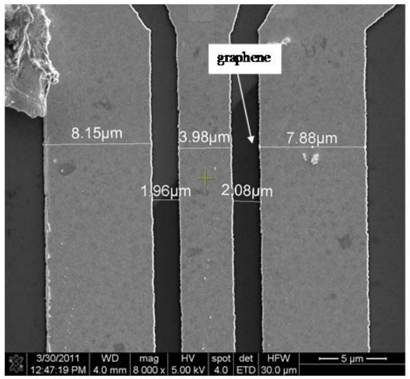
Nanoscale diodes without p-n junctions.

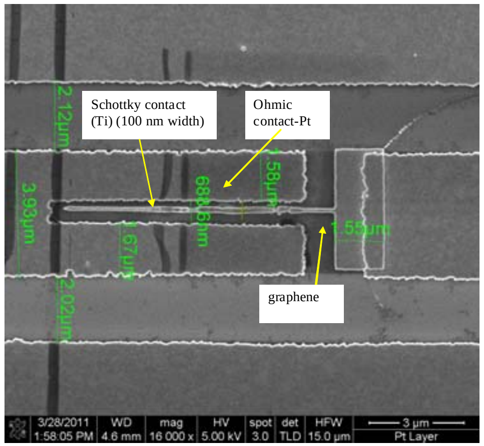
Mircea Dragoman
IMT –Bucharest

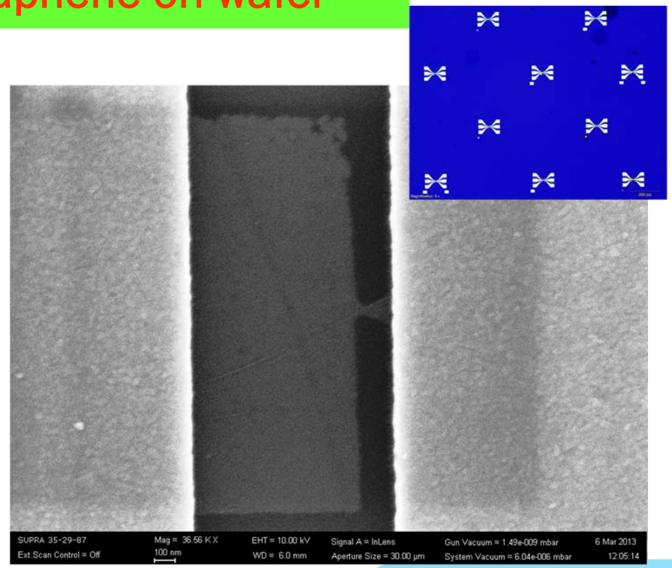
Coplanar electrodes on graphene-graphene radio

Dissimilar electrodes – Schottky diode

Geometric diodes-graphene on wafer

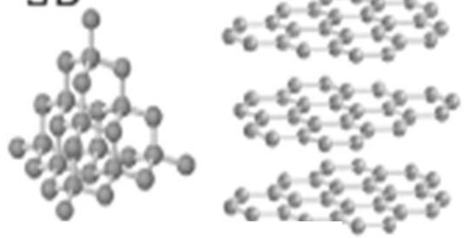




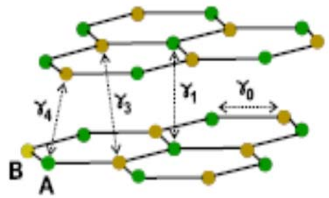


Carbon-based materials

3D

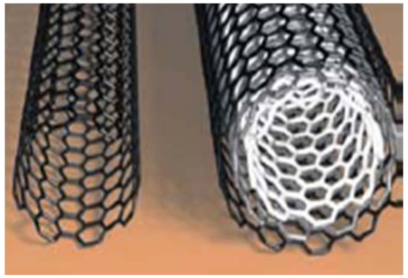


2D



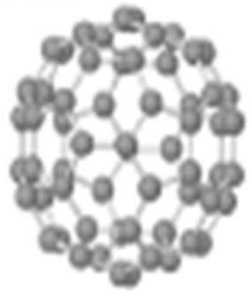
K.S. Novoselov et al., Science 306 (2004) 666
Theory: P.R. Wallace, Phys. Rev. 71 (1947) 622

1D



S. Iijima, Nature 354 (1991) 56

0D



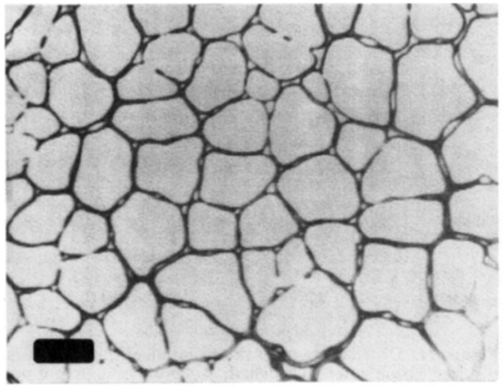
H.W. Kroto et al., Nature 318 (1985) 162

Graphene: Should it exist?

Two-dimensional crystals are thermodinamically unstable!

R.E. Peierls, Ann. I.H. Poincare 5 (1935) 177
N.D. Mermin, Phys. Rev. 176 (1968) 250
L.D. Landau, E.M. Lifshitz, Statistical Physics, Pergamon (1980)

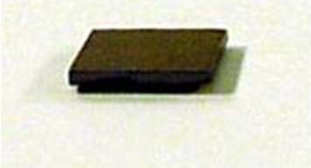
thickness < 20 nm →



G. Reiter, Langmuir 9 (1993) 1344

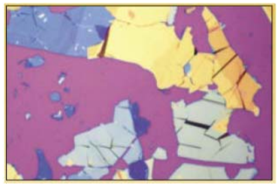
However…..

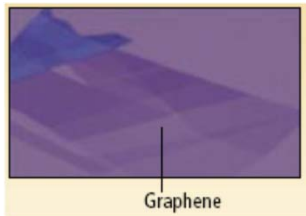
HOPG



rub

deposit on 300 µm SiO_2

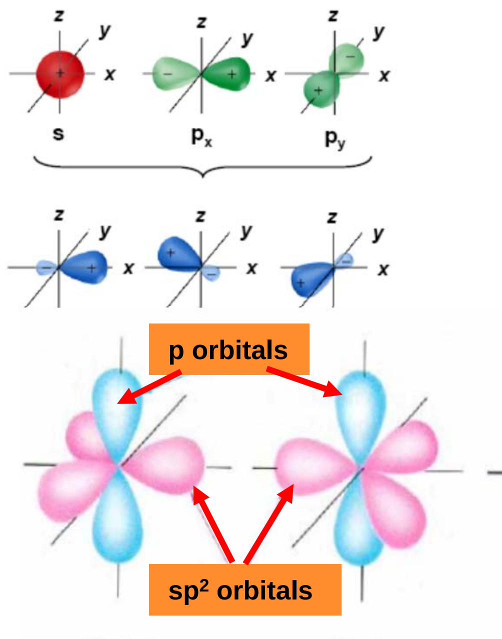




A.K. Geim, P. Kim, Sci. Am., April 2008, 90

thickness ≅ 0.34 nm

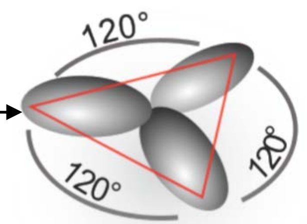
Why the current is flowing in graphene?



