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Graphene Photonics, Plasmonics and Opto-electronics: An overview

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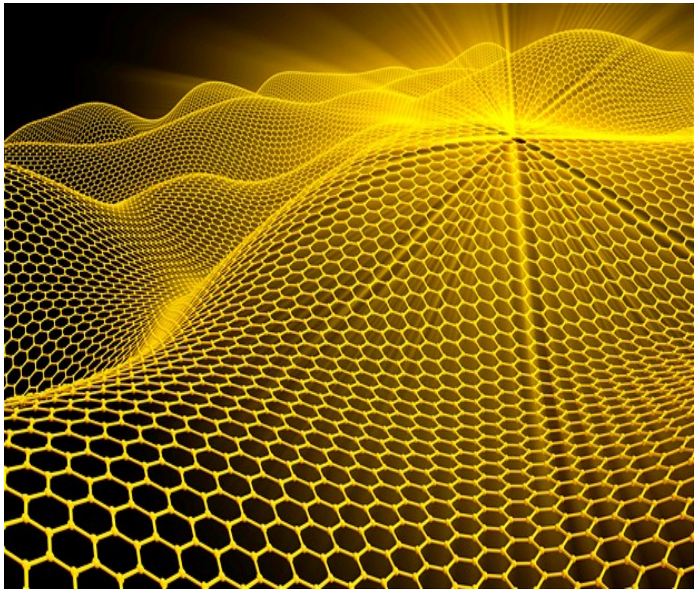
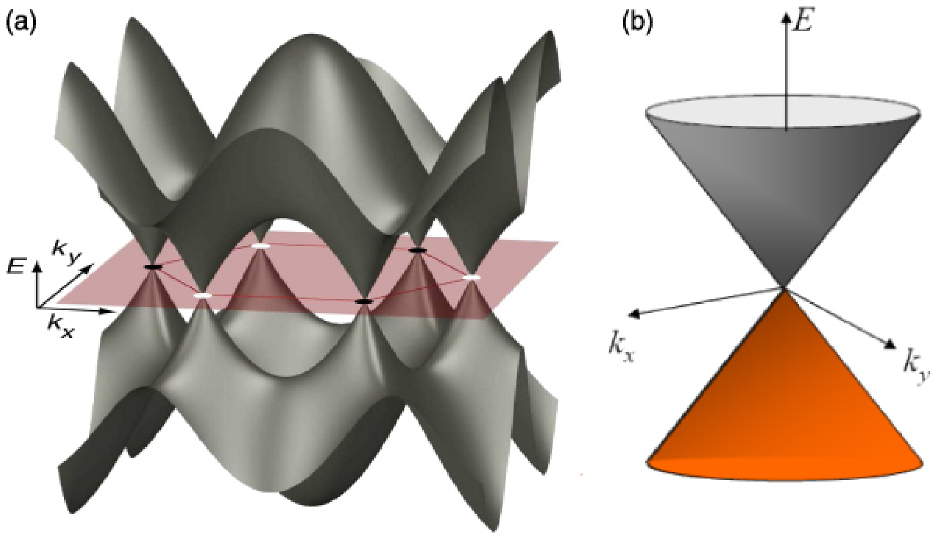
Graphene macroscopic properties

- Very high carrier mobility ($\mu \approx 2\times10^{4}\ \mathrm{cm^{2}V^{-1}s^{-1}}$)
- Very strong (>100 times the strength of steel of the same thickness)
- One atom thick ($a \approx 1.7$ A)
- Very high thermal conductivity ($k \approx 5\times10^{3}\ \mathrm{W\cdot m^{-1}\cdot K^{-1}}$)



Physical Properties

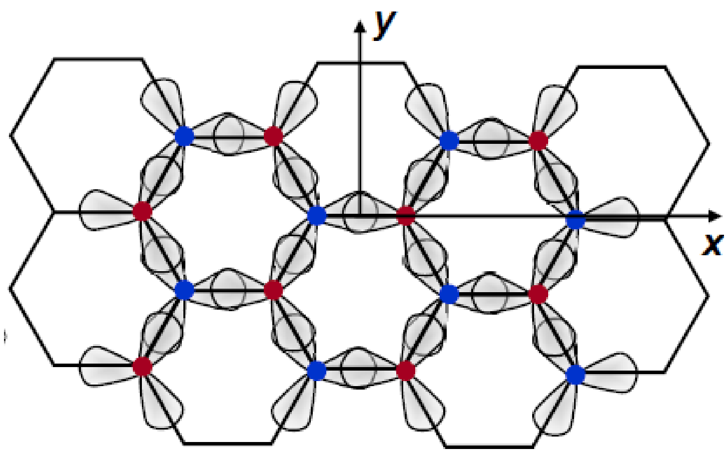


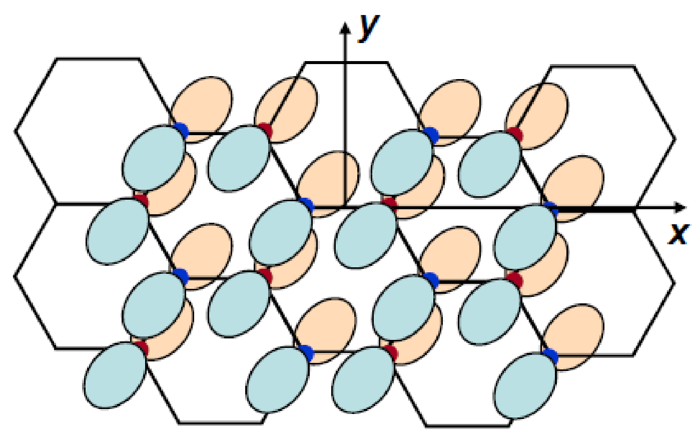
Eva Y Andrei *et al* 2012, *Rep. Prog. Phys.* **75** 056501

- Zero bandgap material
- Linear dispersion in the vicinity of the K points
- Filled valence band and empty conduction band
- Can be electrically or chemically doped

Graphene orbital interactions

- σ bonds via sp_2 orbitals– provide strong binding
- π bonds via p_z orbitals determine electrical and optical properties
- No interaction between sp_2 and p_z by symmetry





Graphene bandstructure

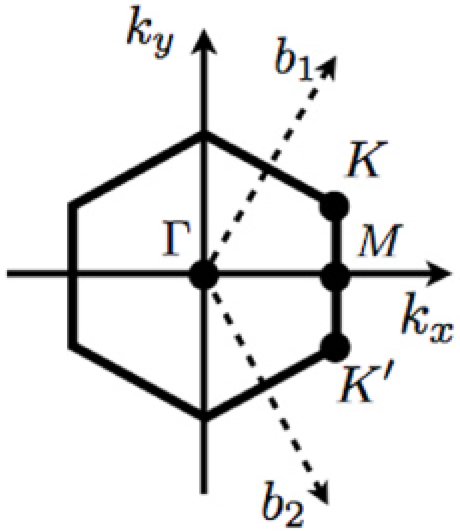
- Utilizing tight-binding approximation to the nearest neighbor

$$E(k) = \pm\gamma\sqrt{1 + 4\cos^2 k_y a\frac{\sqrt{3}}{2} + 4\cos k_y a\frac{\sqrt{3}}{2}\cos k_x a\frac{3}{2}}$$

- When expanded around K point $\mathrm{K} = \frac{2\pi}{3a}\left(1, \frac{1}{\sqrt{3}}\right)$

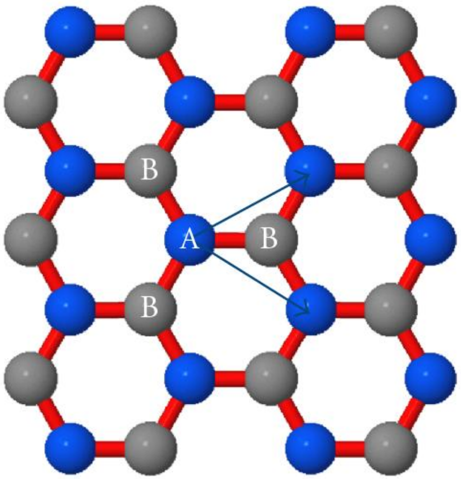
$$E(K) = 0$$

$E(k) = \pm\hbar v_F \left|k\right|$, where $v_F \approx 10^6$



Dirac Fermions

- Graphene lattice can be viewed as sum of two sublattices A and B whose wavefunctions enter solution of tight-binding Hamiltonian as bases.



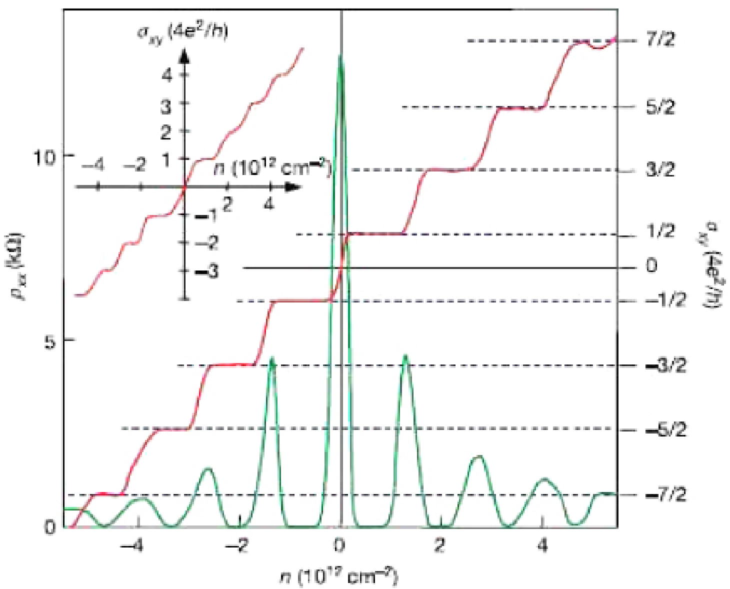
$$\psi = \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix} \rightarrow \begin{pmatrix} \uparrow \\ \downarrow \end{pmatrix}$$

- Hamiltonian can be viewed as

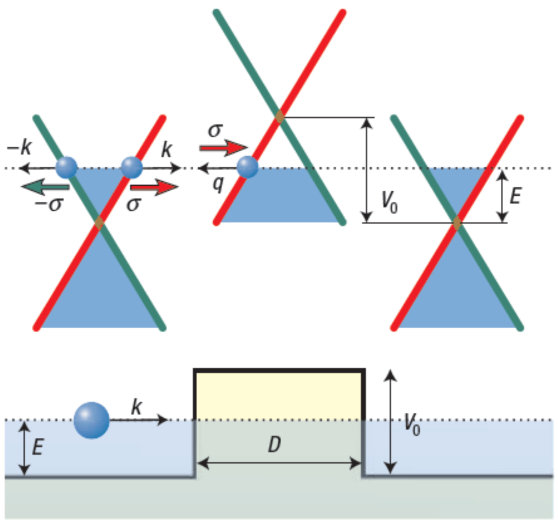
$$v_F \boldsymbol{\sigma} \cdot \mathbf{p}\, \psi = E\psi$$ (Dirac equation for massless particles)

- Existence of solutions with negative energy

Graphene phenomena



Novoselov, K.S.*et al* , *Nature*, v 438, n 7065 (2005)



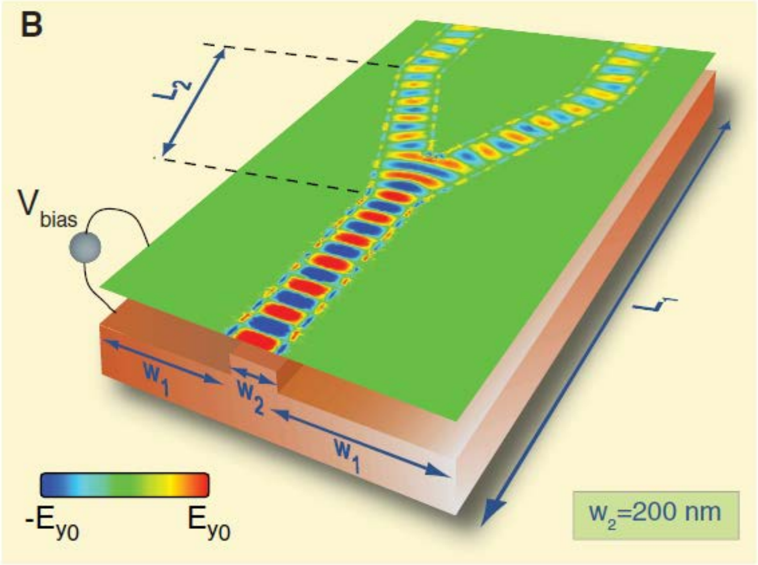
Katsnelson M.I. *et al*, *Nature Physics*, v 2, n 9 (2006)

