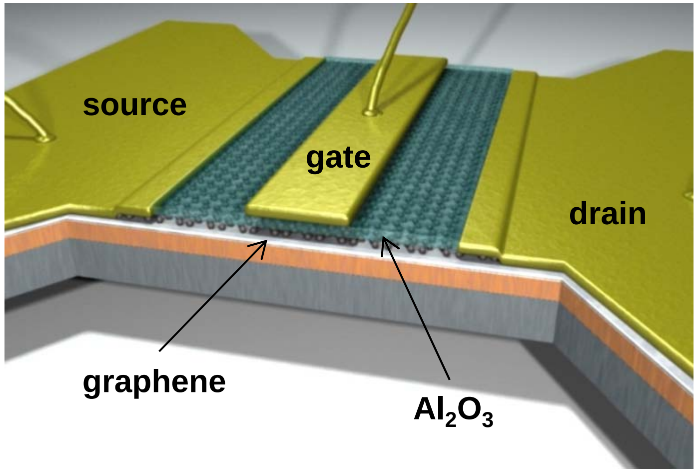
laboratoire pierre aigrain
électronique et photonique quantiques

Microwave Graphene Electronics



B. Plaçais

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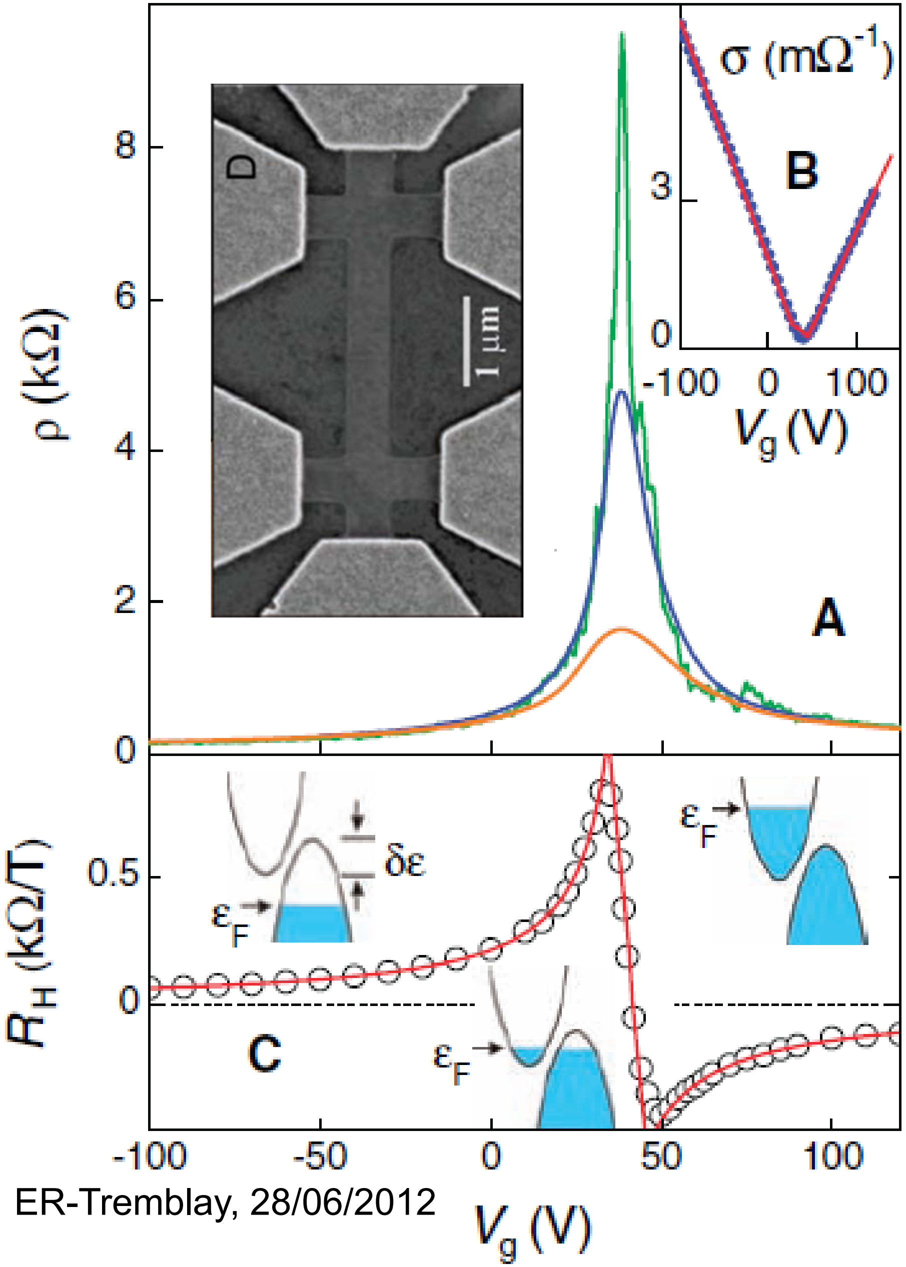
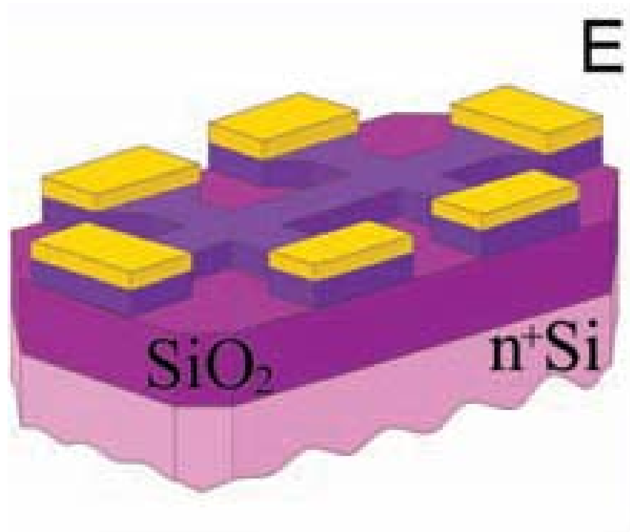
www.lpa.ens.fr

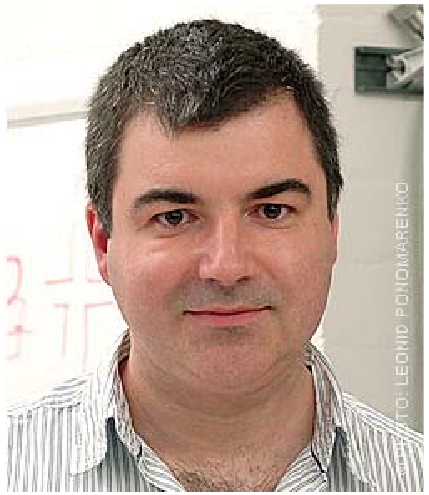
ER-Tremblay, 28/06/2012

« field effect in atomically thin carbon films »

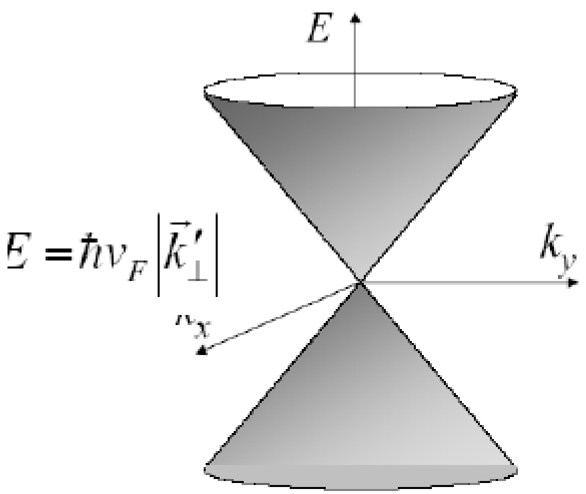
(K. Novoselov et al., Science 2004)

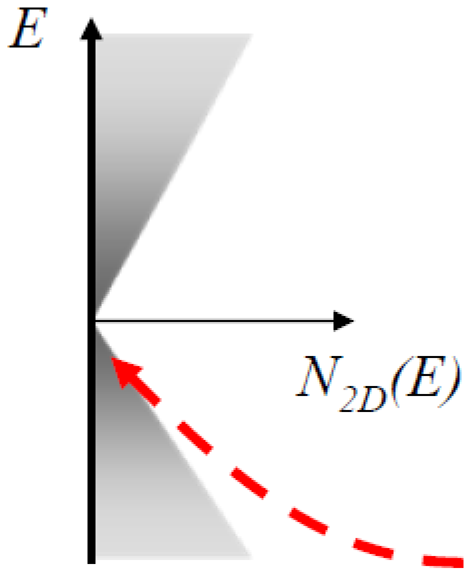




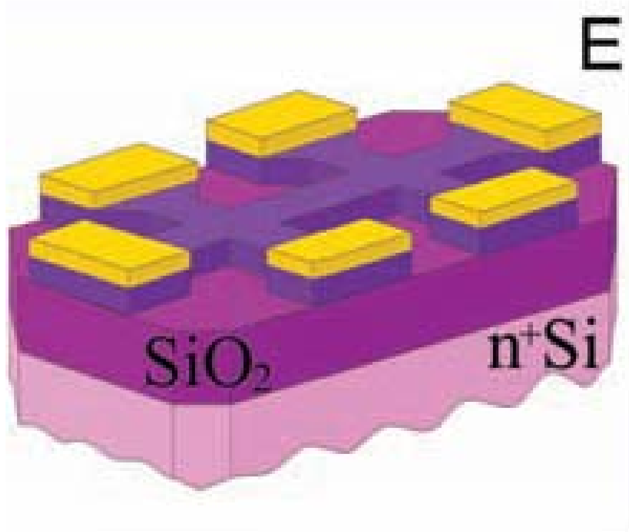


An exceptionnal 2D metal !



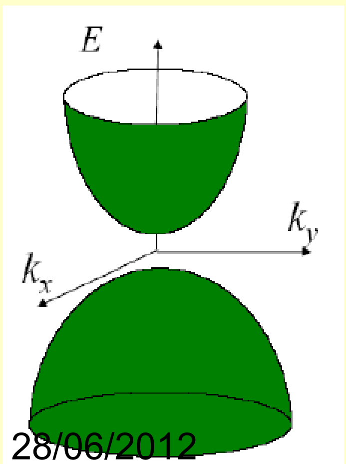


Dirac point



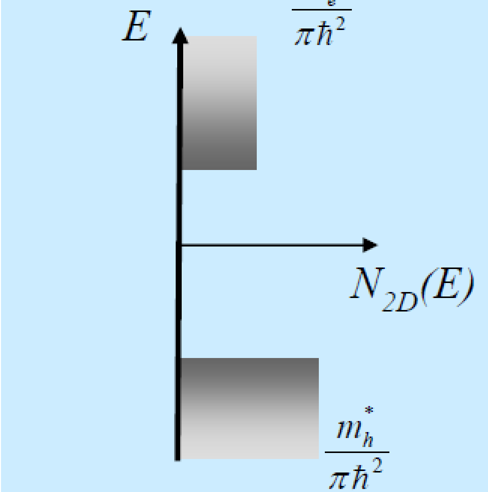
Band structures

$$E = \frac{\hbar^2 k^2}{2m_e^*}$$

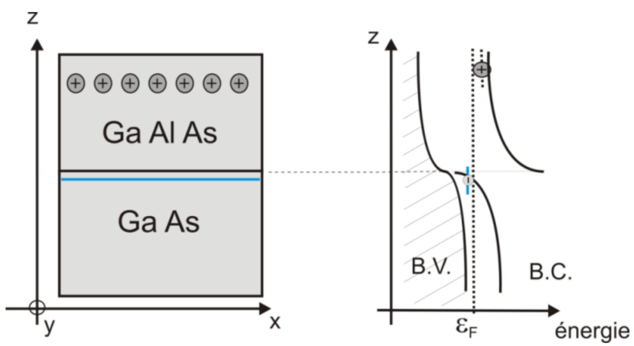


$$E = -\frac{\hbar^2 k^2}{2m_h^*}$$

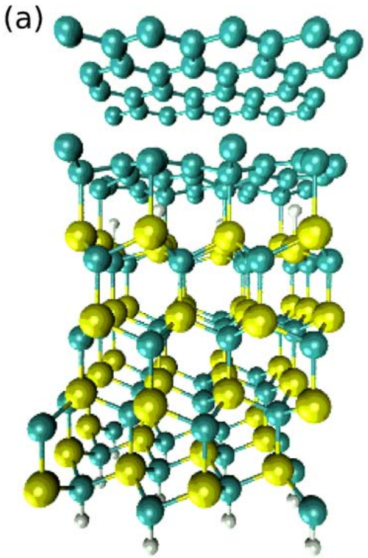
Density of States

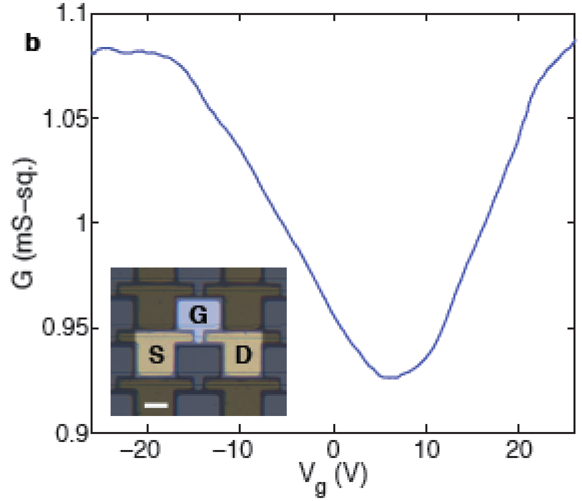


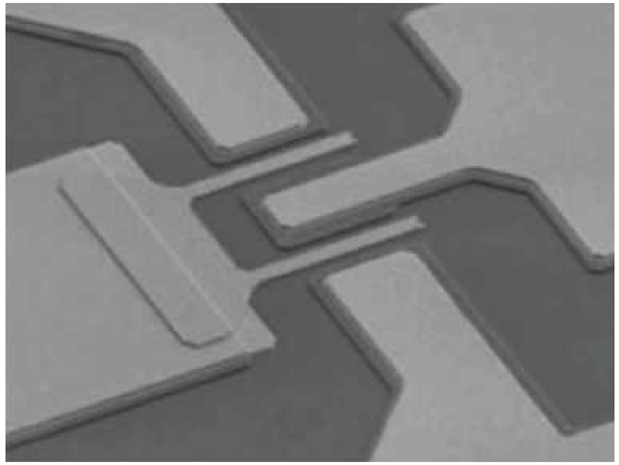
Semi-conducteur classique

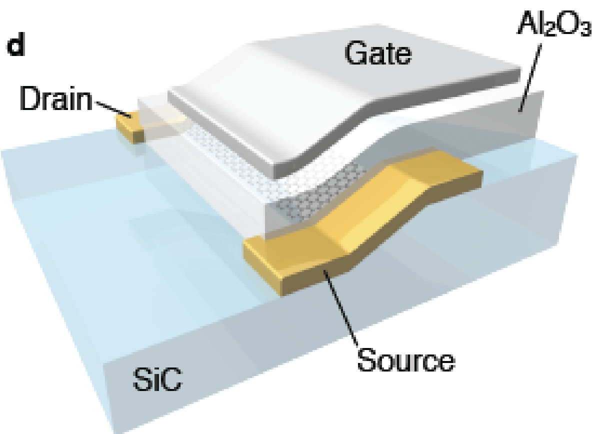


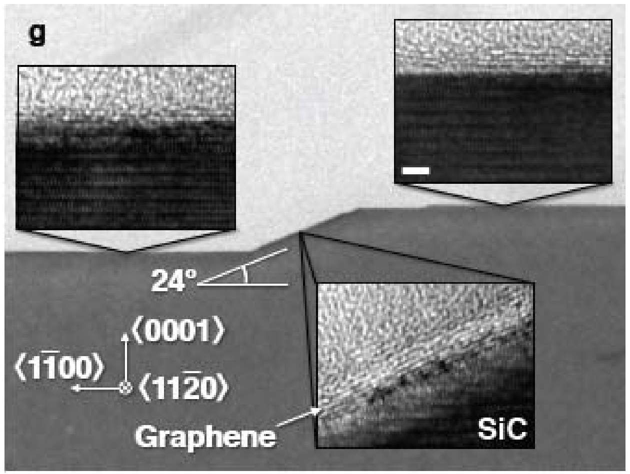
Large scale epitaxial graphene

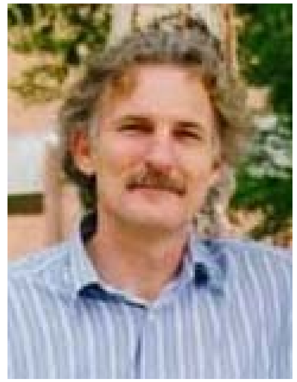






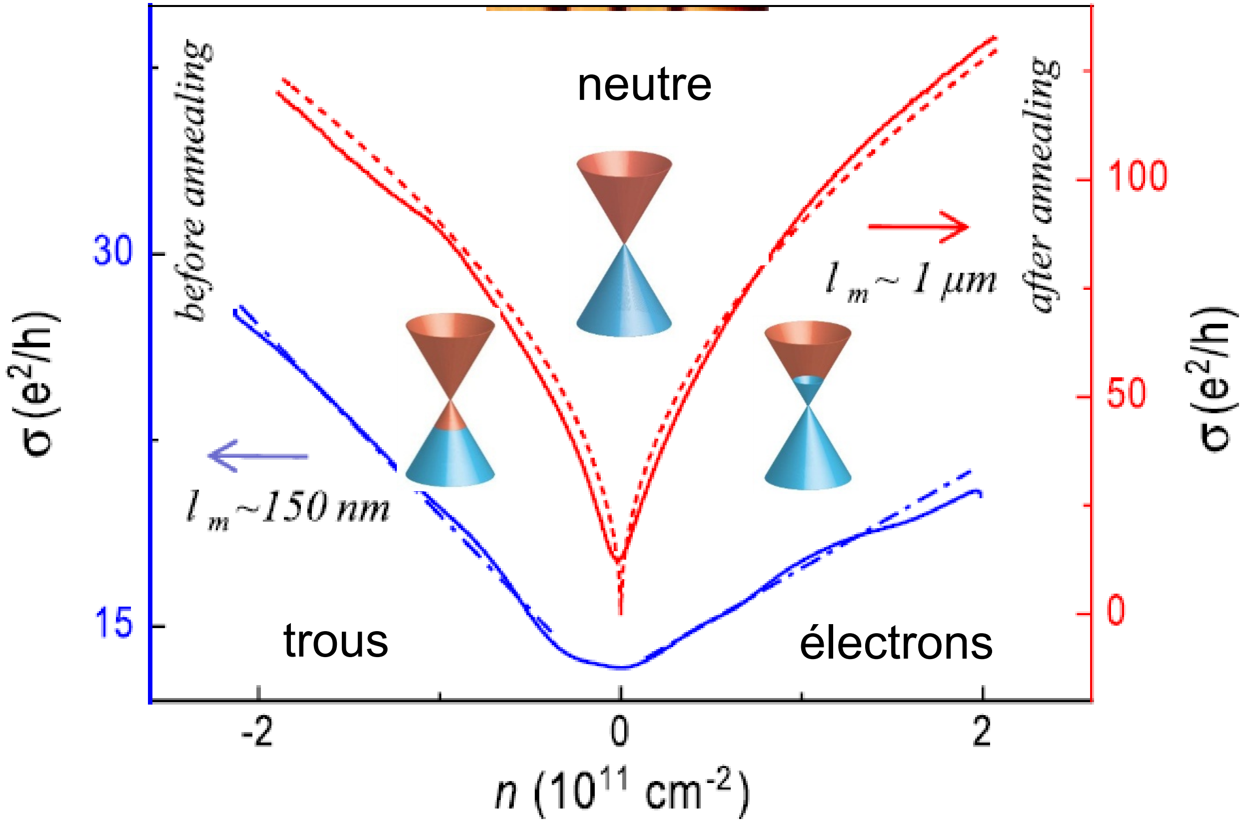




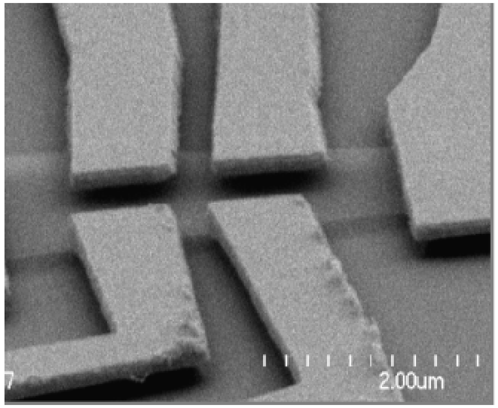


(C. Berger and W. de Heer)

Field-effect in suspended graphene



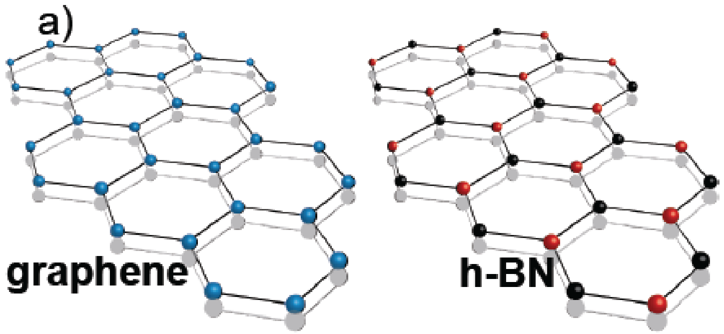
(Bolotin et al. PRL2008)



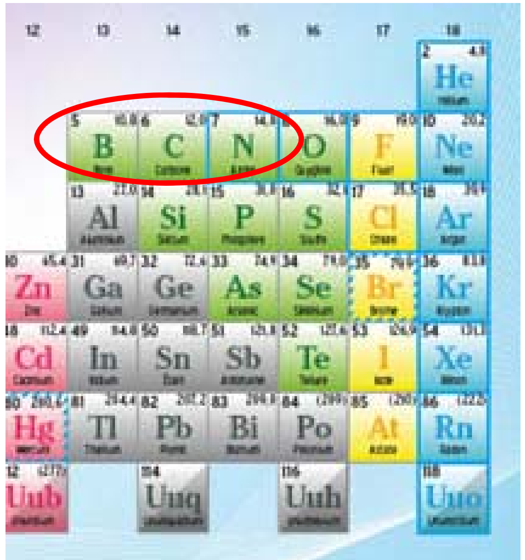
(P. Kim, Le Tremblay 2009)

