Graphene Plasmonics: Theory and Experiments

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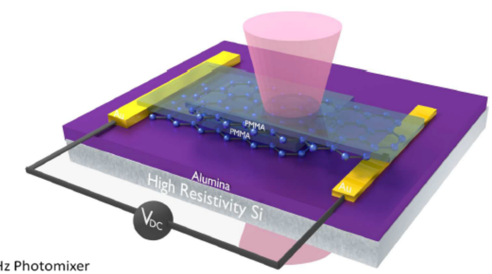

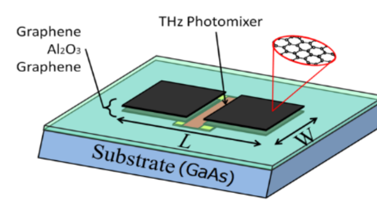

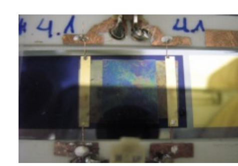

- Prof. Julien Perruisseau-Carrier
- Theory of Graphene plasmonics
  - Unusual electromagnetic properties of graphene
  - Guided devices and antennas @ THz
- Experimental results
  - Surface impedance @ microwaves and THz
  - Graphene stacks
- Concluding remarks

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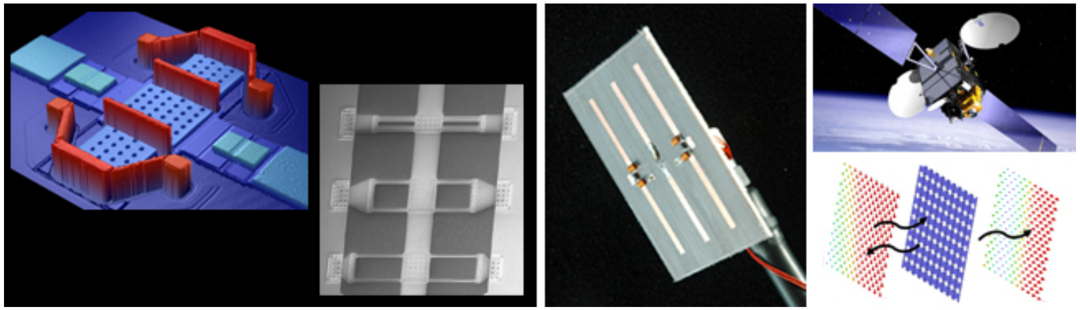
Julien Perruisseau-Carrier (I)

- I first met Julien at APS 2008 @ San Diego
  - Julien was postdoc at CTTC, in Barcelona (Spain).
  - I was fresh PhD student @ UPCT (Spain) and Montréal (Canada).
  - We didn’t meet again in more than 3 years…

Julien Perruisseau-Carrier (II)

- Adaptive MicroNano Wave System - Research Group



- Created in June 2011 at EPFL
- Hosted at EPFL by two labs:
  - LEMA: lema.epfl.ch
  - Nanolab: nanolab.epfl.ch
- Very well funded!
- I was *postdoc* there from Nov. 2011 – March 2014
- Mid size group:
  - 2-3 postdocs
  - 5 PhD studets
  - Many conferences together

Microwaves — THz

Dynamic reconfiguration

- Update device functionality in real time
- Sense and adapt to environment
- Scan space, frequencies, polarization…

Joint antenna-coding techniques

- Higher data-rate and lower-power
- Reduced-complexity HW

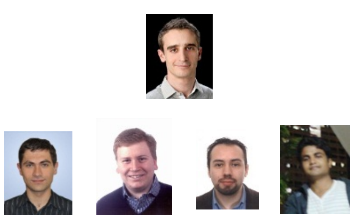
artificial EM materials

- Tailor extraordinary effective EM properties

Use of micro/nano-technology:

Graphene, MEMS, Electroactive polymers…

- EM perf., higher freq., integration, low power
- Novel sensing applications (graphene)



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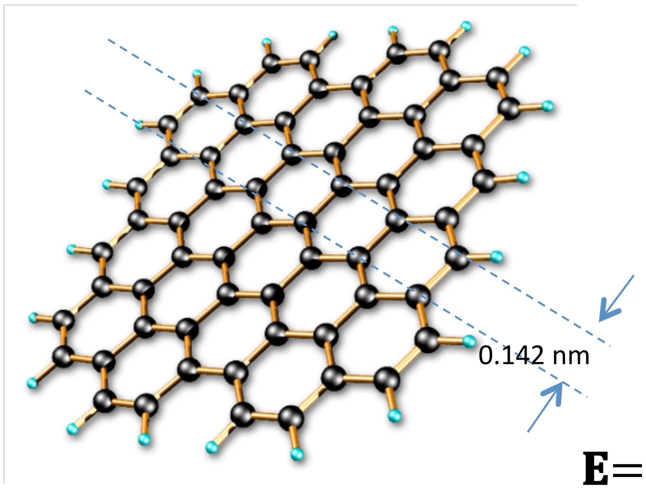
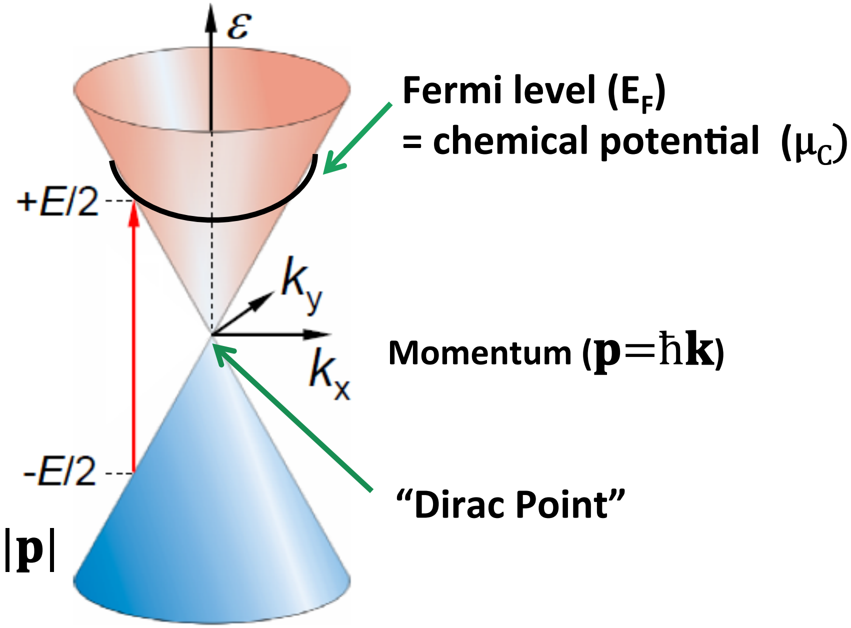
Introduction