- Anomalous quantum Hall effect
  - Ground level effect
  - only one allowed pseudospin type

- Klein tunneling
  - Interband transition at the boundary
  - Veselago lens for electron waves

Optical applications of graphene. Transmitter

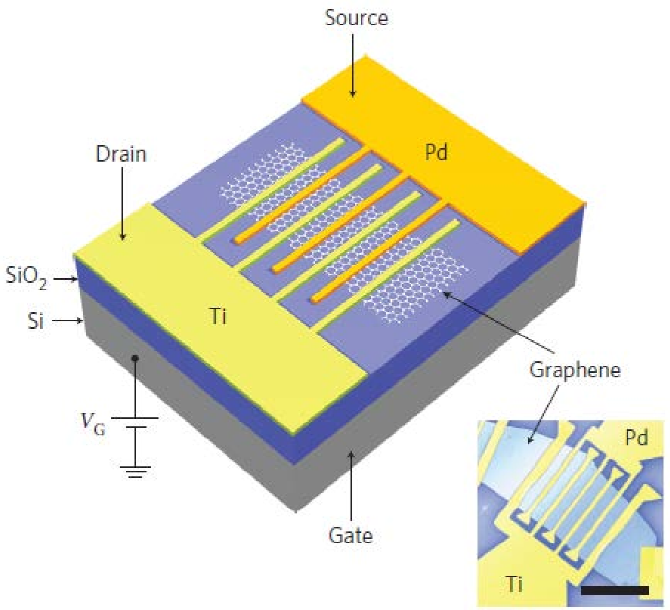
- Waveguiding using SPPs with long lifetime
- Spatially varying Fermi energy creates regions with varying conductivity
- SPPs are reflected in the Fresnel like fashion from the boundaries



Ashkan Vakil and Nader Engheta *Science* 332, 1291 (2011)

Optical applications of graphene. Photodetector

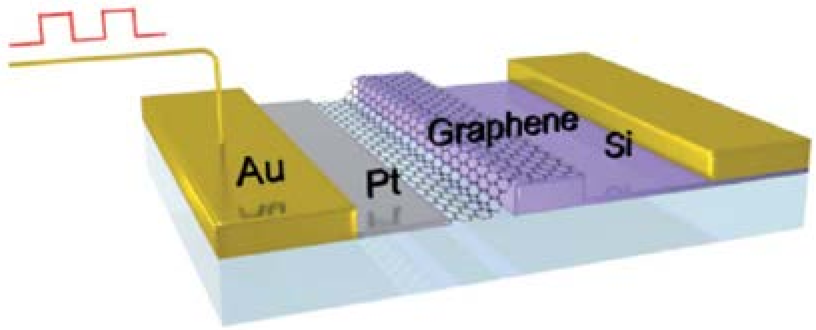
- Broadband operation (514-2400nm)
- Need for metallic fingers due to limited current generation
- Error free detection in the optical carrier frequencies have been demonstrated (10Gbit/s link at the telecom wavelength)



Mueller *et al*, T., *Nature Photonics*, v 4, n 5 (2010)

Optical applications of graphene. Modulator

- Modulation is achieved by tuning Fermi level.
- Takes advantage of interband transition threshold as a switching mechanism
- Optical switch



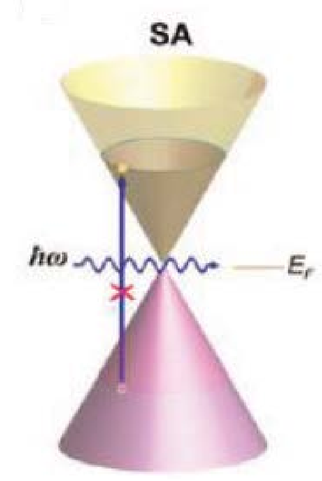
Ming Liu *et al*, *Nature*, v 474, n 7349 (2011)

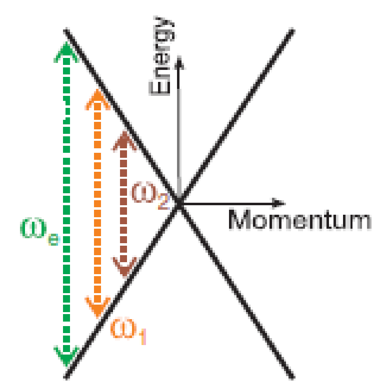
Optical applications of graphene Nonlinear Optics.

- Broadband saturable absorber
  (based on Pauli blocking of
  interband transitions)

- Large third order susceptibility due to resonant transitions leads to efficient harmonic generation, four- wave mixing, etc.

- Optical limiting in graphene flakes





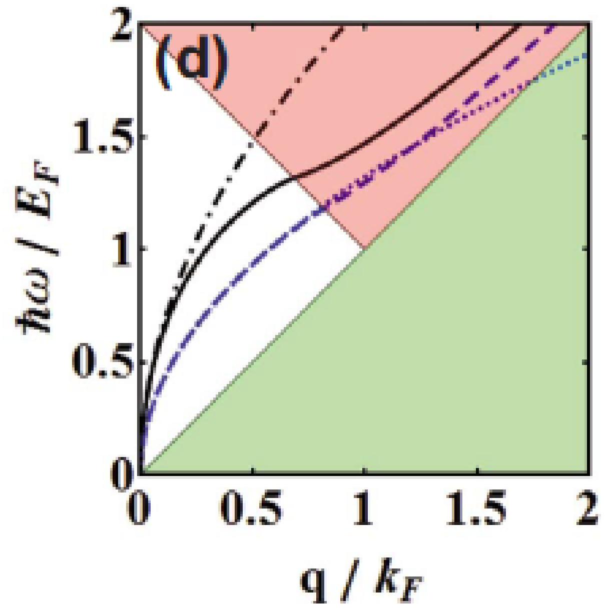
Optical conductivity

- Graphene conductivity determines to a large extent SPP dispersion properties and losses in graphene.

$$\sigma = \sigma_{\text{intra}} + \sigma_{\text{inter}}' + i\sigma_{\text{inter}}''$$

$$\sigma_{intra} = \sigma_0 \frac{4\mu}{\pi} \frac{1}{\hbar\tau_1 - i\hbar\omega}$$

- Nearly constant conductivity for intrinsic graphene
- Sharp cut-off for the interband absorption below the Fermi energy
- Phonon energy threshold at 0.2eV



Surface Plasmon polaritons in graphene

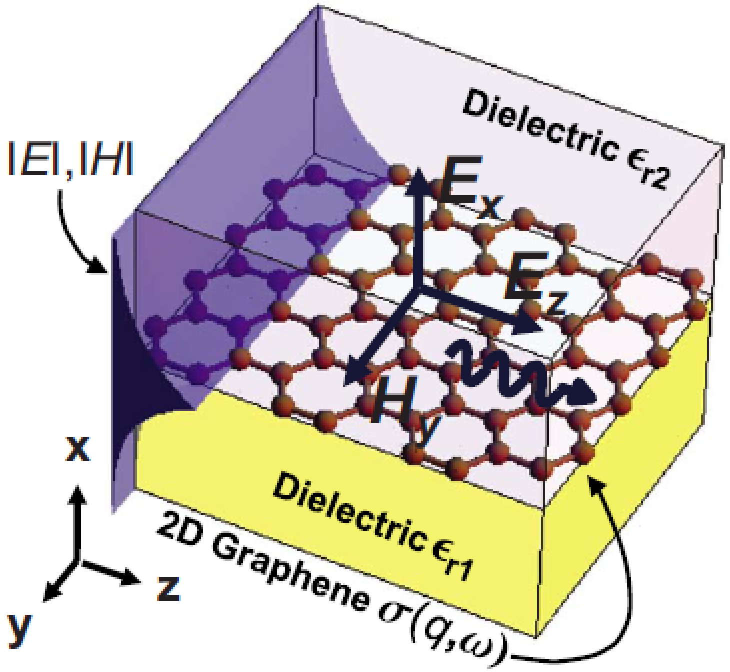
- Solutions are similar to metal/dielectric boundary

- The difference enters in specifying the boundary conditions

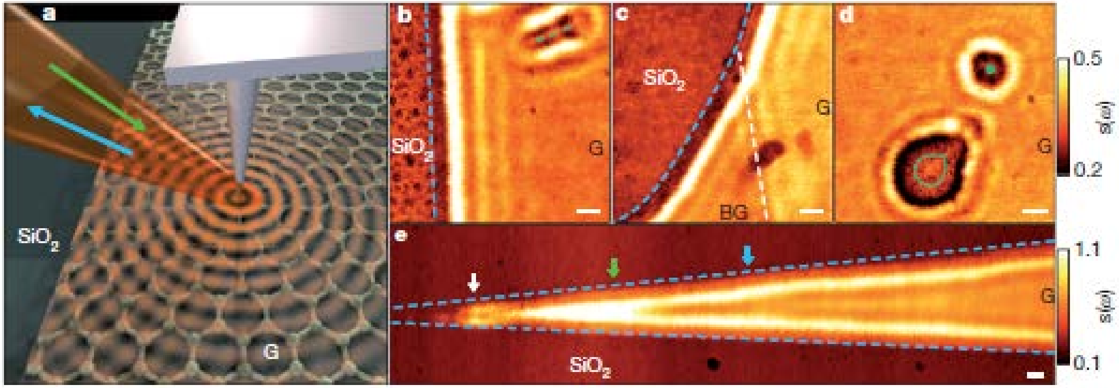
$$\frac{\varepsilon_{r1}}{k_{r1}}+\frac{\varepsilon_{r2}}{k_{r2}}=-\frac{i\sigma}{\omega\varepsilon_0}$$

- Derived classically dispersion has a form of

$$k_{sp}=\frac{\pi\hbar^2\varepsilon_0(\varepsilon_{r1}+\varepsilon_{r2})}{e^2E_F}\omega\left(\omega+\frac{i}{\tau_1}\right)$$



Excitation of SPP in graphene



Fei, Z. *et al*, *Nature*, v 487, n 7405 (2012)

- K vector mismatch impedes direct excitation of SPPs
- Scattering from SNOM metallic tip provides needed in-plane momentum
- Efficient resonant coupling

Excitation of SPP in graphene. Continued.

- SPP wavelength is changing depending on applied bias voltage (Fermi energy)

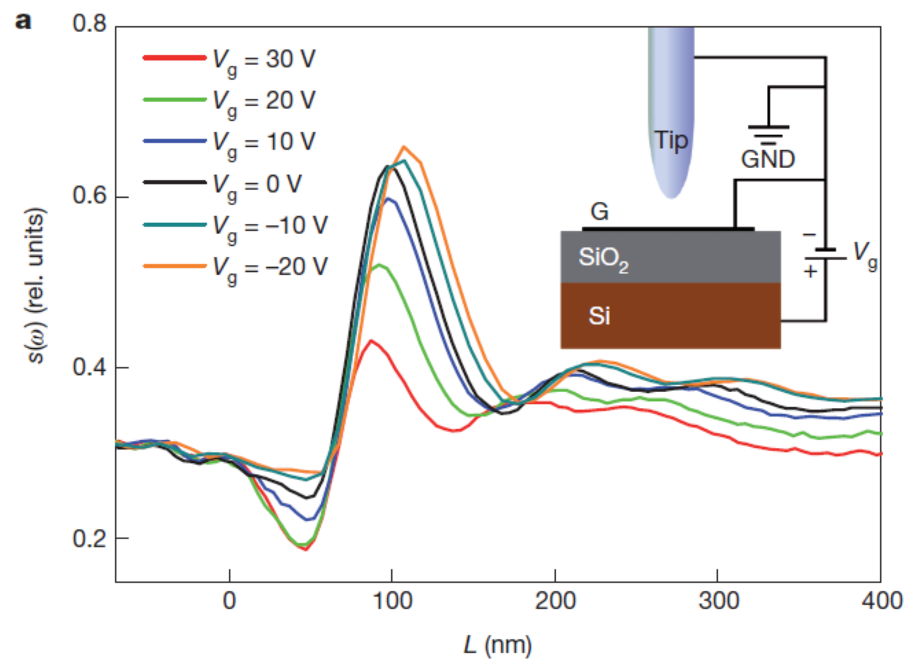
- In the regime of small losses

$$\lambda_P \propto E_F$$

- High degree of confinement

$$\lambda_{IR} / \lambda_p = 50 - 60$$

- Propagation can reach $100\lambda_p$



Fei, Z. *et al*, *Nature*, v 487, n 7405 (2012)