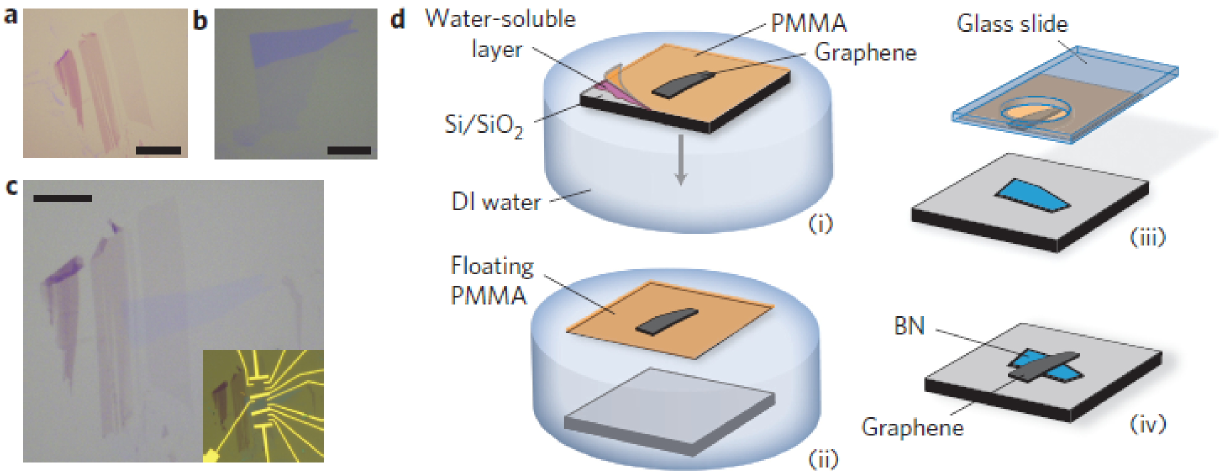
1. **Importance of cleaning by current annealing**
2. **Efficient field effect in layered conductors**
3. **Tunable metal : broad range of electron and hole doping**
4. **Dirac fermion physics : conductivity at neutrality ~4 e^2/h**

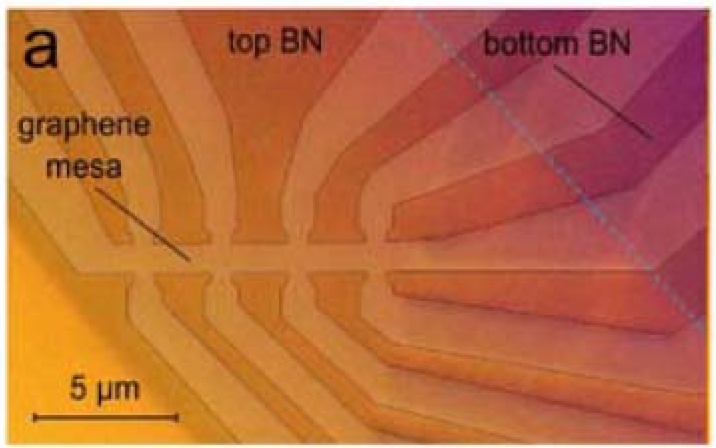
Layered Graphene on layered Boron Nitride



Black & White





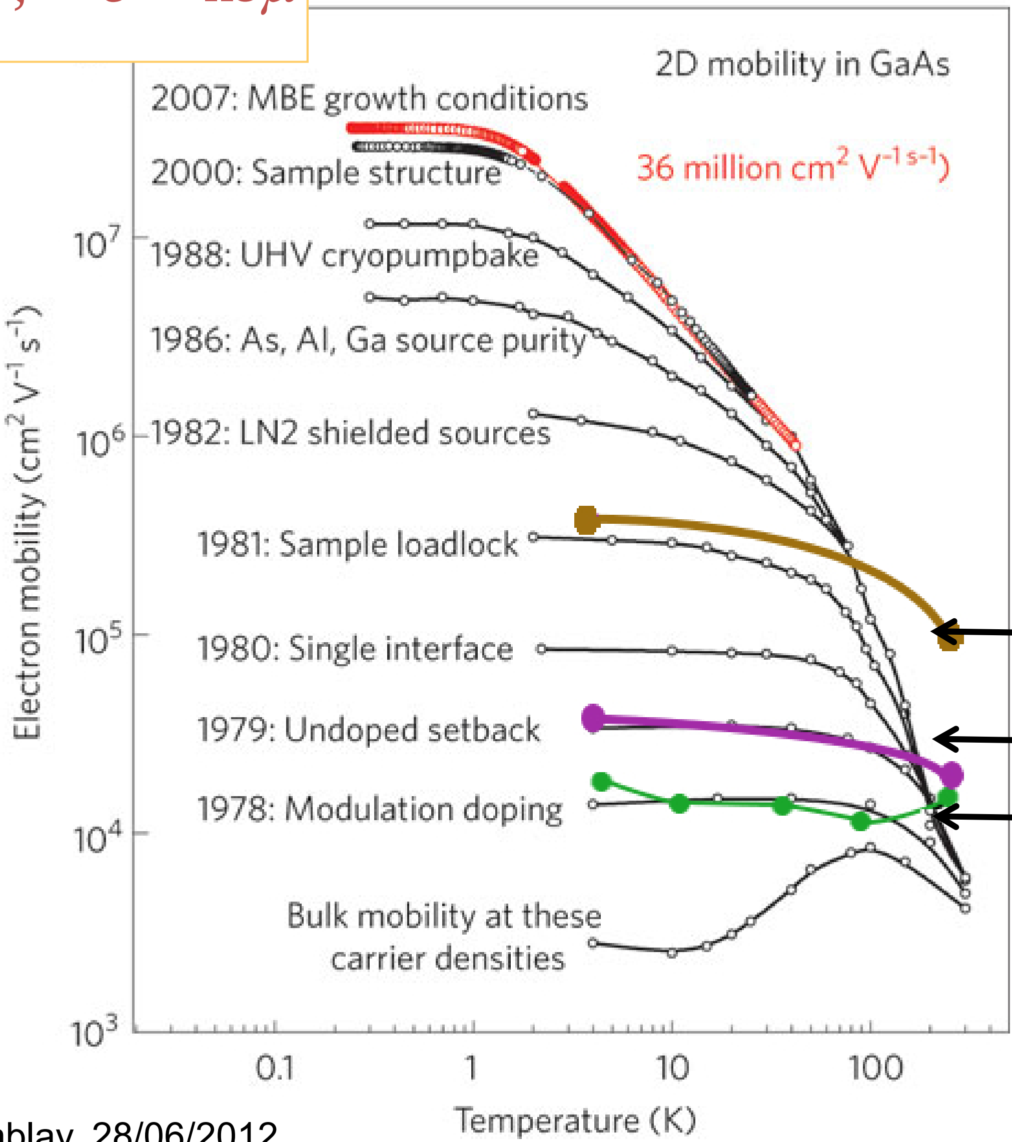


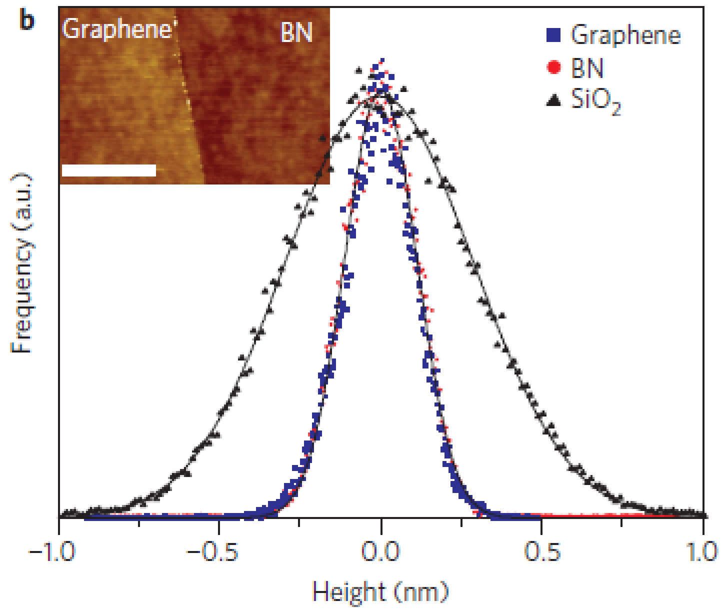
ER-Tremblay, 28/06/2012 ***(Columbia, 2010)***

(Manchester, 2011)

mobility/conductivity at room temperature

$$\mu = \frac{v_d}{E} \quad ; \quad \sigma = ne\mu$$

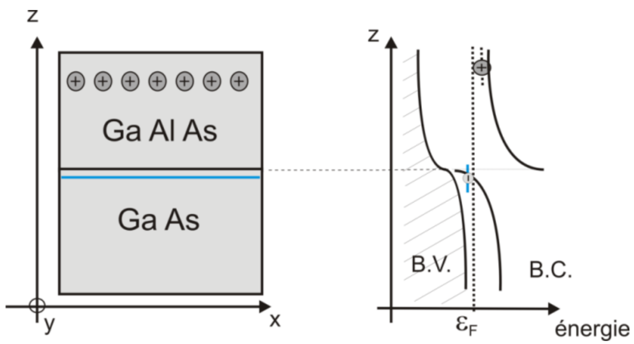




(encaps., Manchester, Nanolett.'2011)

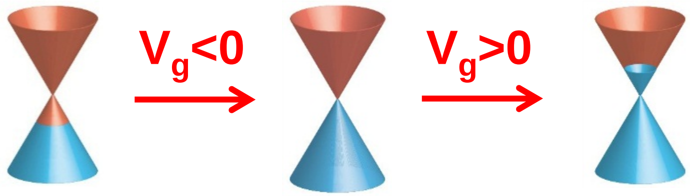
(flake on BN, Columbia Nnano'2010)

(CVD on BN, Berkeley, APL' 2011)



ER-Tremblay, 28/06/2012

List of key-numbers about graphene



- ✓ Gate tunable

e-concentration	$n_s=10^{11}-10^{13}$ cm^{-2}	(symmetry)
chemical potential	E_F = ±350 meV	(from Cr to Pt)
e-color	λ_F= 10-100 nm	(e-quantum optics)
compressibility	$e^2\varkappa$= 10-100 fF µm^{-2}	(Q-capacitance)

✓ high mobility	$0.002 \rightarrow 20$ m^{2}V^{-1}s^{-1}	(!! Dirac Fermions)
✓ Finite residual conductivity :	$4e^2/h$=(6,45 kOhms)$^{-1}$	(! quantum tunneling)
✓ Large Fermi velocity :	v_F=1, 10^6 m/s	(Magic carbon-bond !)
✓ Large sound velocity :	c = 2. 10^4 m/s	(Magic carbon-bond !)

Outline

1) Introduction to magic graphene

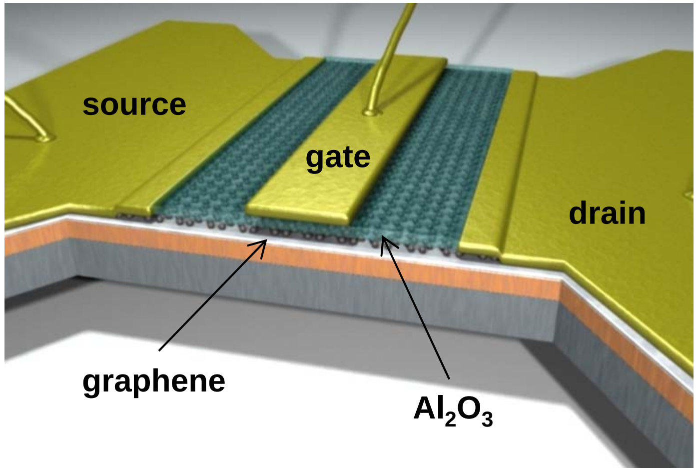
2) Transit frequency of microwave transistors

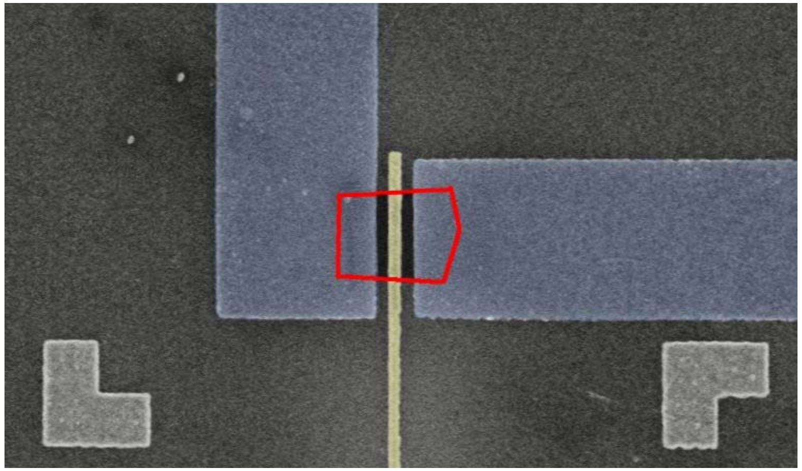
3) Diffusion probed in a field-effect capacitor

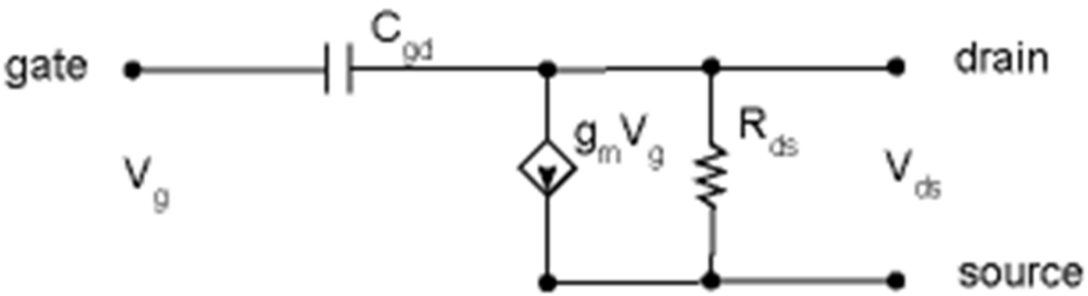
4) Acoustic phonons controls noise of resistors

5) New transistor architectures

Microwave Field Effect Transistor (FET)







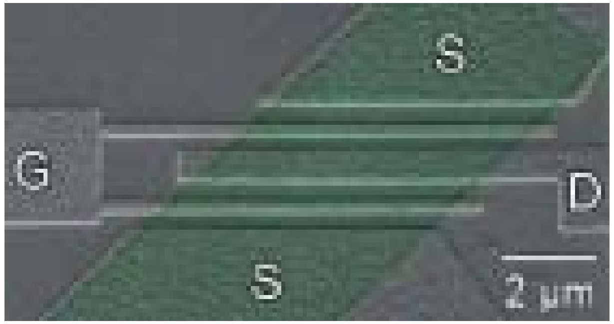
Drain-source resistance R_{ds}
Transconductance g_m
Gate-drain capacitance C_g

$$g_m = \frac{\partial I_{ds}}{\partial V_g} = W \frac{V_{ds}}{L} \frac{\partial ne}{\partial V_g} \times \mu = W \frac{V_{ds}}{L} \frac{C_g}{LW} \times \mu$$

$$f_T = \frac{g_m}{2\pi C_g} = \mu \times \frac{V_{ds}}{2\pi L^2} = \frac{D}{2\pi L^2} \frac{eV_{ds}}{E_F} \leq \frac{D}{2\pi L^2}$$

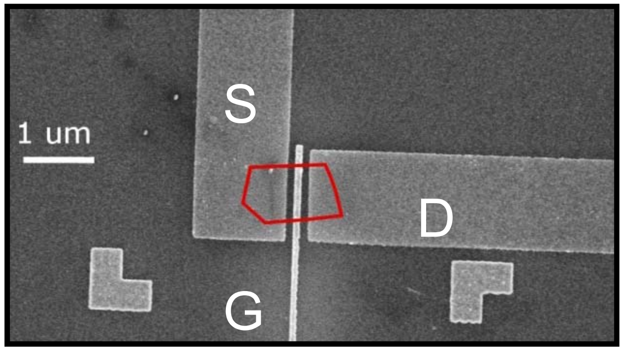
Measuring microwave devices

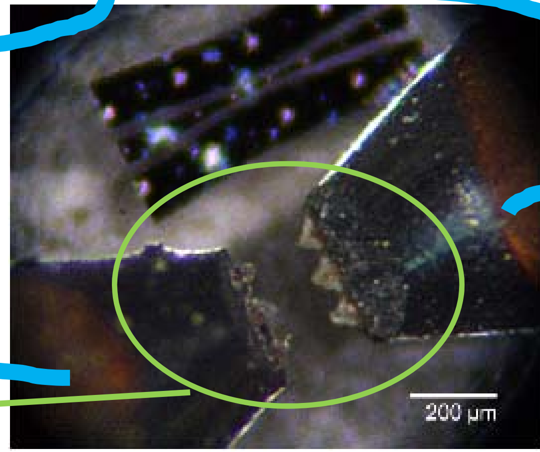
80 GHz transistor (S-parameters)

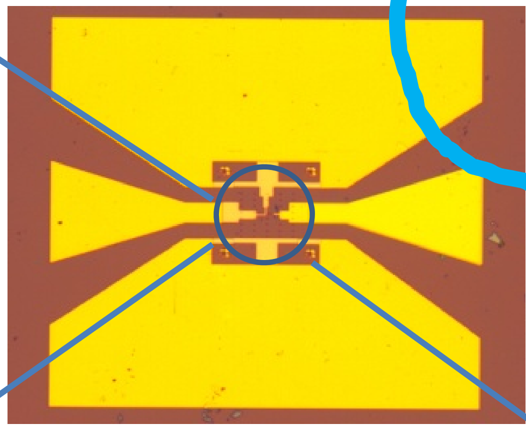


E. Pallecchi et al, APL 99, 113502 (2011)

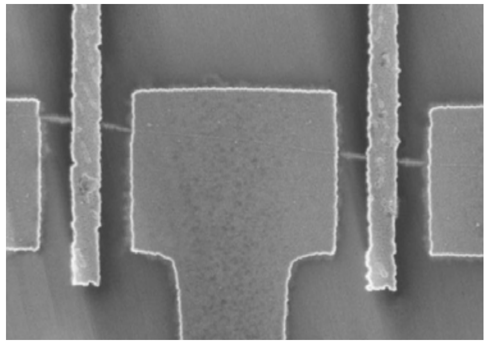
16 GHz nano-transistor (S-paramters)







Wave guide (CPW)