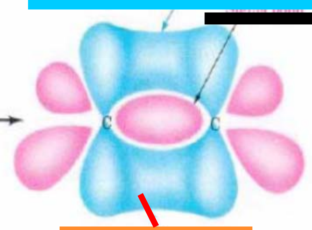
Isolated atom orbitals

Molecule-hybridization of orbitals; localized electrons

σ-electrons

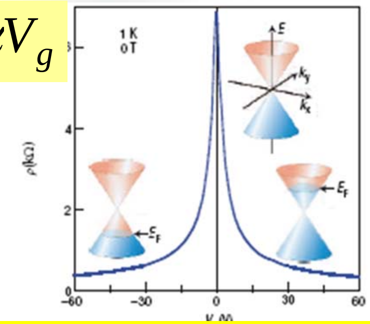


Current flow



π-electrons not hybridized, are not localized

$n \propto \alpha V_g$



sp^2 carbon

sp^2 carbon

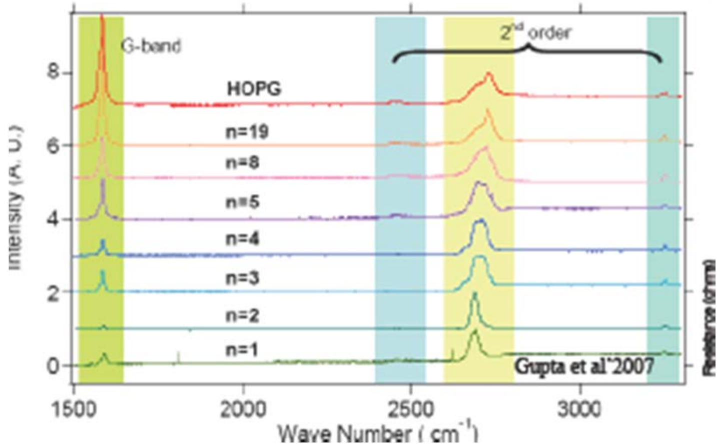
Carbon-carbon double bond

K.S. Novoselov et al., Science 315 (2007) 1379

How we can identify graphene ?

Optical view of different graphene layers (mono, bi and multilayers)

Z.H. Ni et. al., Nano Lett., pp.2758-2763 (2007)

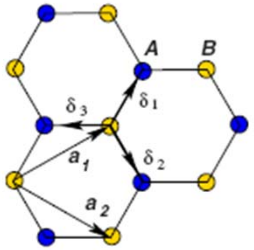


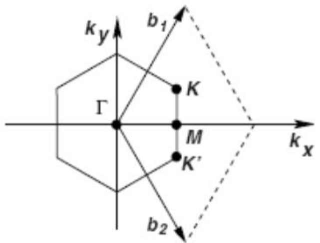
Raman signature

Number of layers

A.C. Ferrari et. al., Pyhs. Rev. Lett. 97 , 187401 (2006)

Band structure



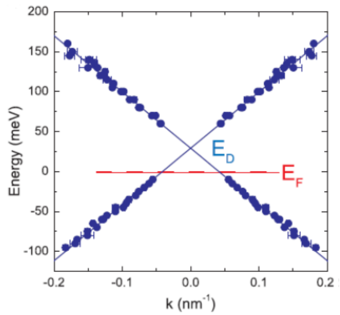


$$E_{\pm}(k) = \pm \hbar v_F \,|k|$$

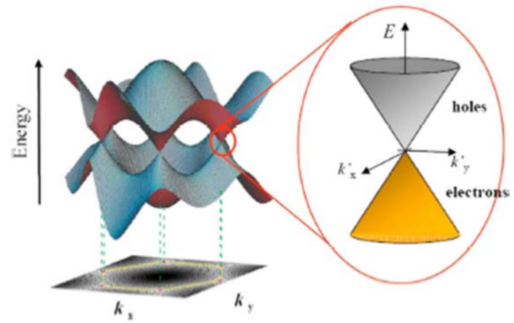
$$v_F \cong c/300$$

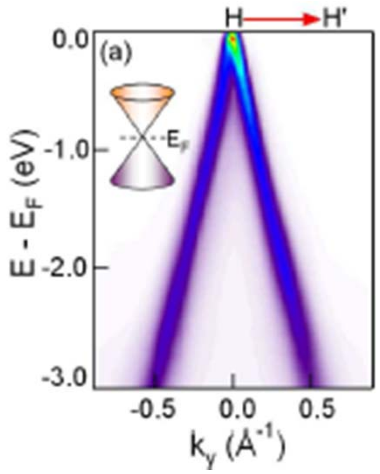
$$E = \sqrt{m^2c^4 + p^2c^2}$$

$$m = 0, \quad c = v_F$$

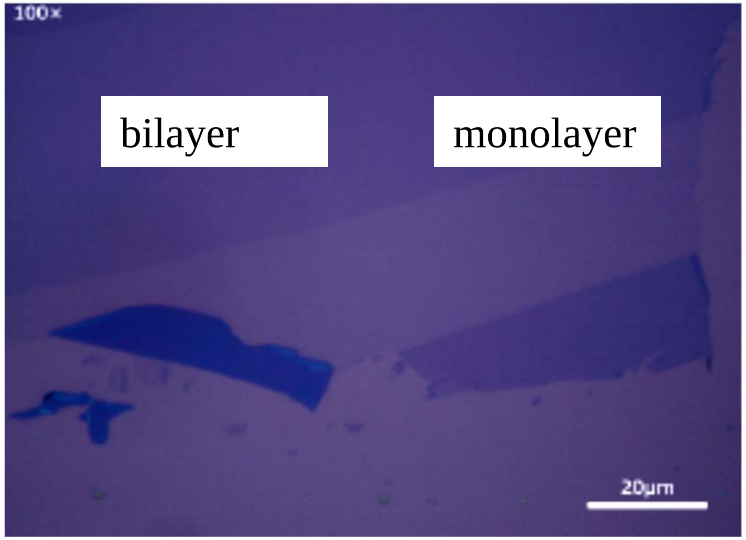


D.L. Miller et al., Science 324 (2009) 924



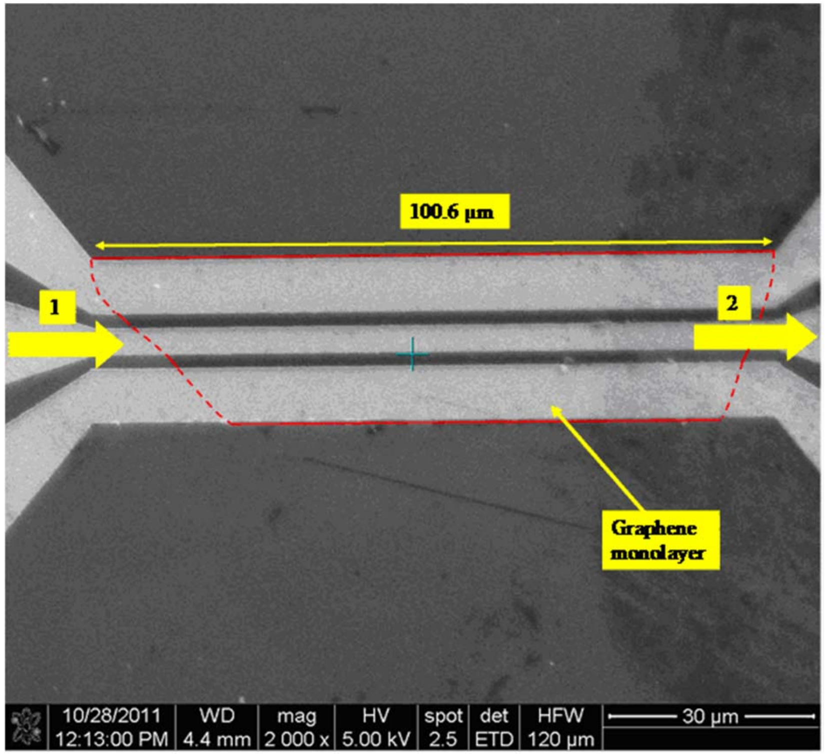


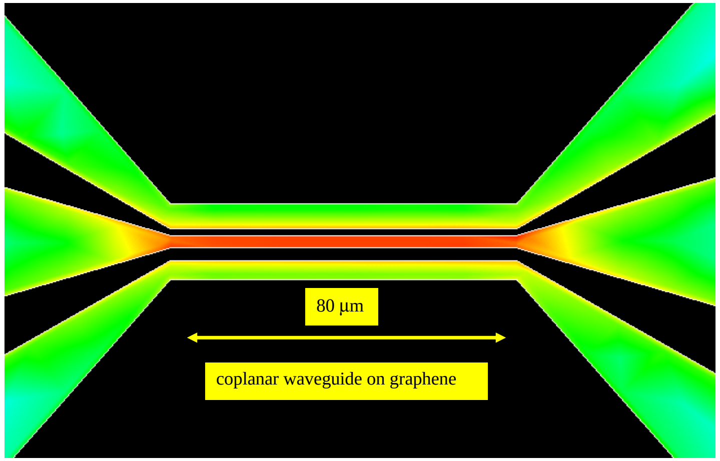
S.Y.Zhou et al., Nature Physics 2 (2006) 595