- Graphene: the "famous" 2D material



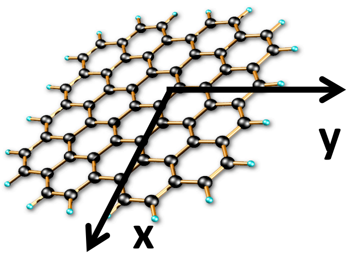


$\mathbf{E}=\pm\hbar v_f|\mathbf{p}|$

  - 2D material: carbon atoms in 2D honeycomb lattice
  - 1 atom thick ≈ infinitesimally thin
  - "Semi-metal" or "zero-gap semiconductor"
  - Ambipolarity: both electrons ($E_f>0$, n type doping) or holes ($E_f<0$, p type doping) can conduct
  - Massless electrons: $E=\sqrt{(\cancel{mc^2})^2+(\hbar v_f p)^2}=\pm\hbar v_f|p|$

Graphene conductivity: *behavior and trends (I)*

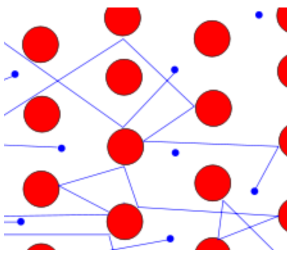
- Graphene is 2D → entirely described by a surface conductivity



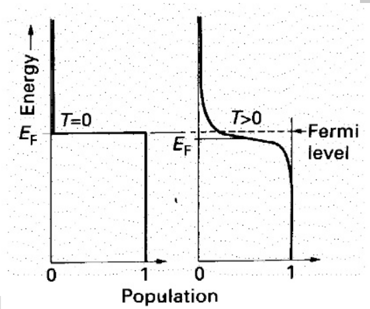
$J = \sigma E$ ⇨ • $H_0 = 0$ • No SD ⇨ $J = \sigma E$

$$\sigma(\omega, \tau, T, \mu_c(E_{bias}))$$

- ***τ* = relaxation time:**
  - Rough interpretation: time between two consecutives "collisions" of an e^- propagating on graphene
  - Large → better conductivity !
  - Highly depends on fabrication → **quality of graphene**



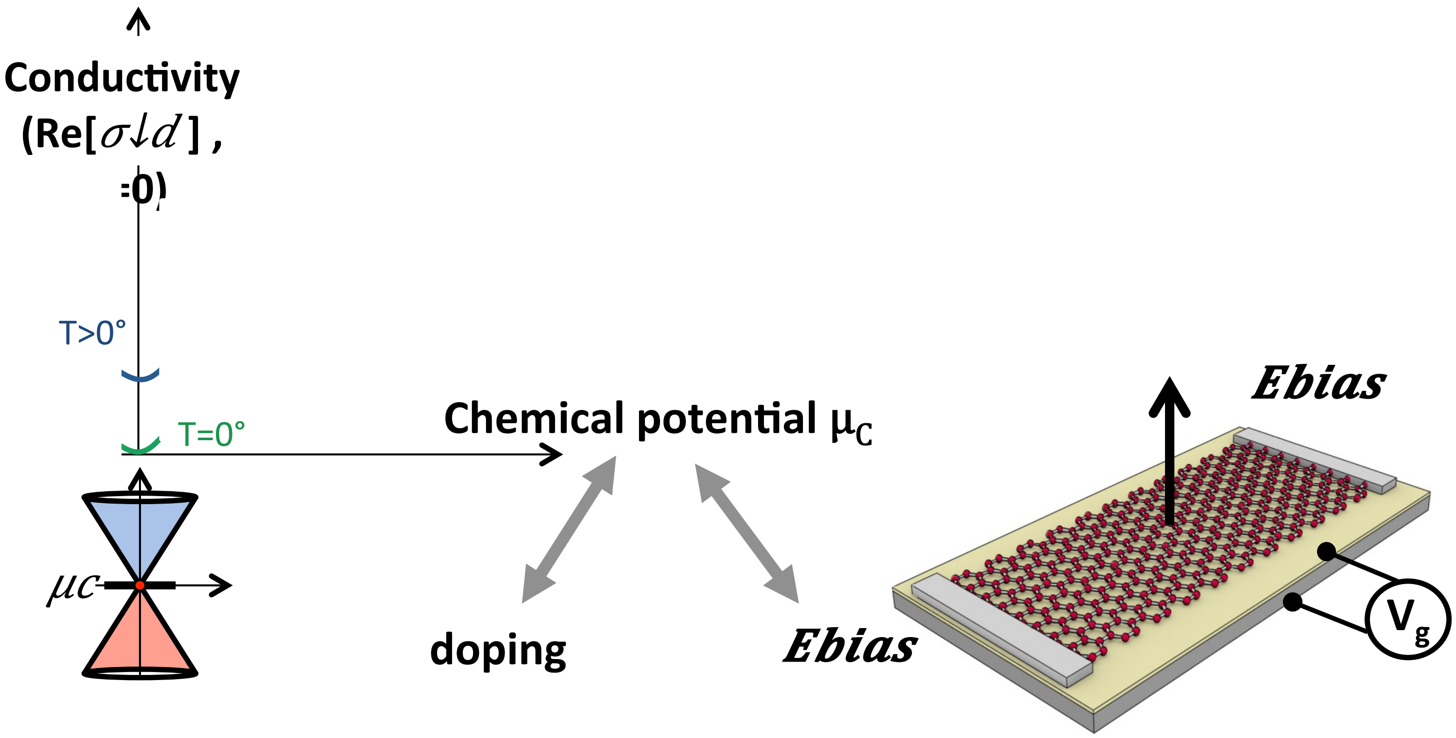
- ***T* = temperature**
  - T relevant only when close to Dirac point (small μ_c).