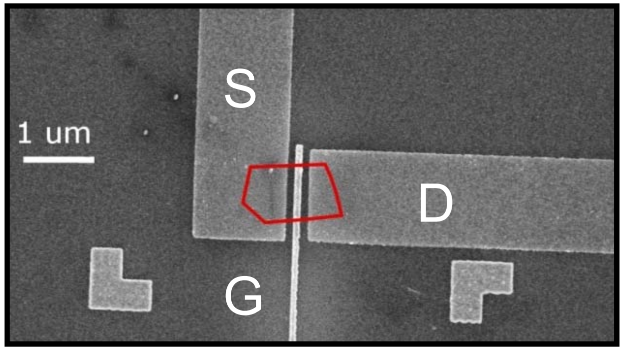


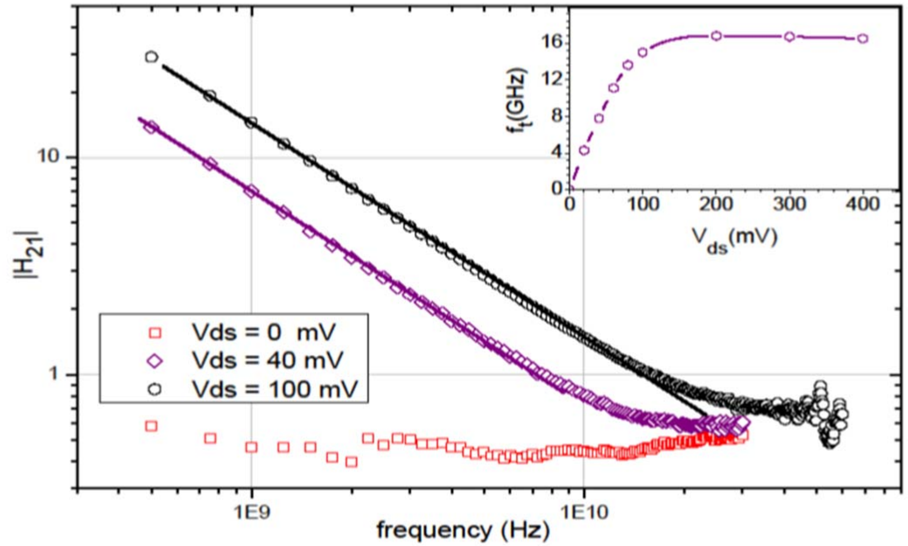
ER-Tremblay, 28/06/2012

J. Chaste et al, Nanoletters 2008, APL 2011)

Transit frequency measurement

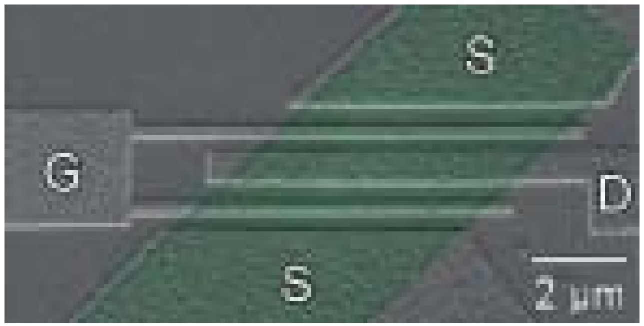
Exfoliated GR on SiO2 : 16GHz

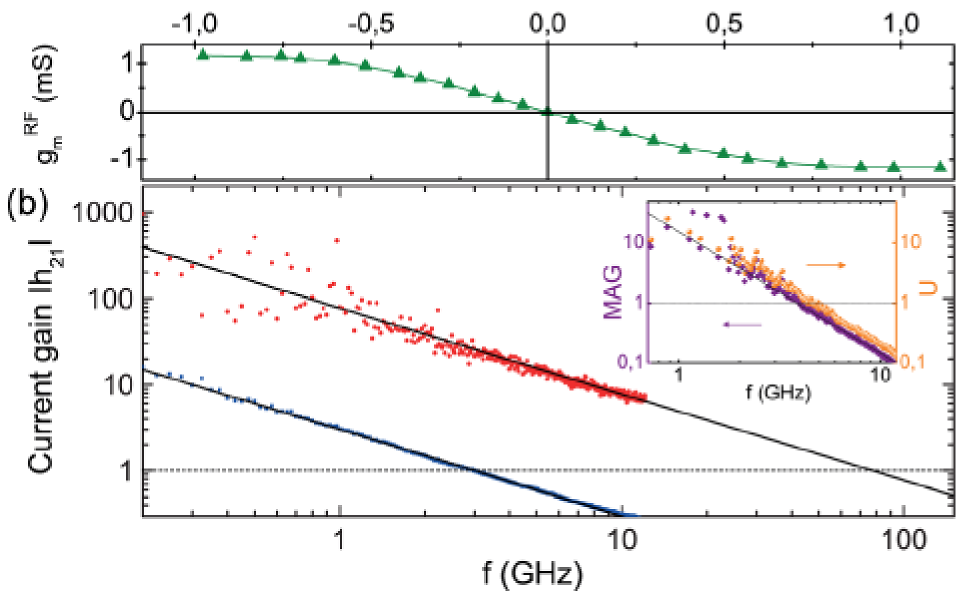




$$\text{current gain} : H_{21} = 1 + j\frac{f_T}{f}$$

Exfoliated GR on Sapphire : 80GHz

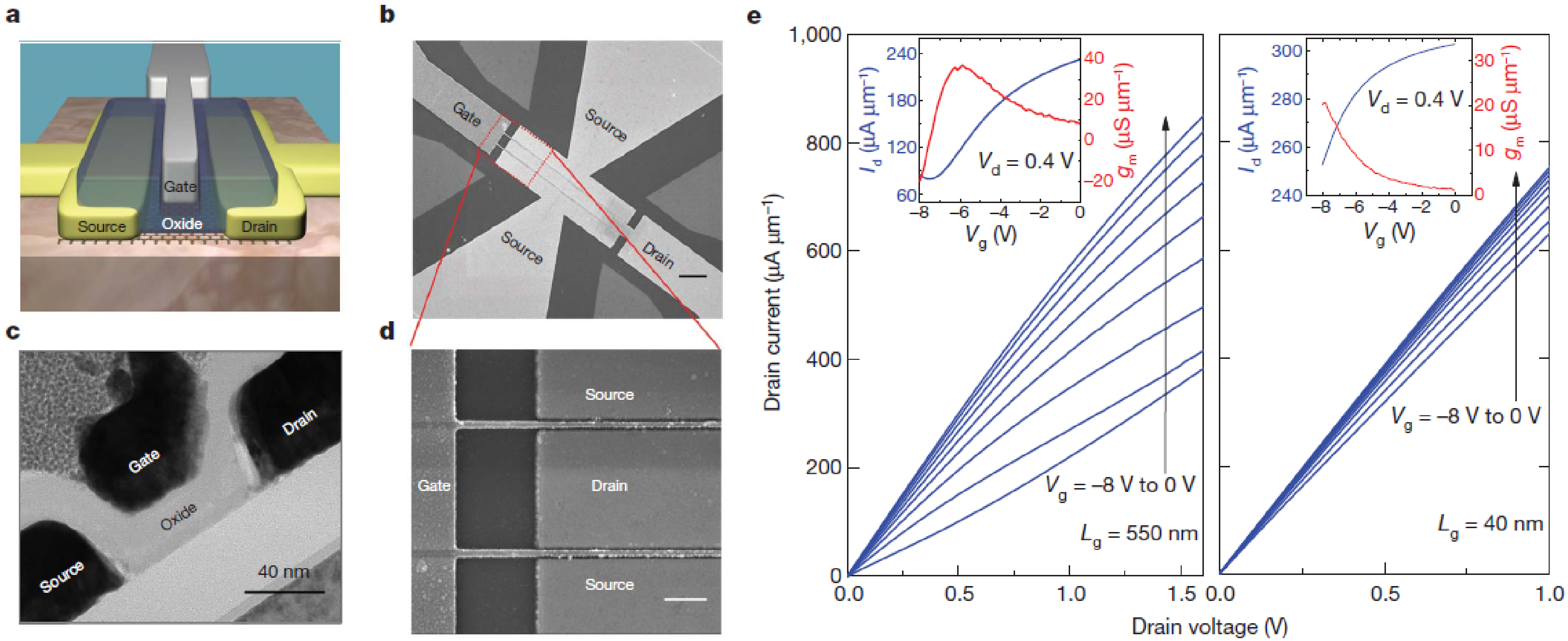




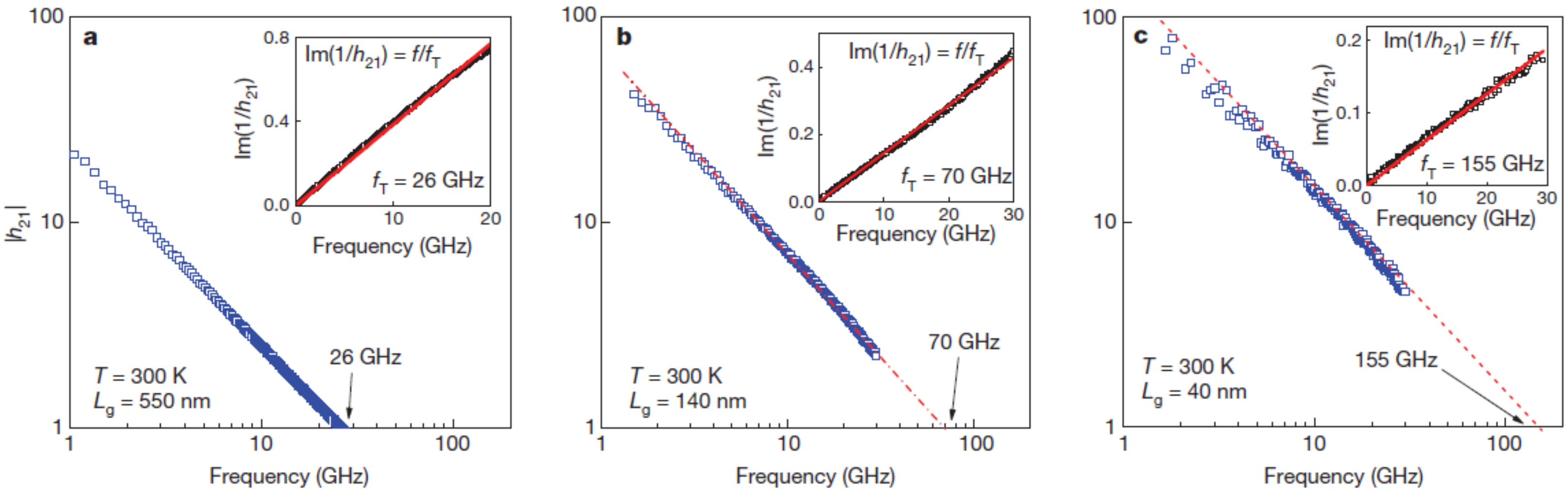
ER-Tremblay, 28/06/2012

(Pallecchi et al., APL 2011)

Kings of microwave transistors (IBM)



(P. Avouris)



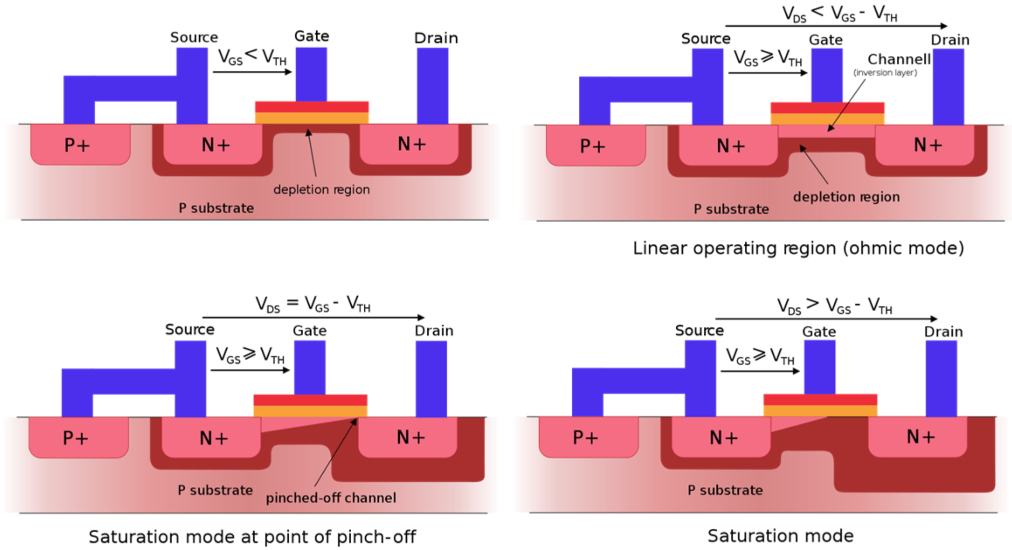
Today 300GHz !
Tomorrow 500GHz ?

ER-Tremblay, 28/06/2012

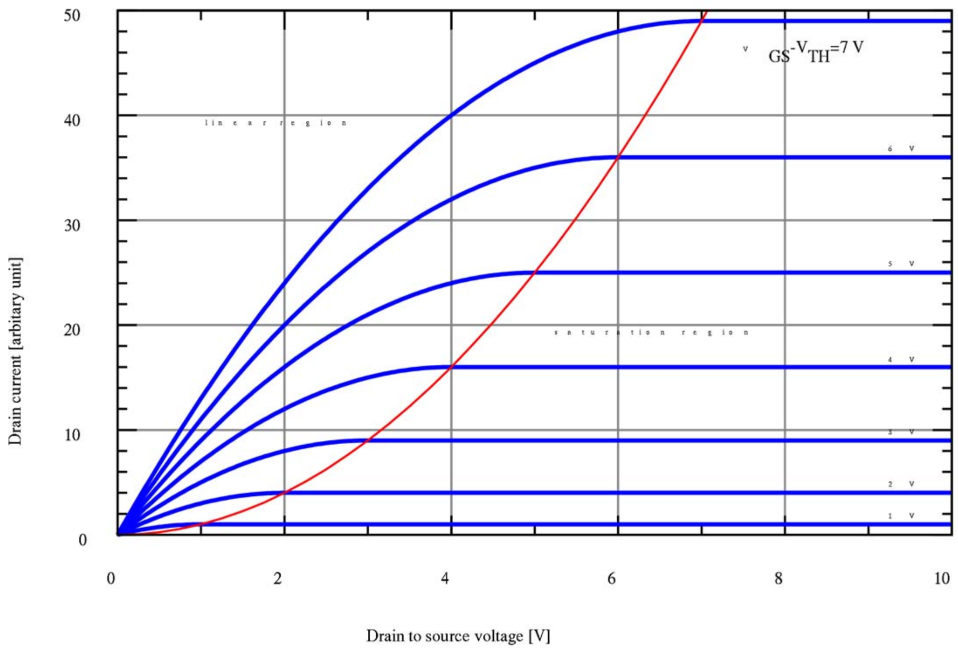
(CVD graphene on diamond, Wu et al., Nature 2011)

MOS-FET transistors for digital applications

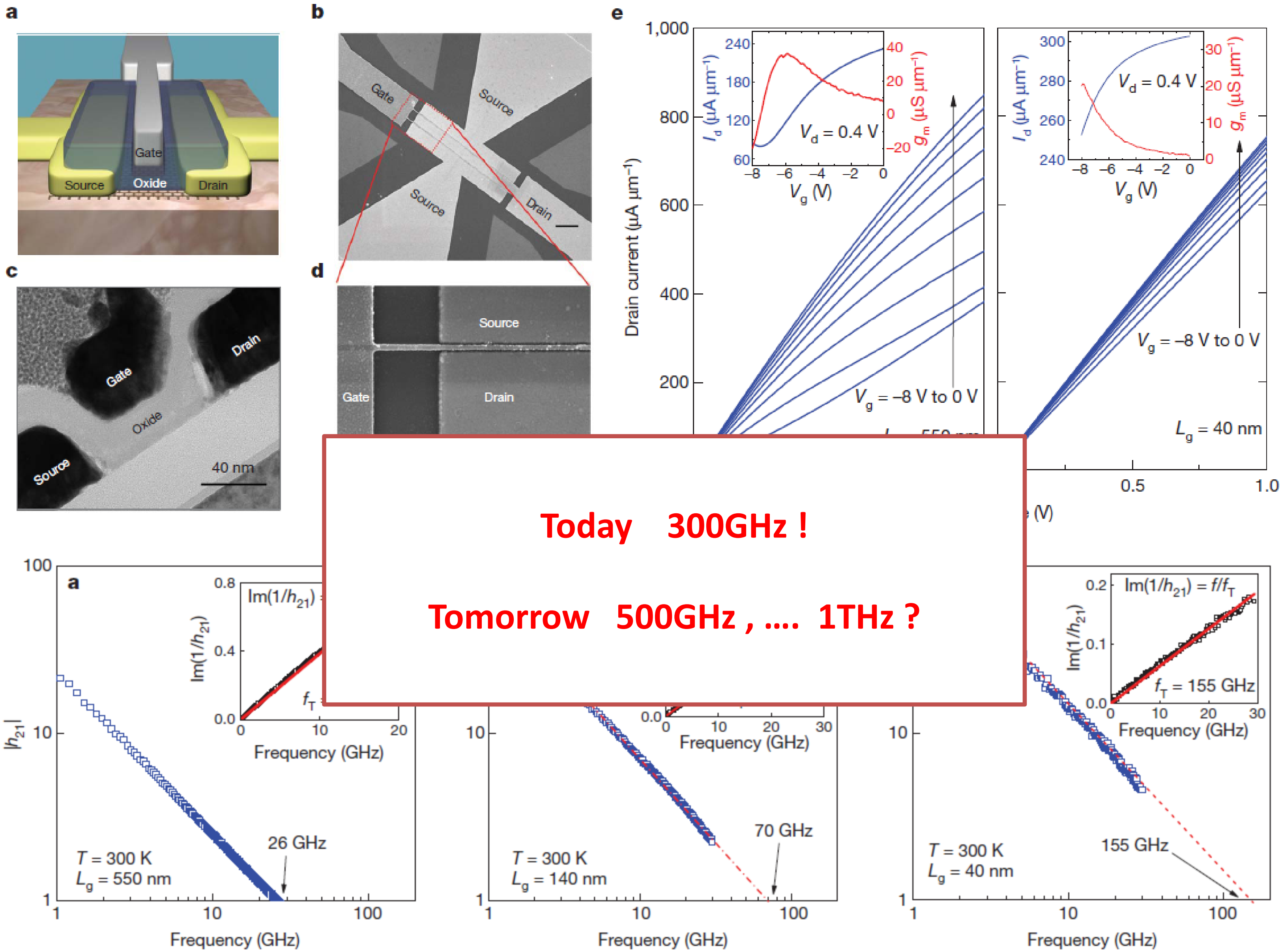
(Pentium 4, INTEL)



(taken from wikipedia.org)



Microwave transistors by IBM



Today 300GHz !

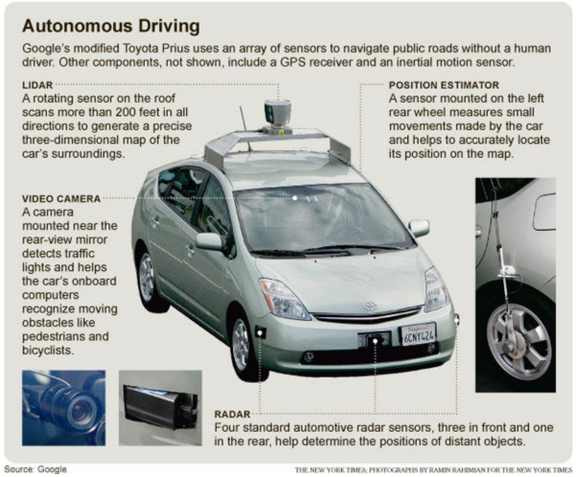
Tomorrow 500GHz , …. 1THz ?

ER-Tremblay, 28/06/2012

(CVD graphene on diamond, Wu et al., Nature 2011)

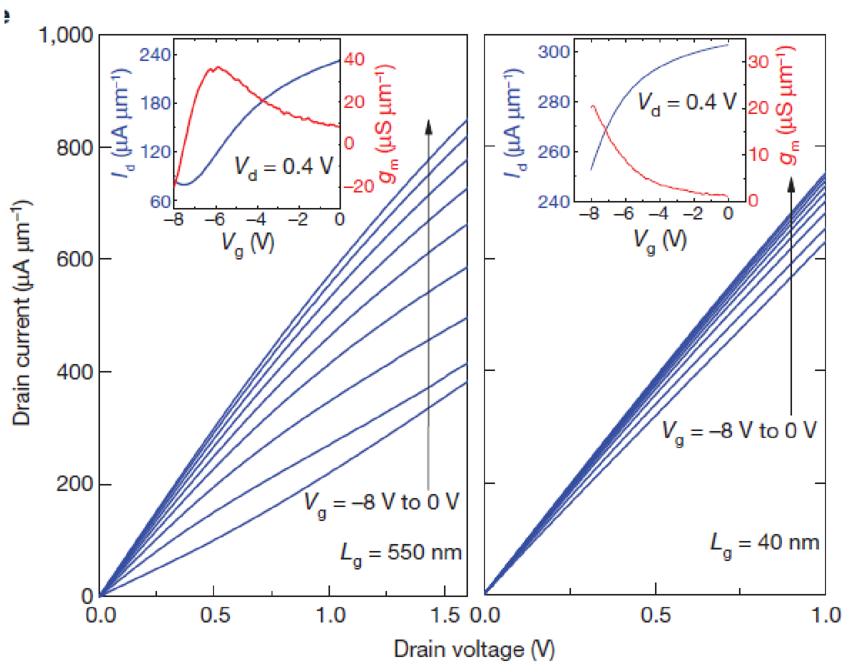
Applications of graphene transistors

radars for aircrafts



radar for (Google) Car

THz imaging



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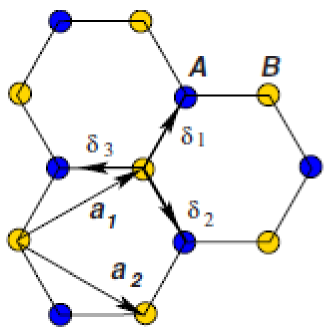
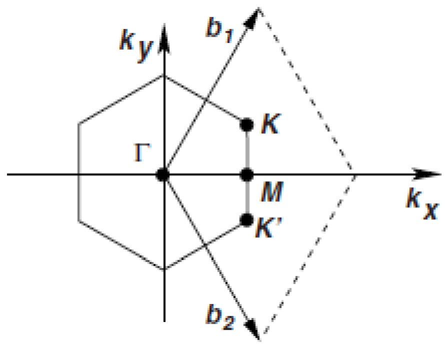
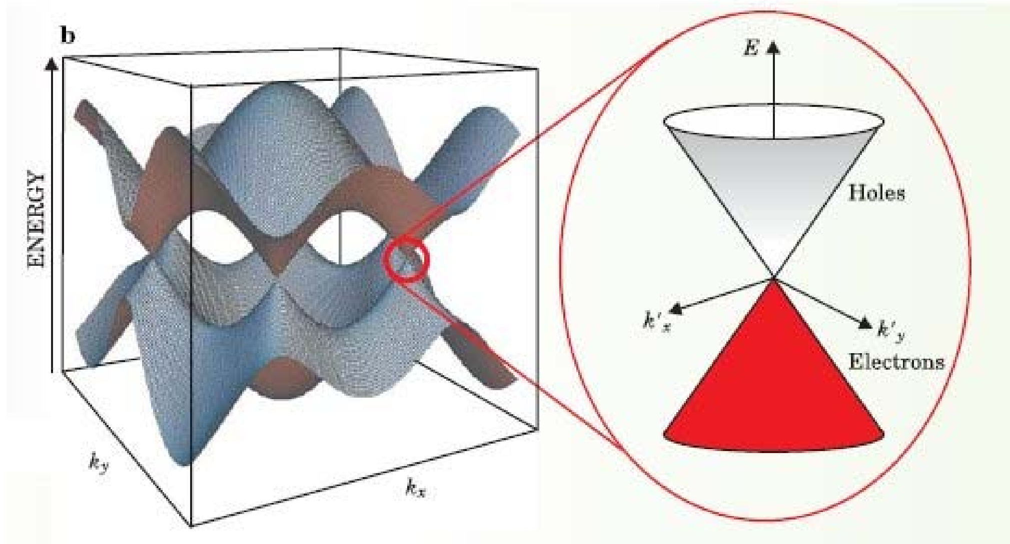
Tight-binding model → Dirac hamiltonian





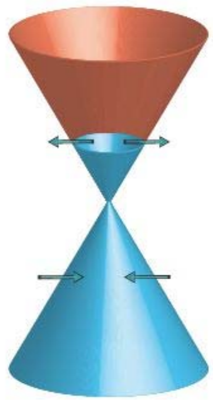


$$H = \hbar v_F \begin{pmatrix} 0 & q_x - iq_y \\ q_x + iq_y & 0 \end{pmatrix} = \hbar v_F\, \boldsymbol{\sigma}.\boldsymbol{q}$$

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

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

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

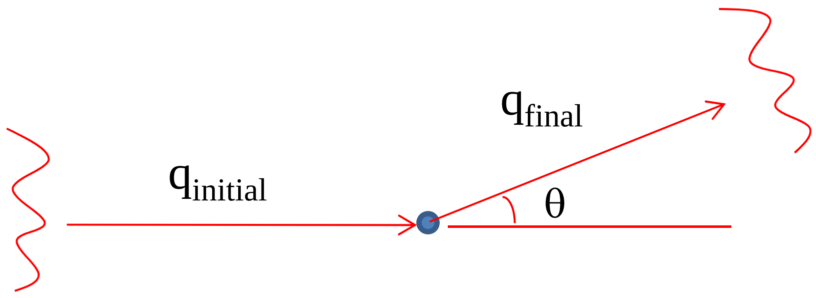


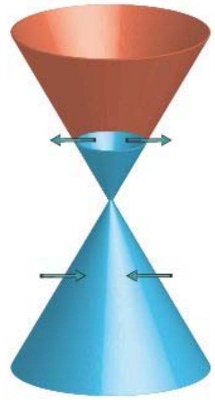
(P.R. Wallace, PRB 1947)

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

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

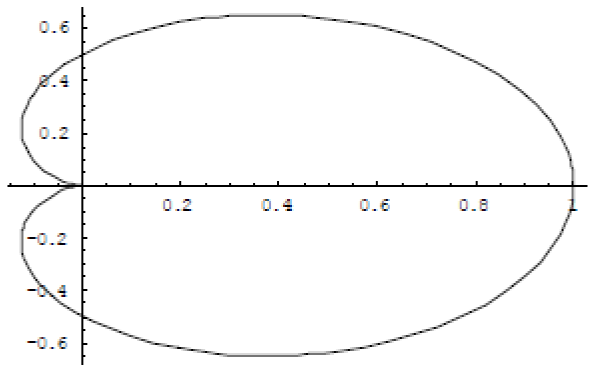
Pseudo-spin supresses back scattering





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

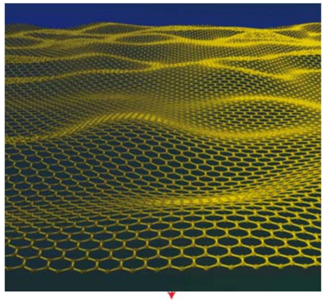
Whence the large mobility at low temperature !

