laboratoire pierre aigrain
électronique et photonique quantiques

À quoi peut servir le graphène en électronique ?

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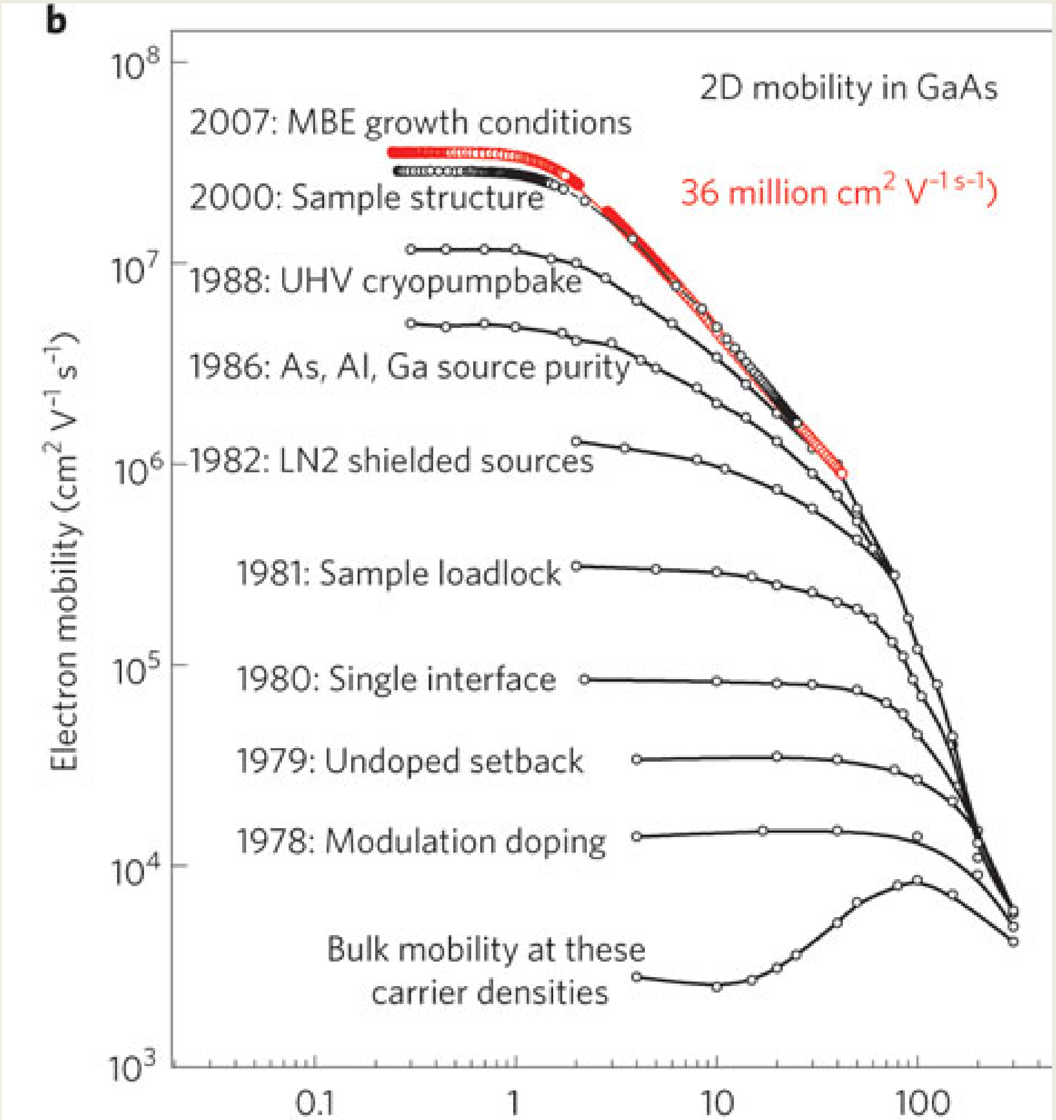
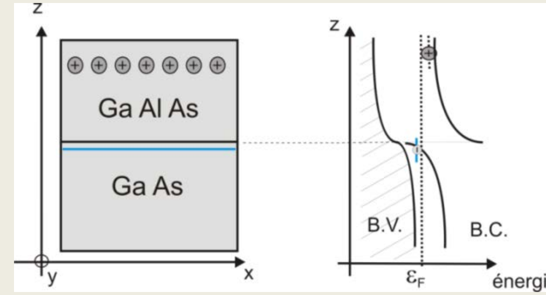
Gas electrons bidimensionnels 2DEG

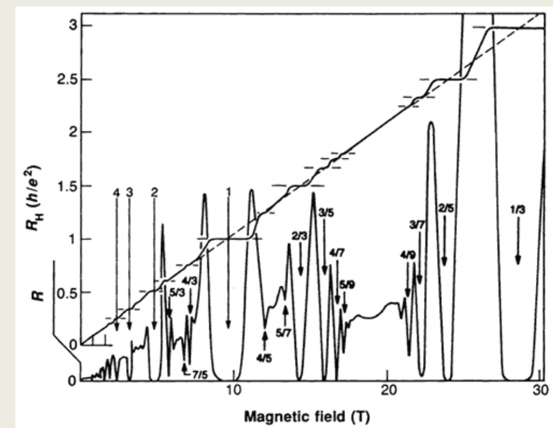
Mobilité : $\mu = v_d / E$



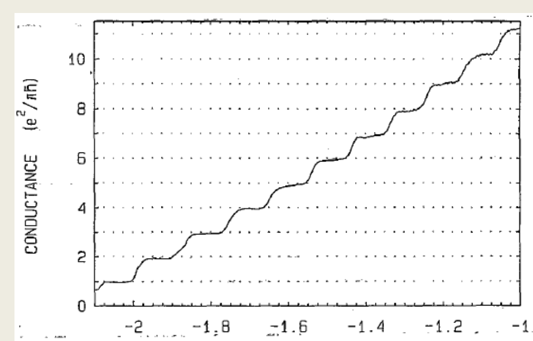
(d'après Tsui et al.)



Effet Hall quantique 1980, 1982

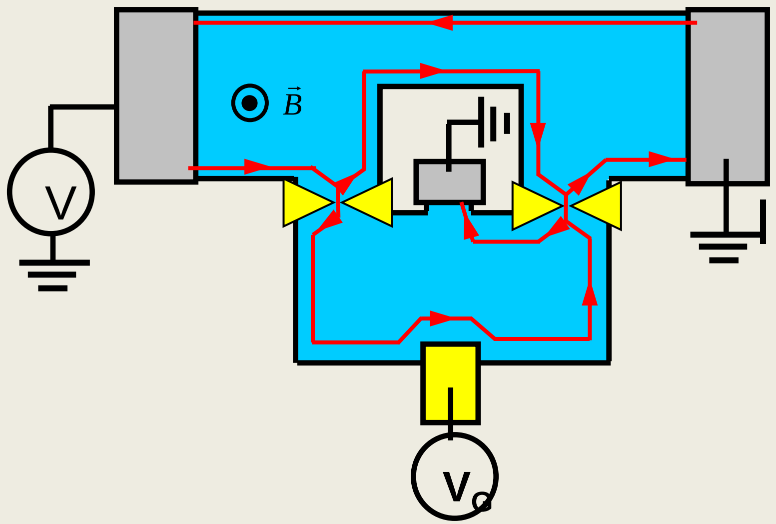


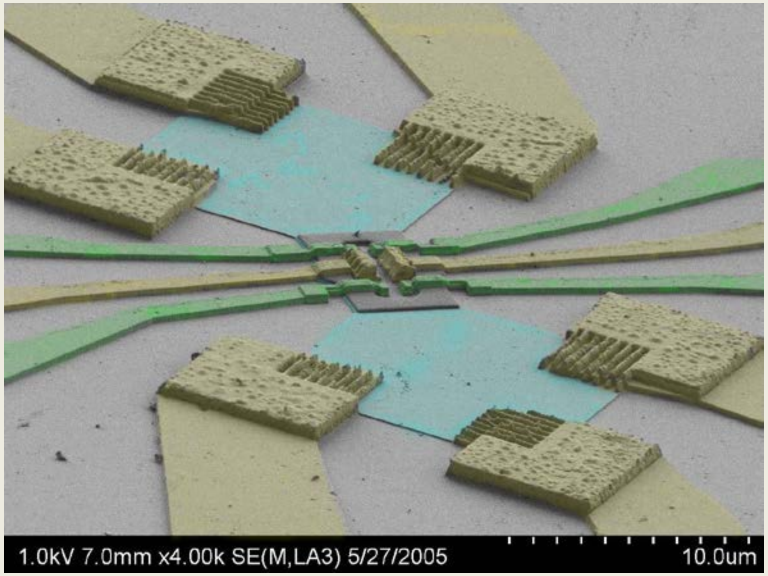
Quantum de conductance 1988



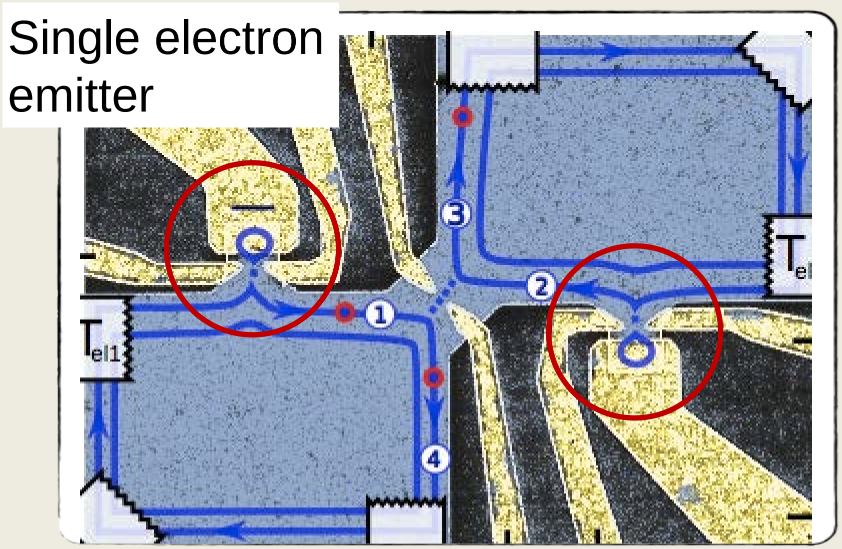
Physique quantique dans les 2DEG

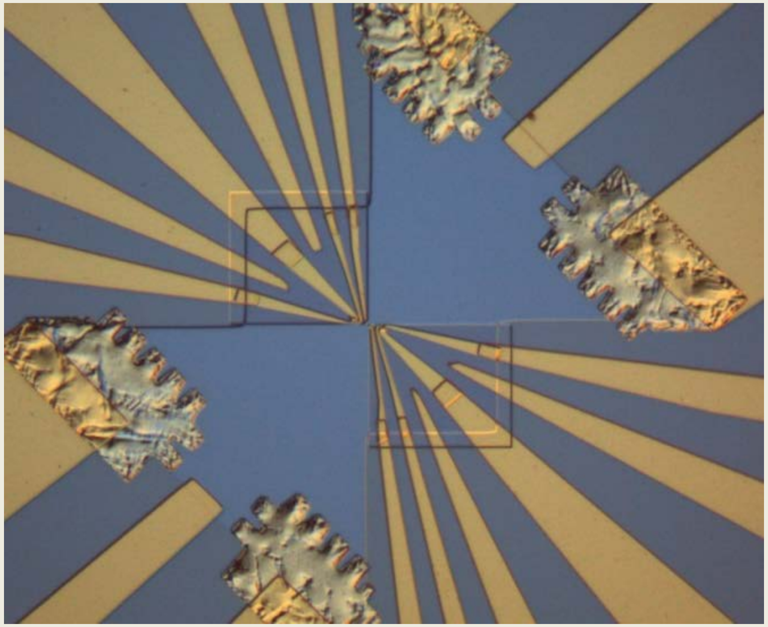
Interféromètres électroniques (2004)





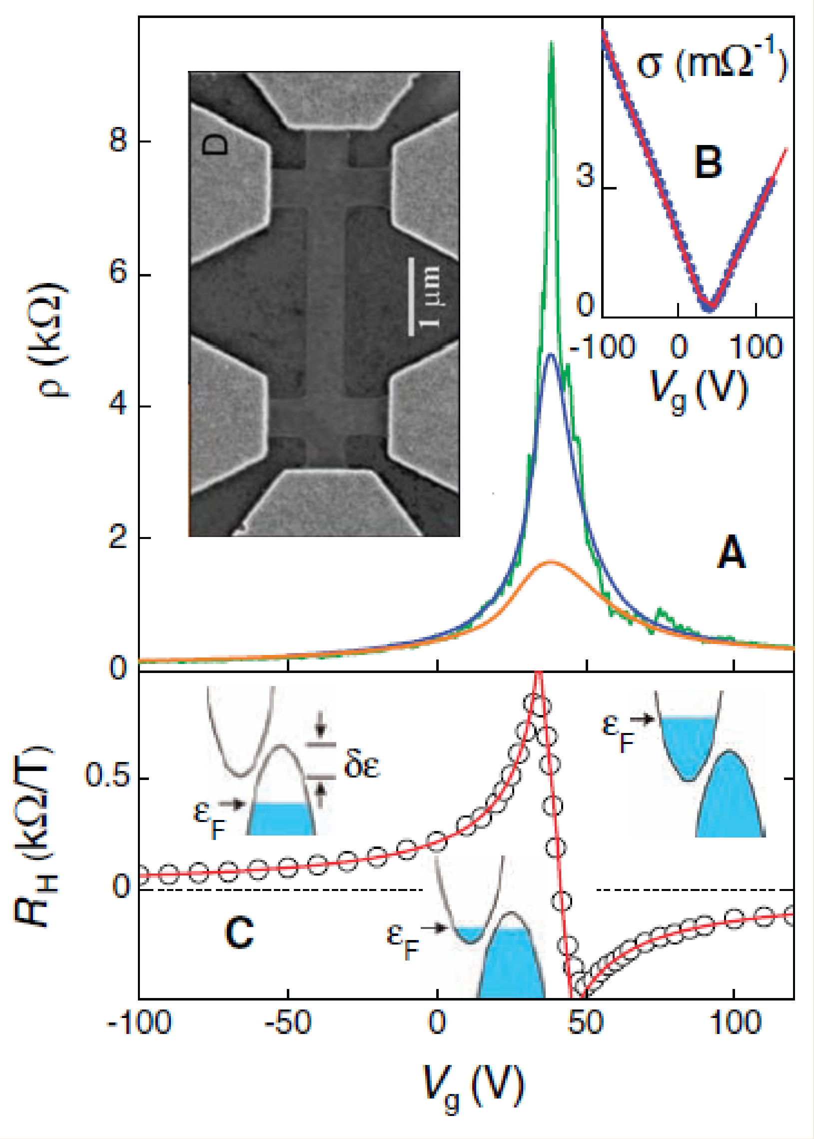
Collisionneurs à électrons uniques (2013)

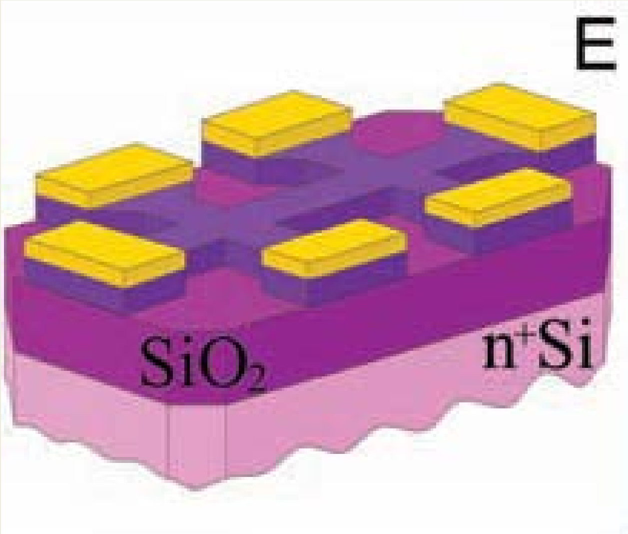




LPN-Marcoussis, SPEC-Saclay, LPA-ENS-Paris

$$\rho^{-1} = ne\mu \qquad ; R_H = B/ne$$



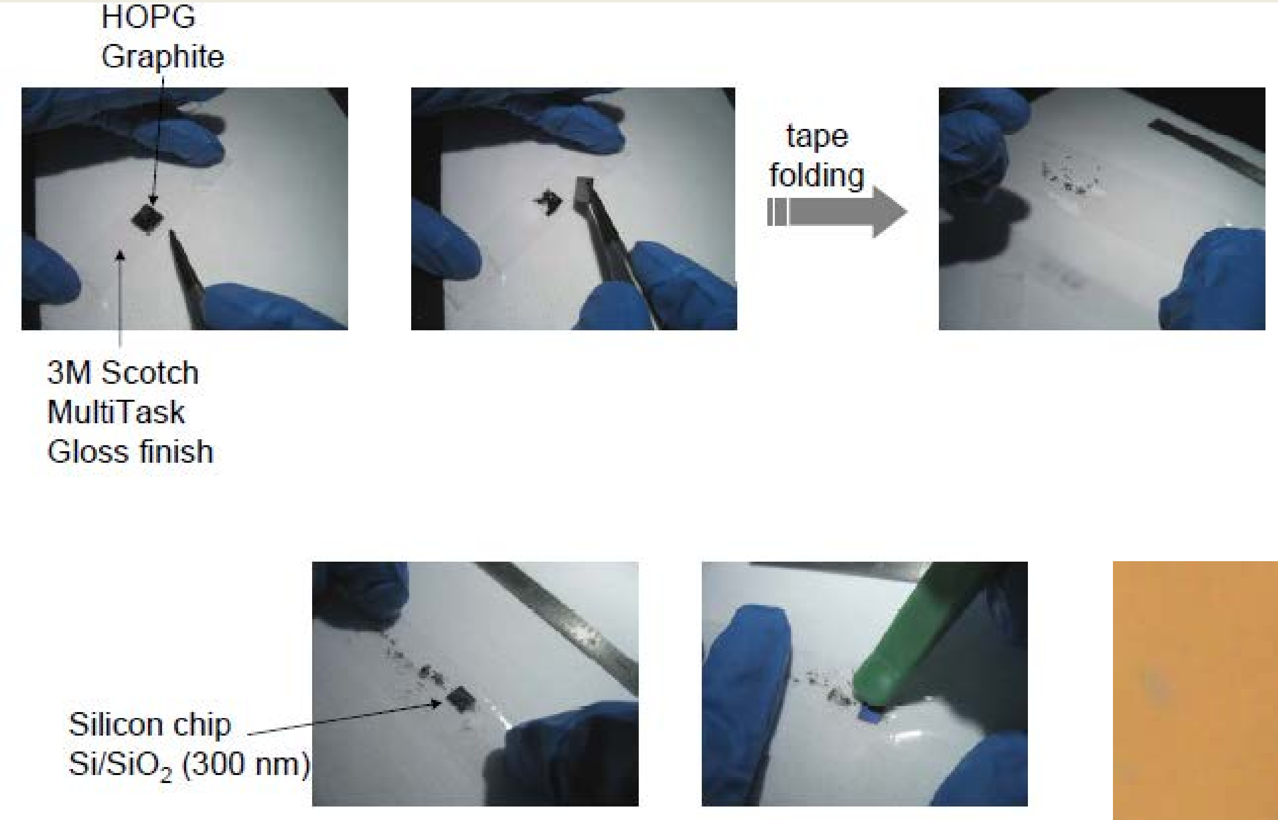


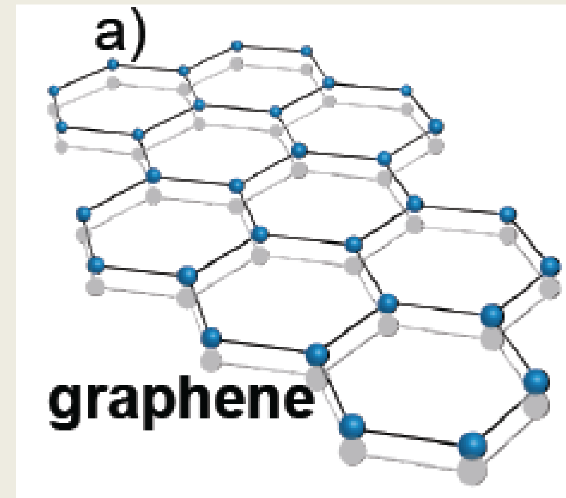
(Novoselov et al., Science 2004)

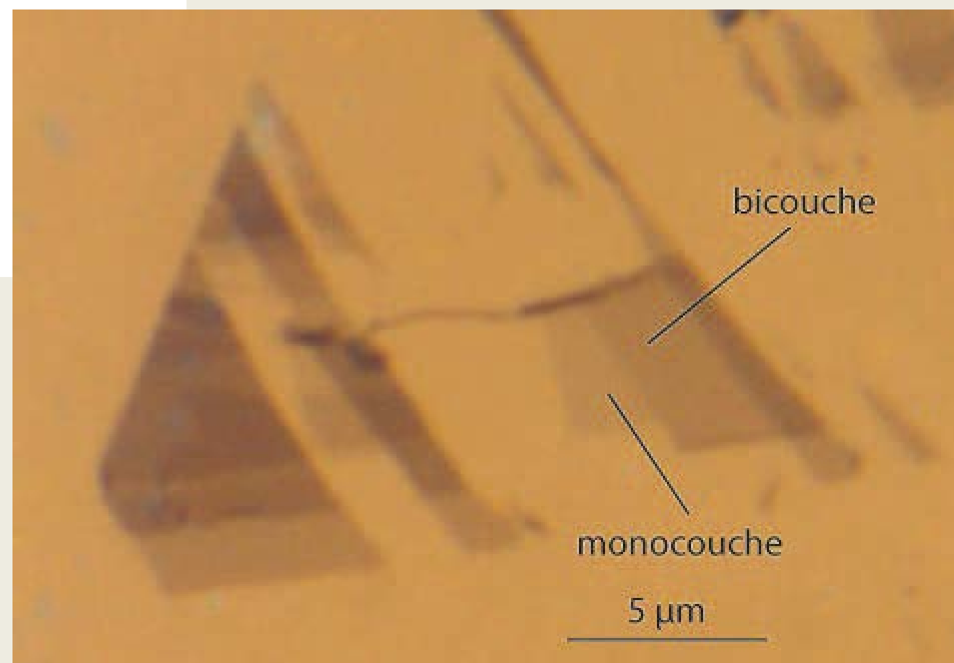
Graphène

- Le graphène et les autres matériaux 2D
- Les cristaux 2D et leurs substrat
- Propriétés étranges des électrons de Dirac
- À quoi peut servir le graphène en électronique ?

