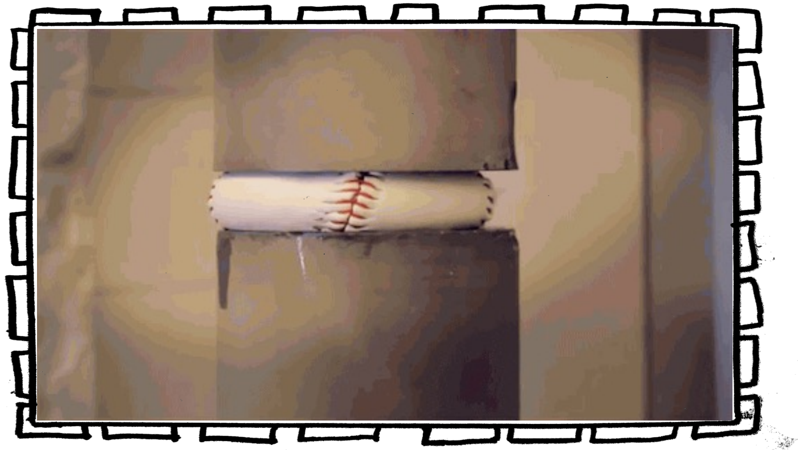
La pression



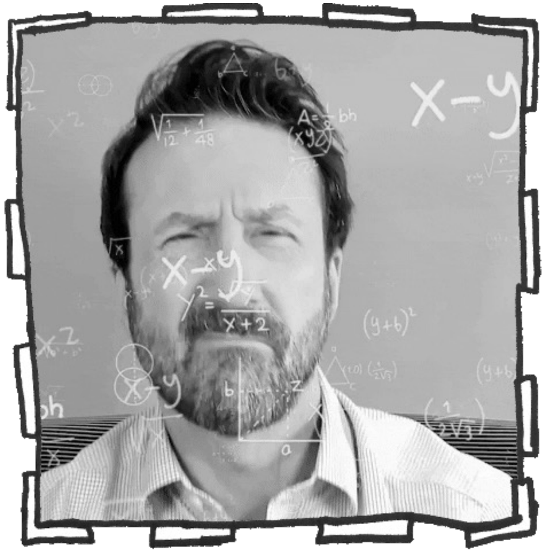
Culture scientifique en L3
Institut Villebon-Charpak, Julien Bobroff

La pression

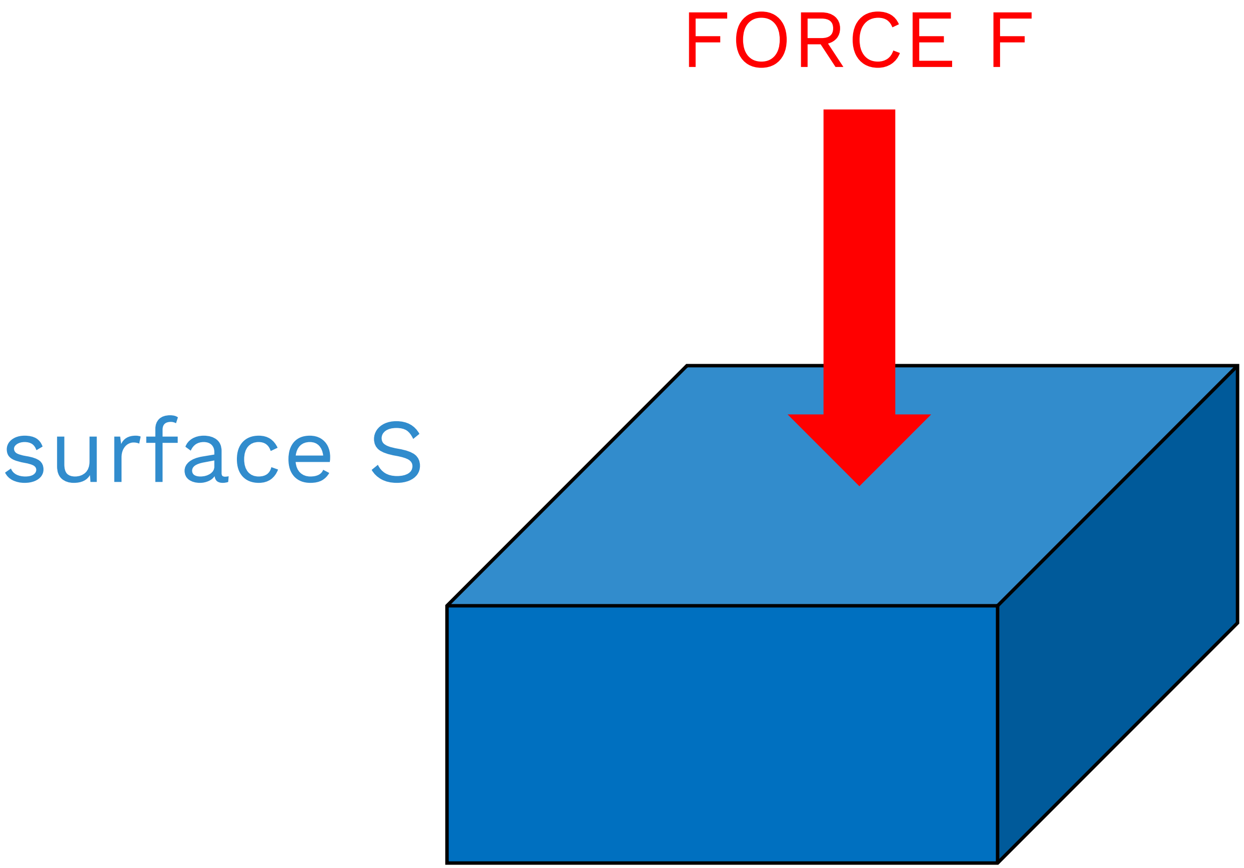
expliquez à un enfant
de 10 ans ce que c'est

La pression

quelles équations ?



la pression



Pression

$$P = \frac{F}{S}$$

plus la surface est petite, plus la pression est grande

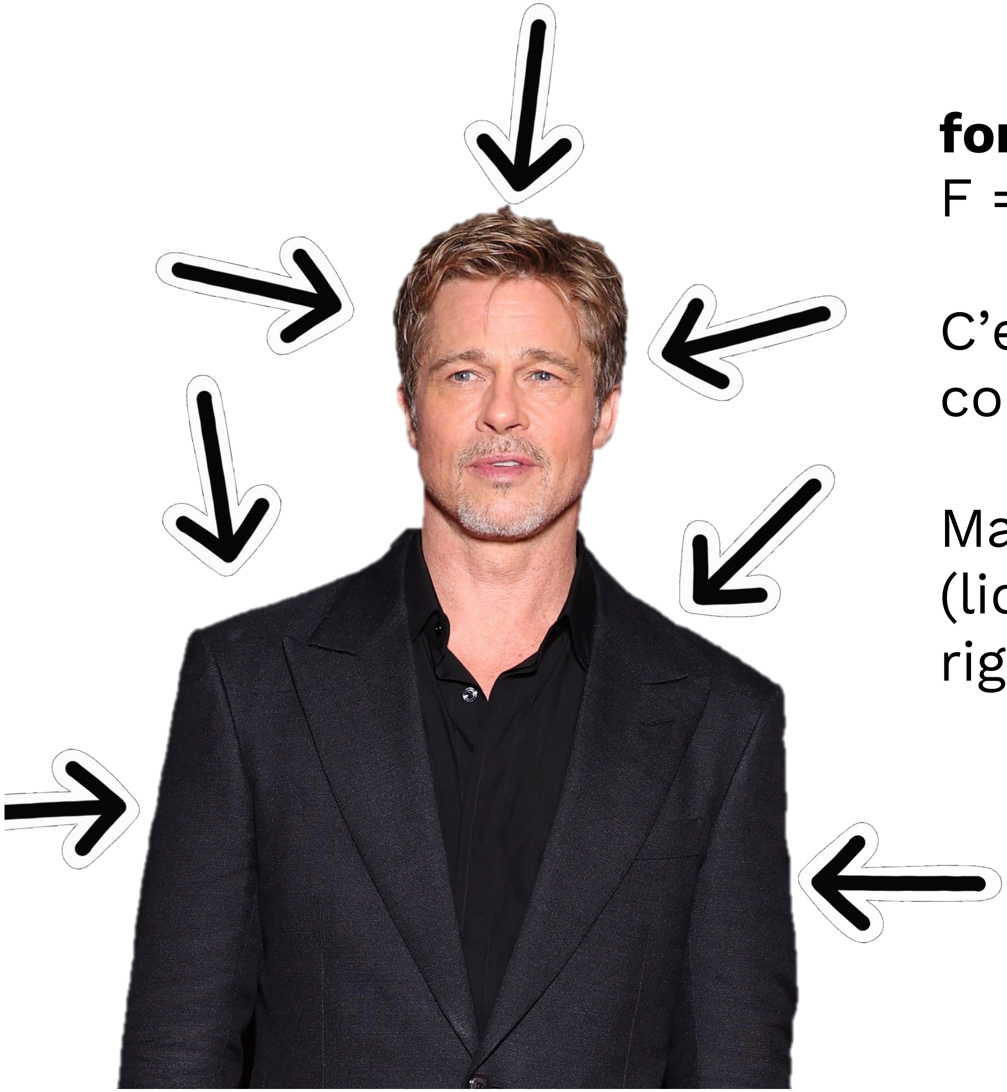
quelques calculs de pression

une feuille sur une table
Pression P = F / S
= 10 x 0,005 / (0,21 x 0,29)
= 0,8 Pascal = 8 10^{-6} Bar

un coup de poing équivaut à 100kg
Pression P = F / S
= 100x10 / (0,05 x 0,05)
= 400 000 Pascal = 4 Bar

un marteau sur un clou : 100 Newton
Pression P = F / S
= 100 / (0,001 x 0,001)
= 25 million de Pascal = 250 Bar

quelle force l'atmosphère exerce sur notre corps ?



force subie :
F = S x P = 1 m^2 x 100 000 = 100 000 Newton

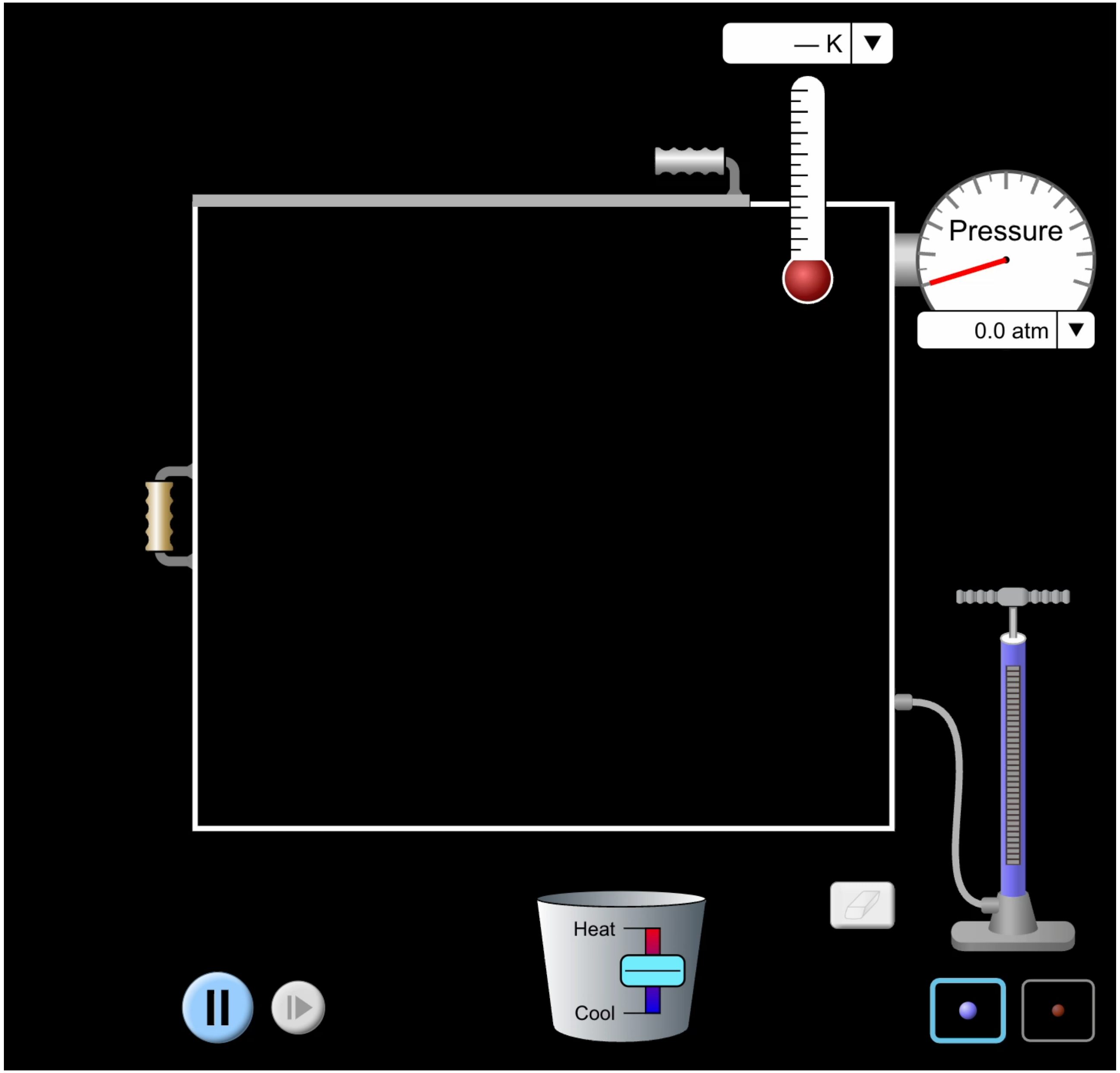
C'est l'équivalent de 10 tonnes sur tout le corps, et 300 kg sur le visage !!!