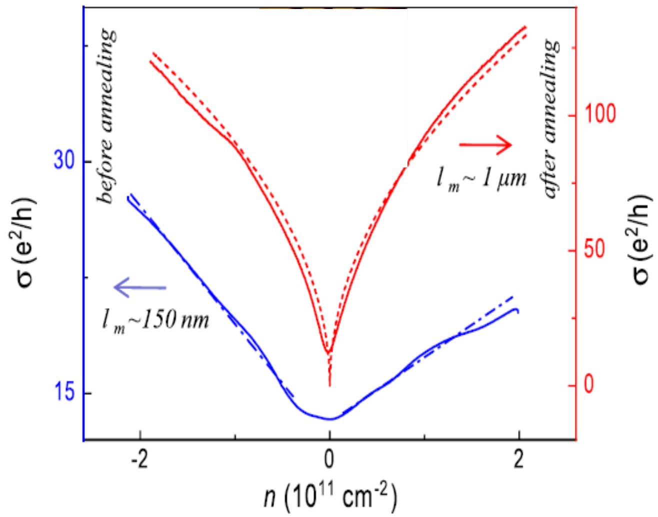


Pseudo-spin opens new scattering channels

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

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



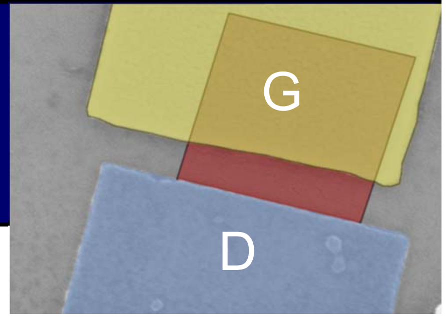


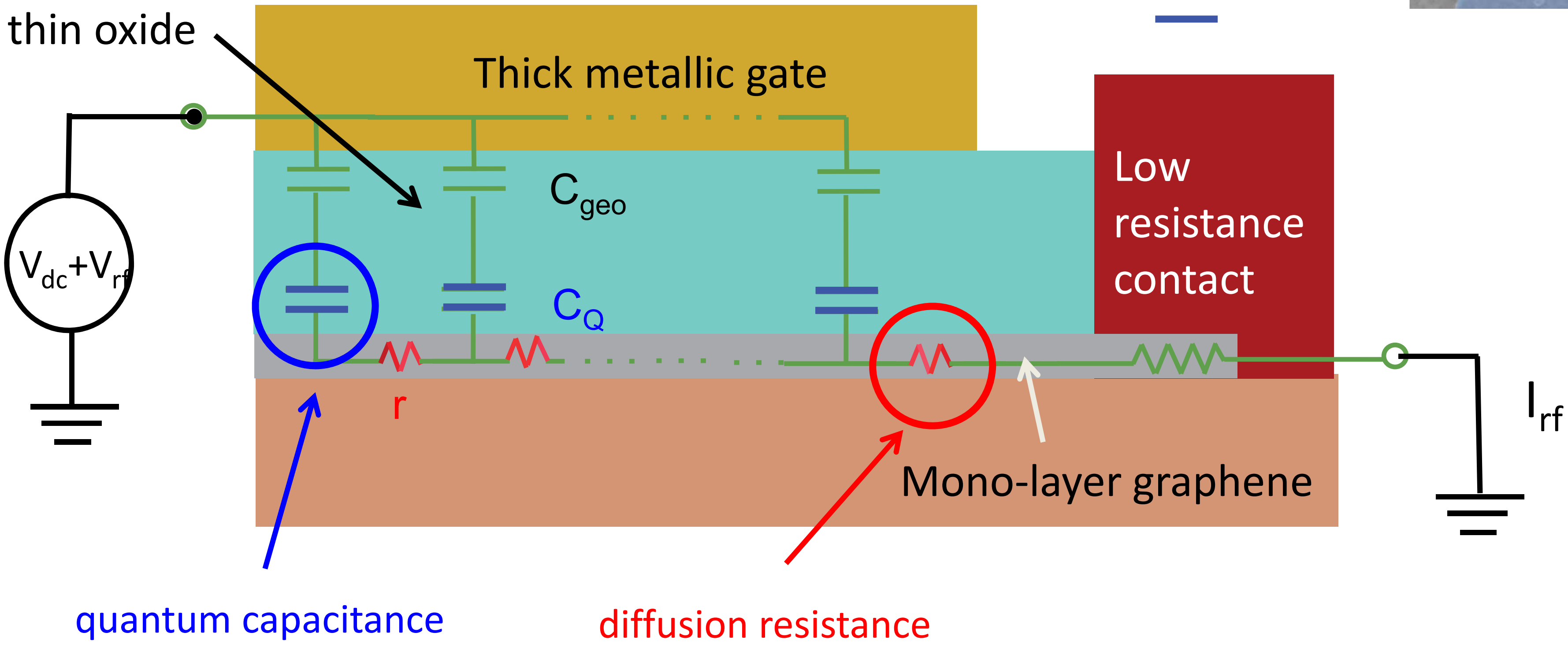
- scalar disorder ($\hat{I}$-term), short range : adsorbates, void, etc...)
- scalar disorder ($\hat{I}$-term), long range : no screening of charged impurities
- gauge field disorder : static distortions like ripples, etc...
- Dirac mass disorder : local lifting of sublattice degeneracy

mechanisms	*scattering time*	*conductivity*
local impurity	$\tau \sim 1/k_F$	$\sigma \sim Const$
local impurity	$\tau \sim \ln k_F/k_F$	$\sigma \sim \ln n_c$
random Dirac-mass	$\tau \sim Const$	$\sigma \sim \sqrt{n_c}$
charged impurity	$\tau \sim k_F$	$\sigma \sim n_c$
resonnant scattering	$\tau \sim k_F \ln^2(k_F)$	$\sigma \sim n_c \ln^2 n_c$
ripples	$\tau \sim k_F^{(2H-1)}$	$\sigma \sim n_c^H$
acoustic phonons	$\tau \sim k_F^2$	$\sigma \sim n_c^{3/2}$

Castro-Neto at el. RMP 2009,
Peres et al. RMP 2010,
Das Sarma et al. RMP 2011,
etc……

A graphene capacitor





Electronic compressibility comes as a quantum capacitance

$$\Delta\mu_L = e\Delta V + \Delta\mu_L$$

$$= e\Delta V + \frac{1}{e}\frac{\partial\mu}{\partial n}\Delta q$$

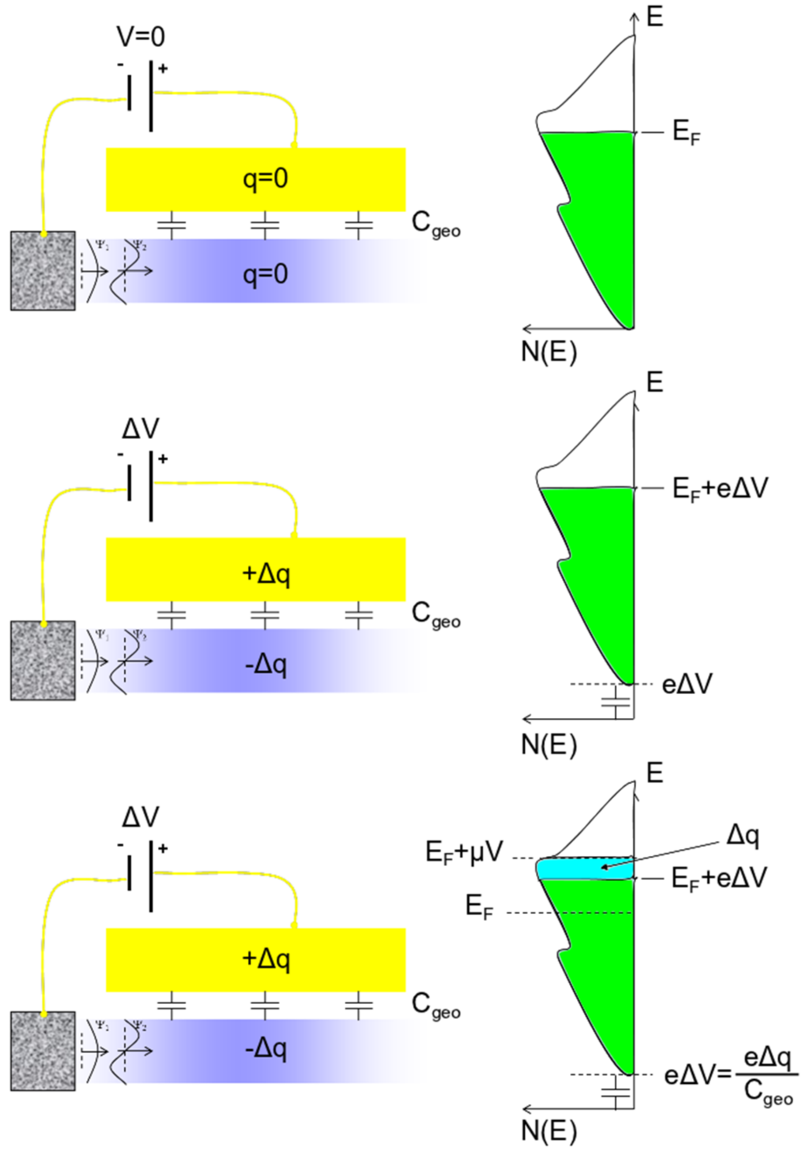
$$\frac{e\Delta q}{C_\mu} = \frac{e}{C_{géo}}\Delta q + \frac{1}{e\chi}\Delta q$$

$$\frac{1}{C_\mu} = \frac{1}{C_{géo}} + \frac{1}{e^2\chi}$$

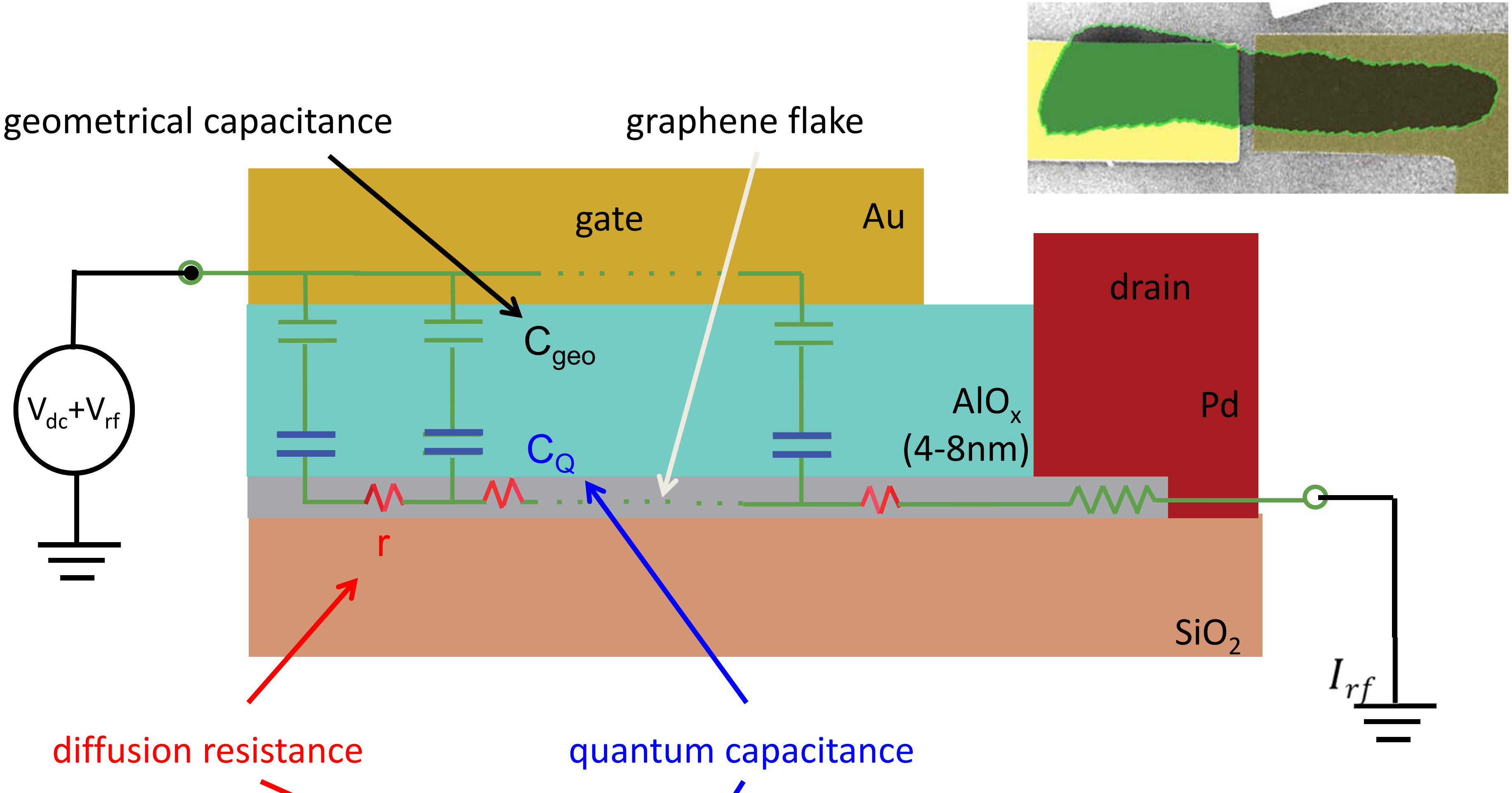
$$C_Q = e^2\chi \rightarrow e^2\rho(E_F) \quad (\mathrm{T} \rightarrow 0)$$

graphene :

$$C_Q = \frac{2e^2 k_B T}{\pi(\hbar v_F)^2}\ln\left[2 + 2\cosh\left(\frac{E_F}{k_B T}\right)\right] \rightarrow \frac{4e^2 E_F}{2\pi(\hbar v_F)^2} \quad (\mathrm{T} \rightarrow 0)$$



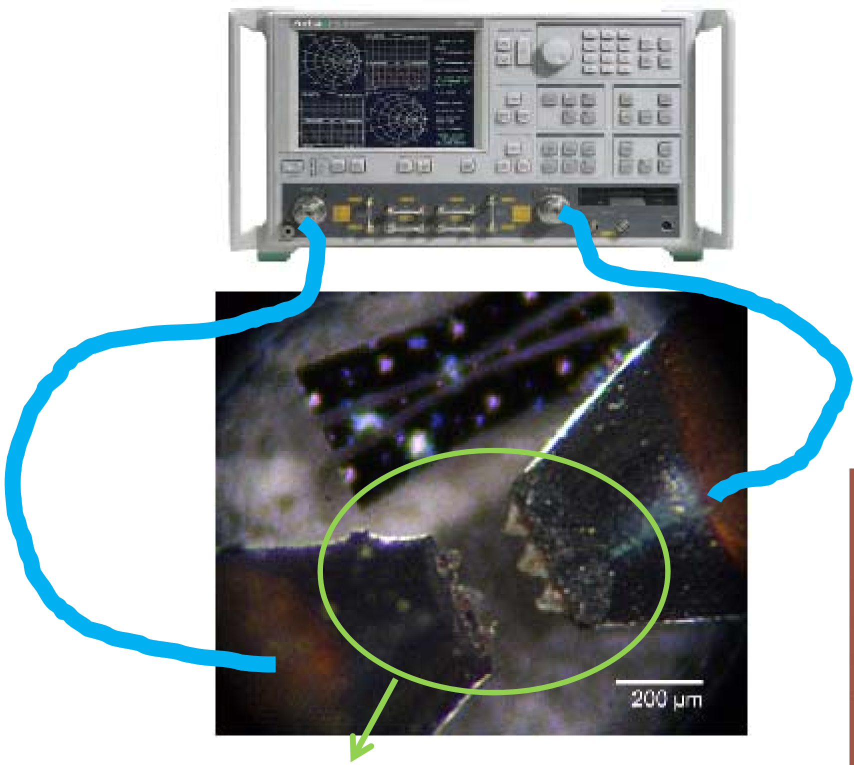
Scattering time as function of energy

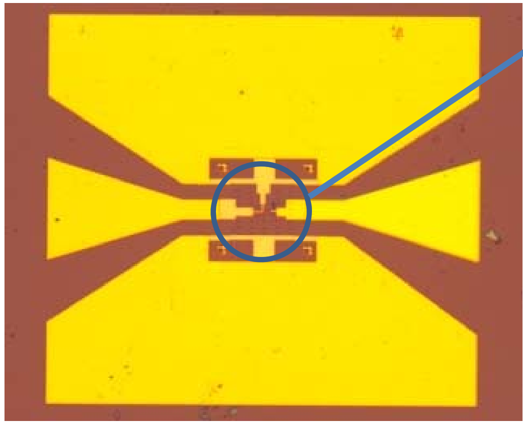


$$\sigma(E_F) = e^2\rho(E_F) < \frac{v_F^2}{2}\tau_{tr}(E_F) >$$ ← Diffusion constant

$$E_F(V_g) = e(V_g - V_{np}) - \int_{V_{np}}^{V_g} c_Q/(c_{geo}+c_Q)dV,$$

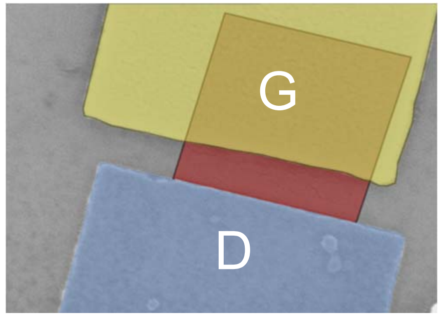
Our graphene RF devices





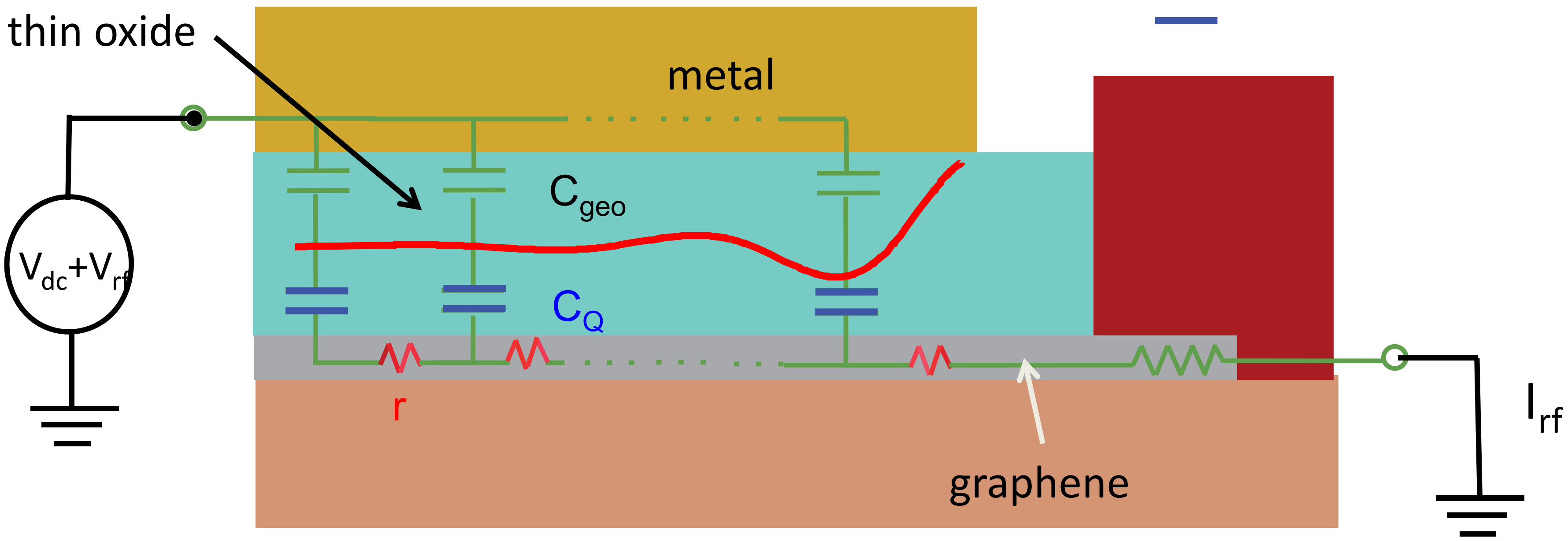
Wave guide (CPW)

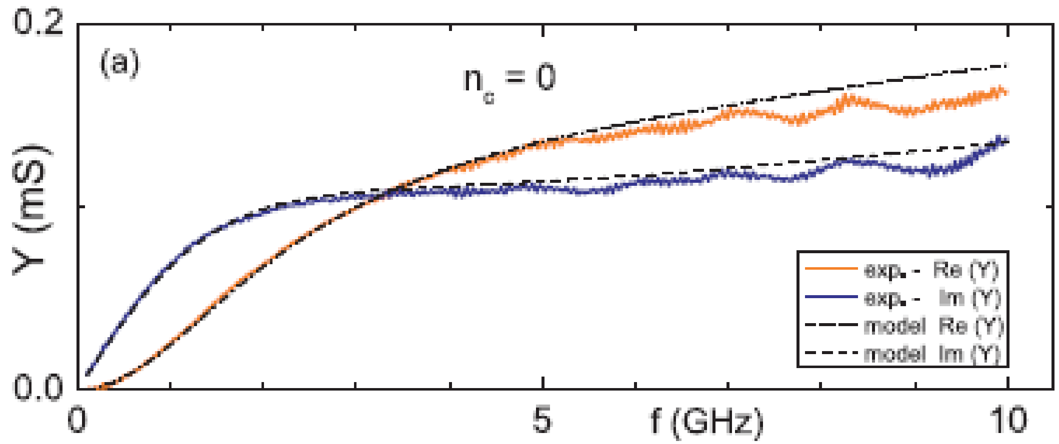
20GHz capacitor (admittance)



