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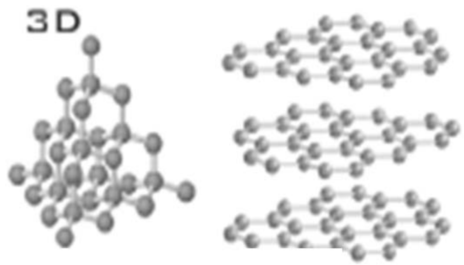
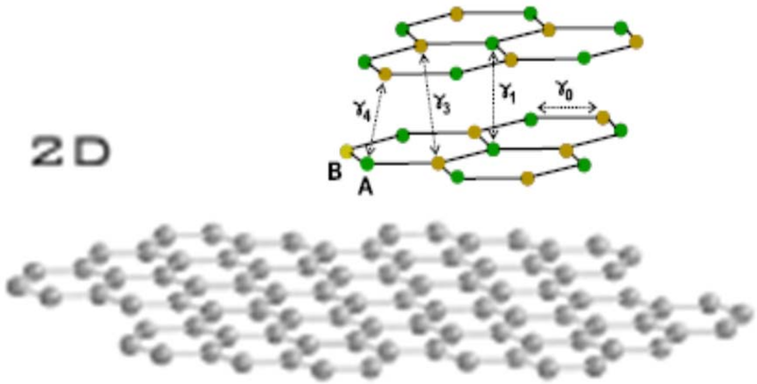
Graphene nanoelectronics for high frequency applications” Dr. Mircea Dragoman, IMT-Bucharest

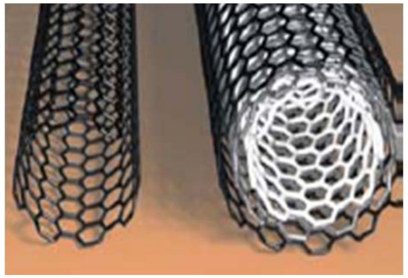
MIRCEA DRAGOMAN

NATIONAL INSTITUTE FOR RESEARCH AND DEVELOPMENT IN MICROTECHNOLOGIES - IMT Bucharest , Romania http://www.imt.ro

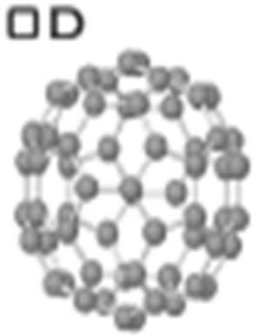
Carbon-based materials







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



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

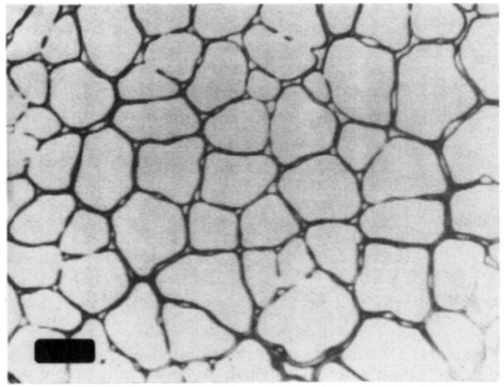
S. Iijima, Nature 354 (1991) 56

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



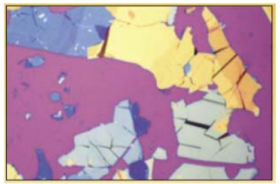
G. Reiter, Langmuir 9 (1993) 1344

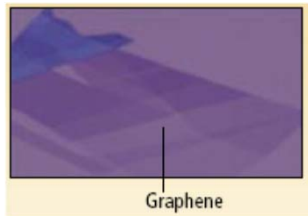
However…..

rub

deposit on

300 µm SiO_2

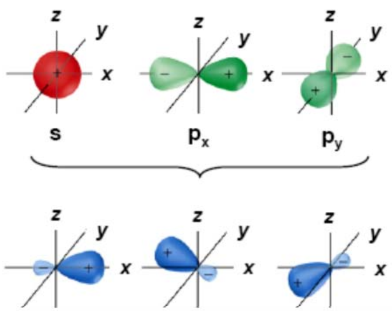




A.K. Geim, P. Kim, Sci. Am., April 2008, 90

thickness ≅ 0.34 nm

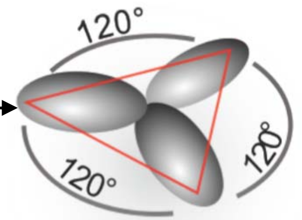
Why the current is flowing in graphene?



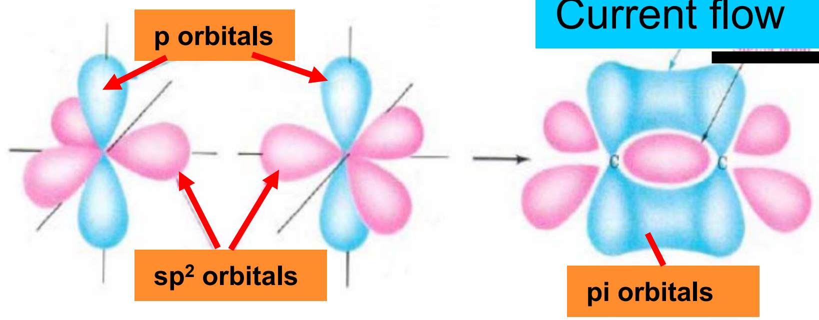
Isolated atom orbitals

Molecule-hybridization of orbitals; localized electrons

σ-electrons

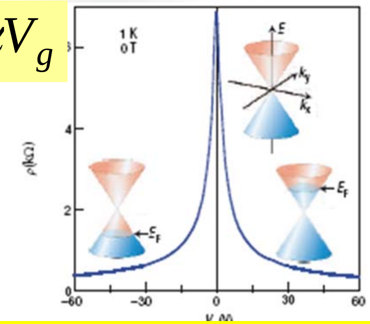


Current flow



π-electrons not hybridized, are not localized

$n \propto \alpha V_g$



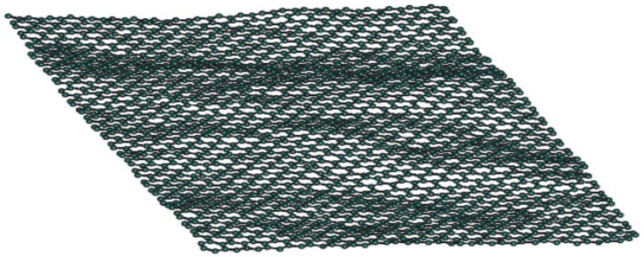
sp² carbon

sp² carbon

Carbon-carbon double bond

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

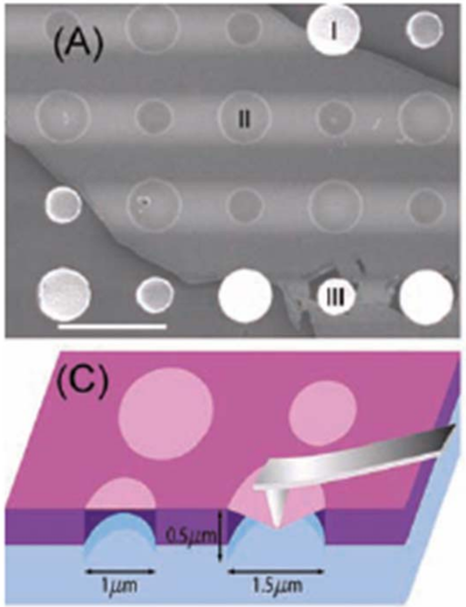
Mechanical properties of graphene



size ≅ 80 Å, h ≅ 0.7 Å at T = 300 K

$a_{C\text{-}C}$ = 1.42 Å

A. Fasolino et al., Nature Mater. 6 (2007) 858



Mechanical properties:

Breaking strength 42 N/m

Young modulus E = 1.5 TPa

Intrinsic stress σ_{int} = 130 GPa

Third-order elastic stiffness D = –2 TPa

C. Lee et al., Science 321 (2008) 385

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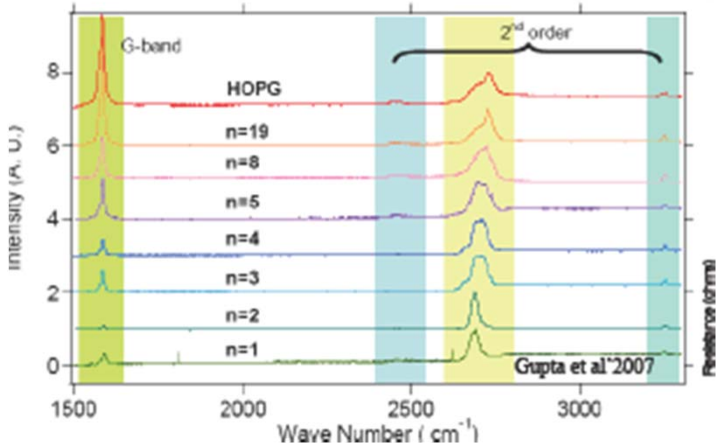
How we can identify graphene ?

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)

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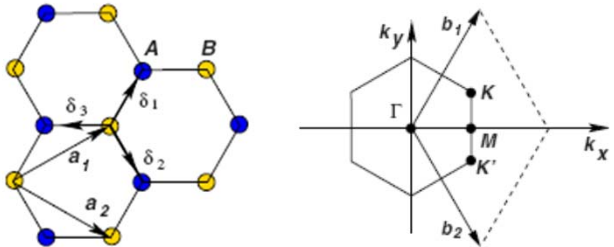
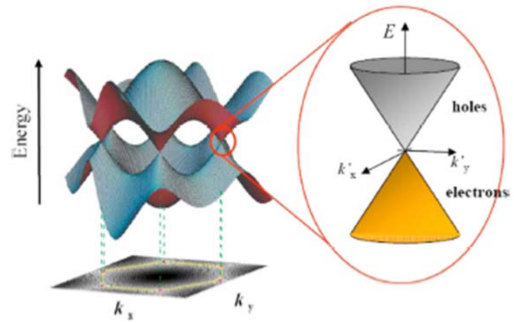
Band structure



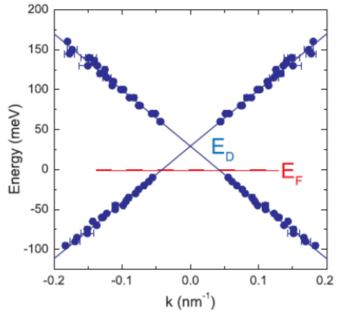


$$E_{\pm}(k) = \pm\hbar v_F \, |k|$$

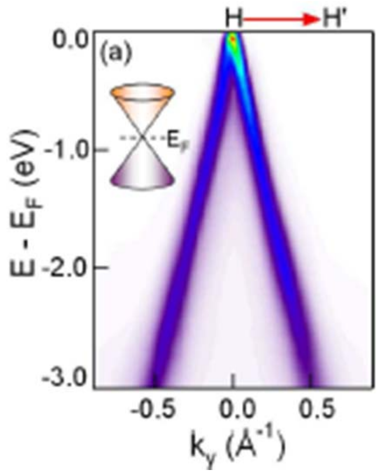
$$v_F \cong c/300$$

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

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



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



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

Why graphene for RF ,THz-1?