Graphene conductivity: *behavior and trends (and II)*

$\sigma_d(\omega, T, \tau, \mu_c(E_{bias}))$

- **Doping** or **static electric field** affect conductivity tensor:



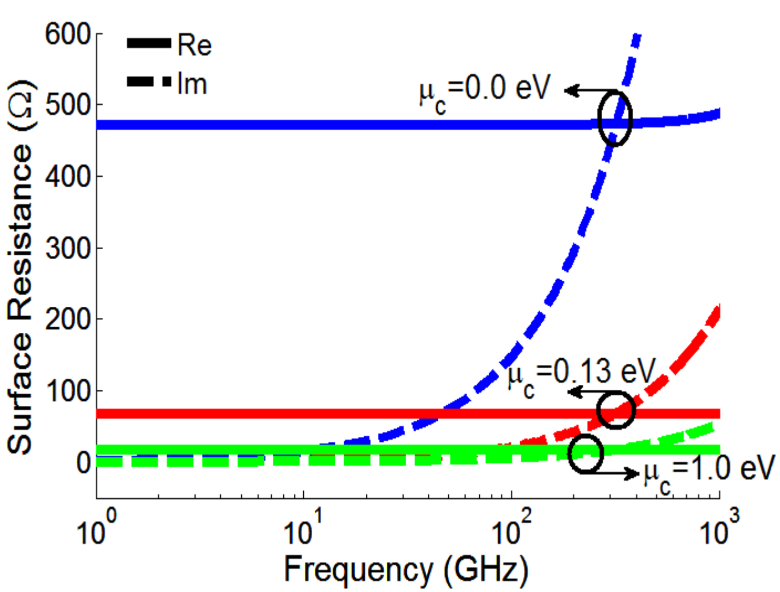
- **Easy *dynamic* control of conductivity!**
- **Real and imaginary parts affected**

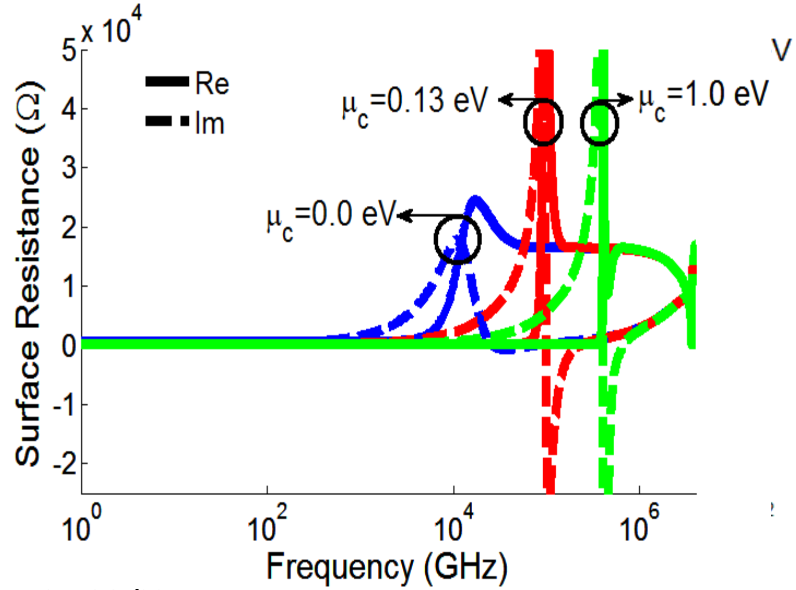
Electromagnetic properties of graphene

- Absence of B_{bias} and neglecting spatial dispersion

$$\sigma = \begin{pmatrix} \sigma_d & 0 \\ 0 & \sigma_d \end{pmatrix} = \sigma_d \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$Z_S = \frac{1}{\sigma_d}$$

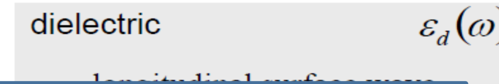




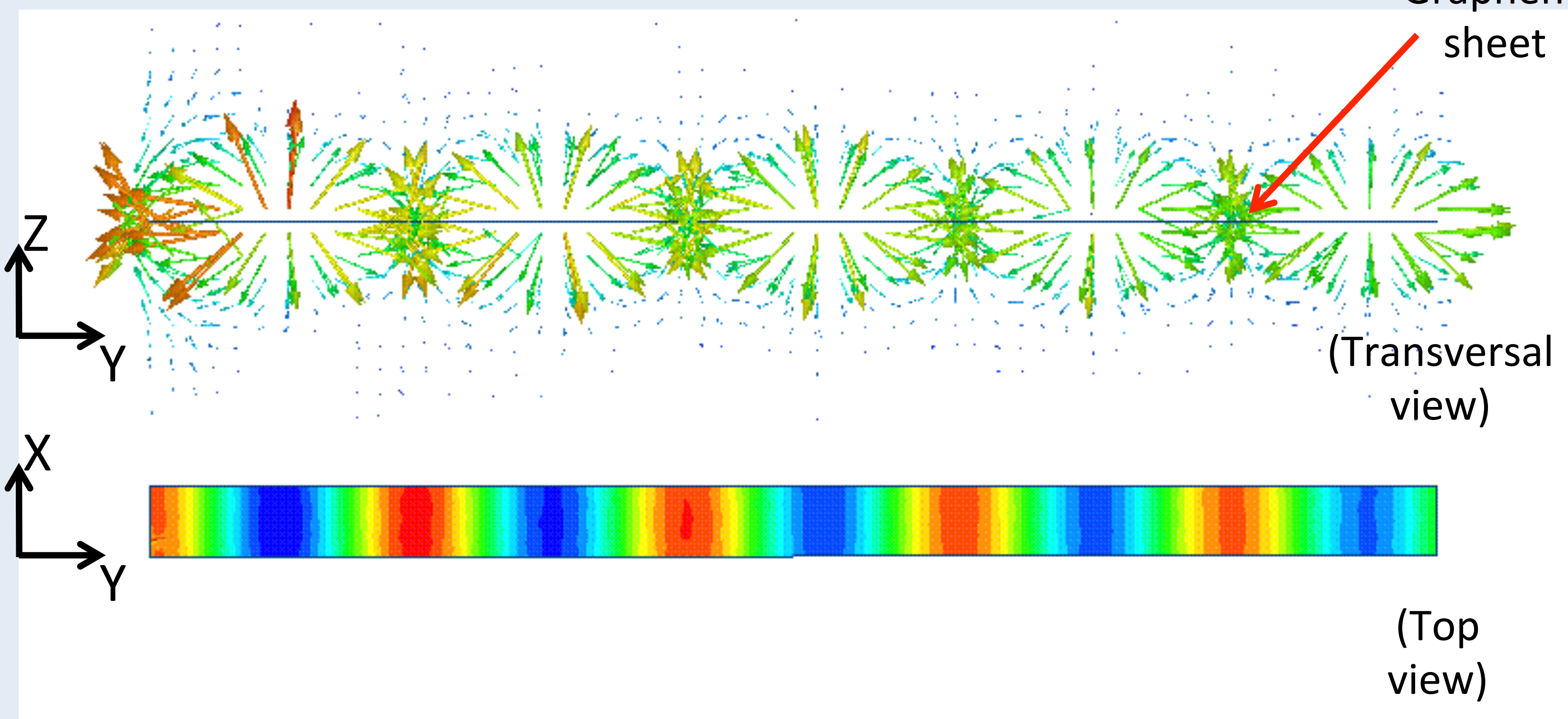
- – @ microwaves: mostly a resistive sheet
- – @ THz: large inductive behavior (→ plasmon propagation)
- – $\uparrow\uparrow \mu_c$:
  - Significant tuning effect
  - Losses decrease