Exfoliation des cristaux de graphène

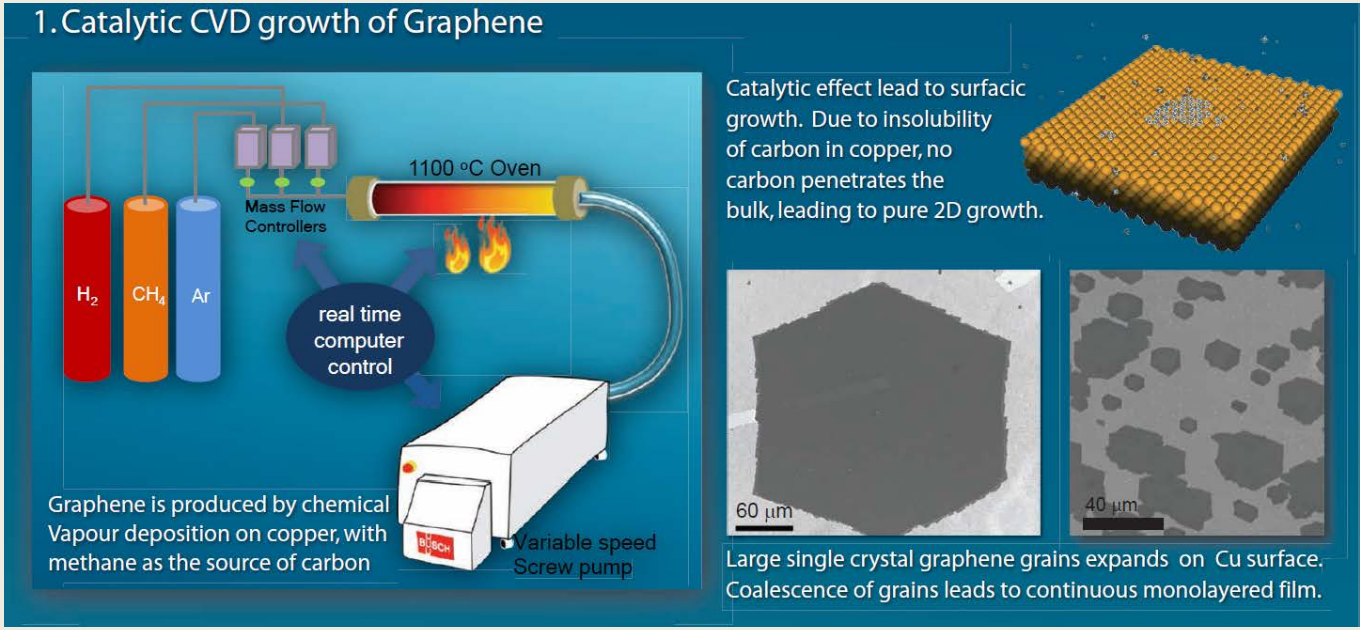


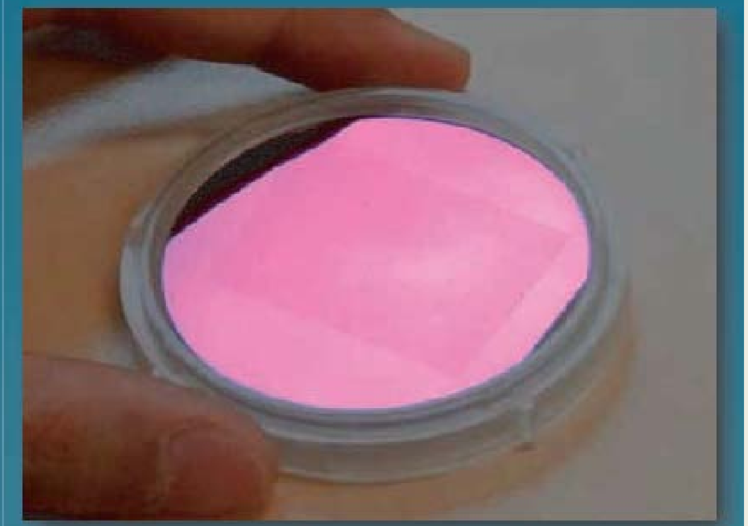




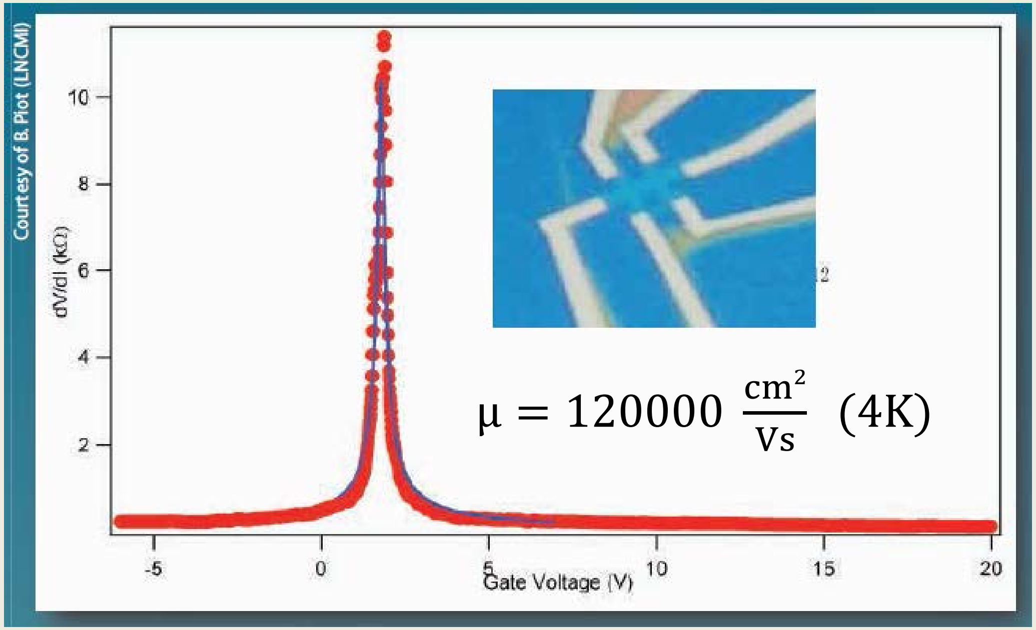
Croissance CVD : Grapheat® @ Néel-CNRS

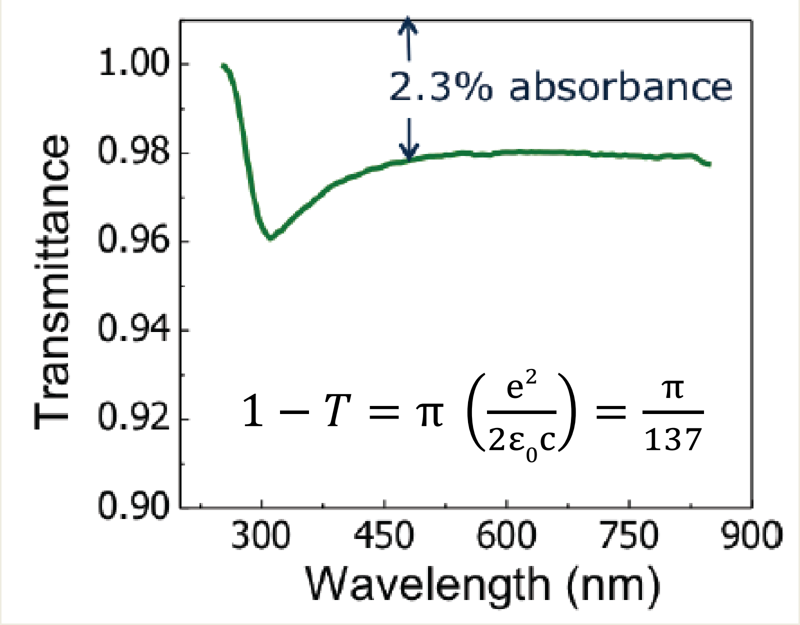
(courtoise V. Bouchiat)



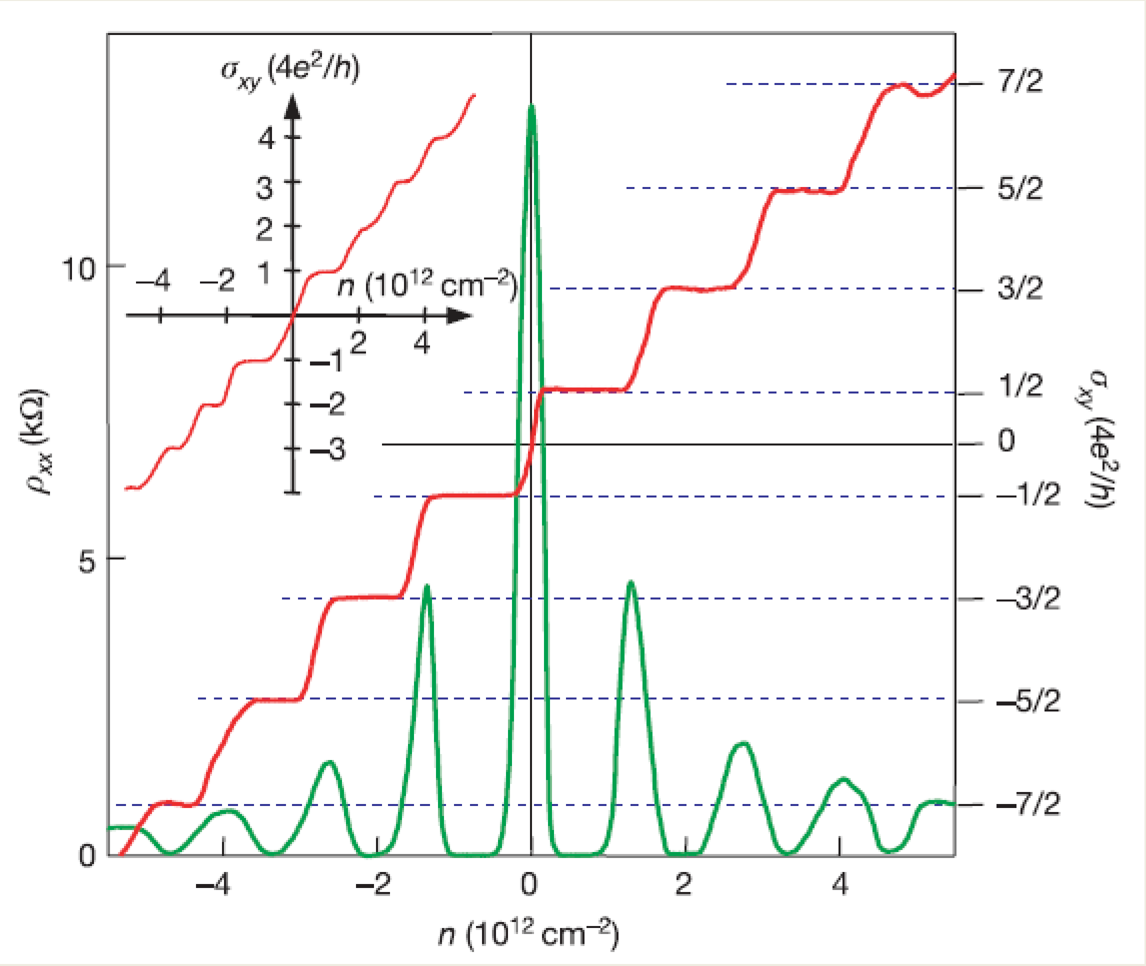


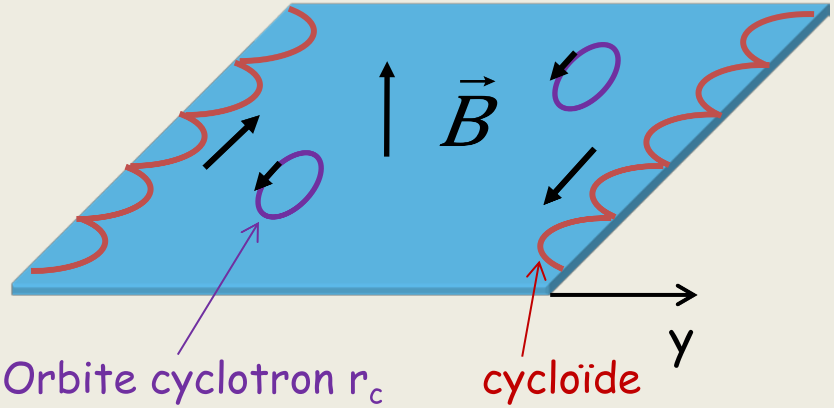
Typical aspect of transferred graphene

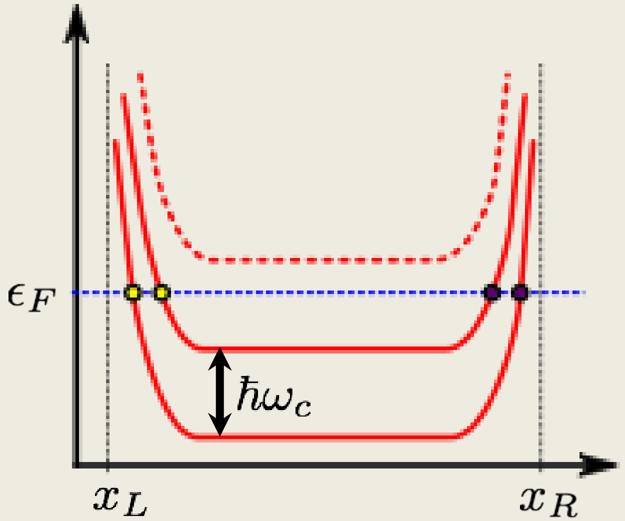




Effet Hall quantique du Graphene

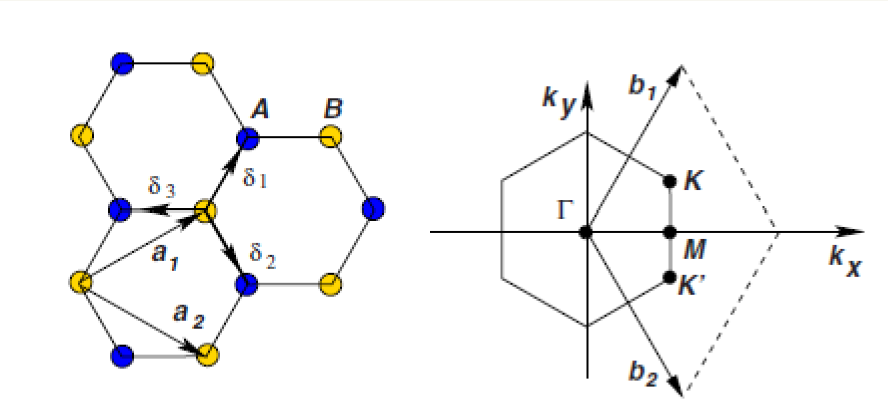


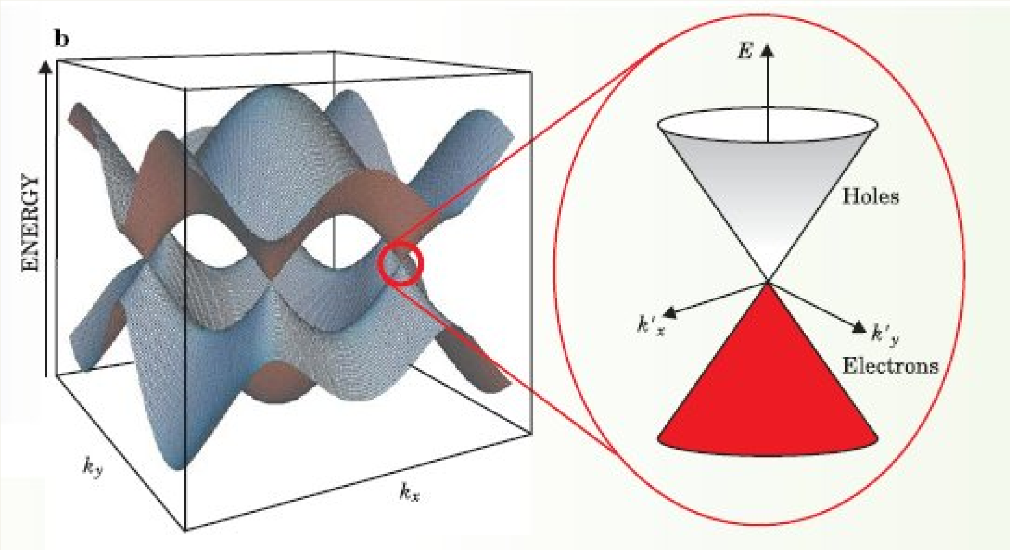




(Novoselov et al., Nature 2005)

Modèle liaisons fortes





(P.R. Wallace, PRB 1947)

- ✓ Deux atomes identiques par maille
  (sous réseaux équivalents A et B)

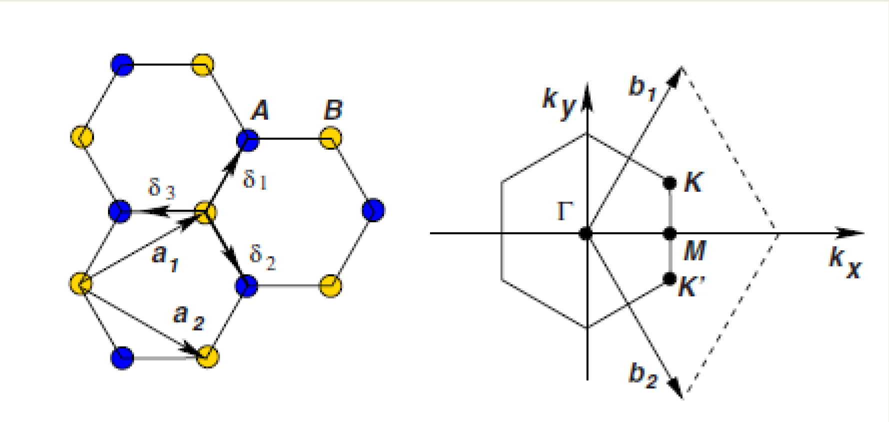
$$H = -t \sum_{i,j,\sigma} (a*_i\, b_j + H.c.)$$

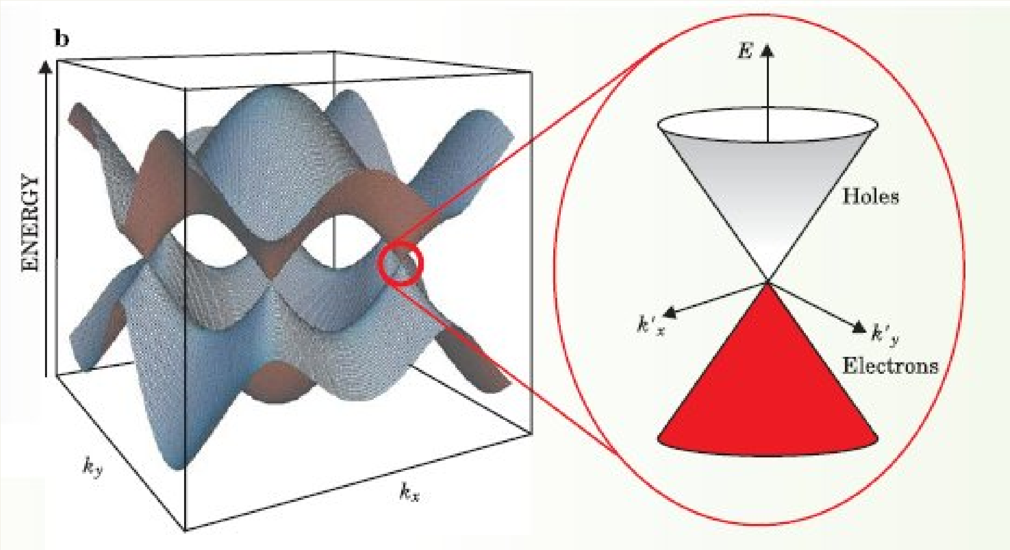
$t \approx 2{,}8\, eV \qquad a \approx 0{,}14\, nm$

- ✓ Deux points de Fermi non-équivalents K et K'

- ✓ Fort recouvrement des orbitales p_z entre premiers voisins

Modèle basse énergie → fermions de Dirac



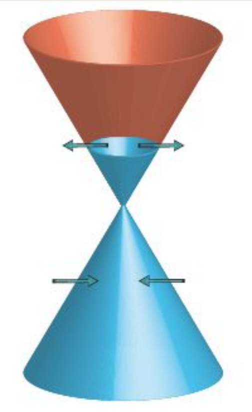


$$H = \hbar v_F \begin{pmatrix} 0 & q_x - iq_y \\ q_x + iq_y & 0 \end{pmatrix} = \hbar v_F\, \boldsymbol{\sigma}.\boldsymbol{q}$$

avec $q = K - k$ et $\boldsymbol{\sigma}$ les matrices de Pauli

$$v_F = \frac{3}{2}\, t\, a = 10^6\ m/s$$

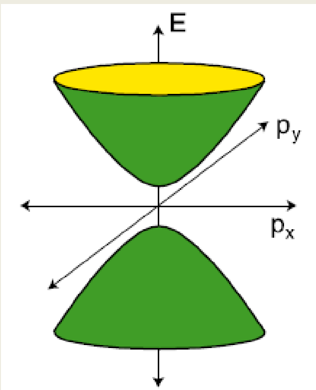
$$\boldsymbol{\Psi}_{\pm K}(q) = \frac{e^{iq.r}}{\sqrt{2}} \begin{pmatrix} 1 \\ \pm e^{i\theta_q} \end{pmatrix} \text{ avec } \theta_q = \tan^{-1}\frac{q_x}{q_y}$$