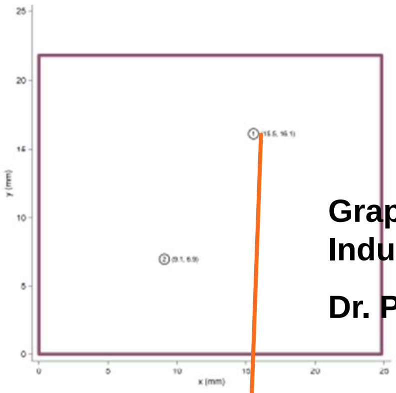
BALLISTIC TRANSPORT

Parameter	*Value and units*	*Observations*
Thermal conductivity	5000 W/mK	Better thermal conductivity than in most crystals
Young modulus	1.5 TPa	Ten times greater than in steel
Mobility	40 000 $cm^2V^{-1}s^{-1}$	At room temperature (intrinsic mobility) maximum mobility : 200 000 $cm^2V^{-1}s^{-1}$) on suspended graphene or graphene on hexagonal BN substrate
Mean free path (ballistic transport)	≈400 nm	At room temperature, but exceeds 1 µm in graphene on hexagonal BN substrate at room temeperature
Electron effective mass	0	At room temperature
Hole effective mass	0	At room temperature
Fermi velocity	c/300=1000000 m/s	At room temperature



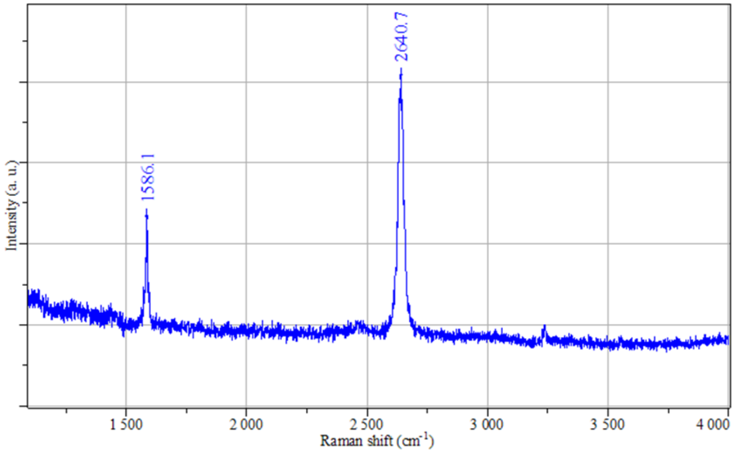


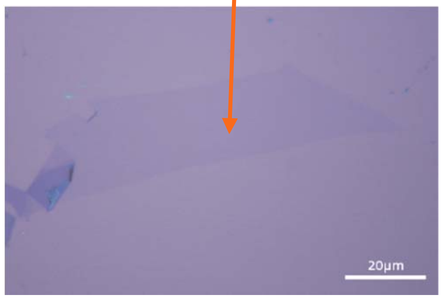
Simulation done at
100 GHz



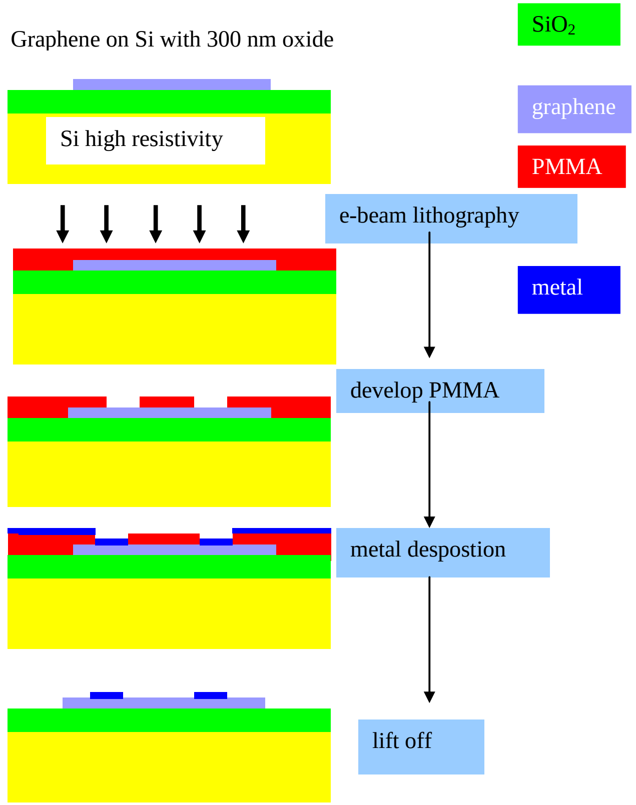
Graph
Indust

Dr. P. I

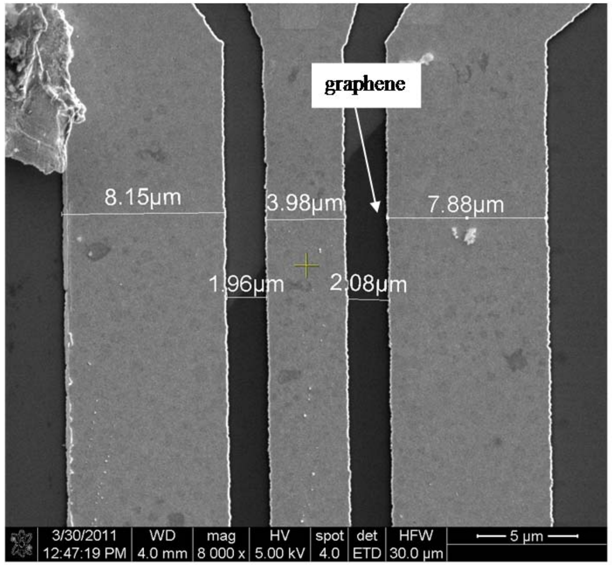


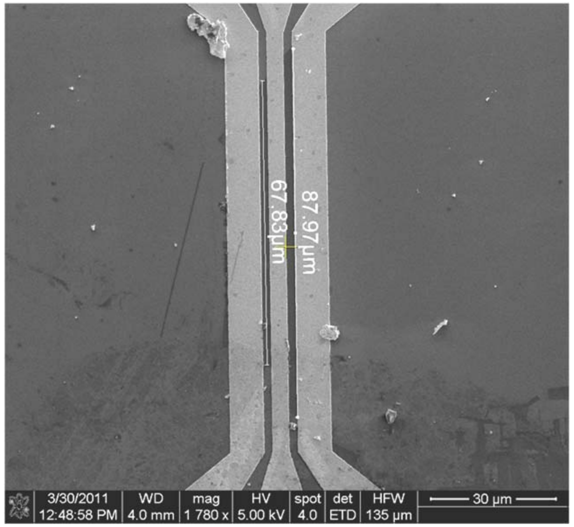


The report between the intensities of 2D and G peaks is around 2 telling us that we have a single layer graphene. The 2D and G Raman peaks positions are 2640 cm^{-1} and 1586cm^{-1},respectively