Surface plasmons on graphene

- Plasmonic modes *on metals* at optics:
  - EM wave propagating at the interface between



Example of plasmon propagation on a graphene sheet

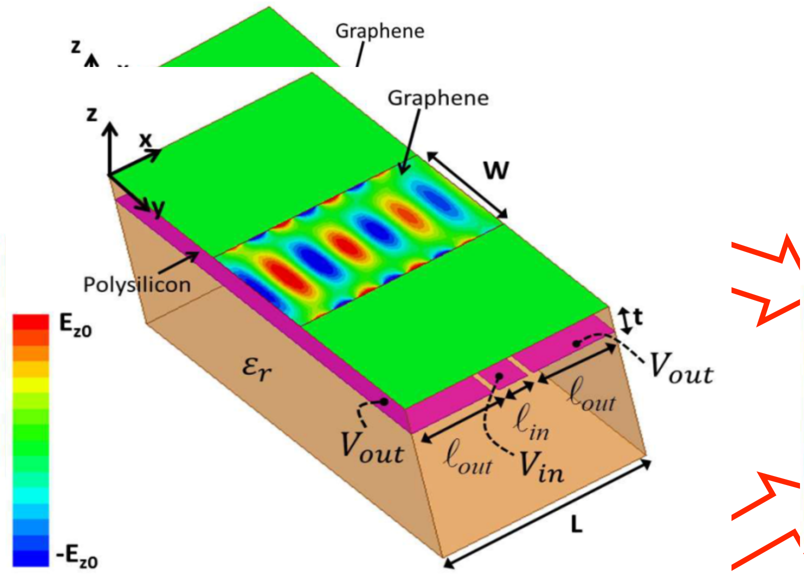


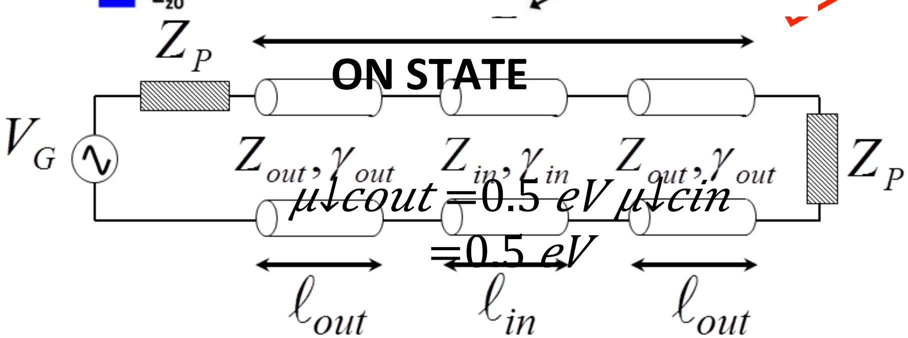
using H static field

[1] M. Jablan, H. Buljan, and M. Soljacic, “Plasmonics in graphene at infrared frequencies,” Physical review B, 2009.
[2] A. Vakil and N. Engheta, “Transformation optics using graphene,” *Science*, vol. 332, pp. 1291–1294, 2011.

Plasmon waveguiding

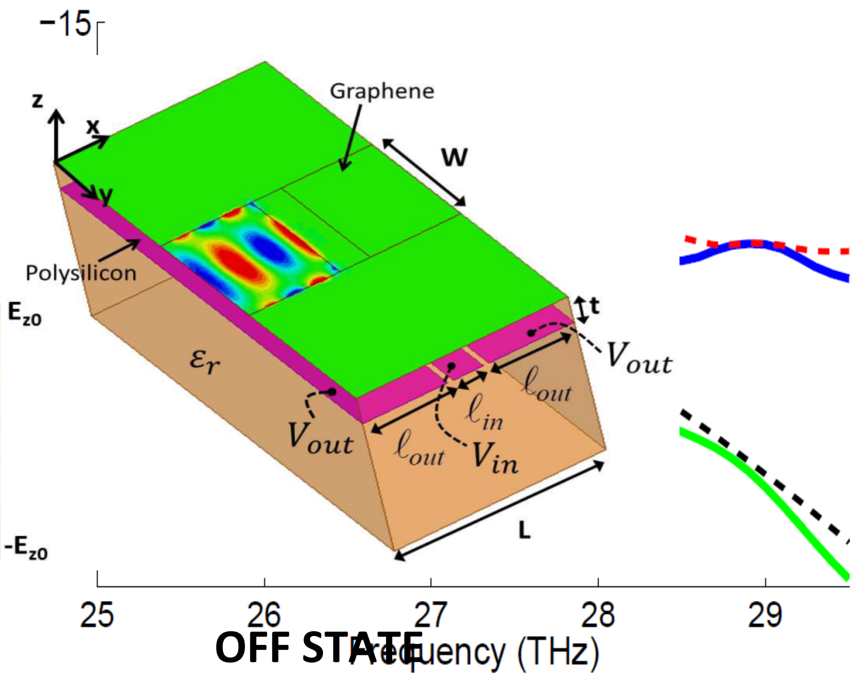
- Transmission line model
  - Simple characterization of surface plasmon propagation on ribbons
  - Excellent agreement with FEM results





