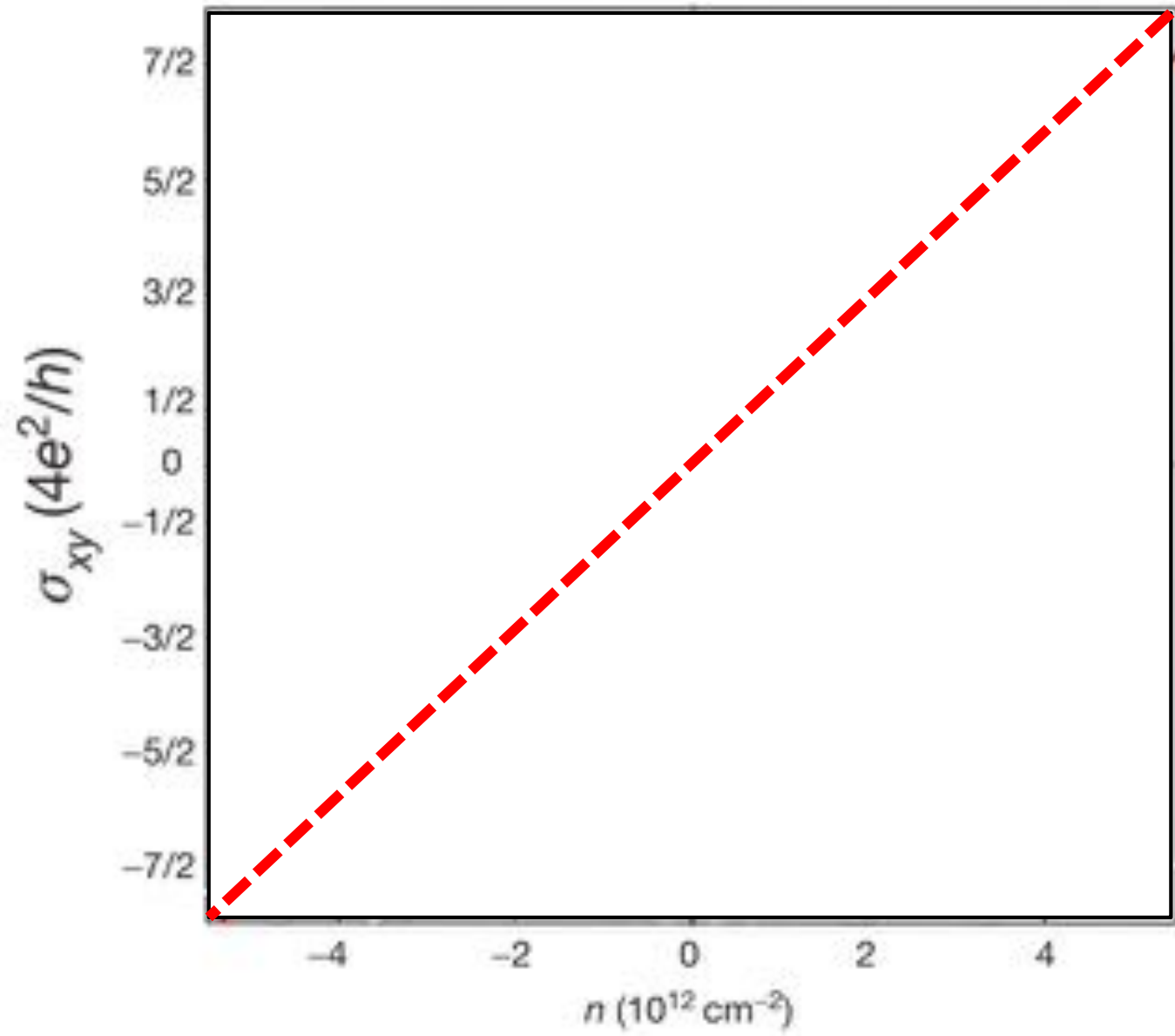