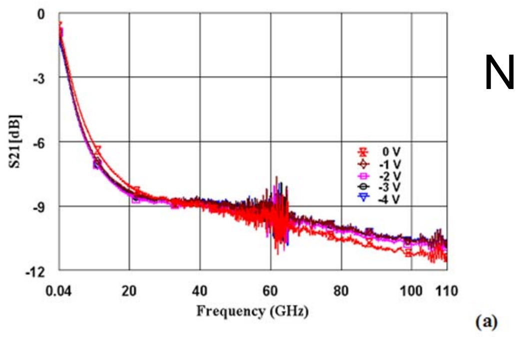


A CLOSER LOOK VIA SEM

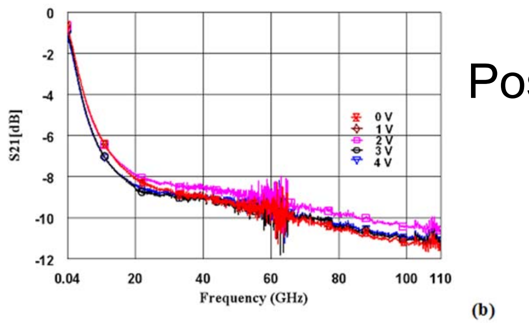




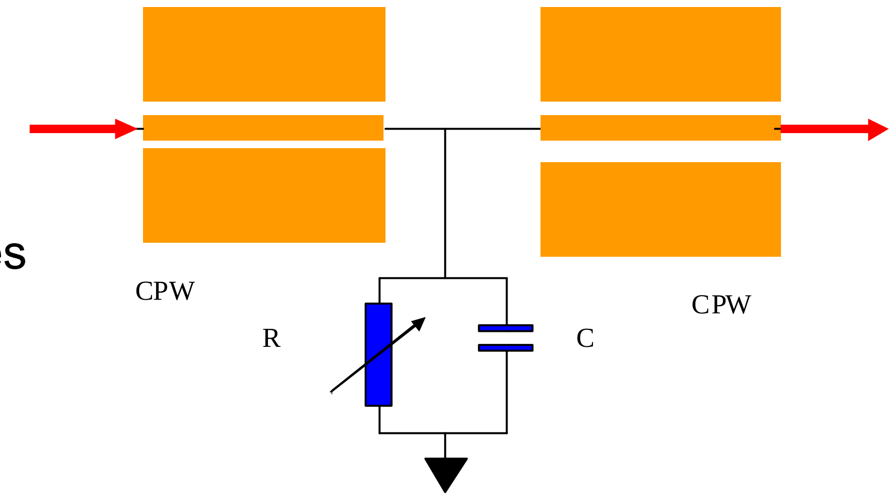
Negative DC voltages



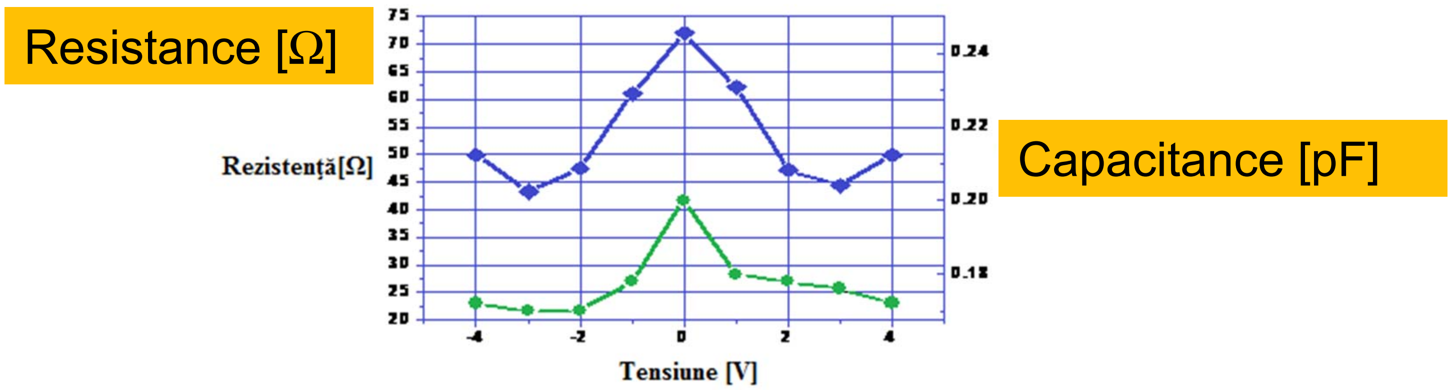
Positive DC voltages



A SIMPLE MODEL



V_{bias} [V]	-4	-3	-2	-1	0	1	2	3	4
R[Ω]	49.7	42.9	46.8	61.75	73	63	46.6	43.6	49
C[pF]	0.173	0.17	0.174	0.179	0.205	0.181	0.179	0.177	0.173



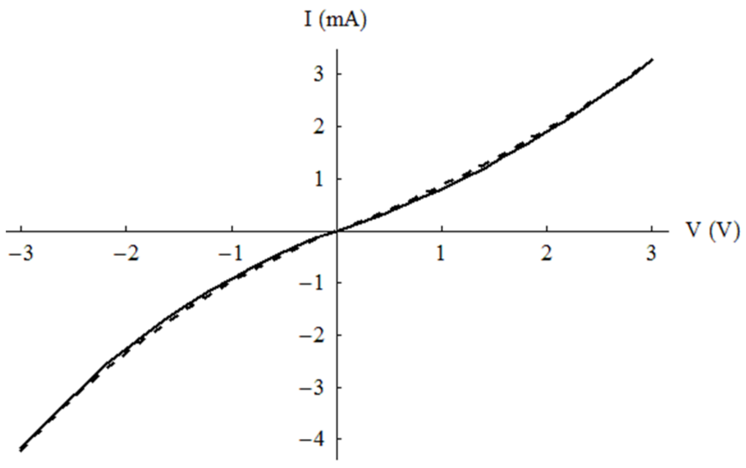
$$I = I_0[\exp(V/V_0) - 1] \quad (1)$$

I_0 and V_0 have the values 3.65 mA and 4.68 V for the positive polarization and -2.6 mA and -3.12 V for the negative polarization regime, respectively. Slightly asymmetric characteristics are typical in graphene devices and are due to graphene-substrate (in our case to graphene-CPW as well) interactions.

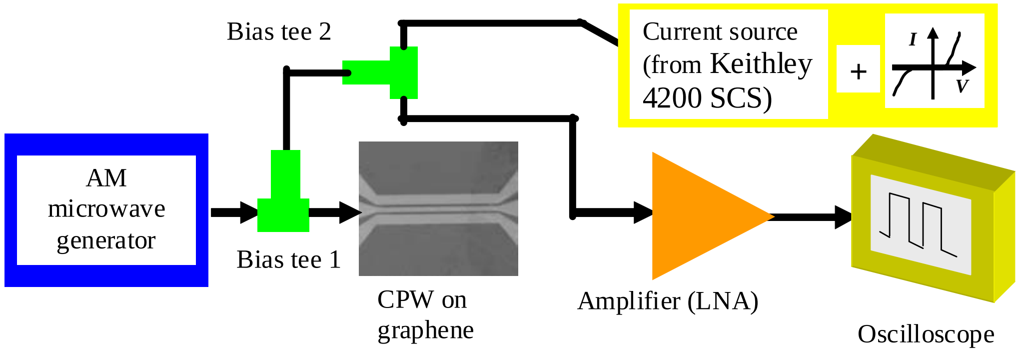
Choosing a operating point I_{av} and V_{av} and developing (1) in a Taylor series, around an operating point it results the demodulating term arround (I_{av}, V_{av}):

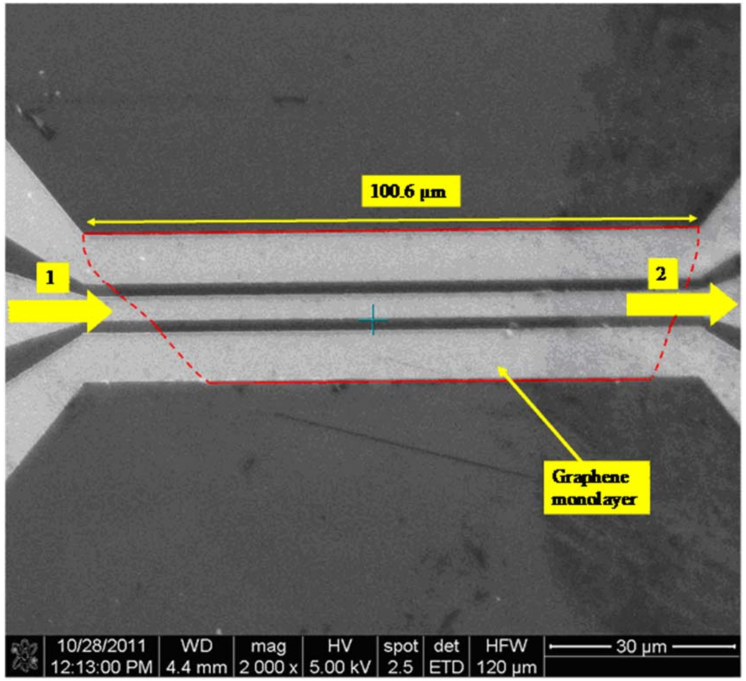
$$\Delta I = I - I_{av} = I_0 \frac{V_{RF}^2}{4V_0^2} \exp(V_{av}/V_0) \quad (2)$$

