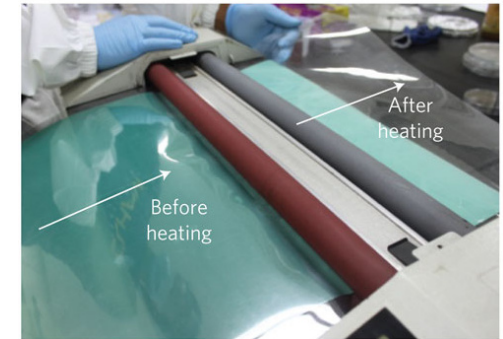




Du rouleau de scotch au rouleau de graphène



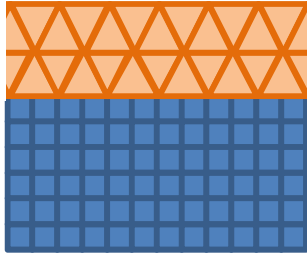
Histoire (courte) et développement de méthodes d'élaboration de graphène

Adrien Michon

Centre de recherche sur l'hétéroépitaxie et ses applications

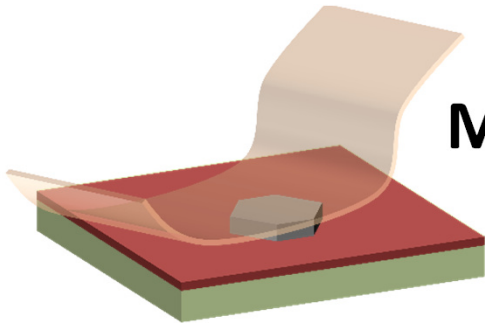
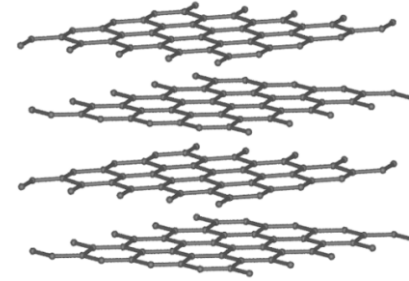
CRHEA - UPR 10 - CNRS

1^{ère} Journée de la physique niçoise



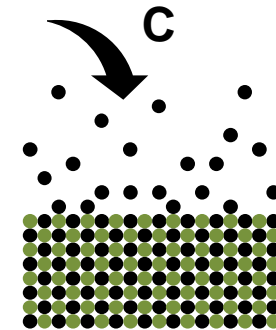
Présentation du CRHEA

Du graphite au graphène

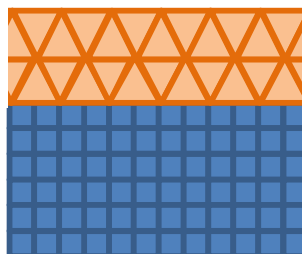


Méthodes de fabrication du graphène

Etude du graphène au CRHEA

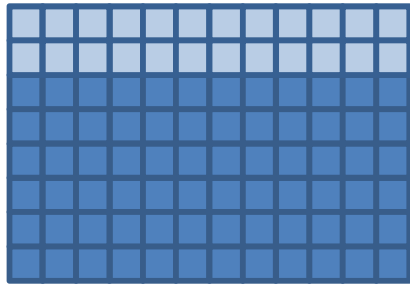


Le Centre de Recherche sur l'Hétéroépitaxie et ses applications (CRHEA)

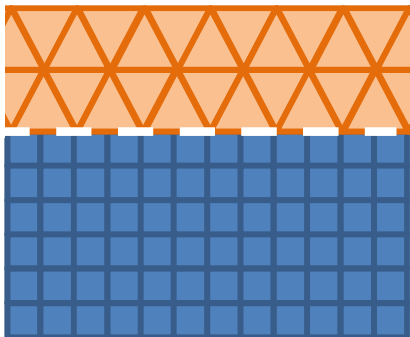


Épitaxie : croissance cristalline de couches minces

Dépôt organisé
(même réseau cristallin)



Substrat
monocristallin



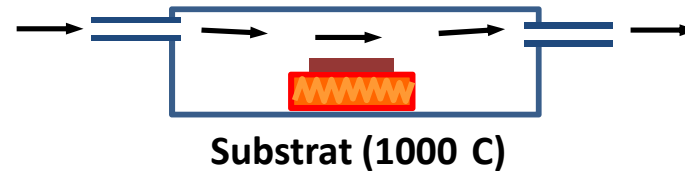
Hétéroépitaxie :
matériaux \neq

Moins d'un atome étranger
pour 10^7 atomes déposés

Épaisseurs : d'une couche atomique
($< \text{nm}$) à quelques μm

Épitaxie par jet moléculaire (en ultraviolette)
ou bien épitaxie en phase vapeur

Gaz vecteur : H_2
Précurseurs :
 SiH_4 (qq 0.1%)



Semiconducteur + épitaxie \Leftrightarrow contrôle des propriétés

Moyens et activités du CRHEA

Epitaxie par jets moléculaires (7) :

- Nitrures (AlN, GaN, InN)
- Nitrures dilués (InGaAsN)
- ZnO, MgO

Epitaxie en phase vapeur (5) :

- Nitrures (AlN, GaN, InN)
- SiC
- Graphène

Moyens de caractérisations :

- **structurales** (microscopie à force atomique, à effet tunnel, électronique à balayage, en transmission, diffraction électronique, de rayons X, photoémission X)
- **optique** (photo-, electro-, cathodoluminescence)
- **électrique** (courant-tension-capacité, effet Hall)

Salle blanche

(micro/nano fabrication de dispositifs)

Electronique :

- Electronique de puissance
- Transport tunnel
- Croissance de graphène

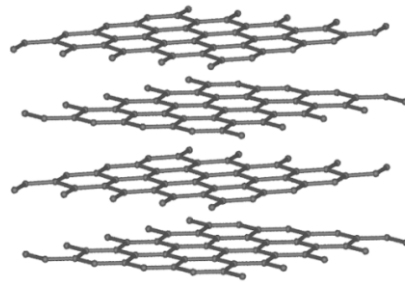
Optoélectronique :

- Diodes blanches
- Laser vert
- Détecteur UV
- Croissance non polaire

Nanosciences / nanotechnologies :

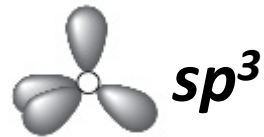
- Photonique
- Croissance de nanofils
- ...

Du graphite au graphène



Hybridation du carbone

Différentes hybridation:



(Ex : méthane)

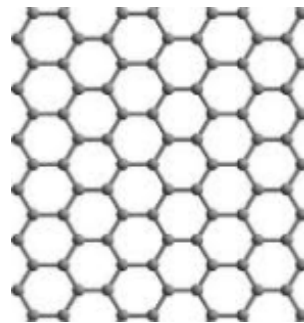


(Ex : éthylène)

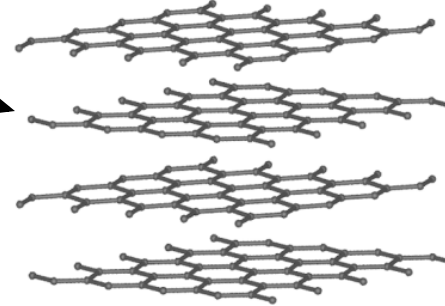


(Ex : acétylène)

Graphène



sp^2

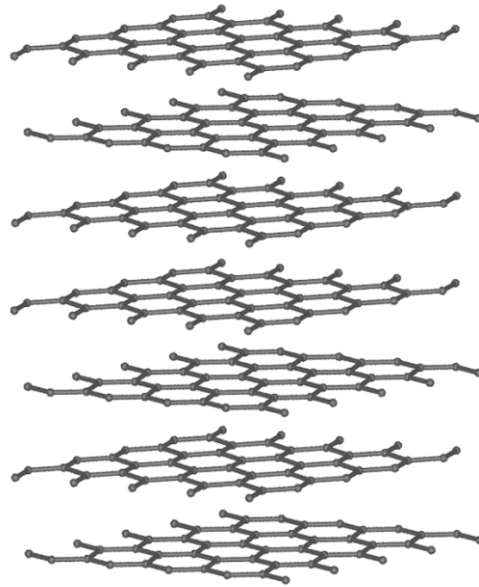


Graphite

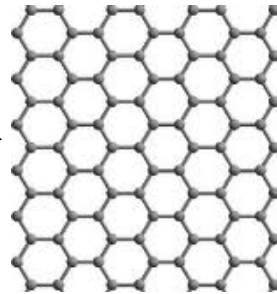
Dans le plan : liaisons covalentes

Inter plans : force de van der Waals

Un objet théorique aux propriétés exceptionnelles...



1947 : calcul de la structure de bande d'un plan de graphite



Philip R. Wallace

Graphène : cristal bidimensionnel de carbone sp^2

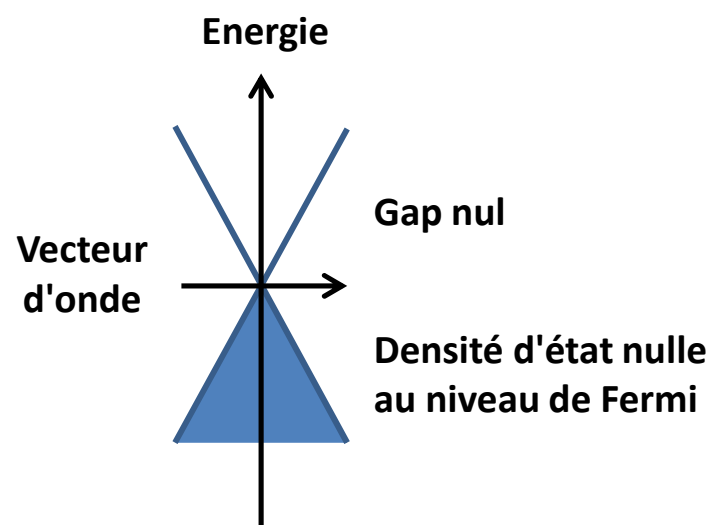
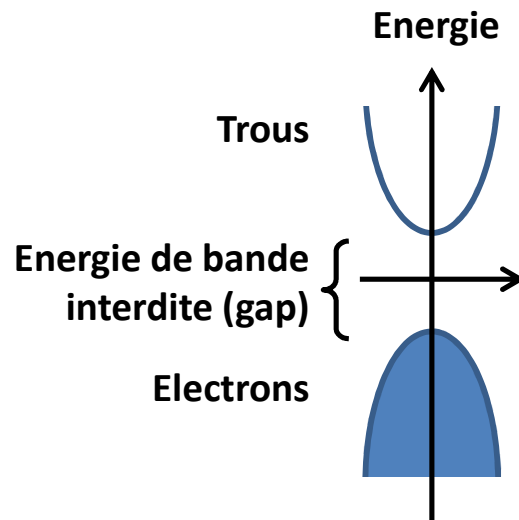
Fortes mobilités électroniques

Résistance mécanique mais flexible

Forte conductivité thermique

Forte absorption optique
($a = \pi\alpha$, 30 MC = 10 nm \Rightarrow a = 50%)

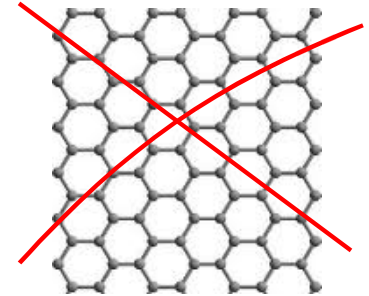
Semiconducteur :
équation de Schrödinger



Graphène :
équation de Dirac

...mais instable

This result excludes conventional crystalline long-range order in two dimensions



La forme strictement bidimensionnel du graphène ne peut pas exister....

... mais d'autres formes de carbone sp^2 sont possibles...

PHYSICAL REVIEW

VOLUME 176, NUMBER 1

5 DECEMBER 1968

Crystalline Order in Two Dimensions*

N. D. Mermin[†]

Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York

(Received 1 July 1968)

If N classical particles in two dimensions interacting through a pair potential $\Phi(\vec{r})$ are in equilibrium in a parallelogram box, it is proved that every $\vec{k} \neq 0$ Fourier component of the density must vanish in the thermodynamic limit, provided that $\Phi(\vec{r}) - \lambda r^2 |\nabla^2 \Phi(\vec{r})|$ is integrable at $r = \infty$ and positive and nonintegrable at $r = 0$, both for $\lambda = 0$ and for some positive λ .

This result excludes conventional crystalline long-range order in two dimensions for power-law potentials of the Lennard-Jones type, but is inconclusive for hard-core potentials. The corresponding analysis for the quantum case is outlined. Similar results hold in one dimension.

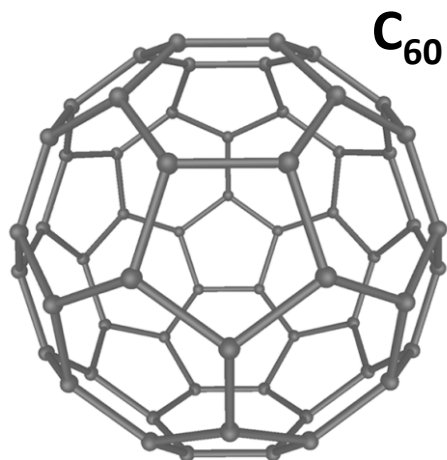
Over thirty years ago Peierls¹ and Landau² concluded that there can be no one- or two-dimensional crystalline long-range order. Computer experiments, however, have since indicated a transition to a two-dimensional crystalline ordered state,³ casting some doubt on the validity of these results in two dimensions. The arguments are not unassailable. Peierls gave a qualitative argument for the general one-dimensional case, and a quantitative argument (only in one dimension, but the extension to two is obvious) based on the harmonic approximation. Landau, on the other hand, used his general theory of second-order phase transitions, which is known to be misleading near the critical point.