Mais heureusement, notre pression interne (liquides) l'équilibre, et notre peau est semi-rigide...

dans un gaz

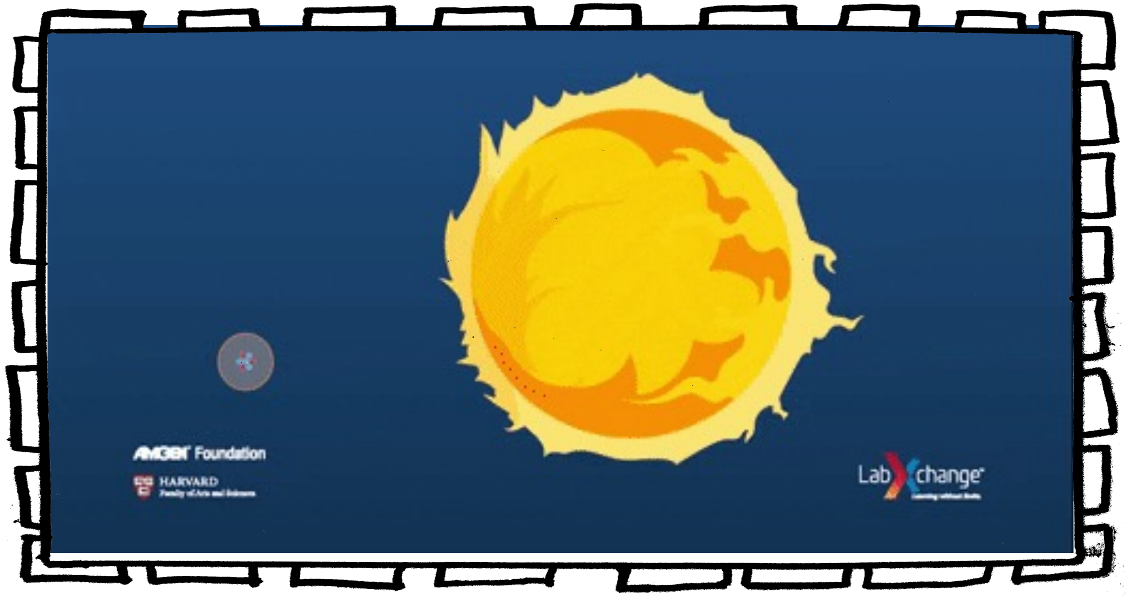
quand on diminue le
nombre de particules,
ça diminue la pression.

A pression nulle,
il n’y a plus de matière.
C’est le vide.



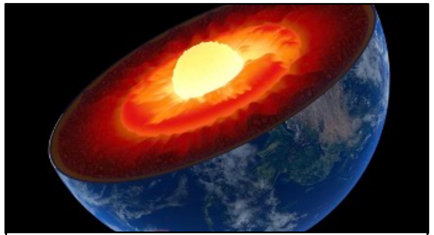
La pression

les ordres de grandeur



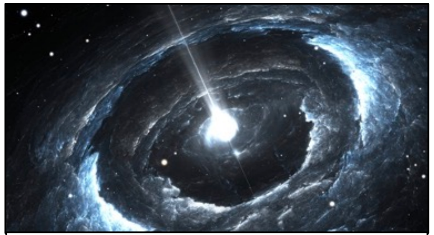
classer du plus vide au plus pressurisé (en Bar)

vide galactique



coeur de la Terre

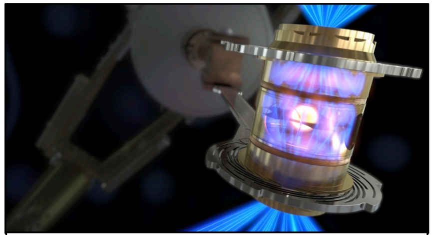
meilleur vide
en labo



étoile à neutrons

pneu

Everest

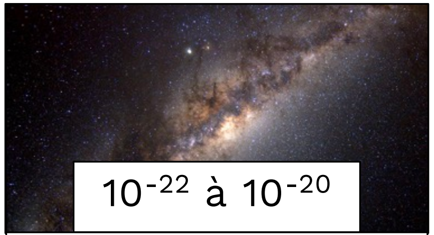


plus haute
pression en labo

à la mer

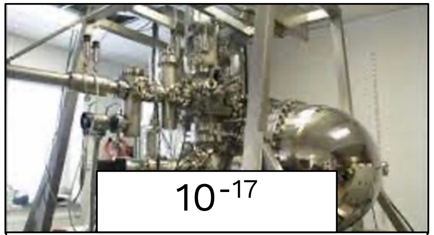
bouteille de
champagne

classer du plus vide au plus pressurisé (en Bar)



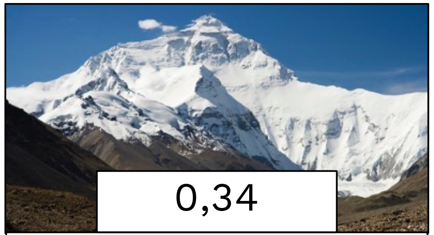
10^{-22} à 10^{-20}

vide galactique



10^{-17}

meilleur vide
en labo



0,34

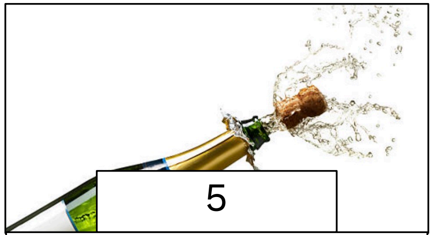
Everest

1,01

à la mer

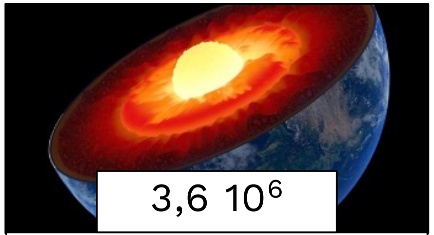
3

pneu



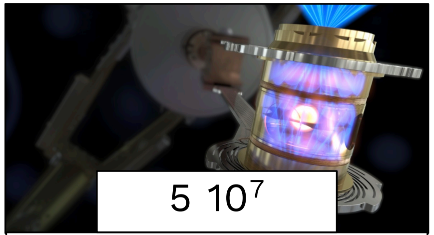
5

bouteille de
champagne



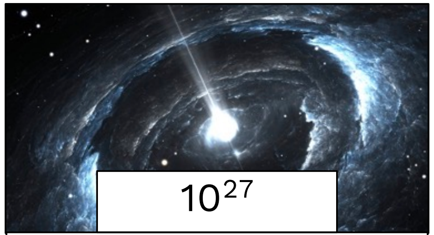
$3{,}6\ 10^{6}$

coeur de la Terre



$5\ 10^{7}$

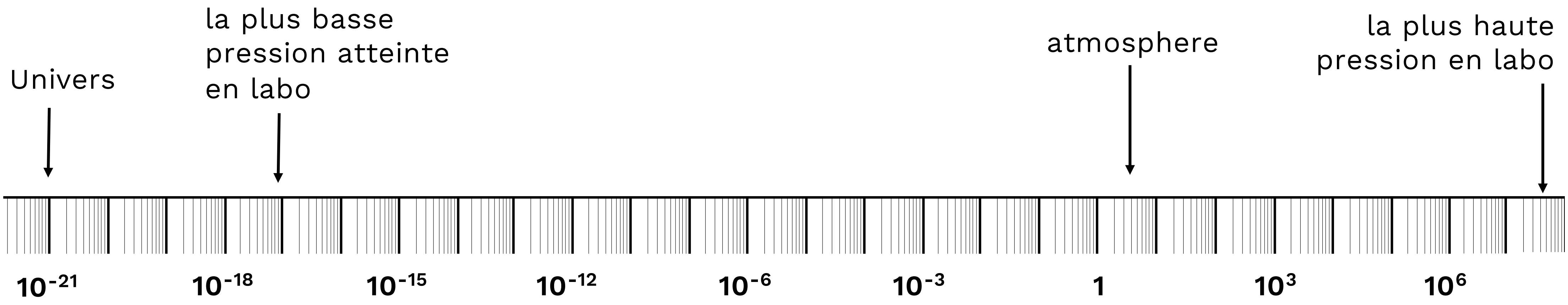
plus haute
pression en labo



10^{27}

étoile à neutrons

pression (Bar)



Univers

la plus basse
pression atteinte
en labo

atmosphere

la plus haute
pression en labo

La pression

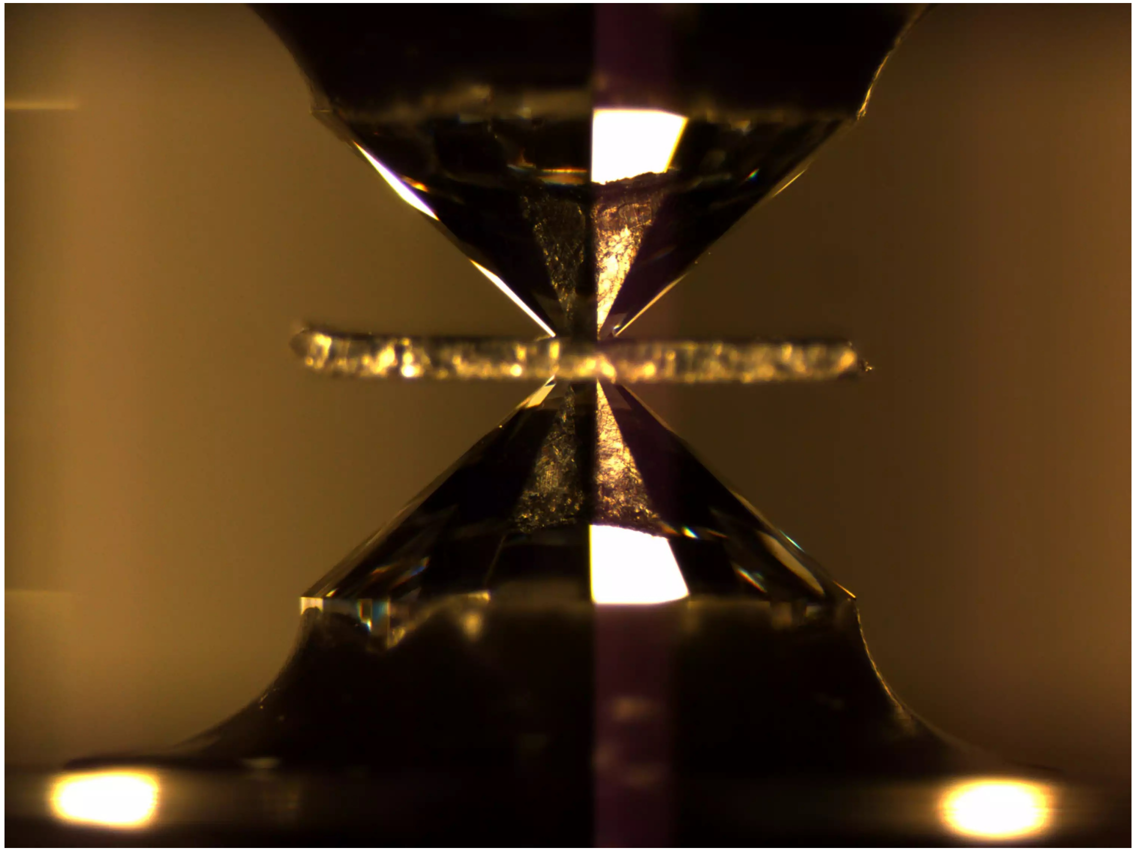
mesure et contrôle

en physique, on utilise la pression :

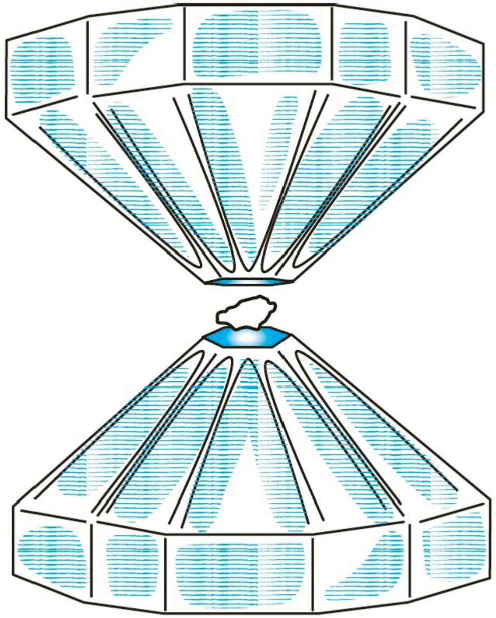
- **pour tester le comportement de la matière**
- **pour créer de nouvelles matières**
- **pour simuler des planètes**
- **pour simuler la Terre**

comment créer une forte pression ?

en utilisant une enclume diamant

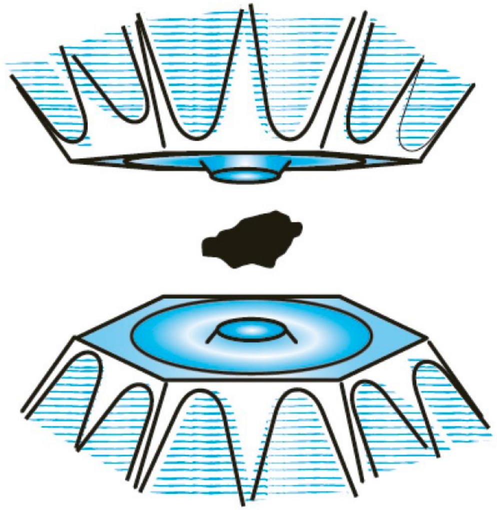


Les enclumes diamant



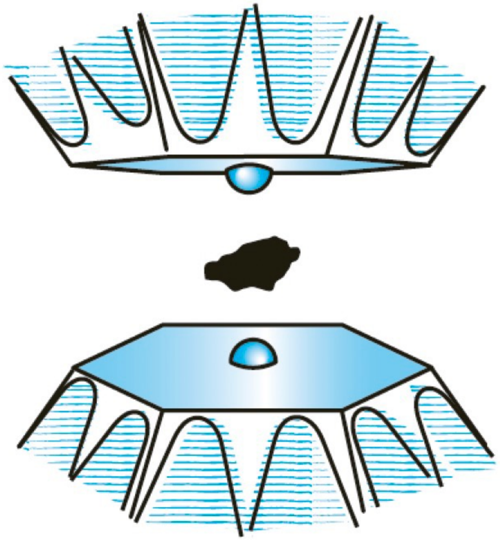
enclume simple

jusqu'à 10^6 Bar



enclume taillée
en torroïode

jusqu'à 5.10^6 Bar

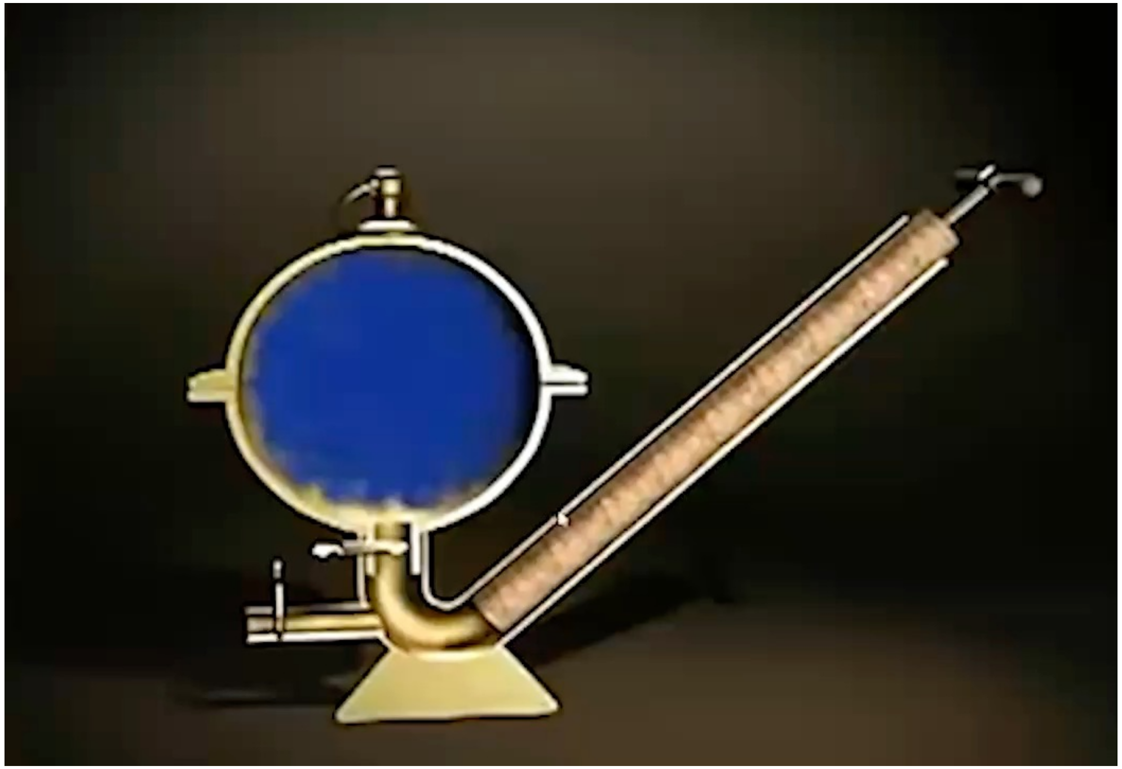


double enclume
avec demi-sphères

jusqu'à 9.10^6 Bar

comment diminuer la pression et faire le vide ?