Plasmon vacuum Rabi splitting

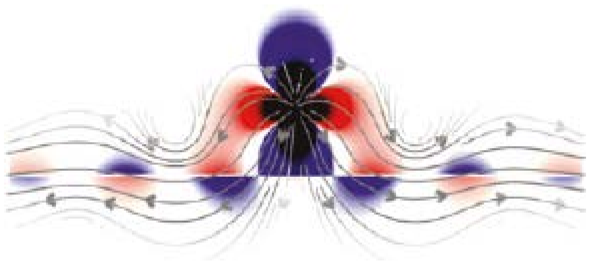
- Emission rate in the vicinity of graphene plane is increased by 1-5 orders of magnitude
- Hamiltonian has a form:

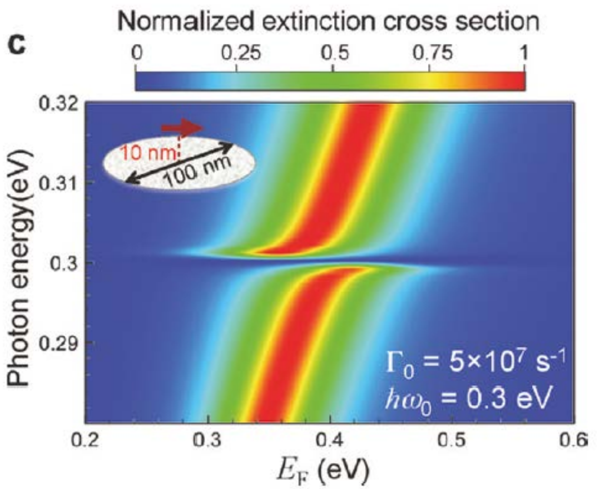
$$H = H_0 + H_{int} + H_{ext}$$

$$H_0 = \hbar\omega_p\left(a^+a + \frac{1}{2}\right) + \hbar\omega_0\sigma^+\sigma - i\hbar\frac{k}{2}a^+a - i\hbar\frac{\Gamma_0}{2}\sigma^+\sigma$$

$$H_{int} = i\hbar g\left(a^+\sigma - a\sigma^+\right)$$

- Strong coupling regime ($g > k, \Gamma_0$) results in Rabi oscillations.



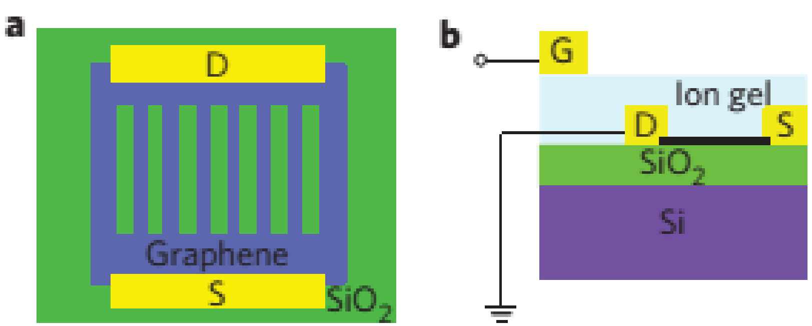


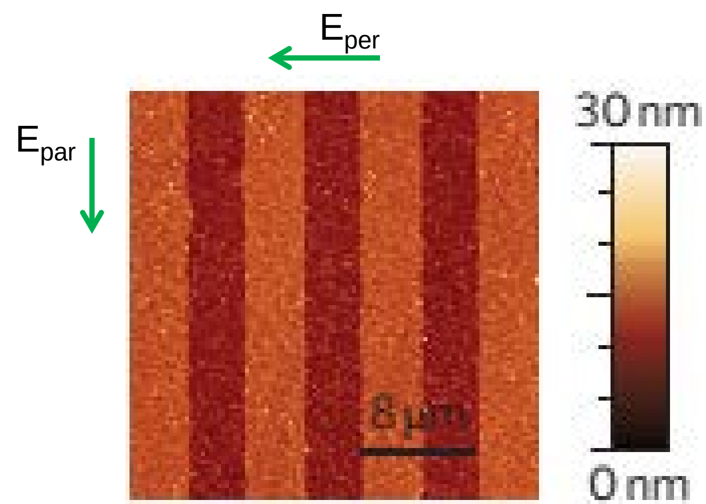
Koppens *et al*, *Nano Letters*, v 11, n 8 (2011)

Plasmonics with Graphene

- Graphene ribbons as tunable metamaterials
- Graphene plasmonic nanostructures and plasmon hybridization
- Monolayer atomic cloak
- Plasmon damping in graphene at mid-infrared.

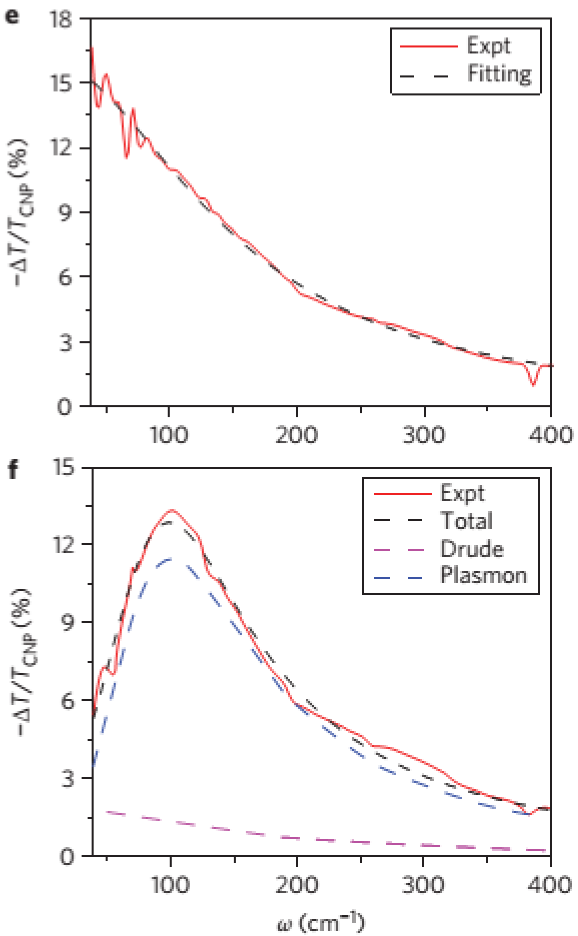
"Tunable Terahertz Metamaterials"





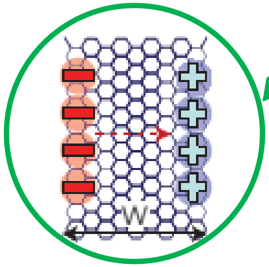
AFM image of a micro-ribbon arrays made on transferred large-area CVD graphene using optical lithography and plasma etching.

Feng Wang's group, UCB, *Nature Nanotechnology*, Oct. 2011



Parallel polarization

Perpendicular polarization



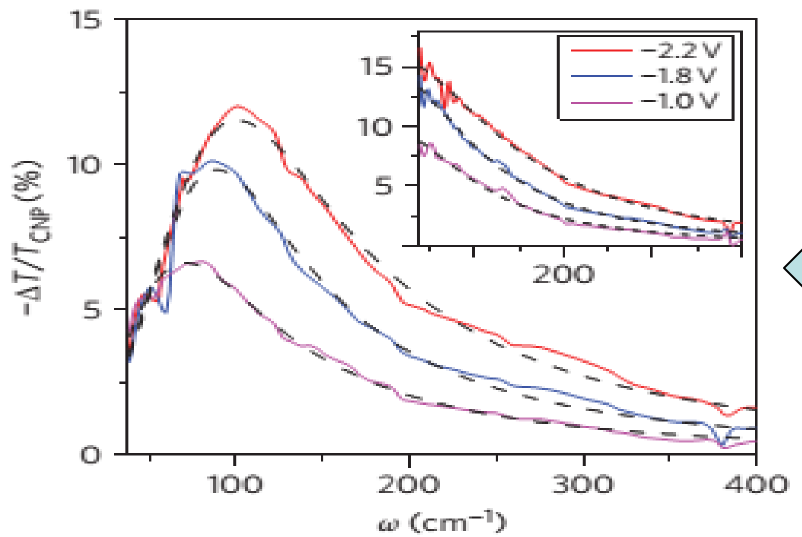
- Along the ribbon the electrical response of charge carriers is similar to that of free carriers.

$$Im\left(\frac{-1}{\omega^2 + i\tau_p^{-1}}\right)$$

- Perpendicular to the ribbon the response is dominated by plasmon oscillations.

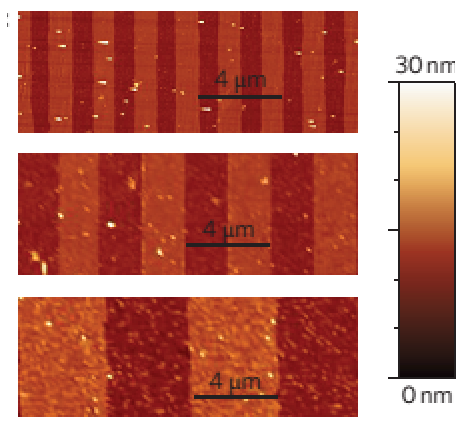
$$Im\left(\frac{-\omega}{\omega^2 - \omega_p^2 + i\omega\tau_p^{-1}}\right)$$

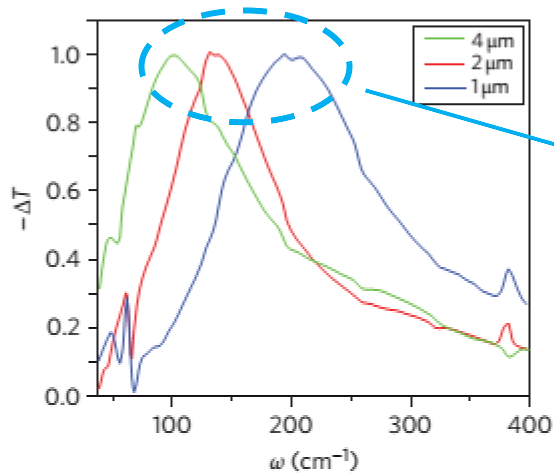
Tuning plasmon resonance through carrier density change