In analogy to the famous Moore law, the Edholm law states that *“the need for higher bandwidth in wireless communications doubles every 18 months”*. In modern wireless LANs the carrier frequency is 5 GHz and the corresponding data rate does not exceed 110-200 Mb/s. However, following the ever increasing demand for wireless communication, the data rate is expected to reach 5Gb/s in 8-10 years.*This means that the carrier frequency for wireless communications should reach and possibly exceed 100 GHz, thus approaching the terahertz domain. Beyond 100 GHz the electronic devices are scarce, therefore graphene devices could paly a role. Why?*

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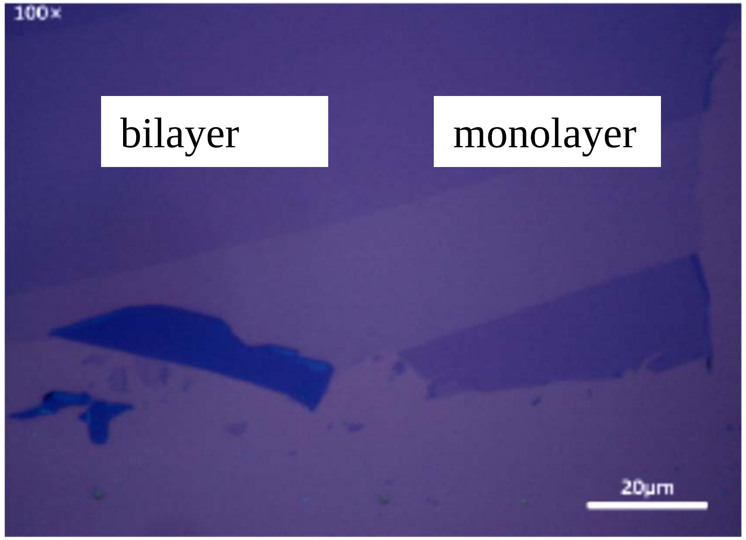
Why graphene for RF ,THz-2?



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**

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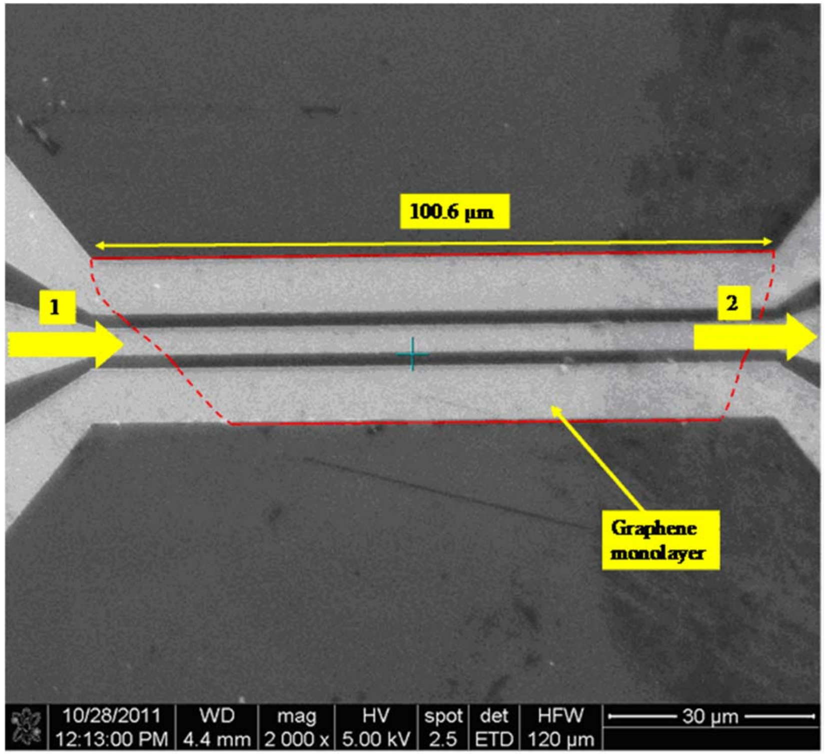
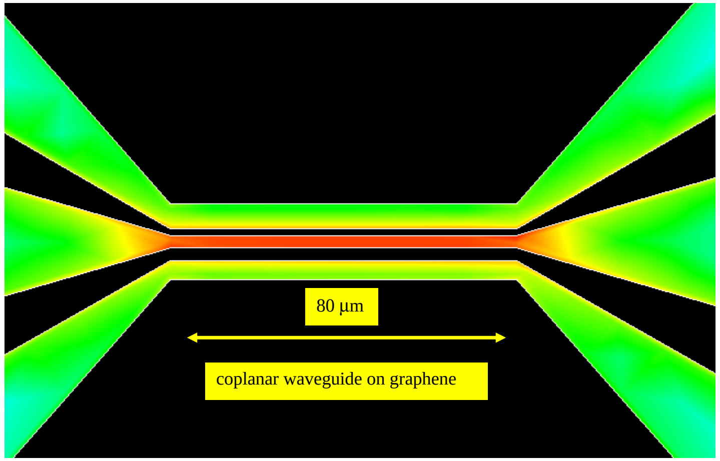
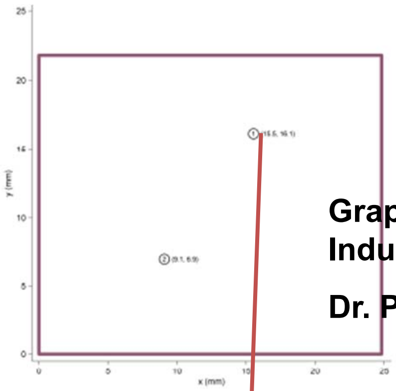
COPLANAR WAVEGUIDE ON GRAPHENE





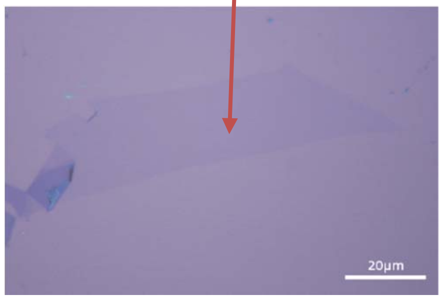
Simulation done at 100 GHz

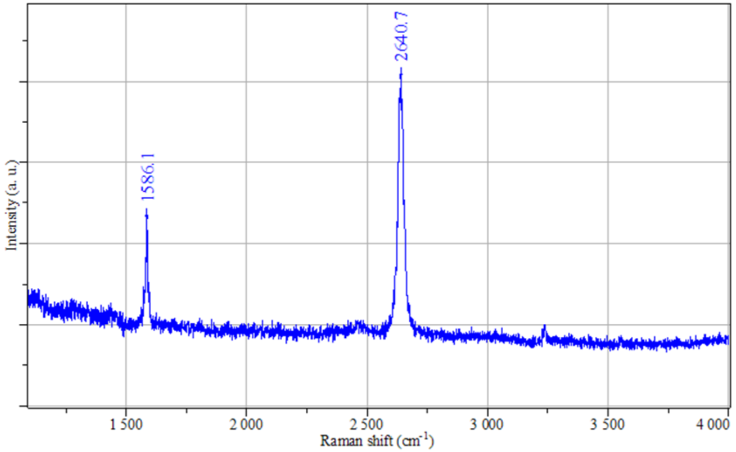
FABRICATION



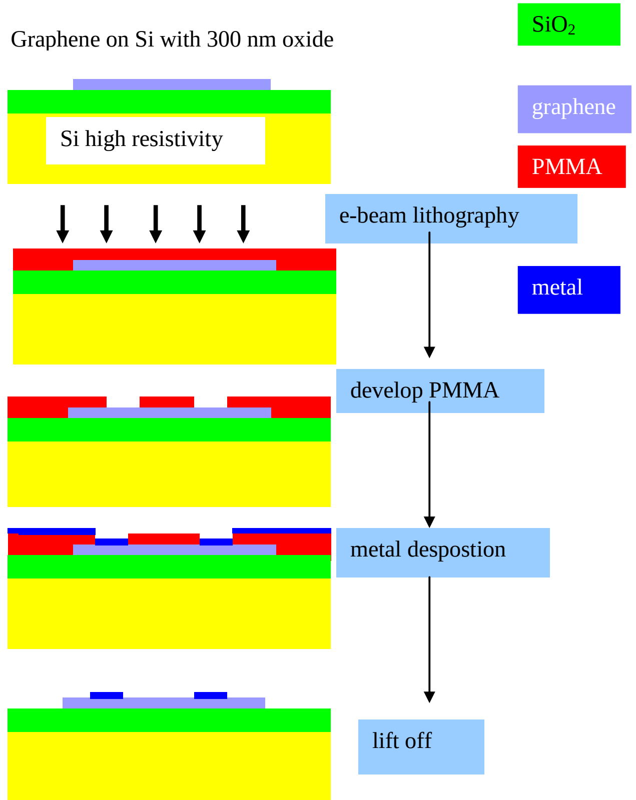
Graph
Indust

Dr. P. I

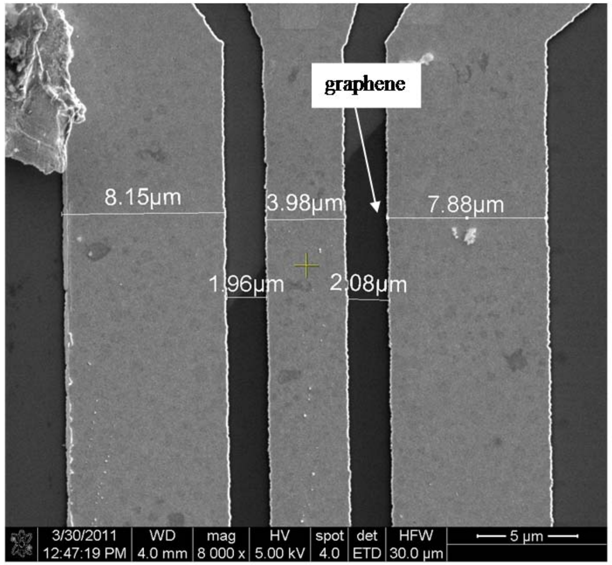


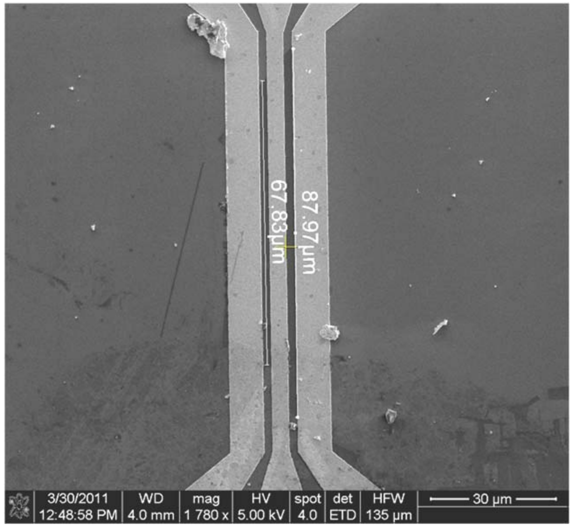


The report between the intensities of 2D and G peaks is around 2 telling us that we have a single layer graphene. The 2D and G Raman peaks positions are 2640 cm^{-1} and 1586cm^{-1},respectively