en utilisant une pompe



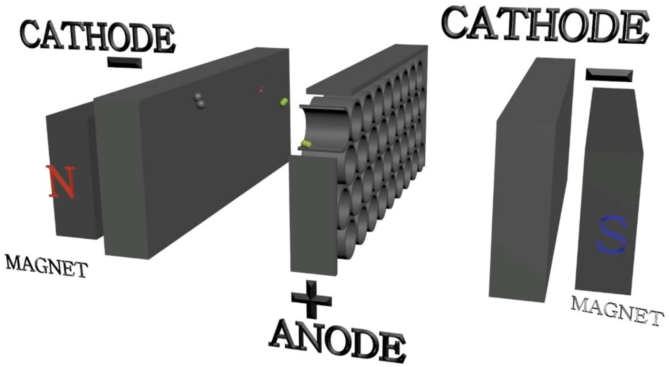
la première pompe à piston
Otto von Guericke, 1650

des pompes à associer pour atteindre les meilleurs vides

pompe turbomoleculaire

cryopompe

pompe à diffusion



pompe à ions

en physique, on utilise le vide :

- **pour observer de petits objets (atomes, molécules, surfaces…) et les manipuler**
- **pour faire de la physique quantique**
- **pour faire de la physique des particules**
- **dans l’exploration spatiale**

La pression

recherches récentes

recherches récentes

1. créer de nouvelles matières avec la pression
2. le record de pression
3. créer des matières sous vide
4. le vide est-il vide ?

recherches récentes

1. **créer de nouvelles matières avec la pression**
2. le record de pression
3. créer des matières sous vide
4. le vide est-il vide ?

Article

Synchrotron infrared spectroscopic evidence of the probable transition to metal hydrogen

https://doi.org/10.1038/s41586-019-1927-3
Received: 12 April 2019
Accepted: 26 November 2019

Paul Loubeyre[1]*, Florent Occelli[1] & Paul Dumas[1,2]

Hydrogen has been an essential element in the development of atomic, molecular and condensed matter physics[1]. It is predicted that hydrogen should have a metal state[2]; however, understanding the properties of dense hydrogen has been more complex than originally thought, because under extreme conditions the electrons and protons are strongly coupled to each other and ultimately must both be treated as quantum particles[3,4]. Therefore, how and when molecular solid hydrogen may transform into a metal is an open question. Although the quest for metal hydrogen has pushed major developments in modern experimental high-pressure physics, the various claims of its observation remain unconfirmed[5–7]. Here a discontinuous change of the direct bandgap of hydrogen, from 0.6 electronvolts to below 0.1 electronvolts, is observed near 425 gigapascals. This result is most probably associated with the formation of the metallic state because the nucleus zero-point energy is larger than this lowest bandgap value. Pressures above 400 gigapascals are achieved with the recently developed toroidal diamond anvil cell[8], and the structural changes and electronic properties of dense solid hydrogen at 80 kelvin are probed using synchrotron infrared absorption spectroscopy. The continuous downward shifts of the vibron wavenumber and the direct bandgap with increased pressure point to the stability of phase-III hydrogen up to 425 gigapascals. The present data suggest that metallization of hydrogen proceeds within the molecular solid, in good agreement with previous calculations that capture many-body electronic correlations[9].

The search for metal hydrogen has a unique place in high-pressure physics. Indisputably, metal hydrogen should exist. Owing to increase in electron kinetic energy because of quantum confinement, pressure should turn any insulator into a metal, as observed for molecular oxygen around 100 GPa some 20 years ago[10]. At first, the prediction of the insulator–metal transition in dense hydrogen was intertwined with the molecular dissociation[2]. However, it was later suggested that metal hydrogen may exist as a proton-paired metal[11]. Quantitative predictions of the stability domain and of the properties of metal hydrogen remain challenging because many contributions could be in effect and should be self-consistently treated[3,4]; for example, many-body electronic correlations, nuclear quantum effects, nuclear spin ordering, coupling between protons and electrons (as suggested by a large Born–Oppenheimer separation parameter), or anharmonic effects. The most advanced calculations, such as diffusion Monte Carlo (DMC) simulations[4,9,12], now go beyond the electronic correlation mean-field description of density functional theory and try to capture many-body electronic correlations. Importantly, metal hydrogen should exhibit notable properties, such as room-temperature superconductivity[13–15], a melting transition at a very low temperature into a superconducting superfluid state[16] and a mobile solid state[17].

The change in the direct bandgap of solid hydrogen was previously measured up to 300 GPa by visible absorption mesurements[18]. By extrapolating to zero the linear decrease of the bandgap with density, the transition to metal hydrogen was predicted to occur around 450 GPa. In this work, we extend the investigation of the direct bandgap decrease down to the near-to-mid-infrared energy range. Infrared measurements provide a non-intrusive method both to disclose structural changes and also to characterize the electronic properties of hydrogen up to its metal transition. Our approach is based on two experimental developments. First, in order to overcome the 400 GPa limit of conventional diamond anvil cells[19], we used the recently developed toroidal diamond anvil cell (T-DAC)[8] that can achieve pressures of up to 600 GPa. Importantly, under extreme pressures, the T-DAC preserves the advantages of the standard diamond anvil cell in terms of stress distribution, optical access and sample size. Synthetic type-IIa diamond anvils were used to provide infrared transparency down to 800 cm^{-1}. Second, an infrared horizontal microscope was designed to be coupled to a collimated exit port of a synchrotron-feed Fourier-transform infrared spectrometer at the SMIS beamline at the SOLEIL synchrotron facility. Such a high-brightness broadband infrared source is essential for measuring, by transmission, satisfactory signal-to-noise

---

[1]CEA, DAM, DIF, Arpajon, France. [2]Synchrotron SOLEIL, Gif-sur-Yvette, France. *e-mail: paul.loubeyre@cea.fr

Nature | Vol 577 | 30 January 2020 | **631**

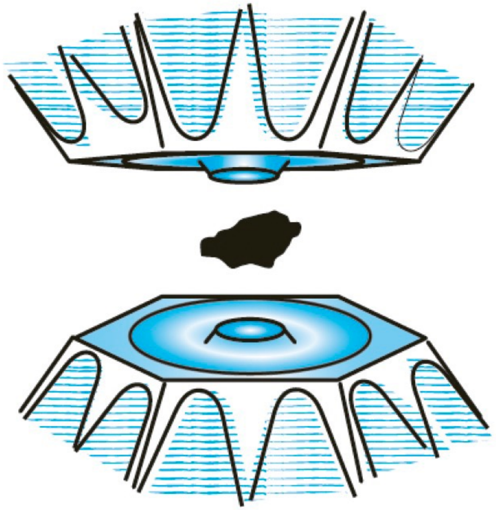
Loubeyre et al., Nature, 631, 577 (2020)

Saclay

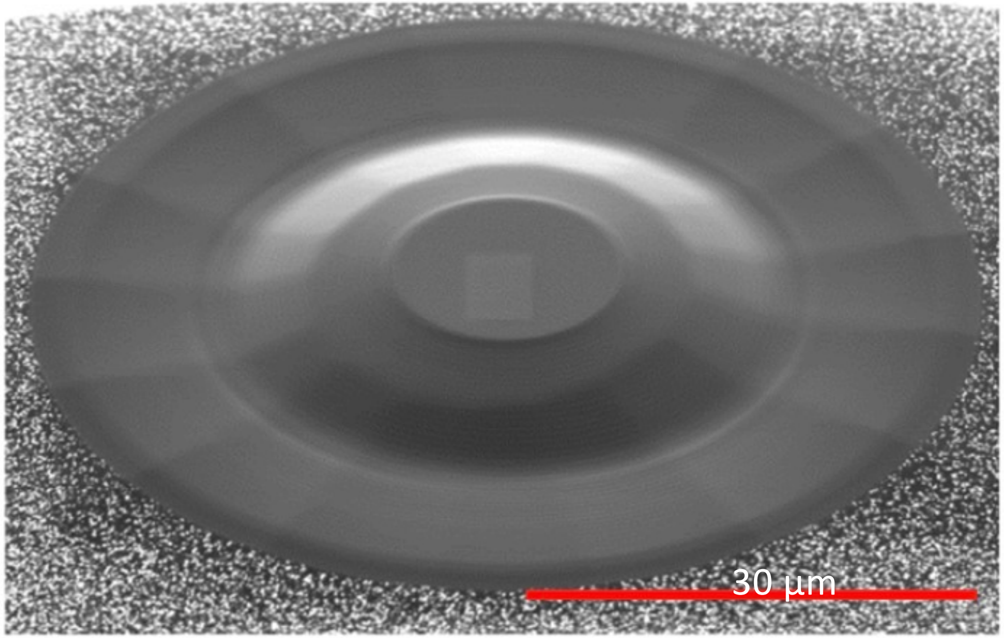
2020

création d’hydrogène métallique sous pression

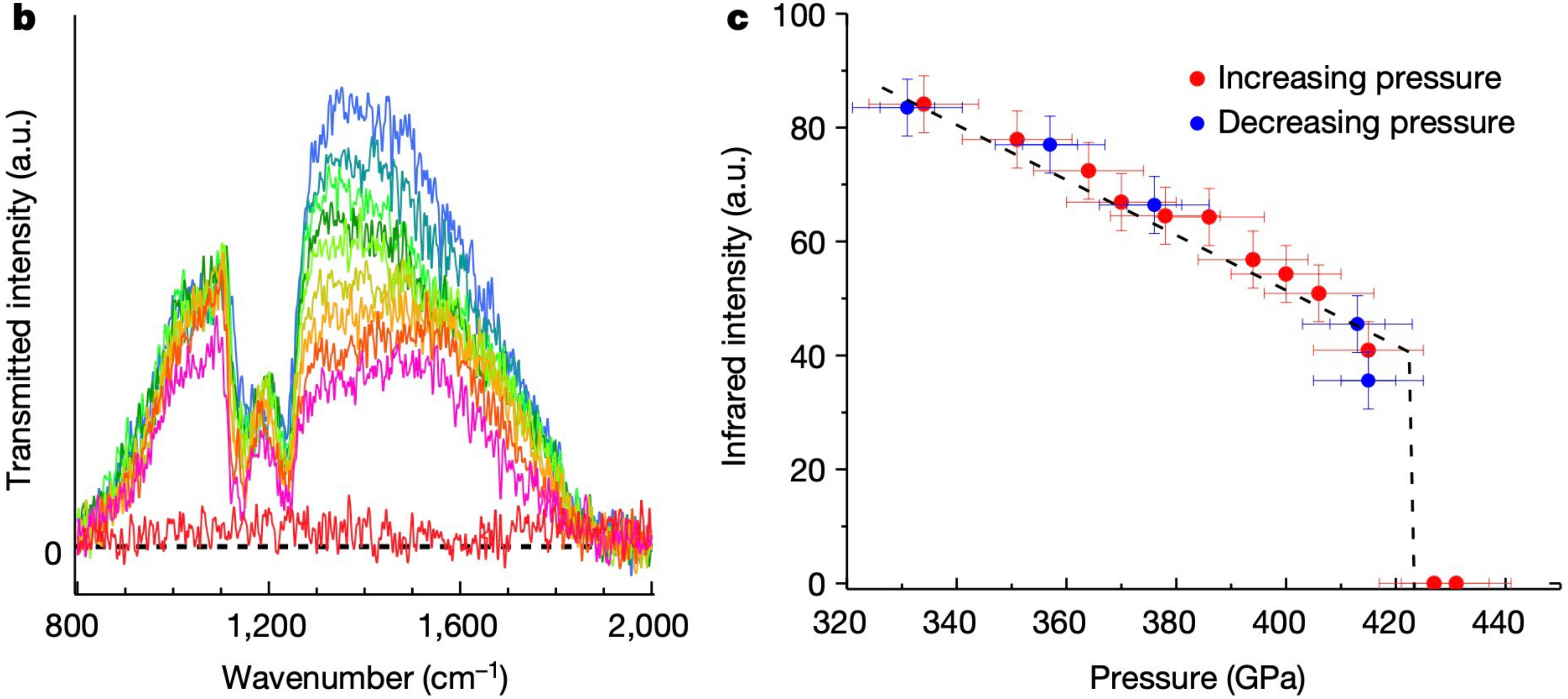
Obtenir des ultra - hautes pressions



enclume taillée
en torroïode



mesures avec de l’hydrogène gazeux



obtention d’hydrogène métallique
au dessus de 4,2 millions de Bar à T=80K

recherches récentes

1. créer de nouvelles matières avec la pression
2. **le record de pression**
3. créer des matières sous vide
4. le vide est-il vide ?