E. Pallecchi et al, PRB 83 (2011)

Evanescent waves to probe diffusion

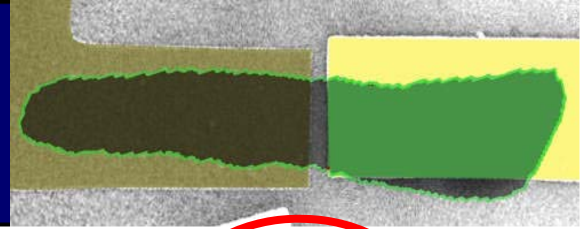


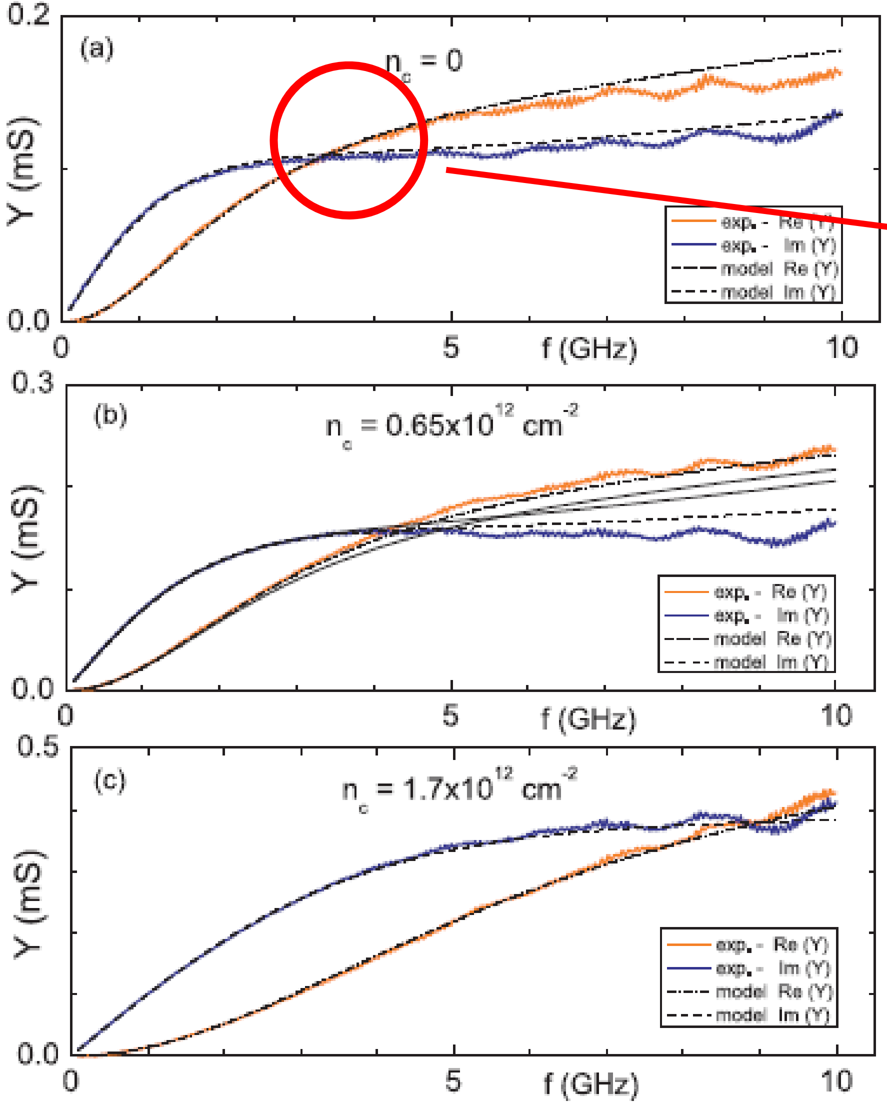


ER-Tremblay, 28/06/2012

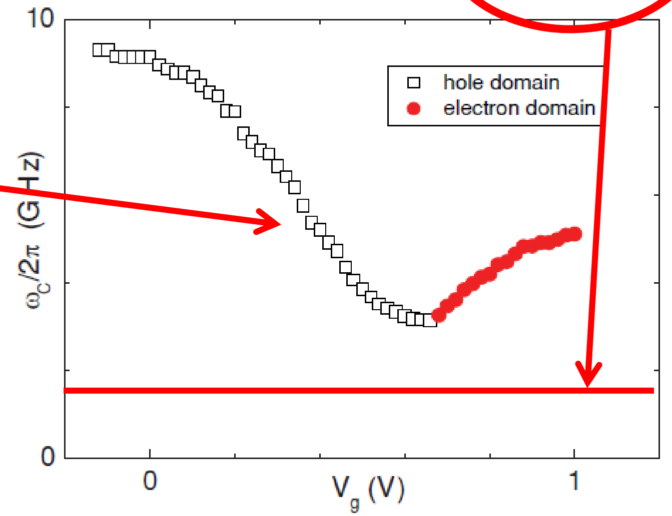
$$Y = \jmath\omega Lc \times \frac{\tanh[(1+\jmath)L/\sqrt{rc\omega}]}{(1+\jmath)L/\sqrt{rc\omega}}$$

Cutt-off frequency





$$\omega_c = \frac{\pi^2}{2}\sigma / c_{geo} L^2 + \frac{\pi^2}{2} \mathcal{D} / L^2 .$$

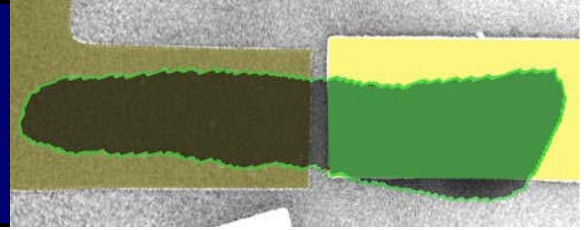


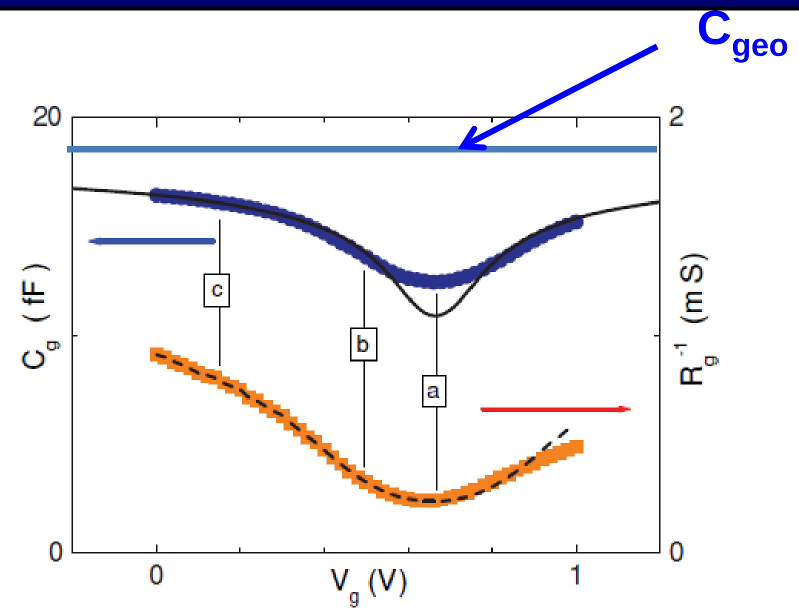
Thouless energy protects graphene device dynamics !

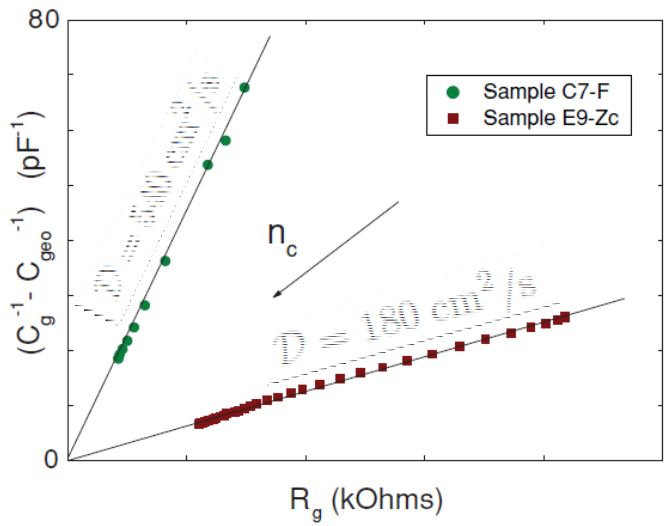
ER-Tremblay, 28/06/2012

(Transport scattering time probed through rf admittance of a graphene capacitor, Pallecchi et al., PRB 2011)

Gate voltage dependence







$$\sigma(E_F) = e^2 \rho(E_F) < \frac{v_F^2}{2} \tau_{tr}(E_F) >$$

$$E_F(V_g) = e(V_g - V_{np}) - \int_{V_{np}}^{V_g} c_Q/(c_{geo} + c_Q) dV \,,$$

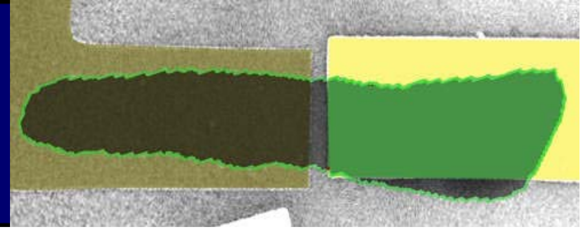
mechanisms	*scattering time*	*conductivity*
local impurity	$\tau \sim 1/k_F$	$\sigma \sim Const$
local impurity	$\tau \sim \ln k_F / k_F$	$\sigma \sim \ln n_c$
random Dirac-mass	$\tau \sim Const$	$\sigma \sim \sqrt{n_c}$
charged impurity	$\tau \sim k_F$	$\sigma \sim n_c$
resonnant scattering	$\tau \sim k_F \ln^2(k_F)$	$\sigma \sim n_c \ln^2 n_c$
ripples	$\tau \sim k_F^{(2H-1)}$	$\sigma \sim n_c^H$
acoustic phonons	$\tau \sim k_F^2$	$\sigma \sim n_c^{3/2}$

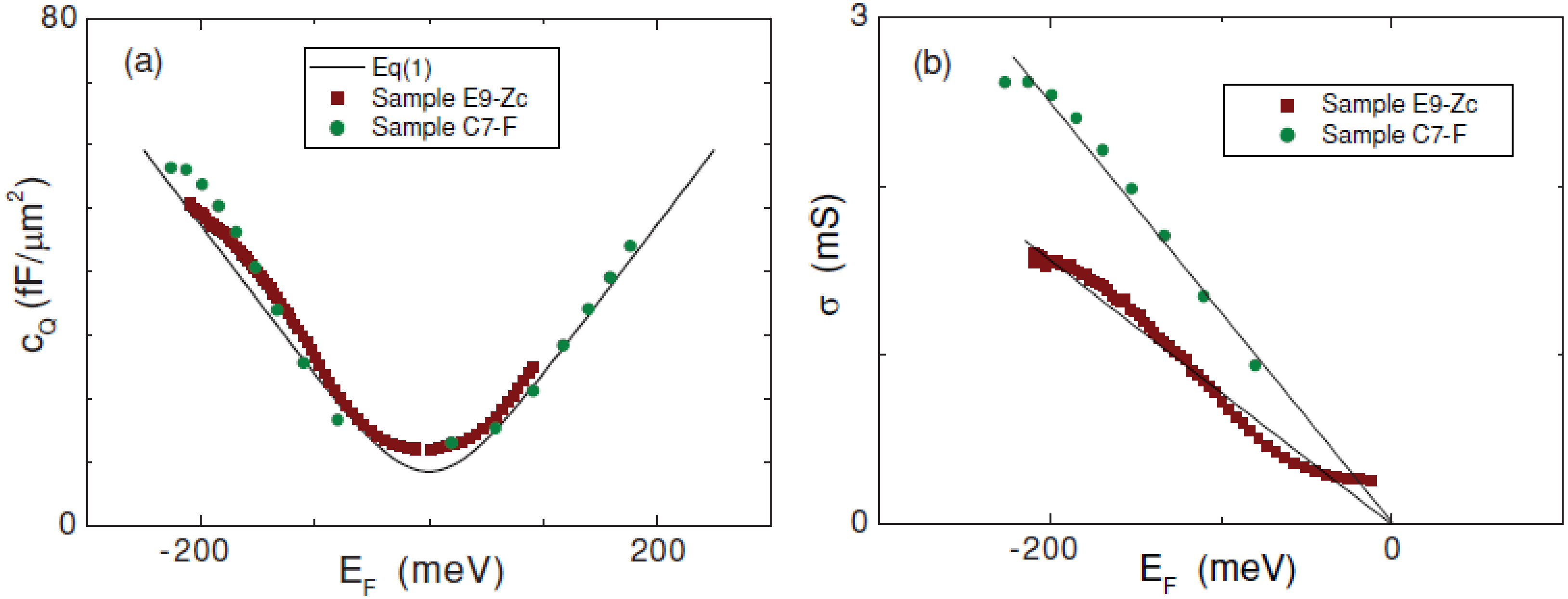
$D(E_F)$ = Const (Dirac-mass disorder)

ER-Tremblay, 28/06/2012

(Pallecchi et al., PRB 2011)

Fermi energy dependence





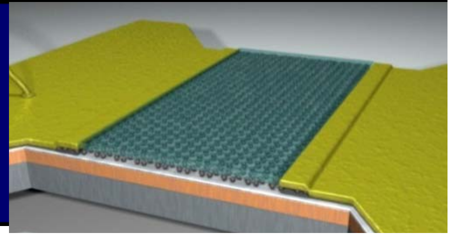
$$E_F(V_g) = e(V_g - V_{np}) - \int_{V_{np}}^{V_g} c_Q/(c_{geo} + c_Q)dV,$$

(Pallecchi et al., PRB 2011)

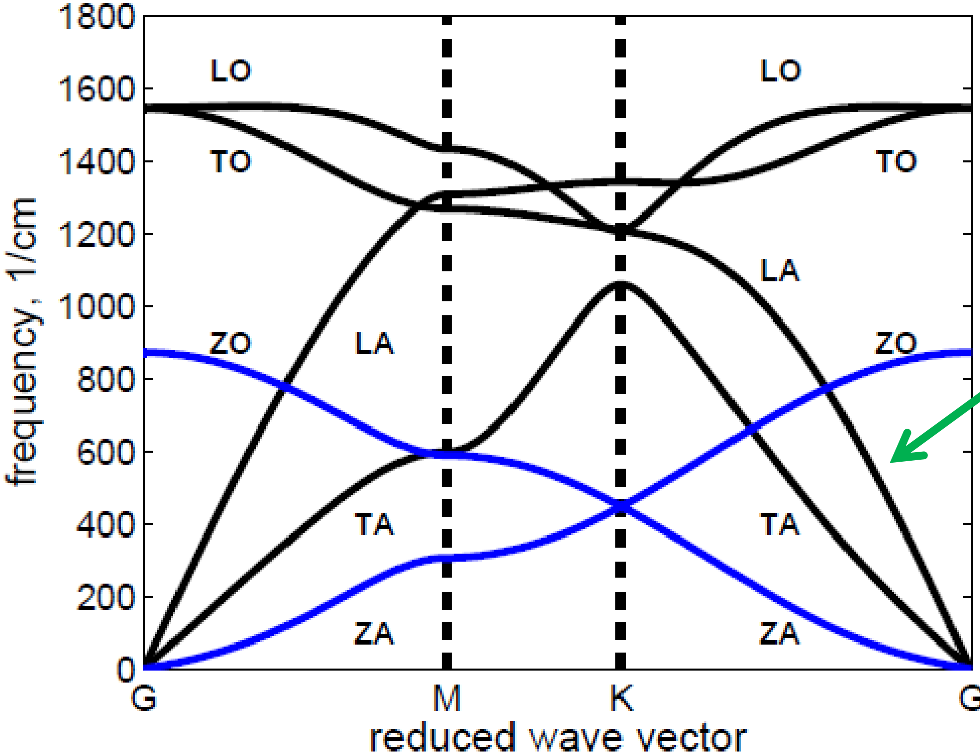
Outline

1) Introduction to magic graphene
2) Transit frequency of microwave transistors
3) Diffusion probed in a field-effect capacitor
4) Acoustic phonons controls noise of resistors
5) New transistor architectures

Electron-phonon in graphene



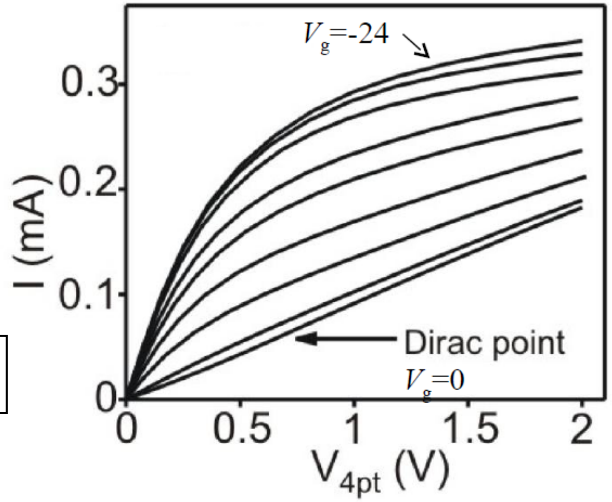
Phonons spectrum

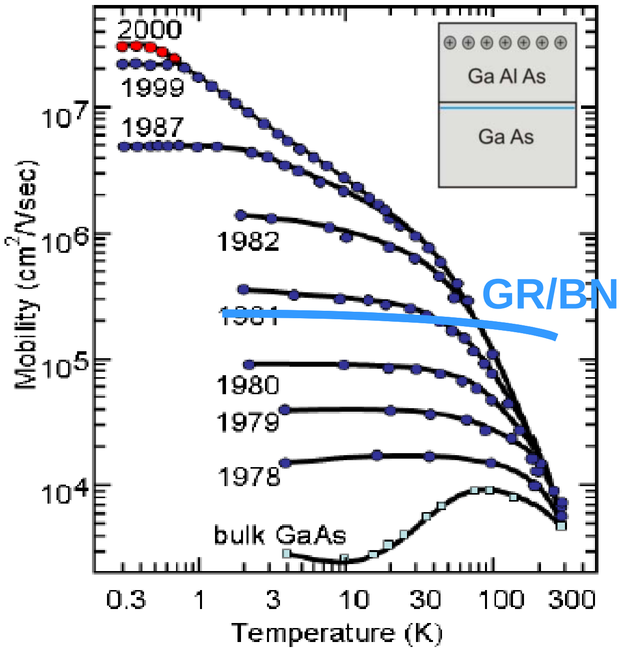


optical (strong)

c = 20 000 m/s !

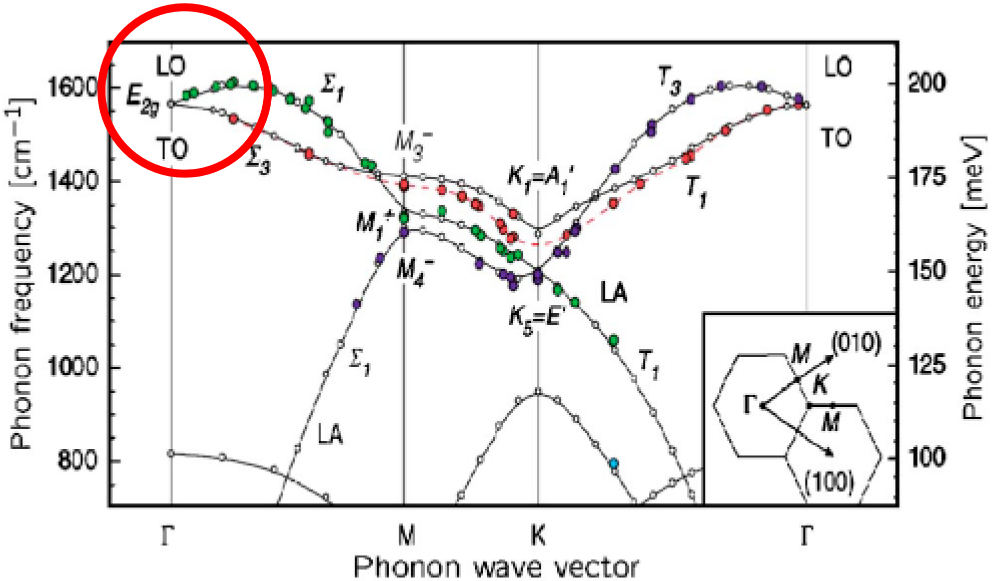
acoustic (weak)





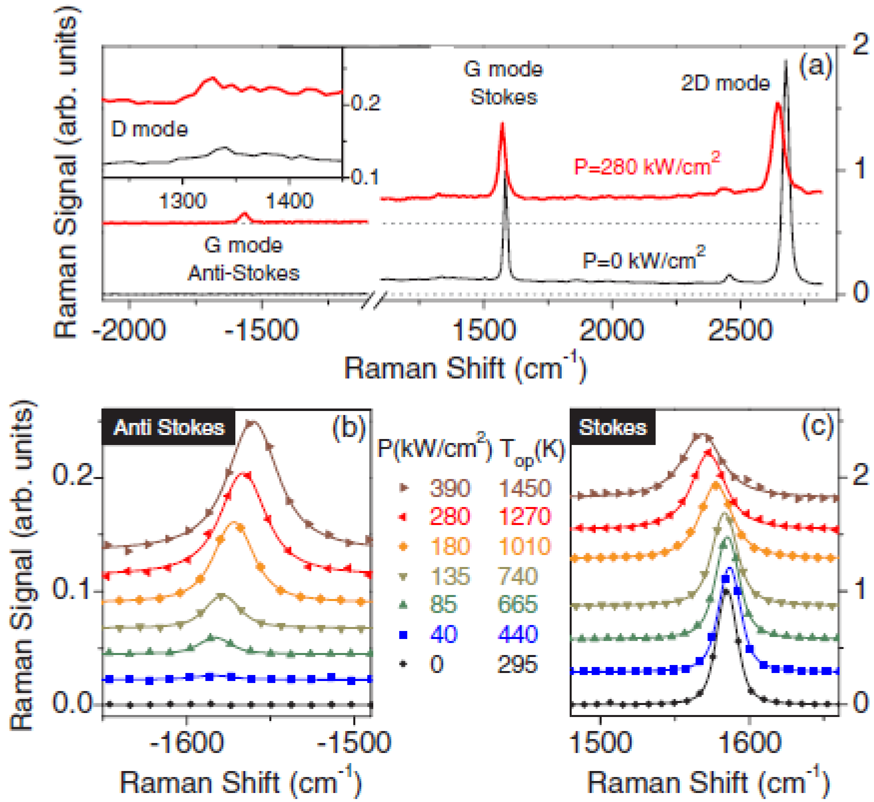
- Large O-Phonon energy
- Weak A-Phonon coupling

Raman spectroscopy



OP interactions (Kohn anomalies)