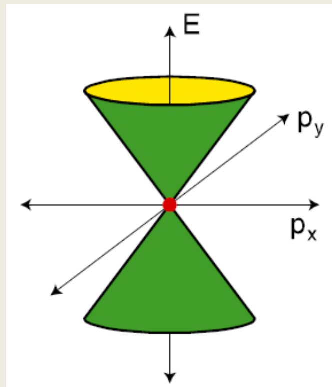


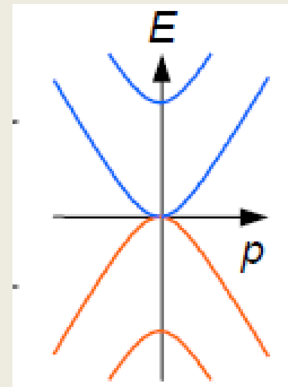
- ✓ Hamiltonien de Dirac (x4)
- ✓ Fonctions onde → spinneur
- ✓ Pseudo spin de sous-réseau
- ✓ Modèle robuste (± 1eV)

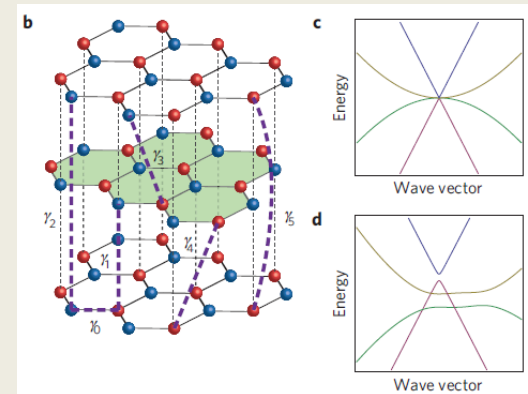
Signatures Hall-Quantique « des Graphenes »

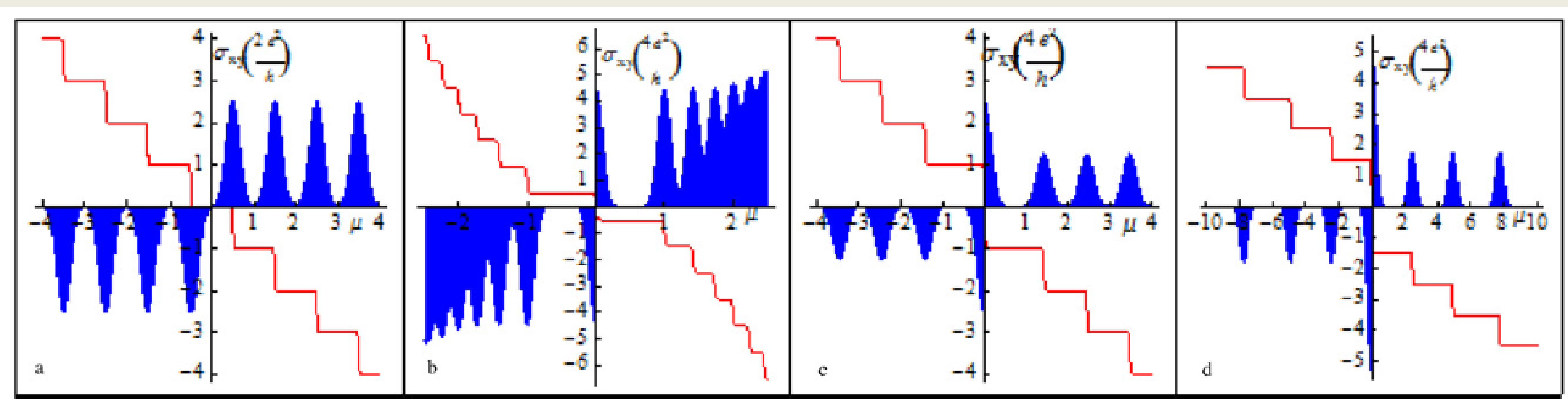
Gas 2D | Graph. 1-couche | Graph. 2-couches | Grap. 3-couches









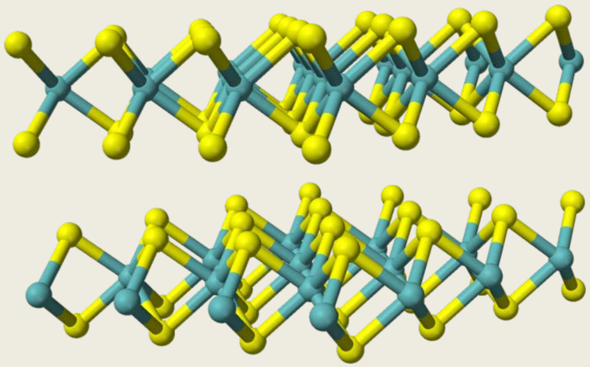


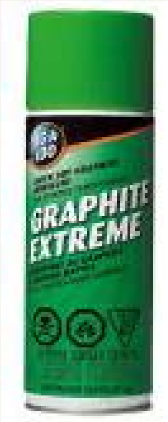
(Barlas et al., Nanotech 2012)

Caractéristiques d'un 2D matériau

1. Crystal 2D d'épaisseur atomique
2. Propriétés dépendent qualitativement du nombre de couches
3. Le transport dépendent à l'ordre zéro de la symétrie du cristal
4. Fortement accordables par des grilles ou autres actions locales

Quid des autres matériaux 2D ?

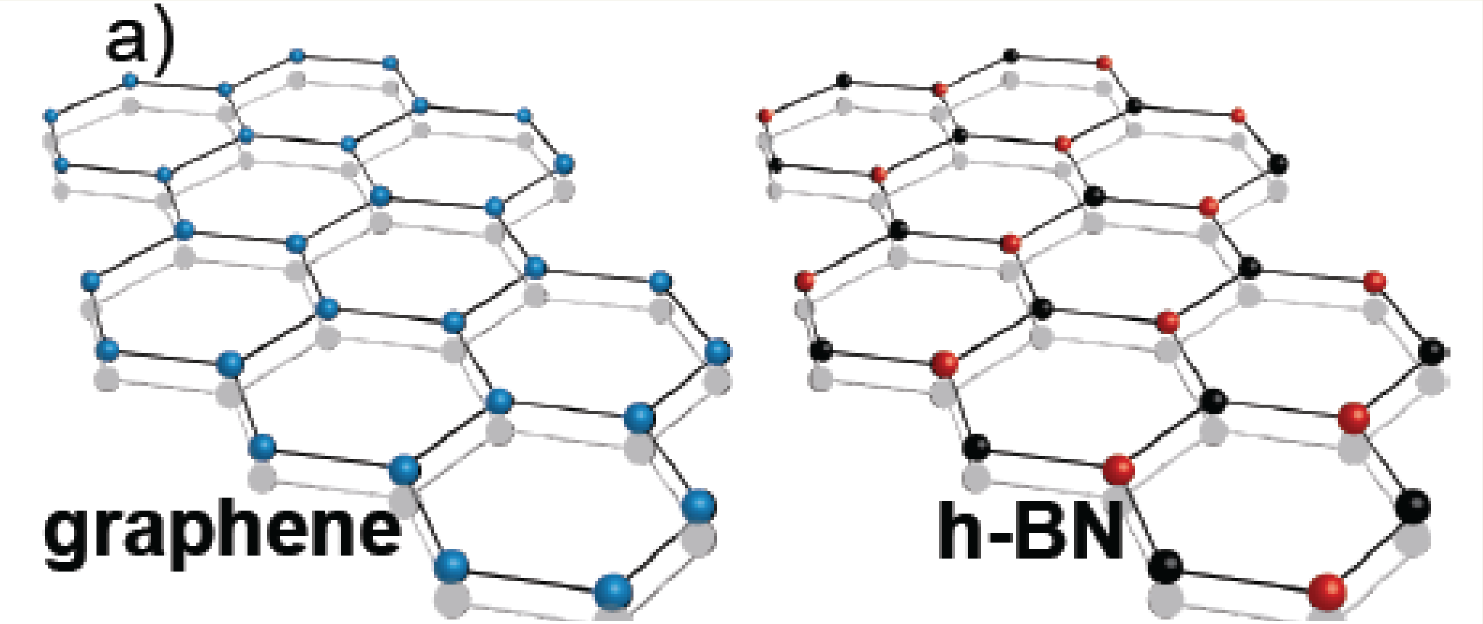




Graphene family	Graphene	hBN 'white graphene'	BCN	Fluorographene	Graphene oxide
2D chalcogenides	MoS_2, WS_2, $MoSe_2$, WSe_2	Semiconducting dichalcogenides: $MoTe_2$, WTe_2, ZrS_2, $ZrSe_2$ and so on	Metallic dichalcogenides: $NbSe_2$, NbS_2, TaS_2, TiS_2, $NiSe_2$ and so on	Layered semiconductors: GaSe, GaTe, InSe, Bi_2Se_3 and so on	
2D oxides	Micas, BSCCO	MoO_3, WO_3	Perovskite-type: $LaNb_2O_7$, $(Ca,Sr)_2Nb_3O_{10}$, $Bi_4Ti_3O_{12}$, $Ca_2Ta_2TiO_{10}$ and so on	Hydroxides: $Ni(OH)_2$, $Eu(OH)_2$ and so on	
	Layered Cu oxides	TiO_2, MnO_2, V_2O_5, TaO_3, RuO_2 and so on		Others	

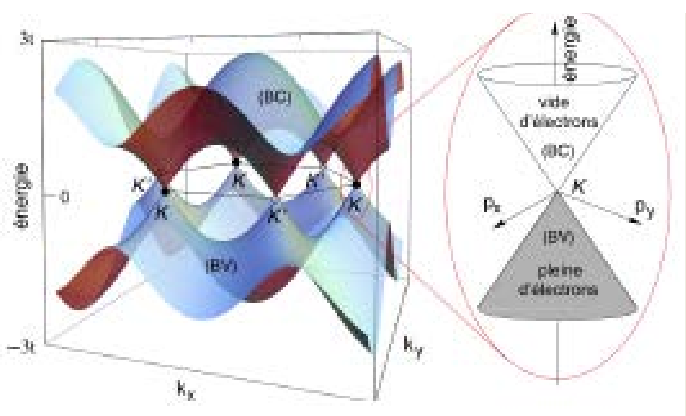
*AK Geim & IV Grigorieva Nature **499**, 419-425 (2013) doi:10.1038/nature12385*

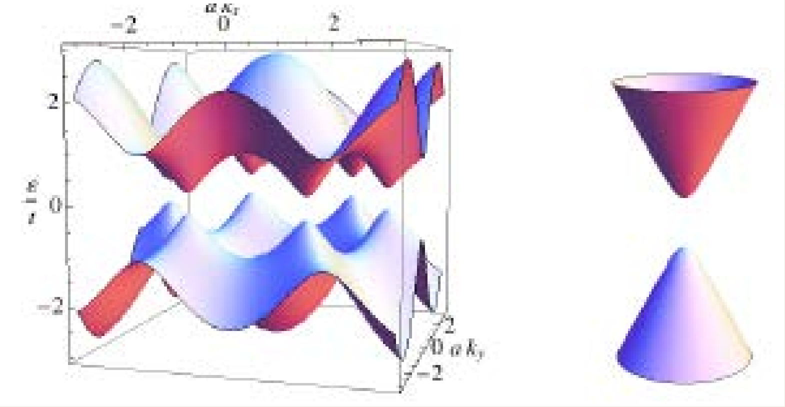
Graphènes en noir et blanc (h-BN)



band-gap = 0

band-gap = 6eV !





J-N. Fuchs, habilitattion, Orsay 2013

Où se procurer du hBN ?

TRÈS BN® Cosmetic Powders

Boron Nitride powders for color cosmetics and skin care

Features / Benefits

- Lamellar crystal structure improves texture
- Soft and lubricious for superior spreading and adherence
- Decreases tack by absorbing excess oils
- Finely divided particle size distributions

  < = 2 um high opacity and soft focus

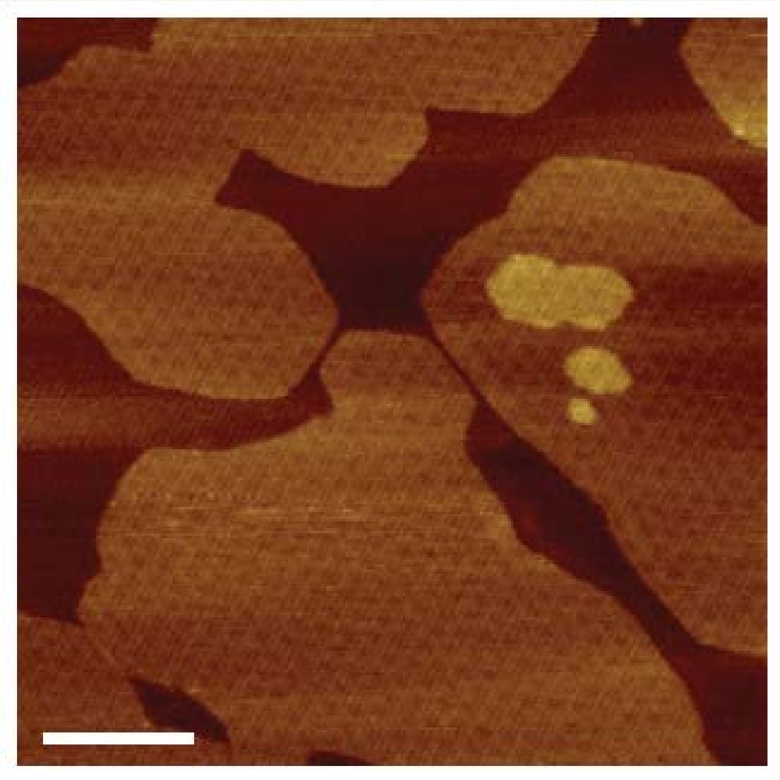
  6 - 8 um for luminous coverage and soft focus

  12- 16 um for translucent appearance

  > 16 um for reflection and luminosity

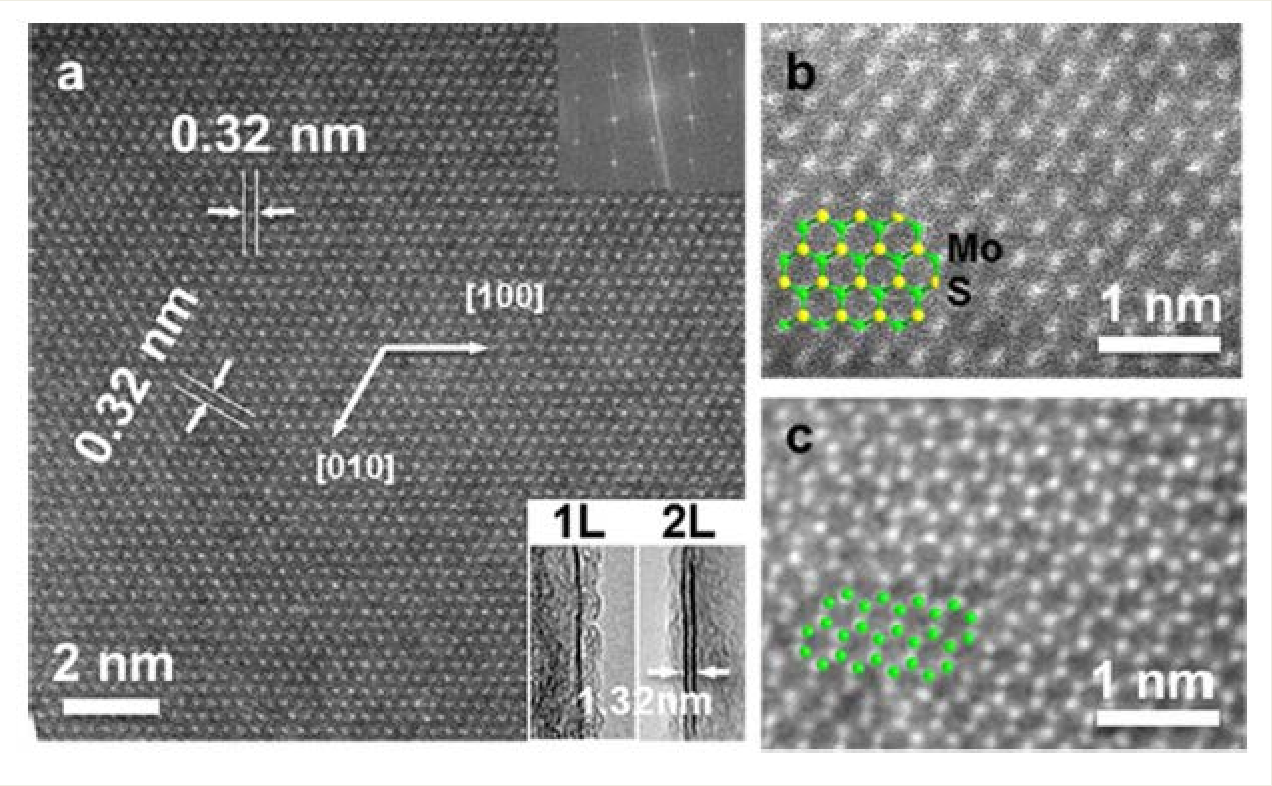
Les 2DMs en grande surface (CVD sur metal)

h-BN



W. Yang et al., Nature Mat. (2013)

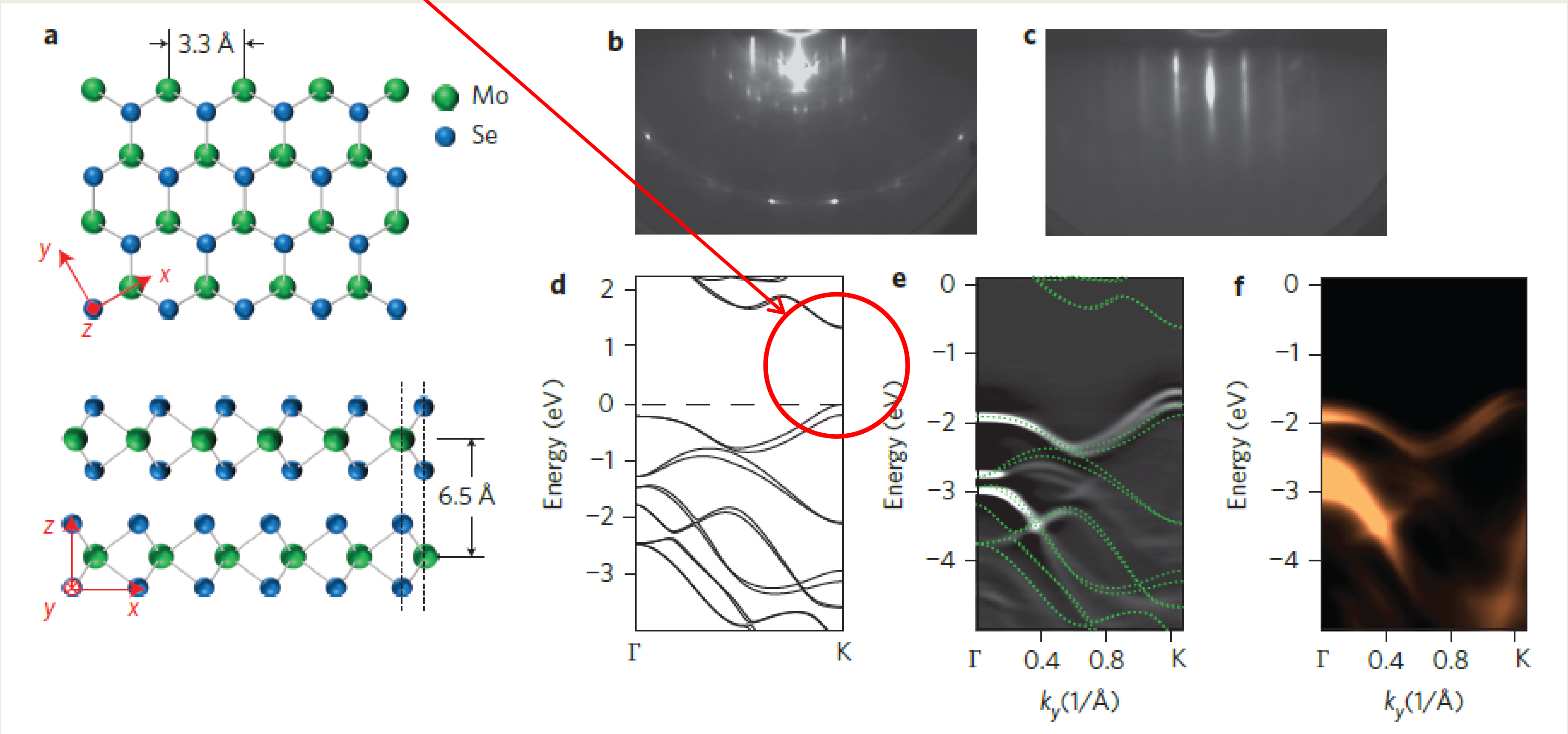
MoS2



Y. Zhang et al., Nature Nanot.. (2013)

Monocouche => gap direct

multicouche => gap indirect



(Y. Zhang et al., Nature Nanotech 2013)