Article

Metastability of diamond ramp-compressed to 2 terapascals

https://doi.org/10.1038/s41586-020-03140-4

Received: 1 June 2020

Accepted: 26 October 2020

A. Lazicki[1✉], D. McGonegle[2], J. R. Rygg[3,4,5], D. G. Braun[1], D. C. Swift[1], M. G. Gorman[1], R. F. Smith[1], P. G. Heighway[2], A. Higginbotham[6], M. J. Suggit[2], D. E. Fratanduono[1], F. Coppari[1], C. E. Wehrenberg[1], R. G. Kraus[1], D. Erskine[1], J. V. Bernier[1], J. M. McNaney[1], R. E. Rudd[1], G. W. Collins[3,4,5], J. H. Eggert[1] & J. S. Wark[2]

Carbon is the fourth-most prevalent element in the Universe and essential for all known life. In the elemental form it is found in multiple allotropes, including graphite, diamond and fullerenes, and it has long been predicted that even more structures can exist at pressures greater than those at Earth's core[1–3]. Several phases have been predicted to exist in the multi-terapascal regime, which is important for accurate modelling of the interiors of carbon-rich exoplanets[4,5]. By compressing solid carbon to 2 terapascals (20 million atmospheres; more than five times the pressure at Earth's core) using ramp-shaped laser pulses and simultaneously measuring nanosecond-duration time-resolved X-ray diffraction, we found that solid carbon retains the diamond structure far beyond its regime of predicted stability. The results confirm predictions that the strength of the tetrahedral molecular orbital bonds in diamond persists under enormous pressure, resulting in large energy barriers that hinder conversion to more-stable high-pressure allotropes[1,2], just as graphite formation from metastable diamond is kinetically hindered at atmospheric pressure. This work nearly doubles the highest pressure at which X-ray diffraction has been recorded on any material.

On Earth, carbon can exist in a number of different allotropes, with graphite and diamond being the most well known, although several others exist[6–8], or have been predicted to be stable[9–11]. Diamond, the face-centred-cubic form of carbon (with space group $Fd\bar{3}m$, here called FC8) has many technologically important properties owing to its compressive strength and high thermal conductivity. The phase diagram of carbon at pressures in the terapascal (TPa) regime is directly relevant to the structure of planets within our Solar System and beyond[4,5]. Theoretical calculations based on density functional theory (DFT) of the crystalline phases of carbon at TPa-scale pressures have a long history[1–3,12–14], with general agreement emerging that body-centred-cubic (BC8; $Ia\bar{3}$) and simple-cubic (SC1; $Pm\bar{3}m$, and SC4; $P4_332$) phases are lower in enthalpy than FC8 above about 1 TPa, with BC8 being the first to satisfy this condition at around 1 TPa (Fig. 1).

Multi-TPa pressures far exceed those that can be achieved under static conditions in the laboratory using anvils[15,16]. Although such high pressures can be obtained with shock compression, this highly entropic process starts to melt diamond above 0.6 TPa, according to a study of changes in entropy manifested in decaying shock waves[17] (Fig. 1). Recently, however, a new dynamic technique known as ramp compression has been developed, in which a sample is compressed on a timescale that is long compared to the sound-wave transit time through the sample, thus reducing dissipative processes and keeping the sample cooler than it would be in the shocked state[18]. With this technique, diamond has previously been ramp-compressed to record-high pressures (more accurately longitudinal stresses, because of the uniaxial loading) of 5 TPa at the National Ignition Facility in Livermore, California, USA[19]. This ramp data gave no indicators of a phase transformation, such as plateaus in the velocity ramp caused by changes in sound speed. A second experimental study has interpreted subtle trends in shock Hugoniot data near the melting point as evidence for the FC8–BC8–liquid triple point near 1 TPa (ref. [20]). However, neither of these studies included a measurement of structure.

In fact, whether and how diamond might transform to one of the predicted phases in a laboratory compression experiment are far from trivial questions to answer, owing to the large enthalpy barriers predicted to exist between the phases (a phenomenon that explains the very existence of ambient-pressure diamond itself, given its metastability compared with graphite). Simulations at zero Kelvin report that the predicted BC8 phase will never form under rapid compression, and the FC8 phase will persist until it becomes mechanically unstable near 3 TPa (ref. [1]). At high temperature, however, the atoms are freed to follow alternative transformation pathways and the enthalpy of formation is lower for some phases. At 2 TPa and 4,000 K, FC8 is predicted to transform to the lower-energy (but still metastable) SC1 phase, and at 300 K and 2.5 TPa FC8 is predicted to transform to another metastable SC4 structure[2]. It is also predicted that BC8 will form at approximately 1 TPa, but only when released from the SC1 phase. To explore this rich

---

[1]Lawrence Livermore National Laboratory, Livermore, CA, USA. [2]Department of Physics, Clarendon Laboratory, University of Oxford, Oxford, UK. [3]Laboratory for Laser Energetics, University of Rochester, Rochester, NY, USA. [4]Department of Mechanical Engineering, University of Rochester, Rochester, NY, USA. [5]Department of Physics and Astronomy, University of Rochester, Rochester, NY, USA. [6]Department of Physics, University of York, York, UK. ✉e-mail: lazicki1@llnl.gov

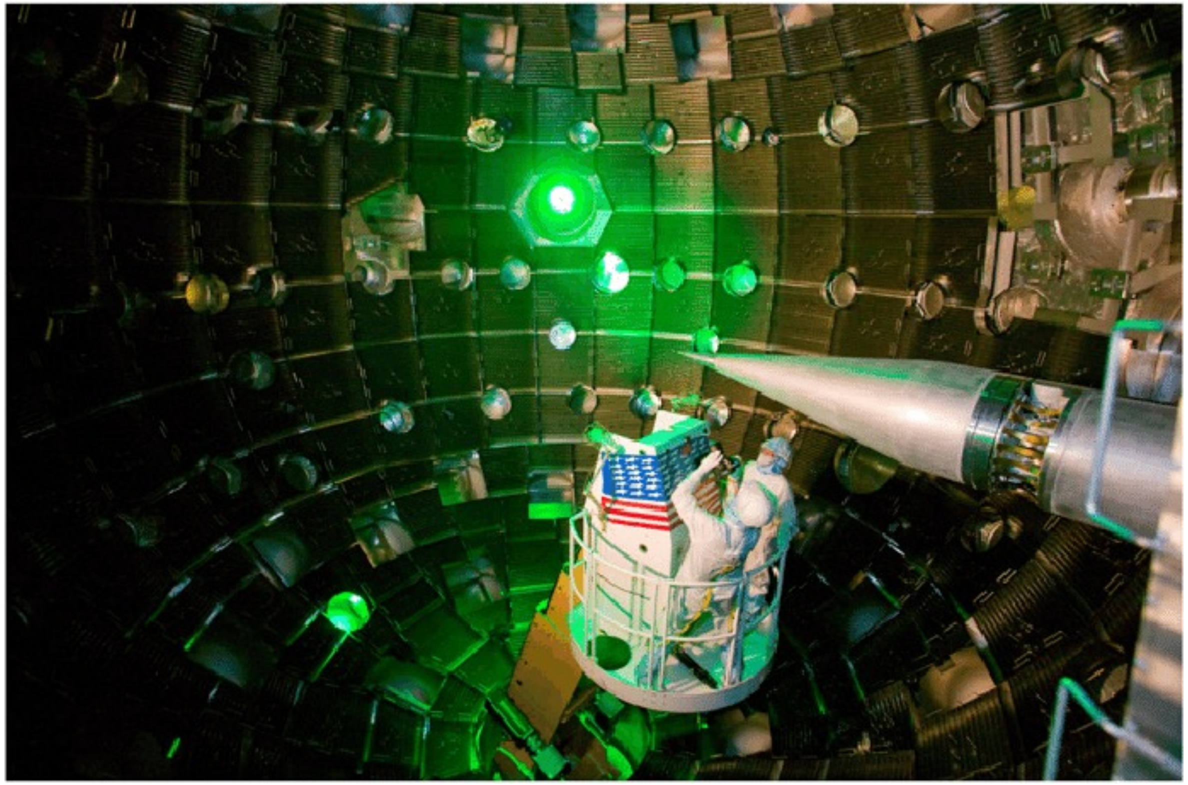
A. Lazicki et al., Nature 589, 532 (2021)

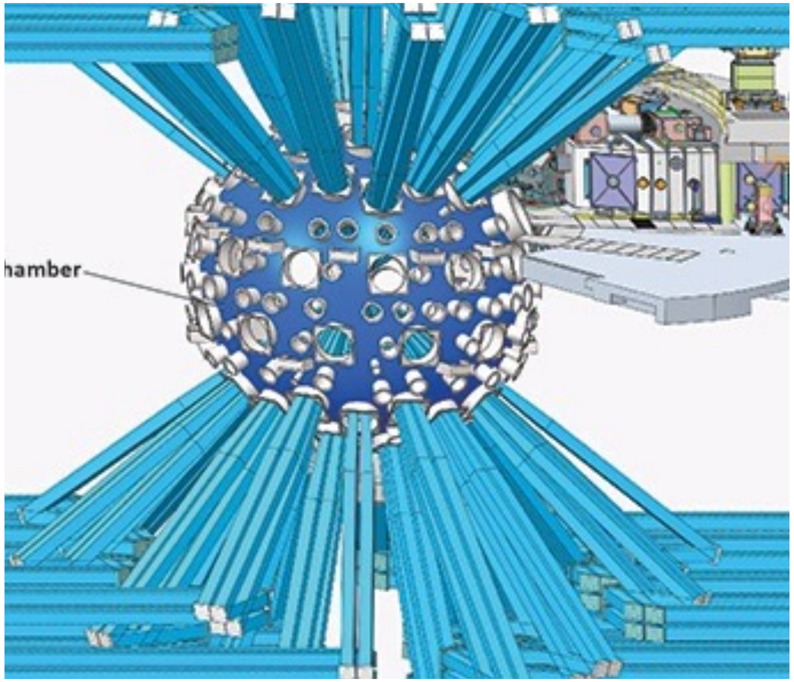
Livermore, USA

2021

Effet d'une pression de 20 millions de Bar sur du diamant.

Obtenir des ultra - hautes pressions par laser

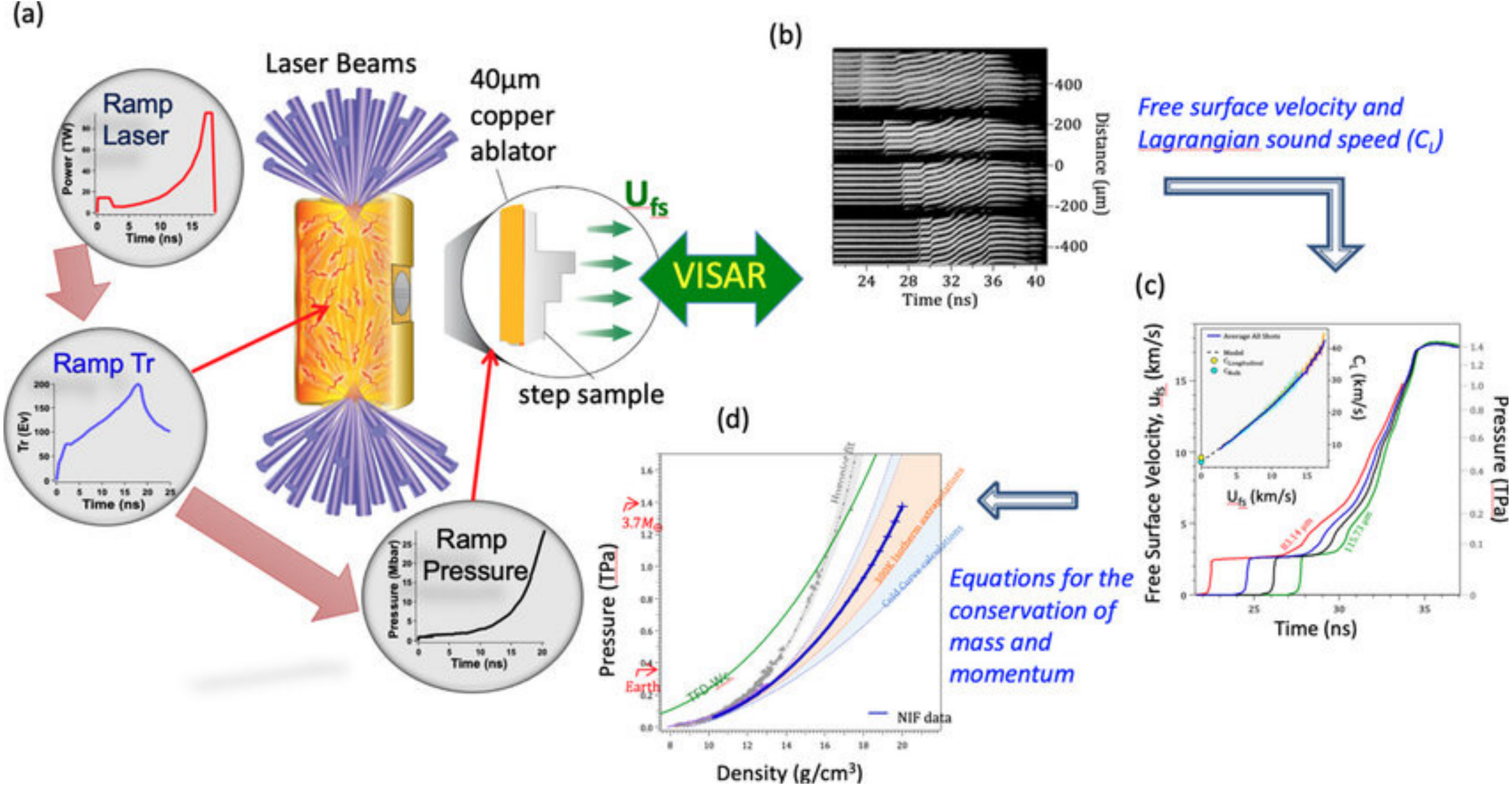




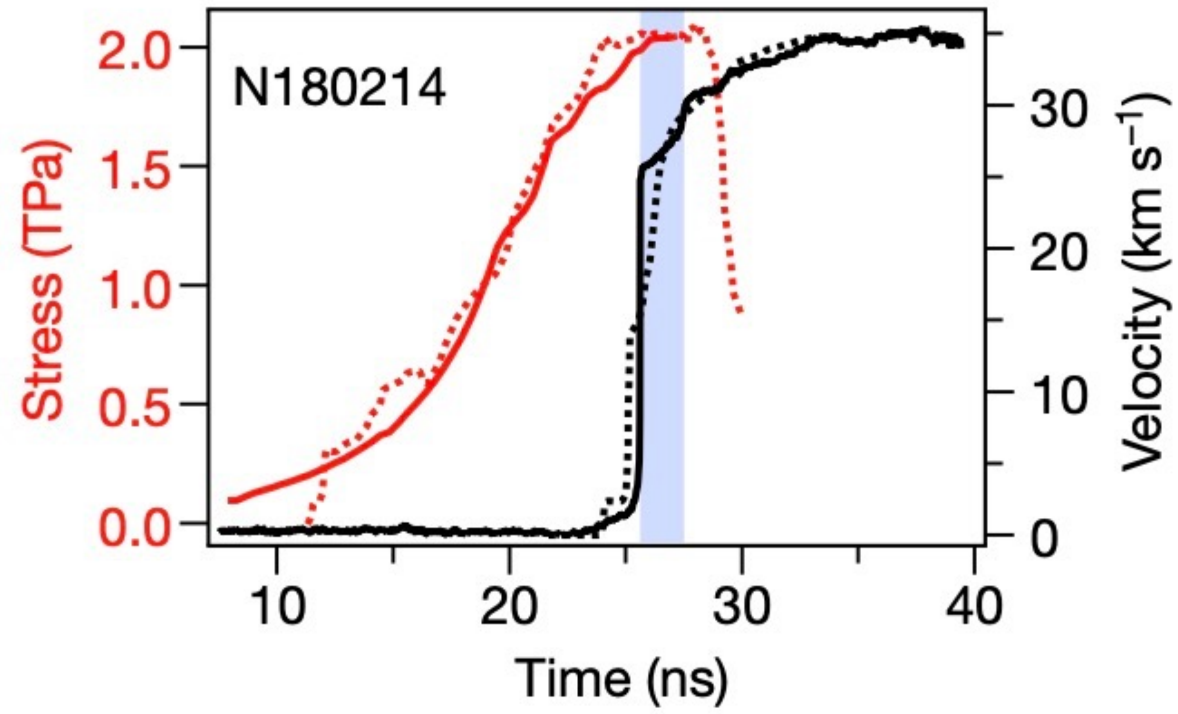
176 laser – puissance pic 2, 2 TW pendant 20 ns