A CLOSER LOOK VIA SEM





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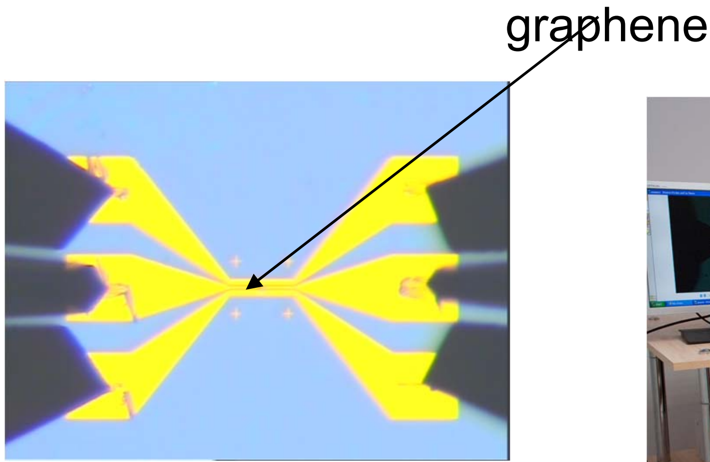
MEASUREMENTS-1



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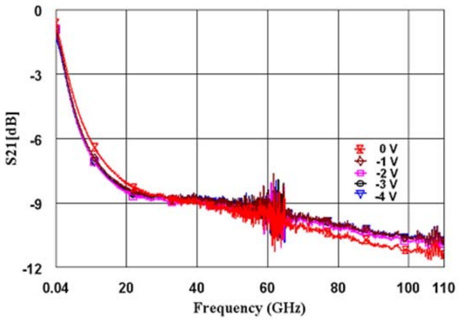
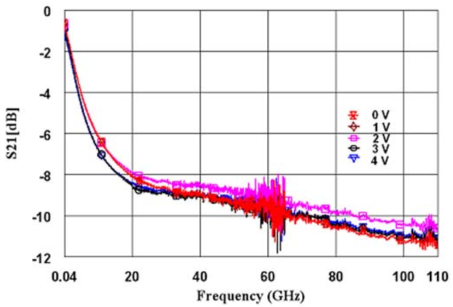
MEASUREMENTS-2



(a)

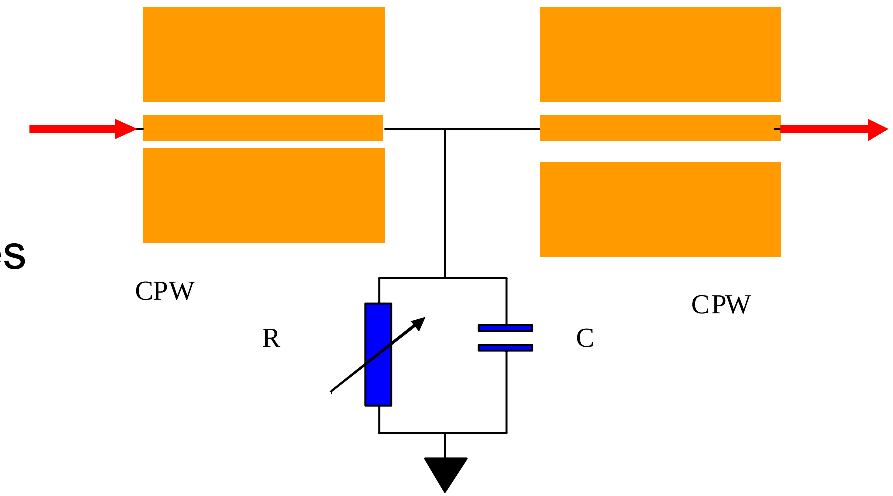
Negative DC voltages



(b)

Positive DC voltages

A SIMPLE MODEL



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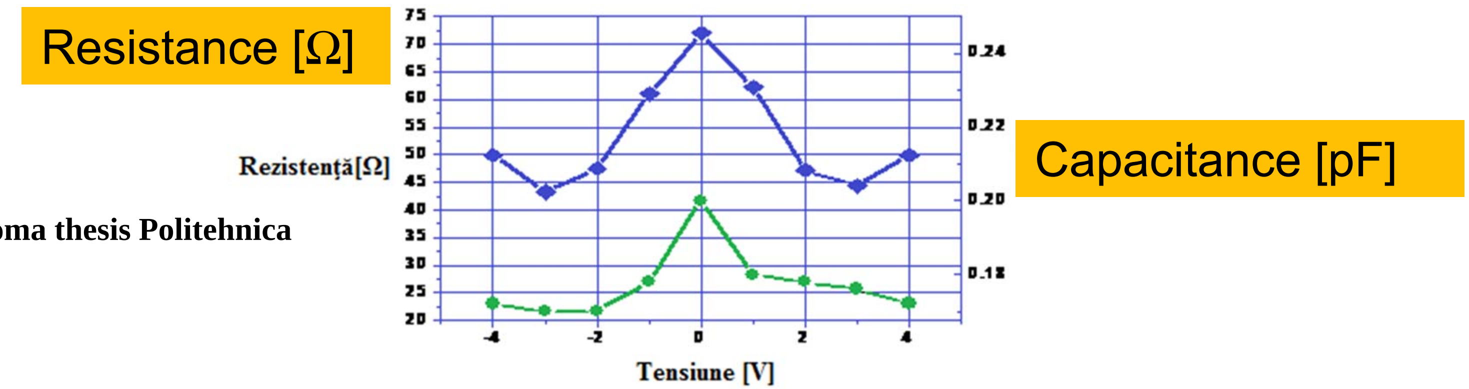
RESULTS-1

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



(Cristina Iancu – diploma thesis Politehnica Univ. Bucharest 2012)

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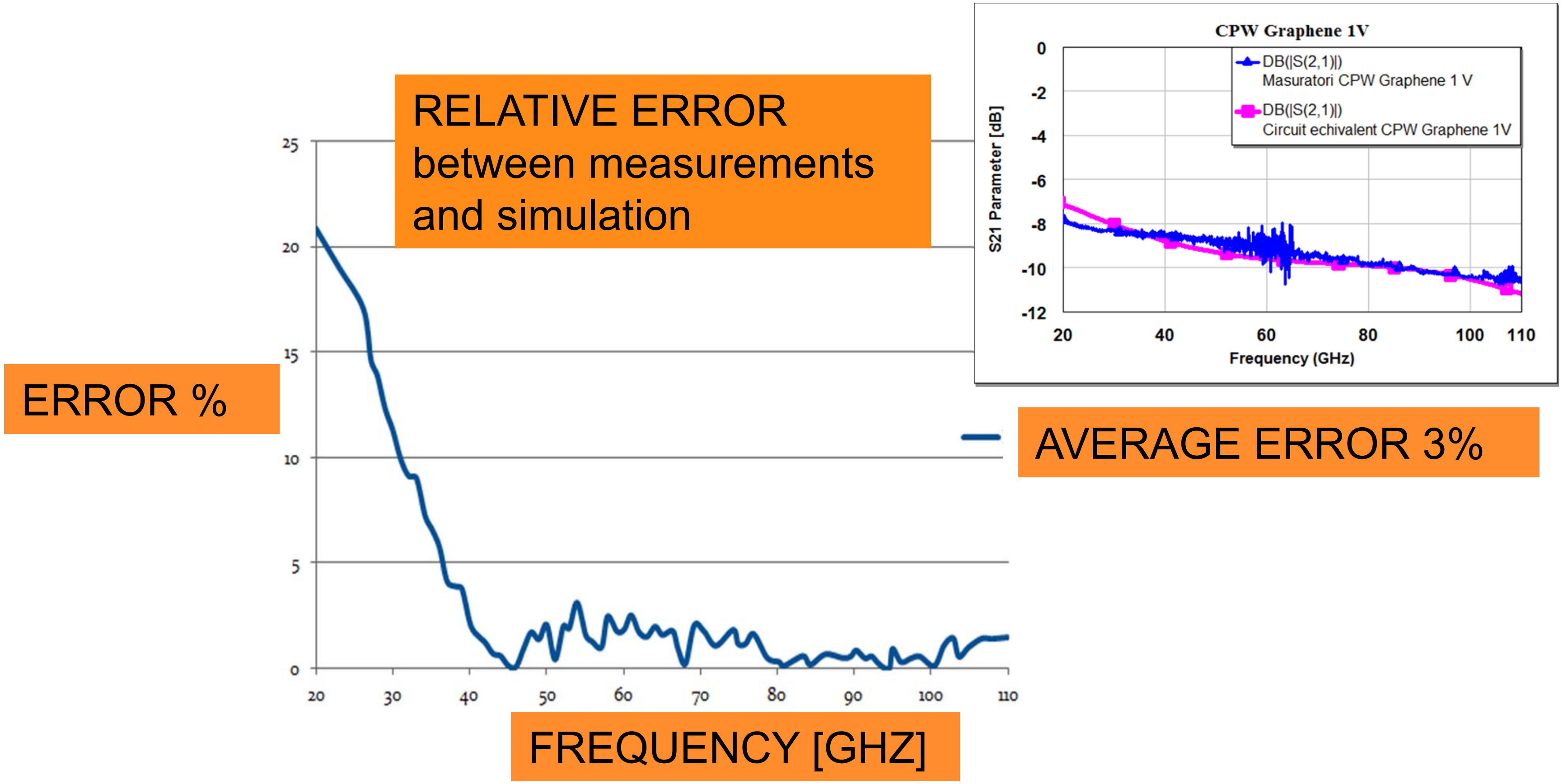