Within the past two years a series of exact arguments have appeared, extending Hohenberg's⁴ use

ities to other applications of Bogoliubov's inequality. To keep algebraic complications to a minimum we consider in detail only classical crystals. The generalization to the quantum case is briefly described in the Appendix.

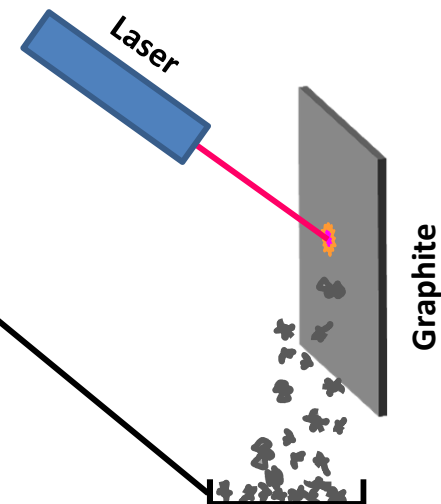
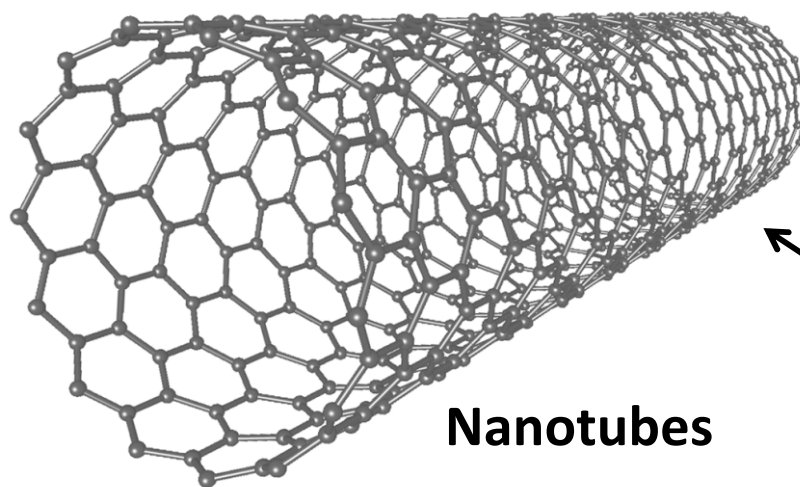
Consider, then, classical particles interacting through a pair potential $\Phi(\vec{r})$. The form of the argument depends on whether one uses periodic or impenetrable wall boundary conditions. Impenetrable wall conditions will be used here for two reasons: existence theorems for the free energy will be required which have only been proved in the impenetrable wall case; furthermore enclosing the system within fixed walls provides a convenient mechanism for localizing and orienting the supposed crystal, which must be supplied by suitable fictitious forces in the periodic case.⁷ Thus

Fullerènes et nanotubes

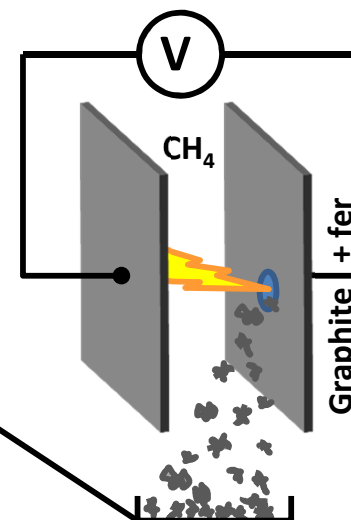


- 1985 : observation de C_{60}
(H. Kroto, R. Curl, R. Smalley)

- 1991 : Observation de
nanotubes, S. Iijima

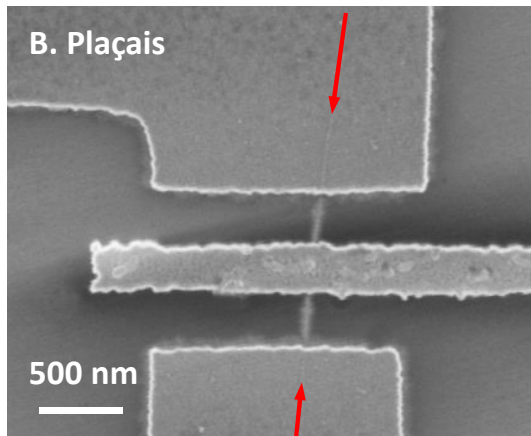


Amélioration ▼



Fabrication et applications

Cristal 1 D



Nanotube, $\varnothing = 2 \text{ nm}$

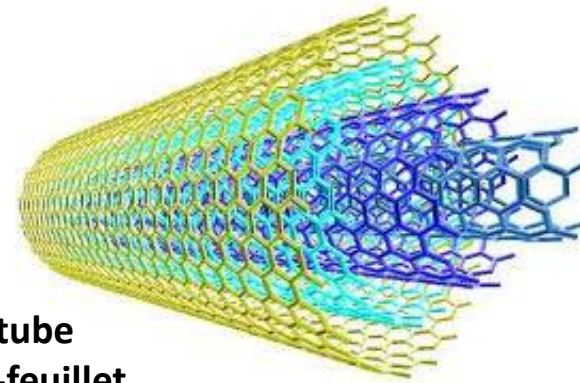
Contact :

Grille \Rightarrow transistor

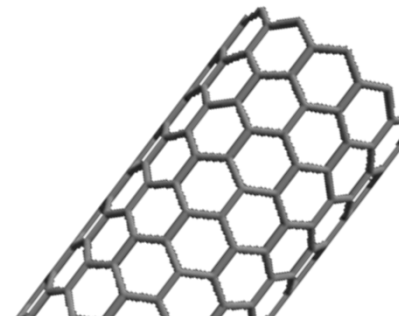
Fonctionnalisation \Rightarrow détecteur

Champ magnétique \Rightarrow transport

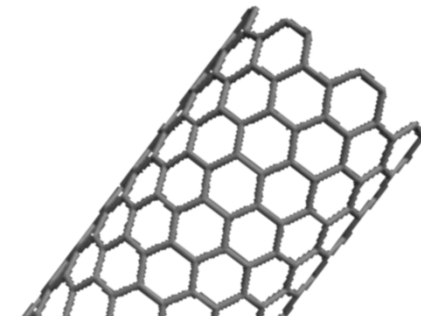
Mais technologie lourde...



**Nanotube
multi-feuillet**



**Zig-zag
(semiconducteur)**



**Armchair/chaise
(métallique)**

**... et propriétés des nanotubes
difficile à contrôler**

1975 : un travail (un peu) passé inaperçu

2000 : ébullition autour du graphène

Intérêt des nanotubes,
mais difficultés de process...

Graphène potentiellement plus
attrayant, mais supposé instable...

Surface Sci
© North-Hol

...distinguishable from a bulk graphite single crystal regarding its structural and electronic properties. In addition, we have shown that it is possible to isolate a single graphene plane covering most of the substrate. A number of potential experiments, in particular, angle-resolved studies, could clearly

LEED AND AUGER ELECTRON OBSERVATIONS OF THE SiC (0001) SURFACE

A.J. VAN BOMMEL, J.E. CROMBEEN and A. VAN TOOREN
Philips Research Laboratories, Eindhoven, The Netherlands

JOURNAL OF APPLIED PHYSICS

Solid-state decomposition of silicon carbide for growing ultra-thin heteroepitaxial graphite films

A. Charrier
GPEC, UMR CNRS 6631, Faculté des Sciences de Luminy, Université de la Méditerranée, F-13288, Marseille Cedex 9, France

A. Coati
INFN, Dipartimento di Fisica, Università di Padova, via Marzolo 8, 33100 Padova, Italy

T. Argunova
Joffe Physico-Technical Institute of the Russian Academy of Sciences, Polytekhnicheskaya Street 26, 194021 Saint Petersburg, Russia

F. Thibaudau
GPEC, UMR CNRS 6631, Faculté des Sciences de Luminy, Université de la Méditerranée, F-13288, Marseille Cedex 9, France

Y. Garreau and R. Pinchaux
LURE, CNRS-MENRS-CEA, Bâtiment 209D, Centre Universitaire Paris-Sud, BP34, F-91898 Orsay Cedex, France

I. Forbeaux and J.-M. Debever
GPEC, UMR CNRS 6631, Faculté des Sciences de Luminy, Université de la Méditerranée, F-13288, Marseille Cedex 9, France

M. Sauvage-Simkin
GPEC, UMR CNRS 6631, Faculté des Sciences de Luminy, Université de la Méditerranée, F-13288, Marseille Cedex 9, France

PHYSICAL REVIEW B

VOLUME 58, NUMBER 24

15 DECEMBER 1998

Heteroepitaxial graphite on 6H-SiC(0001): Interface formation through conduction-band electronic structure

I. Forbeaux, J.-M. Themlin,* and J.-M. Debever

Groupe de Physique des Etats Condensés, UMR CNRS 6631, Case 901, Faculté des Sciences de Luminy, F-13288 Marseille Cedex 9, France
(Received 10 August 1998)

...annealed at elevated temperatures under vacuum, silicon carbide surfaces show a tendency towards reconstruction. Using the sensitivity of empty conduction-band states dispersion towards the structural quality of the surface, we have used angular-resolved inverse photoemission spectroscopy (KRIPES) to monitor the formation of crystalline graphite on 6H-SiC(0001) surfaces. The KRIPES spectra obtained after annealing at 1400 °C are characteristic of azimuthally oriented, graphite multilayers of very good single-layer quality. For lower annealing temperatures, the ordered interface already presents most of the features of graphite as soon as 1080 °C. The observation of unshifted π^* states, which reveals a very weak interaction with the substrate, is consistent with the growth of a van der Waals heteroepitaxial graphite lattice on SiC(0001) with a coincidence lattice of $(6\sqrt{3} \times 6\sqrt{3})R30^\circ$ symmetry. The growth of the first layer proceeds on top of adatoms characteristic of the $(\sqrt{3} \times \sqrt{3})R30^\circ$ reconstruction. These adatoms are derived from Si vacancies in the C-rich subsurface layers of the SiC substrate. This strongly anisotropic reconstruction can be viewed as a diamondlike phase which acts as a precursor to graphite formation by subsequent layer growth. In this framework, previously published soft x-ray photoemission spectra find a

CONCLUSION

The reconstruction of interest in graphite, observed in connection with the growth of carbon such as nanochannels, is made of honeycomb-like layers of carbon atoms bonded to their neighbors. From the analysis of the electronic properties such as

surfaces with a silicon termination, 6H-SiC(0001) and 3C-SiC(111), present the same stacking sequence down to four Si-C bilayers from the surface.⁹ Low-energy-electron-diffraction (LEED) (Refs. 9–11) has revealed several surface reconstructions which have also been studied using techniques such as Auger-electron spectroscopy (AES).^{8,12,13} electron-energy-loss spectroscopy (EELS) and x-ray photoemission spectroscopy (XPS) have also been used to study the surface structure of SiC(0001) and SiC(111) surfaces.

1975 : un travail (un peu) passé inaperçu

2000 : ébullition autour du graphène

Intérêt des nanotubes,
mais difficultés de process...

Graphène potentiellement plus
attrayant, mais supposé instable...