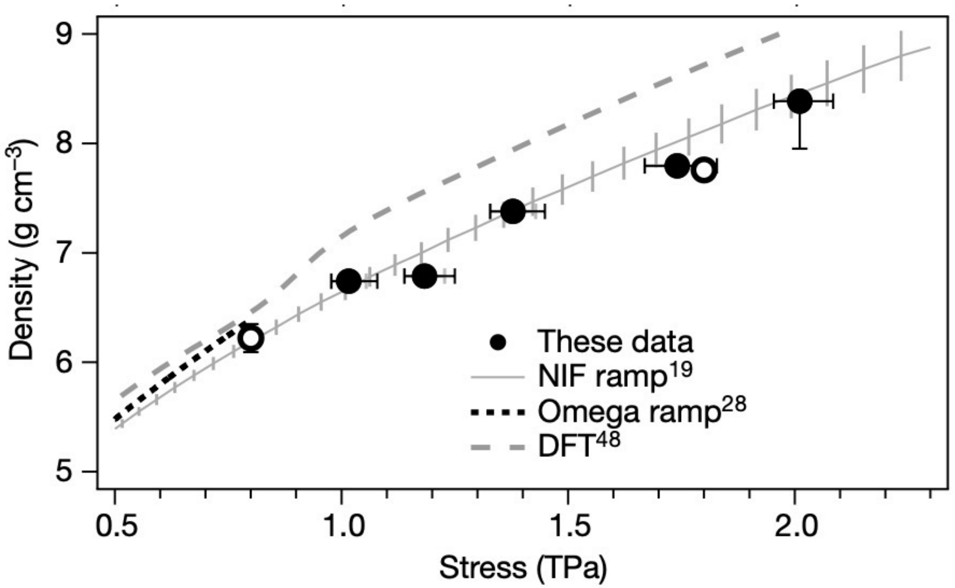
Obtenir des ultra - hautes pressions par laser

Obtenir des ultra - hautes pressions par laser



Obtenir des ultra - hautes pressions par laser





recherches récentes

1. créer de nouvelles matières avec la pression
2. le record de pression
3. **créer des matières sous vide**
4. le vide est-il vide ?

nanoenergy advances

Article

Surface Charge: An Advantage for the Piezoelectric Properties of GaN Nanowires

Tanbir Kaur Sodhi [1,2], Pascal Chrétien [2], Quang Chieu Bui [1], Amaury Chevillard [1], Laurent Travers [1], Martina Morassi [1], Maria Tchernycheva [1], Frédéric Houzé [2] and Noelle Gogneau [1,*]

[1] Centre de Nanosciences et Nanotechnologies, Université Paris-Saclay, CNRS, UMR9001, Boulevard Thomas Gobert, 91120 Palaiseau, France; tanbirkaursodhi@gmail.com (T.K.S.); quang-chieu.bui@universite-paris-saclay.fr (Q.C.B.); amaury.chevillard@c2n.upsaclay.fr (A.C.); laurent.travers@c2n.upsaclay.fr (L.T.); martina.morassi@c2n.upsaclay.fr (M.M.); maria.tchernycheva@c2n.upsaclay.fr (M.T.)

[2] Laboratoire de Génie Electrique de Paris, CNRS, CentraleSupélec, Université Paris-Saclay, 3 & 11 Rue Joliot-Curie, 91192 Gif-sur-Yvette, France; pascal.chretien@geeps.centralesupelec.fr (P.C.); frederic.houze@geeps.centralesupelec.fr (F.H.)

* Correspondence: noelle.gogneau@c2n.upsaclay.fr

Abstract: The optimization of the new generation of piezoelectric nanogenerators based on 1D nanostructures requires a fundamental understanding of the different physical mechanisms at play, especially those that become predominant at the nanoscale regime. One such phenomenon is the surface charge effect (SCE), which is very pronounced in GaN NWs with sub-100 nm diameters. With an advanced nano-characterization tool derived from AFM, the influence of SCE on the piezo generation capacity of GaN NWs is investigated by modifying their immediate environment. As-grown GaN NWs are analysed and compared to their post-treated counterparts featuring an Al_2O_3 shell. We establish that the output voltages systematically decrease by the Al_2O_3 shell. This phenomenon is directly related to the decrease of the surface trap density in the presence of Al_2O_3 and the corresponding reduction of the surface Fermi level pinning. This leads to a stronger screening of the piezoelectric charges by the free carriers. These experimental results demonstrate and confirm that the piezo-conversion capacity of GaN NWs is favoured by the presence of the surface charges.

Keywords: GaN NWs; surface charge effects; piezoelectric conversion

check for updates

Citation: Sodhi, T.K.; Chrétien, P.; Bui, Q.C.; Chevillard, A.; Travers, L.; Morassi, M.; Tchernycheva, M.; Houzé, F.; Gogneau, N. Surface Charge: An Advantage for the Piezoelectric Properties of GaN Nanowires. *Nanoenergy Adv.* **2024**, *4*, 133–146. https://doi.org/10.3390/nanoenergyadv4020008

Academic Editor: Chris R. Bowen

Received: 31 July 2023
Revised: 5 March 2024
Accepted: 26 March 2024
Published: 2 April 2024

1. Introduction

The development of new ultracompact and highly efficient energy harvesting technologies is a key worldwide challenge, spurred by the constantly increasing use of portable smart objects both in our daily lives, as well as in high-tech applications. Among the available sources of renewable energies, mechanical deformations and vibrations originating from bodily or vehicular movements, acoustic waves, displacing fluids or friction present the advantage of being ubiquitous, available at all times and highly suitable for multiscale integration. These can be converted into an electrical output via piezoelectric systems.

In this context, nano-generators integrating piezoelectric nanowires (NWs) represent a very promising alternative compared to conventional piezo-generators based on 2D or bulk materials. In fact, thanks to their large aspect ratio and quasi-perfect crystalline quality, NWs are characterised by superior mechanical and piezoelectric properties [1–3]. In addition, NWs characterised by sub-100 nm diameters exhibit nanometre-scale phenomena, opening up new possibilities for the modulation of their properties.

The first demonstration of direct piezoelectric conversion from 1D nanostructures was evidenced with ZnO NWs [4]. Following the establishment of this new concept, other piezoelectric nanostructures have demonstrated their ability to convert a mechanical input into an electrical signal, such as PZT [5], CdS [6], CdSe [7], $BaTiO_3$ [8], $KNBO_3$ [9], GaAs [10],

Nanoenergy Adv. **2024**, *4*, 133–146. https://doi.org/10.3390/nanoenergyadv4020008 https://www.mdpi.com/journal/nanoenergyadv

Sodhi et al., nanoenergy Avd. 4, 133 (2024)

Saclay

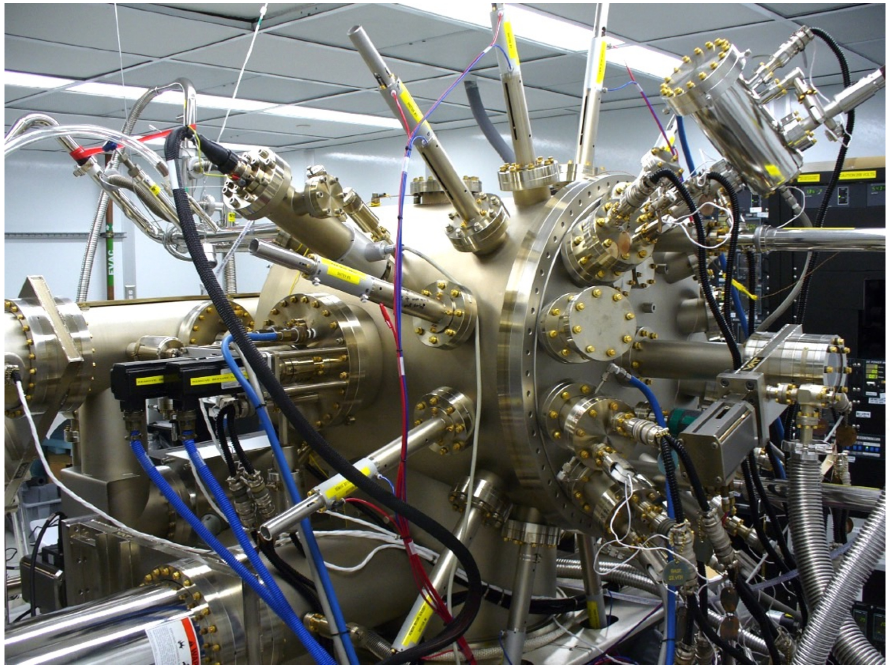
2024

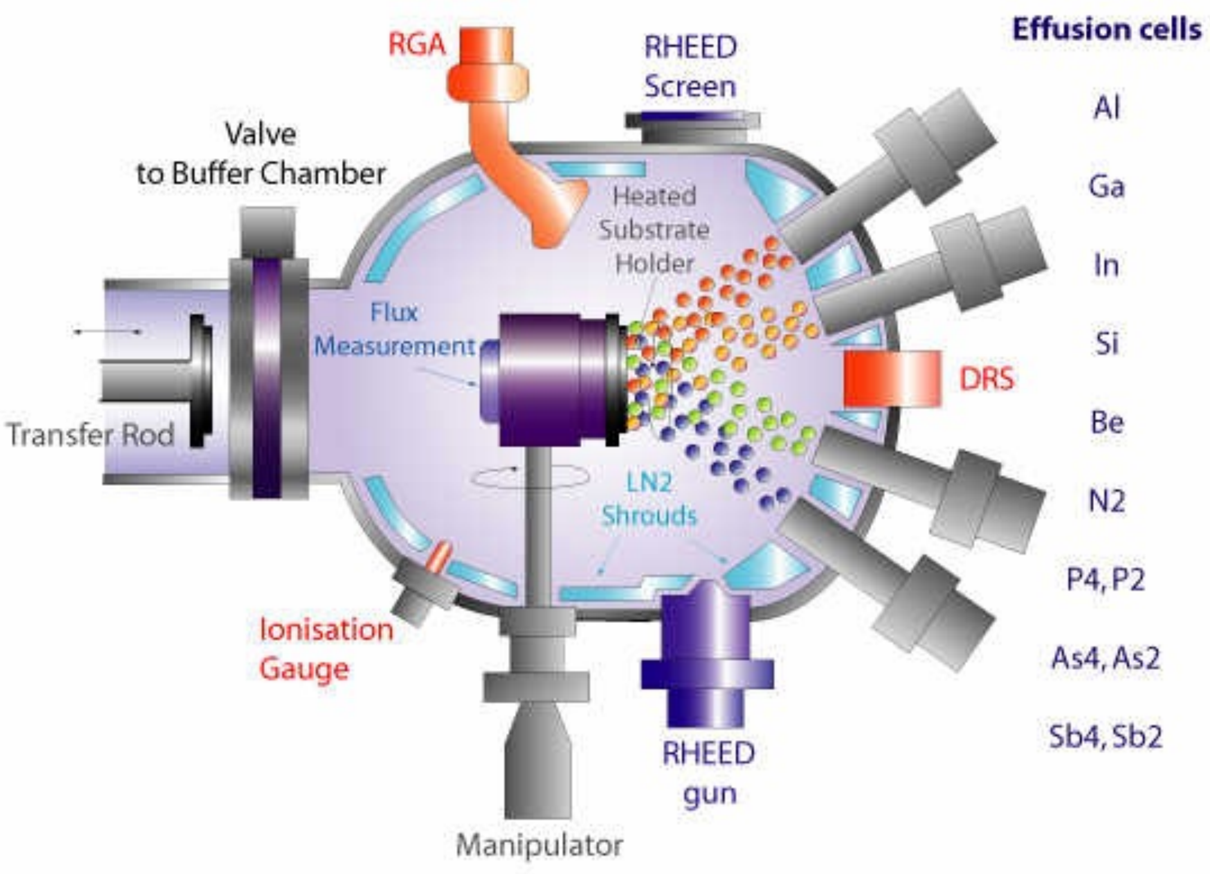
fabrication et mesure de nanofils pour convertir le mouvement en énergie