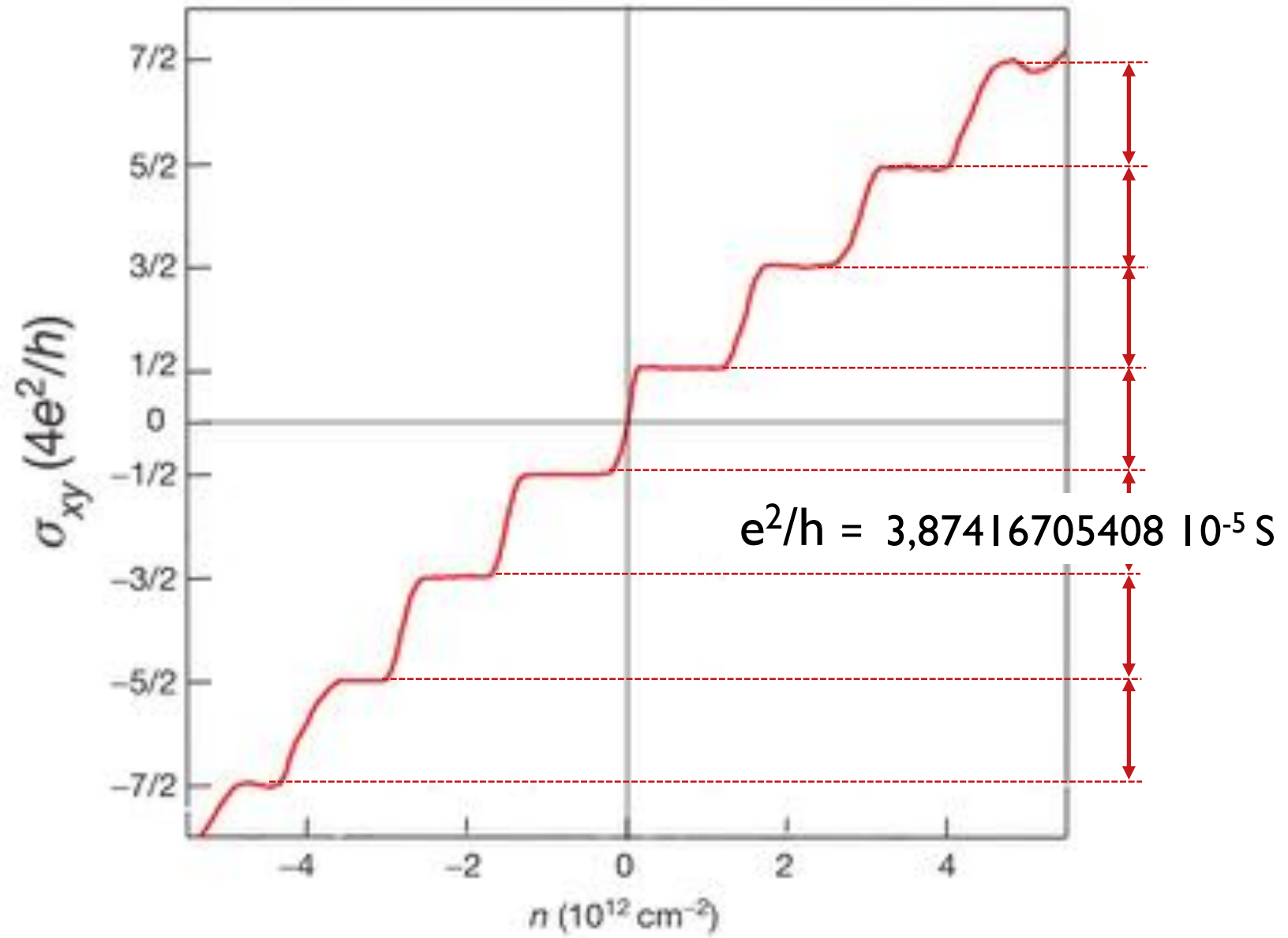




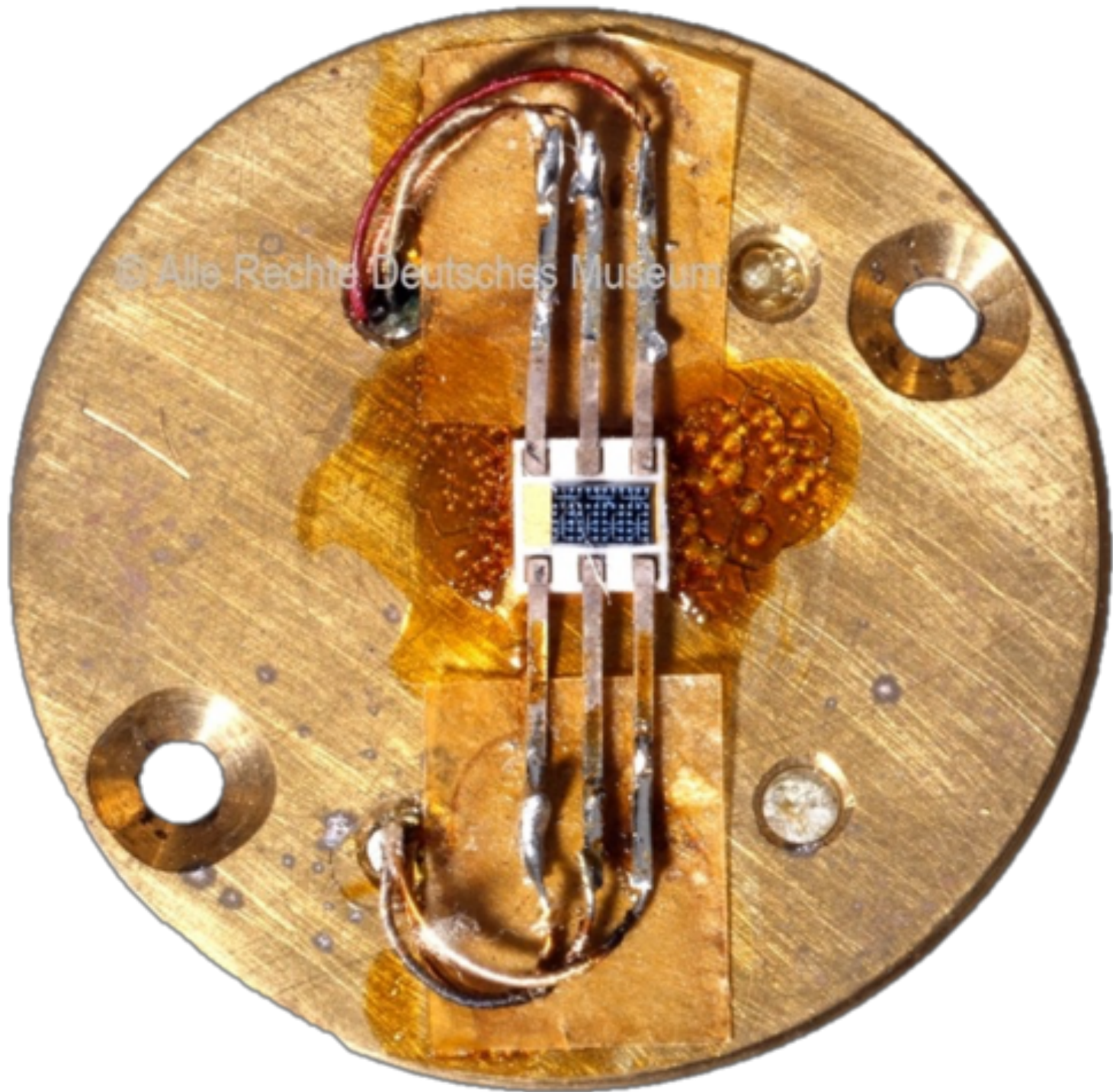