... distinguishable from a bulk graphite single crystal regarding its structural and electronic properties. In addition, we have shown that it is possible to isolate a single graphene plane covering most of the substrate. A number of potential experiments, in particular angle-resolved studies, could clearly

Travaux expérimentaux sur
des monocouches de graphite

+

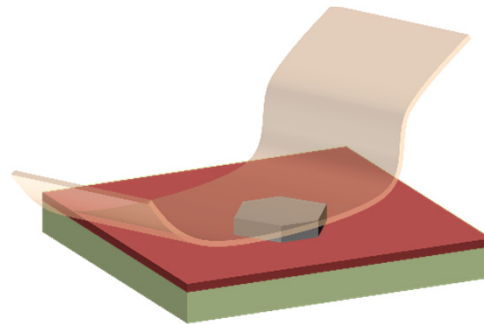
Demande électronique croissante
et limitations de la loi de Moore



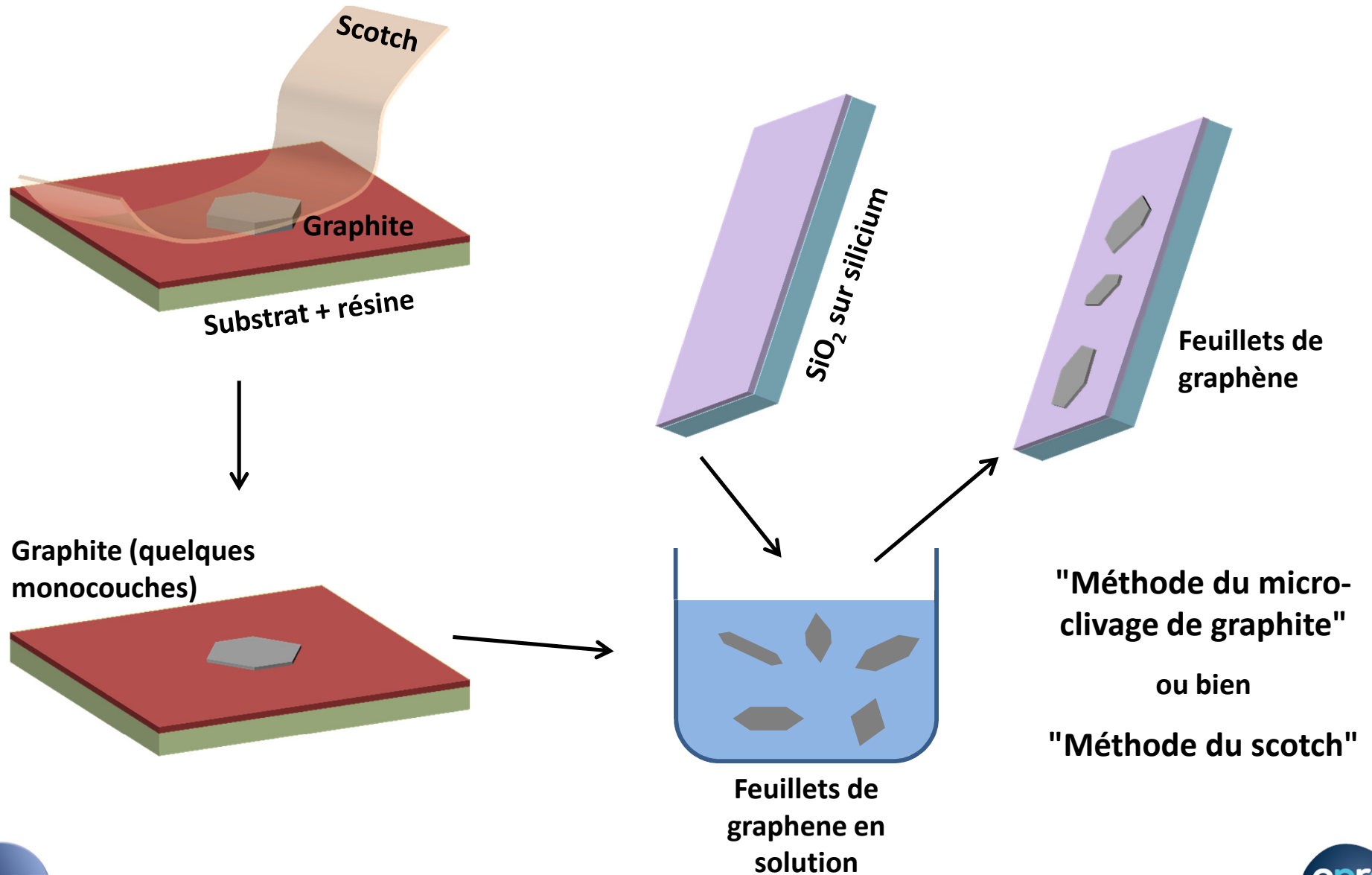
2 premiers travaux sur le graphène
(fabrication + étude du transport) :

- Oct. 2004 : méthode du scotch
- Déc. 2004 : recuit de SiC

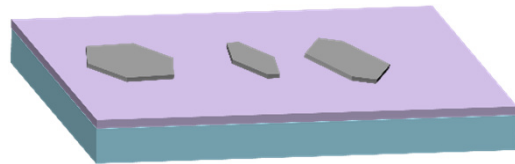
Méthodes de fabrication du graphène



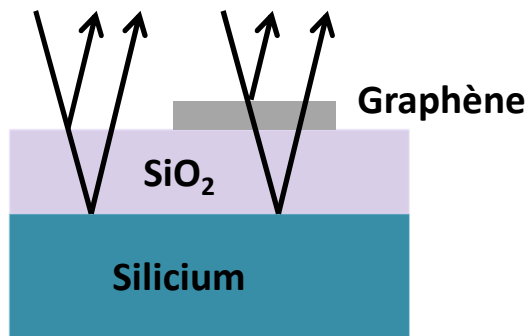
Expériences fondatrices - N 1 : déposer le graphène



Expériences fondatrices - N 2 : trouver le graphène

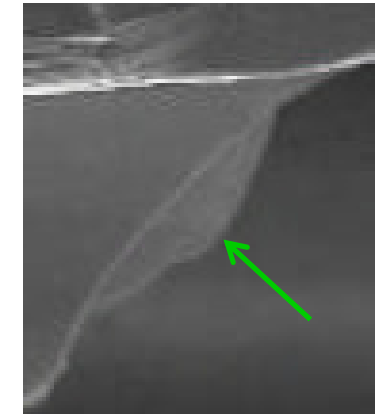
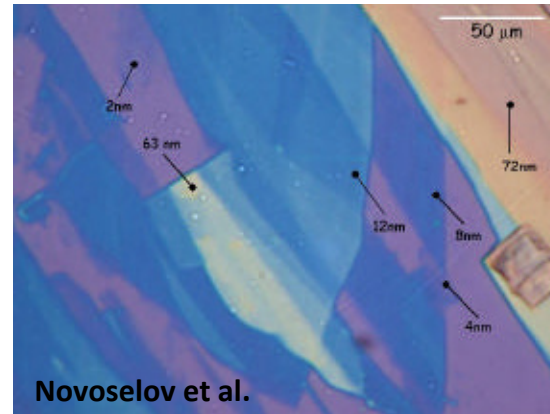


Feuillets de graphène



Différence de marche
avec et sans graphène
⇒ différence de couleur

Microscope optique



Microscope
électronique
à balayage

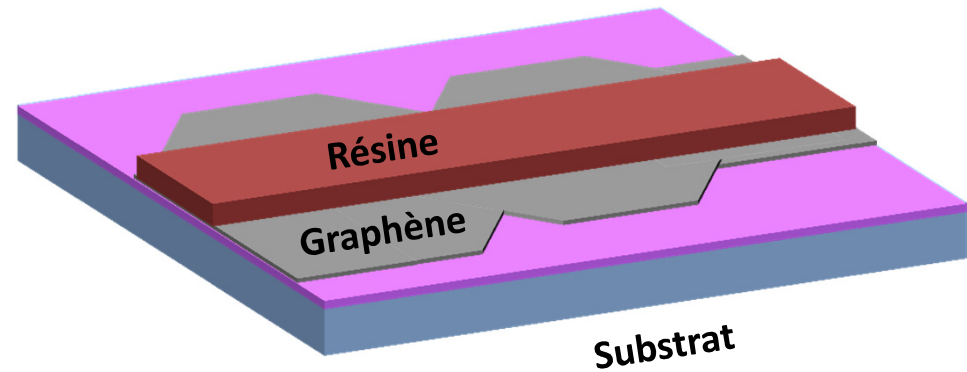
Feuillets visibles au microscope optique : trop épais !
(> 1.5 nm / 5 couches)

⇒ feuillets visibles au microscope électronique mais
invisible au microscope optique : OK

Expériences fondatrices - N 3 : contacter et mesurer

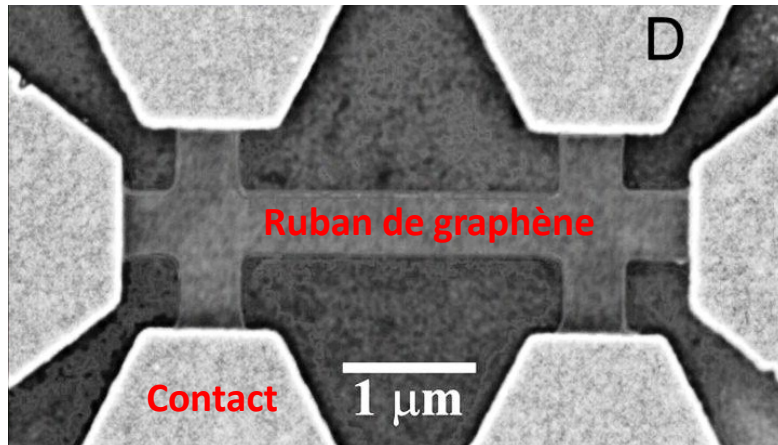
Couche 2D sur un substrat :
utilisation de technologies "classique"

Lithographie + attaque plasma

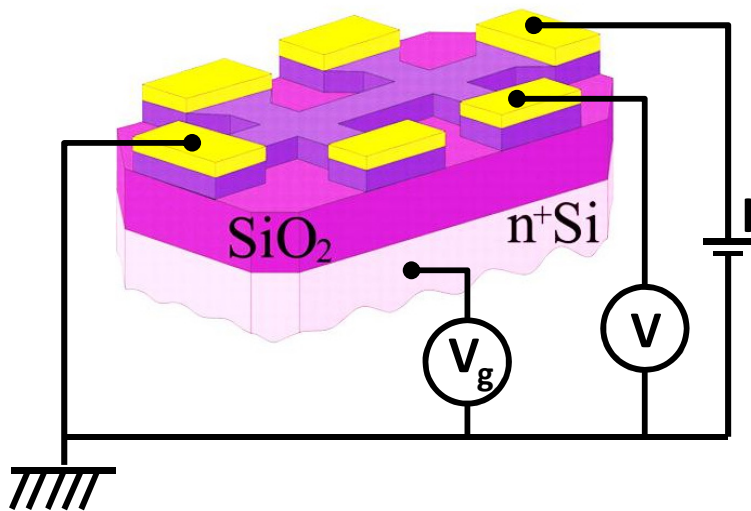


Expériences fondatrices - N 3 : contacter et mesurer

Lithographie électronique et autres process

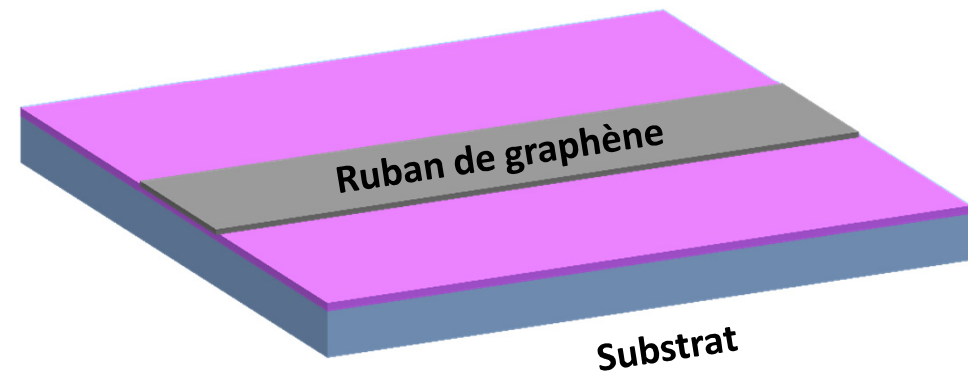


Novoselov *et al.*, Science 306 (octobre 2004)



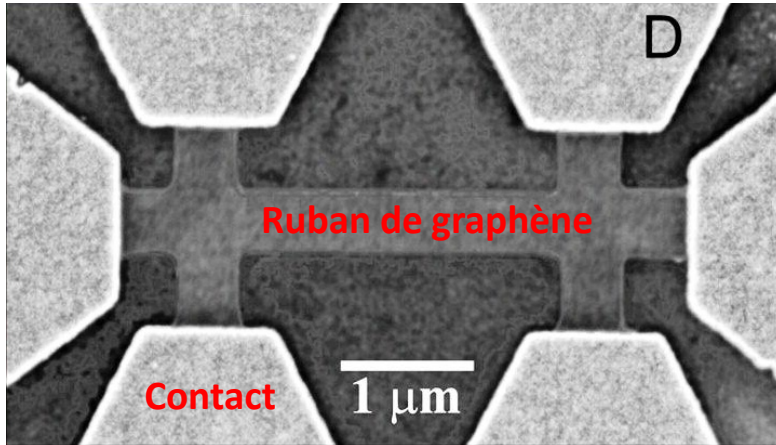
Couche 2D sur un substrat :
utilisation de technologies "classique"