$$|E_f| \propto n^{1/2}$$

$$\omega_p \propto |E_f|^{1/2}$$

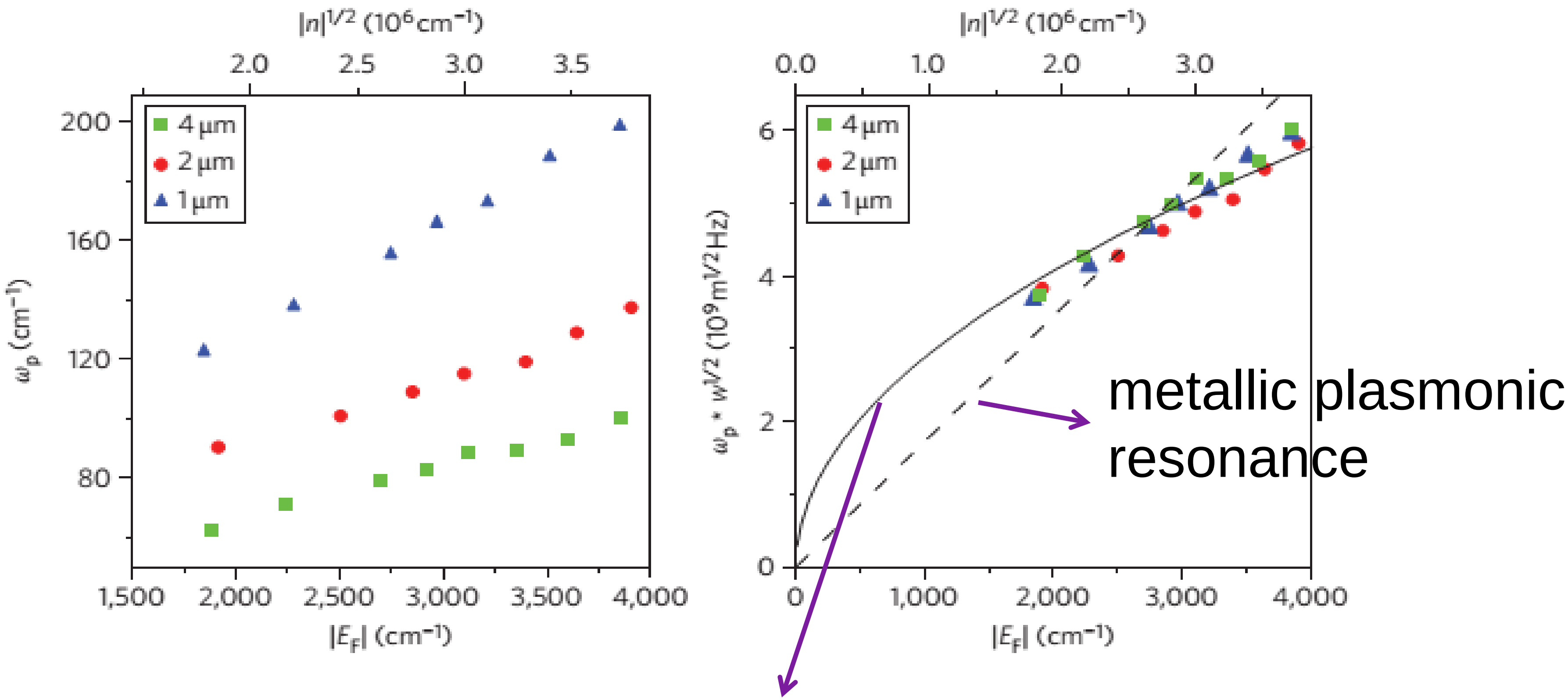




Resonance shifts with changing ribbon width

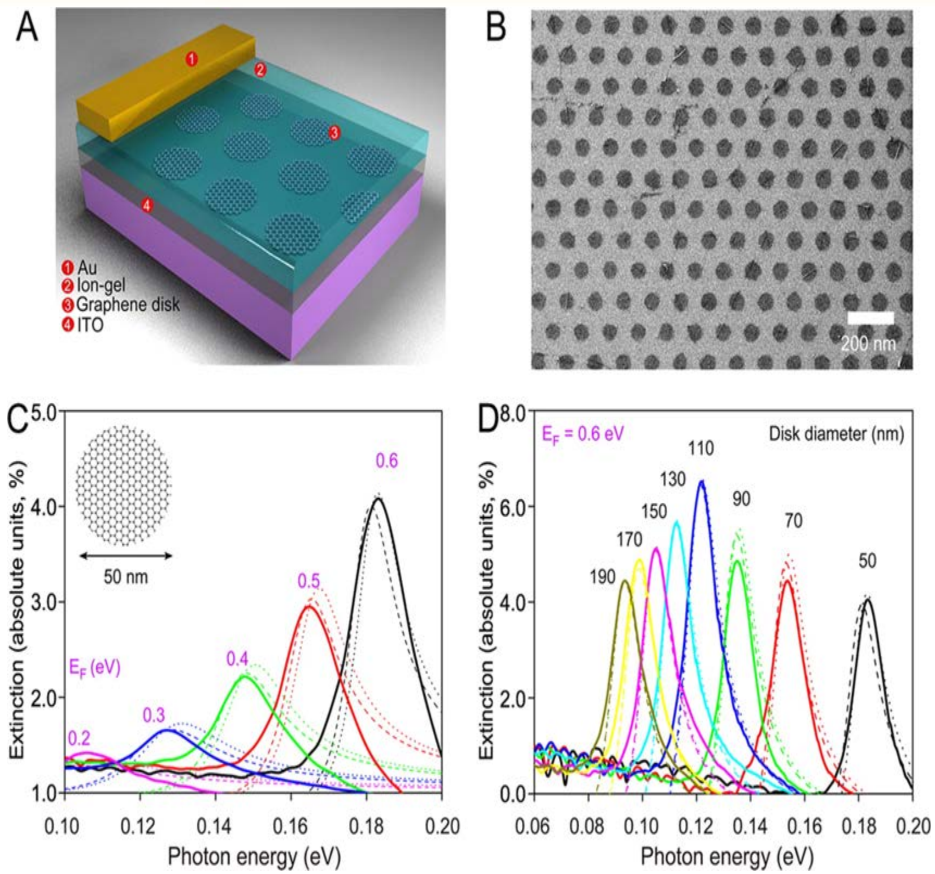
Another tuning parameter !!!

$$\omega_p \propto W^{-1/2}$$



Graphene plasmonic resonance

"Hybridization of localized plasmons in nanostructured graphene"



A. Schematic of the device
B. SEM image
C. Extinction spectra of 50 nm disk with lattice spacing 120nm. Dotted and dashed curves are simulations whereas the solid curves are experimental
D. Extinction spectra for various disk diameter and lattice spacing.

Disk geometry is another way for tuning resonances !!!

Naomi Halas and F. Xavier Garcia de Abajo, *ACS Nano*, 2013

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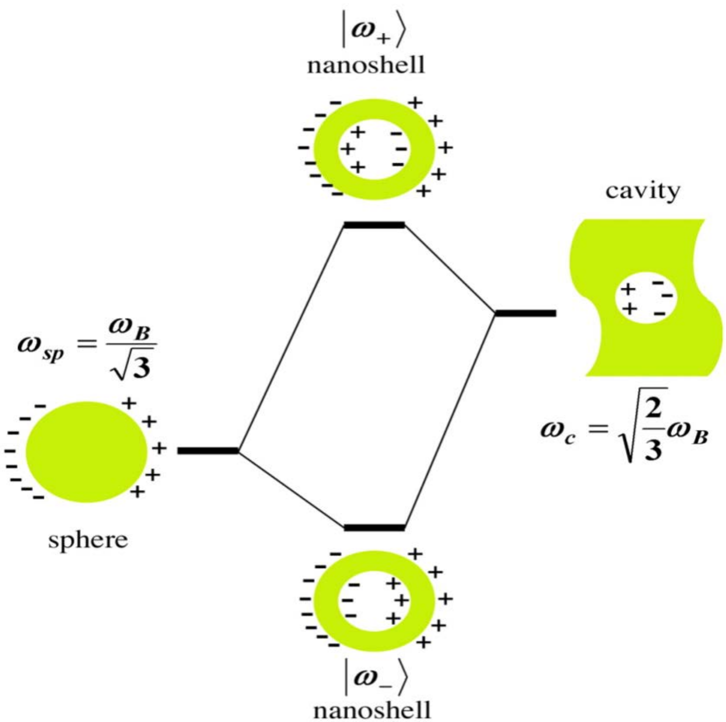
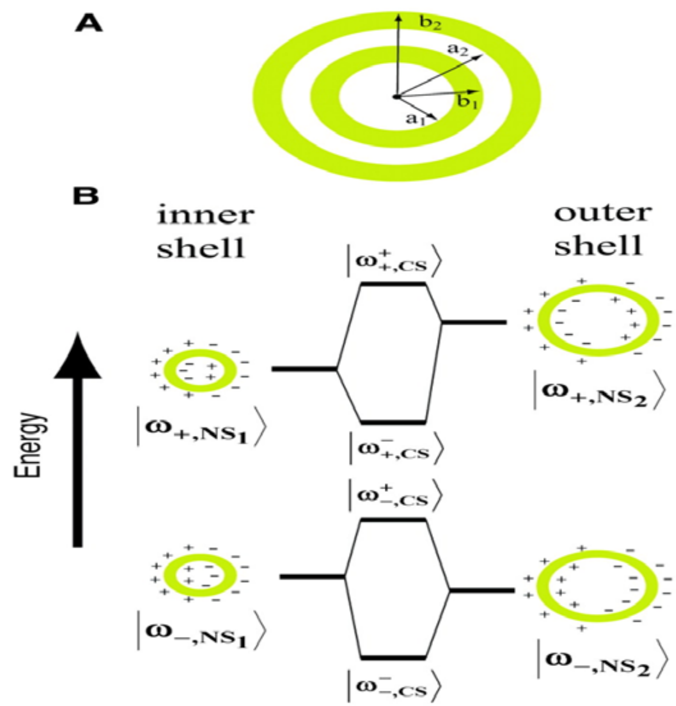
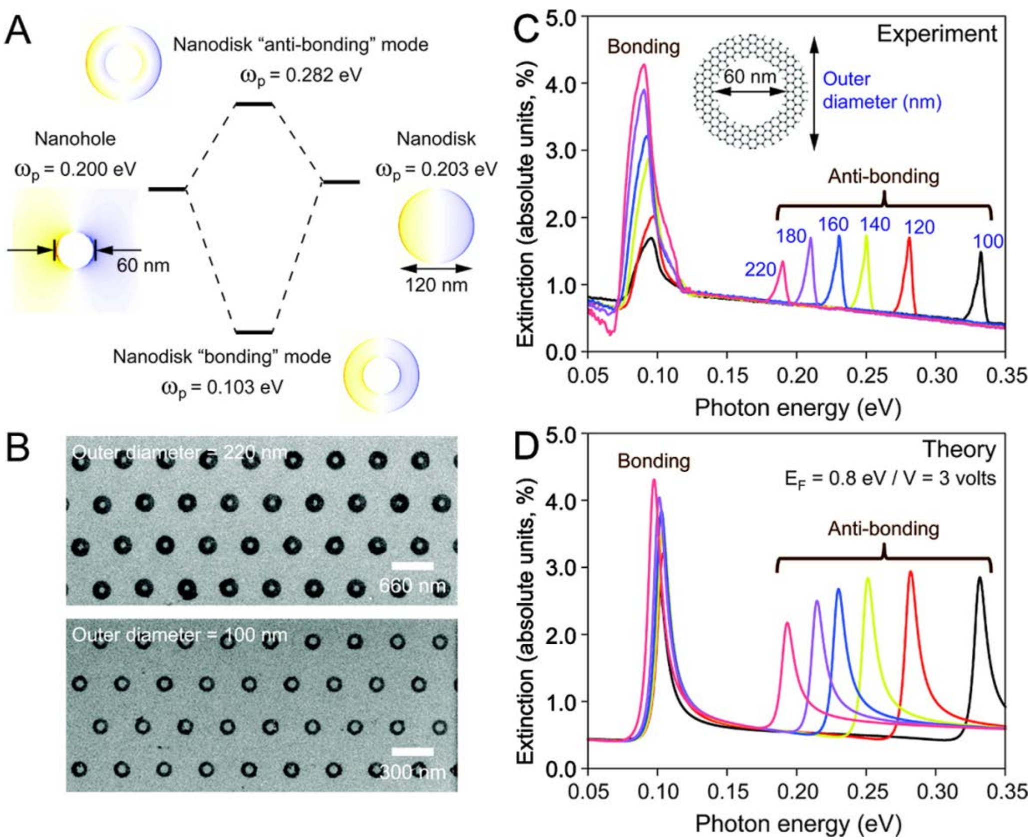
One can use the same concept of hybridization in molecular orbital theory to look at hybridized plasmon resonances