Graphène

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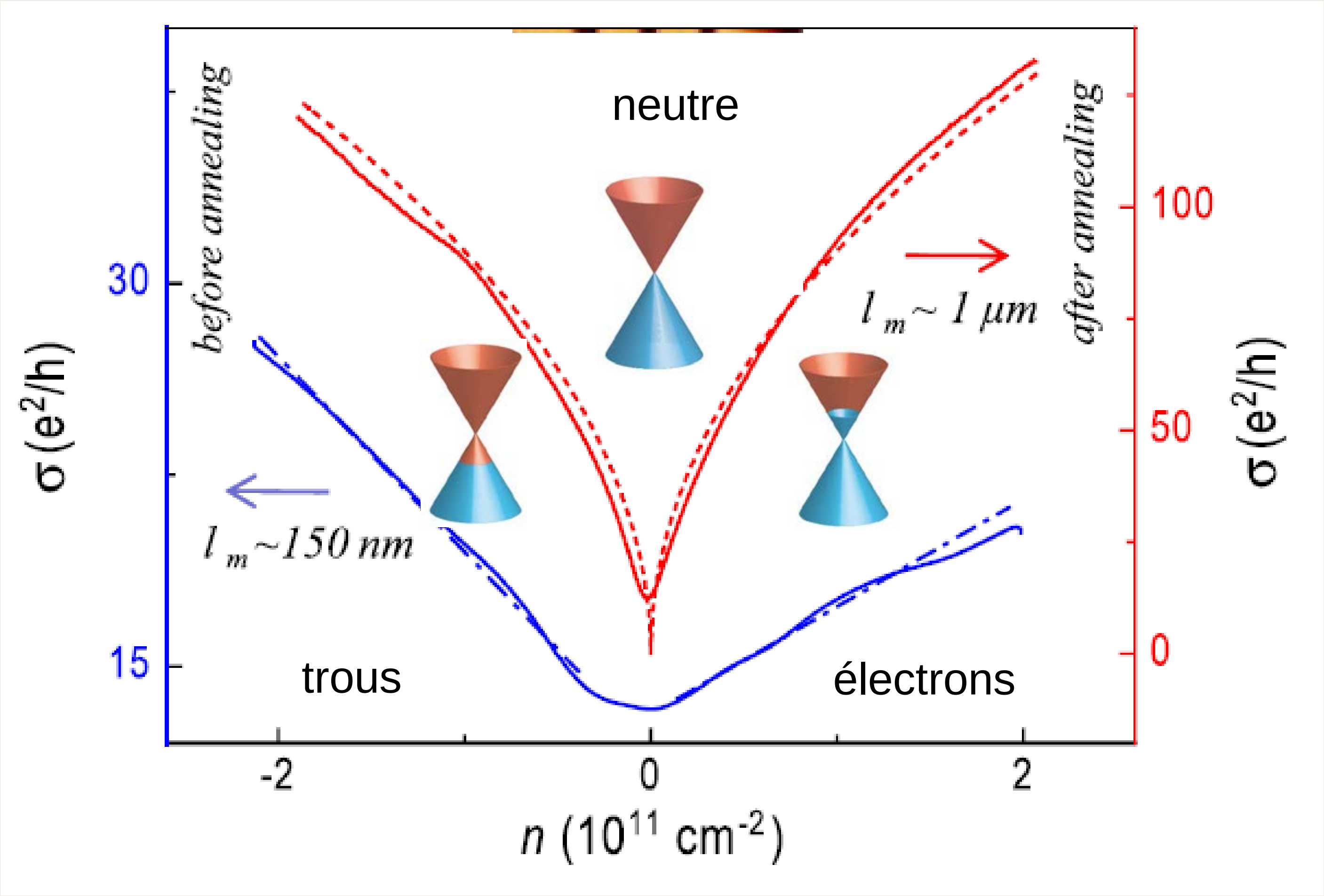
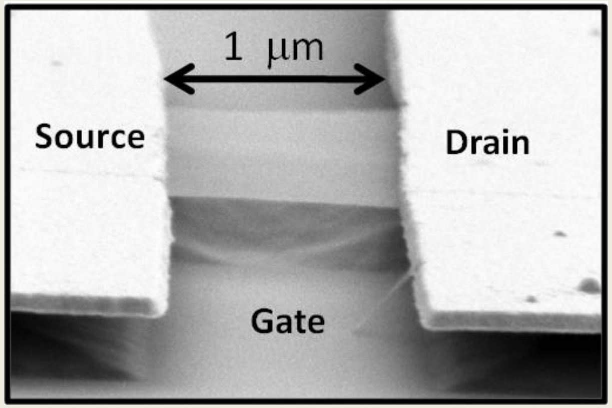
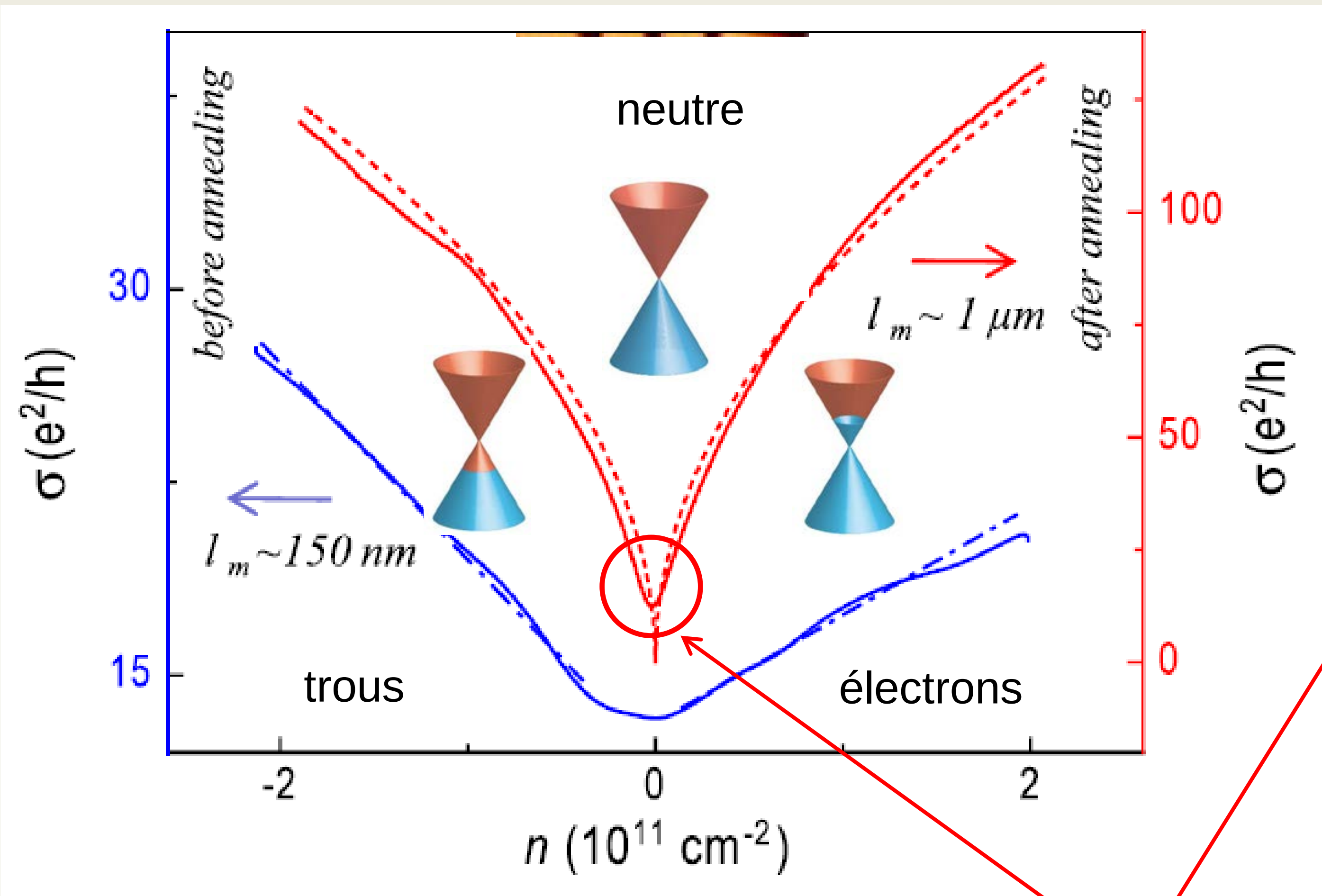
Le graphène suspendu

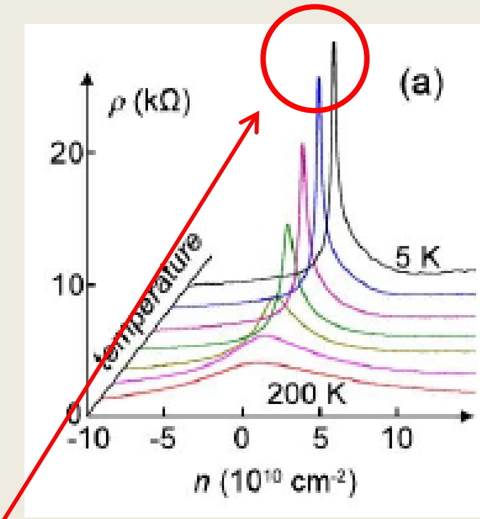




(K.I. Bolotin et al. PRL2008)

Transport à la limite quantique



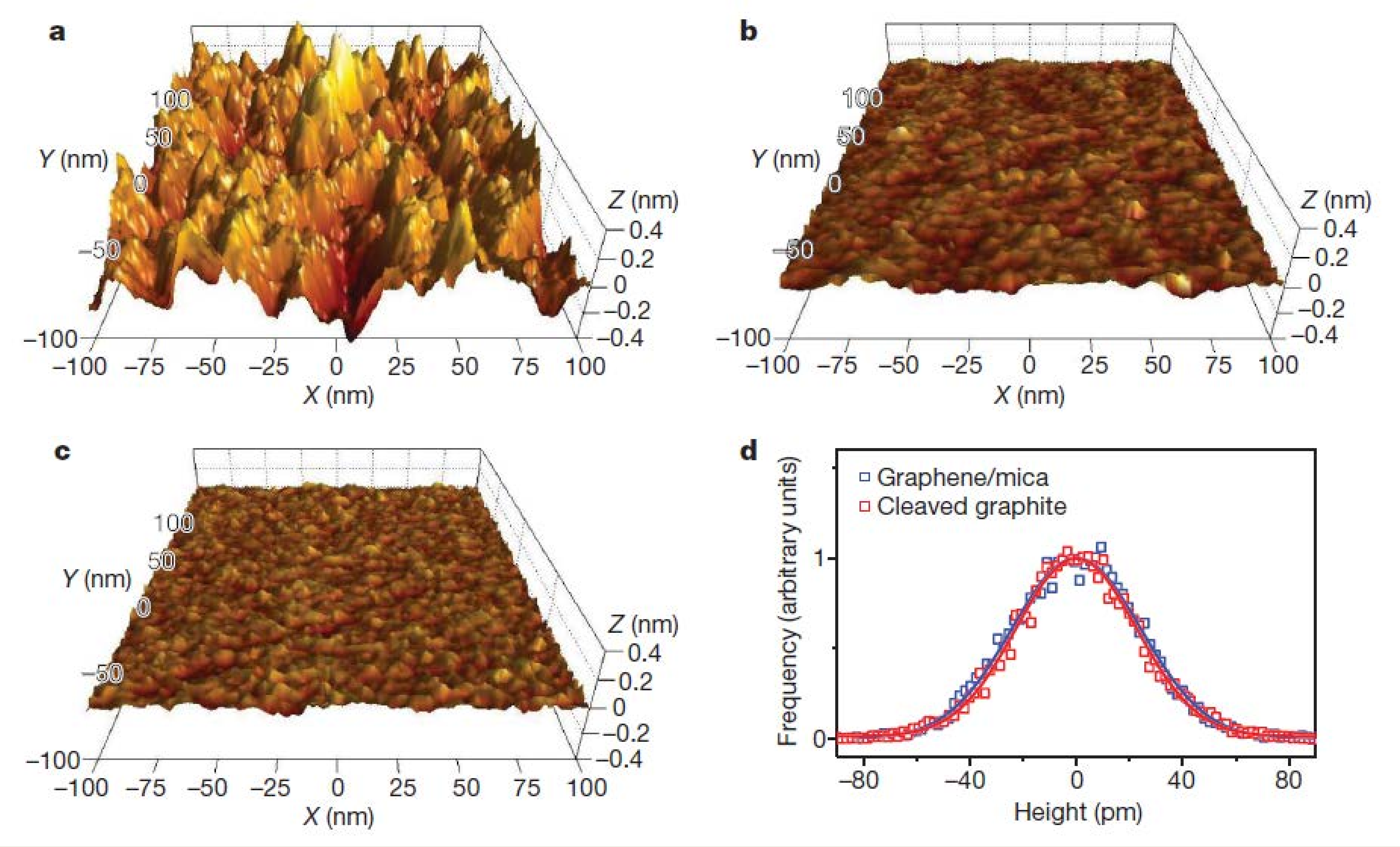


(E.V. Castro et al. PRL2010)

(K.I. Bolotin et al. PRL2008)

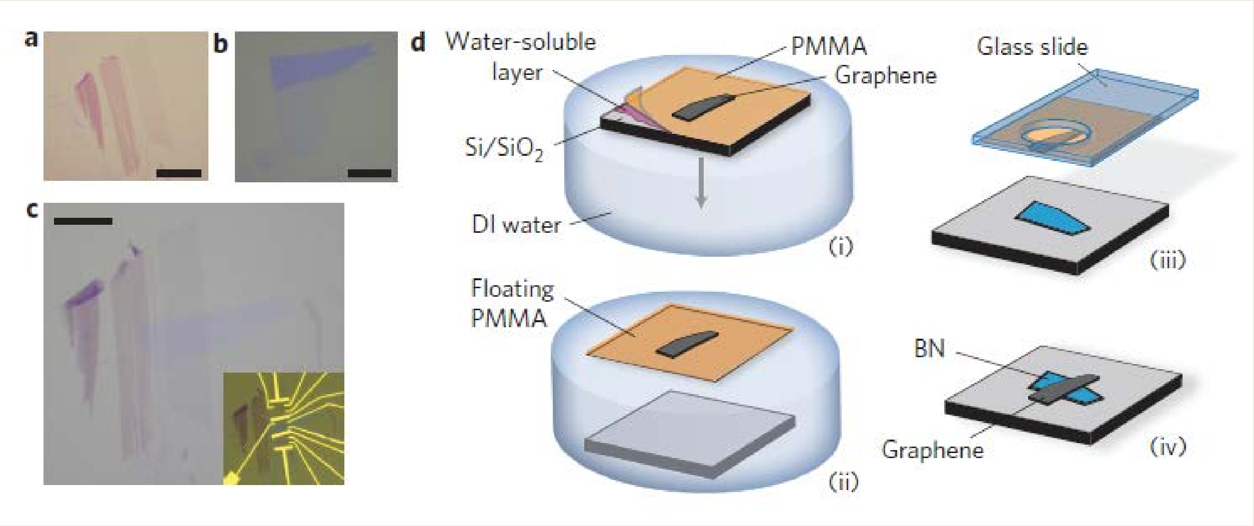
Conductivité minimum $\sigma \sim \frac{4e^2}{h}$

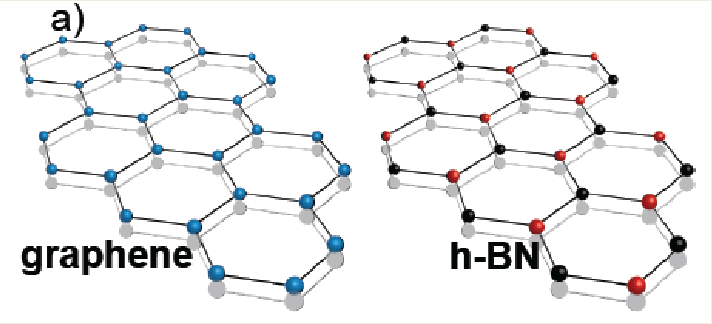
Tapis de fakir ou moquette haute laine

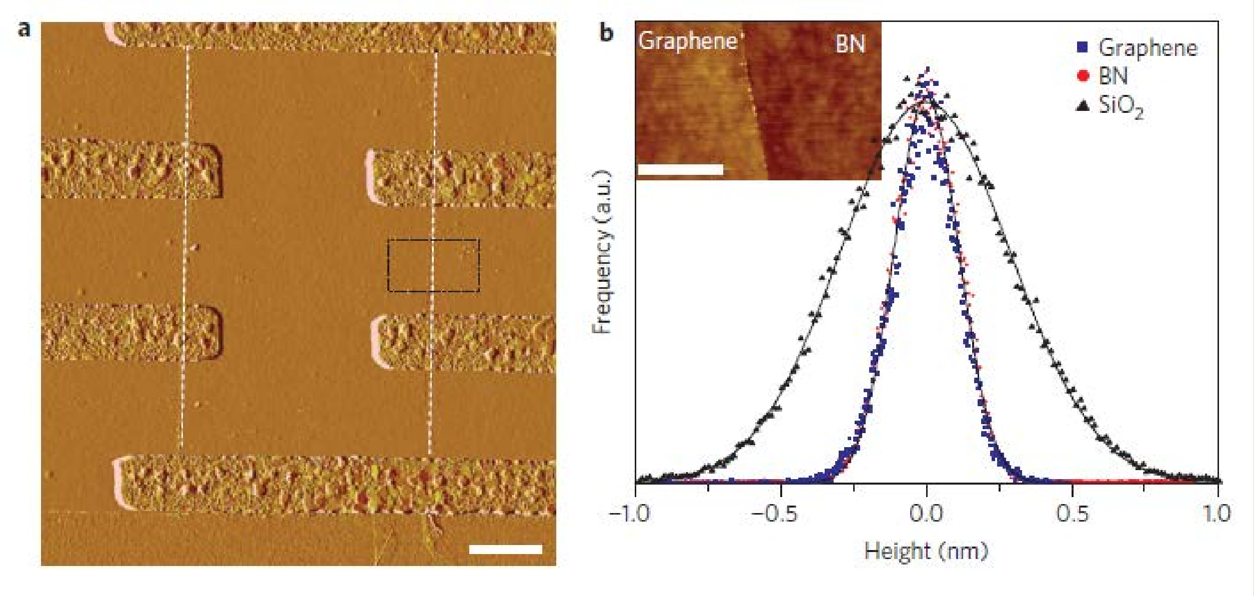


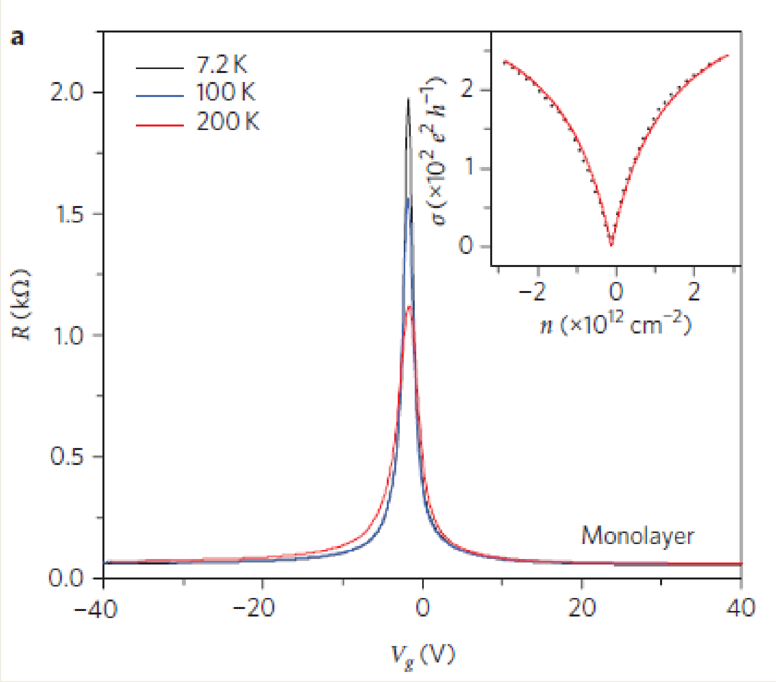
(Lui et al., Nature 2009)

Exfolié sur un autre matériau 2D, e.g. h-BN



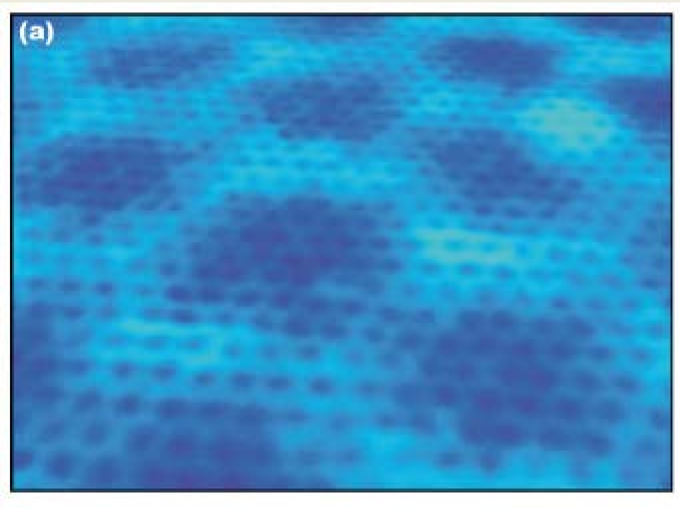




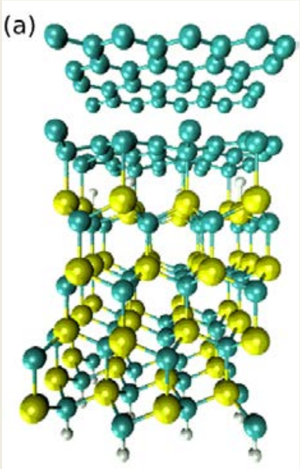


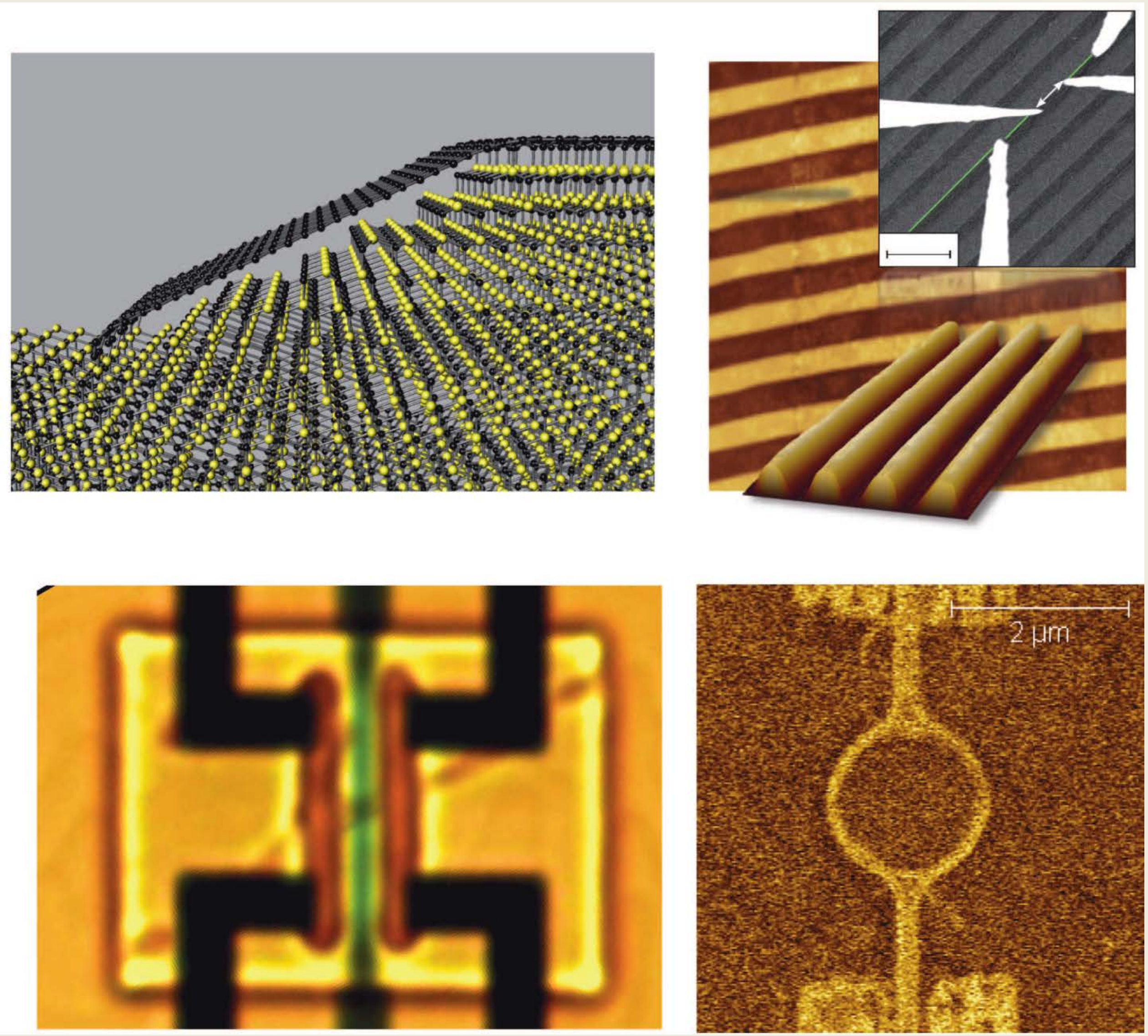
(Dean et al., Nanoletters 2010)