Lithographie + attaque plasma

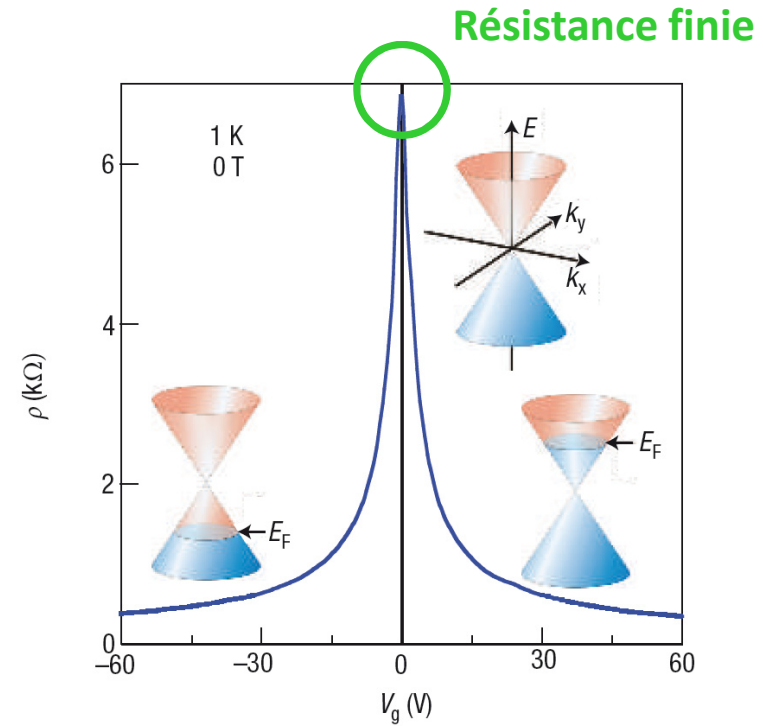
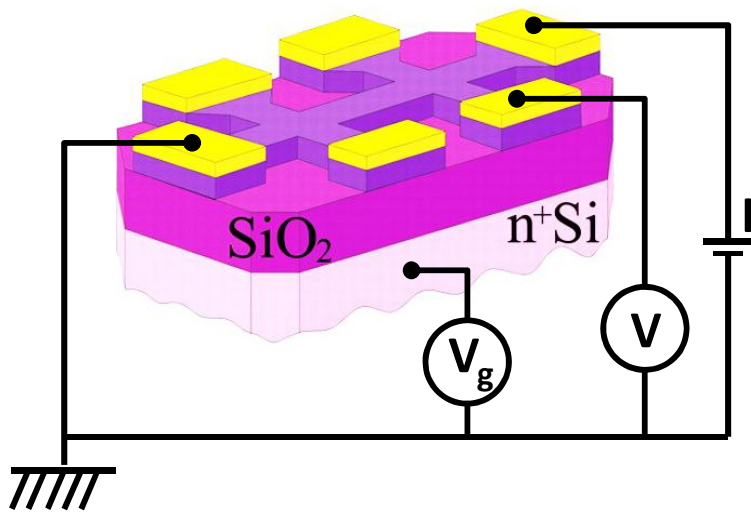


Expériences fondatrices - N 3 : contacter et mesurer

Lithographie électronique et autres process



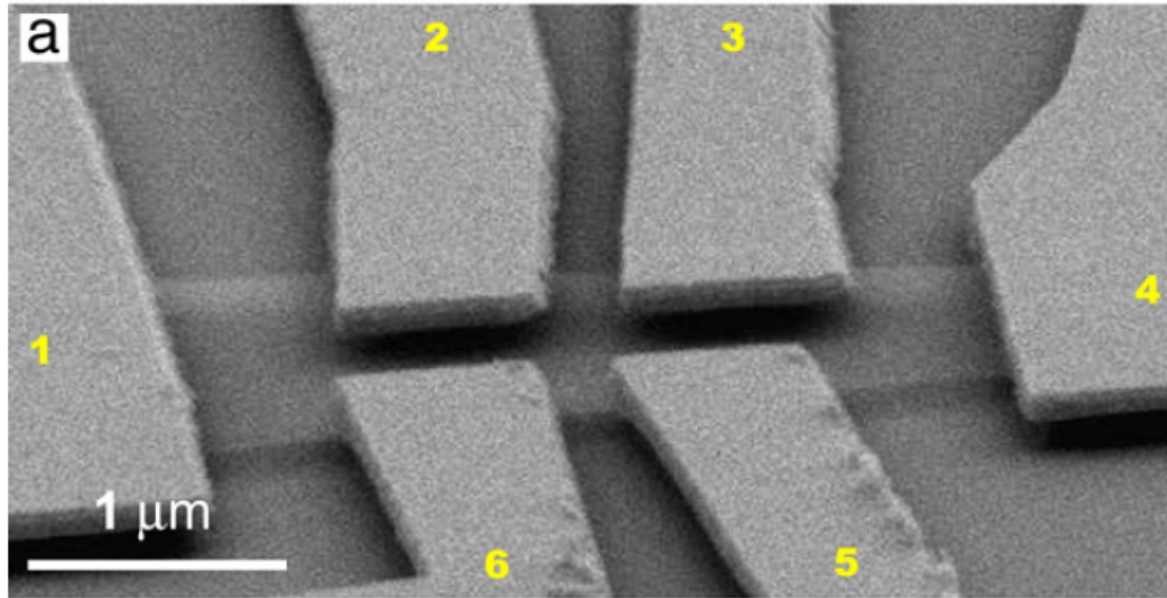
Novoselov *et al.*, Science 306 (octobre 2004)



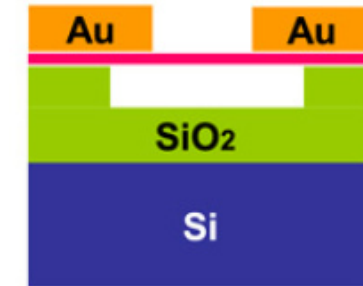
Effet de champs dans le graphène :
dopage (et chute de résistance)
induit par un champ électrique

Mobilité : 3 000 à 30 000 cm²/V.s

Graphène exfolié : graphène haute performance



Bolotin *et al.*, Sol. State Com. 146 (2008)



Graphène suspendu

Record de mobilité :
230 000 cm²/V.s !
(5 K, 2.10¹¹ e⁻/cm²)

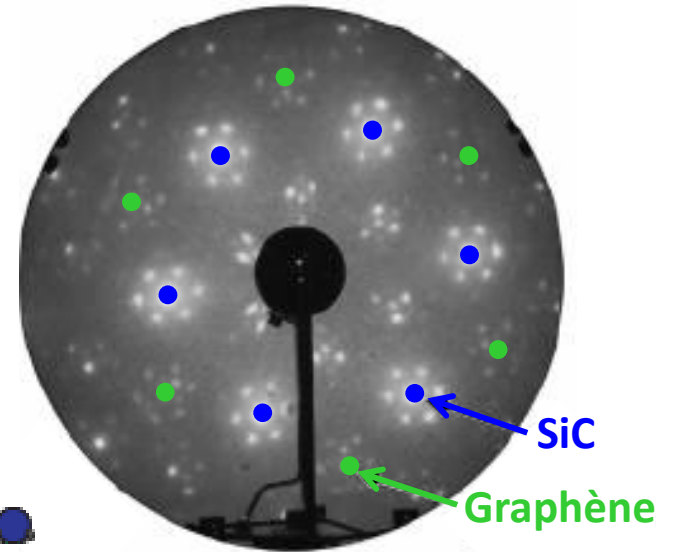
Physique fondamentale :
méthode du scotch intéressante

Pour les applications :
difficile à envisager
(microprocesseur : quelques 10⁸ transistors)

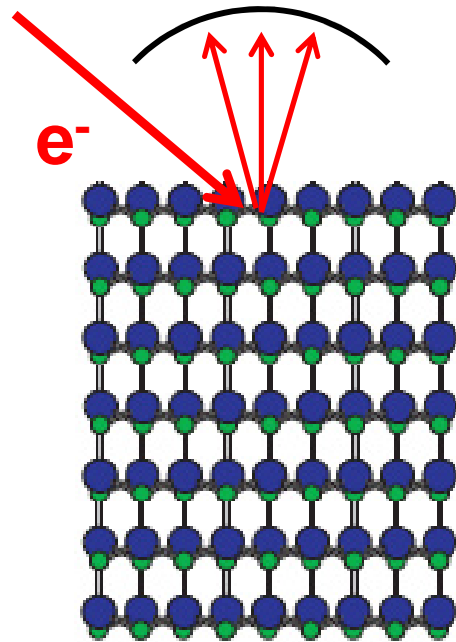
Recuit de SiC



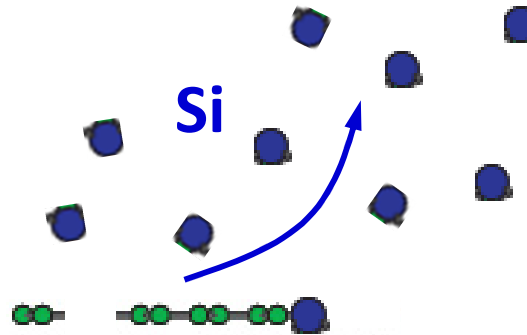
Diffraction d'électrons de faible énergie (LEED)
(diffraction de surface)



Berger *et al.*, J. Phys. Chem. B 108 (décembre 2004)

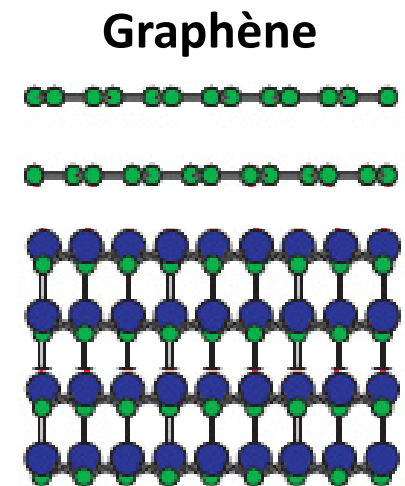


SiC



Si

Ultravide 1100 C



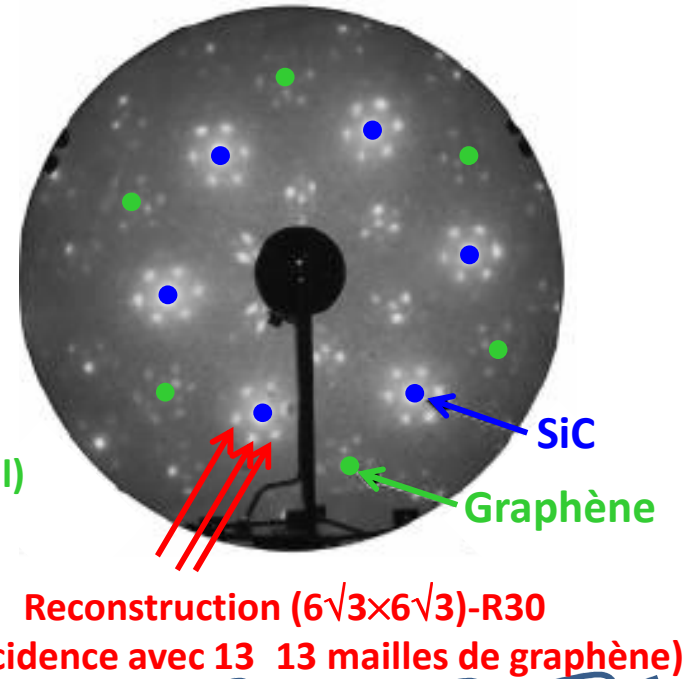
Graphène

Recuit de SiC

Face silicium :

- liaisons covalentes graphène/substrat
- reconstruction d'interface $(6\sqrt{3}\times 6\sqrt{3})\text{-R}30$
- empilement hexagonal

Limite la
mobilité
électronique



Couche de graphène (empilement hexagonal)

Couche "N 0" (mélange carbone sp^2 / sp^3)

Liaisons covalentes

Riedl
et al.

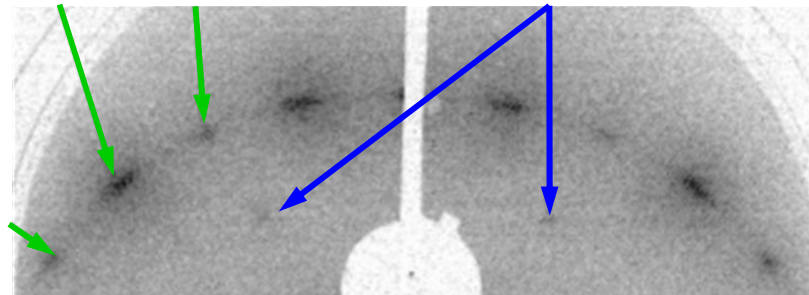
Emtsev et al.

Graphène

15 0

SiC

30



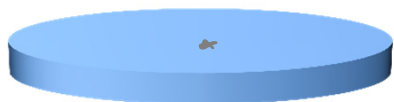
Hass et al.