OP/AP populations

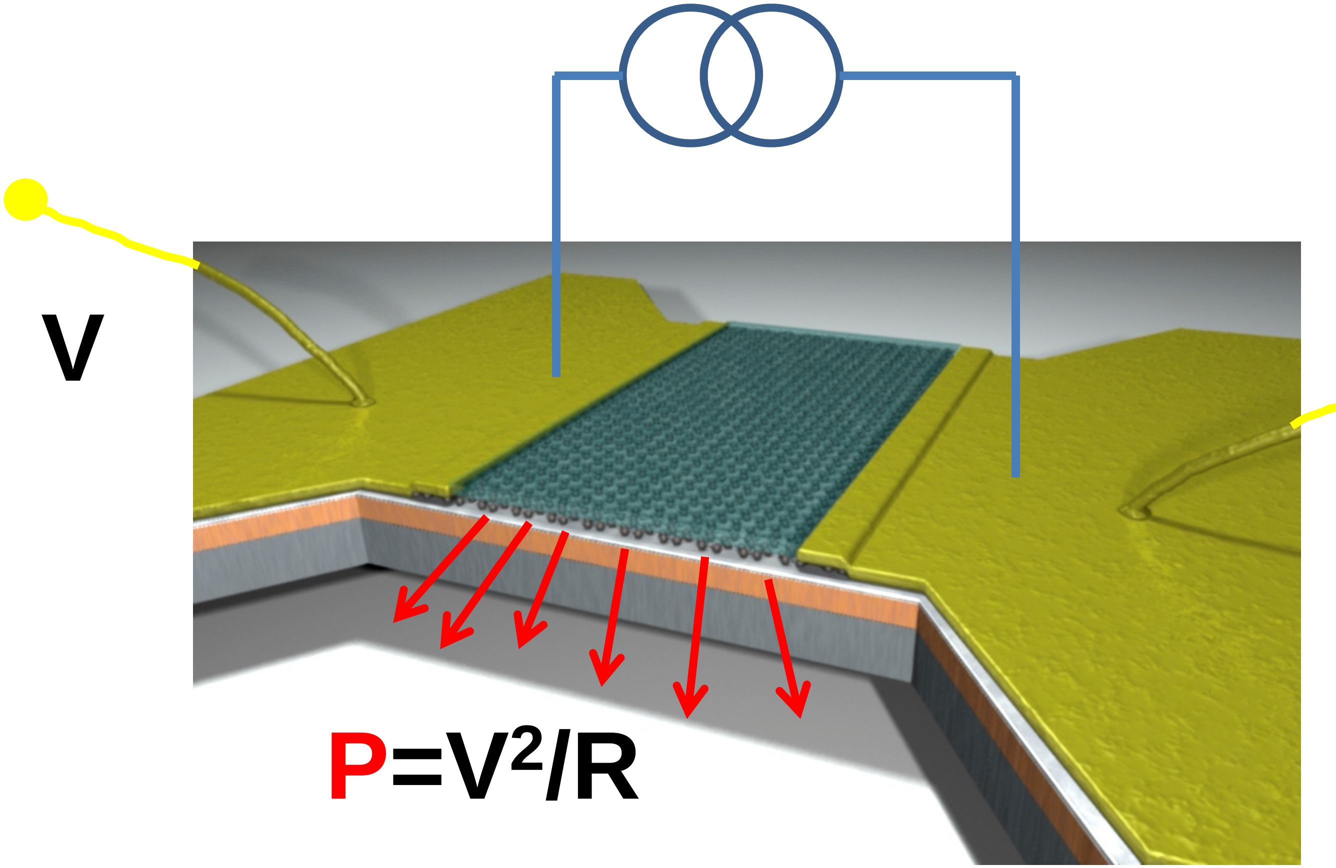


(Berciaud, Han, Mak,Brus,Kim, Heinz, PRL2010)

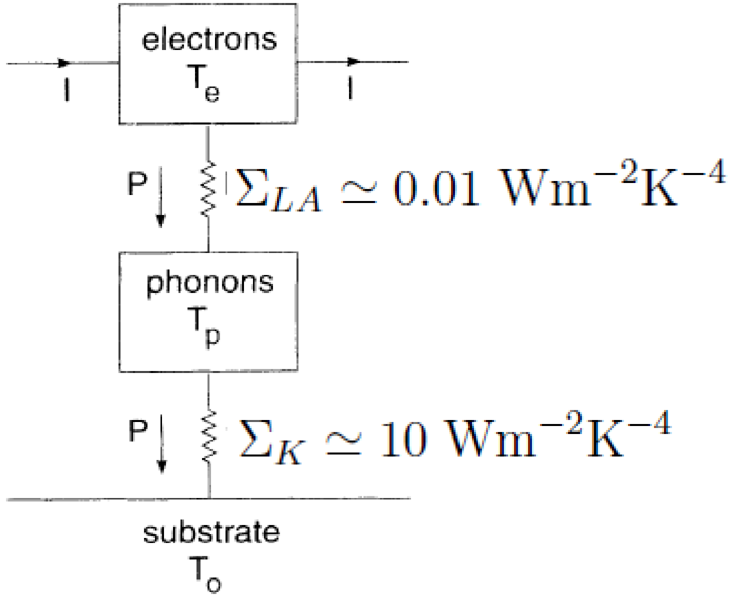
Hot -electron experiment

$S_I = 4k_B T_e / R$

V



$P = V^2/R$



$$V \cdot I = Volume \times \Sigma(T_e^5 - T_{ph}^5) \qquad (3D)$$ (metals)

$$V \cdot I = Area \times \Sigma(T_e^4 - T_{ph}^4) \qquad (2D)$$ (graphene ?)

$$V \cdot I = Length \times \Sigma(T_e^3 - T_{ph}^3) \qquad (1D)$$ (nanotubes)

Hot -electron experiment

cooling power (metals)

$$Q = Volume \times \Sigma \left(T_e^5 - T_{ph}^5\right) \quad (3D)$$

$$Q = Area \times \Sigma \left(T_e^4 - T_{ph}^4\right) \quad (2D)$$

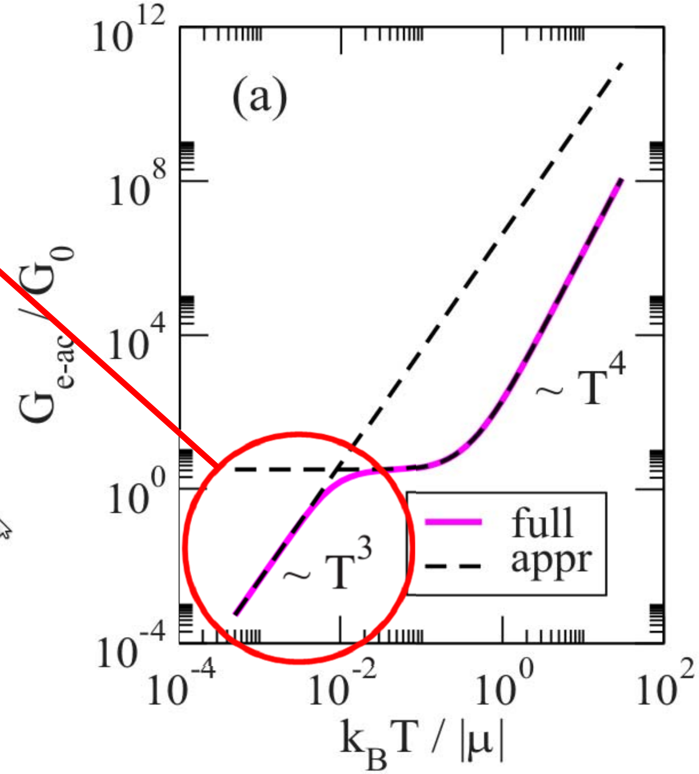
$$Q = Length \times \Sigma \left(T_e^3 - T_{ph}^3\right) \quad (1D)$$

(1D nanotubes, Wu et al. APL 2011)

$$\Sigma_{LA} = \frac{\pi^2 D^2 k_B^4}{15\rho\hbar^5 v_F^3 c^3} \times |E_F|$$

heat sink

$$G = 4\Sigma T^3 \Delta T$$



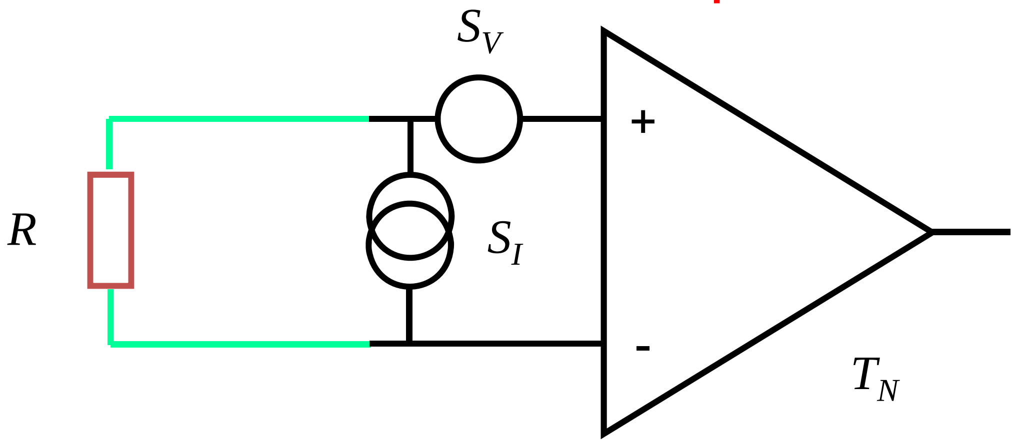
Theory : Viljas et al. PRB 2010

ER-Tremblay, 28/06/2012

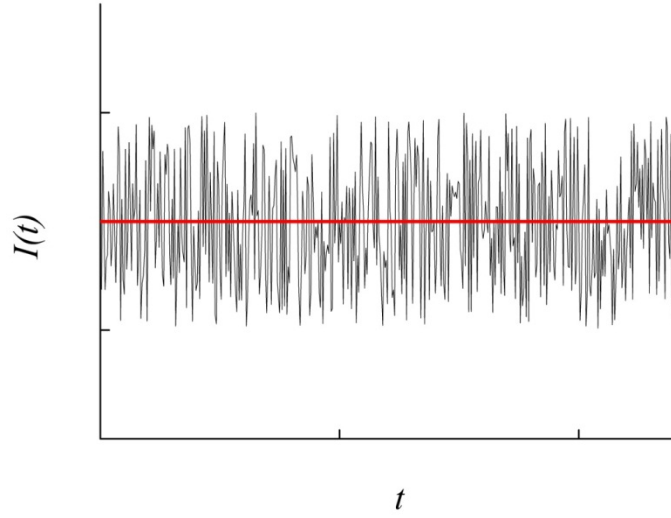
(Kubakaddi, PRB 2009, Viljas-Heikkila, PRB 2010)

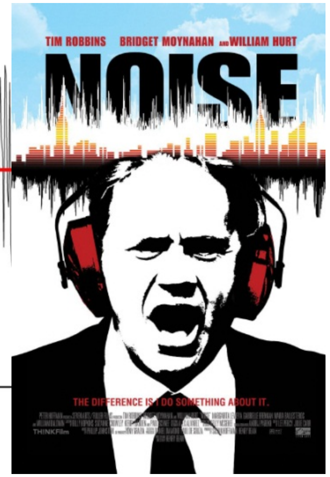
What is electrical noise ?

Noise of an amplifier

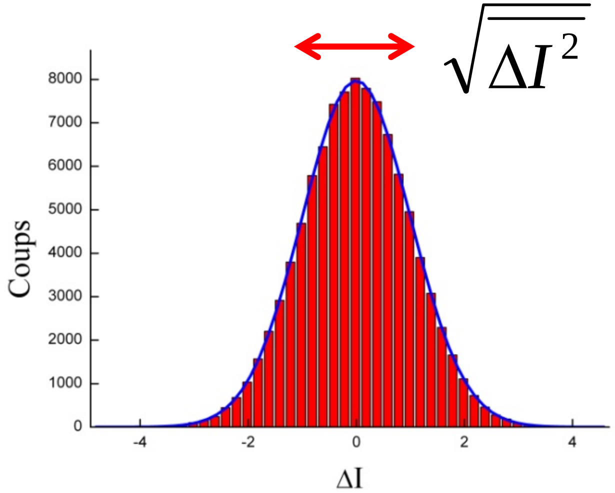


$$S_V^{in} = S_V + R^2 S_I$$





Statistical distribution

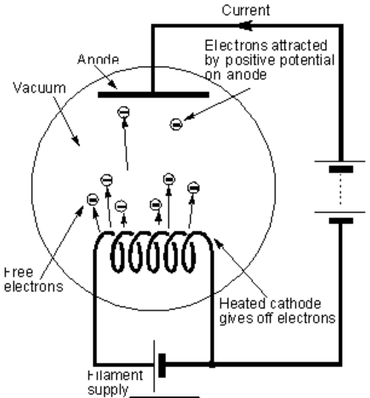


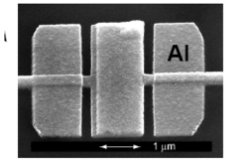
Fluctuations : $\Delta I(t) = I(t) - \overline{I(t)}$

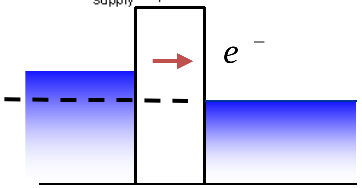
Noise spectrum : $\overline{\Delta I^2(t)} = \int S_I(\nu)\,\Delta\nu$