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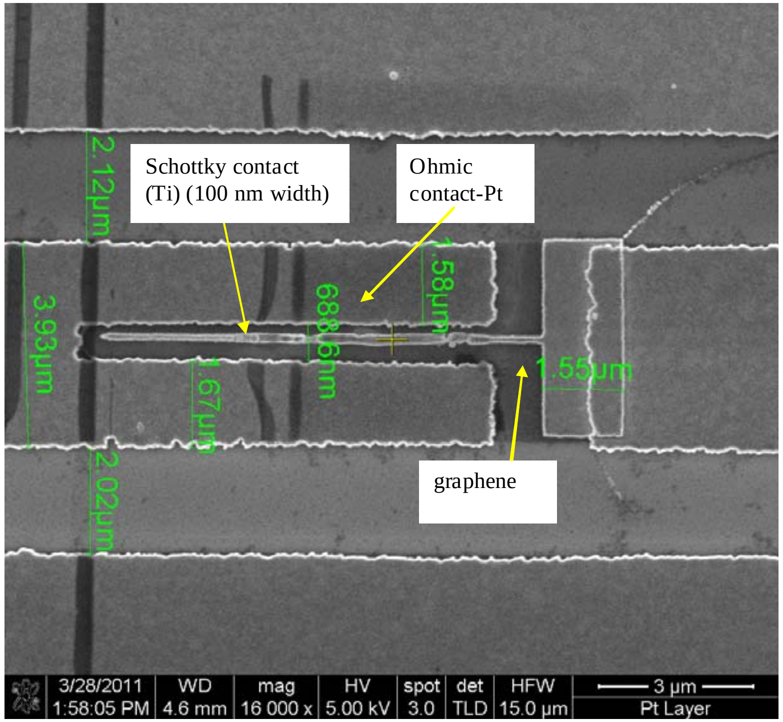

SCHOTTKY DIODE VIA DISSIMILAR METALS

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

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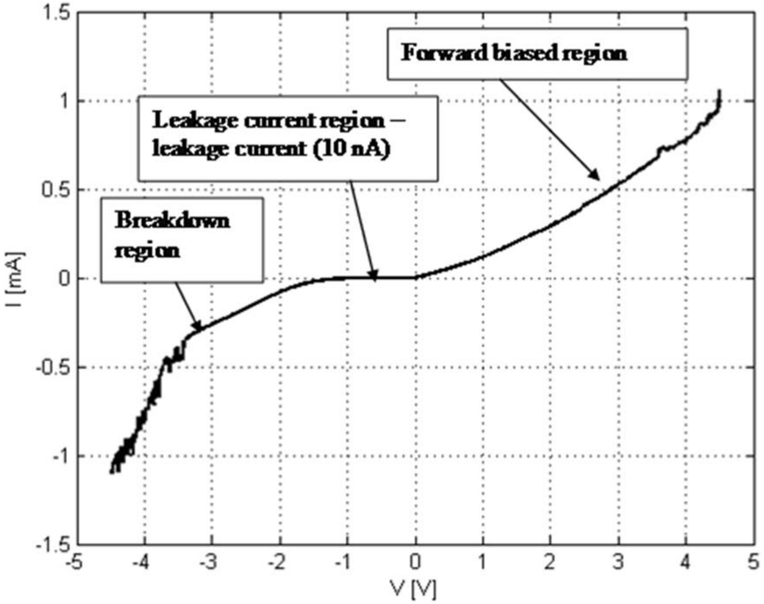
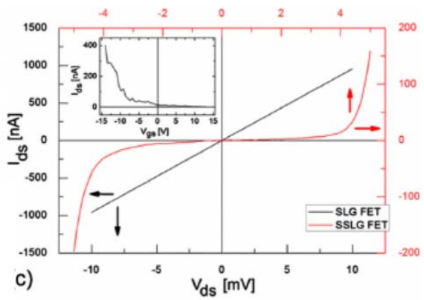
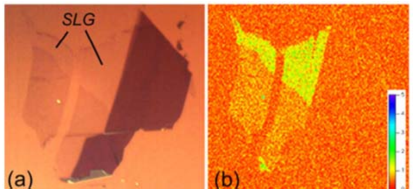
RESULTS







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, Celestij... ...00f, 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!

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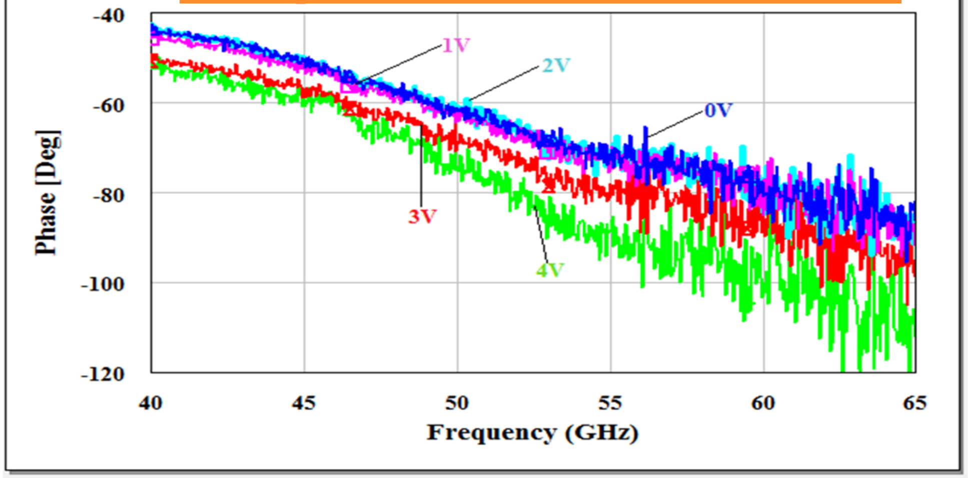
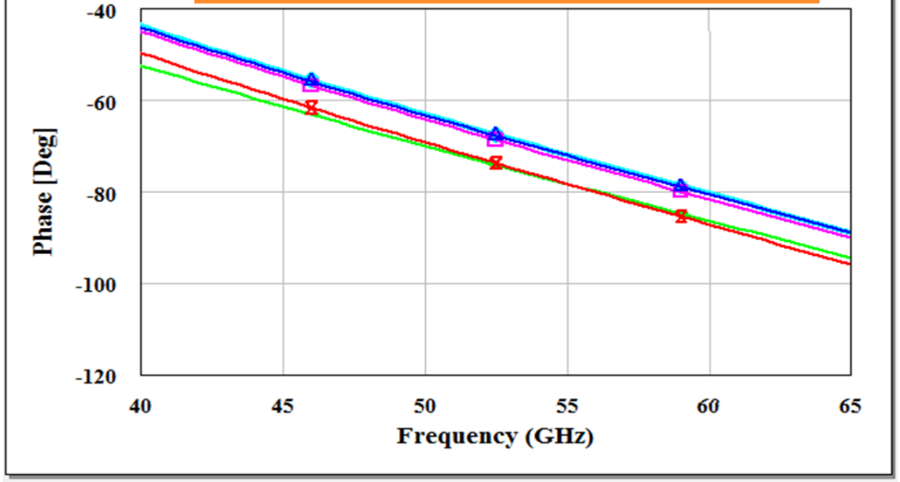
MEASURED



SIMULATED



A GRAPHENE PHASE SHIFTER

(Cristina Iancu – diploma thesis Politehnica Univ., Bucharest 2012)

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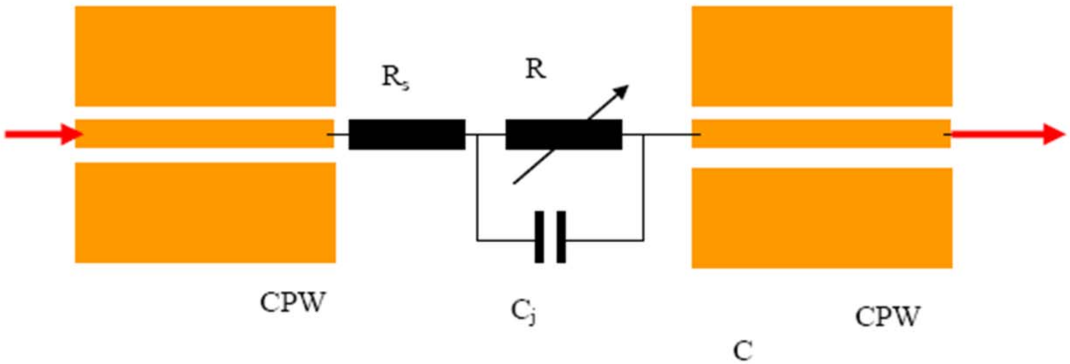

Bias voltage (V)	R_S [Ω]	R_J [kΩ]	C_J [fF]
0V	60	12	3.5
1V	60	8	3.5
2V	60	8	3.5
3V	60	0.85	3.5
4V	60	0.61	3.5