Épitaxié à la surface de SiC



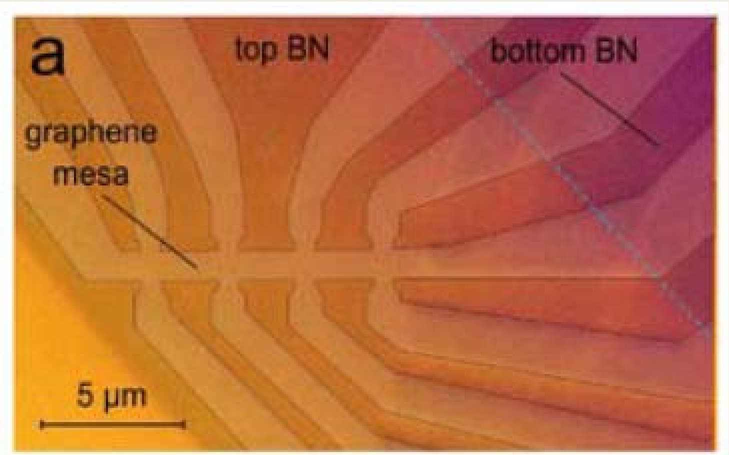
(Courtesy of P. Mallet, Néel)

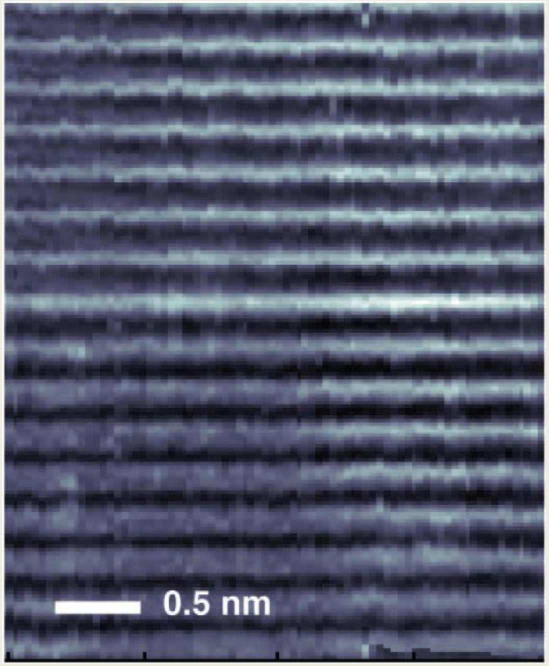


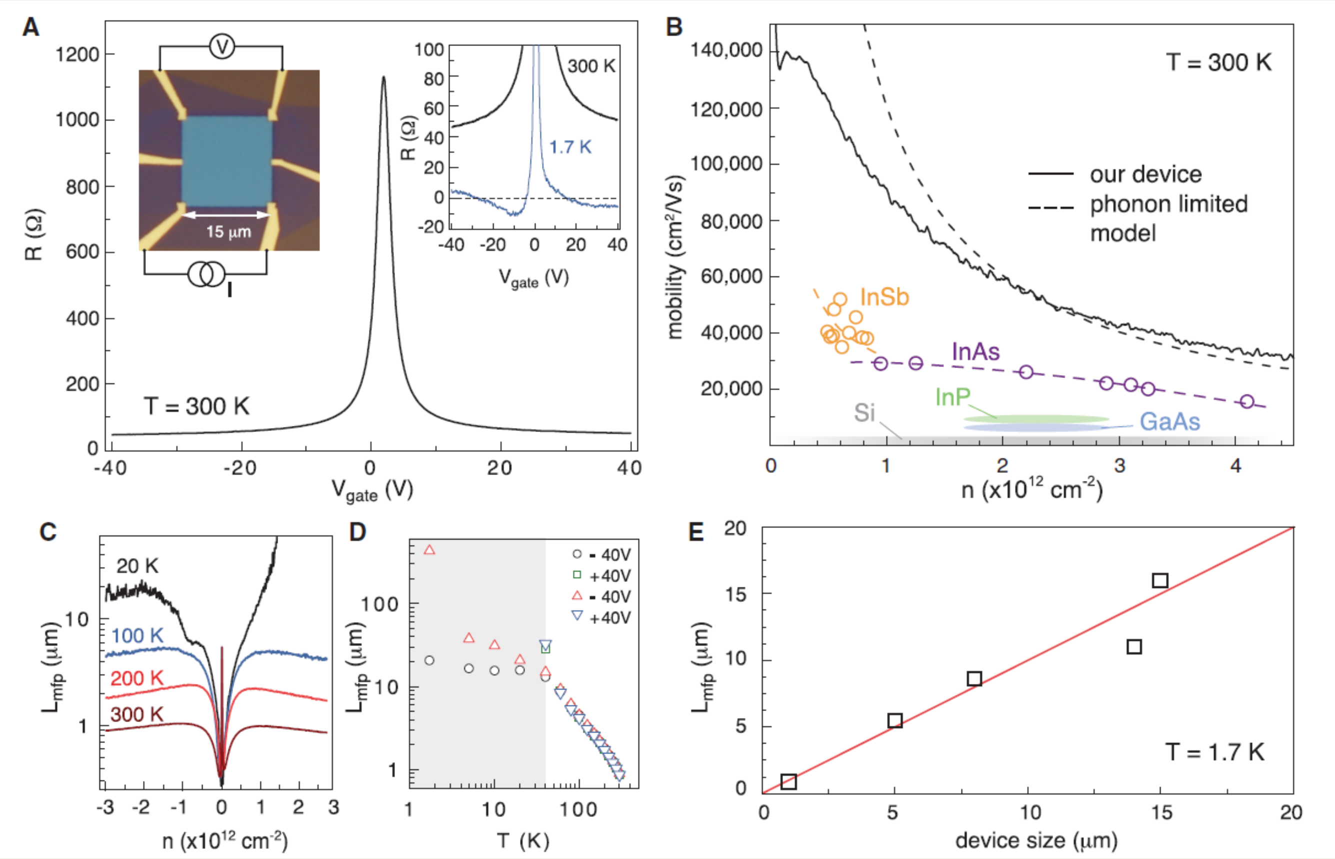


(Baringhaus et al. Nature 2014)

Balistique : encapsulé entre cristaux de h-BN

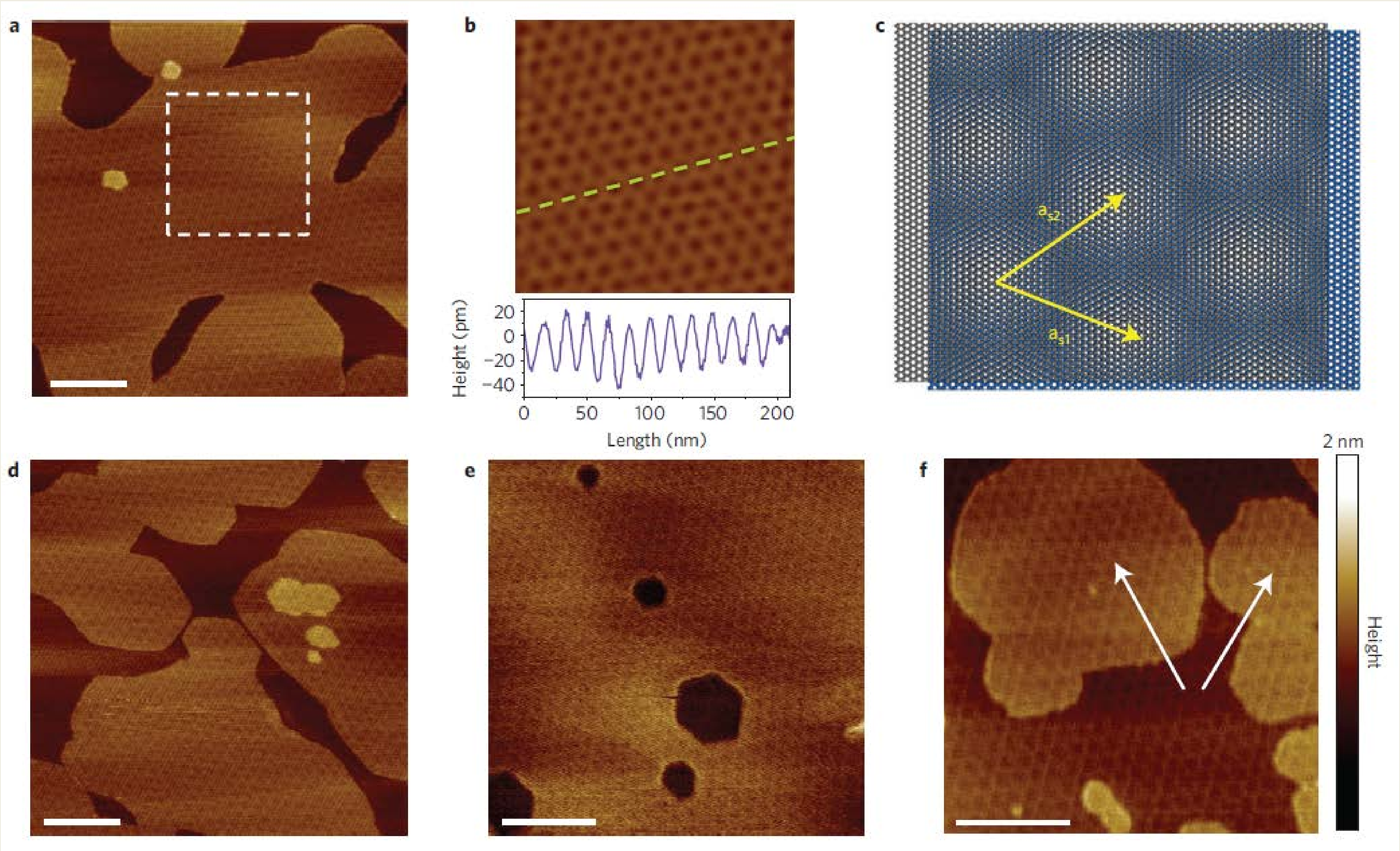






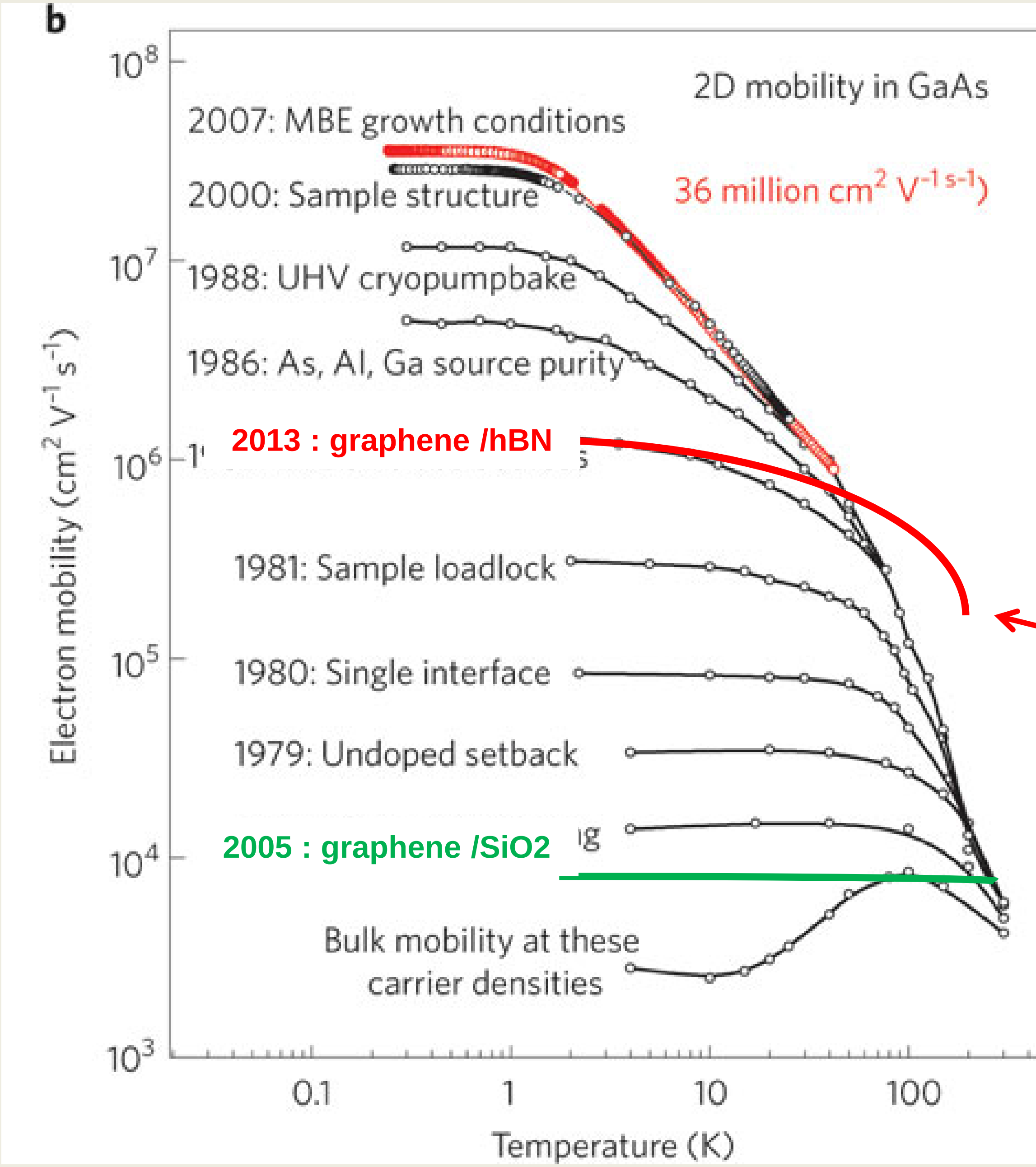
L. Wang et al., Science 342, 614 (2013)

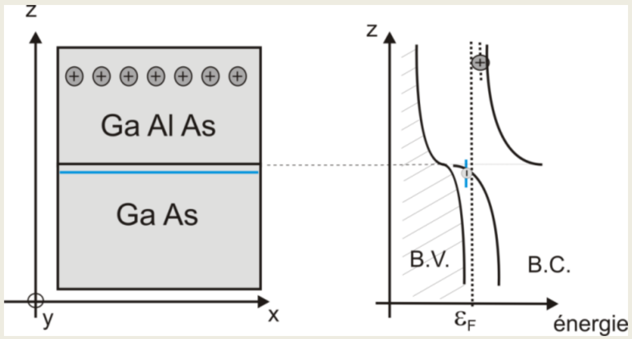
Ou par croissance directe sur h-BN



(W. Jang et al., Nature Nanotech 2014)

Haute mobilité même à température ambiante





Very weak effect of phonons

Room temperature applications ?

Graphène

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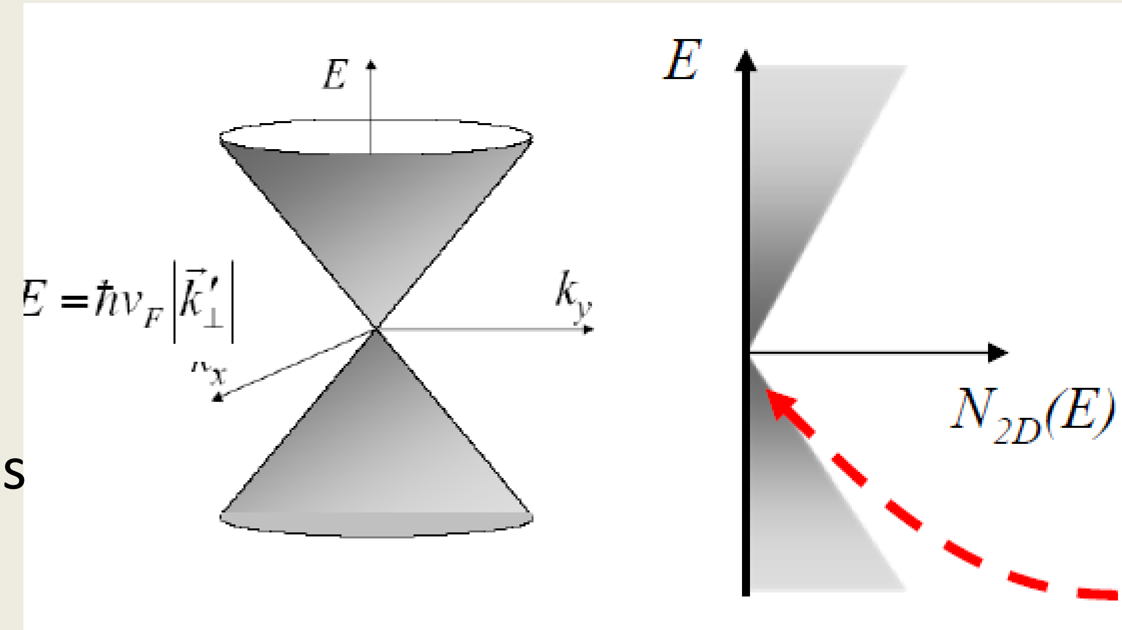
- À quoi peut servir le graphène en électronique ?

Comparatif 2DEG-graphène

Electrons de Dirac

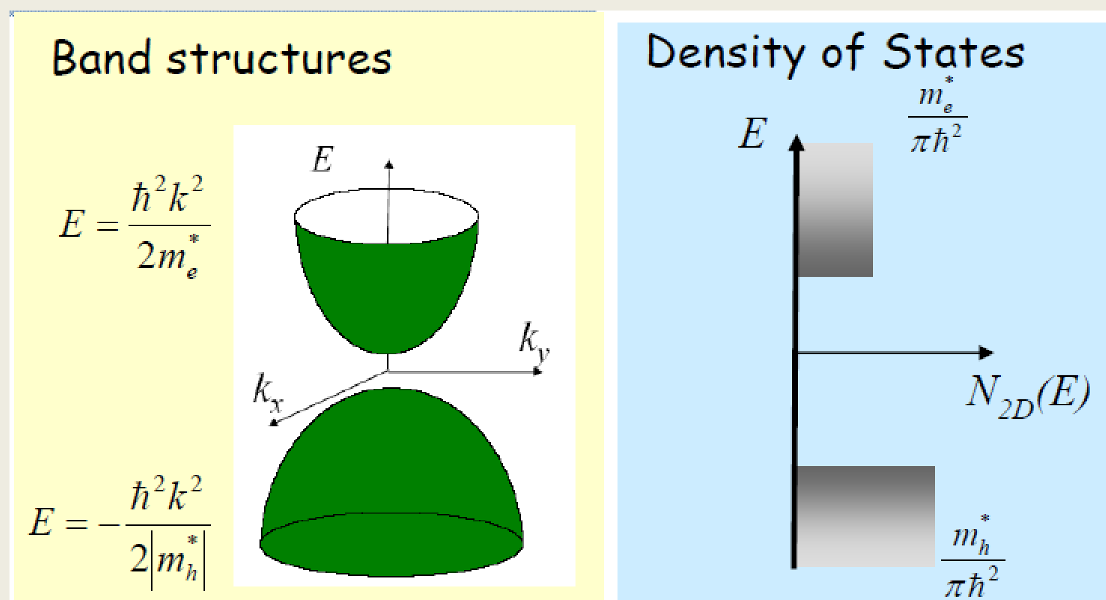
Relation dispersion linéaire
Fermions de masse nulle
Symétrie électron-trou
Pas de bande interdite
Singularité de la densité d'états
La fonction d'onde = spineur