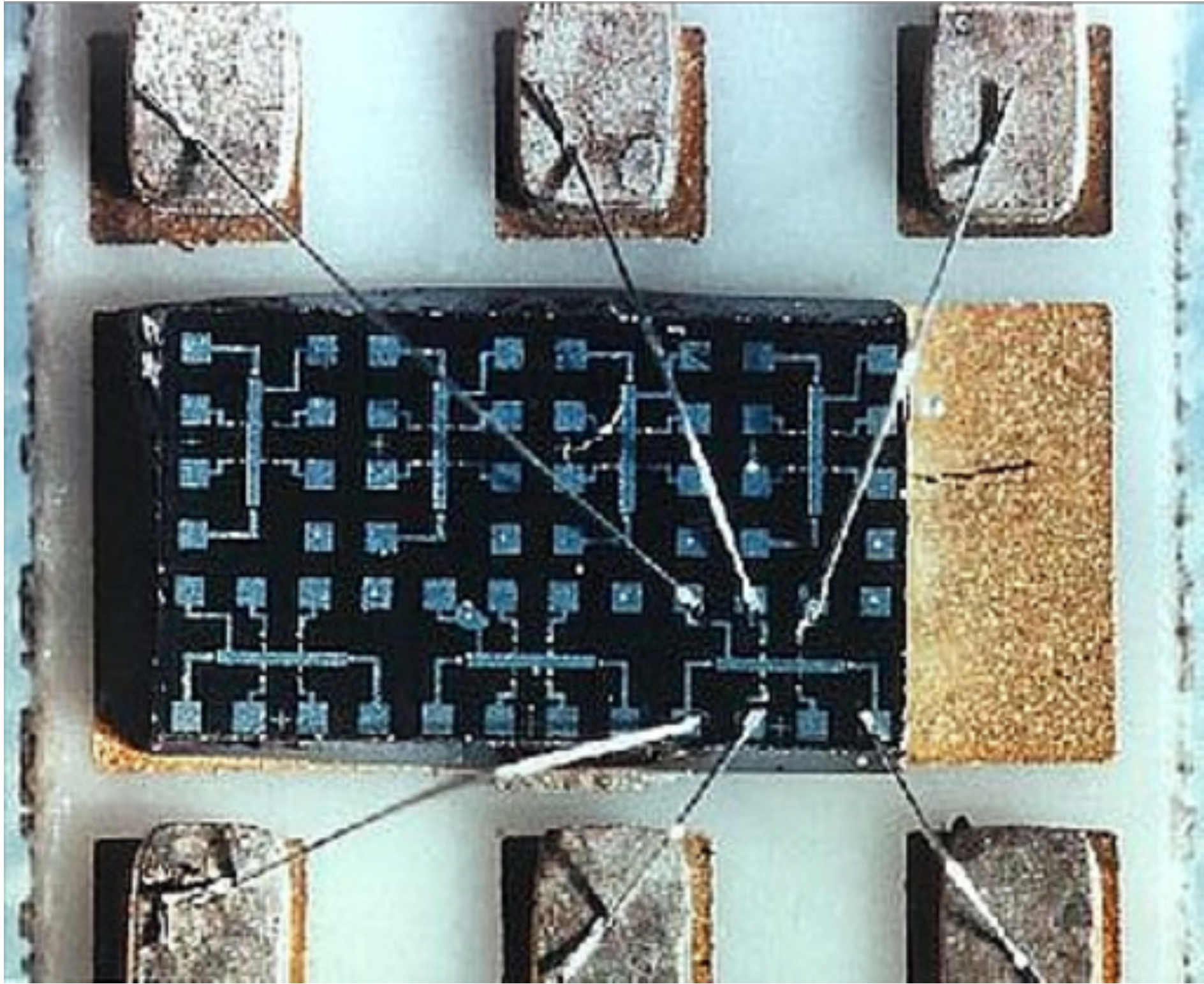