Physics of noise

Shot-noise and/or Thermal noise

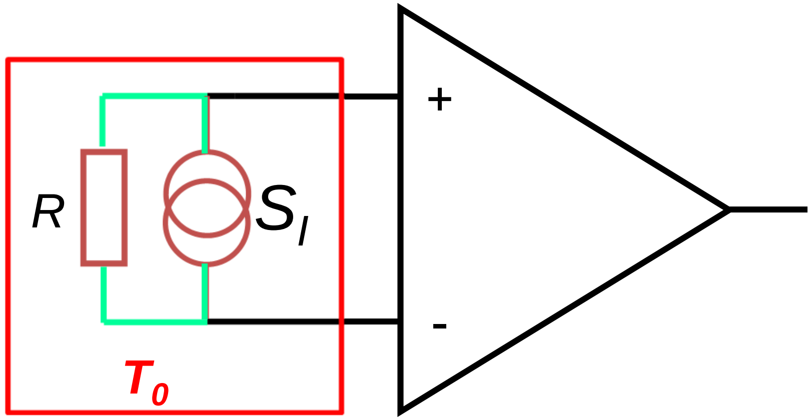






W. Schottky

$$S_I = 2e\bar{I}$$

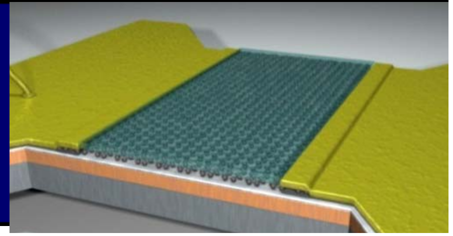


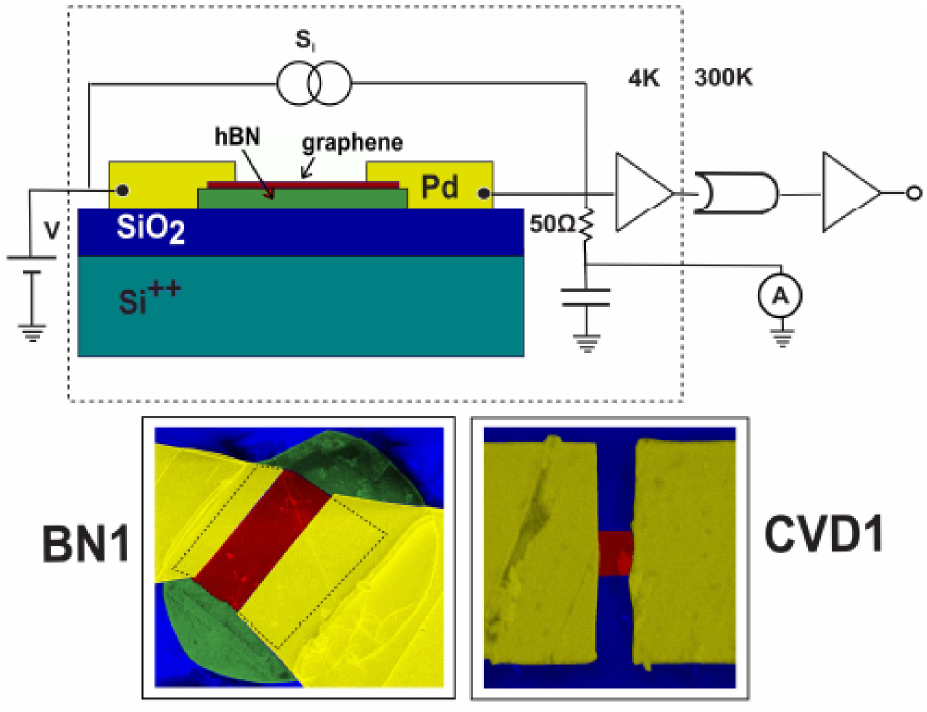
J.B. Johnson

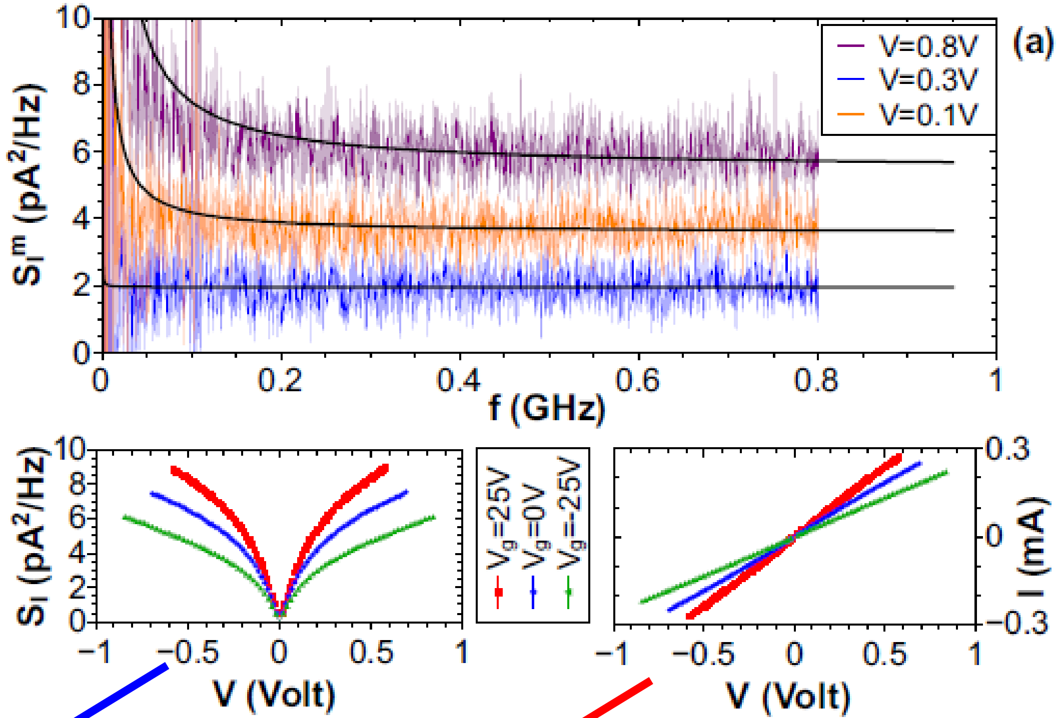
H. Nyquist

$$S_I = 4 k_B T_0 / R$$

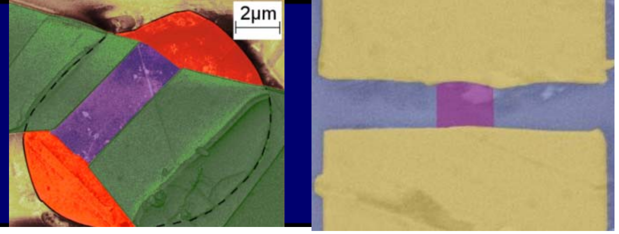
Noise thermometry



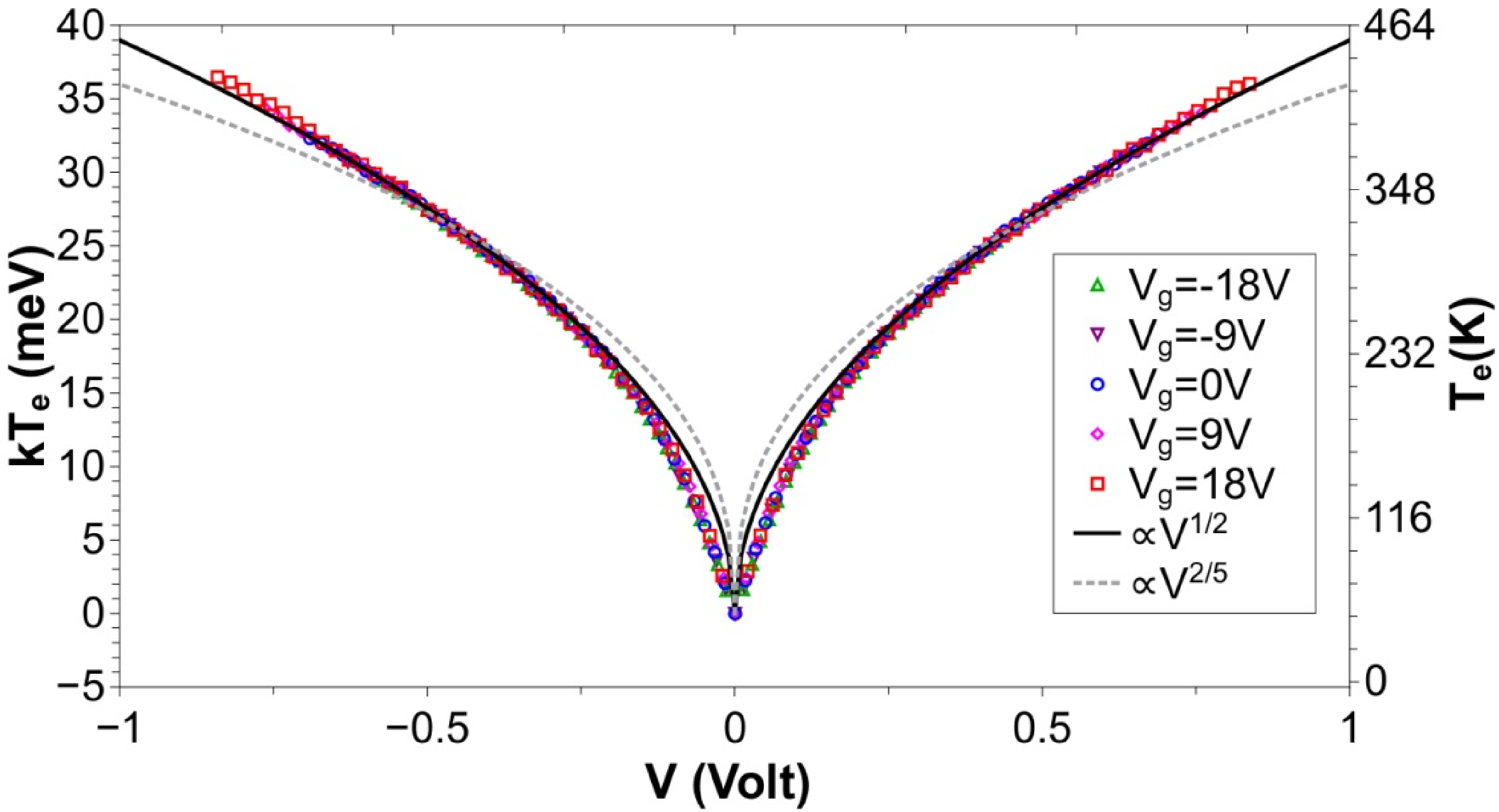




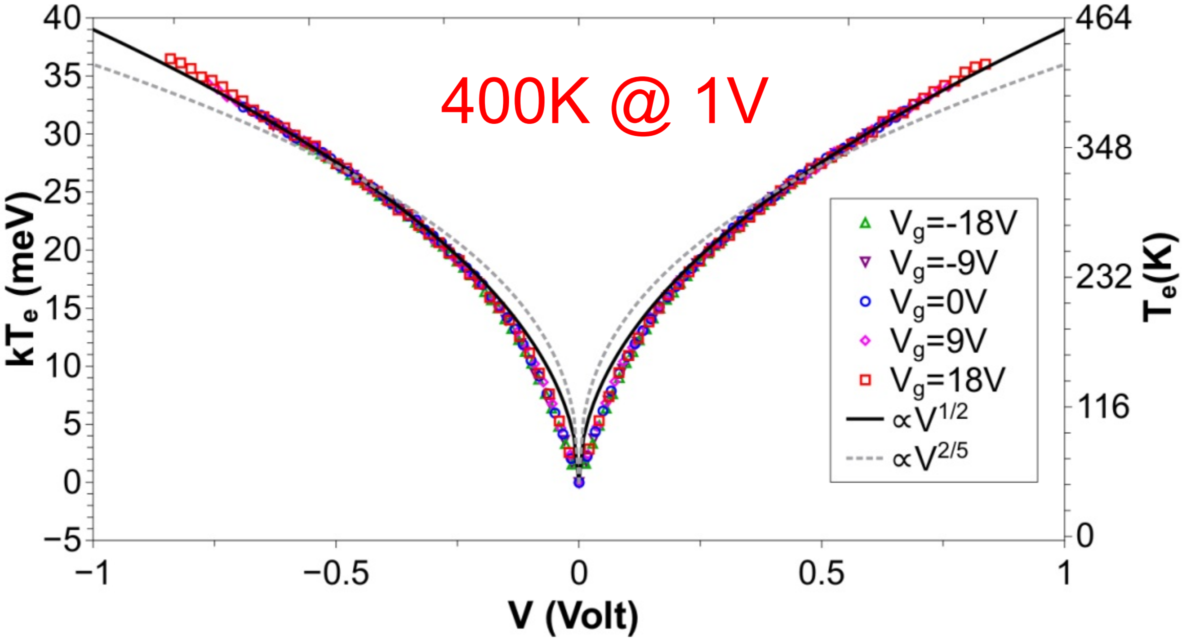
$$S_I(V_g,V_{ds}) = 4\,G(V_g,V_{ds})\,k_B[T_N + \langle T_e\rangle_x(V_g,V_{ds})]$$

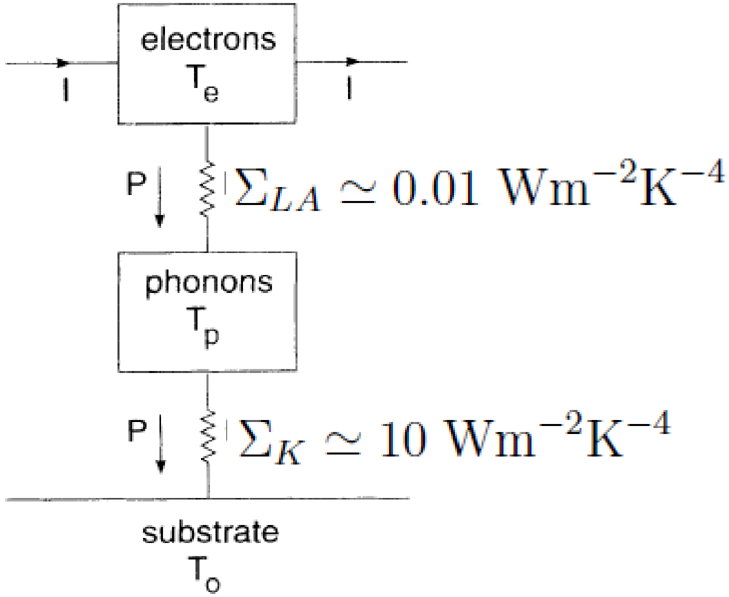


$T \sim P^{1/4} \sim V^{1/2}$!



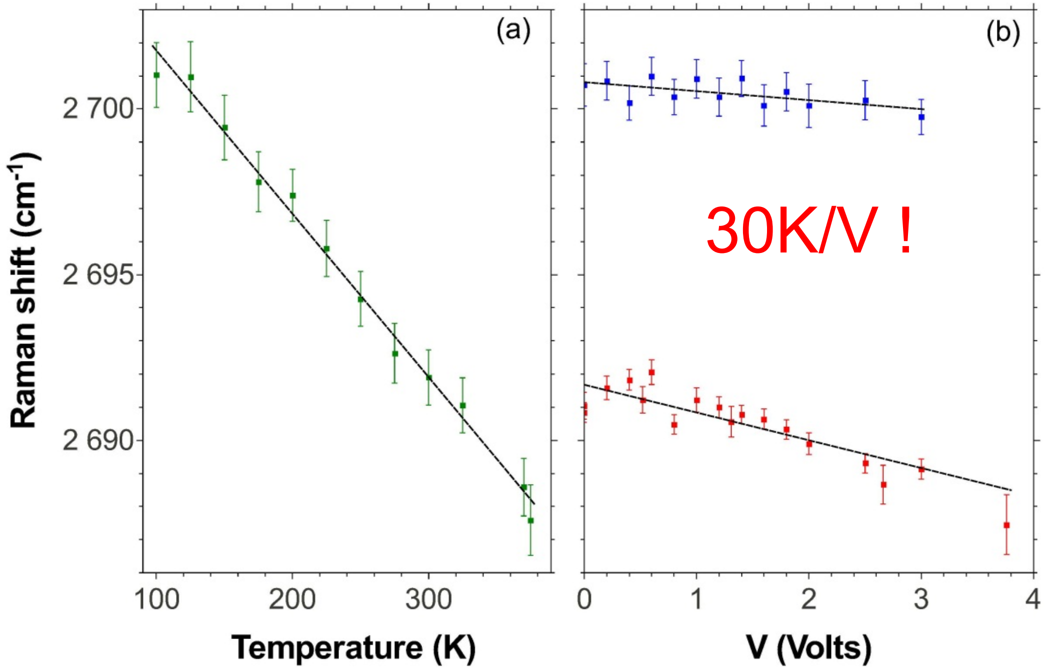
Hot electrons but cold phonons





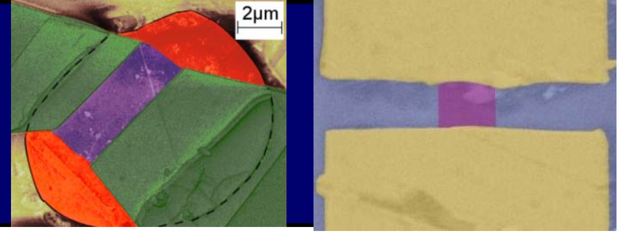
A. Betz et al., arXiv:1203.2753v1

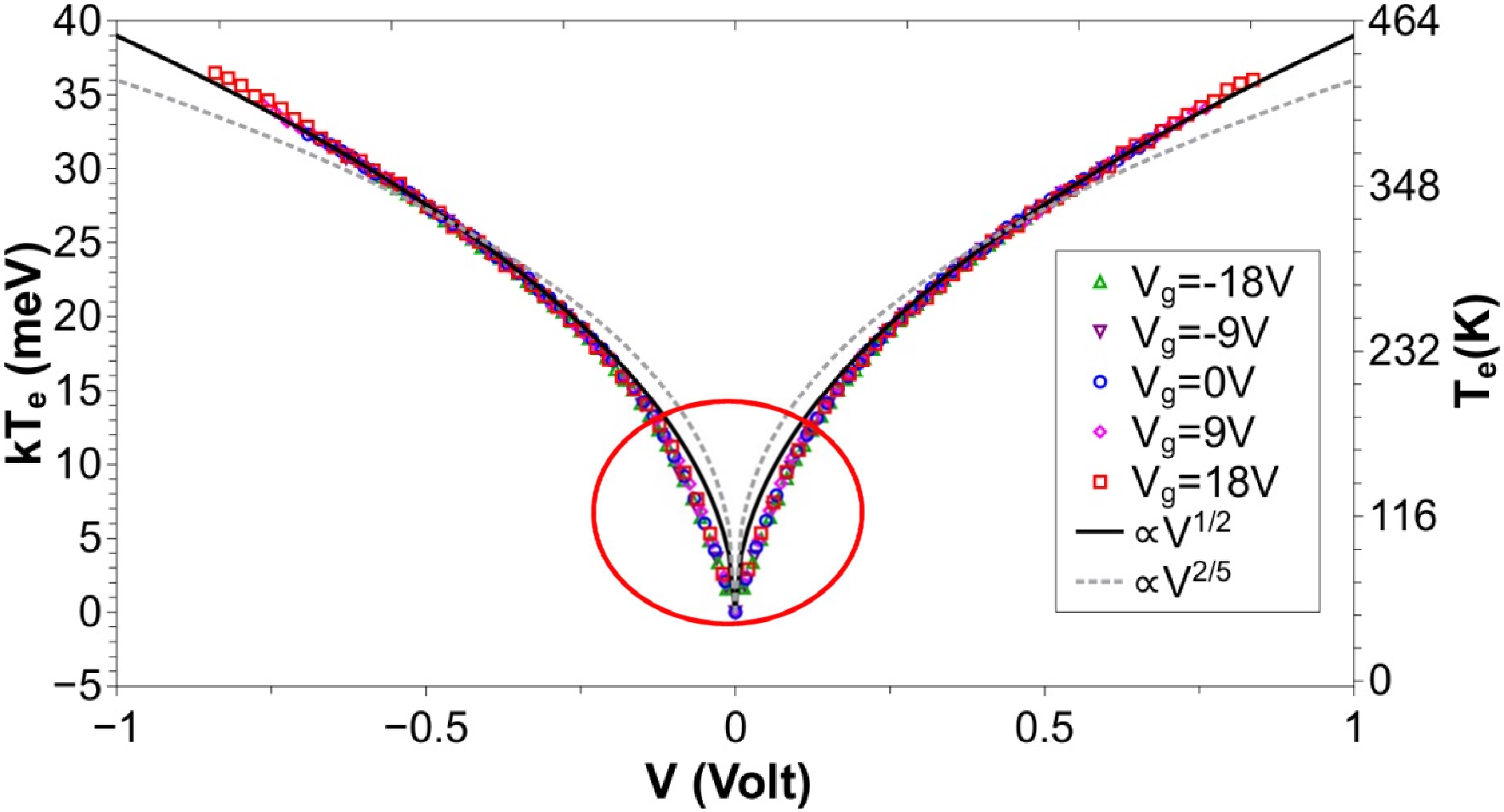
Fabien Vialla, D. Brunel and C. Voisin



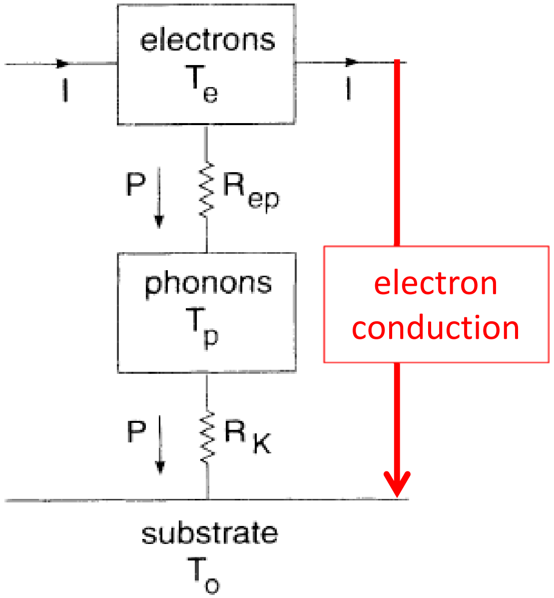
ICN Barcelone, 17/02/2012

The P=Σ T^4 dependence





Electronic temperature profile



Heat equation, sample $L \times W$

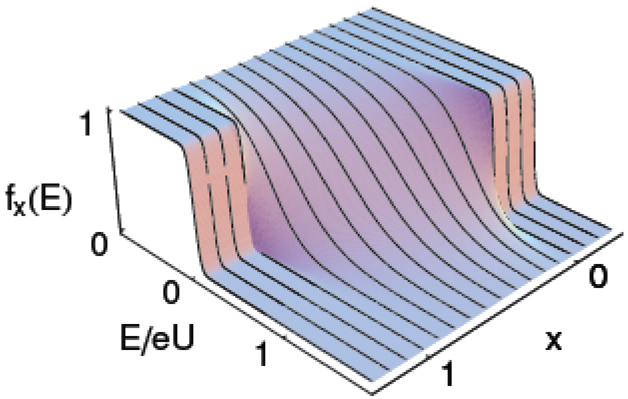
$$\frac{\mathcal{L}}{2R}\frac{L^2\partial^2 T^2(x)}{\partial x^2} = -\frac{V^2}{R} + LW\Sigma\left[T^4(x) - T_{ph}^4\right]$$

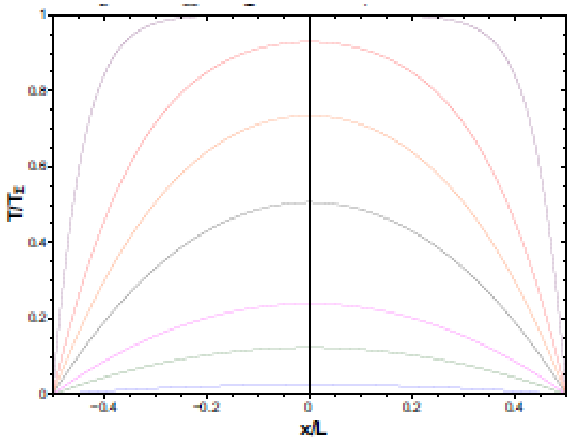
$$\mathcal{L} = \pi^2 k_B^2/3e^2$$

Lorenz number

$$\Sigma_{LA} = \frac{\pi^2 D^2 k_B^4}{15\rho\hbar^5 v_F^3 c^3} \times |E_F|$$

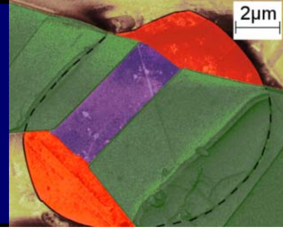
LA-phonons coupling constant

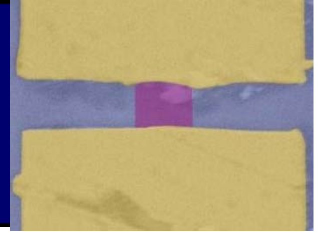


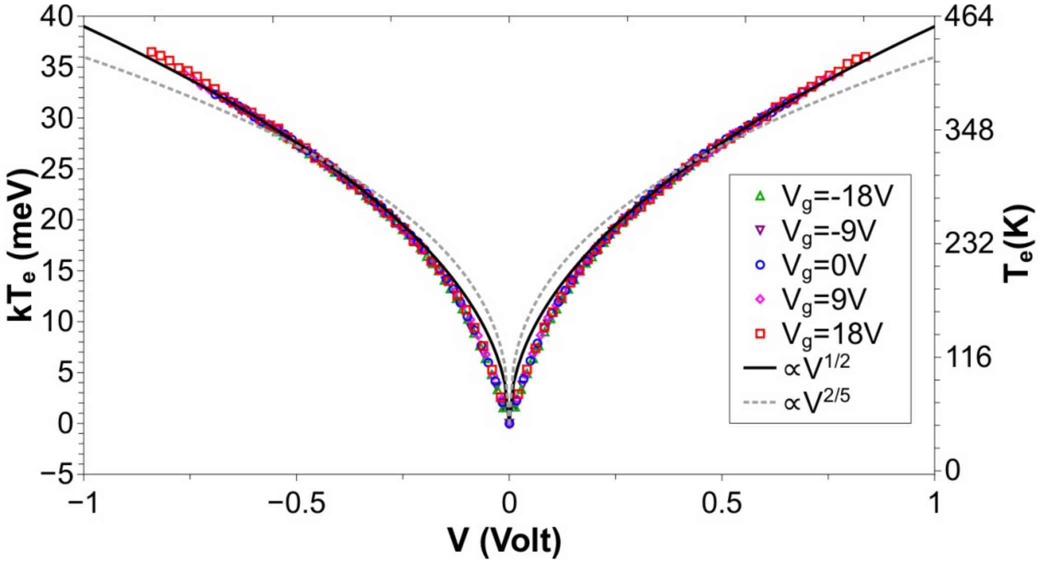


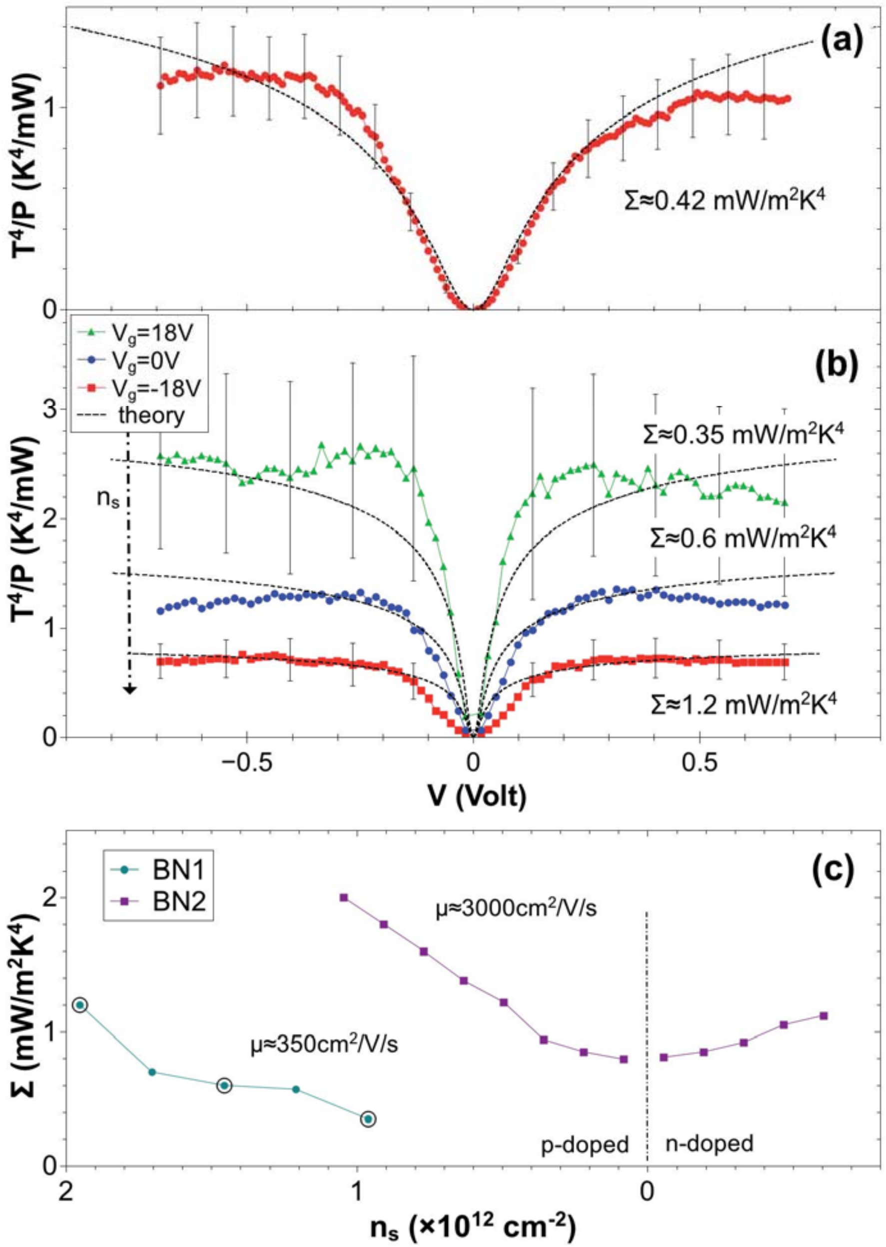
$$T_e = < T(x) >$$

The P=Σ T^4 dependence







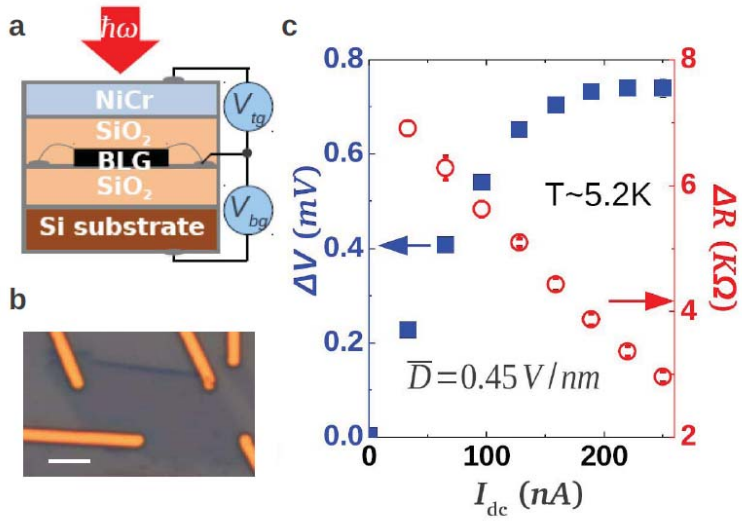


$$\frac{\mathcal{L}}{2R}\frac{L^2\partial^2T^2(x)}{\partial x^2} = -\frac{V^2}{R} + LW\Sigma\left[T^4(x) - T^4_{ph}\right]$$