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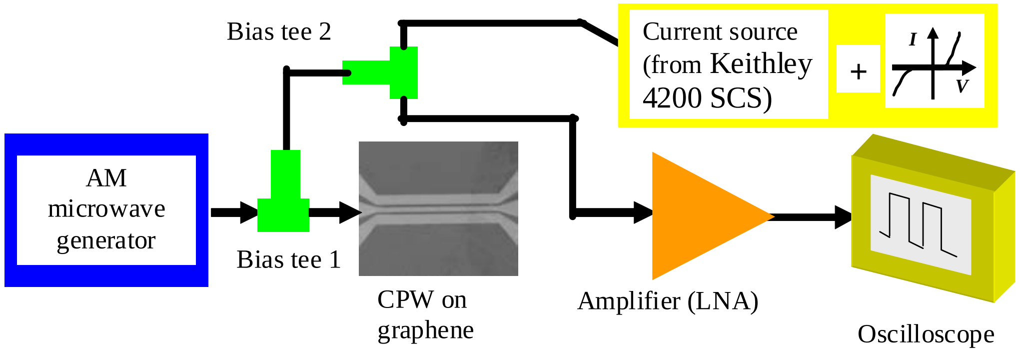
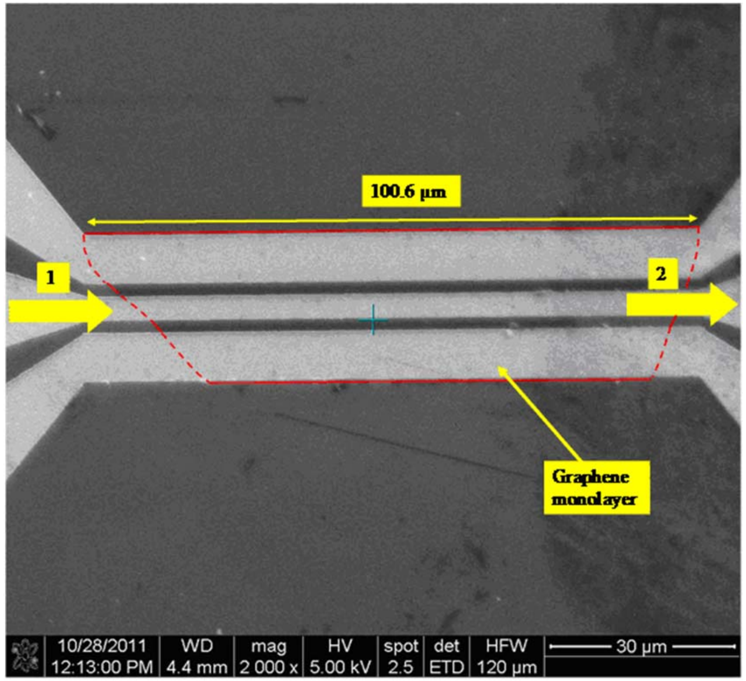
GRAPHENE RADIO





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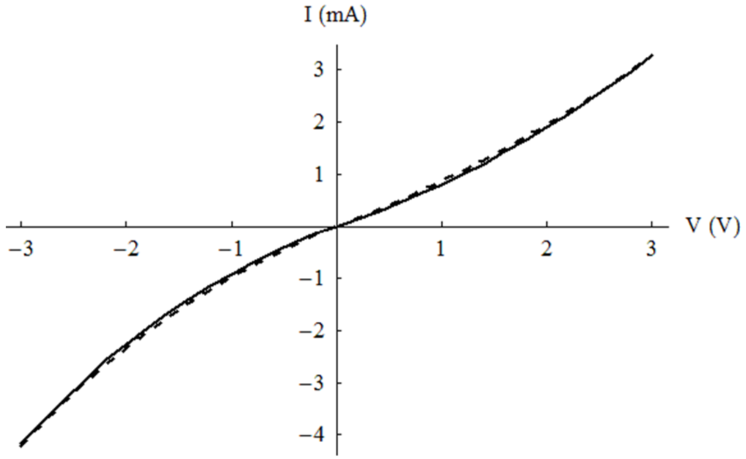
$$I = I_0[\exp(V/V_0) - 1] \qquad (1)$$

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}):

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

V_{RF}-the value of the RF signal

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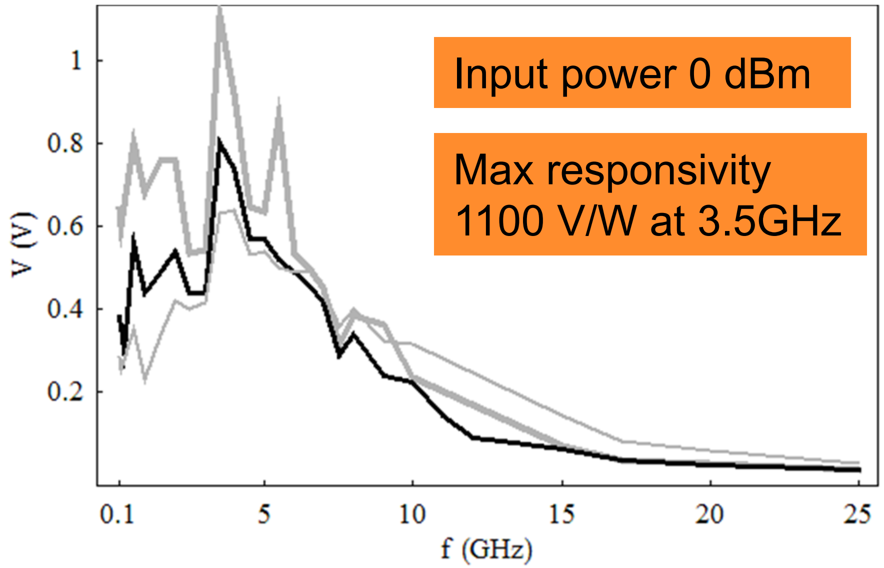

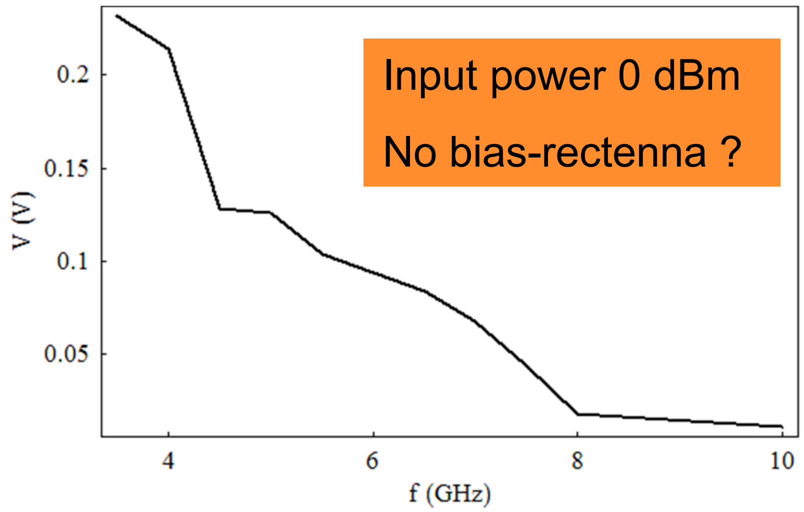

The detected DC voltage as a function of frequency for various DC currents: 1 mA (thin gray line), 2 mA (black line), 3 mA (thick gray line).

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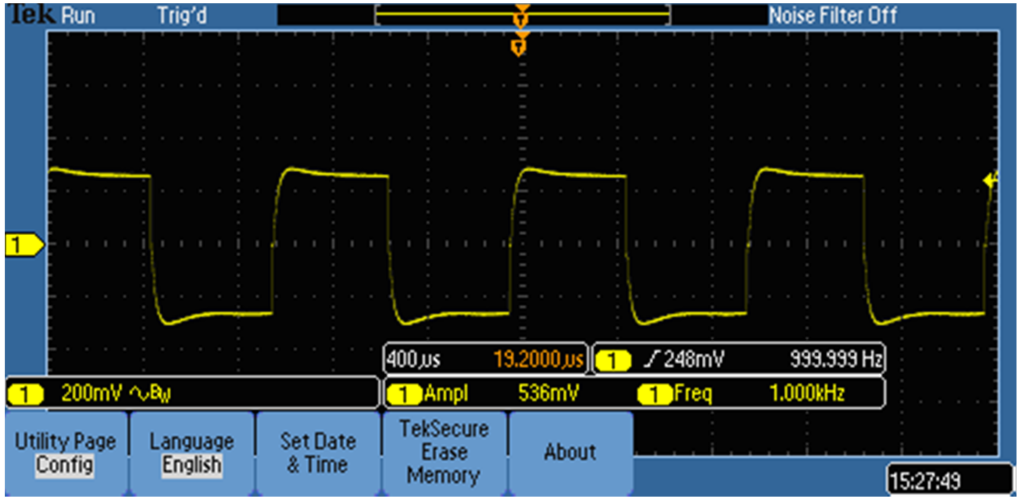

Demodulated signal in time 1 kHz

GRAPHENE FETs

After K.Kim et al. Nature A role for graphene in silicon-based semiconductor devices479, 338–344, (2011)

material	f_t(GHz)	L_g(mm)	Wg(µm)	Mobility(cm^2/Vs)	g_m(mS/µm)	Comments
Graphene with nanowire gate	1420(not measured) Measured - 300 GHz	56	2	10000	2.3	
Graphene CVD grown	155	40	30	500-600	0.02	
Graphene Epitaxial	100	240		1000-1500	0.15	
Silicon	485	29	30	1400	1.3	30 –SOI CMOS technology gate 45 nm length
InP	385	50	40	15000	1.2	
InAs	628	30	100	13200	1.62	

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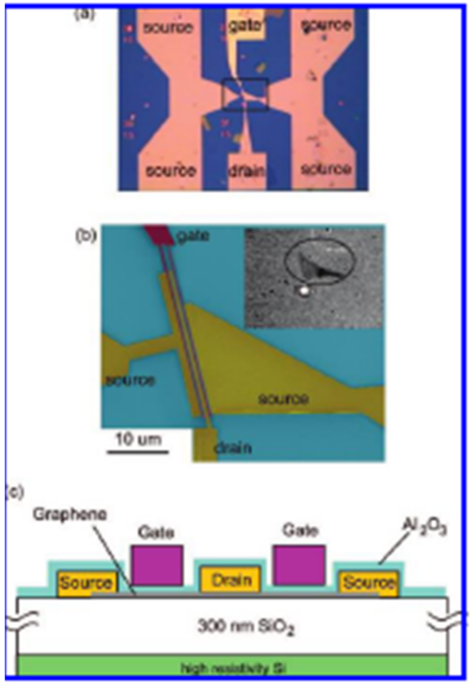

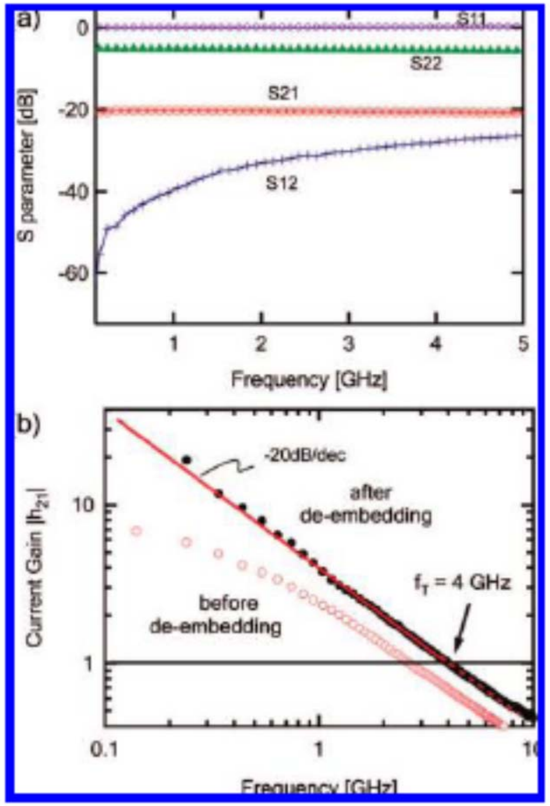

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LETTERS

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422-426

Operation of Graphene Transistors at Gigahertz Frequencies

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Received November 3, 2008; Revised Manuscript Received December 9, 2008