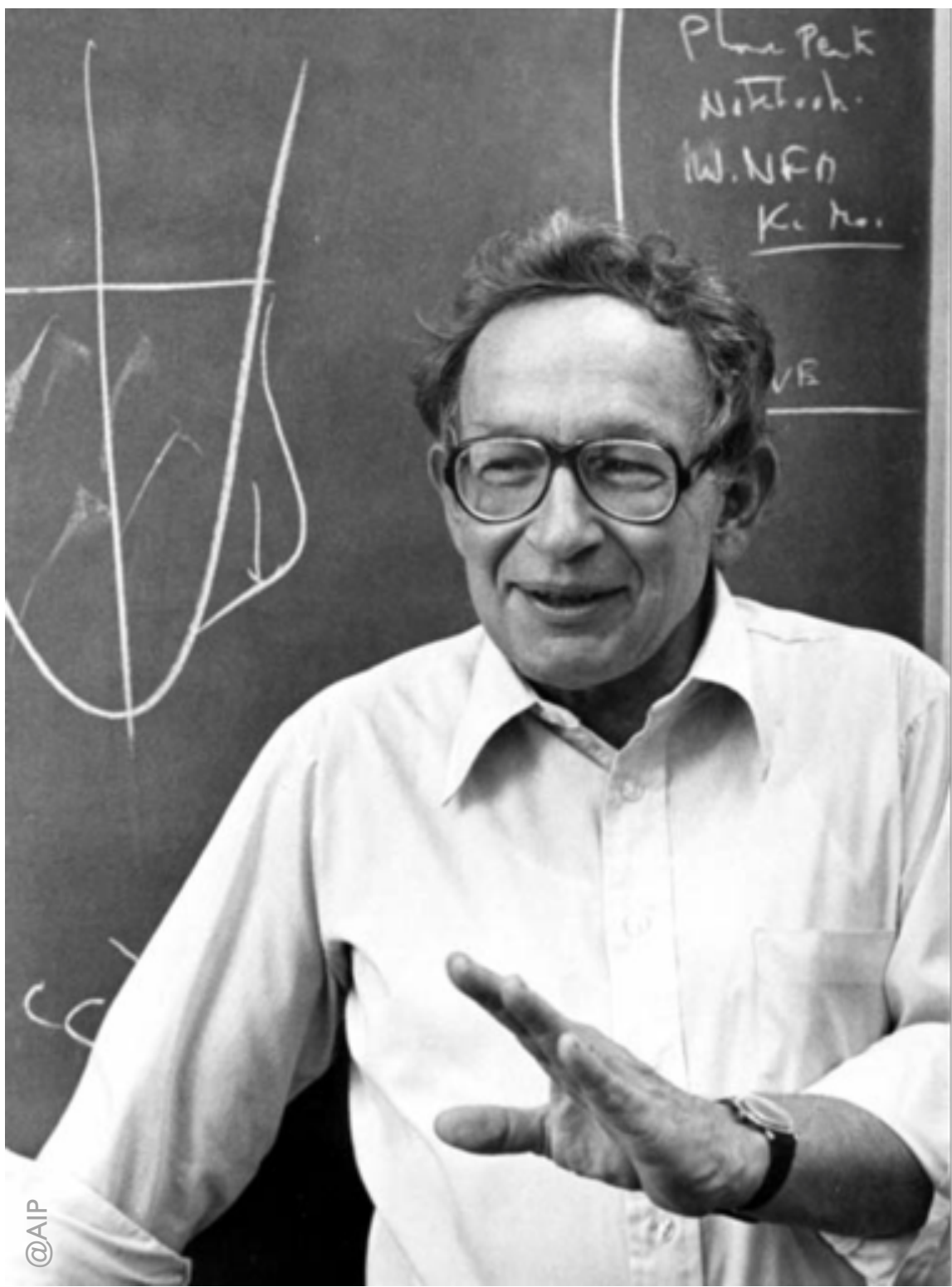


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