Face carbone

- pas de reconstruction d'interface
- désordre d'orientation dans le plan

Forte mobilités

Intérêt du recuit de SiC

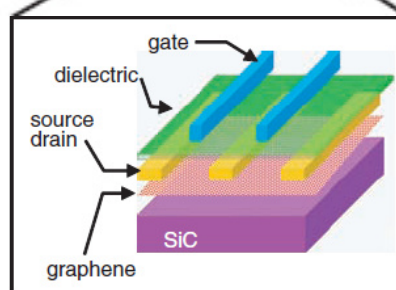
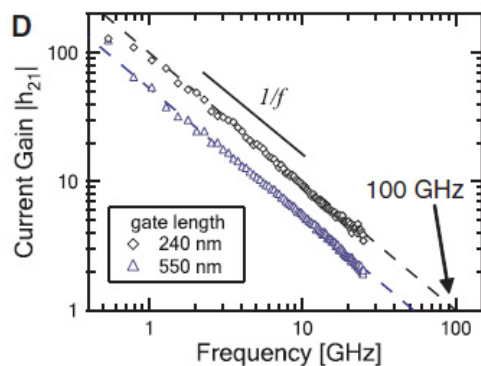
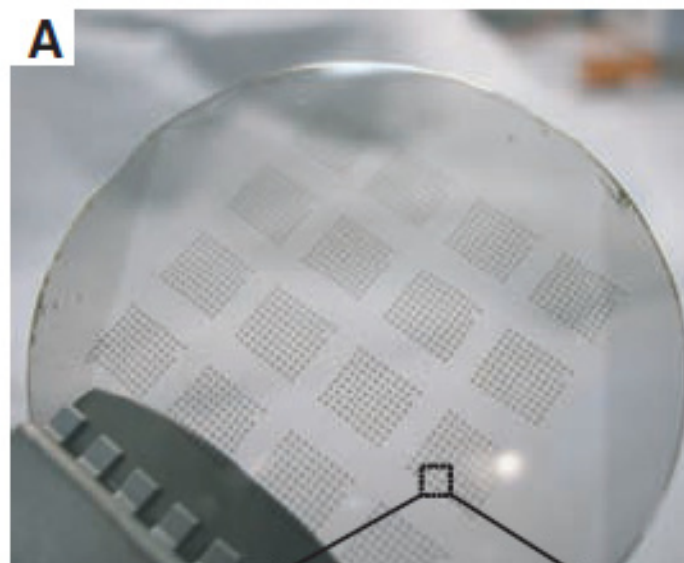


Scotch :
1 feuillet de graphène
= 1 transistor



Recuit de SiC :
autant que voulu
(limité par la techno)

Lin *et al.*, Science 327 (2010)



1400 transistors

Scotch :
230 000 cm²/V.s

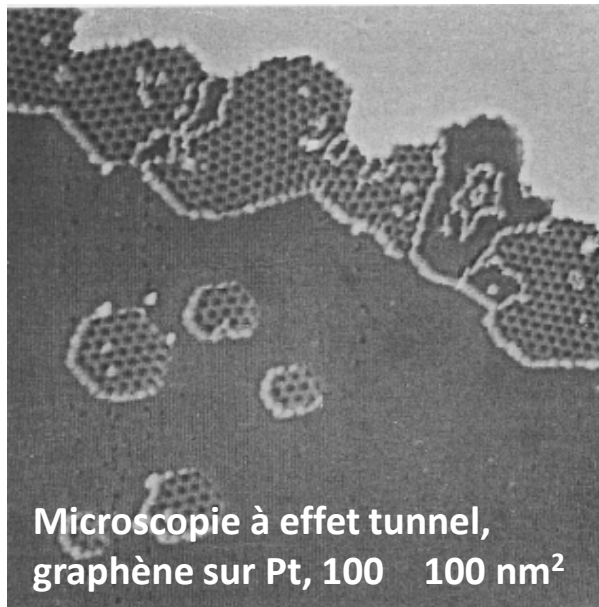
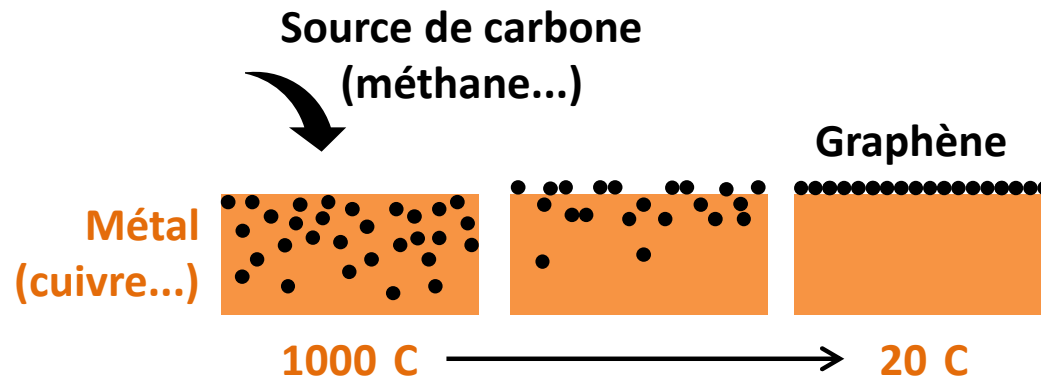
Recuit de SiC :
30 000 cm²/V.s (face C)
10 000 cm²/V.s (face Si)

Si Ø 5 cm : 15 €
SiC Ø 5 cm : 300 €

Ø max Si : 30 cm
Ø max SiC : 10 cm

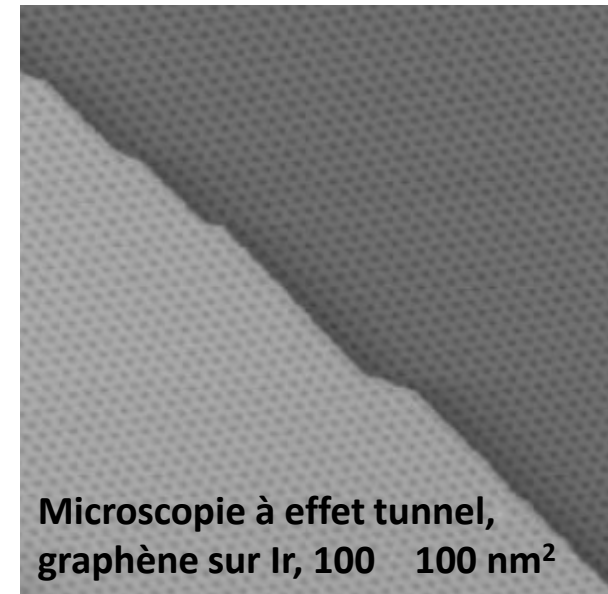
SiC/Si :
Coût substrat 20
Coût techno 10

Croissance de graphène sur métal (CVD)



Microscopie à effet tunnel,
graphène sur Pt, 100 100 nm²

Land *et al.*, Surf. Sci. 264 (1992)



Microscopie à effet tunnel,
graphène sur Ir, 100 100 nm²

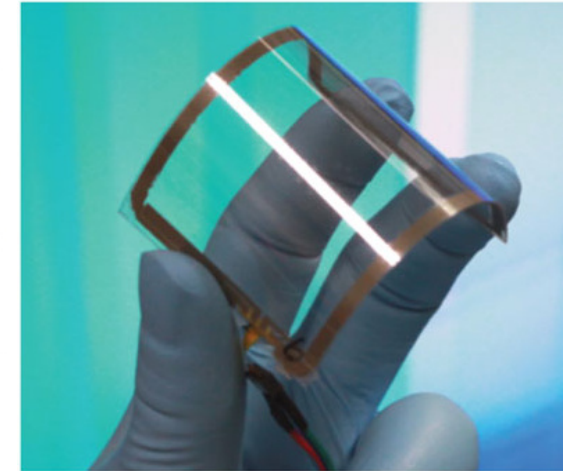
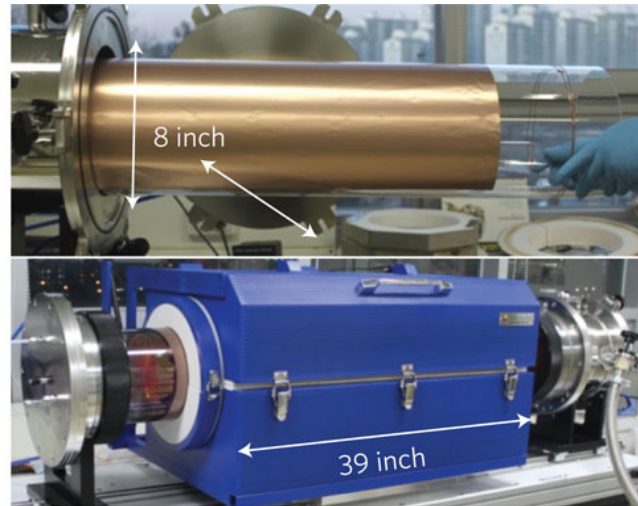
Coraux *et al.*, Nano Lett. 8 (2008)

Perfectionnements :

- limitation de l'épaisseur (utilisation de films métalliques ou de cuivre)
- mise au point de méthodes de transfert sur substrat isolant

Premières applications du graphène

CVD sur métal :
de 100 à 10 000 cm²/V.s
selon substrat et procédé

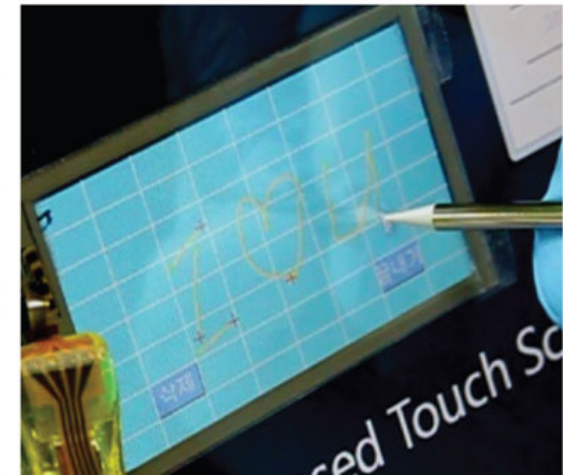
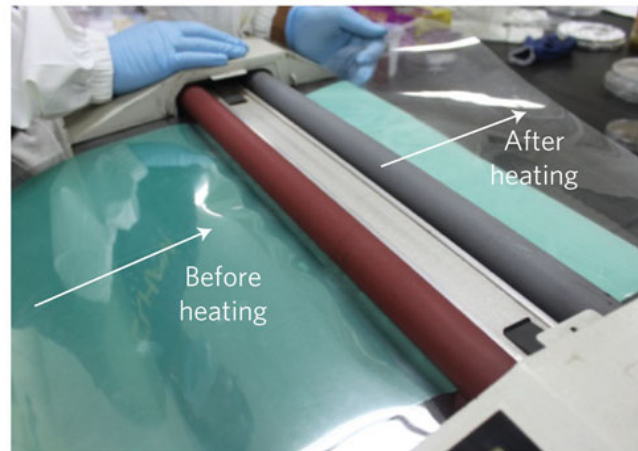


Forte absorption optique
($a = \pi\alpha$, 30 MC = 10 nm => $a = 50\%$)

mais très fort rapport

transparence optique

résistance électrique



Bae *et al.*, Nat. Nanotech. 5 (2010)

Première application du graphène : électrode transparente,
en remplacement de l'ITO (oxyde d'indium et d'étain),
plus couteux et moins flexible

Recyclage de carbone

Ruan *et al.*, ACS Nano 5 (2011)

Growth of Graphene from Food, Insects, and Waste

Gedeng Ruan,^{†,‡} Zhengzong Sun,^{†,‡} Zhiwei Peng,[†] and James M. Tour^{†,*,§,*}

[†]Department of Chemistry, [‡]Department of Mechanical Engineering and Materials Science, and [§]Richard E. Smalley Institute for Nanoscale Science and Technology, Rice University, 6100 Main Street, Houston, Texas 77005, United States. ^{*}These authors contributed equally to this work.

Graphene, in its monolayer form, is an attractive two-dimensional material with an atomically thick honeycomb structure.^{1–3} Due to its extraordinary electrical,⁴ mechanical,⁵ thermal,⁶ and spintronic⁷ properties, graphene has the potential to be applied in nanoelectronic devices.^{8,9}

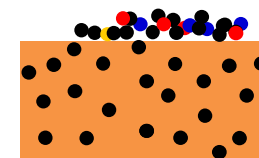
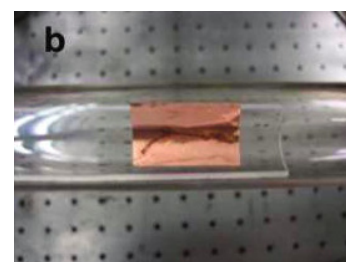
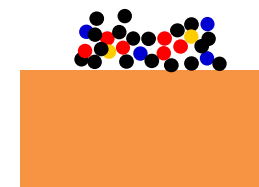
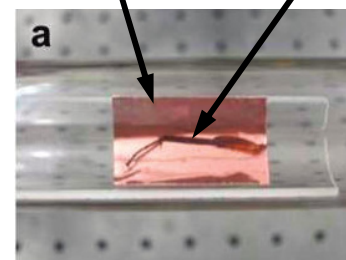
ABSTRACT In its monolayer form, graphene is a one-atom-thick two-dimensional material with excellent electrical, mechanical, and thermal properties. Large-scale production of high-quality graphene is attracting an increasing amount of attention. Chemical vapor and solid-state methods have been developed to grow graphene on copper foil.

EXPERIMENTAL METHODS

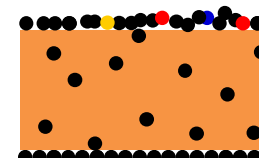
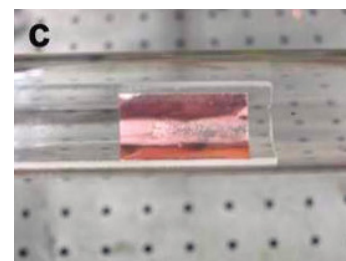
Growth and Transfer of Graphene Samples. Six different carbon sources were used: Girl Scout cookie (the Girl Scouts of America Troop 25080 from Houston, Texas, provided the cookies, short-bread flavor), chocolate (Chocolate Kennedy Half Dollar Gold Coins), grass (Ophiopogon picked at Rice University), plastic (Fisherbrand polystyrene Petri dishes, catalog #08-757-12), dog feces (Miniature Dachsund), and a cockroach leg (American cockroach caught in a house). The grass and the dog feces were dehydrated in a vacuum oven (102 Torr) at 65 °C for 10 h before being used in the growth process.