ON STATE

$\mu_{c,out}=0.5\ eV$, $\mu_{c,in}=0.5\ eV$



OFF STATE

$\mu_{c,out}=0.5\ eV$, $\mu_{c,in}=0.2\ eV$

$\mu_{c,out}=0.5\ eV$, $\mu_{c,in}=0.1\ eV$

$\ell_{out}=\ell_{in}=1\mu m$

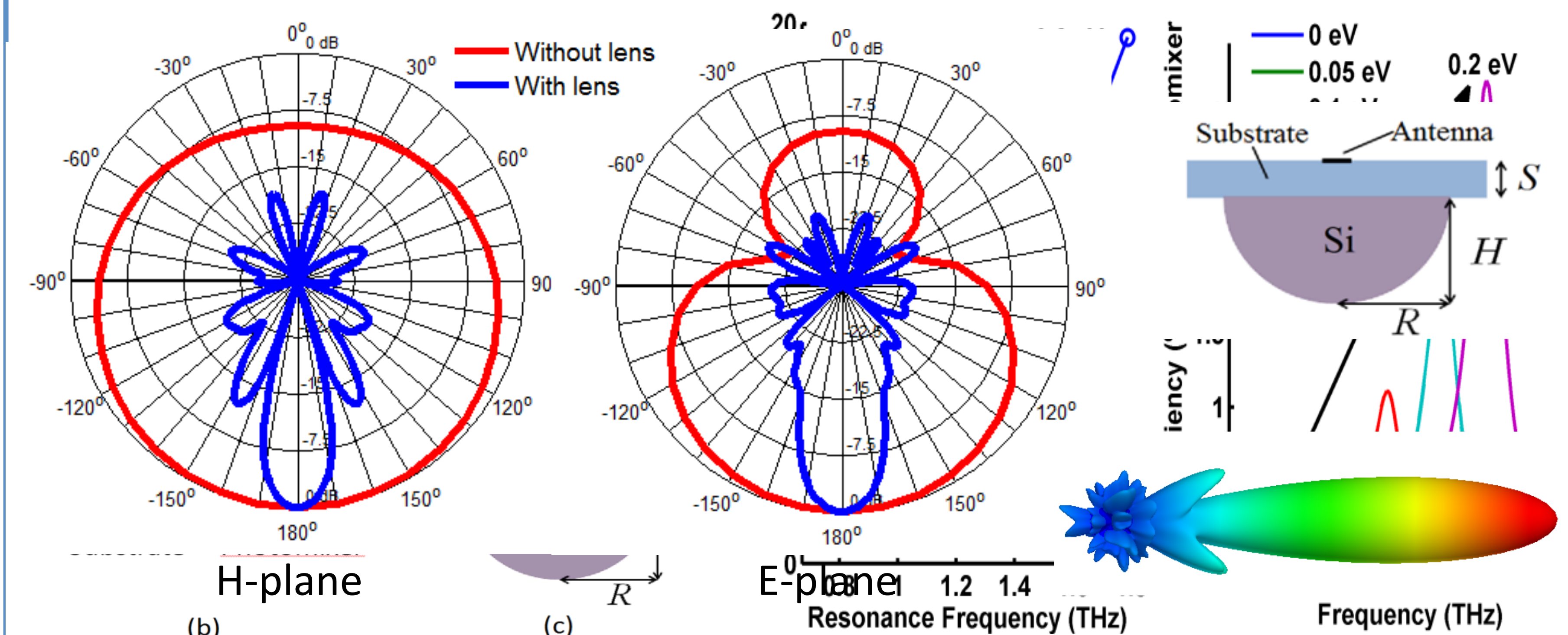
$\tau=0.15\ ps$

$T=300°\ K$

J.S. Gomez-Diaz and J. Perruisseau-Carrier "Graphene-based plasmonic switches at near infrared frequencies", **Optics Express**, vol. 32, pp. 15490-15504, 2013.

Graphene-based patch antennas at THz

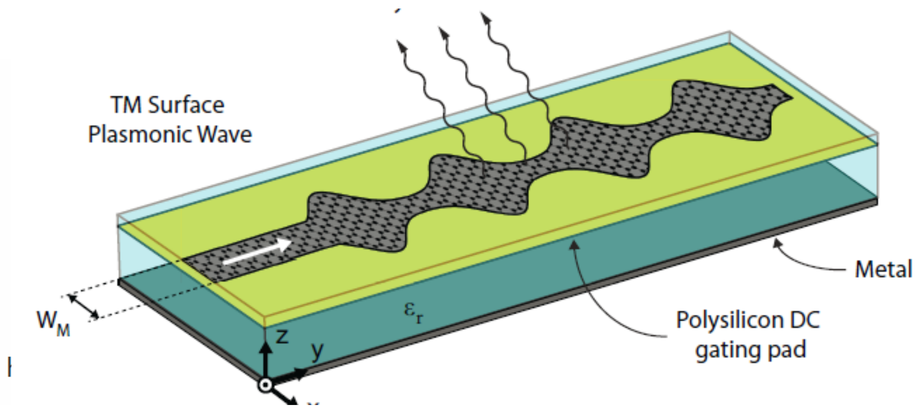
- Graphene frequency-reconfigurable THz plasmonic dipole
  - Exploit plasmonic resonances: miniaturized (≈λ_0/20)
  - Powerful and simple reconfiguration
  - Good radiation efficiency