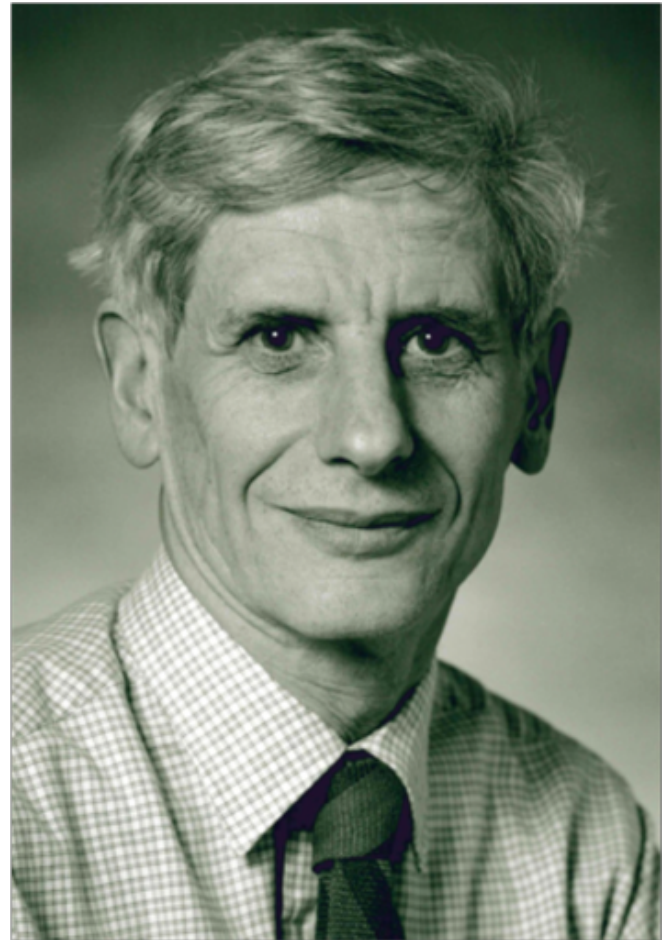