ARTICLE

Cuivre Patte de cafard



1050 C



Graphène

Bilan

3 méthodes d'élaboration de graphène "haute performance"

Méthode du scotch

- propriétés : ★★★★★
- coût-simplicité : ∅
- ⇒ recherche fondamentale

Recuit de SiC

- propriétés : ★★★
- coût-simplicité : ★(★)
- ⇒ applications (de niche ?)

CVD sur métal

- propriétés : ★ à ★★★★★
- coût-simplicité : ★★★ à ★
- ⇒ déjà des applications

Autres méthodes plus chimiques :

Extraction de graphite/oxyde de graphite par ultrasons

Synthèse de graphène/oxyde de graphène par voie chimique

Formation de graphène pendant la préhistoire

Graphene: In Our Food Stuffs since Mesolithic Age

Manav Saxena, Sabyasachi Sarkar

Department of Chemistry, Indian Institute of Technology Kanpur, Kanpur-208016, Uttar Pradesh, India
msaxena@iitk.ac.in

Fire is one of the five elements by which the universe has been created as per the mythologies of Hindu, Babylonian, Greece, Chinese, Japanese, Buddhist, and Tibetan [1]. Fire is an important discovery by human which revolutionized their life. The use of fire pushed up the evolution of human from *Homo erectus* to *Homo sapiens* during the Mesolithic age (200,000-40,000 years ago). Fire

known method of cooking. Roasting technique is very popular among us in day-today life. This is the roasting that unknowingly giving us a material, named Graphene, of too much value, in free of cost.

The author here will explain the presence of graphene in our daily food stuffs as shown in figure 1. The

International Conference on Graphene 2012



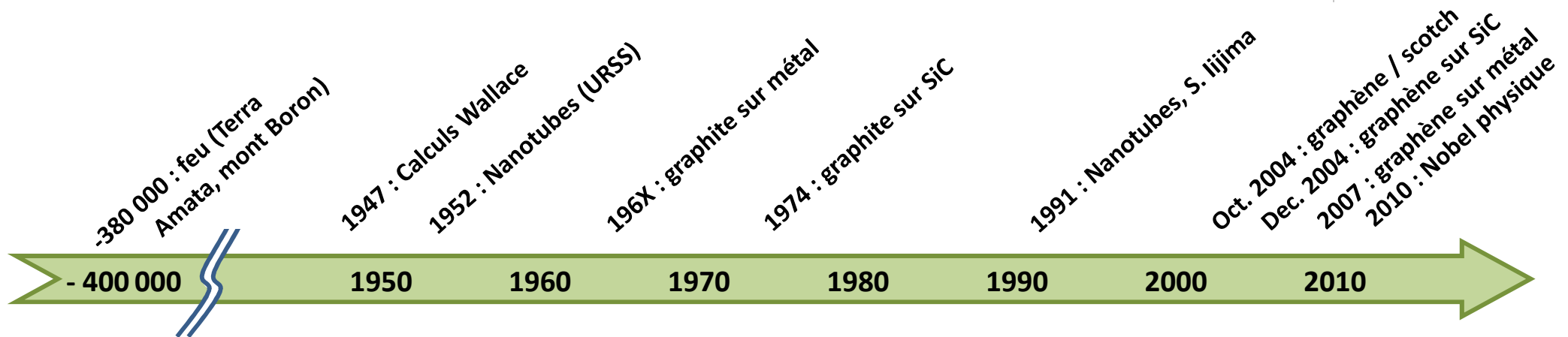
Formation de graphène pendant la préhistoire

Graphene: In Our Food Stuffs since Mesolithic Age

Manav Saxena, Sabyasachi Sarkar

Department of Chemistry, Indian Institute of Technology Kanpur, Kanpur-208016, Uttar Pradesh, India
msaxena@iitk.ac.in

Fire is one of the five elements by which the universe has been created as per the mythologies of Hindu, Babylonian, Greece, Chinese, Japanese, Buddhist, and Tibetan [1]. Fire is an important discovery by human which revolutionized their life. The use of fire pushed up the evolution of human from *Homo erectus* to *Homo sapiens* during the Mesolithic age (200,000-40,000 years ago). Fire



Graphène au CRHEA

**Adrien Michon, Marc Portail, Elodie Roudon, Stéphane Vézian,
Denis Lefebvre, Philippe Vennéguès, Olivier Tottereau,
Sébastien Chenot, Yvon Cordier**
CRHEA, Valbonne



Marcin Zielinski, Thierry Chassagne
NOVASiC, Valbonne



**Antoine Tiberj, Benoit Jouault, Sylvie Contreras,
Jean-Roch Hutzinger, Jean Camassel**
L2C, Montpellier



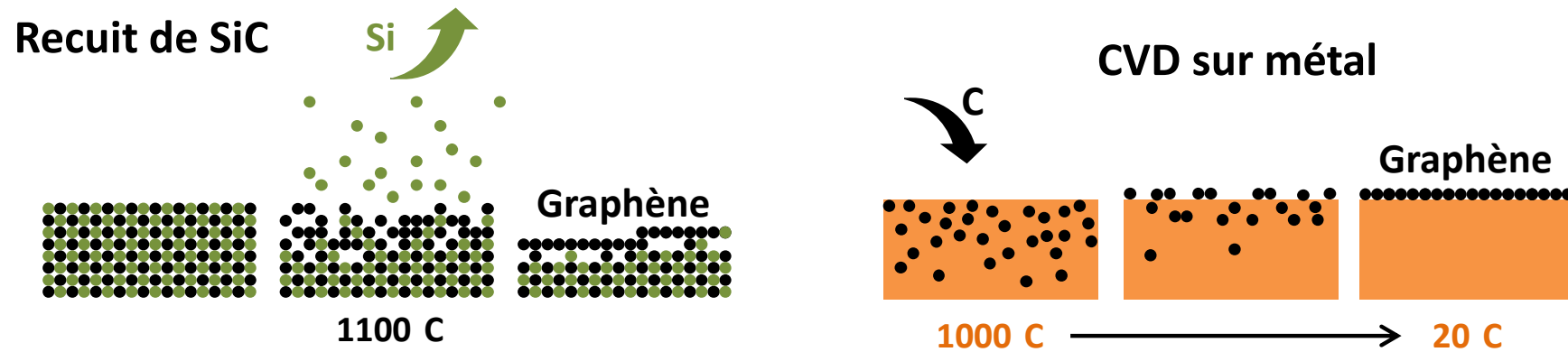
Ludovic Largeau, Olivia Mauguin
LPN, Marcoussis



Fabien Cheynis, Frédéric Leroy, Pierre Müller
CiNaM, Marseille



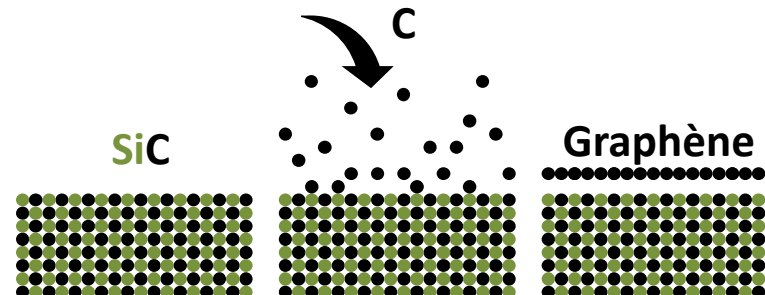
Croissance épitaxiale de graphène ?



Croissance indirecte, alimentée par le substrat

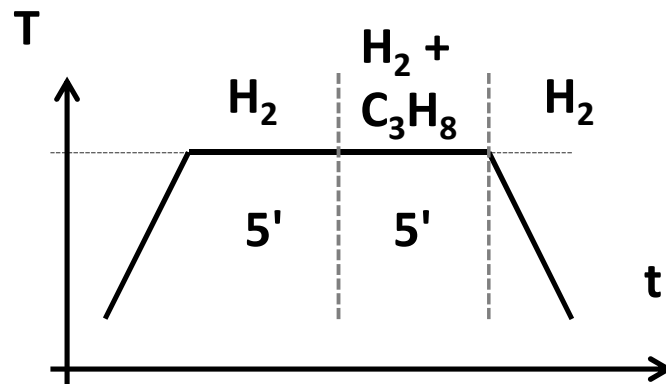
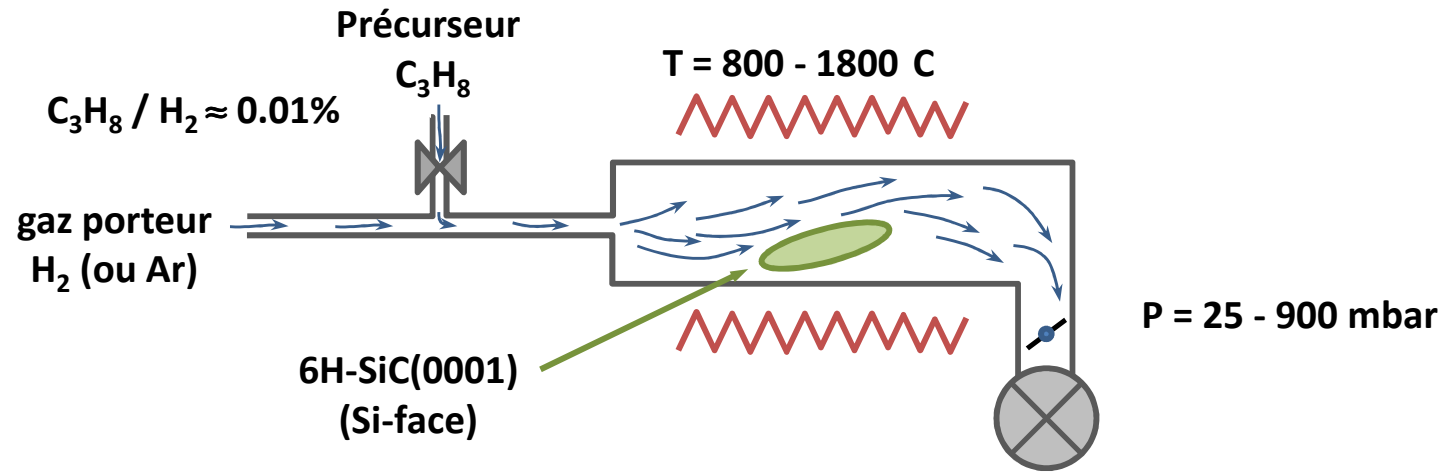
Possibilité de croissance directe ?

Première démonstration sous ultraviolette en 2009 (IEMN, Lille)



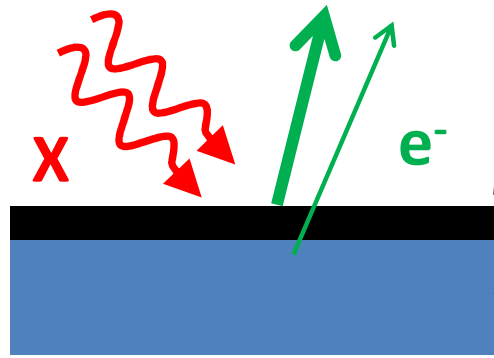
Croissance en phase vapeur ?

Méthode de croissance : *chemical vapor deposition* (CVD)



Formation de graphène ?