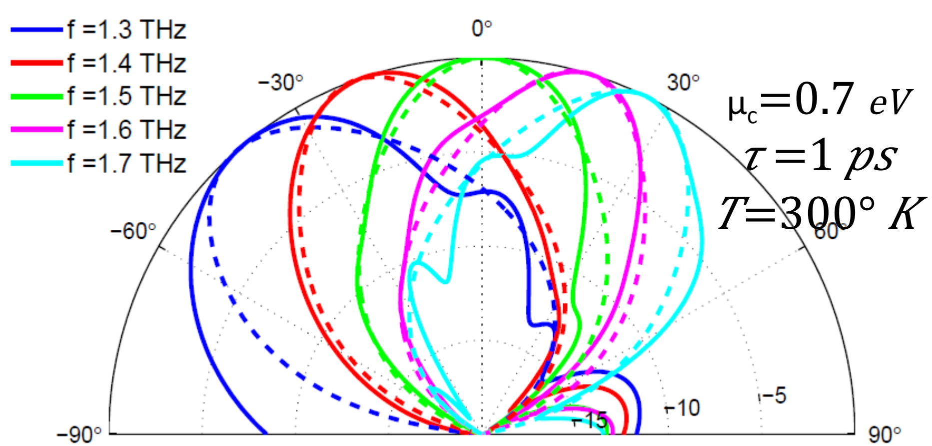


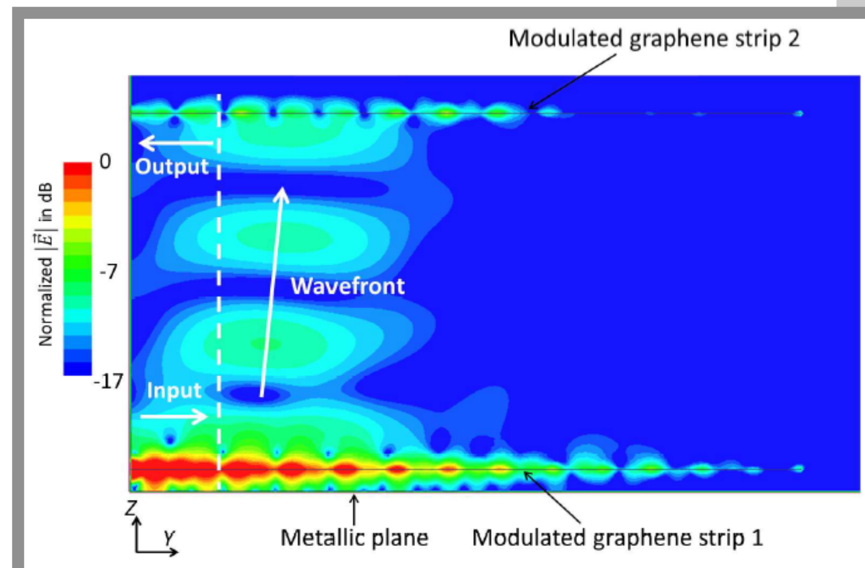
[1] M. Tamagnone, J. S. Gomez-Diaz, J. Mosig, and J. Perruisseau-Carrier, "Reconfigurable terahertz plasmonic antenna concept using a graphene stack," **Applied Physics Lett**., 101, 214102, 2012 [2] M. Tamagnone, J.S .Gomez-Diaz, J. R. Mosig, and J. Perruisseau-Carrier “Analysis and Design of Terahertz Antennas Based on Plasmonic Resonant Graphene Sheets.”, **Journal of Applied Physics**, 112, 114915, 2012.

Beamscanning THz leaky-wave antennas

- Based on sinusoidally-modulated surfaces:
  - Demonstration of the concept viability. Theoretical analysis.
  - Full-wave simulations confirm theoretical predictions







4.8μm and g = 0.2μm.

[1] M. Esquius-Morote, J.S. Gomez-Diaz, and J. Perruisseau-Carrier, "Periodically-Modulated Graphene Leaky-Wave Antenna for Electronic Beamscanning at THz", **IEEE Transactions on Terahertz Science and Technology**, 4, 116-122, January, 2014. [2] J. S. Gomez-Diaz, M. Esquius-Morote, and J. Perruisseau-Carrier, "Plane wave excitation-detection of non-resonant plasmons along finite-width graphene strips", **Optic Express**, 21, 24856-24872, 2013.

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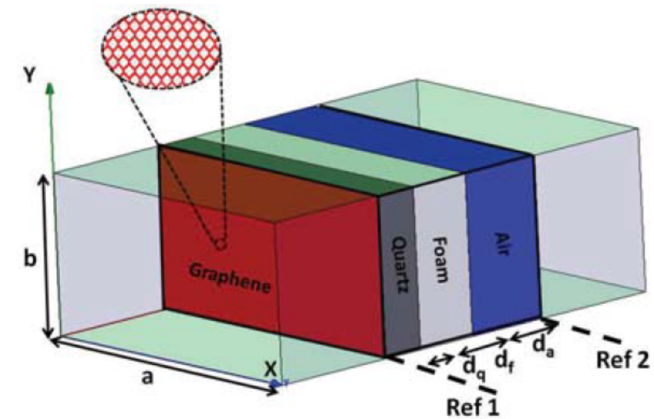
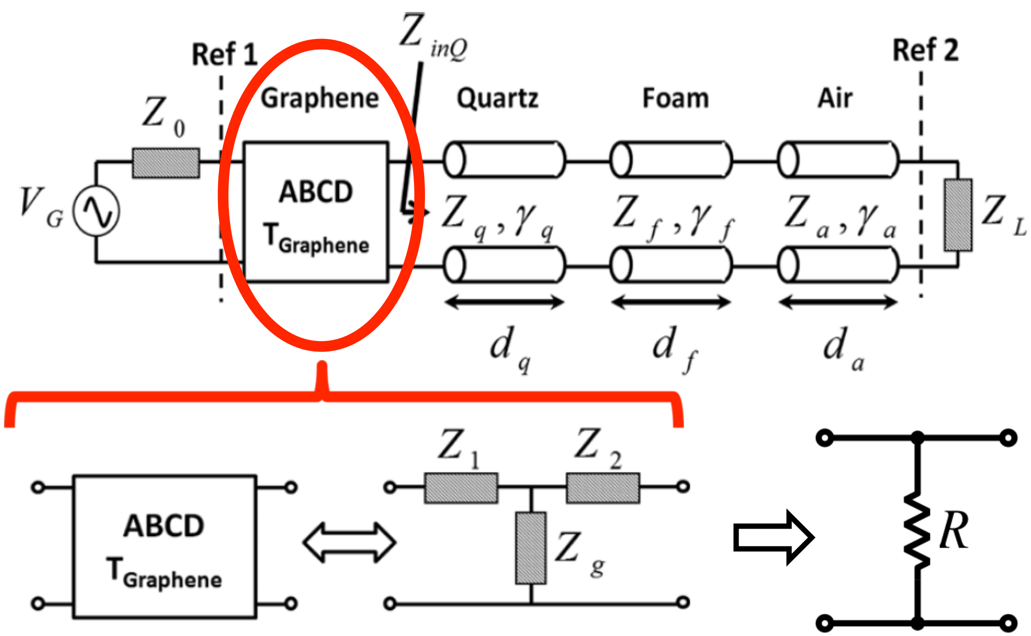
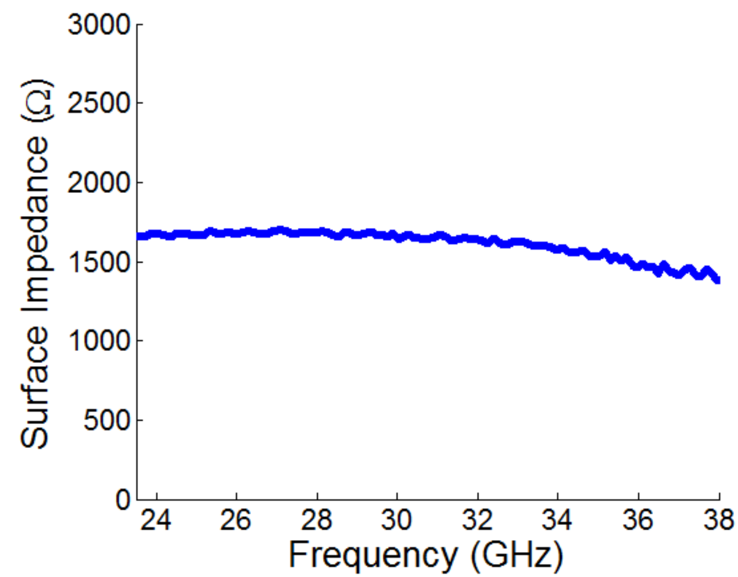
Measurements @ microwaves