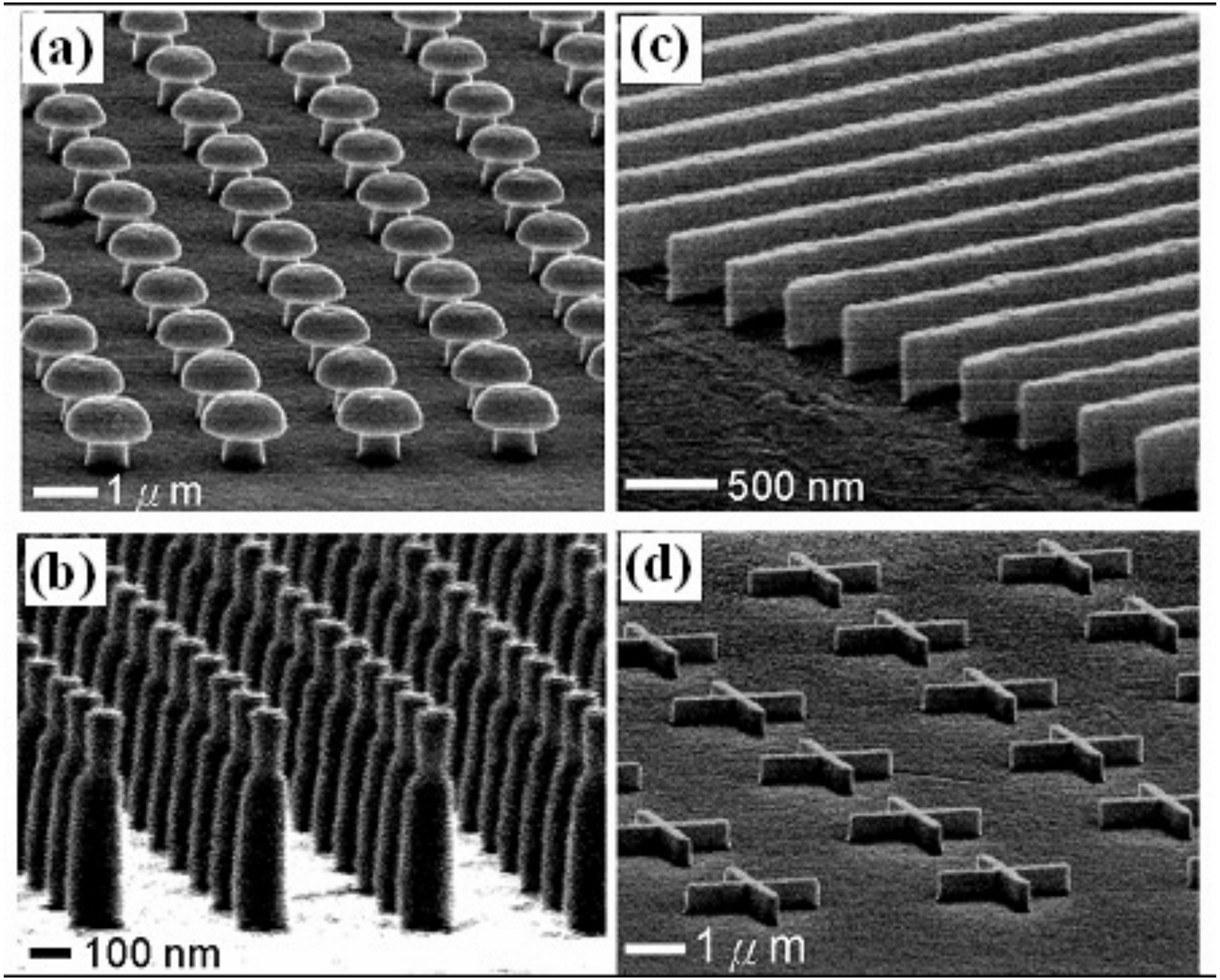
fabriquer des surfaces par épitaxie

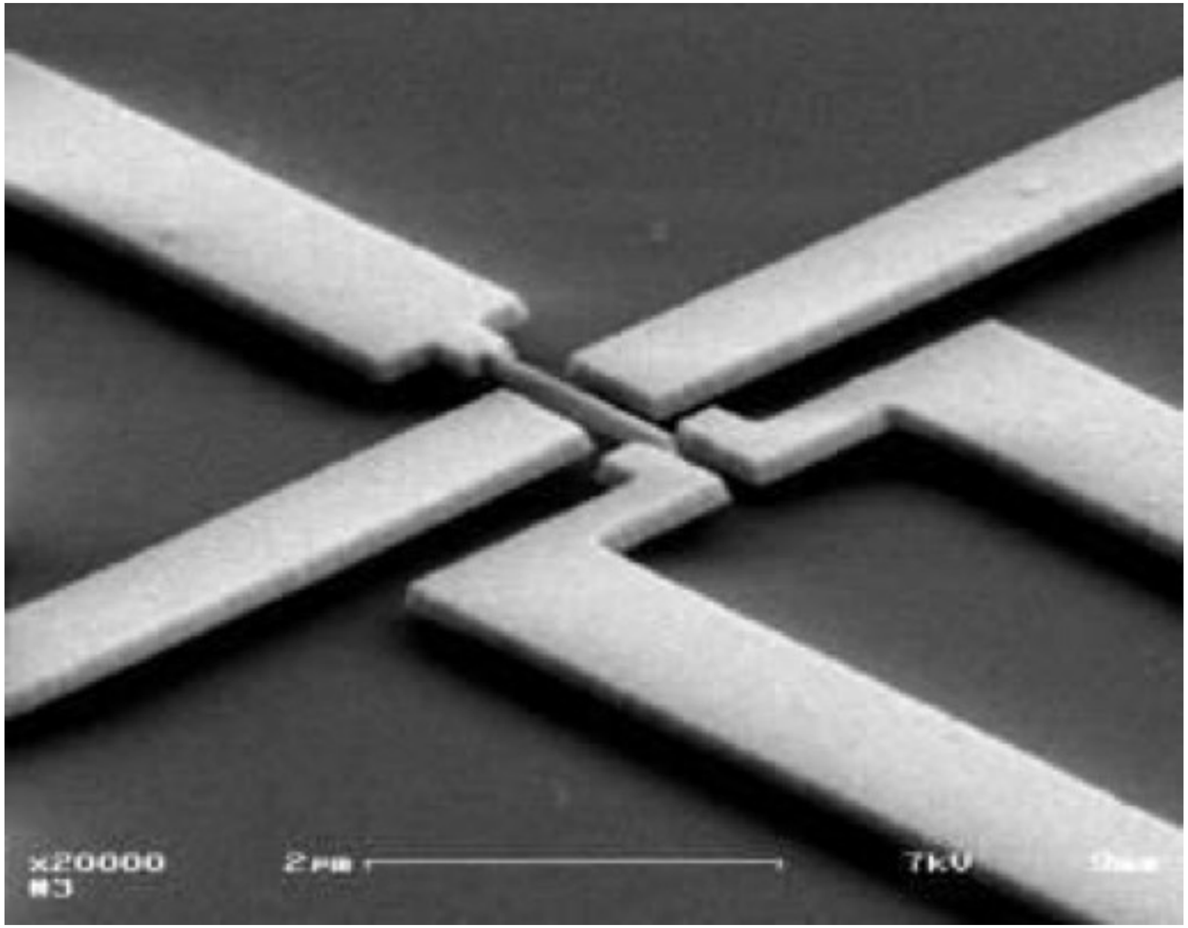
fabriquer des surfaces par épitaxie

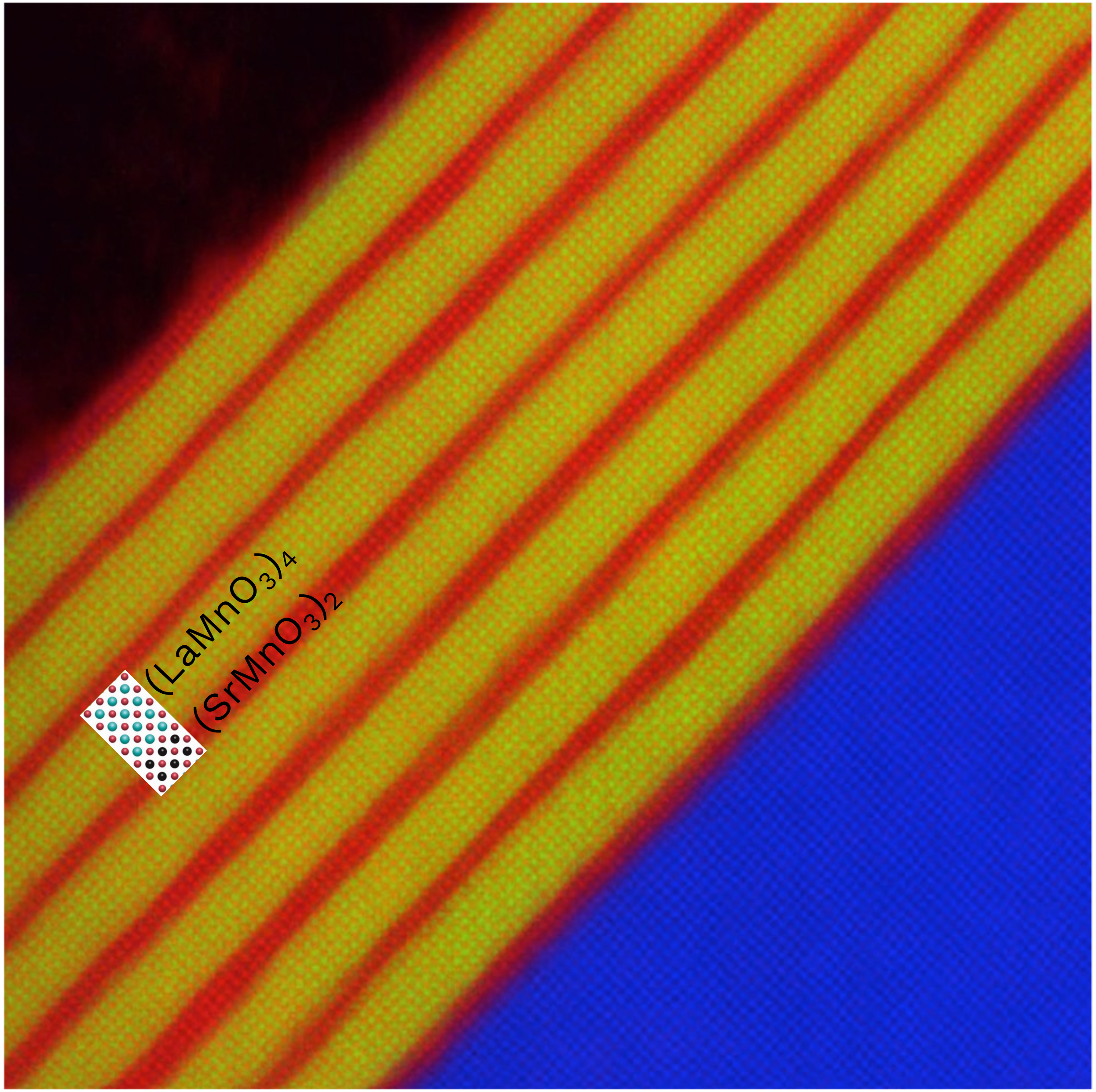
Epitaxie par jets moléculaires






(a)
1 μm
(c)
500 nm
(b)
100 nm
(d)
1 μm

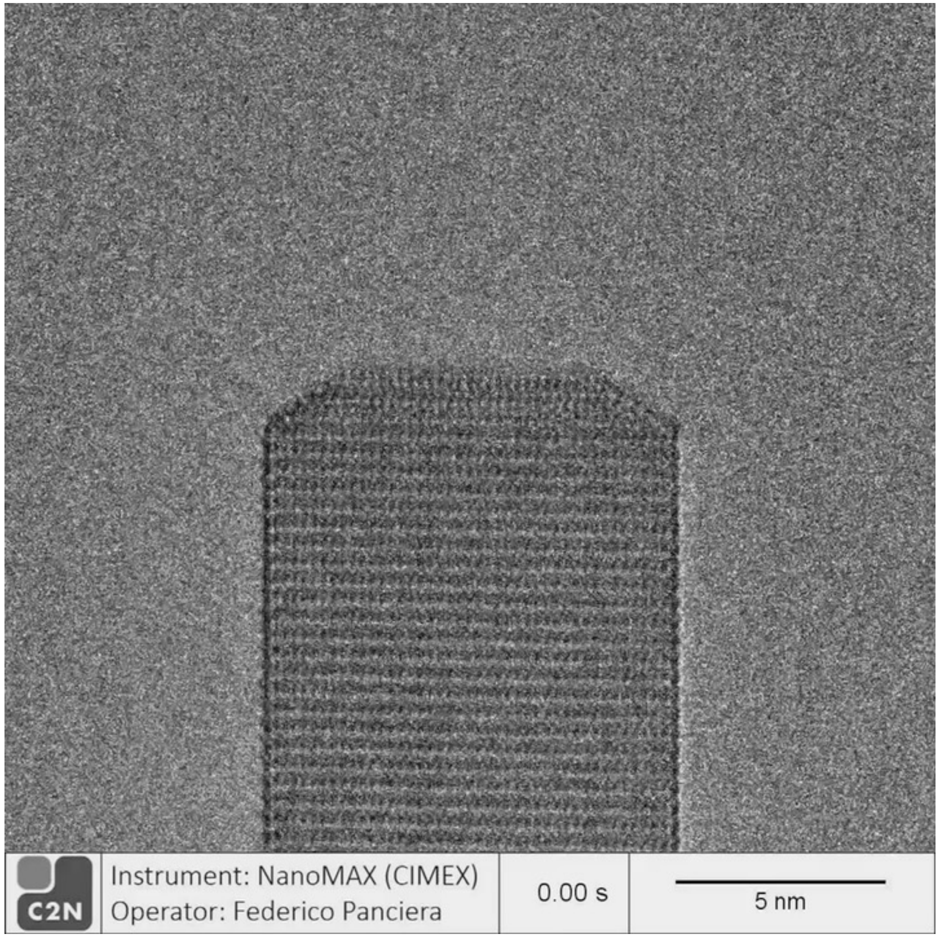

x20000
#3
2 μm
7kV



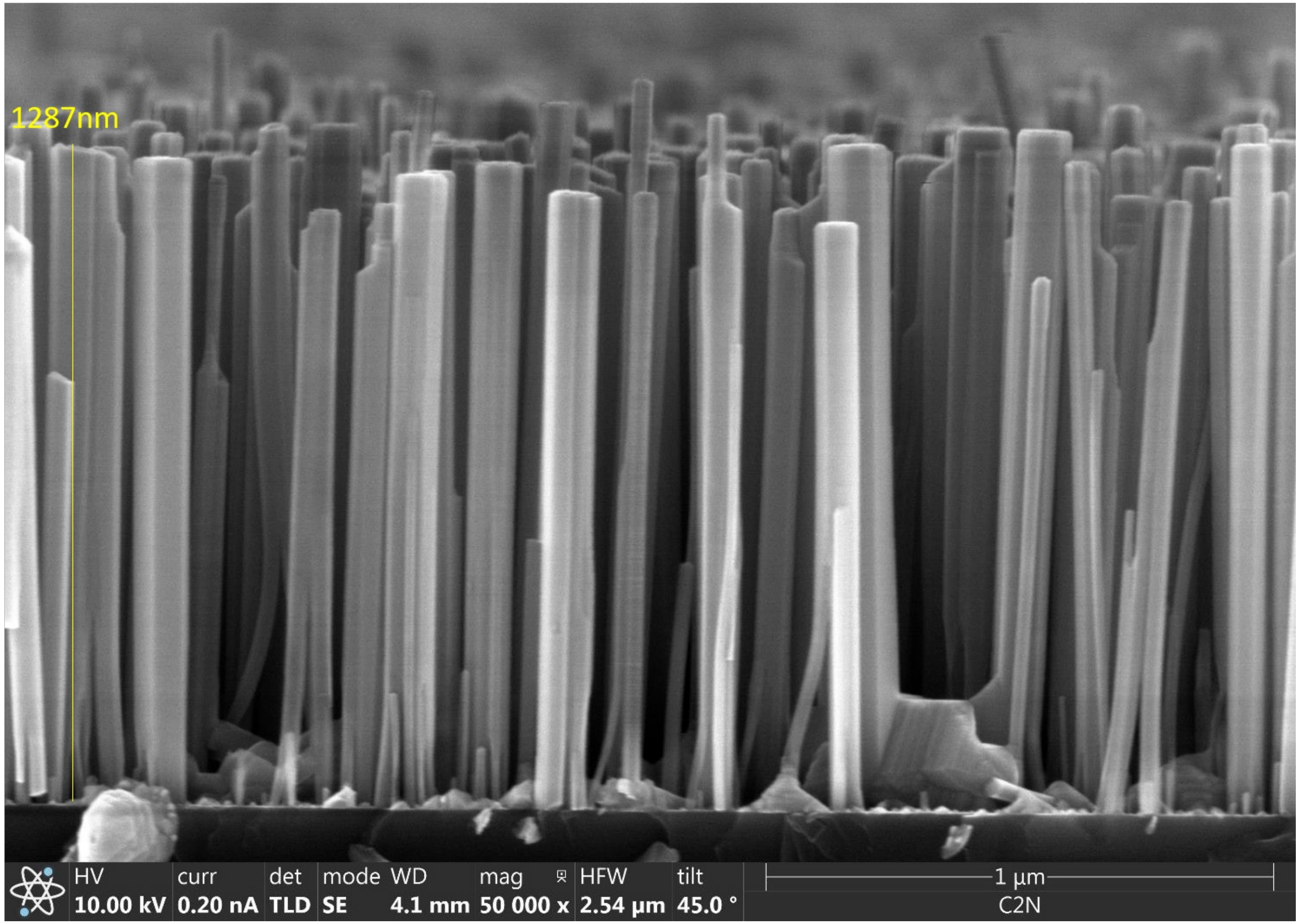
@D. Muller, Cornell

fabriquer des surfaces par épitaxie

croissance d’un nanofil
de GaN

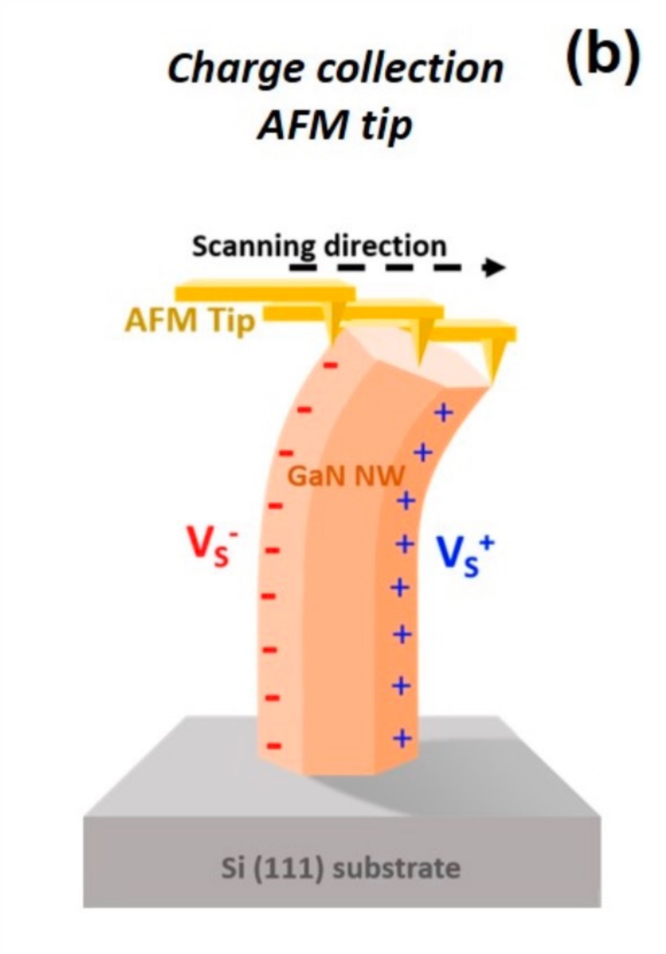


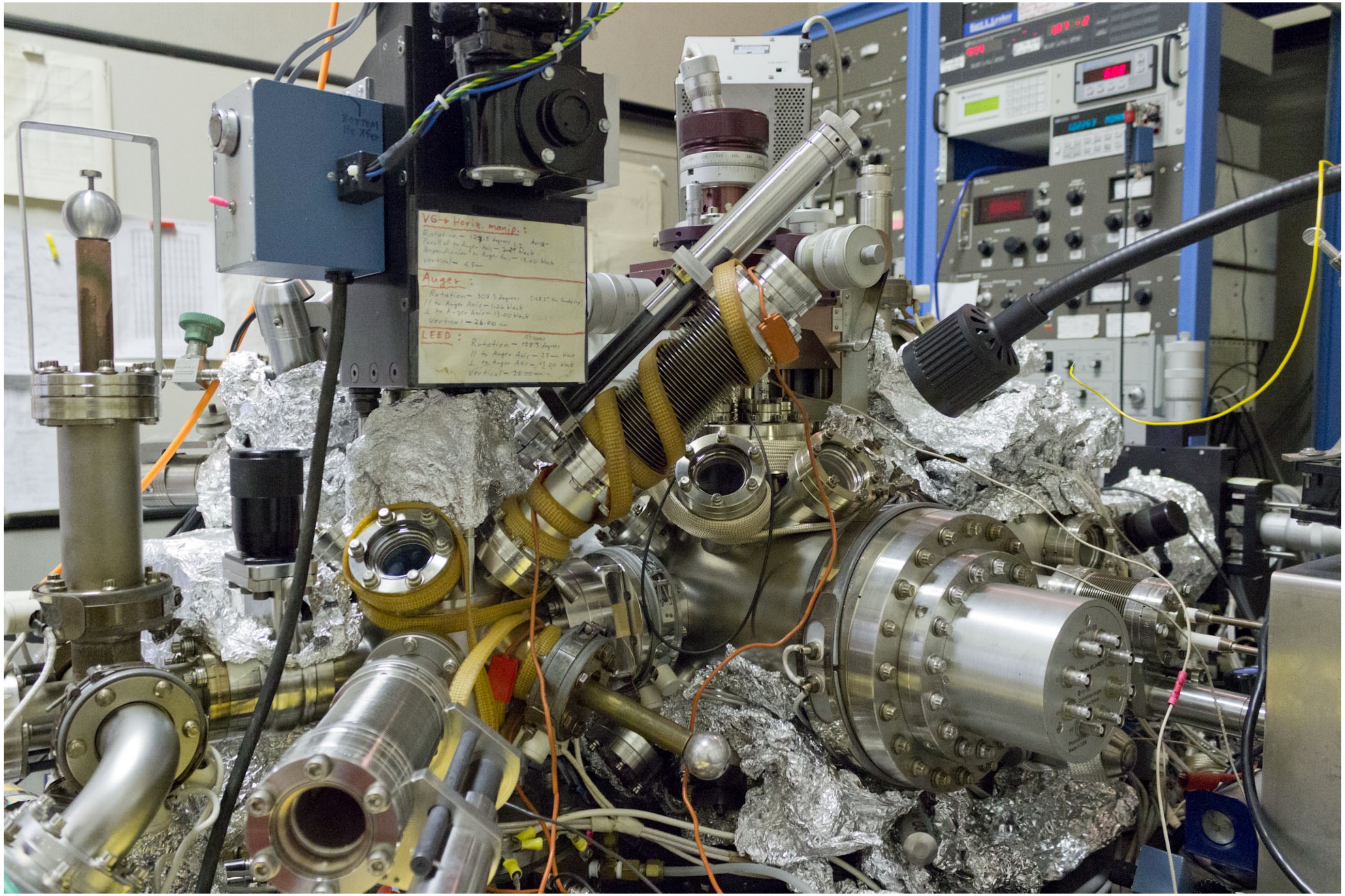
fabriquer des surfaces par épitaxie



fabriquer des surfaces par épitaxie

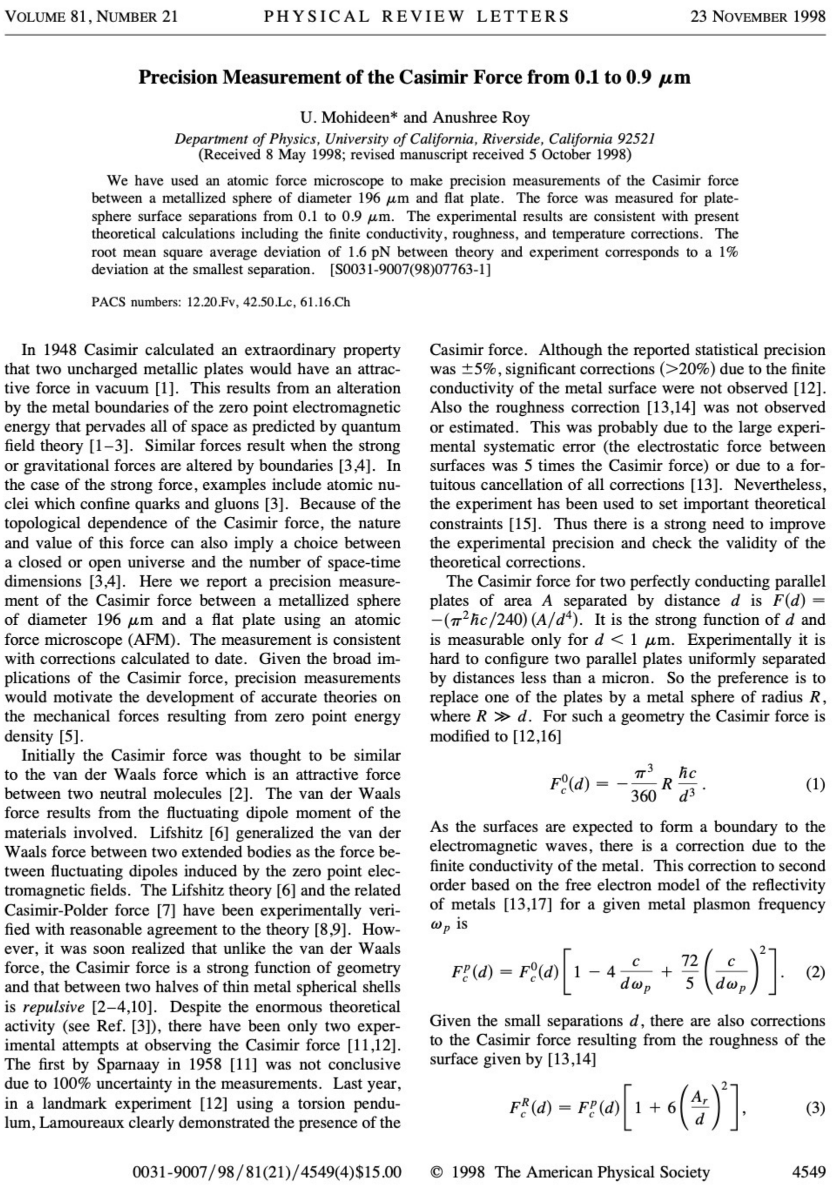
quand on déforme les nanofils de GaN, il apparaît une tension électrique : c’est l’effet piezo-électrique qui permet de convertir le mouvement en électricité.




BOTTOM He Xfer
VG → Horiz. manip.:
Rotation – 128.5 degrees
Parallel to Auger Axis – 1.2 black
Perpendicular to Auger Axis – 13.00 black
Vertical – <5mm
Auger:
Rotation – 309.5 degrees
// to Auger Axis – 1.26 black
⊥ to Auger Axis – 13.00 black
Vertical – 26.00 mm
LEED:
Rotation – 128.5 degrees
// to Auger Axis – 25 mm black
⊥ to Auger Axis – 13.00 black
Vertical – 26.00 mm

recherches récentes

1. créer de nouvelles matières avec la pression
2. le record de pression
3. créer des matières sous vide
4. **le vide est-il vide ?**



VOLUME 81, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1998

Precision Measurement of the Casimir Force from 0.1 to 0.9 μm

U. Mohideen* and Anushree Roy
Department of Physics, University of California, Riverside, California 92521
(Received 8 May 1998; revised manuscript received 5 October 1998)

We have used an atomic force microscope to make precision measurements of the Casimir force between a metallized sphere of diameter 196 μm and flat plate. The force was measured for plate-sphere surface separations from 0.1 to 0.9 μm. The experimental results are consistent with present theoretical calculations including the finite conductivity, roughness, and temperature corrections. The root mean square average deviation of 1.6 pN between theory and experiment corresponds to a 1% deviation at the smallest separation. [S0031-9007(98)07763-1]

PACS numbers: 12.20.Fv, 42.50.Lc, 61.16.Ch