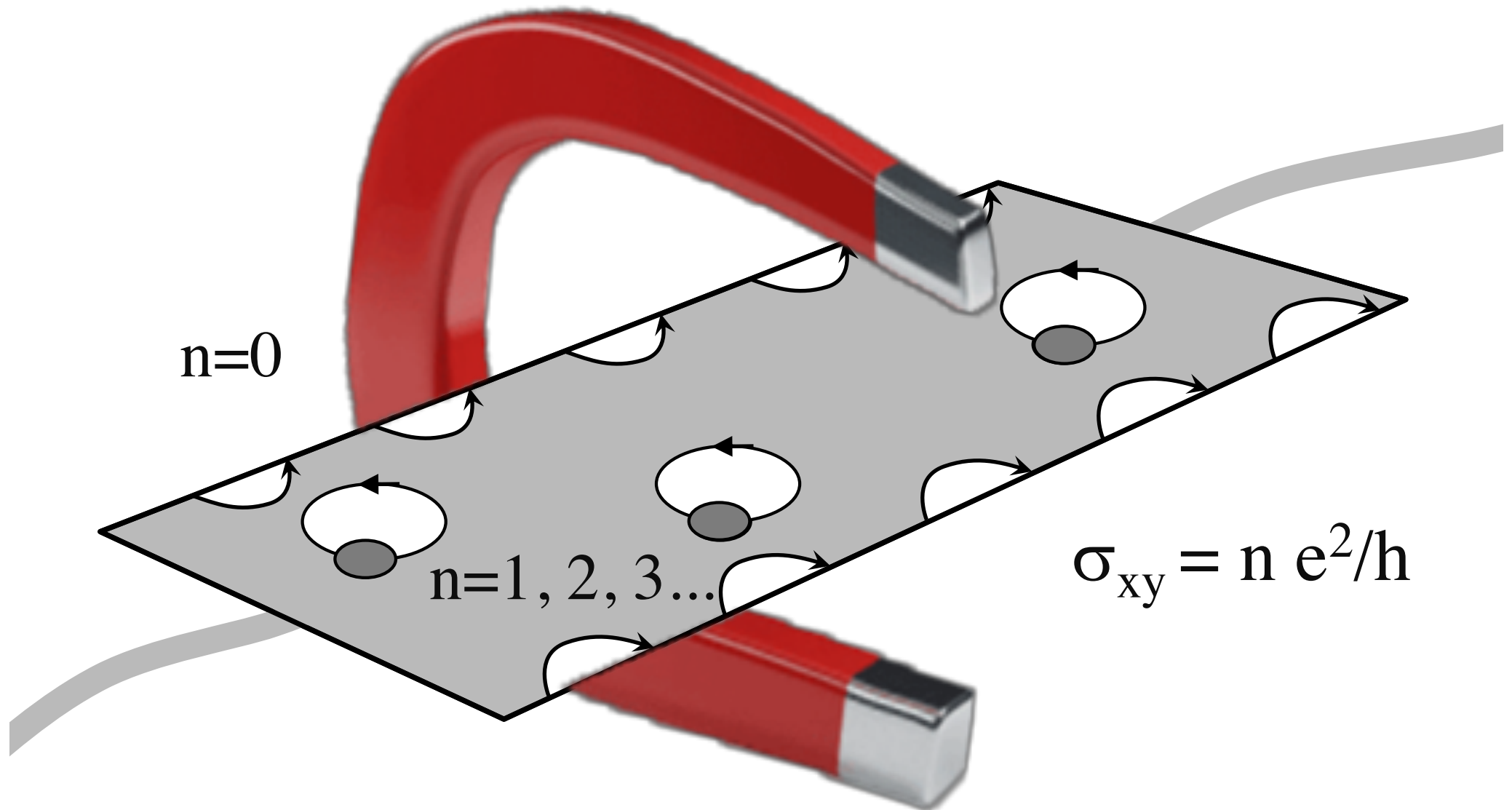
Plane Park  
Notebook.  
W. NFA  
K. No.