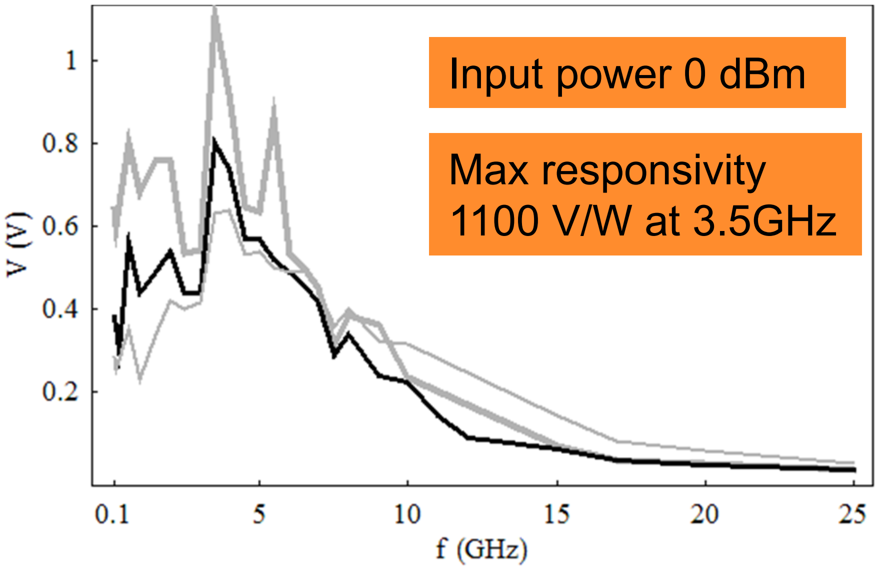
V_{RF}-the value of the RF signal

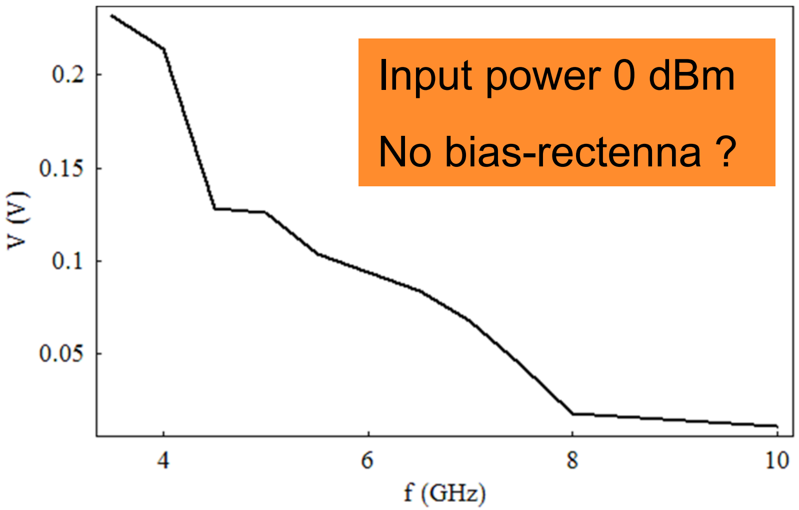


GRAPHENE RADIO

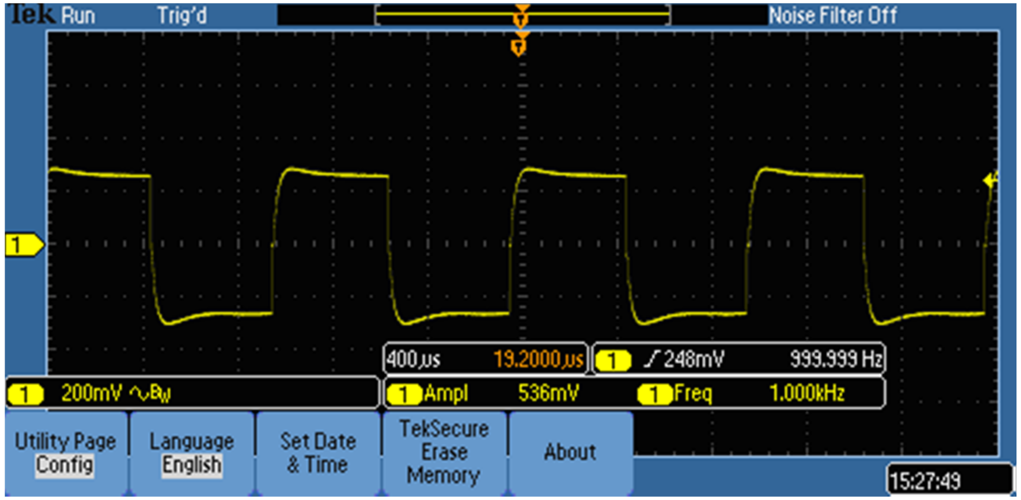






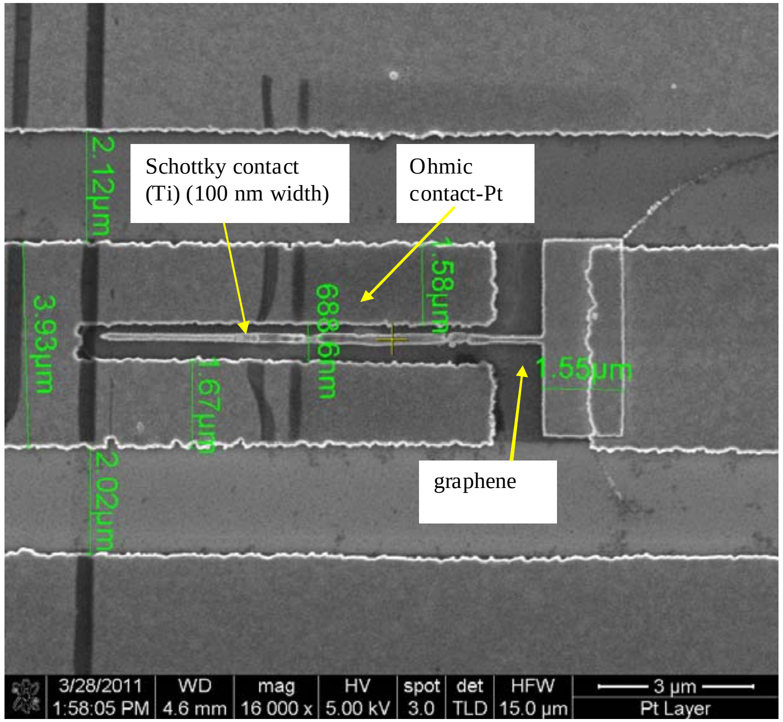


The detected DC voltage as a function of frequency for various DC currents: 1 mA (thin gray line), 2 mA (black line), 3 mA (thick gray line).



Demodulated signal in time 1 kHz

SCHOTTKY DIODE VIA DISSIMILAR METALS



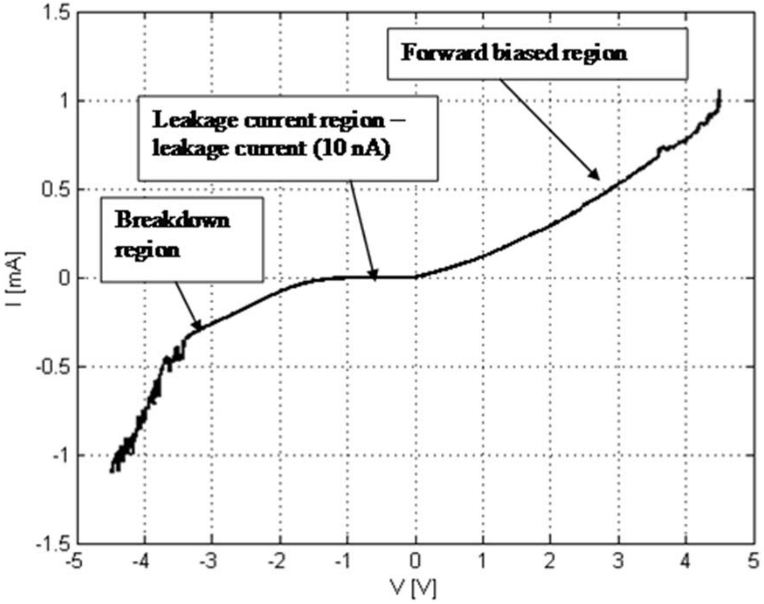
Schottky metals for graphene

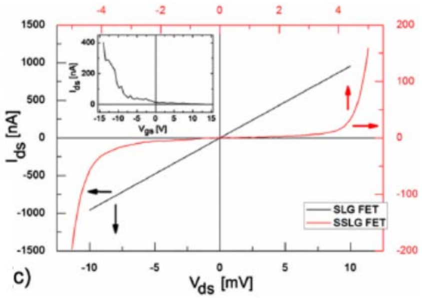
Metal	Work function (eV)
Al	-4.27 eV (the best)
Cr	-4.5 eV
Ti	-4..3 3 eV