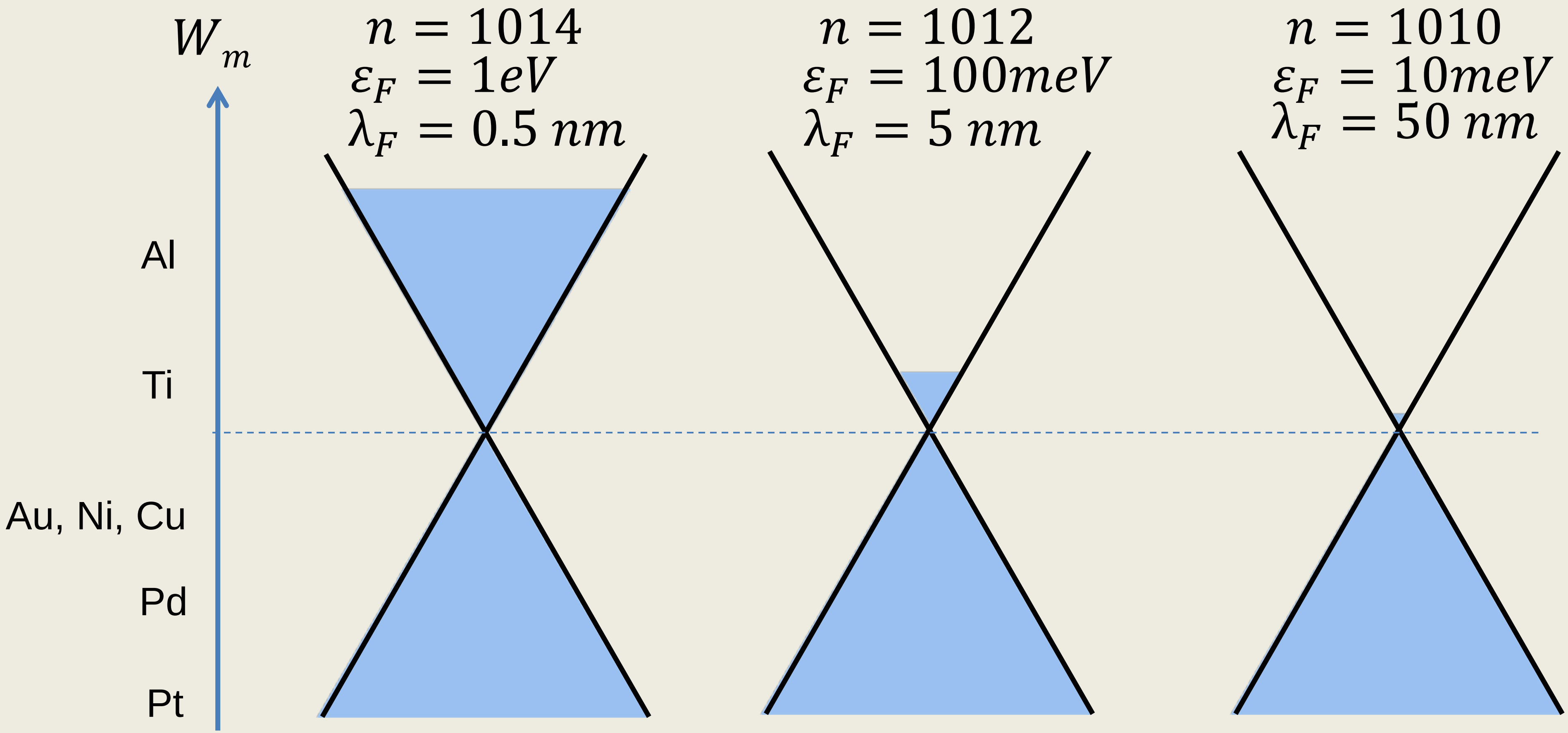
Dirac point

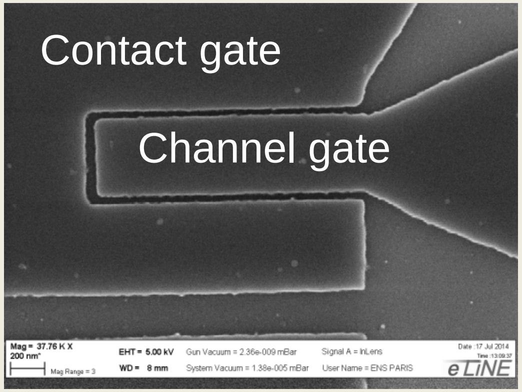
Electrons de Schrödinger

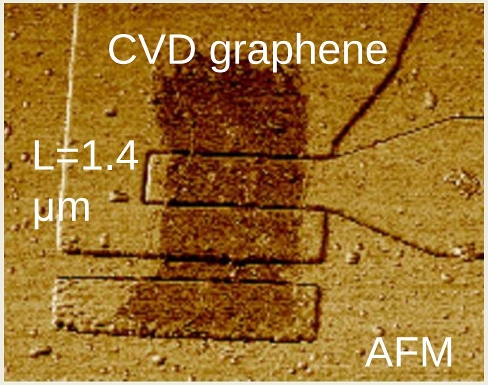
Dispersion parabolique
Fermions massifs
Electrons ≠ trous
Une bande interdite
Fonctions de Bloch scalaires

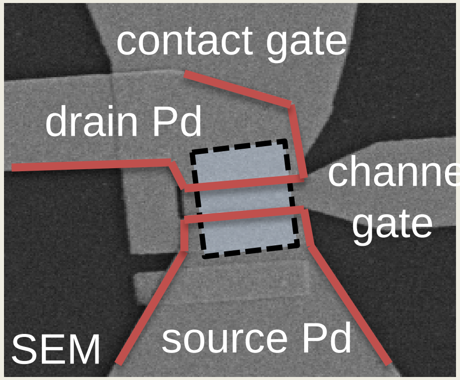


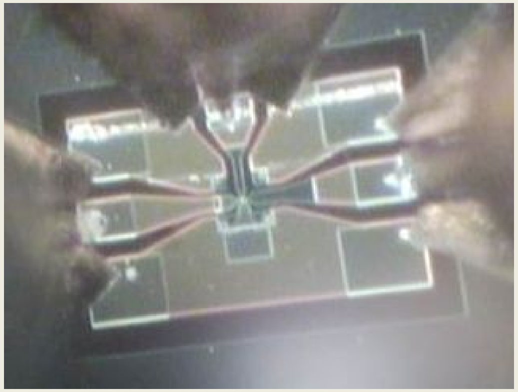
Un effet de champ très efficace



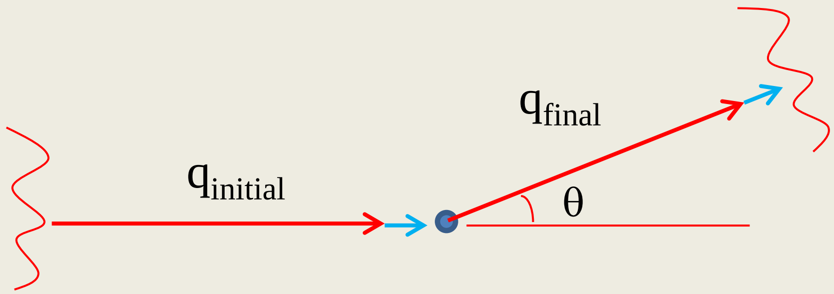


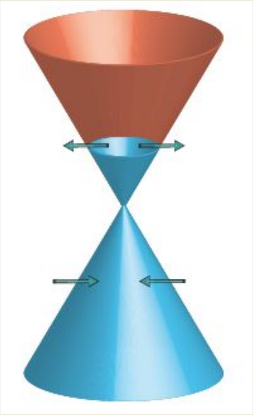






Effet spinneur et suppression de la rétrodiffusion

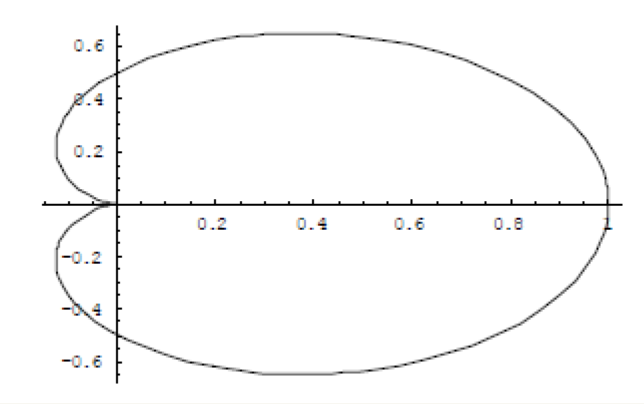




$$\tau^{-1} \propto \int d\theta\,(1 - \cos\theta)(\mathbf{1} + \mathbf{cos}\,\boldsymbol{\theta})\,|V(q)|^2$$

Conductivité : $\sigma = e^2 N(\varepsilon_F)\, v_F{}^2 \tau / 2$

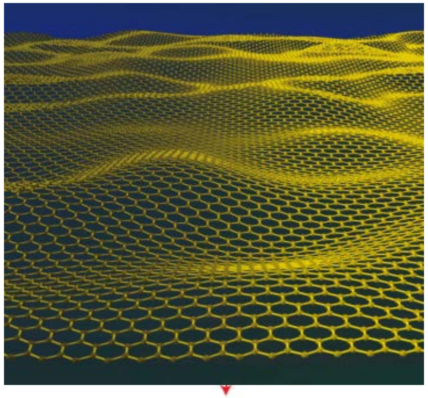
- Suppression de la rétrodiffusion directe
- D'où les grandes valeurs de mobilité
- Mais pas seulement …./….



Des mécanismes exotiques de diffusion

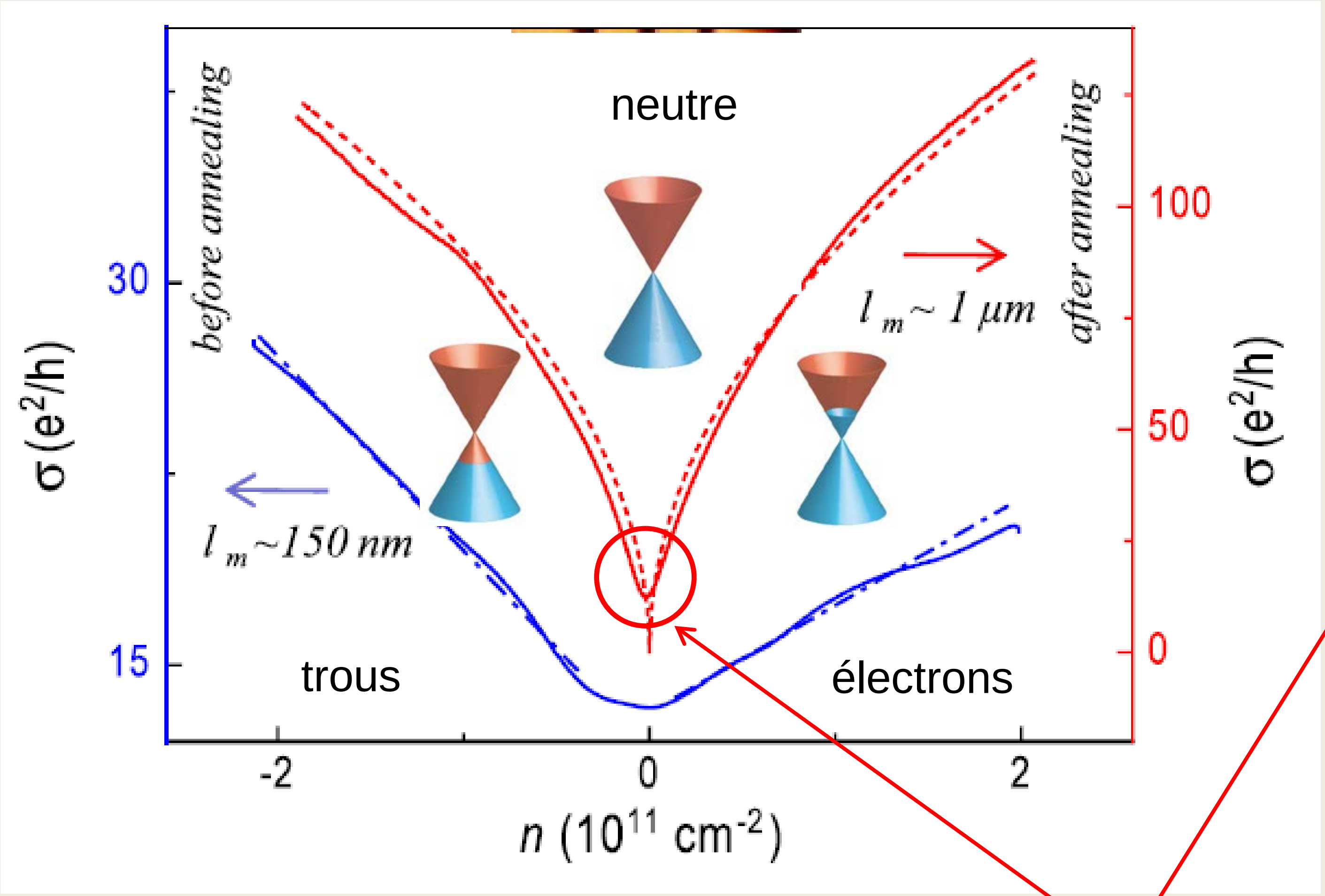
	scalar		gauge-field		Dirac-mass
$H_K = \hbar v_F \sigma \cdot q$	$+ \quad V(q)\hat{I}$	$+$	$\alpha\sigma \cdot U$	$+$	$\delta m^* \sigma_z$

$$\hat{I} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

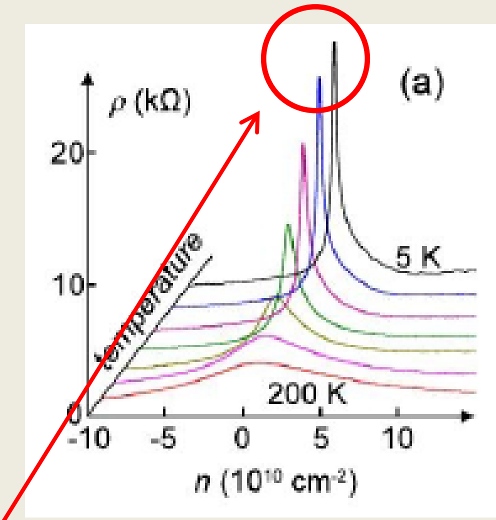


- scalar disorder ($\hat{I}$-term), short range : adsorbates, void, etc...)
- scalar disorder ($\hat{I}$-term), long range : no screening of charged impurities
- gauge field disorder : static distortions like ripples, etc...
- Dirac mass disorder : local lifting of sublattice degeneracy

Transport à la limite quantique



(K.I. Bolotin et al. PRL2008)



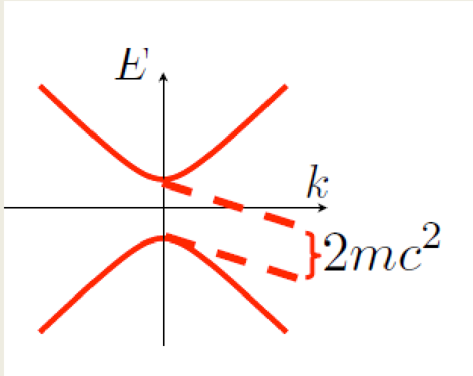
(E.V. Castro et al. PRL2010)

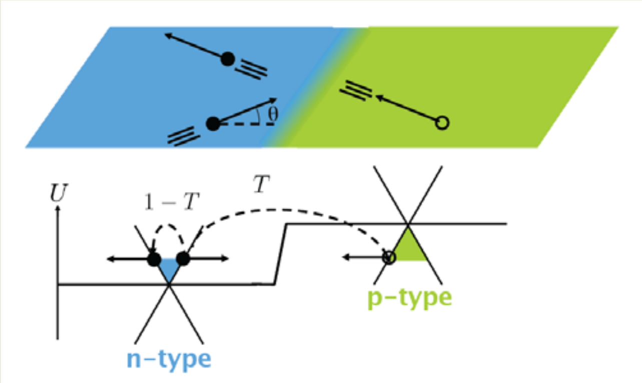
Conductivité minimum $\sigma \sim \frac{4e^2}{h}$

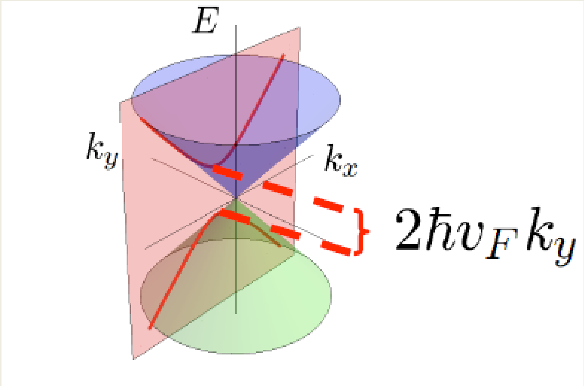
Des propriétés de réfraction anormales

Fermions relativistes massifs

Porteurs du graphène



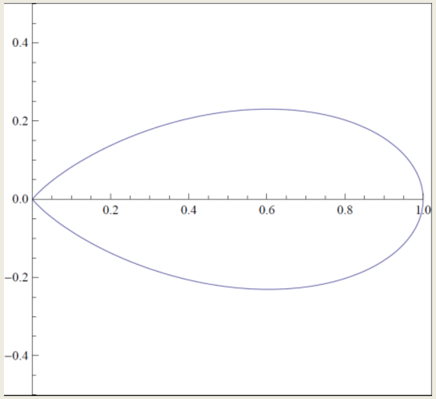




$$E = \pm\sqrt{(mc^2)^2 + (\hbar\, c\, k)^2}$$

$$T(q_y) = exp\left(-\pi\hbar\, v_F k_c{}^2 / \frac{\partial U}{\partial x}\right)$$

(F. Sauter, Z. Phys. 1931)



$$E = \pm\sqrt{\left(\hbar\, v_F\, q_y\right)^2 + (\hbar\, v_F\, q_x)^2}$$

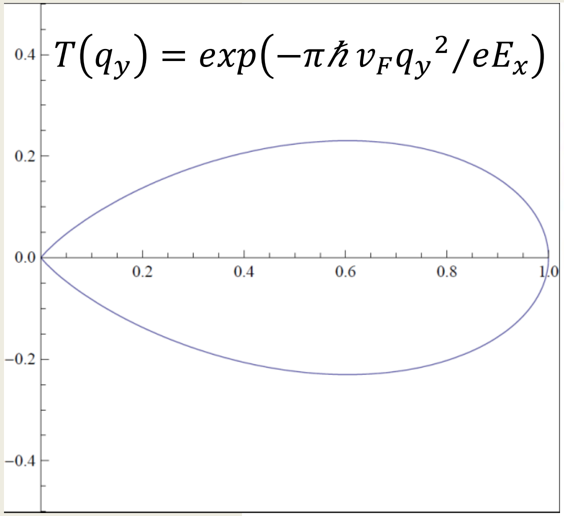
$$T(q_y) = exp\left(-\pi\hbar\, v_F q_y{}^2 / eE_x\right)$$

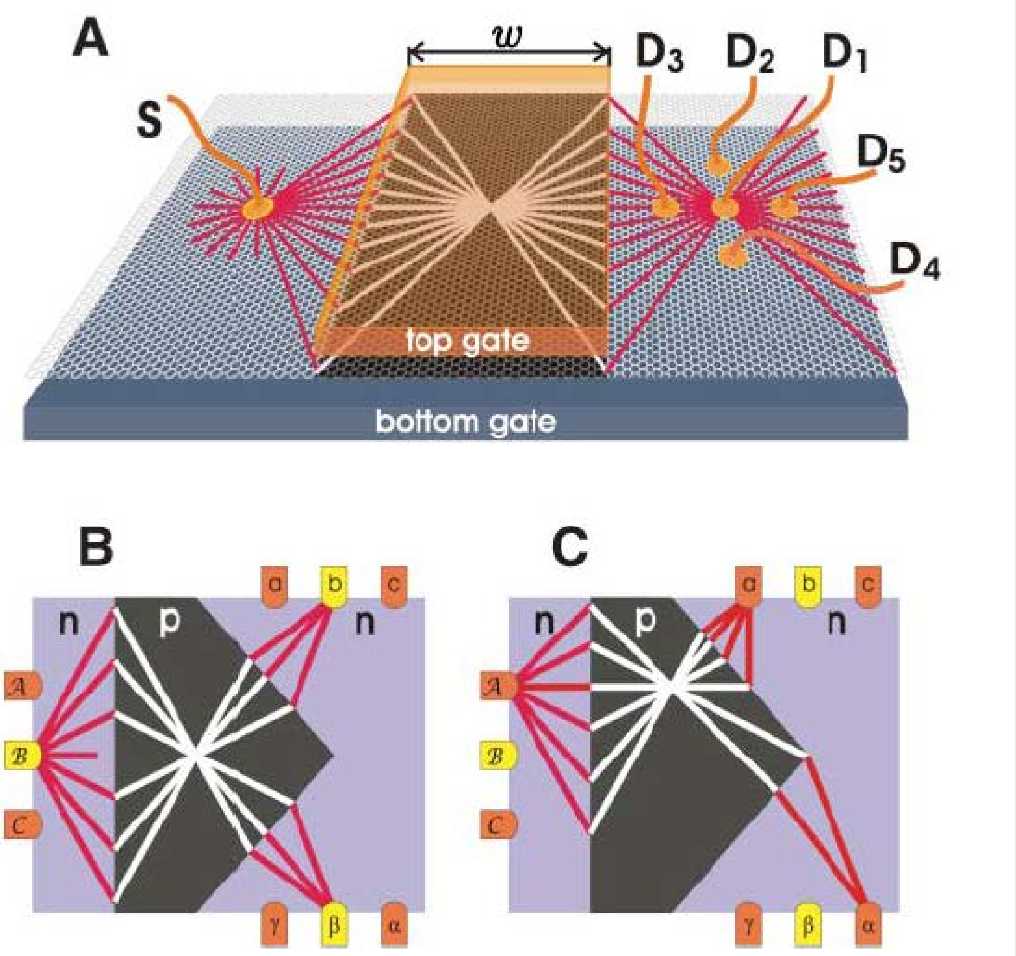
(Cheianov-Falko, PRB 2006)

Transmisssion parfaite en incidence normale !