In 1948 Casimir calculated an extraordinary property that two uncharged metallic plates would have an attractive force in vacuum [1]. This results from an alteration by the metal boundaries of the zero point electromagnetic energy that pervades all of space as predicted by quantum field theory [1–3]. Similar forces result when the strong or gravitational forces are altered by boundaries [3,4]. In the case of the strong force, examples include atomic nuclei which confine quarks and gluons [3]. Because of the topological dependence of the Casimir force, the nature and value of this force can also imply a choice between a closed or open universe and the number of space-time dimensions [3,4]. Here we report a precision measurement of the Casimir force between a metallized sphere of diameter 196 μm and a flat plate using an atomic force microscope (AFM). The measurement is consistent with corrections calculated to date. Given the broad implications of the Casimir force, precision measurements would motivate the development of accurate theories on the mechanical forces resulting from zero point energy density [5].

Initially the Casimir force was thought to be similar to the van der Waals force which is an attractive force between two neutral molecules [2]. The van der Waals force results from the fluctuating dipole moment of the materials involved. Lifshitz [6] generalized the van der Waals force between two extended bodies as the force between fluctuating dipoles induced by the zero point electromagnetic fields. The Lifshitz theory [6] and the related Casimir-Polder force [7] have been experimentally verified with reasonable agreement to the theory [8,9]. However, it was soon realized that unlike the van der Waals force, the Casimir force is a strong function of geometry and that between two halves of thin metal spherical shells is *repulsive* [2–4,10]. Despite the enormous theoretical activity (see Ref. [3]), there have been only two experimental attempts at observing the Casimir force [11,12]. The first by Sparnaay in 1958 [11] was not conclusive due to 100% uncertainty in the measurements. Last year, in a landmark experiment [12] using a torsion pendulum, Lamoureaux clearly demonstrated the presence of the Casimir force. Although the reported statistical precision was ±5%, significant corrections (>20%) due to the finite conductivity of the metal surface were not observed [12]. Also the roughness correction [13,14] was not observed or estimated. This was probably due to the large experimental systematic error (the electrostatic force between surfaces was 5 times the Casimir force) or due to a fortuitous cancellation of all corrections [13]. Nevertheless, the experiment has been used to set important theoretical constraints [15]. Thus there is a strong need to improve the experimental precision and check the validity of the theoretical corrections.