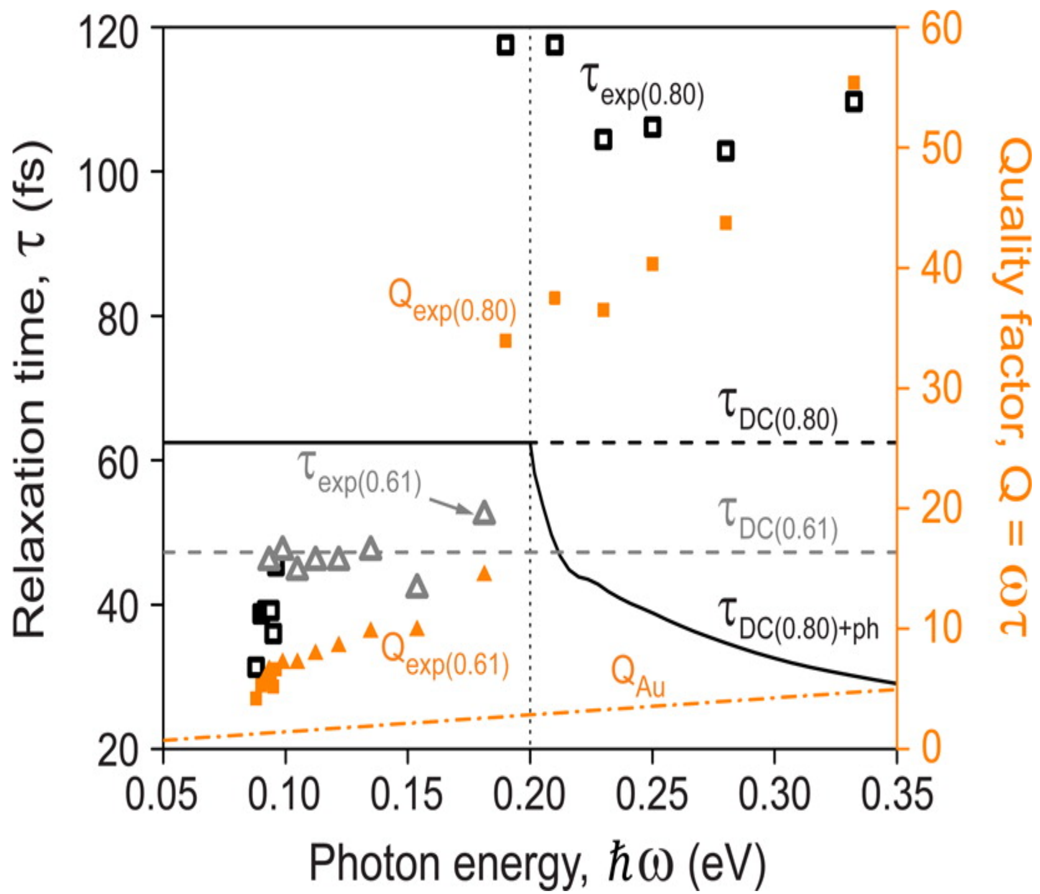
N.J.Halas, P. Nordlander, Science, 2003



A. Concept of plasmon hybridization

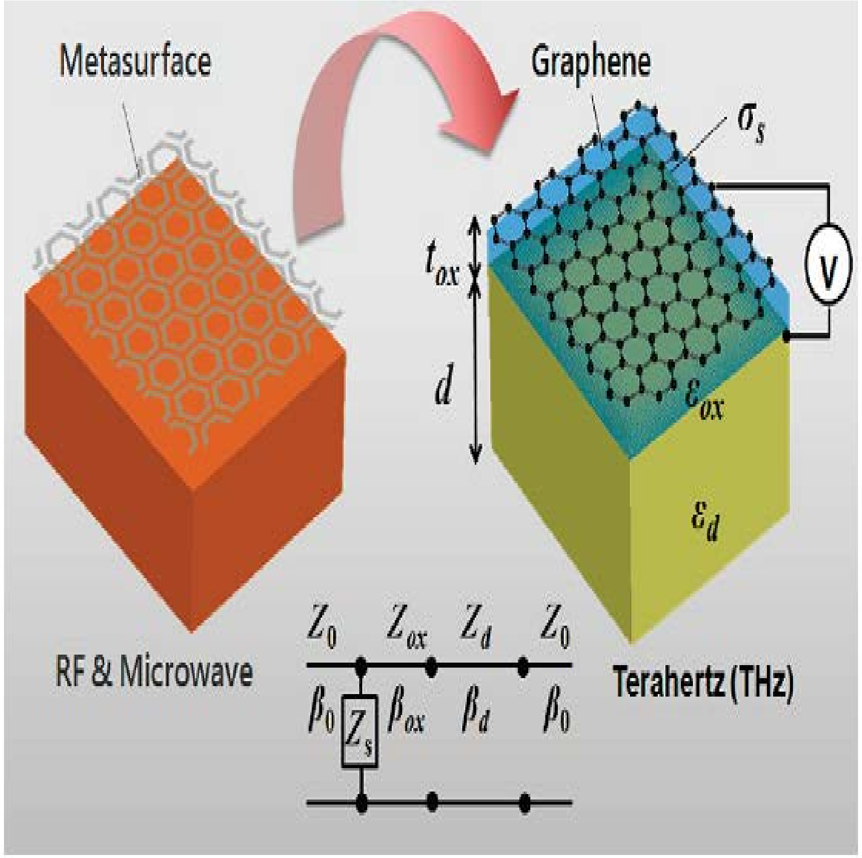
B. SEM image. edge-to-edge separation is twice the outer diameter.

C and D show experimental and simulation results. The authors attribute the observed decrease in strength (expt. case) to poor quality of rings for small dimensions. They also state a resonance at 2.8 µm for 80 nm outer dia.



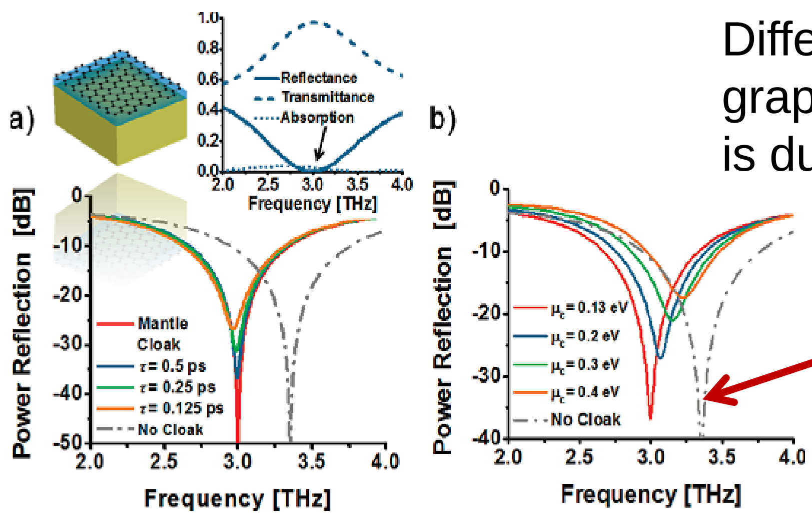
- Lifetimes are longer for the anti-bonding mode than for the bonding mode.
- The lifetime increases from energies at 0.1eV up to energies at 0.2eV. After this decay through phonons keeps the lifetimes almost constant.
- The solid black curve is lifetime calculated from the DC mobility with an added component due to decay through phonons.
- The quality factor supersedes that of gold in small particles.

"Monolayer Surface Cloak"



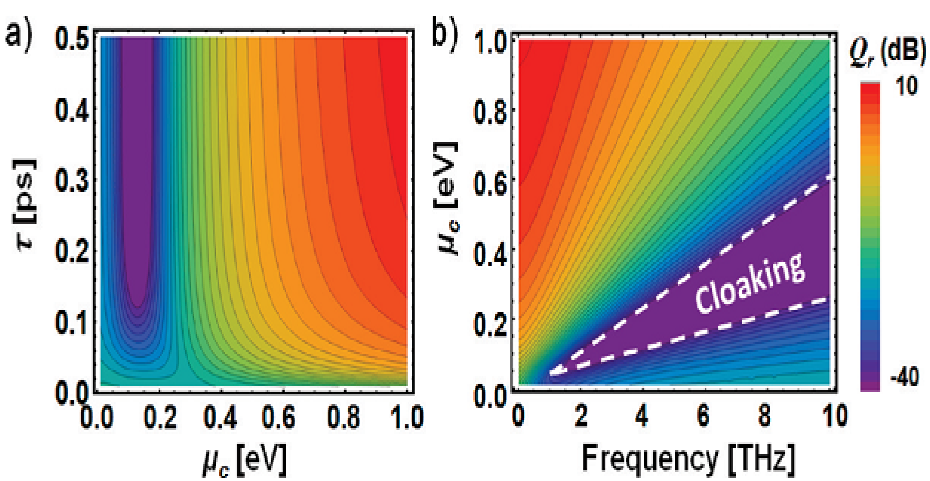
- The problem is modeled as a transmission line impedance matching to minimize reflections.
- Graphene monolayer has a Fermi level of 0.13eV. The SiO_2 layer has a thickness of 1.56μm and a relative permittivity of 3.9. The dielectric slab has a permittivity of 5.
- Graphene sheet is modeled as a dispersive shunt with an impedance given by $Z_s = R_s - iX_s$.
- Now the problem reduces to adjusting X_s so that there is a perfect match between the input and the line impedance.

Pai-Yen Chen and Andrea Alu, *ACS Nano*, 2011



Difference in reflected power for the graphene layer and ideal mantle cloak is due mainly due to absorption.

Fabry-Perot resonances

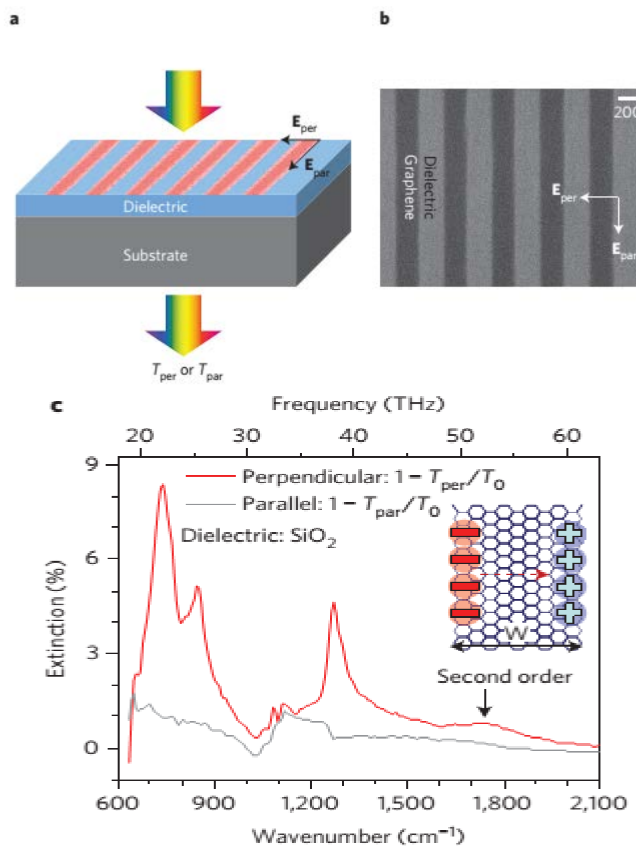


The cloaking function is deteriorated for small relaxation times

$$C_{ox}V_g = en$$

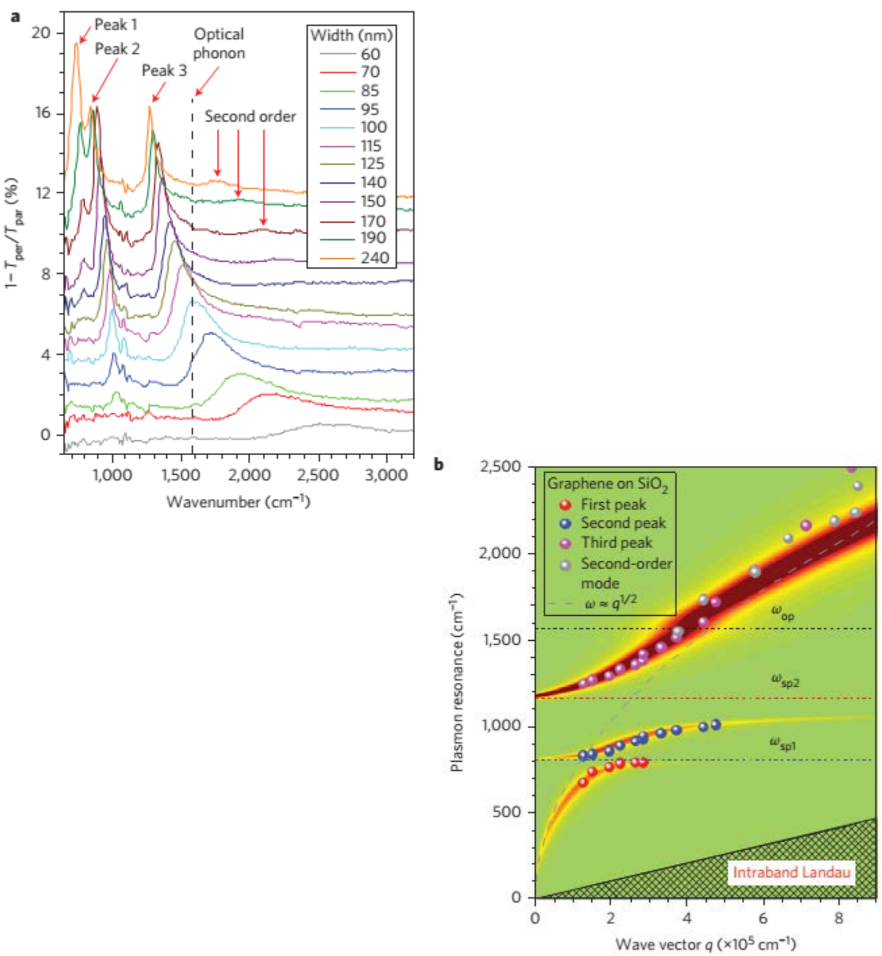
Tuning the Fermi level allows us to adjust the frequency. !!!

"Damping Pathways"



- Mid-infrared regime.
- Plasmon damping through optical phonons as well as surface polar phonons are considered.
- Two types of substrates are used: (a) polar SiO_2 and non-polar diamond-like-carbon(DLC).
- Fig. A and B show the schematic and the SEM image of nano-ribbon array.
- Fig. C shows extinction spectra on SiO_2 layer with a ribbon width of 240nm.
- Multiple resonance peaks corresponding to only single one in micro-ribbon.