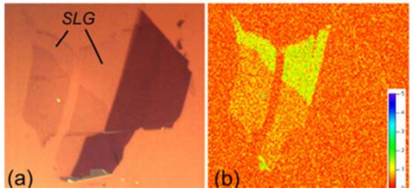
Graphene work function -4.5 eV

Ohmic metals for graphene

Metal	Work function (eV)
Pd	-5. 12 eV
Pt	-5.6 eV







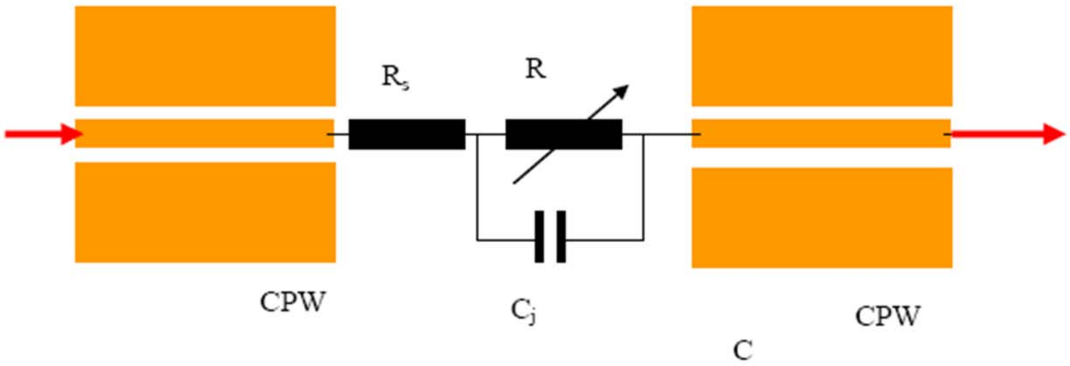
APPLIED PHYSICS LETTERS 97, 163101 (2010)

Modified, semiconducting graphene in contact with a metal: Characterization of the Schottky diode

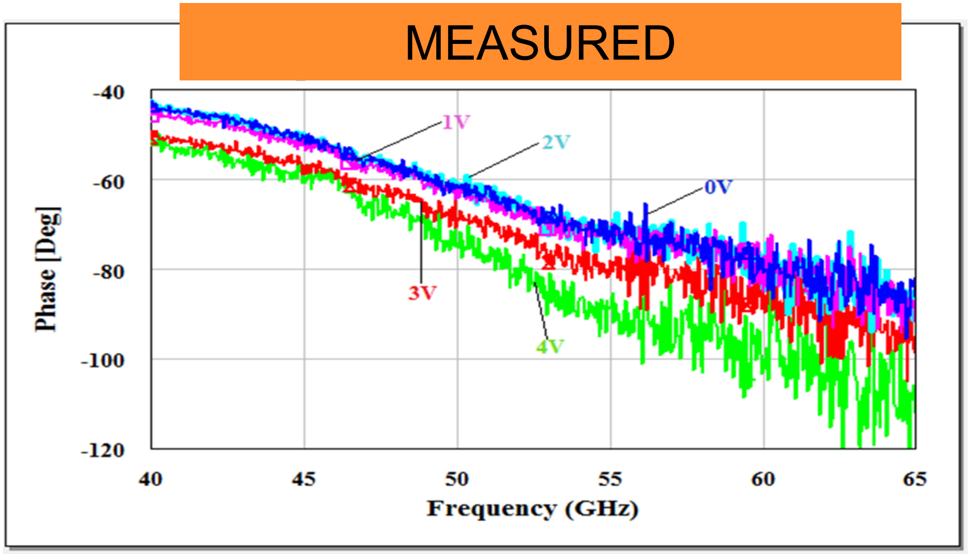
Amirhasan Nourbakhsh,[1,2,a)] Mirco Cantoro,[1,3] Afshin Hadipour,[1] Tom Vosch,[4] Marleen H. van der Veen,[1] Marc M. Heyns,[1,5] Bert F. Sels,[2] and Stefan De Gendt[1,4]

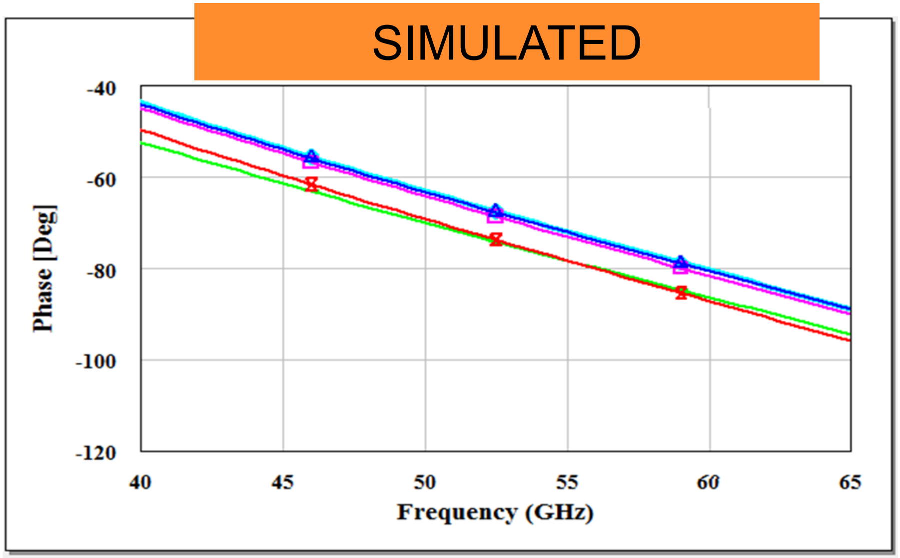
[1]*IMEC, Kapeldreef 75, B-3001 Leuven, Belgium*
[2]*Dept. of Microbial and Molecular Systems, uven, Kasteelpark Arenberg 23, B-3001 Leuven, Belgium*
[3]*Dept. of Physics and Astronomy, K. U. Leu tijnenlaan 200d, B-3001 Leuven, Belgium*
[4]*Dept. of Chemistry, K. U. Leuven, Celestijn 0f, B-3001 Leuven, Belgium*
[5]*Dept. of Metallurgy and Materials Enginee . Leuven, Kasteelpark Arenberg 44, B-3001 Leuven, Belgium*

Our results-currents at mA level!



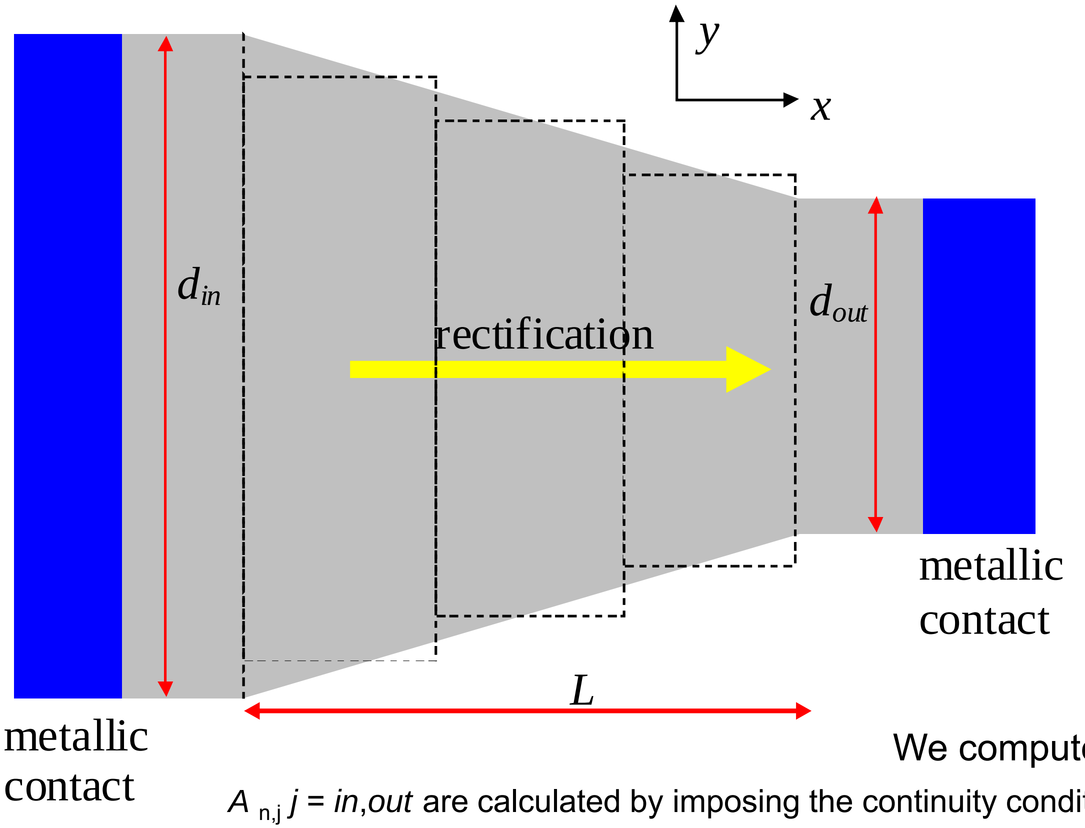
Bias voltage (V)	R_S [Ω]	R_J [kΩ]	C_J [fF]
0V	60	12	3.5
1V	60	8	3.5
2V	60	8	3.5
3V	60	0.85	3.5
4V	60	0.61	3.5