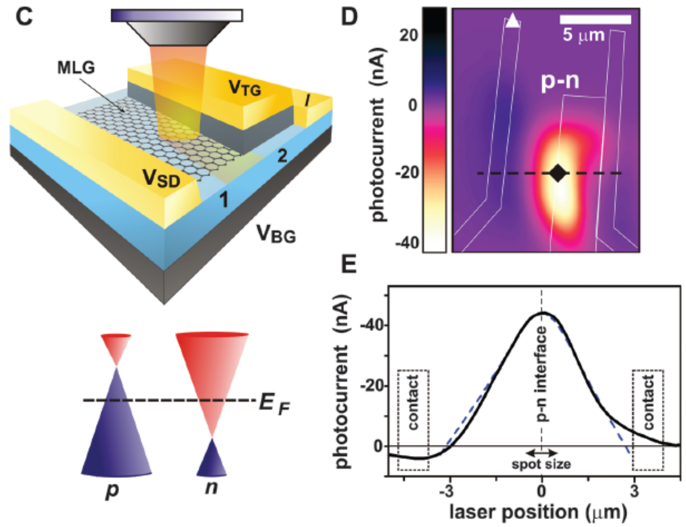
$\Sigma \sim \Sigma_{LA}/10$! (lattice disorder)

ER-Tremblay, 28/06/2012

Hot-electron bolometers

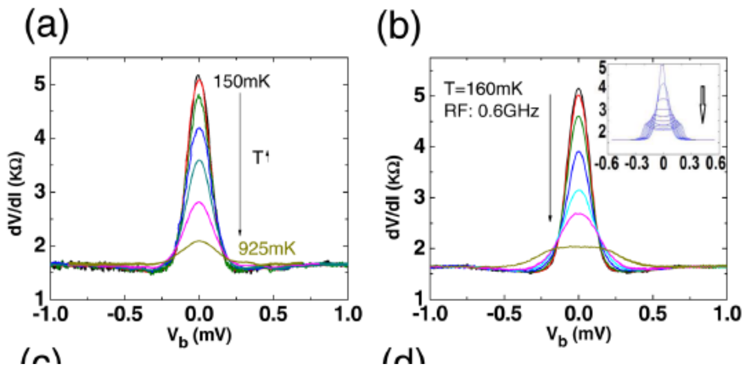


Yan et al., Nature nano 2012

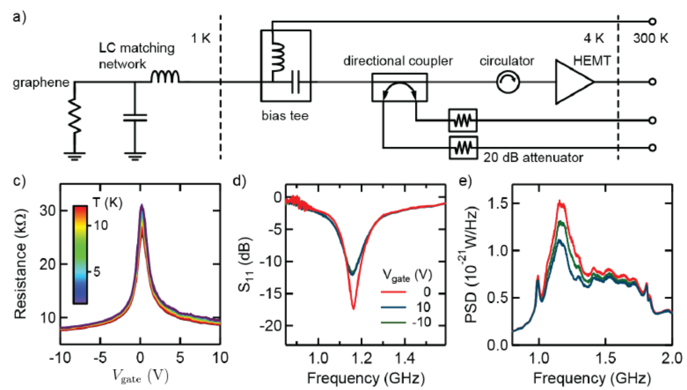


Gabor et al., Science 2011

$$\Sigma_{LA} = \frac{\pi^2 D^2 k_B^4}{15\rho\hbar^5 v_F^3 c^3} \times |E_F|$$



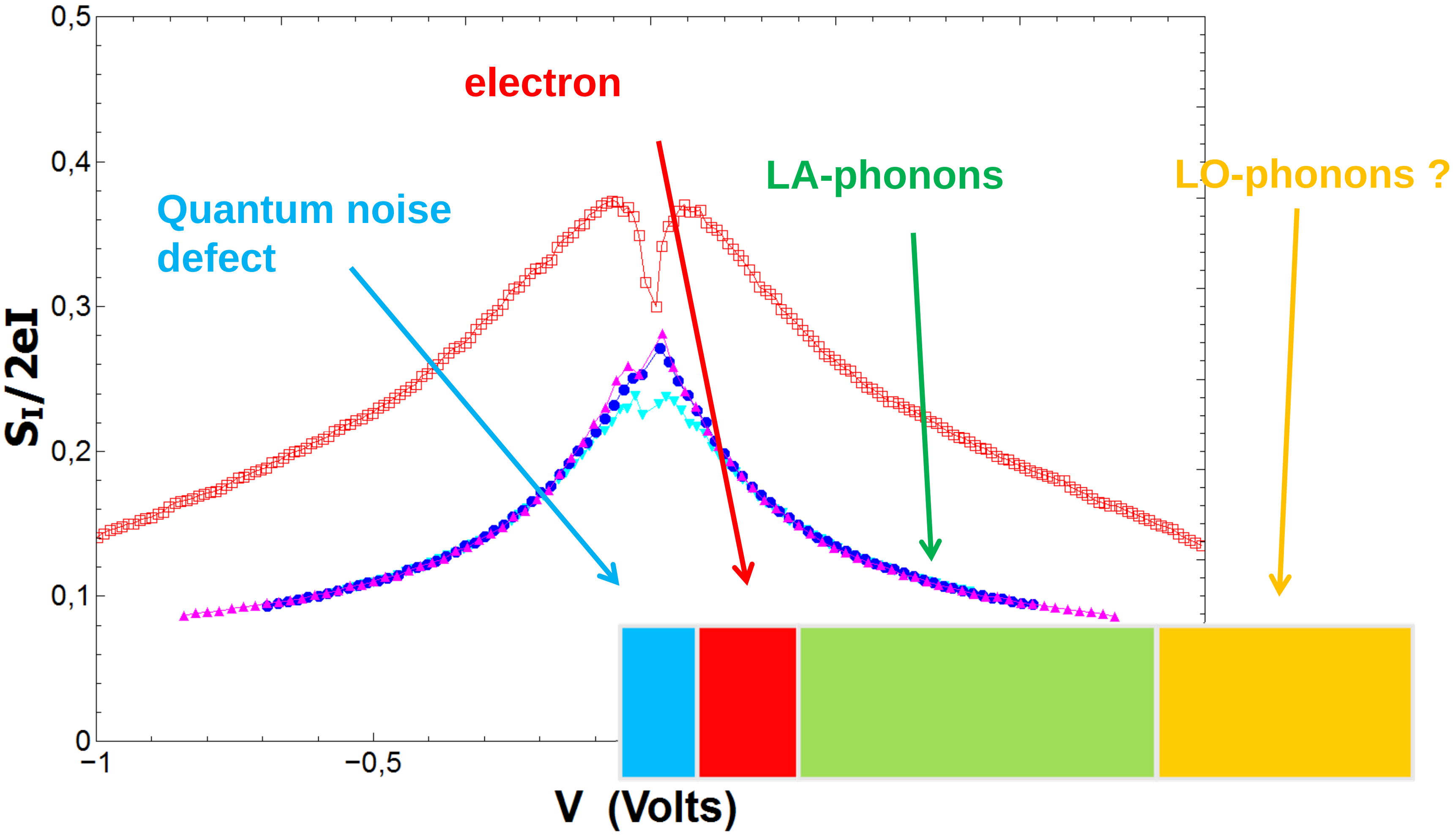
Vora et al., APL 2012



Fong-Schwab arXiv 2012

ER-Tremblay, 28/06/2012

electronic cosmology seen by noise



Outline

1) Introduction to magic graphene

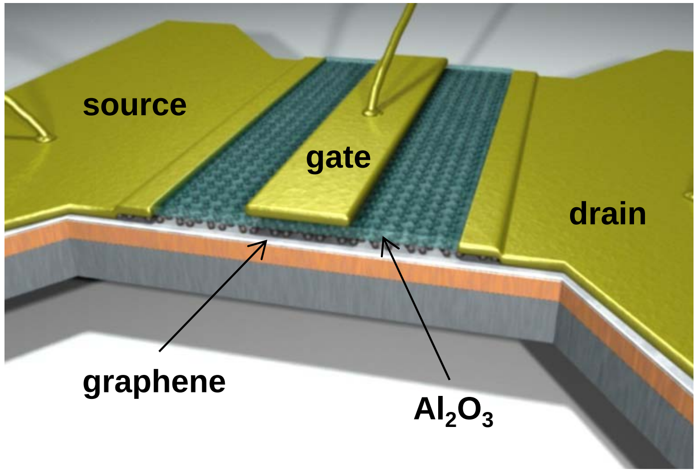
2) Transit frequency of microwave transistors

3) Diffusion probed in a field-effect capacitor

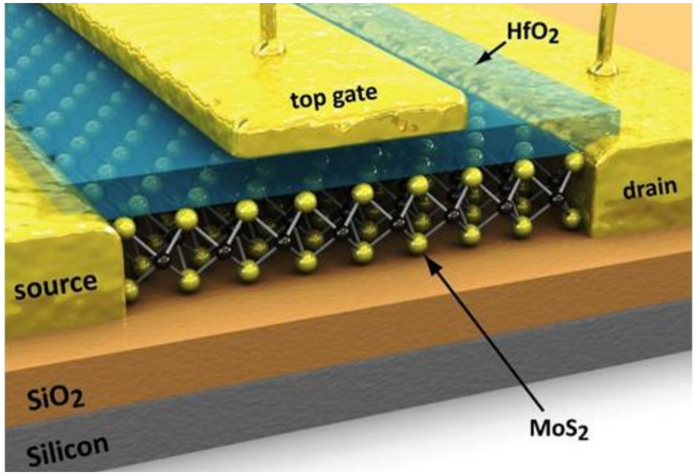
4) Acoustic phonons controls noise of resistors

5) New transistor architectures

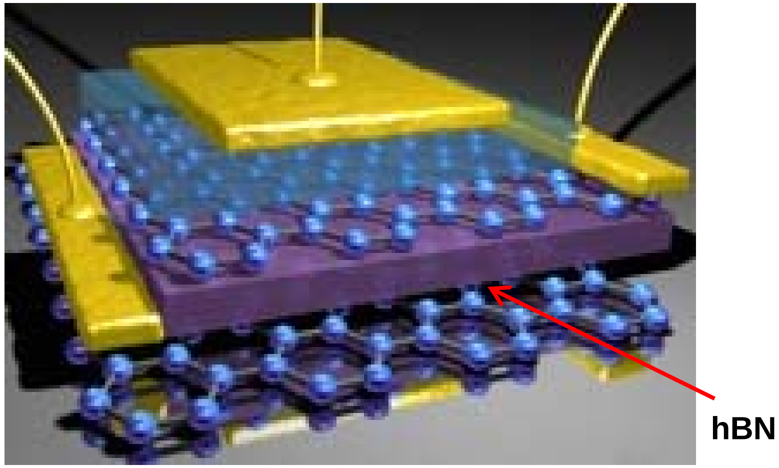
Zoo of graphene transistors



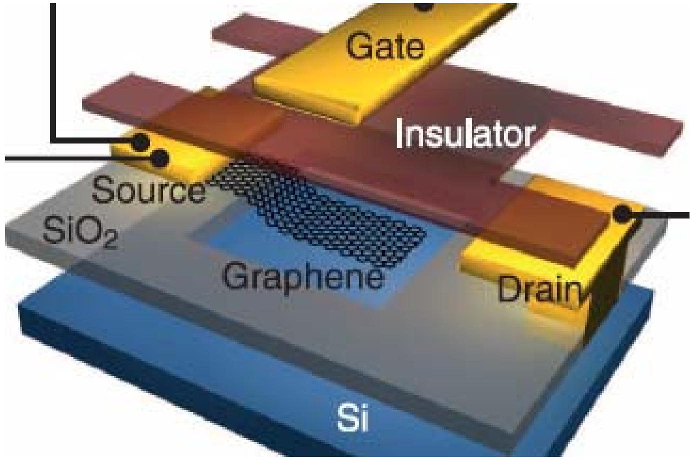
Gr-FET



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



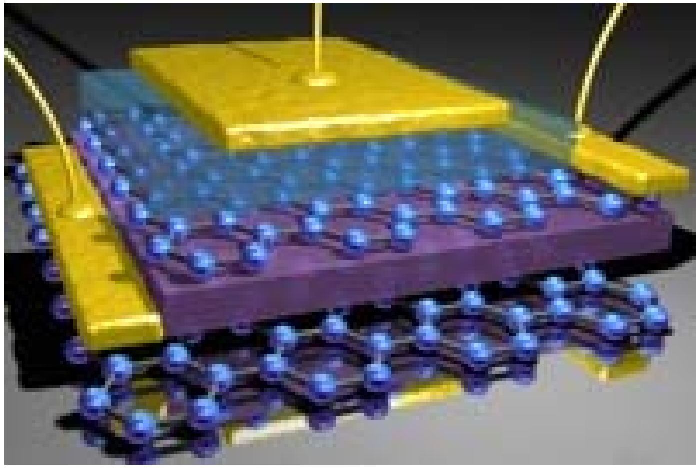
Gr/hBN (2011) - Tunnel transistor

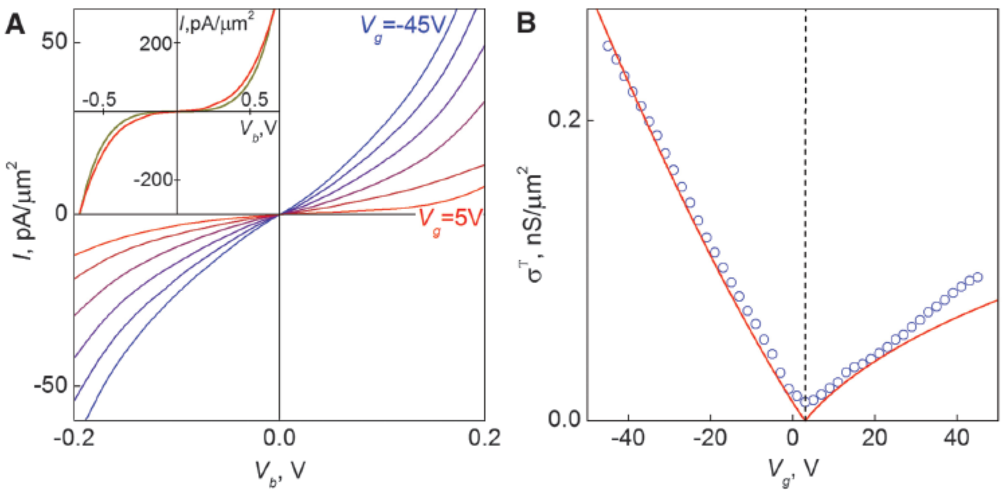


Gr/Si (2012) Shottky-transistor

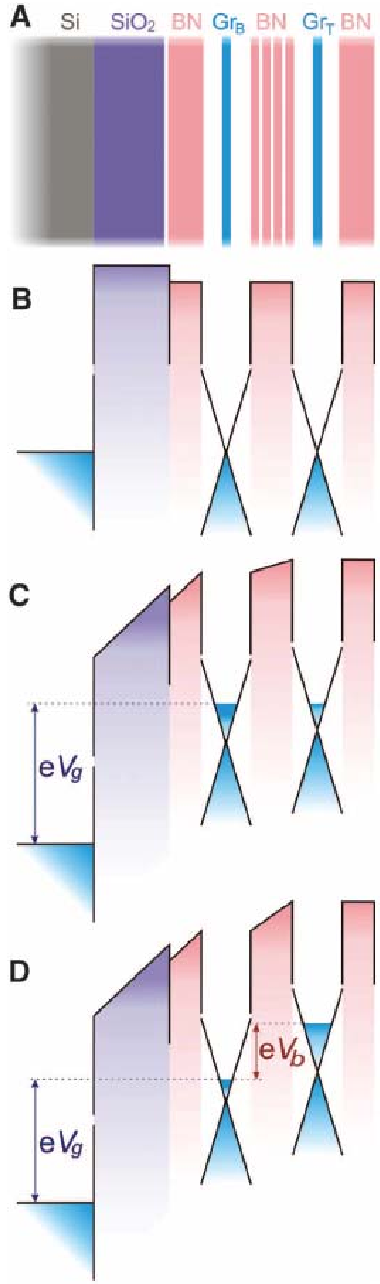
ER-Tremblay, 28/06/2012

Vertical tunnel barrier

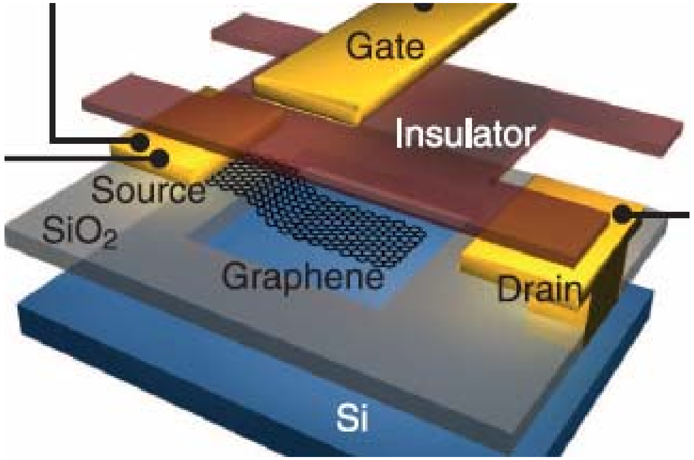


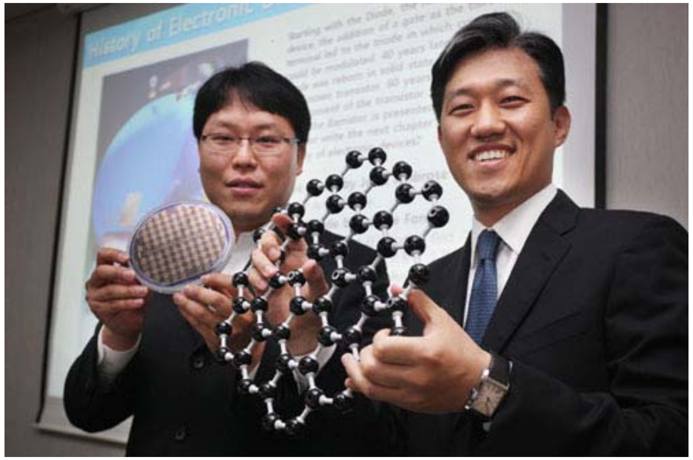


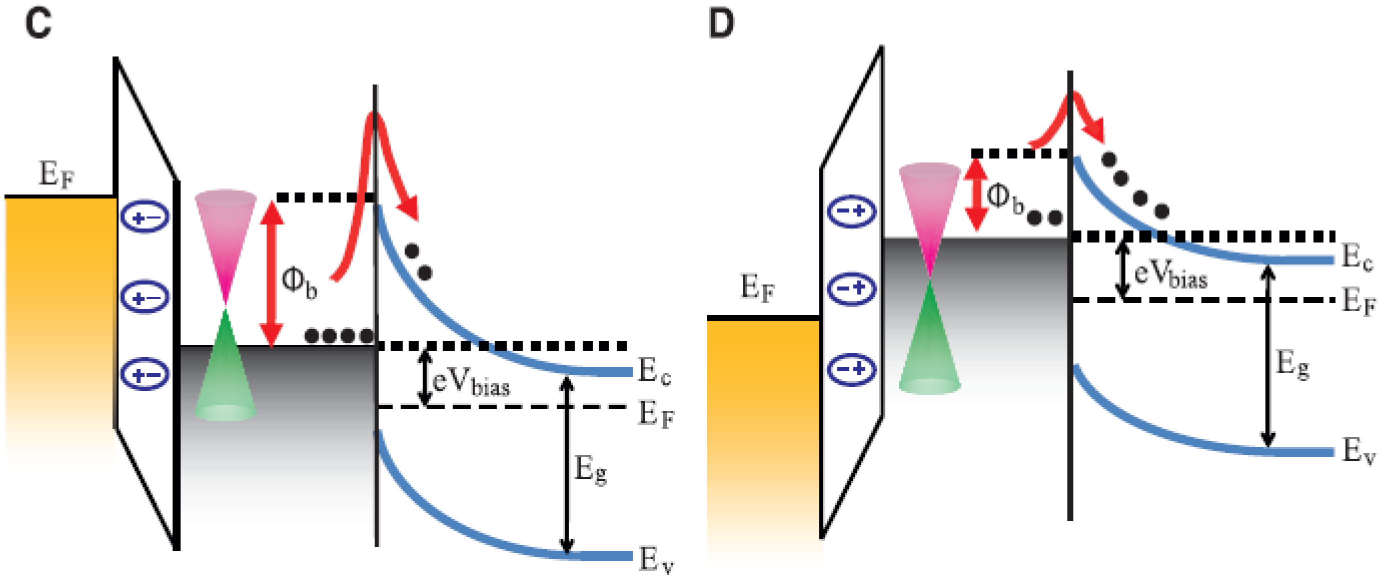
(Britnell et al. Science 2012)



Barristor by Samsung



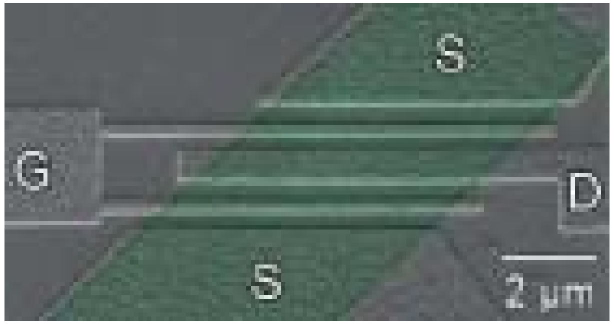




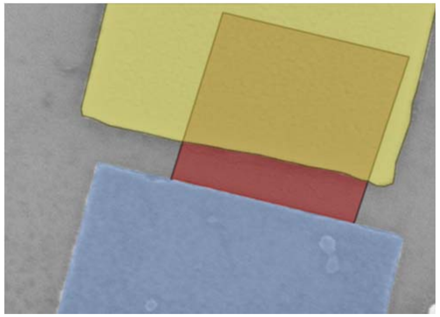
ER-Tremblay, 28/06/2012

(H. Yang, H.-J. Chung et al. Science 2012)

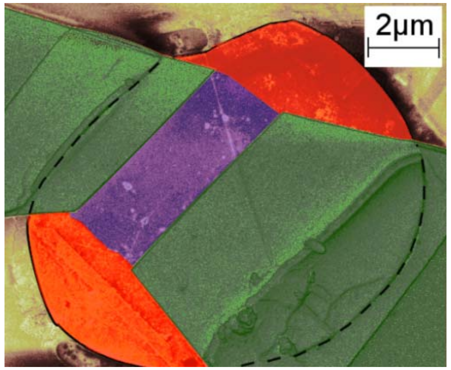
Summary



- Transistor: large transit frequencies



- Capacitor : anomalous diffusion



- Resistor : weak electron-phonon
- Devices : High-speed LNA’s, sensitive bolometers !

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Bernard Plaçais