- Micro-millimeter waves
  - Contactless RWG-based measurement.
  - Extraction with “self-calibration procedure”
  - Complex surface impedance obtained



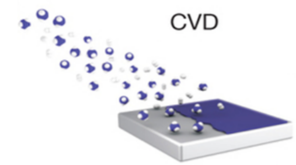


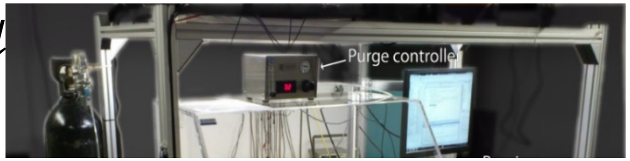


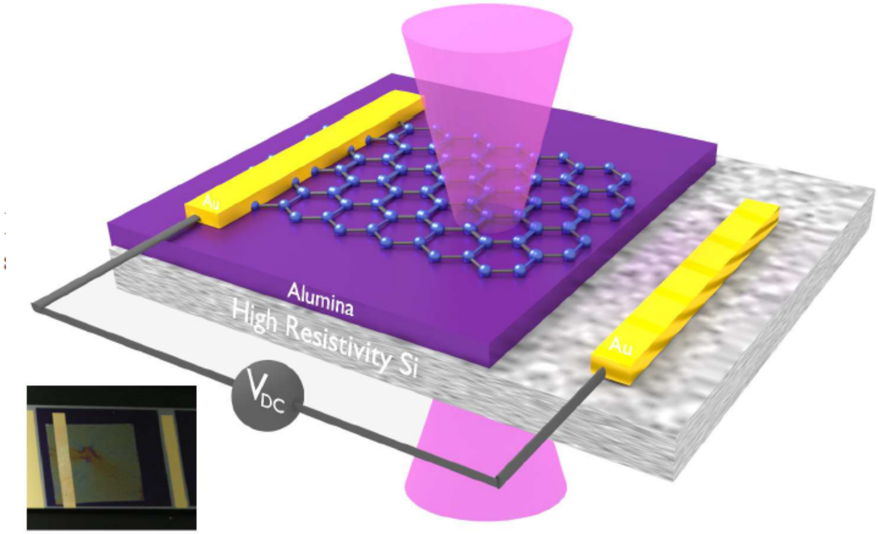
J.S. Gomez-Diaz, J. Perruisseau-Carrier, P. Sarma and A. Ionescu, “Non-Contact Characterization of Graphene Surface Impedance at Micro and Millimeter Waves”, **Journal of Applied Phys**ics, vol. 111, p. 114908, 2012.

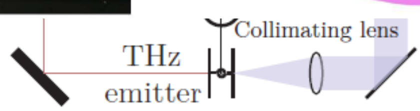
Measurements @ THz

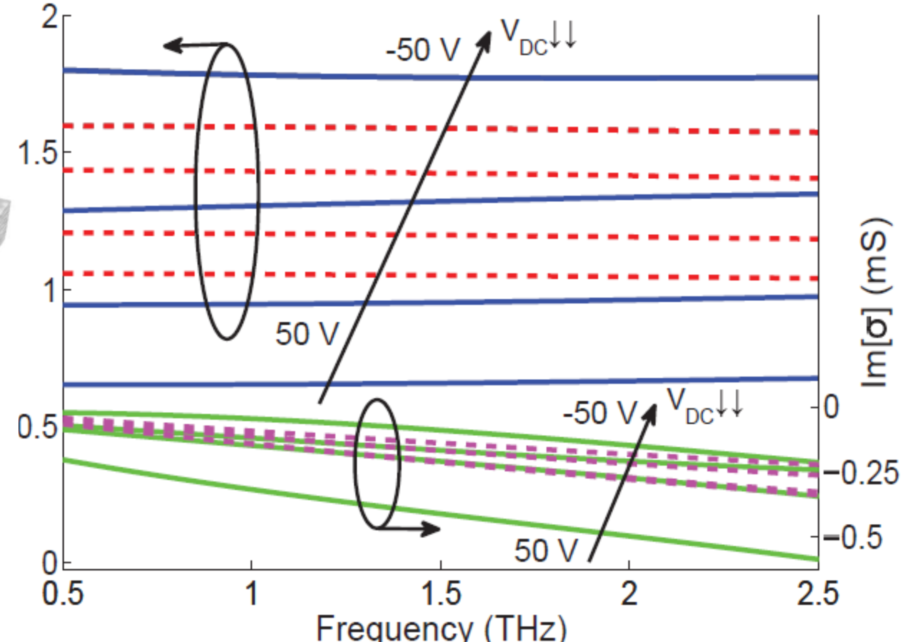
- Single-layer graphene structures: Measurements
  - CVD fabrication of graphene on several substrates
  - Measurements based on THz Time-domain Spectroscopy
  - Good agreement with theory
  - Unbiased graphene: $\tau=0.025$ ps and $\mu\downarrow$