Phaedon Avouris and Fengian Xia, Nature Photonics, May 2013

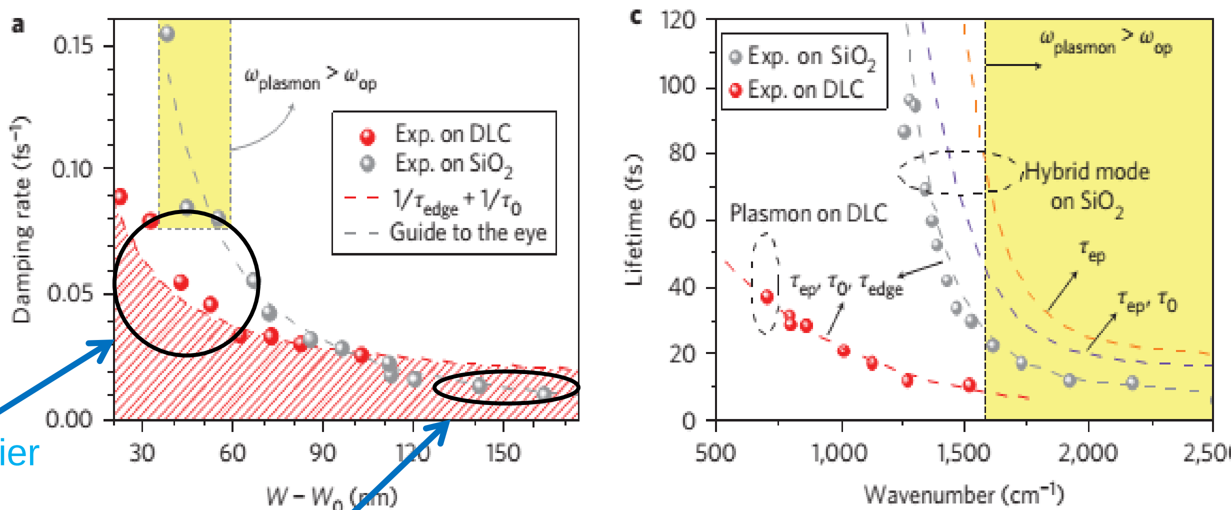


a. Peaks blue-shift with decreasing W. The spectral weight is gradually transferred from peak 1 to peak 3 through peak 2 with decreasing W. Line width of the third peak increases as W decreases.

b. Intensity plot of the loss function overlaid on the resonant peaks.

Decay paths:

- Radiative processes
- e-h pairs
- Inelastic scattering with phonons
- Elastic carrier scattering
- Surface phonon states (if present)

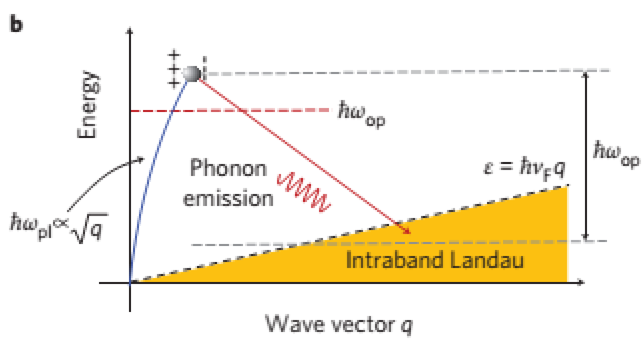


Elastic carrier scattering

$\tau_{ep} \rightarrow$ *phonon emission*

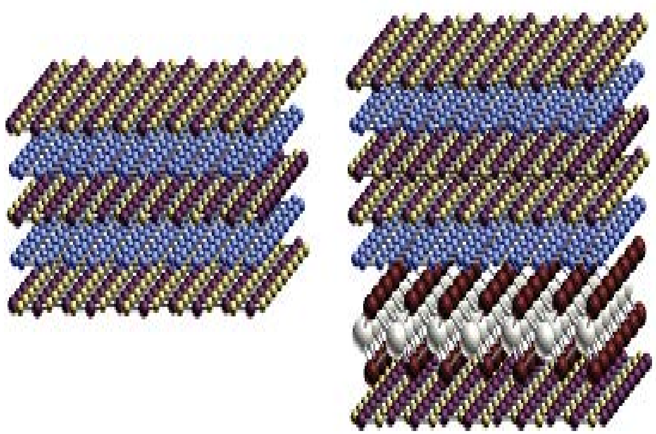
$\tau_0 \rightarrow$ *bulk scattering*

$\tau_{edge} \rightarrow$ *edge scattering*



Higher phonon like nature of the hybrid resonance

"Food for Thought"



K. Novoselov, *Nobel Lecture,* 2010

- Can there exist other 2D crystals?
- YES, they can. For example, $NbSe_2$, MoS_2 , etc.
- These 2D layers can be stacked up as shown and they have the potential to exhibit extraordinary characteristics leading to novel application in optics and electronics.

Arindam Ghosh, IISc, *Nature Nanotechnology*, Oct 2013

Applications and Prospects

- Application of Graphene
  - Graphene Photo-detector
  - Surface Plasmon Enhanced Photo Detector
  - Graphene Modulator

- Future Prospect

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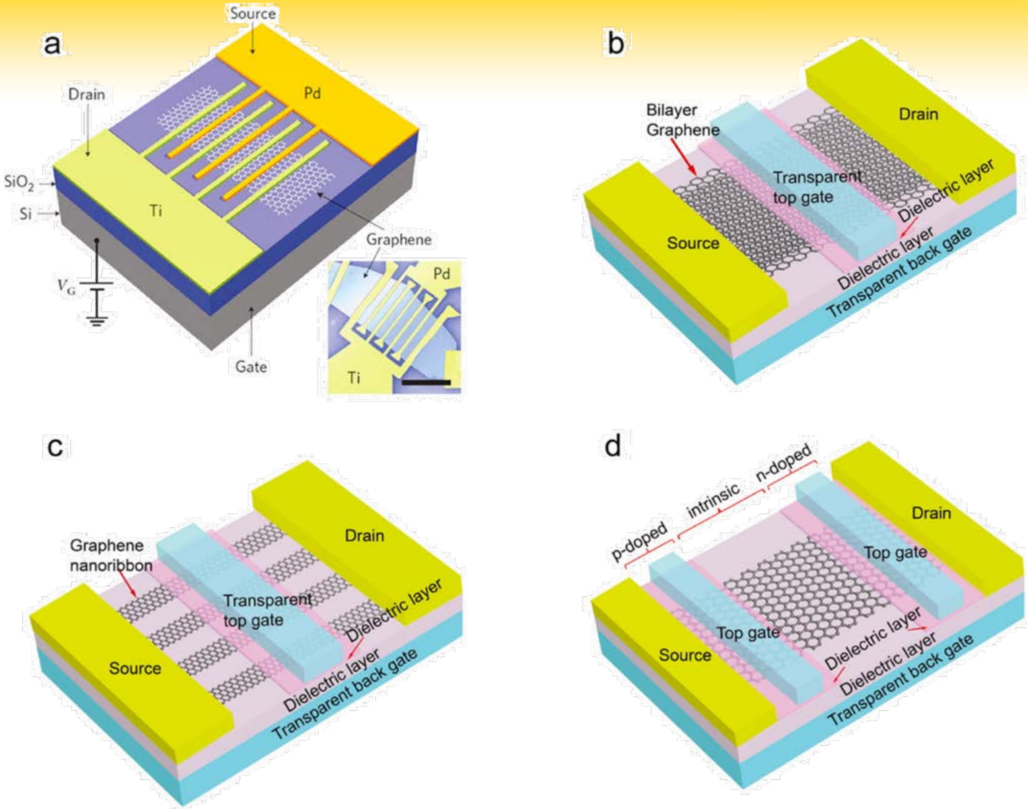
Graphene Photodetectors



(a) Mueller, Thomas; Xia, Fengnian; Avouris, Phaedon Nature Photonics 2010

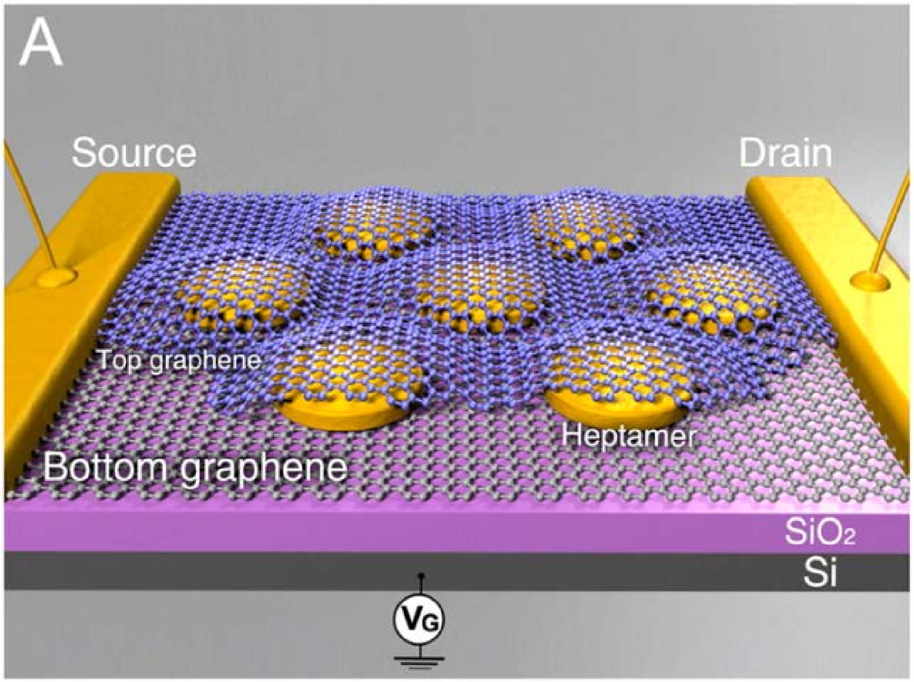
(b) Ryzhii, V.; Ryzhii, M. Phys Rev 2009