A GRAPHENE PHASE SHIFTER

BALLISTIC GEOMETRIC GRAPHENE DIODE



$$d_{in} > d_{out}$$

D_{out}=100nm

D_{in}=20 nm

L=200nm

$$d_j = d_{in} - (d_{in} - d_{out})\, j/(N+1)$$

$$V_j = -jeV/(N+1)$$ Potential energy

$$k_{n,j} = \mathrm{sgn}(E - V_j)\sqrt{(E-V_j)^2/(\hbar^2 v_F^2) - (n\pi/d_j)^2}$$

We compute:

$$T = \sum_{n=1}^{N_{out}} |A_{n,out}|^2 \Big/ \sum_{n=1}^{N_{in}} |A_{n,in}|^2$$

$A_{n,j}$ j = *in*,*out* are calculated by imposing the continuity conditions at each interface for the spinorial solutions of the Dirac equation in region *j*:

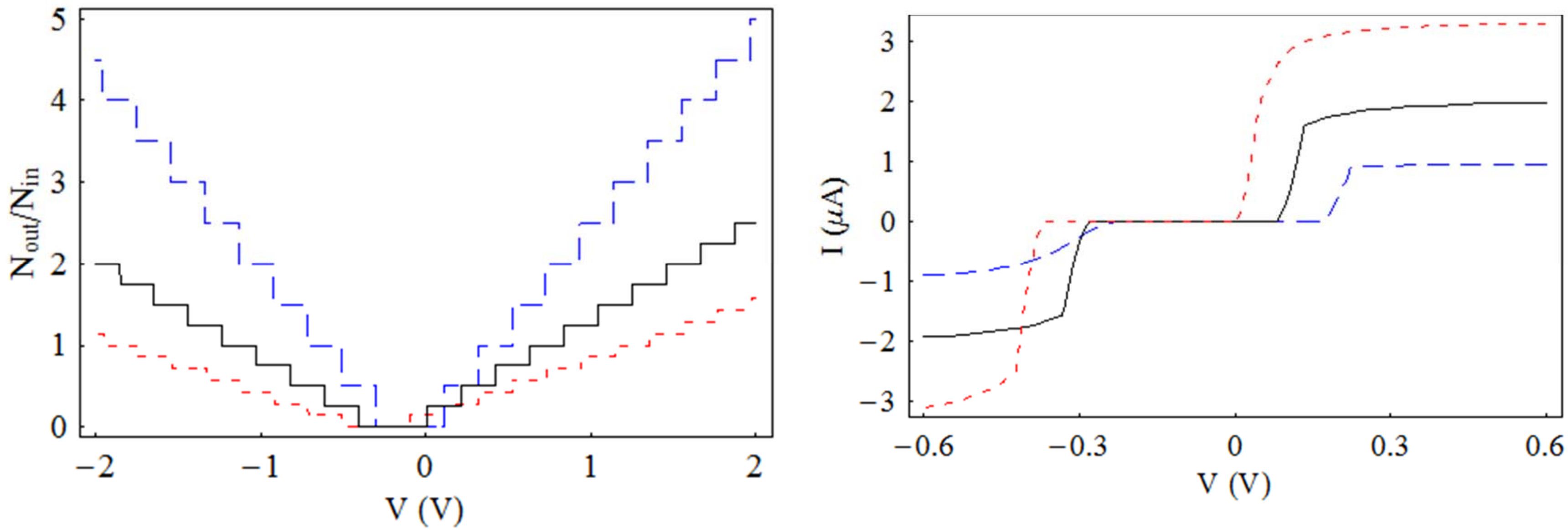
$$\Psi_j(x,y) = \begin{pmatrix} \sum_{n=1}^{N_j} [A_{n,j}\exp(ik_{n,j}x) + B_{n,j}\exp(-ik_{n,j}x)]\sin(2n\pi y/d_j) \\ \sum_{n=1}^{N_j} [A_{n,j}\exp(ik_{n,j}x) - B_{n,j}\exp(-ik_{n,j}x)]\sin(2n\pi y/d_j) \end{pmatrix}$$

$$N_j = \mathrm{Int}[d_j \mid E - V_j \mid /(\pi\hbar v_F)]$$

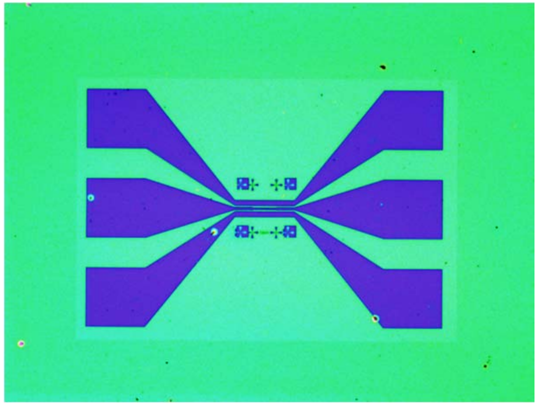
Number of modes

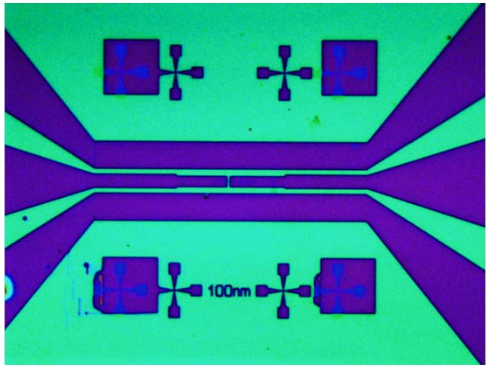
The results are independent on the number of discretization regions *N*. Although there are a finite number of outgoing modes for both voltage polarizations, in all cases there is a voltage range in which no charge carriers are transmitted since for these *V* values the number of outgoing modes, and hence the current, vanishes. This region, with a width given by $\pi\hbar v_F \; / \; d_{out}$