Photoémission X (XPS)



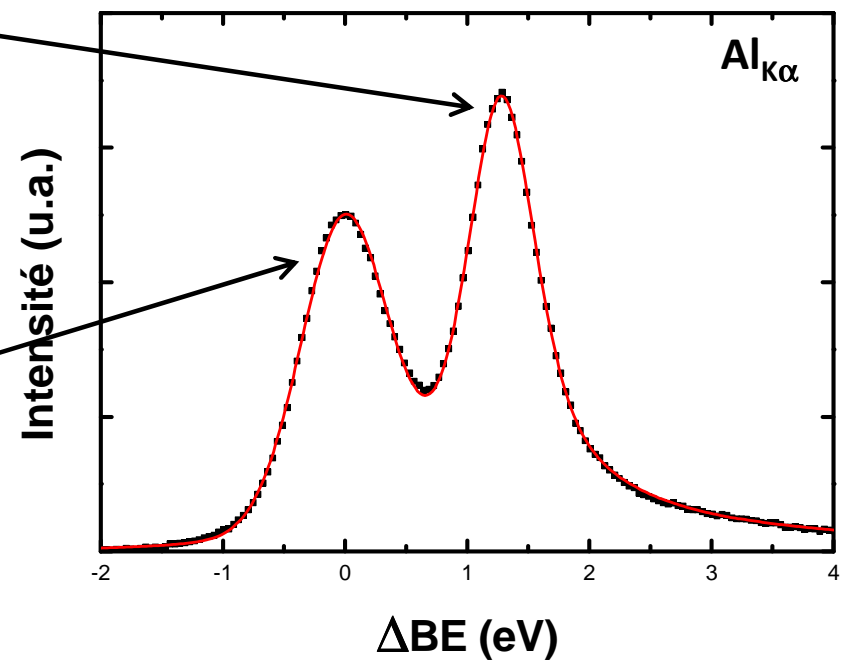
Electrons :
caractérisation de la surface

- Caractérise :
- atomes présents
 - environnement des atomes

Carbone sp^2 :
graphène

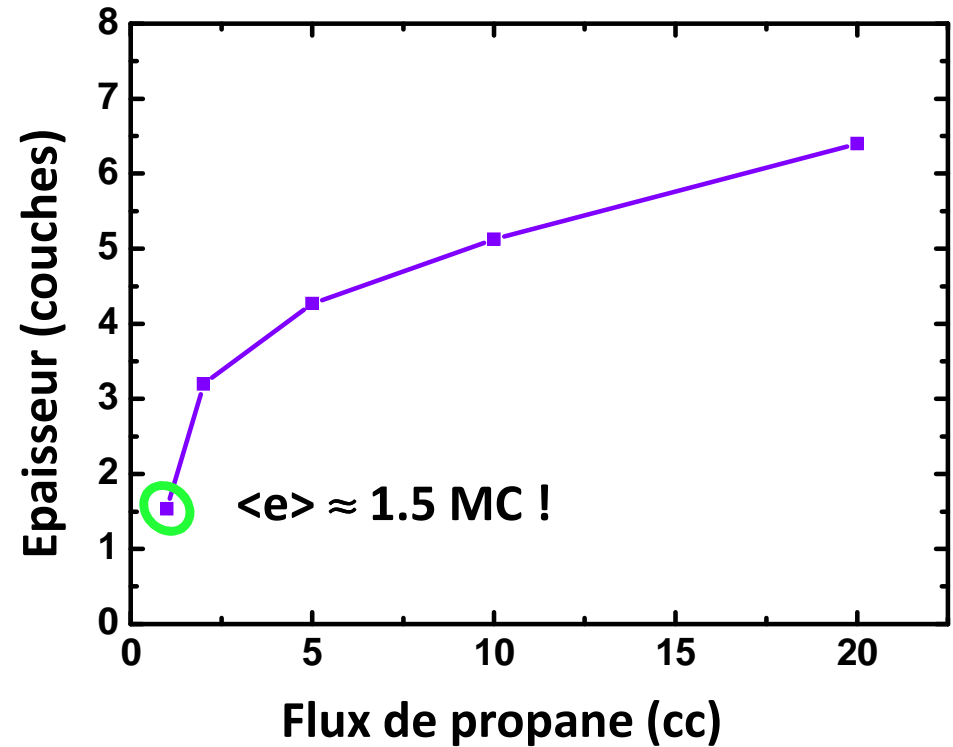
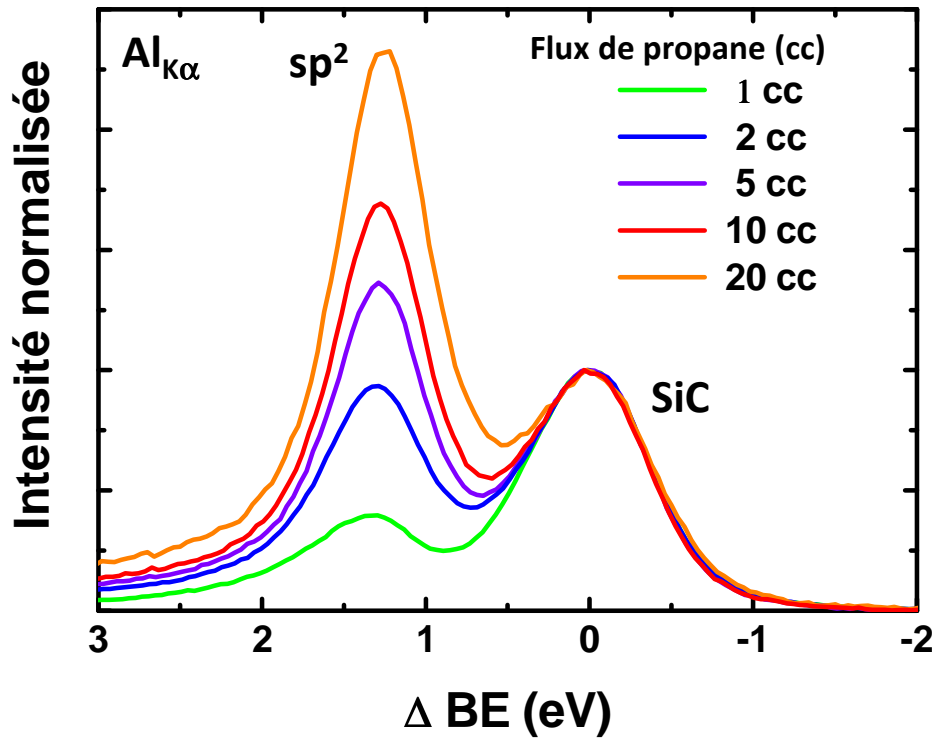
Carbone sp^3 :
SiC

Autour de $E = 283.5$ eV : carbone



XPS réalisé à l'Ecole des Mines
Merci à E. Darque Ceretti et F. Georgi

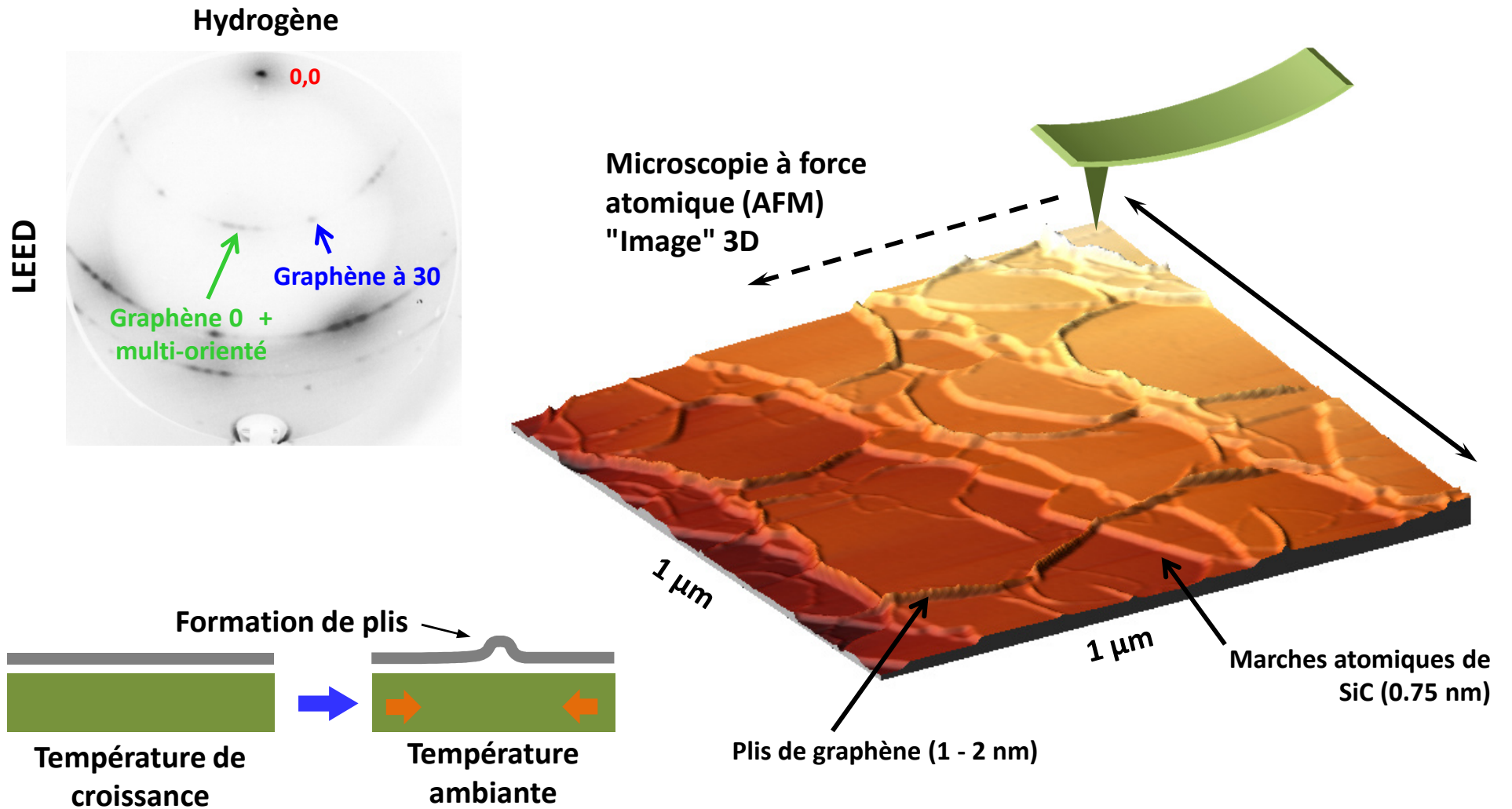
Effet du flux de propane



Croissance directe de graphène

Première croissance directe en phase vapeur (2010, ex-aequo avec Cornell University)

Croissance sous hydrogène (face silicium)



Graphène faiblement lié au substrat (comme sur la face carbone)

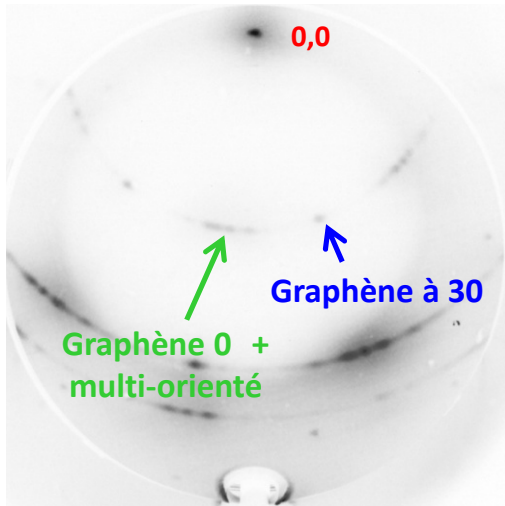


SiC saturé par hydrogène

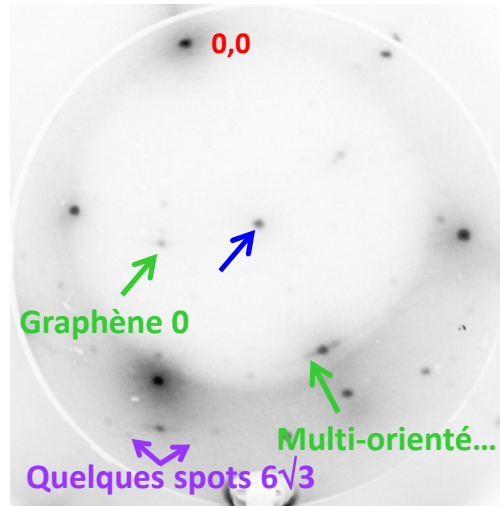
Effet du gaz vecteur

LEED

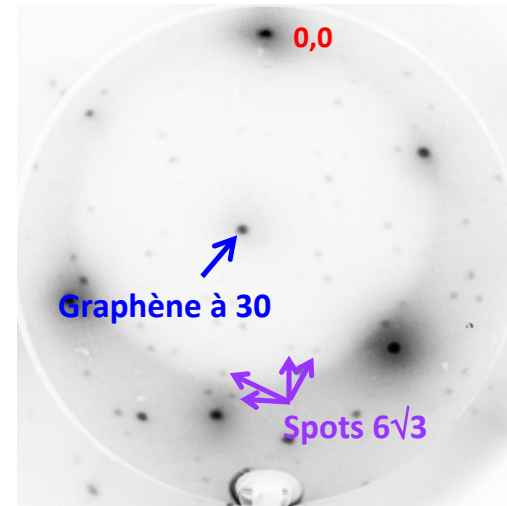
Hydrogène



Hydrogène / Argon

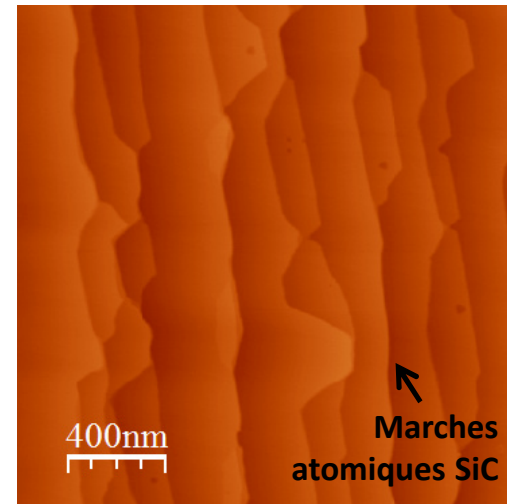
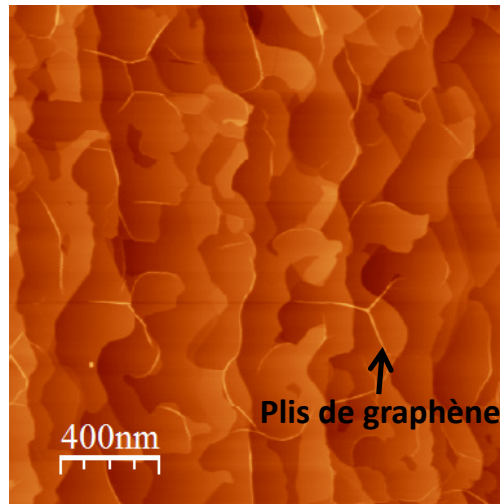
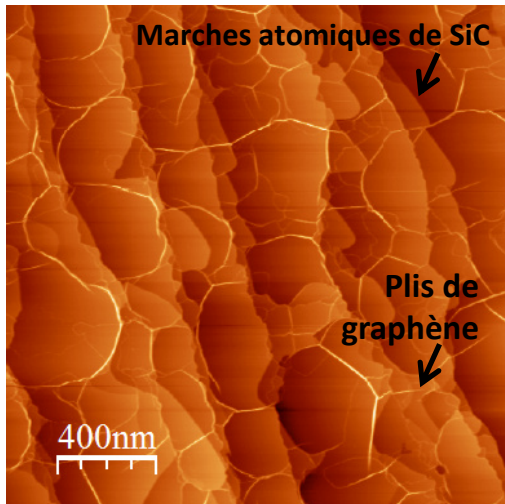