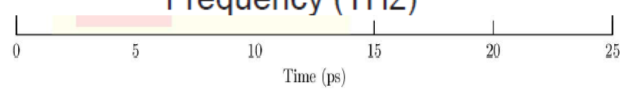






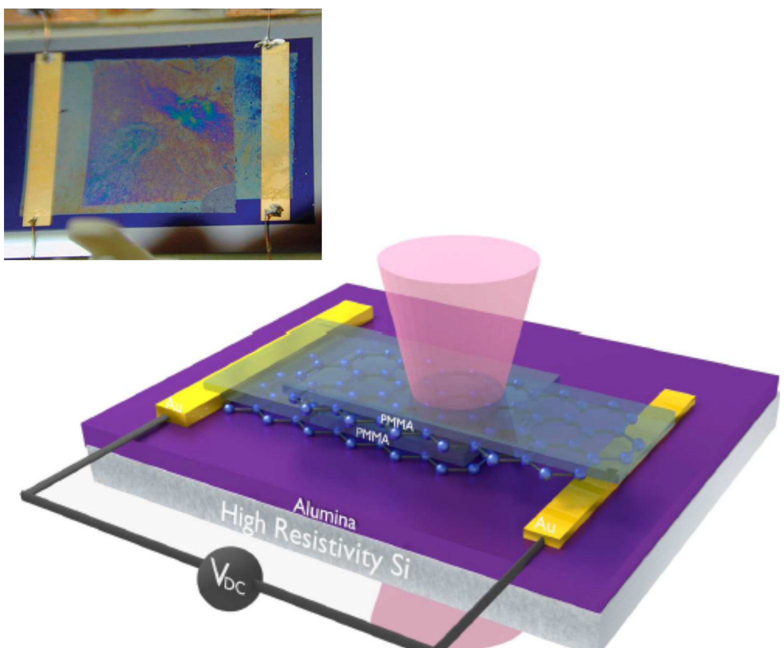


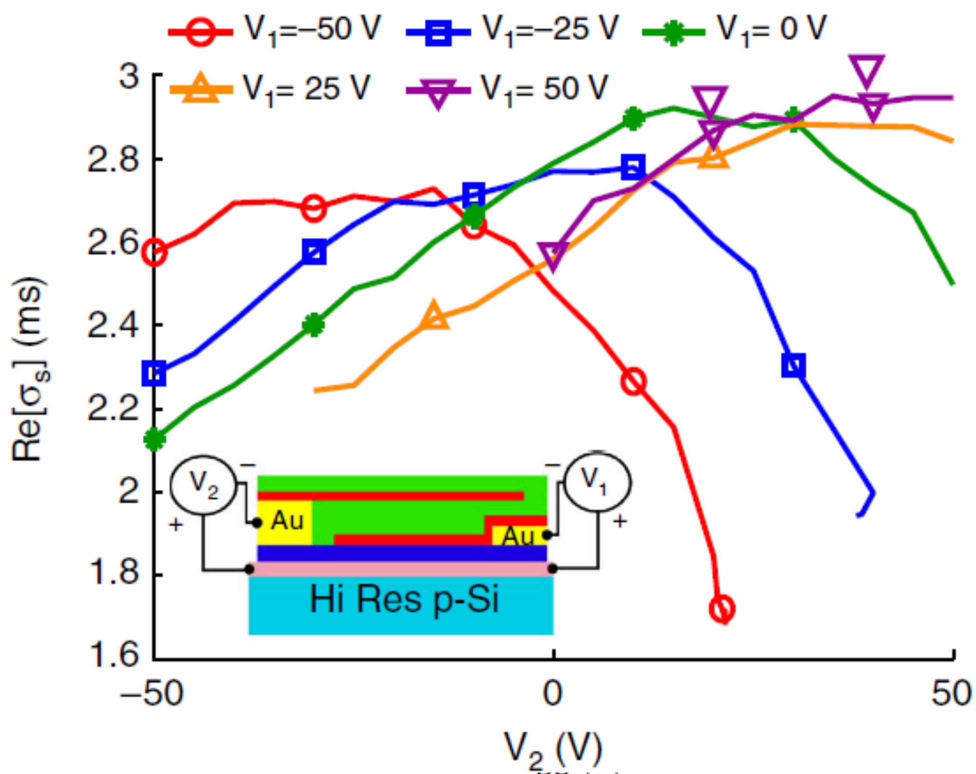




Graphene stacks

- Graphene stacks: Advanced reconfigurable capabilities
  - One graphene layer bias the other one and vice-versa
  - Boost reconfiguration range
  - Analysis, design, fabrication and measurement at THz





J.S. Gomez-Diaz, C. Moldovan, S. Capdevilla, L. S. Bernard, J. Romeu, A. M. Ionescu, A. Magrez, and J. Perruisseau-Carrier, "Self-biased Reconfigurable Graphene Stacks for Terahertz Plasmonics", **Nature Communications**, vol. 6, pp. 6334, 2015.

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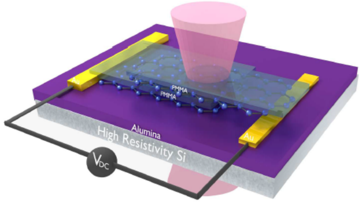
- Prof. Julien Perruisseau Carrier

1979-2014

  – *We have reviewed some of Julien's most significant contributions to Graphene plasmonics:*
    - Surface plasmons @ THz + reconfiguration
    - Novel devices: Waveguides, Antennas, etc.
    - Graphene stacks at THz: boosted reconfigurable capabilities



  – His research activities were even broader:
    - Reflectarrays, MIMO technology, signal processing, MEMS, etc.

Thanks a lot for your attention !

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