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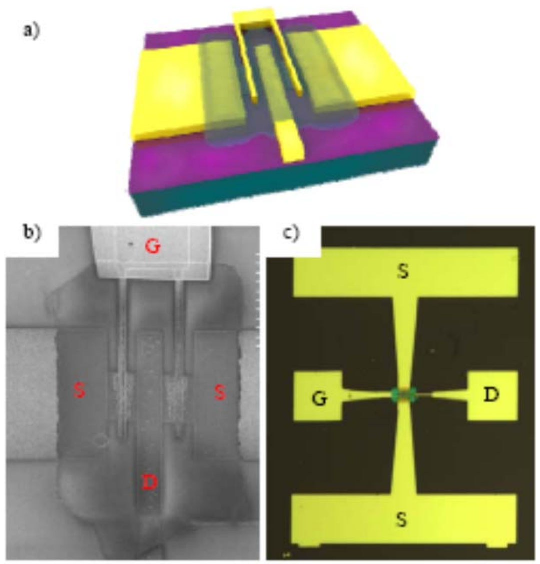

Fig.1 Graphene FET structure. (a) schematic depiction of the GFET on a Si/SiO2 substrate; (b) SEM micrograph of the graphene transistor; (c) image of the entire probed RF device structure.

f_c=14.5 GHz

ALD for gate

LETTERS

Current saturation in zero-bandgap, top-gated graphene field-effect transistors

INANC MERIC[1], MELINDA Y. HAN[2], ANDREA F. YOUNG[3], BARBAROS OZYILMAZ[3†], PHILIP KIM[3] AND KENNETH L. SHEPARD[1*]

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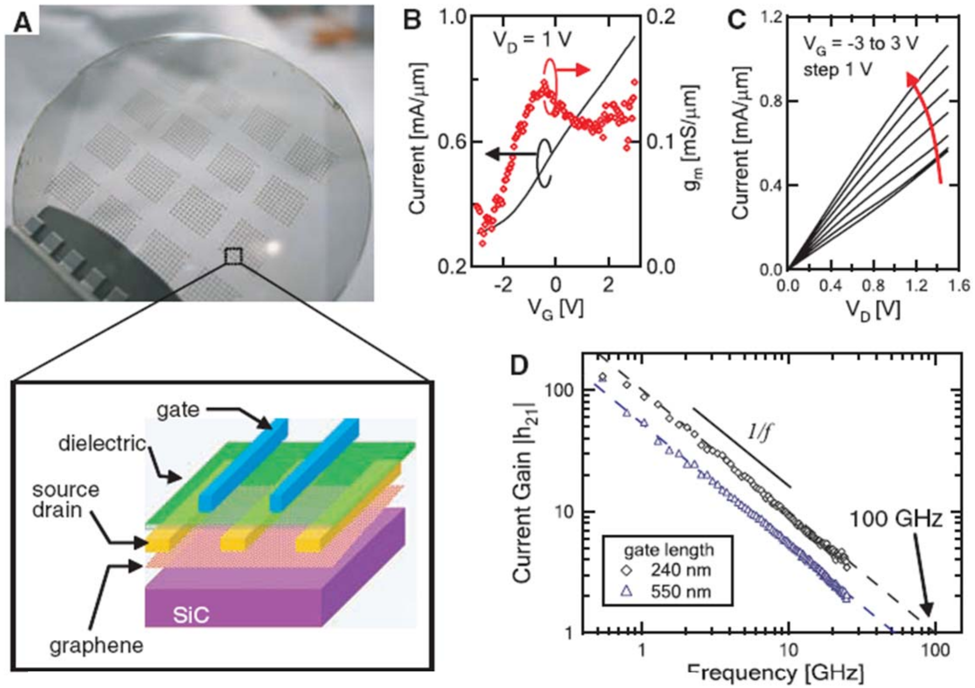
WS Micro-nanoelctronica , micronanosisteme

On wafer graphene FET- 100 GHz
cutoff frequency 100 GHz



100-GHz Transistors from Wafer-Scale Epitaxial Graphene

Y.-M. Lin,* C. Dimitrakopoulos, K. A. Jenkins, D. B. Farmer, H.-Y. Chiu, A. Grill, Ph. Avouris*

662 5 FEBRUARY 2010 VOL 327 SCIENCE www.sciencemag.org

SiC substrate-graphene epitaxial grown

10 nm HfO_2

Mobility low :1500 cm^2/Vs

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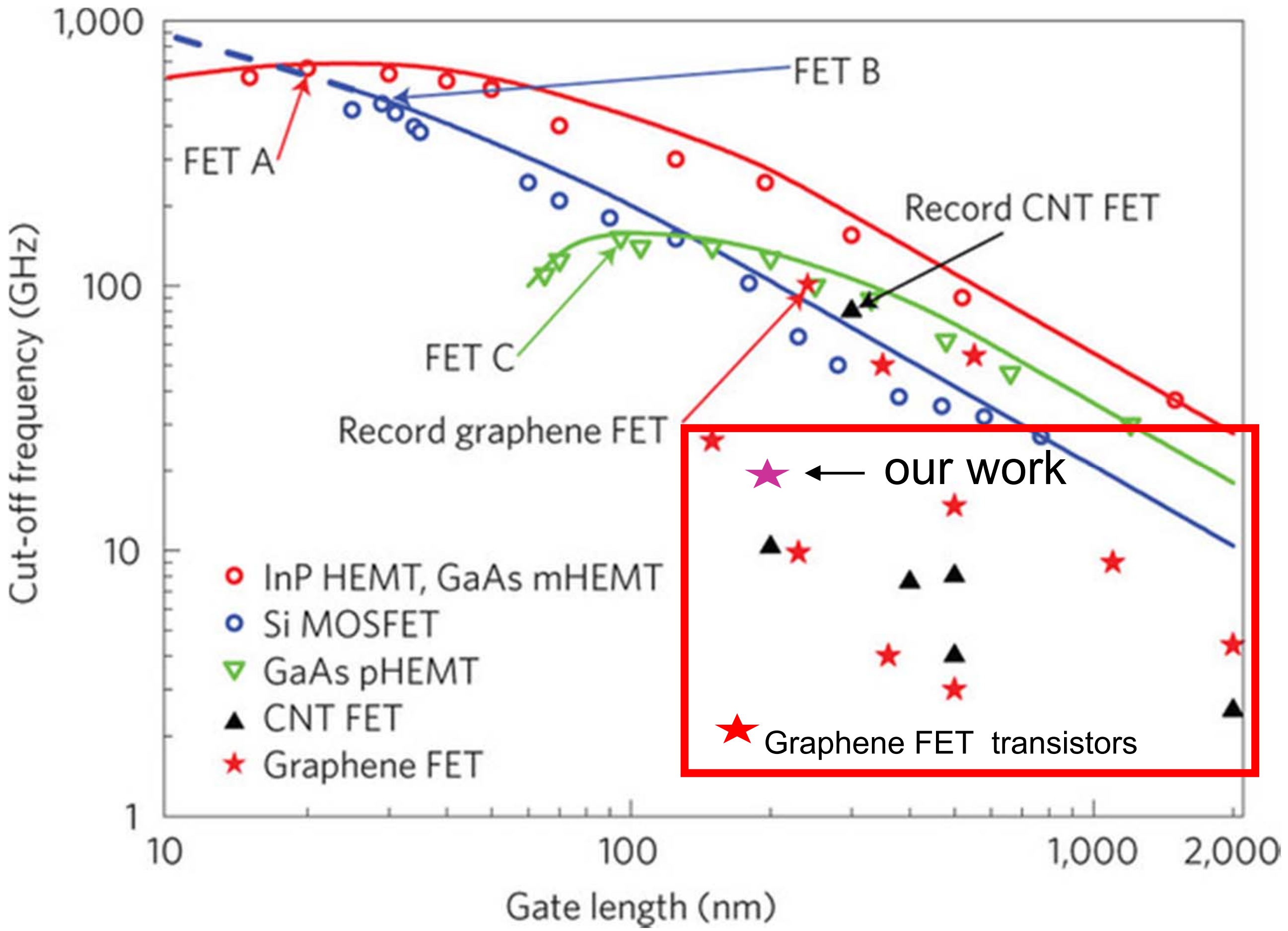

From: Graphene transistors , F.Schwiertz, Nature Nanotehnology vol. 6, 2010

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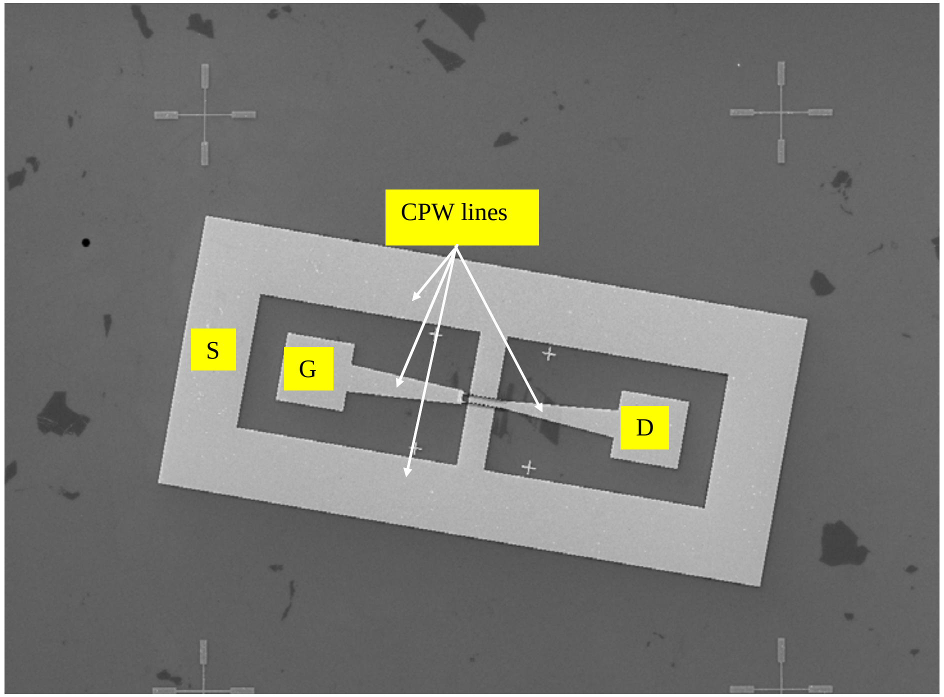