Argon

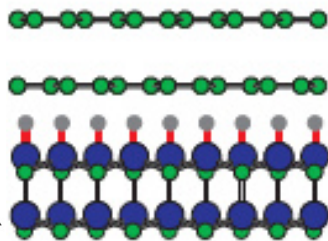


AFM

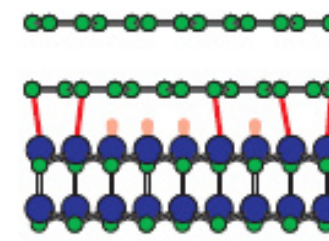
Echelle verticale 5 nm



Effet de l'hydrogène sur l'interface graphène/SiC

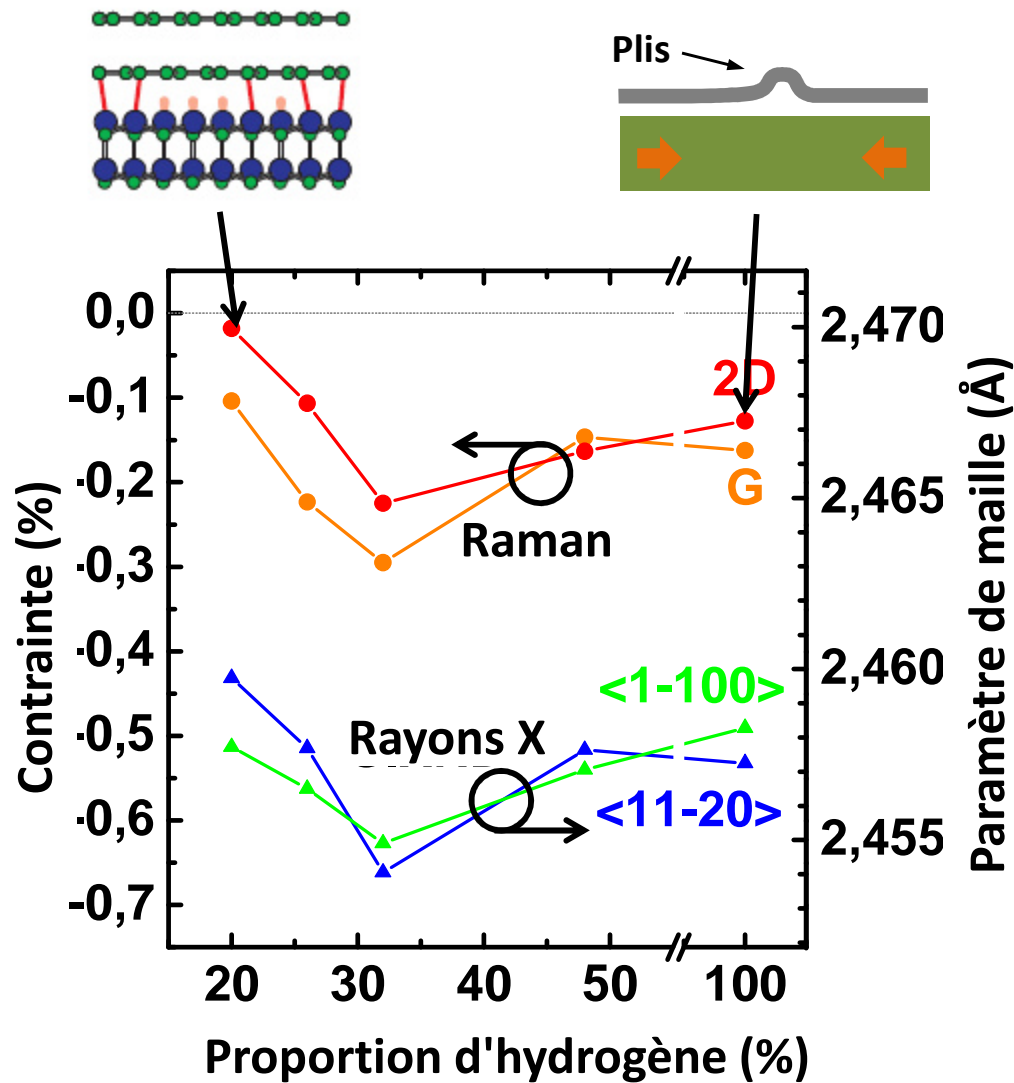


Riedl et al. (2009)



Riedl et al. (2009)

Etude des contraintes



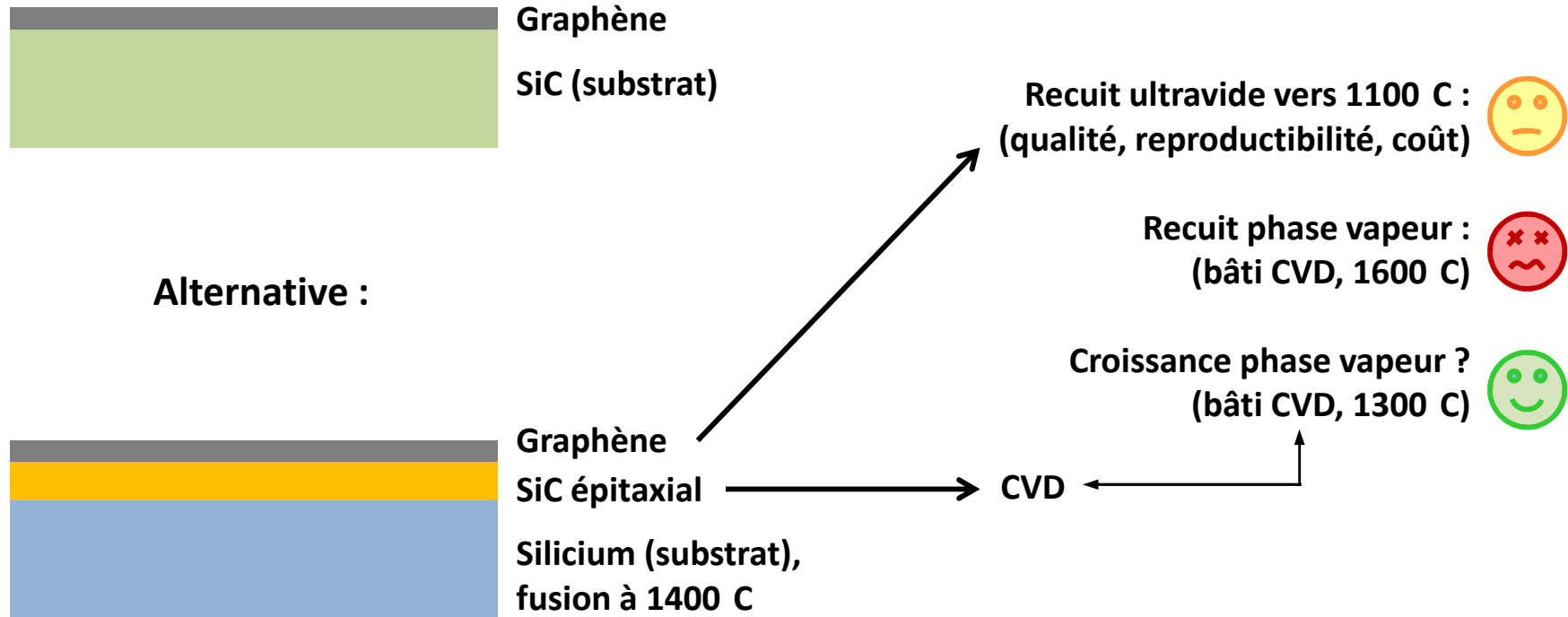
- Propriétés structurales :
présence de liaisons graphène/
substrat, défauts dans le graphène...

- Compréhension des mécanismes de
croissance

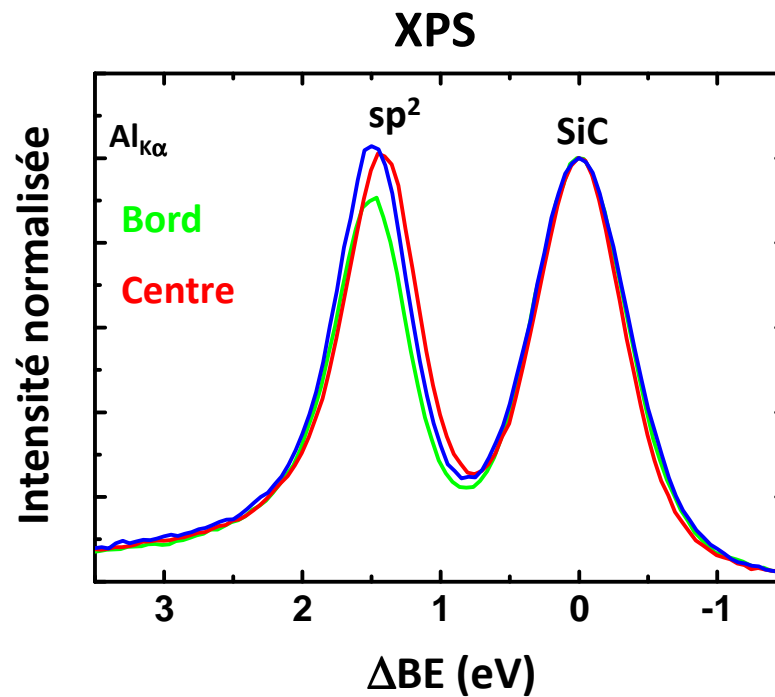
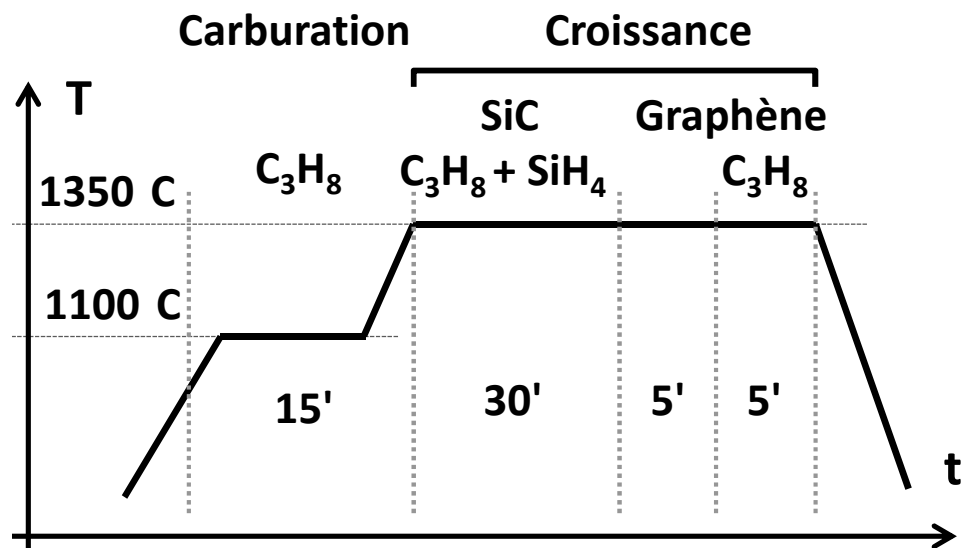
- Effet des contraintes sur les
propriétés électroniques
(mobilité, gap)

Spectroscopie Raman :
collaboration L2C, Montpellier
Diffraction X :
collaboration LPN, Marcoussis

Graphène sur silicium



Graphène sur 3C-SiC sur silicium



Possibilité de croissance de graphène sur silicium

Autres résultats et conclusion

Croissance directe sur semiconducteur

Sur SiC :

- Croissance en ultravide (2009)
- Croissance en phase vapeur (2010)

Avantages :

- reproductibilité
- contrôle direct de la croissance
- croissance sur d'autres substrats

- SiC/silicium
- Saphir (Al_2O_3)



Croissance directe

- propriétés : ★★★
 - coût-simplicité : ★★(★)
- ⇒ plus d'applications

Méthode du scotch

- propriétés : ★★★★★
 - coût-simplicité : ∅
- ⇒ recherche fondamentale

Recuit de SiC

- propriétés : ★★★
 - coût-simplicité : ★(★)
- ⇒ applications (de niche ?)

CVD sur métal

- propriétés : ★ à ★★★★★
 - coût-simplicité : ★★ ★ à ★
- ⇒ déjà des applications