(c) Ryzhii, V.; Ryzhii, M. J. Appl Phys 2009

(d) Ryzhii et al. J. Appl Phys 2010,

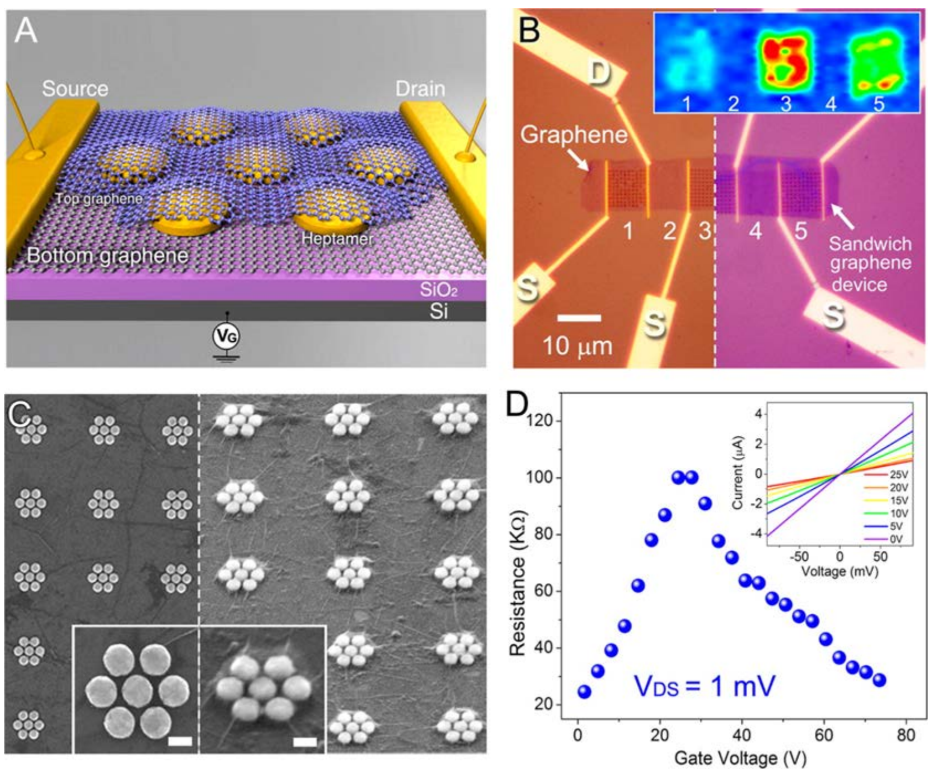
Bao & Loh *ACS Nano* 2012

Graphene Sandwitch Photodetector



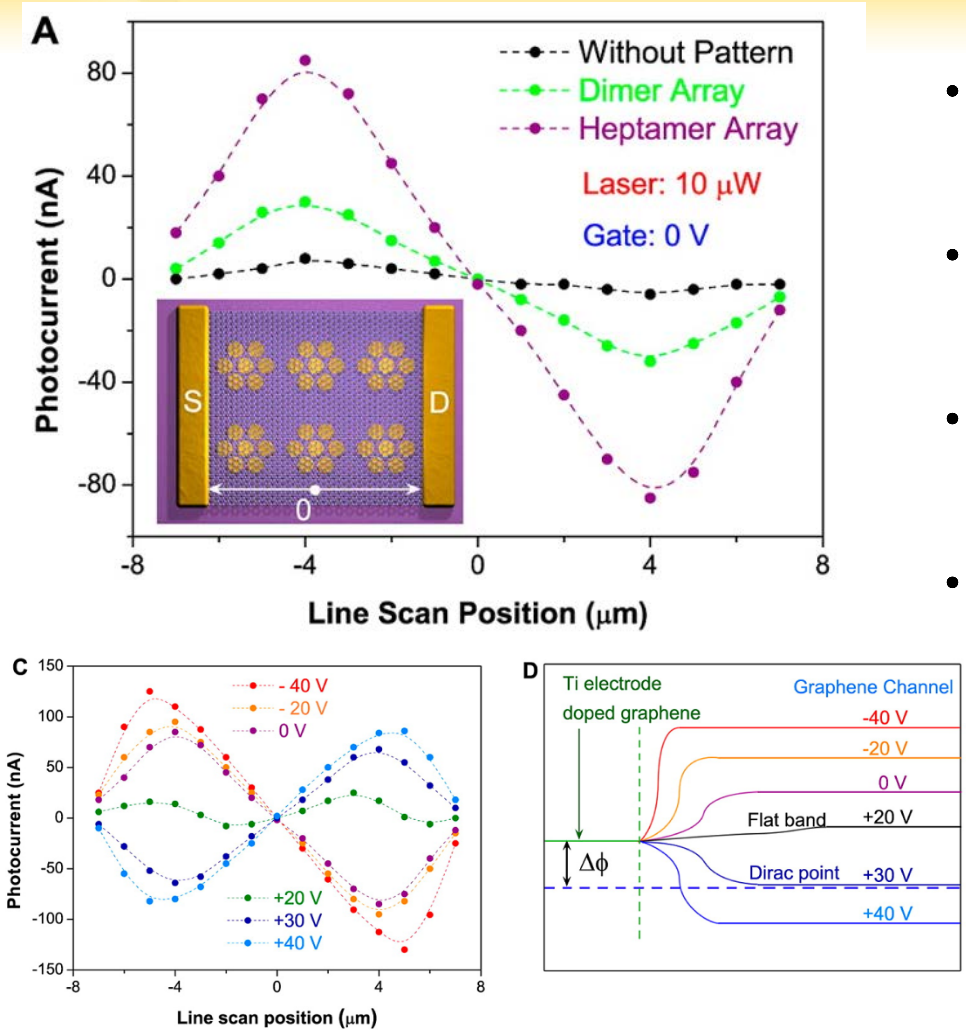
- Plasmonic Antenna Sandwitched between two monolayers of Graphene
- Antenna contributes to enhancement of photocurrent through
  - Transfer of Hot electron generated in the antenna structure upon plasmon decay
  - Plasmon enhanced excitation of intrinsic graphene electrons

Zheyu Fang, Zheng Liu, Yumin Wang, Pulickel M. Ajayan, Peter Nordlander, and Naomi J. Halas "**Graphene-Antenna Sandwich Photodetector**", *ACS Nano Letters* 2012

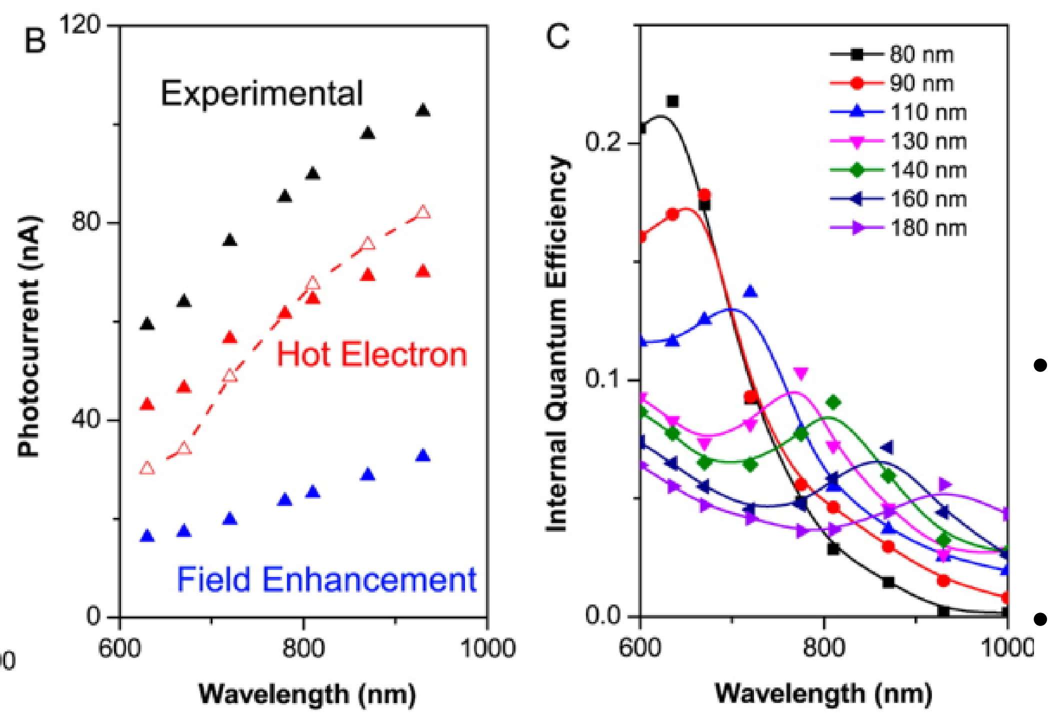


- B. Optical Micrography image of graphene layer before and after deposition of second layer of graphene.
- C. SEM Image of Graphene Layer
- D. Electrical Transport Characteristics of the device. Drain Bias 1mV
  - Band Crossing energy (Dirac Point) reached at peak resistivity (V_G ~ 30V)

Photocurrent Characterization of Antenna

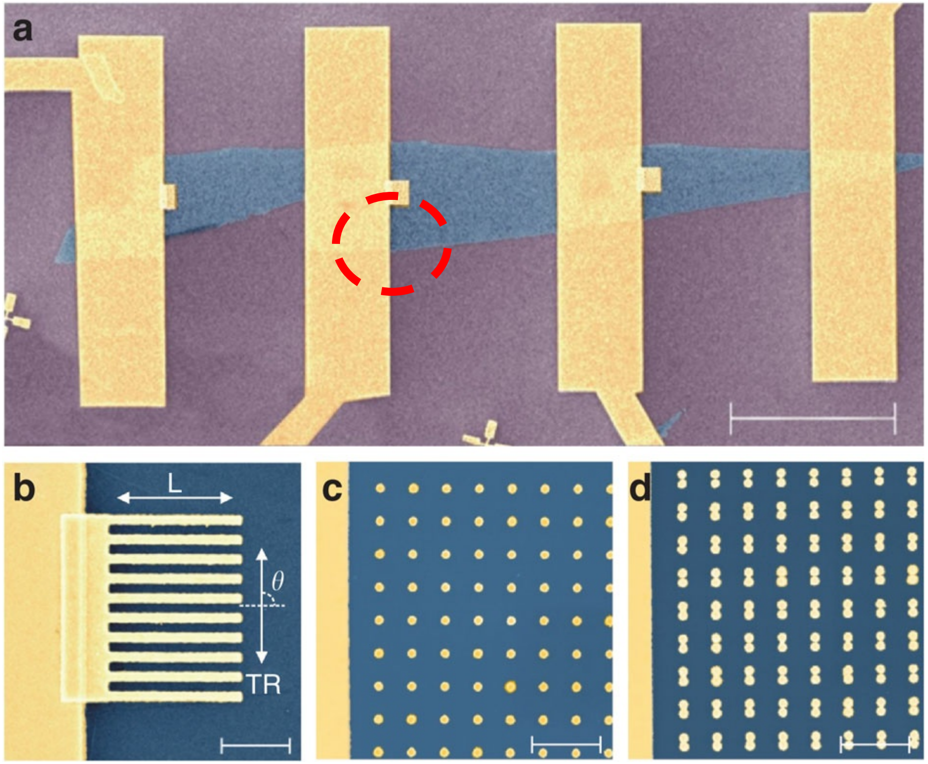


- Local photocurrent measurement with Line Scan (λ=785nm , 1μm beam spot)
- Dimer and Heptamer array Fano resonance tuned to incident λ=785nm .
- Significant Photocurrent enhancement with the patterned nano antennas
- Incident Light at Fano resonant wavelength, Heptamer provides **3 folds** photocurrent enhancement over dimer and **8 folds** enhancement over pristine Graphene.



- HE Contribution to Photo Current:
  - Field Enhancement (direct excitation: Calculated from FDTD simulation
  - Subtracted from Experimental Photocurrent
- Internal Quantum Efficiency:
  - Higher for smaller antenna size.
- Combining Graphene with antennas extends optical sensitivity.