VE



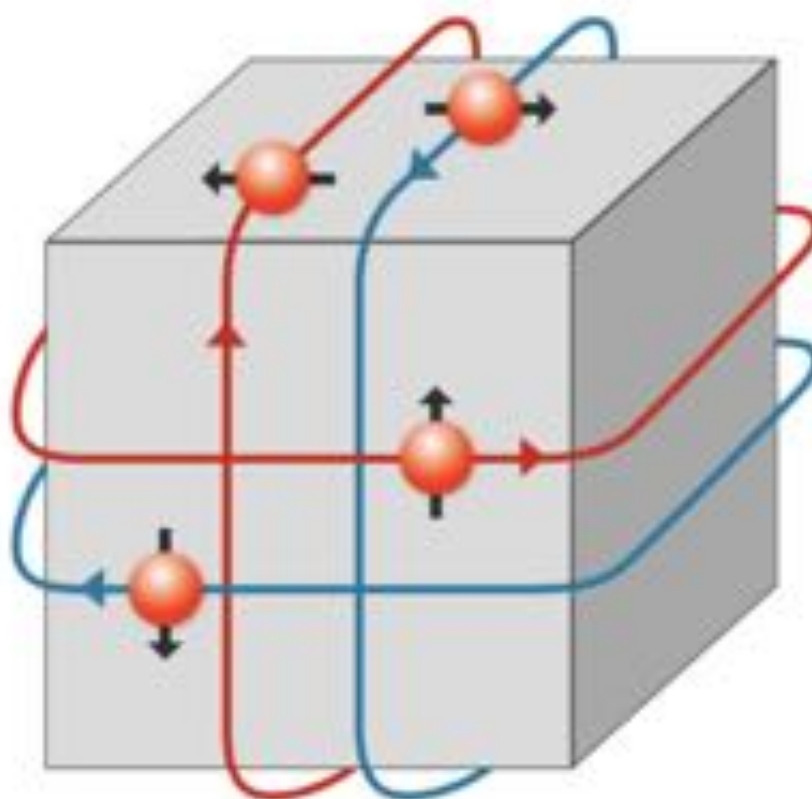


$$\sum_{\epsilon_{\mu}(\mathbf{k}) <} \frac{i}{2\pi} \int_{\mathbf{k} \in \text{BZ}} d^2\mathbf{k} \langle \nabla_{\mathbf{k}} u_{\mu}(\mathbf{k}) | \times | \nabla_{\mathbf{k}} u_{\mu}(\mathbf{k}) \rangle \cdot \hat{z} = \text{entier } n$$

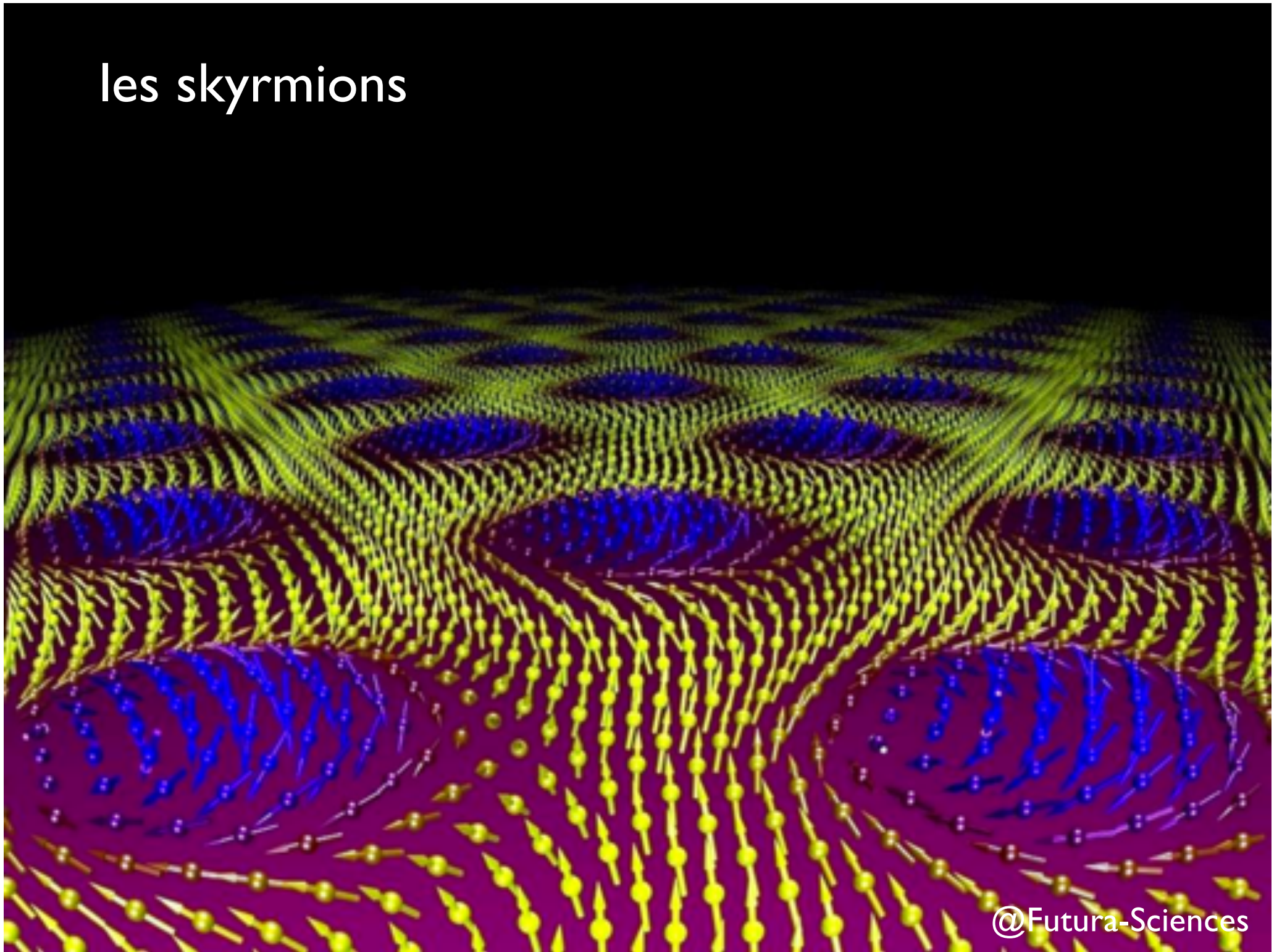








# les skyrmions



pour conclure

Utilisation principale des nanofabrications:  
des composants pour l'électronique

d'autres utilisations :

- pour des petits capteurs
- pour des médicaments
- pour mieux comprendre la physique
- pour contrôler la chimie
- ...