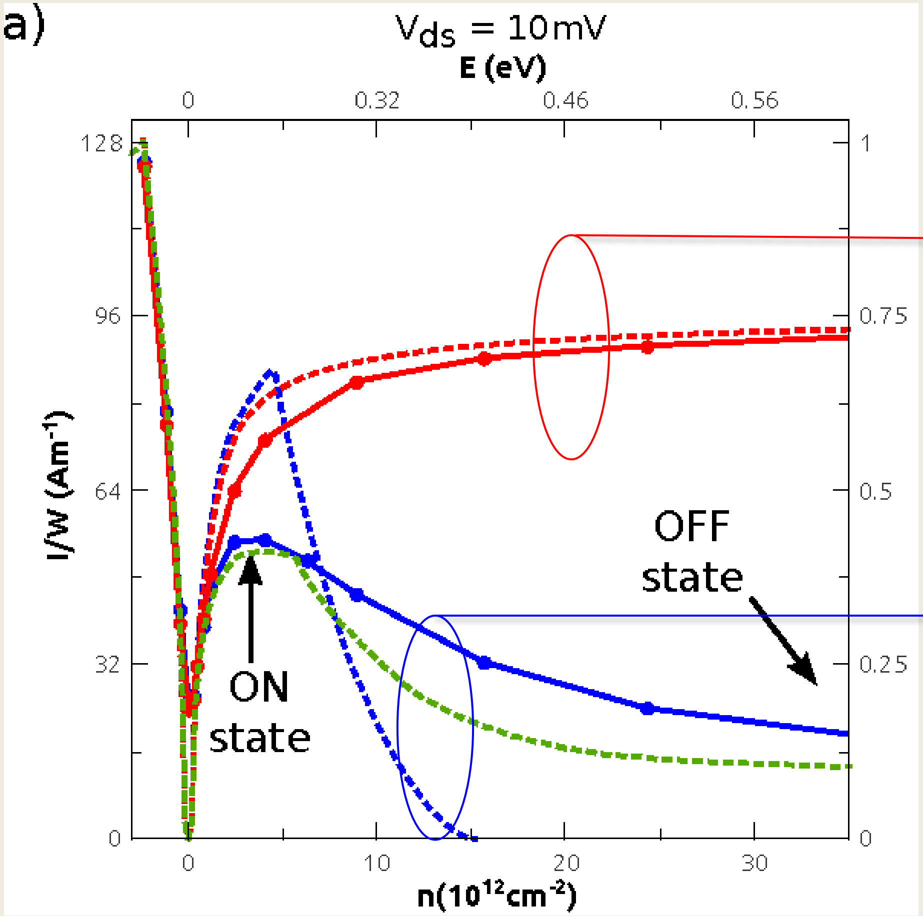
(Ando et al., J. Phys. S. J 1998)

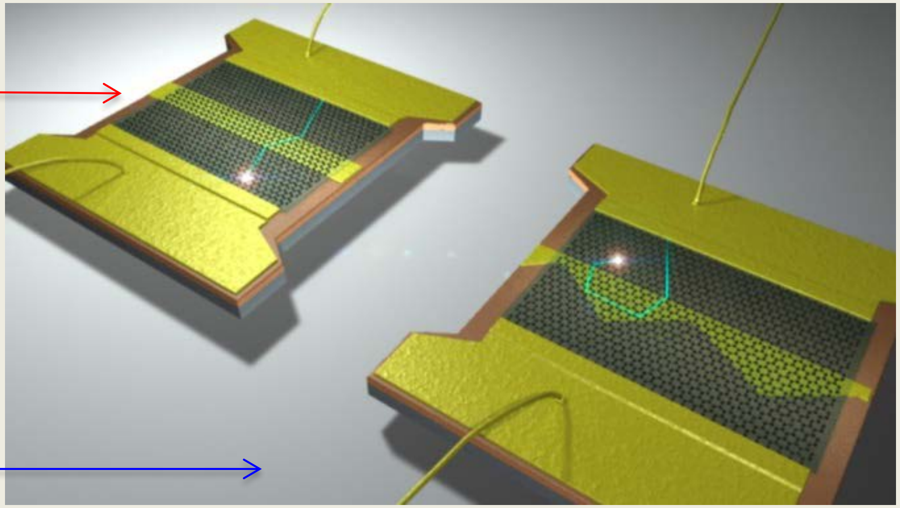
lentille de Vasalego





(Cheianov et al., Science 2007)





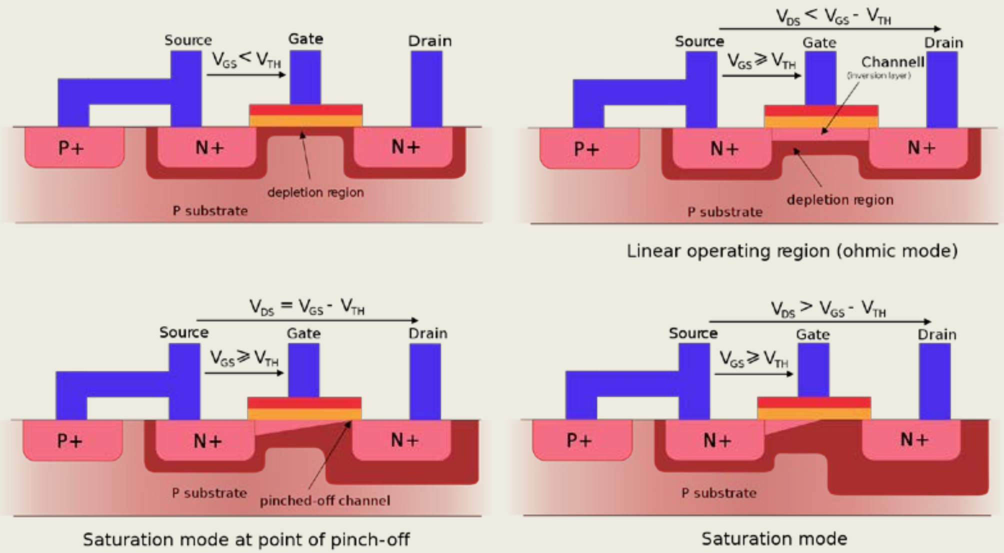
(Wilmart et al., 2DM 2014)

Graphène

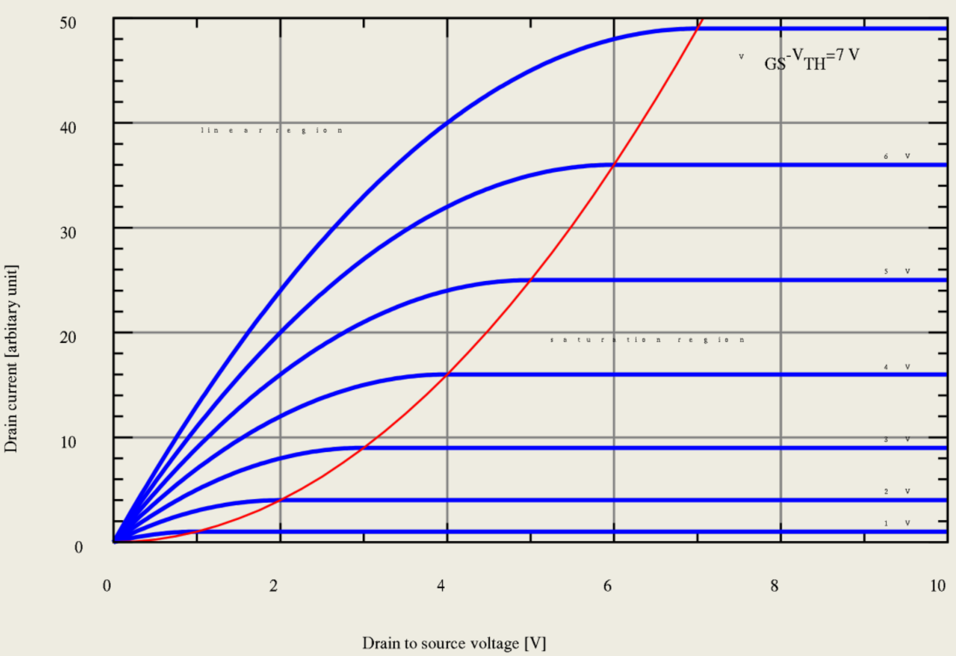
- Le graphène et les autres matériaux 2D
- Les cristaux 2D et leurs substrat
- Propriétés étranges des électrons de Dirac
- À quoi peut servir le graphène en électronique ?

un Pentium Graphène ?

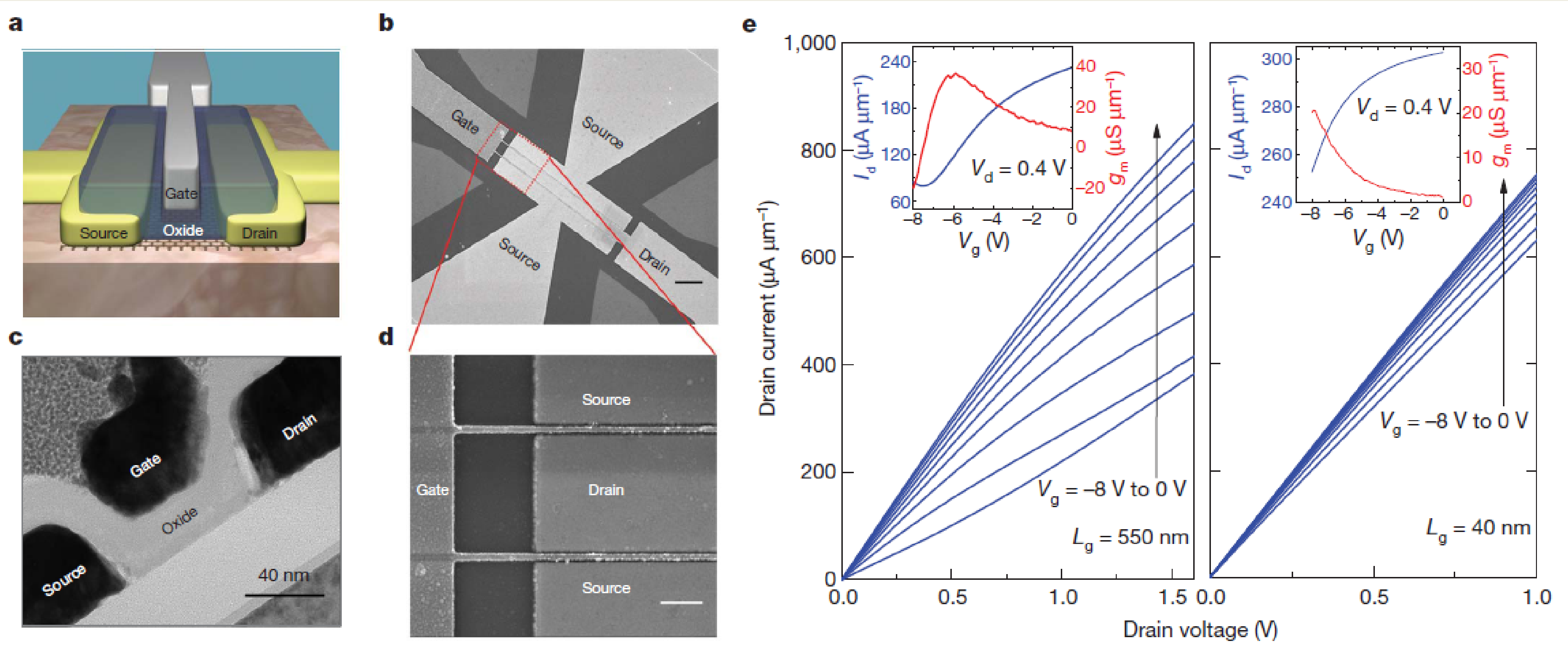
(Pentium 4, INTEL)

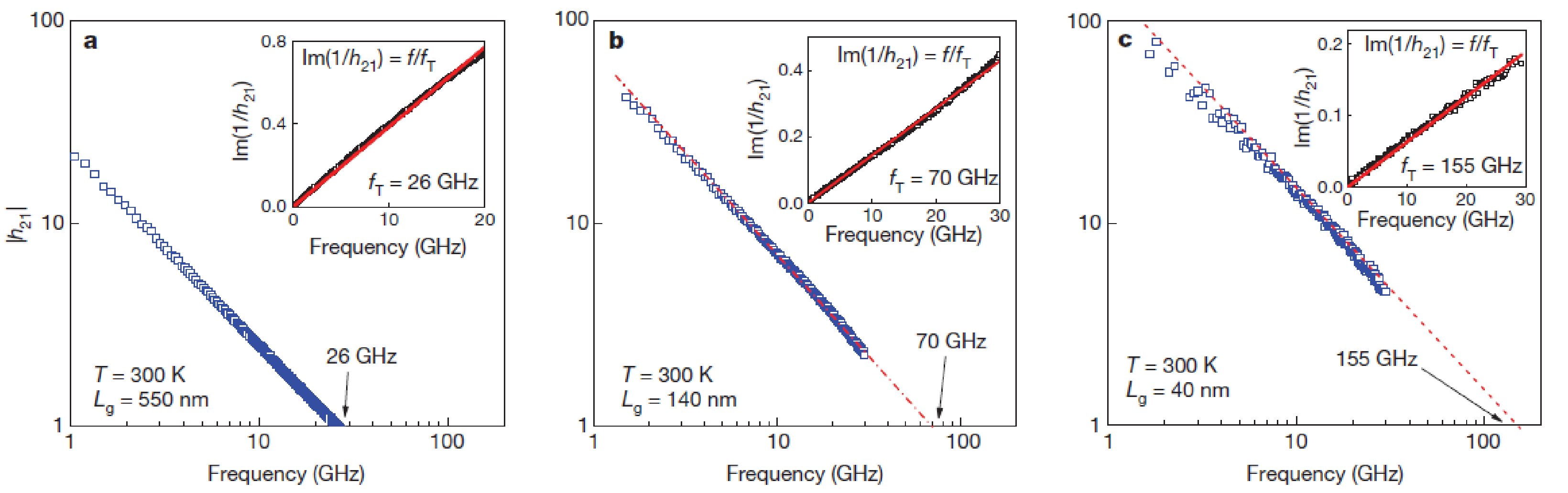


(taken from wikipedia.org)



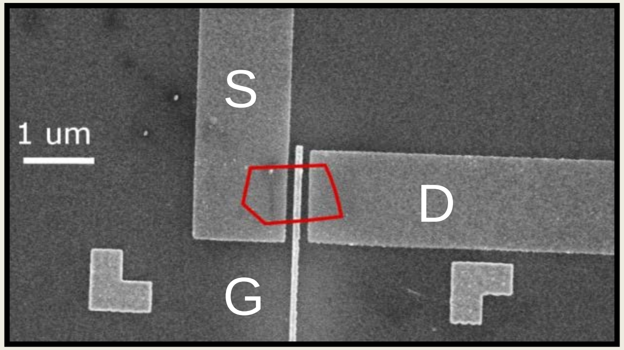
Le FET graphène classique (G-FET)



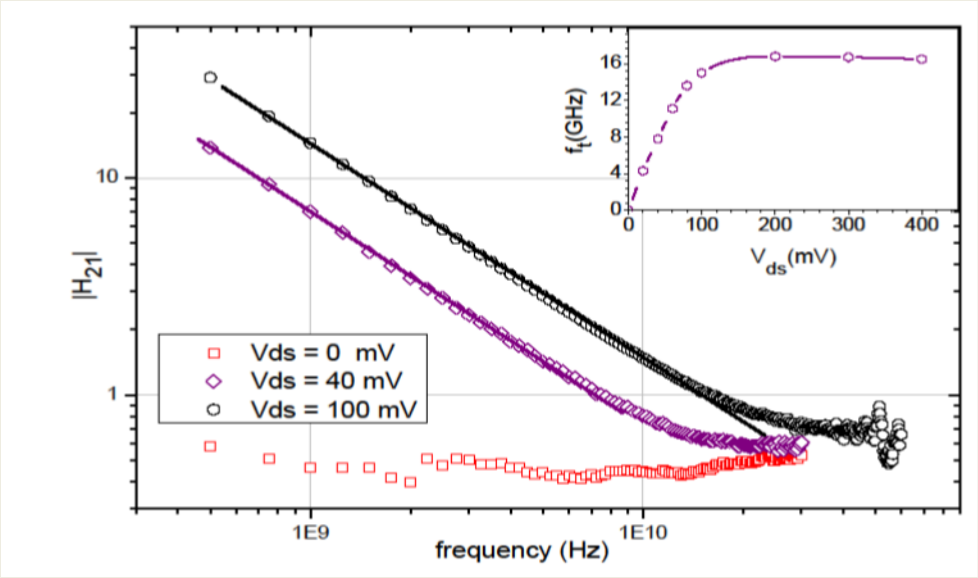


(Wu et al., Nature 2011)

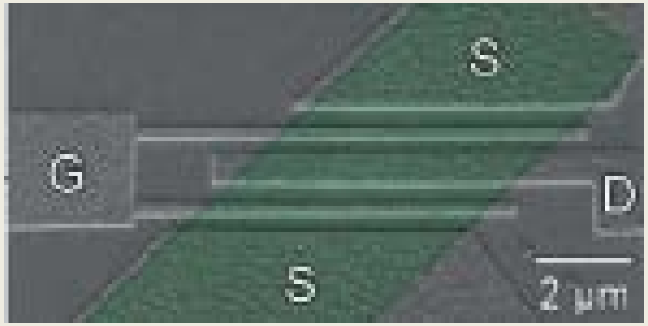
Le FET et nano-FET au LPA

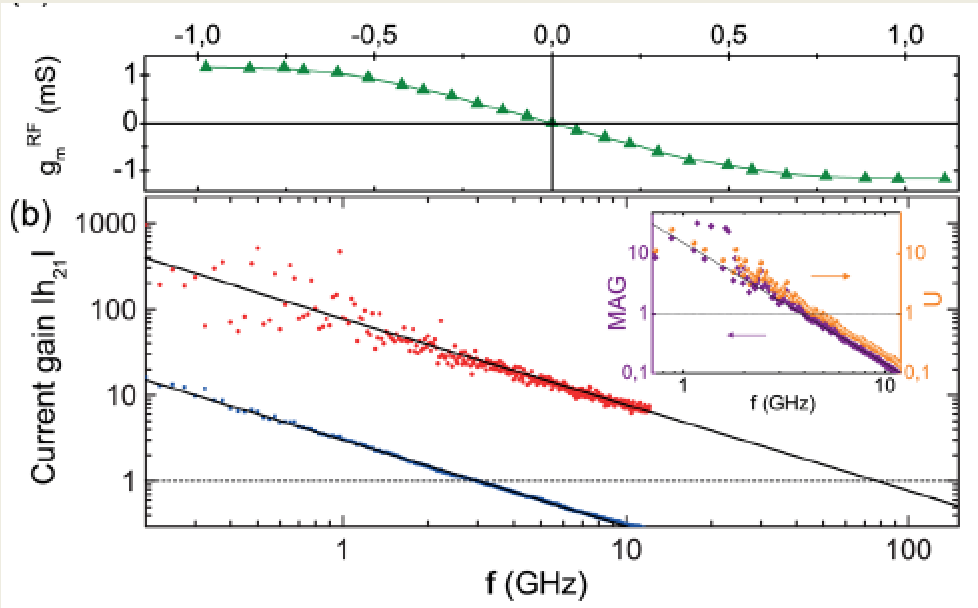


(Pallecchi et al., J. Phys. C 2014)



Exfoliated GR on Sapphire : 80GHz



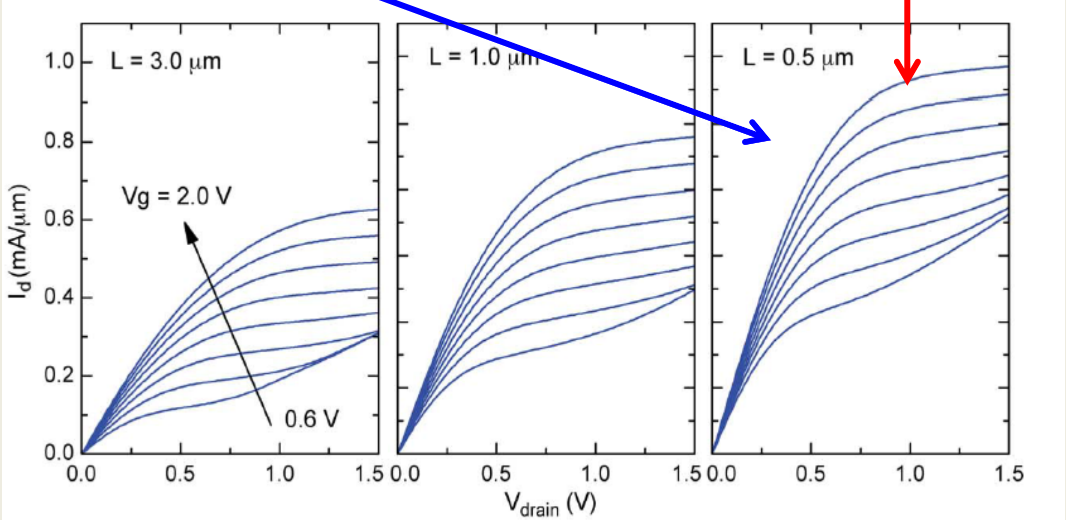


(Pallecchi et al., APL 2011)

Le FET graphène sur BN (GoBN-HEMT)

haute mobilité

saturation par les phonons



(b)

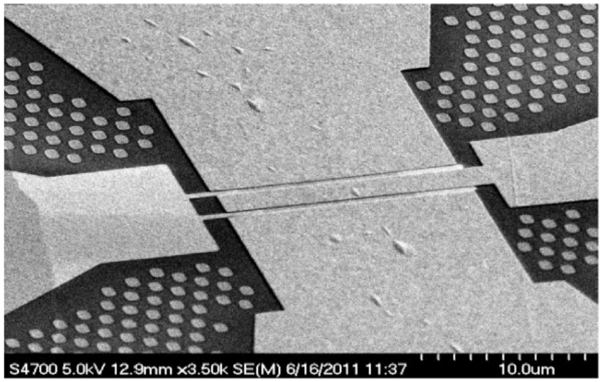
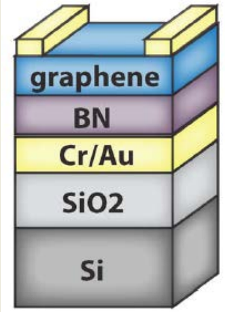
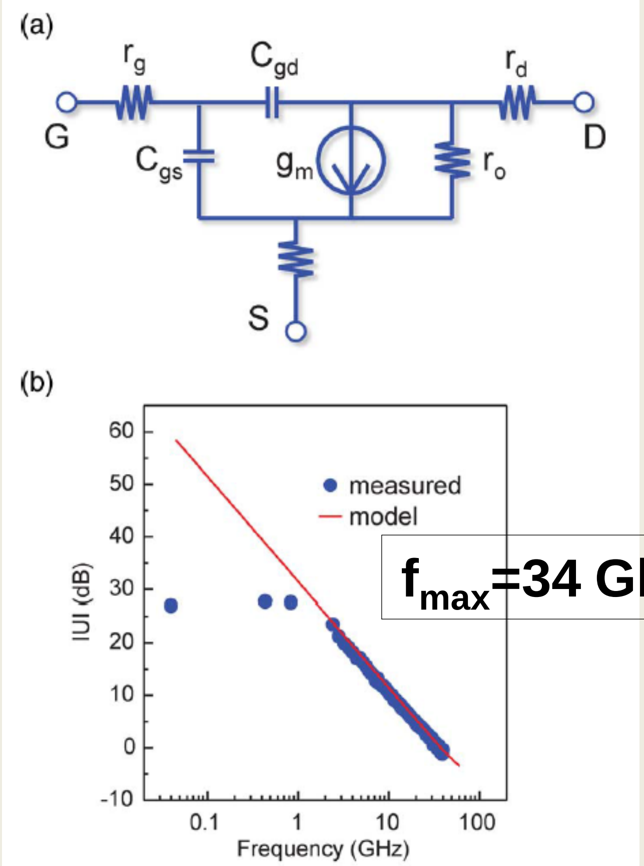


Figure 1. GFET device structure. (a) Schematic illustration of the back-gated GFET device. (b) SEM micrograph of a completed structure.