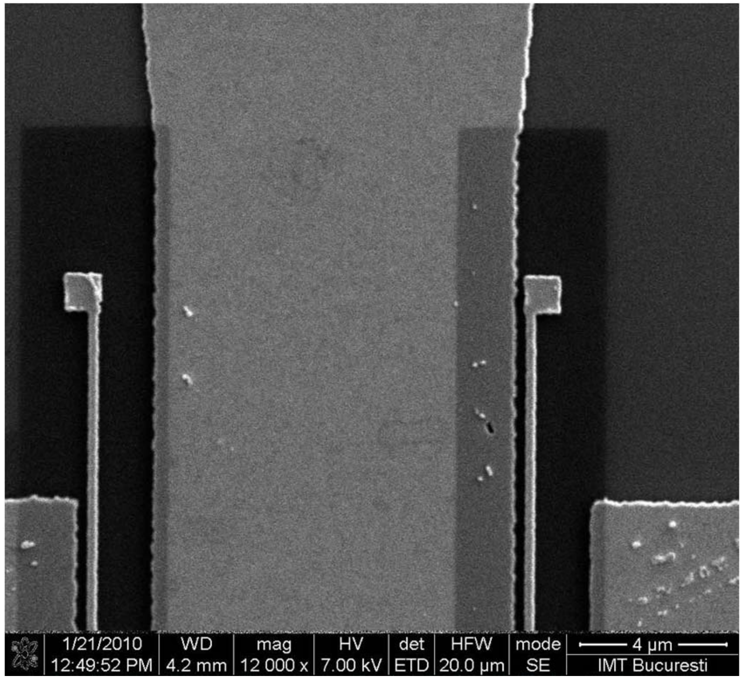

The relevant dimensions of the graphene FET are: gate length 200 nm, source-drain distance 2 µm and source-drain width 40 µm . The gate dielectric is a 100 nm thick PMMA layer

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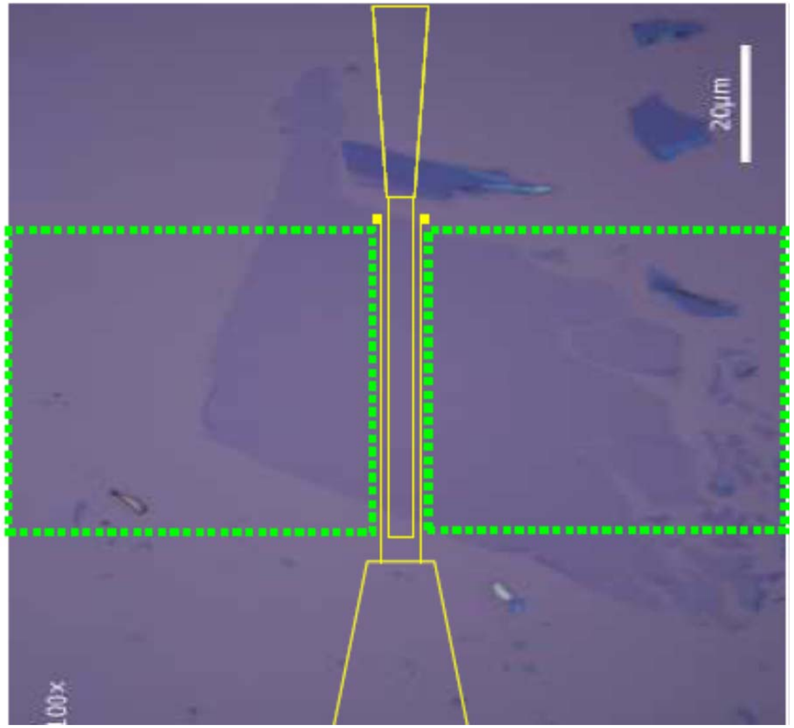

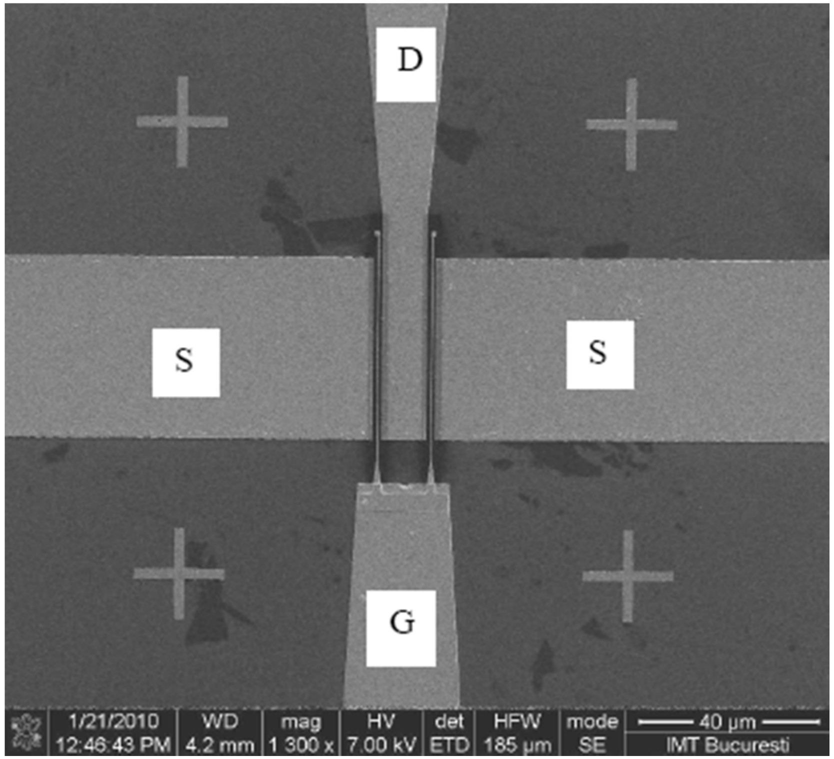

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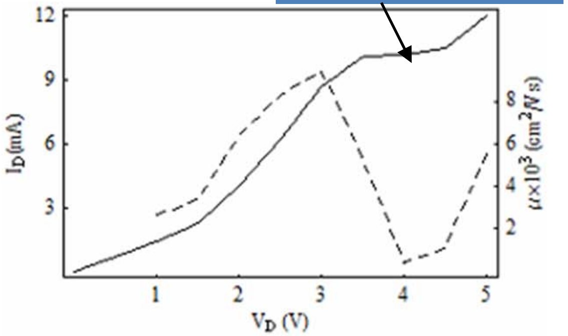
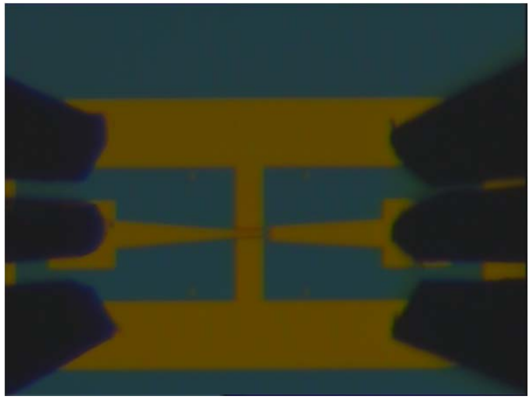
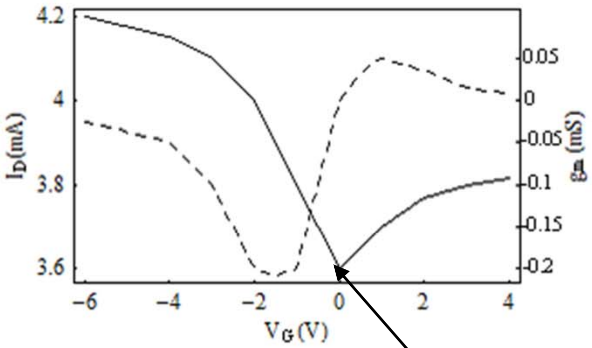
Dirac point



(a)

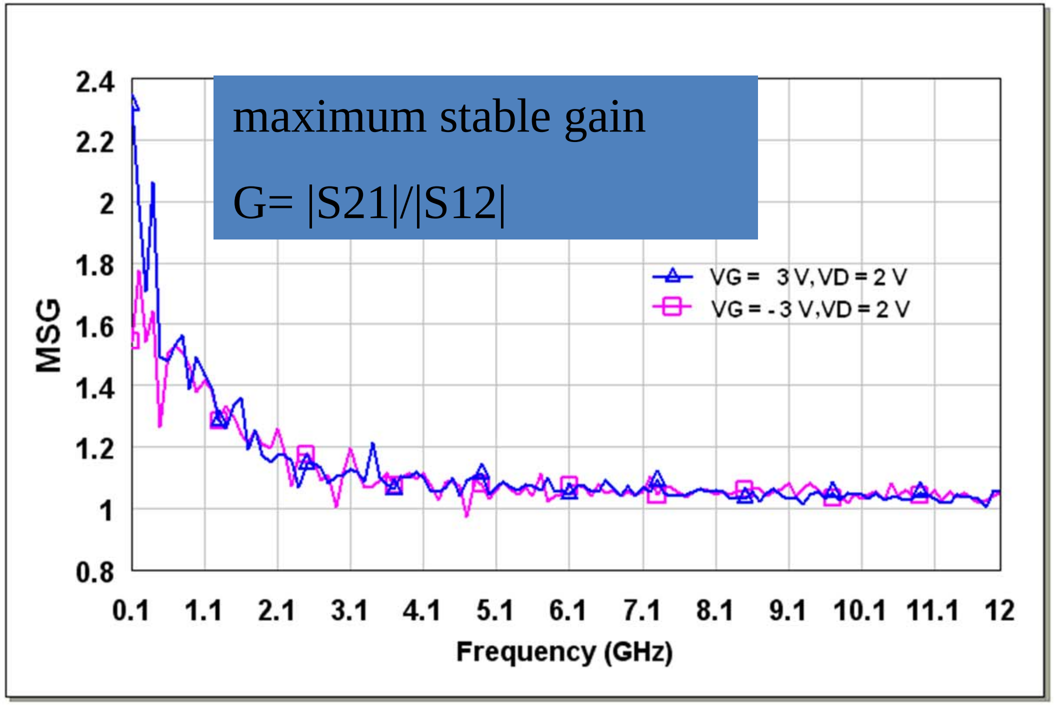


cutoff frequency =80 GHz



(b)