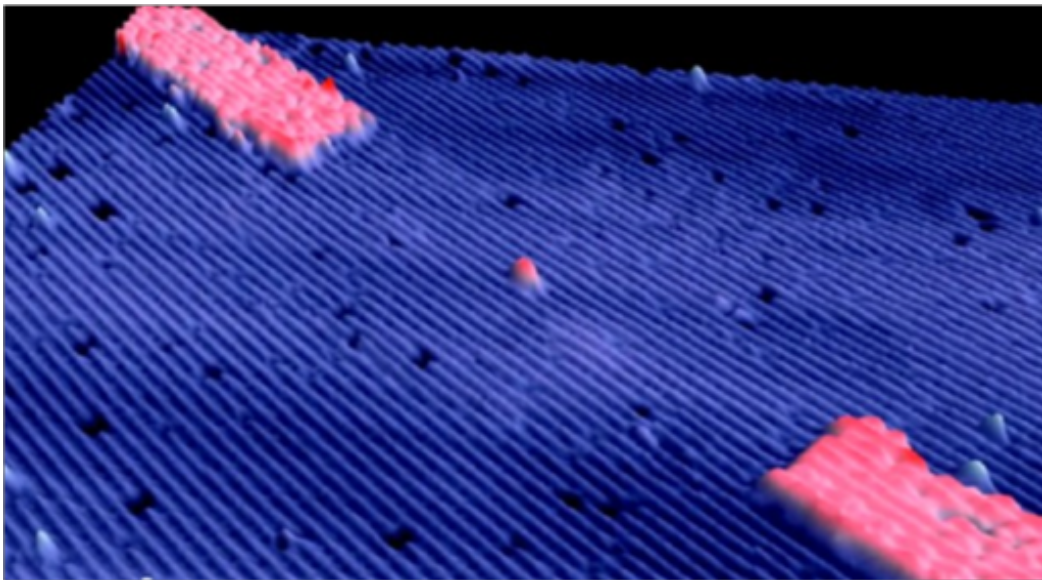
# quelques enjeux de société :

- la fabrication nano : un enjeu industriel  
(1 usine de microprocesseurs = qq milliards d'€)
- les matières premières : un enjeu géopolotique
- la recherche fondamentale et le lien avec les applications
- des composants pour l'environnement
- quelle toxicité ?



# quel futur ?

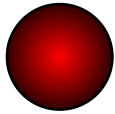
- miniaturiser encore plus en électronique
- construire sur mesure le macro depuis le nano
- créer de nouvelles matières
- fabriquer des ordinateurs quantiques
- l'intelligence artificielle



transistor à un seul atome

# résumé

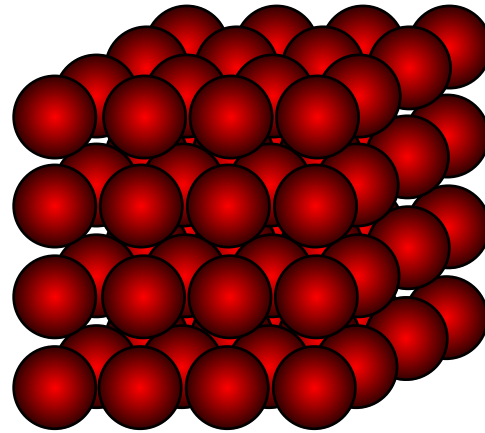
l'atome



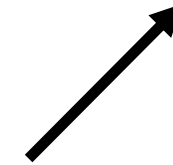
physique  
quantique



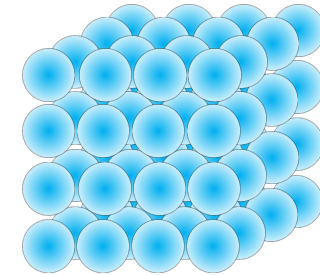
physique des  
solides



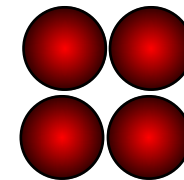
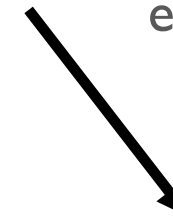
physique classique  
mais propriétés  
compréhensibles  
seulement avec la quantique



technologies  
quantiques



basses températures :  
effets quantiques collectifs



nanophysique :  
retour à la quantique