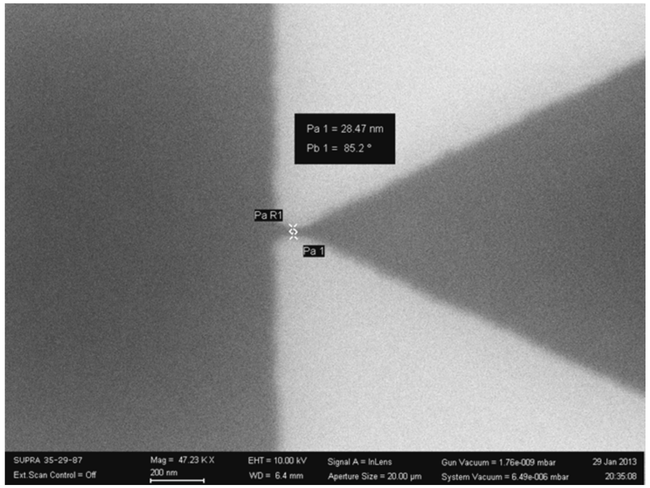
E_F

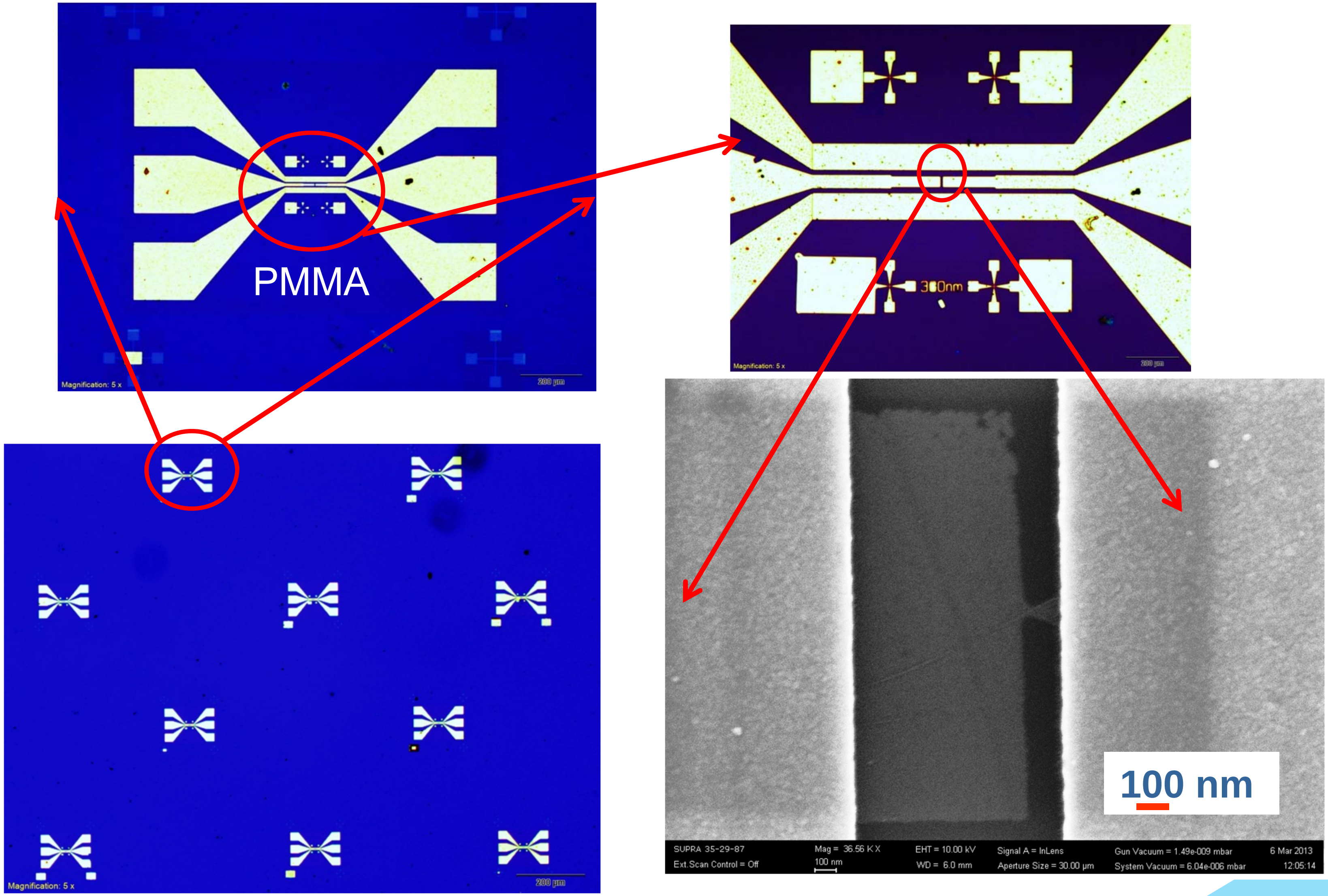


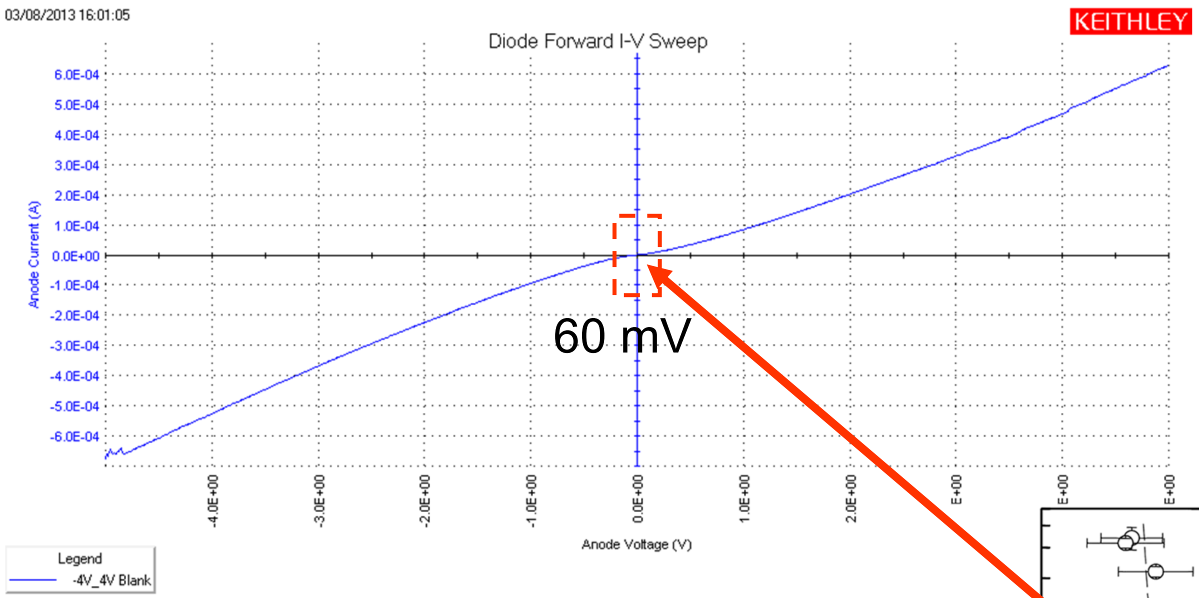
E_F= 0 (blue dashed line), 0.1 eV (solid black line) and 0.2 eV (red dotted line).

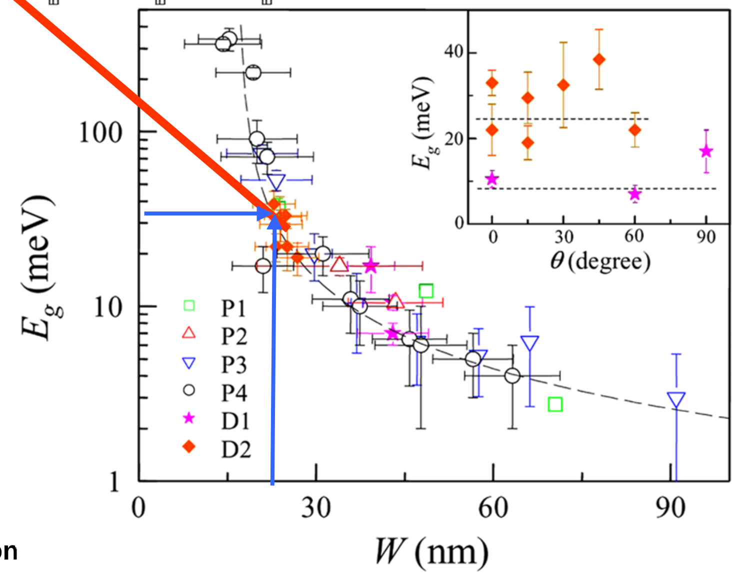



100nm


Pa 1 = 28.47 nm
Pb 1 = 85.2 °
Pa R1
Pa 1
SUPRA 35-29-87
Ext.Scan Control = Off
Mag = 47.23 K X
200 nm
EHT = 10.00 kV
WD = 6.4 mm
Signal A = InLens
Aperture Size = 20.00 µm
Gun Vacuum = 1.76e-009 mbar
System Vacuum = 6.49e-006 mbar
29 Jan 2013
20:35:08


PMMA
Magnification: 5 x
200 µm
Magnification: 5 x
200 µm
Magnification: 5 x
200 µm
100 nm
SUPRA 35-29-87
Ext.Scan Control = Off
Mag = 36.56 K X
100 nm
EHT = 10.00 kV
WD = 6.0 mm
Signal A = InLens
Aperture Size = 30.00 µm
Gun Vacuum = 1.49e-009 mbar
System Vacuum = 6.04e-006 mbar
6 Mar 2013
12:05:14





kbT=27 meV at room temperature

E_g=60 meV

C=3 aF

R=10K Ω

τ= 30fs fc=6 THz

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