Dirac point



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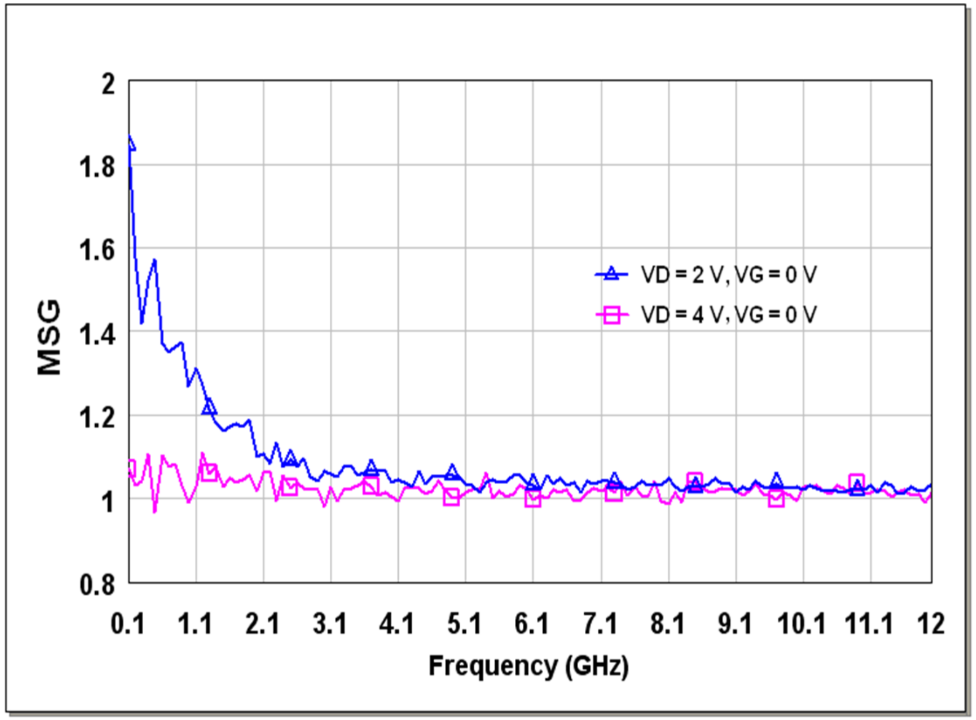
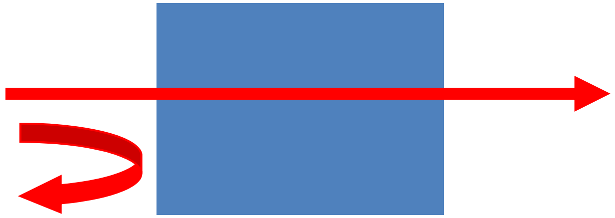
Microwave behavior at the Dirac point in graphene



FET graphene far from Dirac point



FET graphene at the Dirac point

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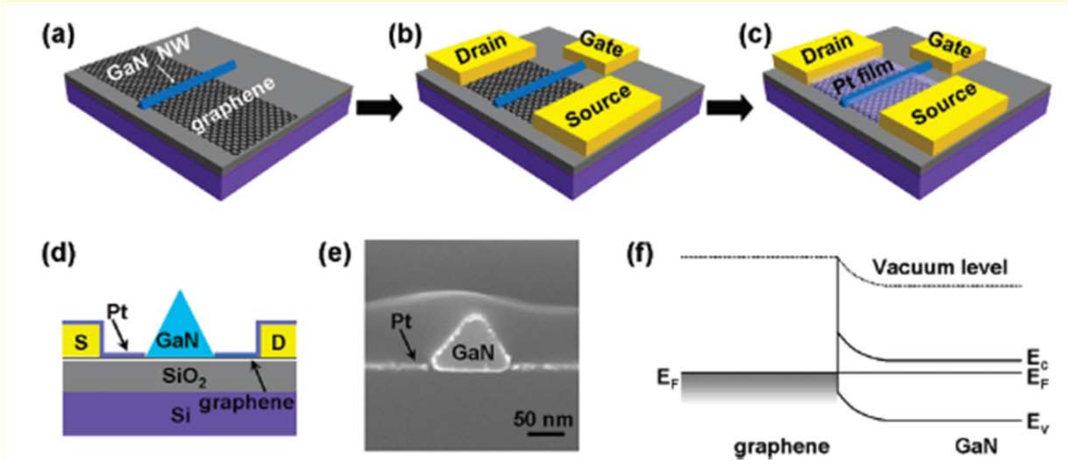


Perspectives:

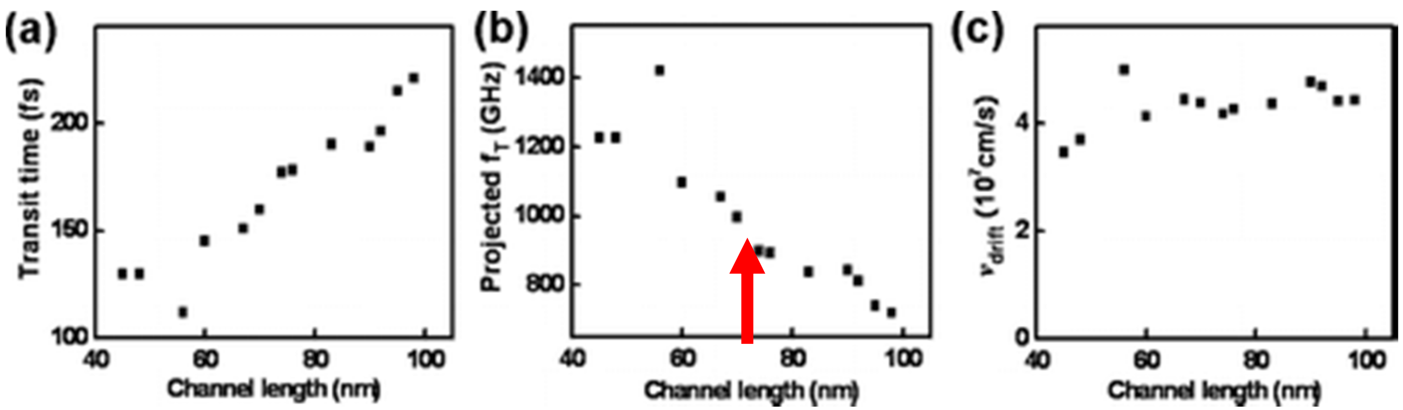
In 1.5 years the cutoff frequency of graphene FET transistors has increased from few GHz up to 800 GHz

NANO LETTERS

Sub-100 nm Channel Length Graphene Transistors

Publication Date (Web): September 3, 2010

Cutoff frequency 800 GHz



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Graphene at THz

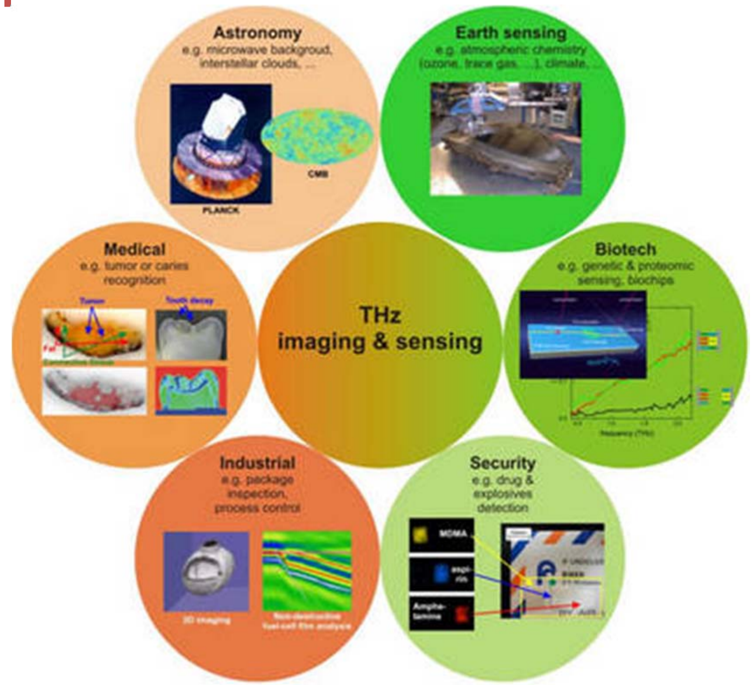
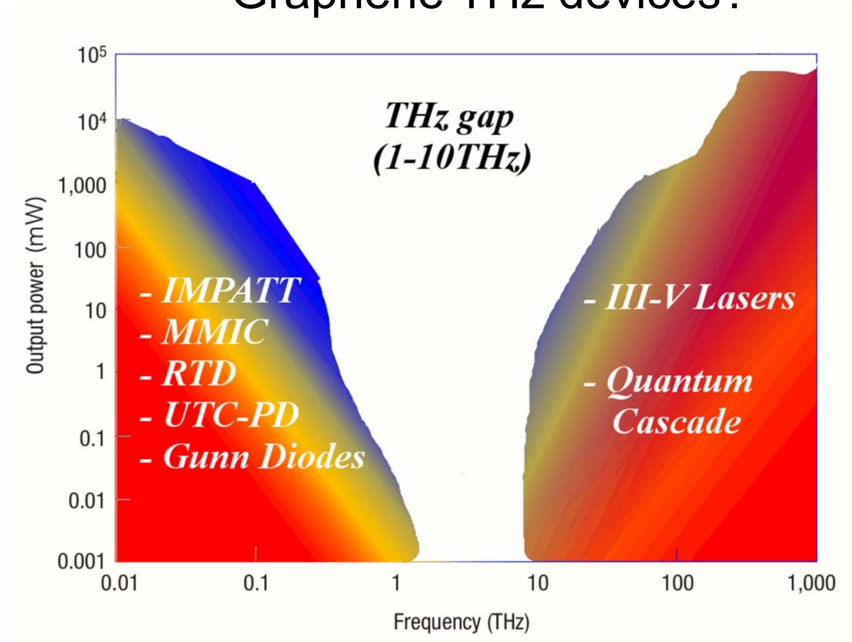


Illustration of some exemplary applications of Terahertz radiation.
P. de Maagt, P. Haring Bolivar and C. Mann, Terahertz science, engineering and systems-from space to earth applications, Encyclopedia of RF and Microwave Engineering, Ed. by K. Chang, pp. 5175-5194 (John Wiley & Sons, Inc., 2005) ISBN 0-471-27053-9.

Graphene THz devices?



Done by G. Deligeorgis project Tera Wi-Phee

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