The Casimir force for two perfectly conducting parallel plates of area A separated by distance d is $F(d) = -(\pi^2 \hbar c/240)(A/d^4)$. It is the strong function of d and is measurable only for $d < 1$ μm. Experimentally it is hard to configure two parallel plates uniformly separated by distances less than a micron. So the preference is to replace one of the plates by a metal sphere of radius R, where $R \gg d$. For such a geometry the Casimir force is modified to [12,16]

$$F_c^0(d) = -\frac{\pi^3}{360} R \frac{\hbar c}{d^3}. \qquad (1)$$

As the surfaces are expected to form a boundary to the electromagnetic waves, there is a correction due to the finite conductivity of the metal. This correction to second order based on the free electron model of the reflectivity of metals [13,17] for a given metal plasmon frequency ω_p is

$$F_c^p(d) = F_c^0(d)\left[1 - 4\frac{c}{d\omega_p} + \frac{72}{5}\left(\frac{c}{d\omega_p}\right)^2\right]. \qquad (2)$$

Given the small separations d, there are also corrections to the Casimir force resulting from the roughness of the surface given by [13,14]

$$F_c^R(d) = F_c^p(d)\left[1 + 6\left(\frac{A_r}{d}\right)^2\right], \qquad (3)$$

Mohideen et Roy, PRL 4549, 82 (1998)

Riverside, USA

1998

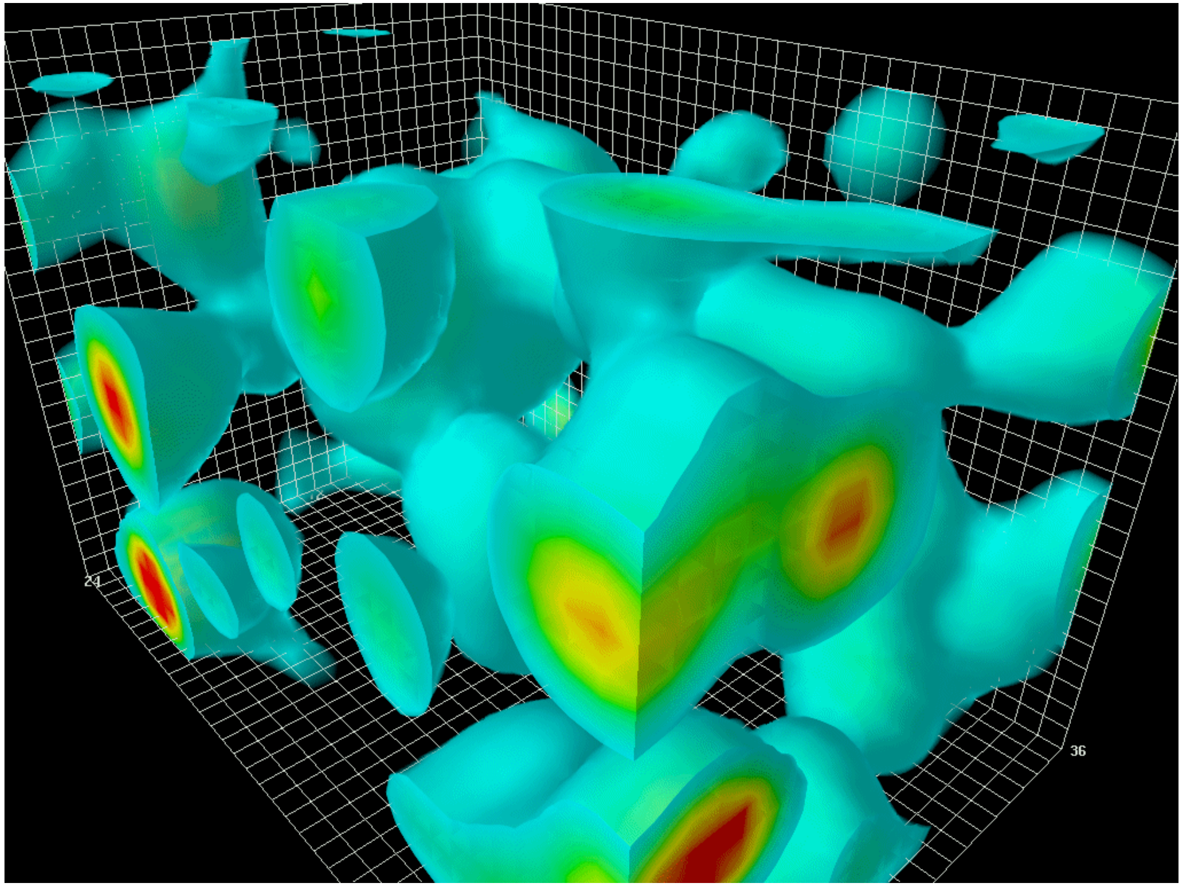
démonstration de l'existence d'une force de Casimir dans le vide

les fluctuations quantiques du vide

il est impossible de mesurer certaines quantités simultanément très précisément, par exemple l’énergie et le temps.

Donc dans une région vide, pendant un intervalle de temps très court, il peut apparaître des énergies même si il n’y a rien !

les fluctuations quantiques du vide

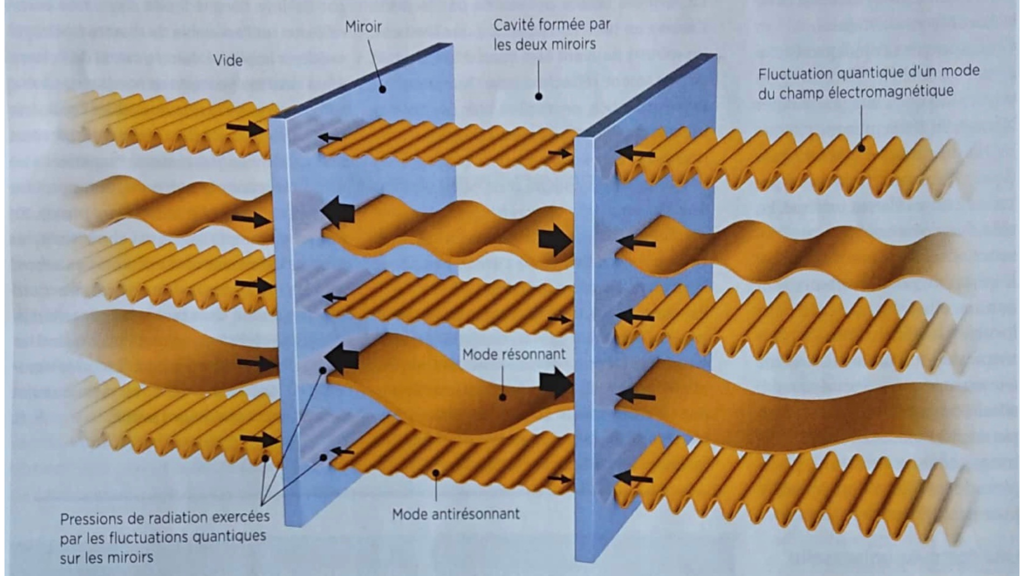


gluon-field configurations averaged over in describing the vacuum properties of QCD.

@Derek Leinweber

les fluctuations quantiques du vide

Fig. 1 Une force attractive dans le vide



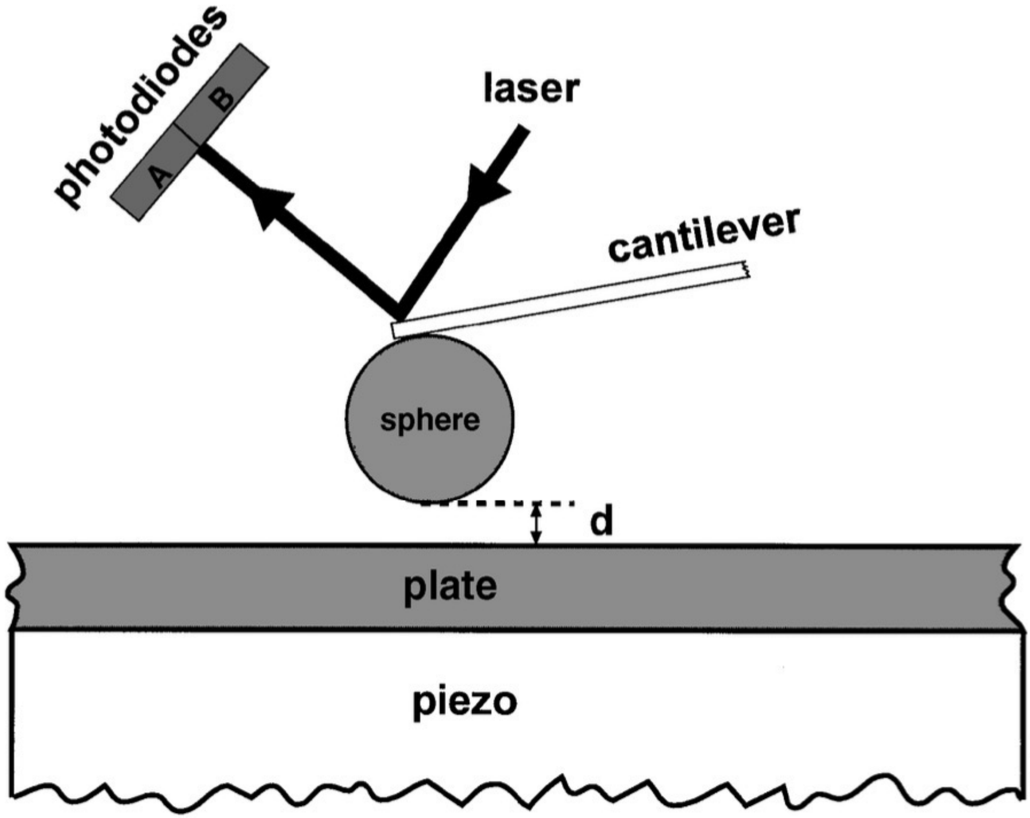
▲ Même en l'absence de matière, le champ électromagnétique fluctue (ondulations). Les fluctuations quantiques du vide sont modifiées entre les deux miroirs. Certaines sont augmentées (modes résonnants), d'autres diminuées (modes antirésonnants) par rapport aux fluctuations à l'extérieur de la cavité. Au total, les pressions exercées de l'extérieur l'emportent : les deux miroirs sont poussés l'un vers l'autre.

prédiction : ces fluctuations font apparaître une force entre deux plaques métalliques, la force de Casimir.

$$F(a)/A = \frac{\pi^2}{240}\frac{\hbar c}{a^4} = 0.016\,\frac{1}{a^4}\,\mathrm{dyn}\,(\mu m)^4/\mathrm{cm}^2,$$

les fluctuations quantiques du vide

la mesure expérimentale



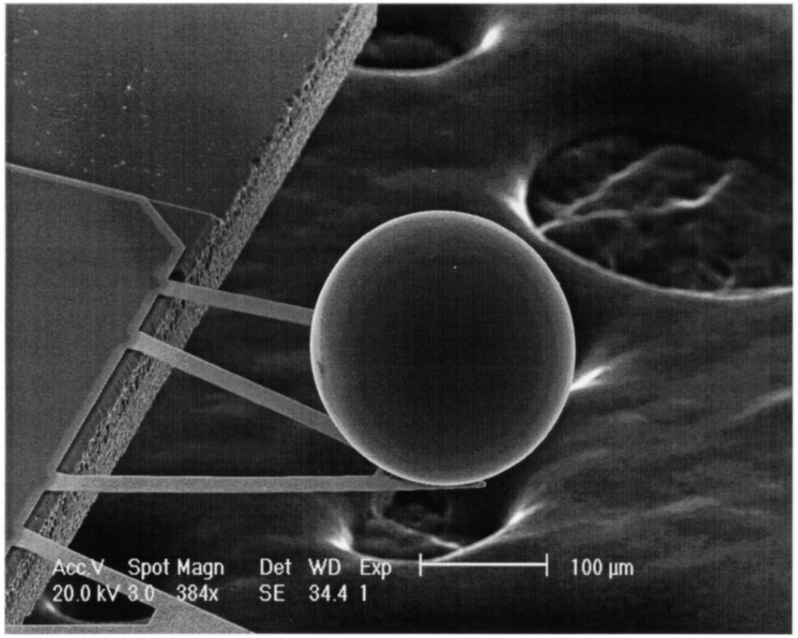
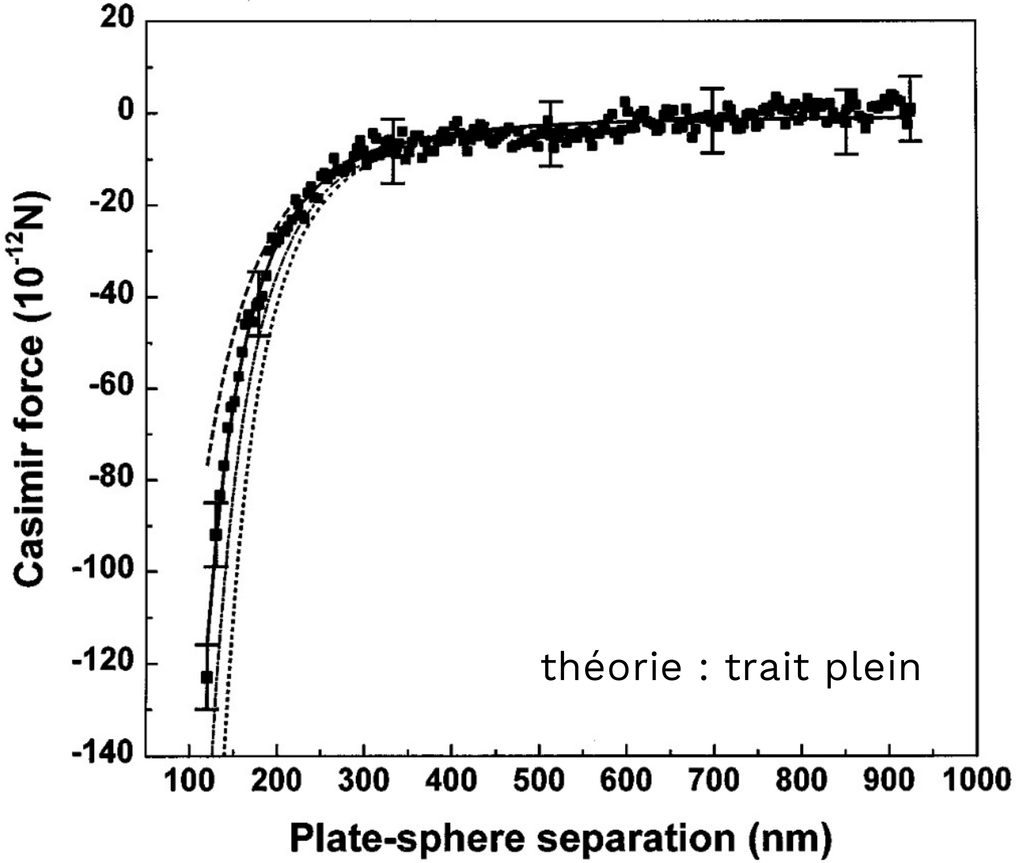


FIG. 2. Scanning electron microscope image of the metallized sphere mounted on a AFM cantilever.

les fluctuations quantiques du vide

la mesure expérimentale



théorie : trait plein

Il y a bien une force de Casimir en 1/r^4

La pression

Qu'avez-vous retenu ?

La pression

Cachez vos notes, et tentez d'écrire en quelques mots…

1 ou 2 ordres de grandeur

un truc que vous avez retenu sur la physique associée

un résultat de recherche récente