(b)

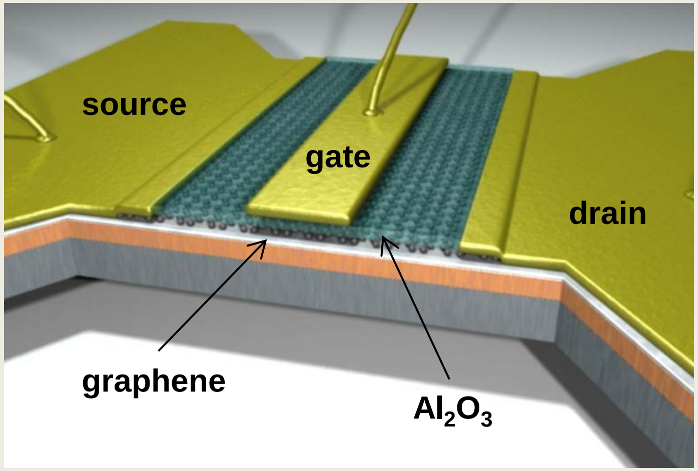


f_{max}=34 Ghz

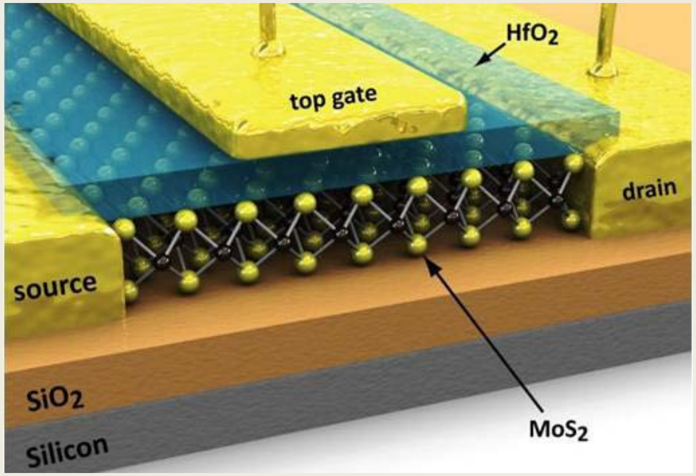
(c)

g_m	19 ms	r_s, r_d	12.5 Ω
r_o	98 Ω	C_{gd}	17 fF
r_g	19 Ω	C_{gs}	34 fF

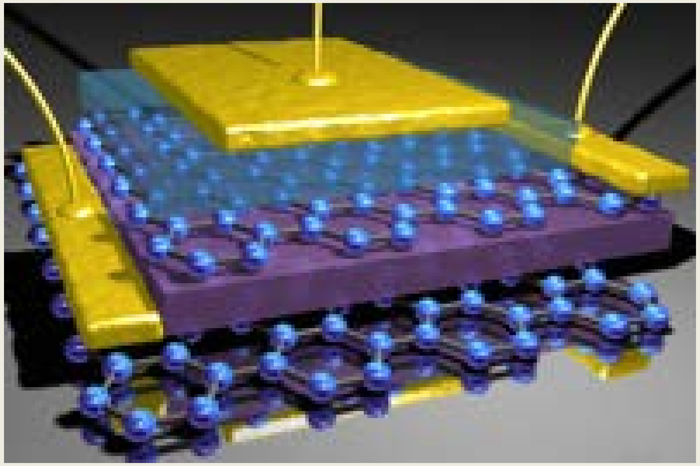
Variantes de transistors



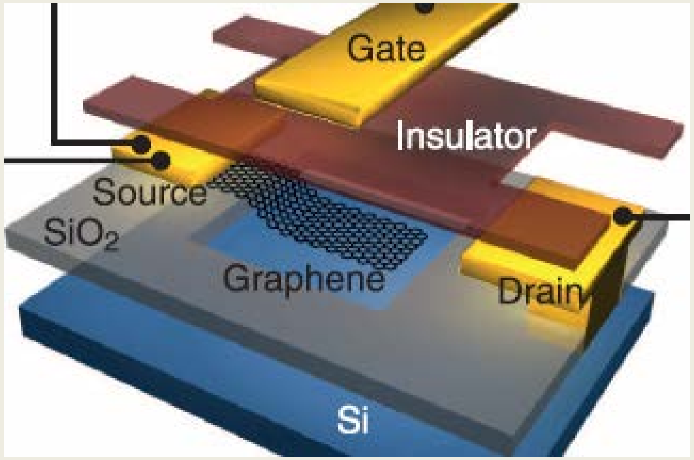
Gr-FET



MoS_2-MOSFET
(B. Radisavljevic et al. Nature nano 2011)



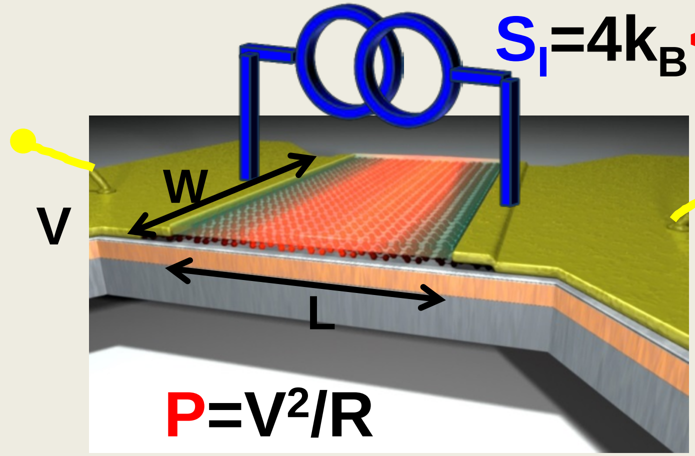
Gr/BN/Gr (Nature 2011) - Tunnel transistor



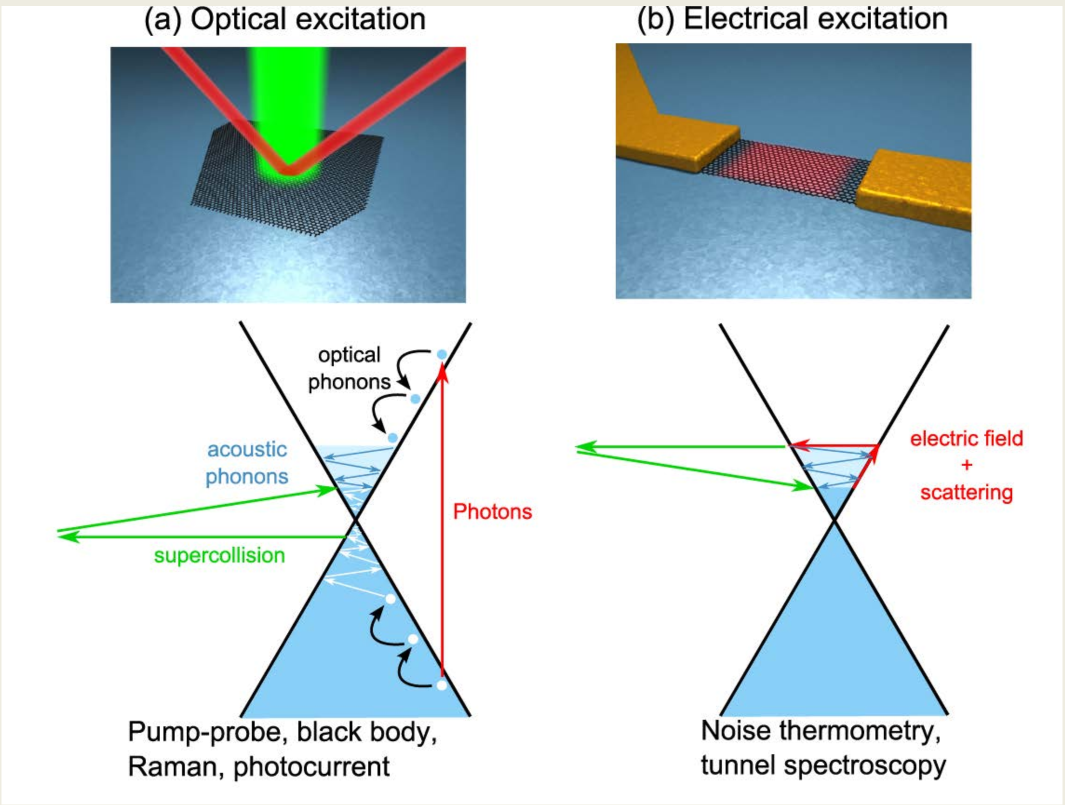
Gr/Si (Science 2012) - Baristor

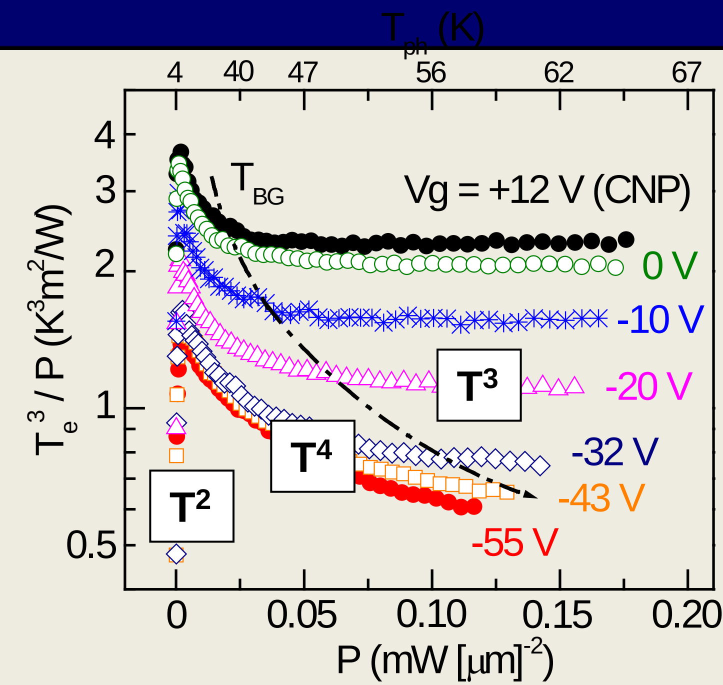
Bolomètres sensibles et rapides

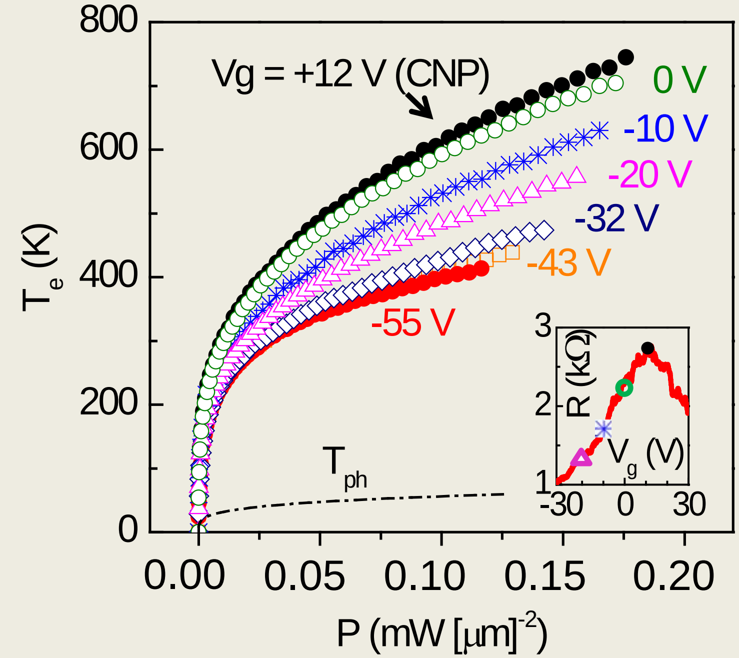
$S_I=4k_B\langle T_e\rangle/R$



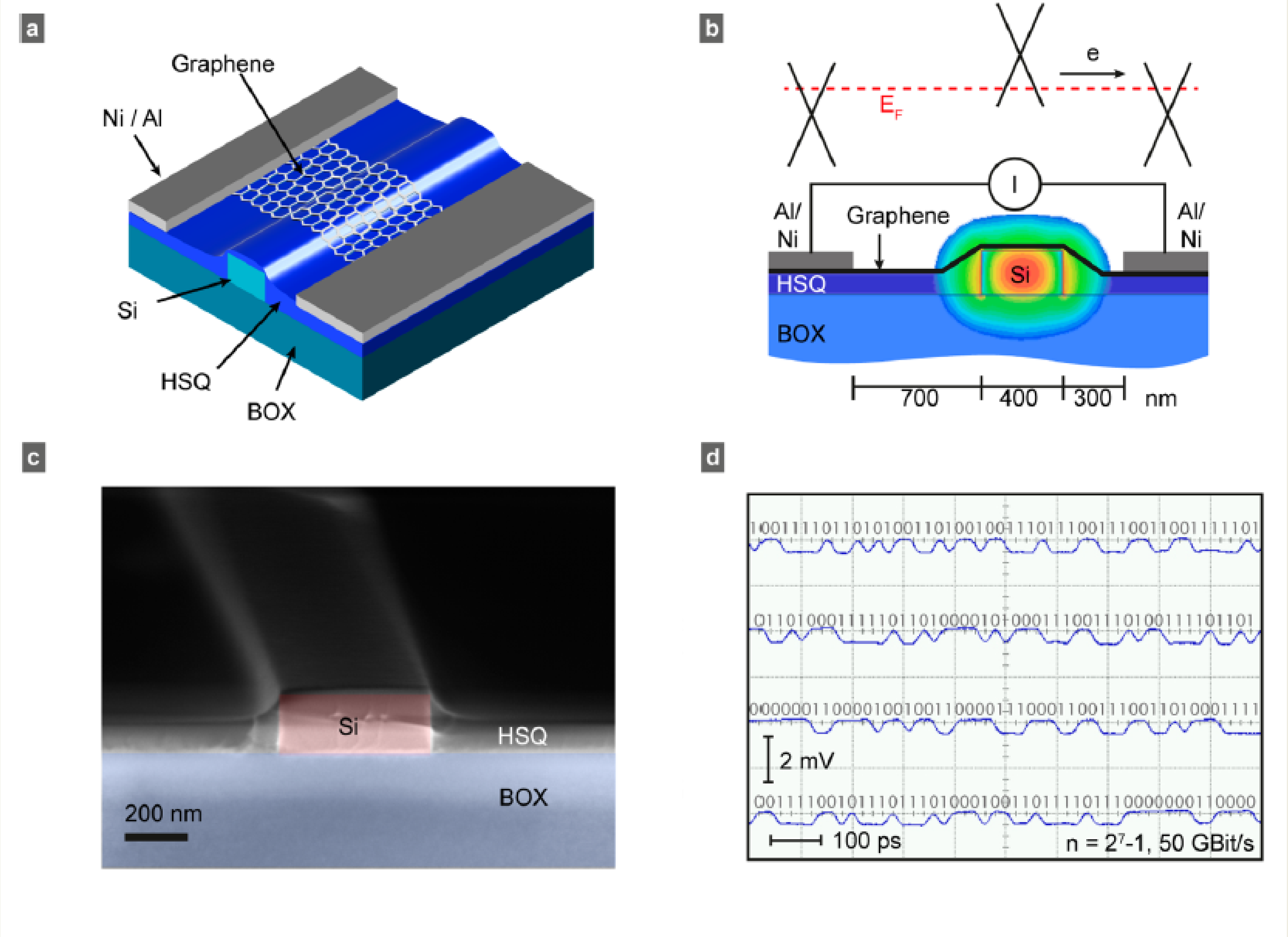
$P=V^2/R$





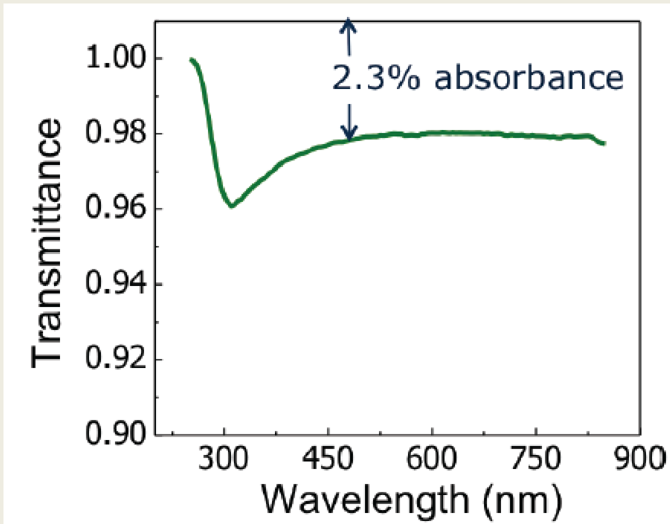


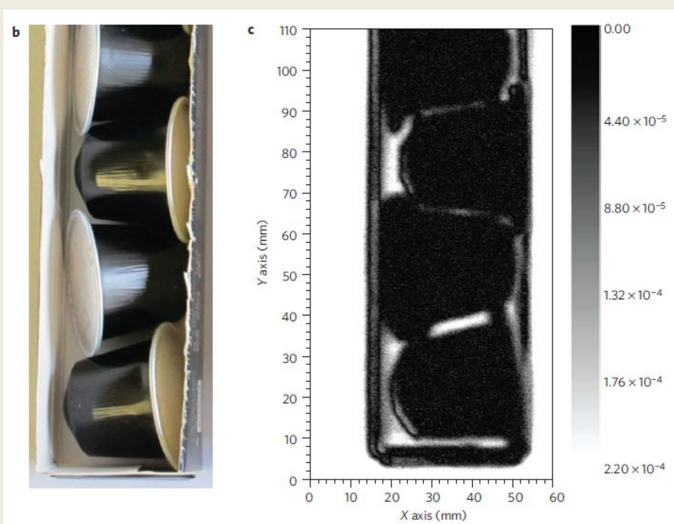
50 GBit/s Graphene Photodetectors

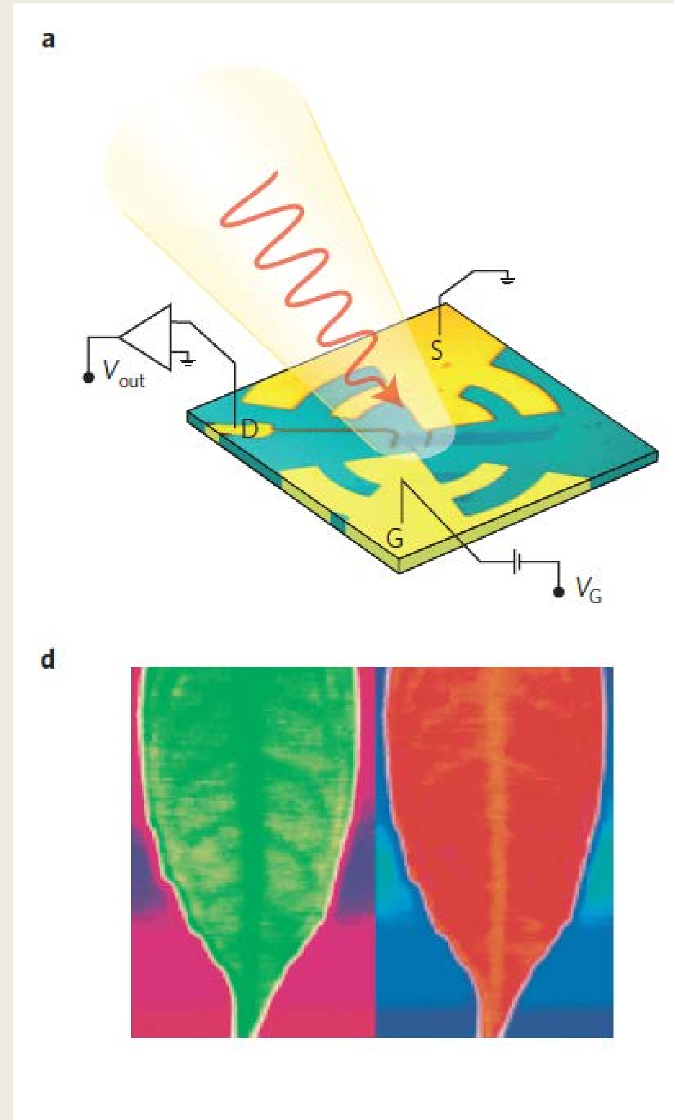


(Schall et al. ACS photonics 2014)

Photodetecteurs graphene du Visible au THz







(Vicarelli et al. Nature Material 2012)

Et aussi …….

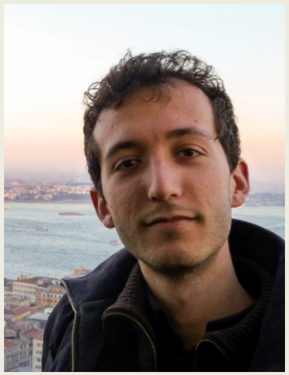
- ✓ Graphène pour le nouveau standard de résistance (Schöpfer-LNE)
- ✓ Graphène pour la spintronique (Sénéor-UMPhi-Thalès)
- ✓ Electronique flexible graphène (Happy-IEMN, Derycke-Saclay)

Conclusions

1. Crystal 2D d'épaisseur atomique
2. Le transport dépendent à l'ordre zéro de la symétrie du cristal
3. Fortement accordables par des grilles ou autres actions locales
4. Phénoménologie très riche
5. Applications en électronique et optoélectronique rapides

Graphene team

Mesoscopic physics team



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