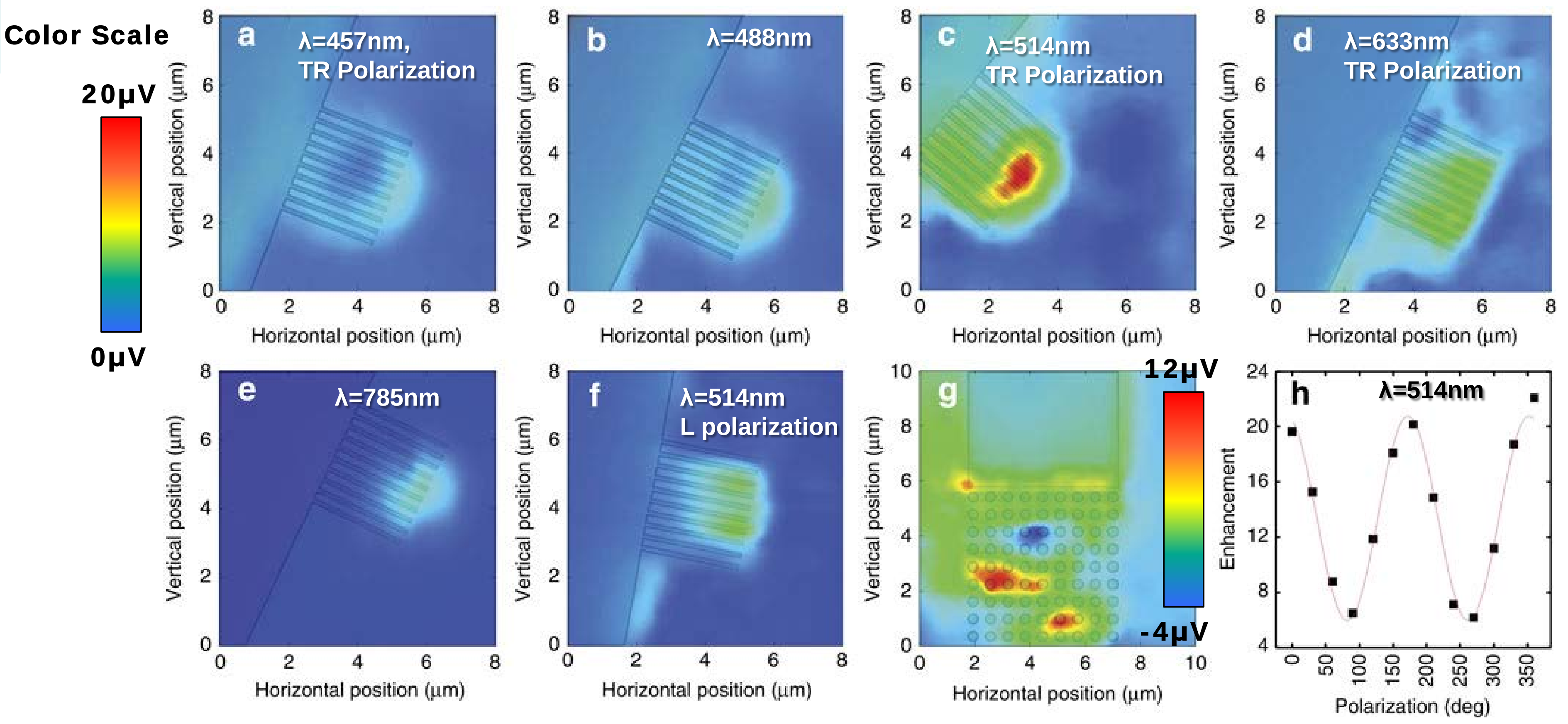
SPP Enhanced Graphene Photodetector



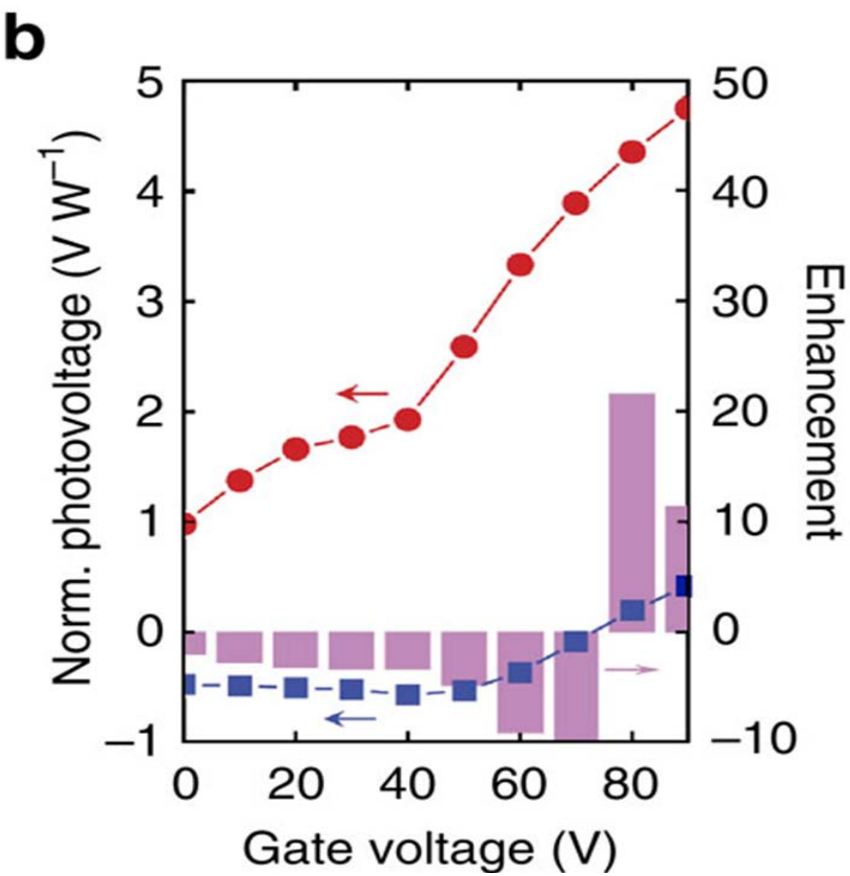
- Problems for Graphene Photodetector
  - Low light Absorption
  - Difficulty of extracting photo electrons
  - Absense of photo current for uniform illumination (voltage-current produced in two terminals will be in opposite polarity.
- Solution: Use plasmonic Nanostructures near contacts
  - Incident light converted to plasmonic oscillation.
  - Enhancement of local electric field.
- **Blue** = Graphene, **Purple** = SiO2, **Yellow** = Ti/Au electrodes (1µm scale)

T.J. Echtermeyer, A.K. Geim, A.C. Ferrari & K.S. Novoselov et al. "**Strong plasmonic enhancement of photovoltage in graphene**", *Nature Communications* 2011

Photo Voltage Map of Nano Structured Contacts



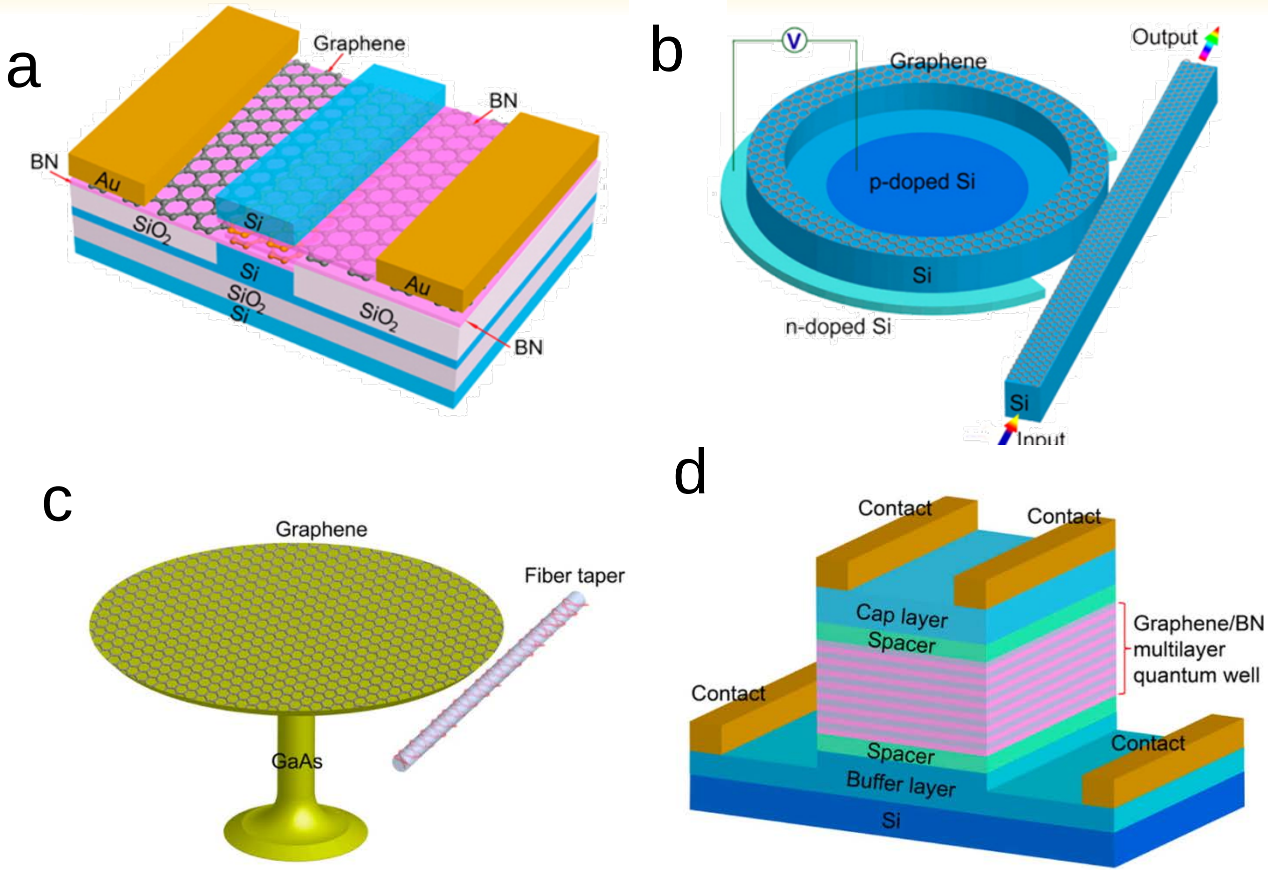
Finger Width 100nm, Pitch 300nm, Spot Size ~1.5μm, 90V Gate Voltage



- Normalized Photovoltage:
  - **Blue**: Illumination closed to Flat part of Contact (FC)
  - **Red**: Illumination close to Structured part of Contact (SC)

- Enhancement over more than one order of magnitude.

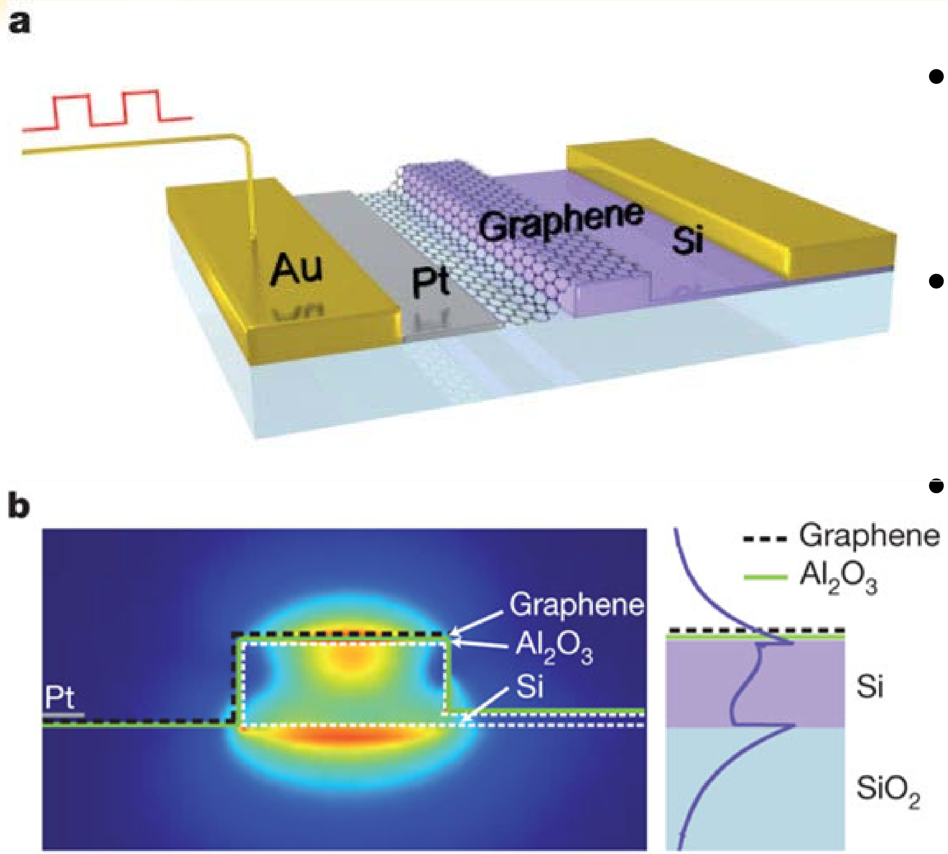
Proposed Schematics of Graphene based optical modulators



(a) Kim, K. et al. Nature 2011

Bao & Loh *ACS Nano* 2012

Graphene Optical Modulator

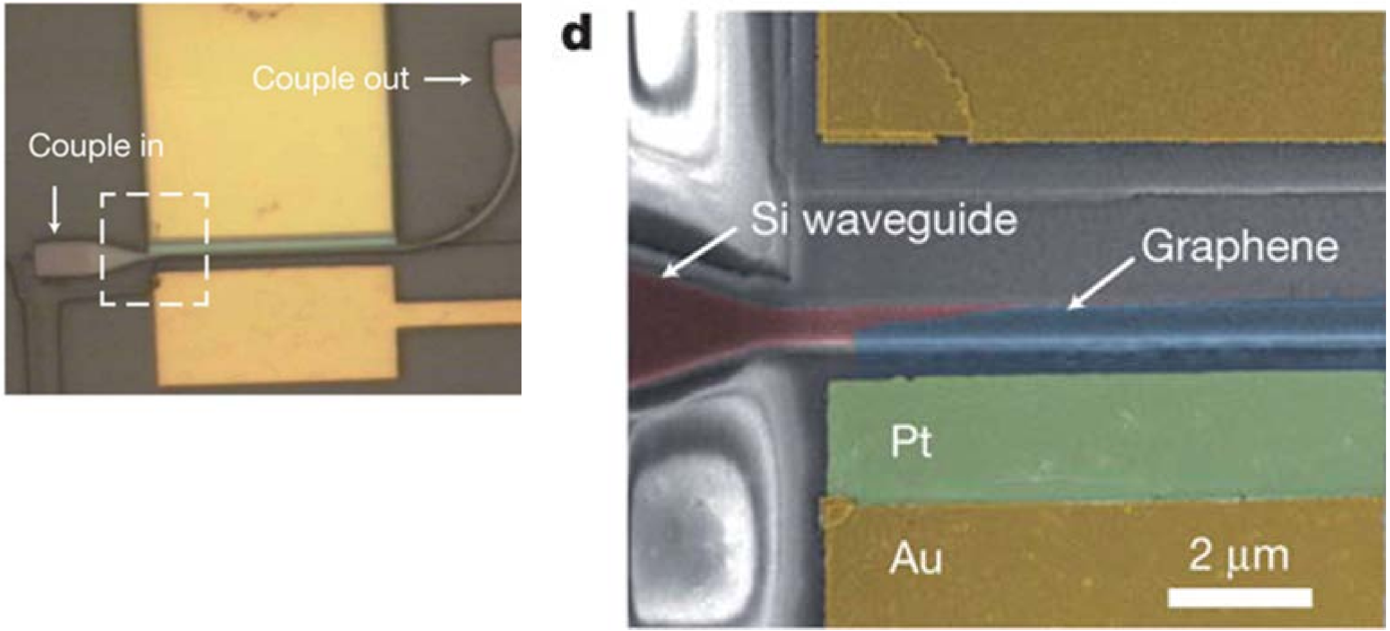


- Waveguide-integrated graphene-based electro-absorption modulator
- Modulation by **actively tuning Fermi level** of monolayer graphene.
- 250nm **Si** waveguide connected with 50nm **Si** to one Au electrode. 7nm **Al_2O_3** spacer, followed by mechanically transferred **graphene** sheet. Counter electrode connected with **Pt**.

Ming Liu, Xiaobo Yin, Erick Ulin-Avila, Baisong Geng, Thomas Zentgraf, Long Ju, Feng Wang & Xiang Zhang"**A graphene-based broadband optical modulator**", *Nature* 2011

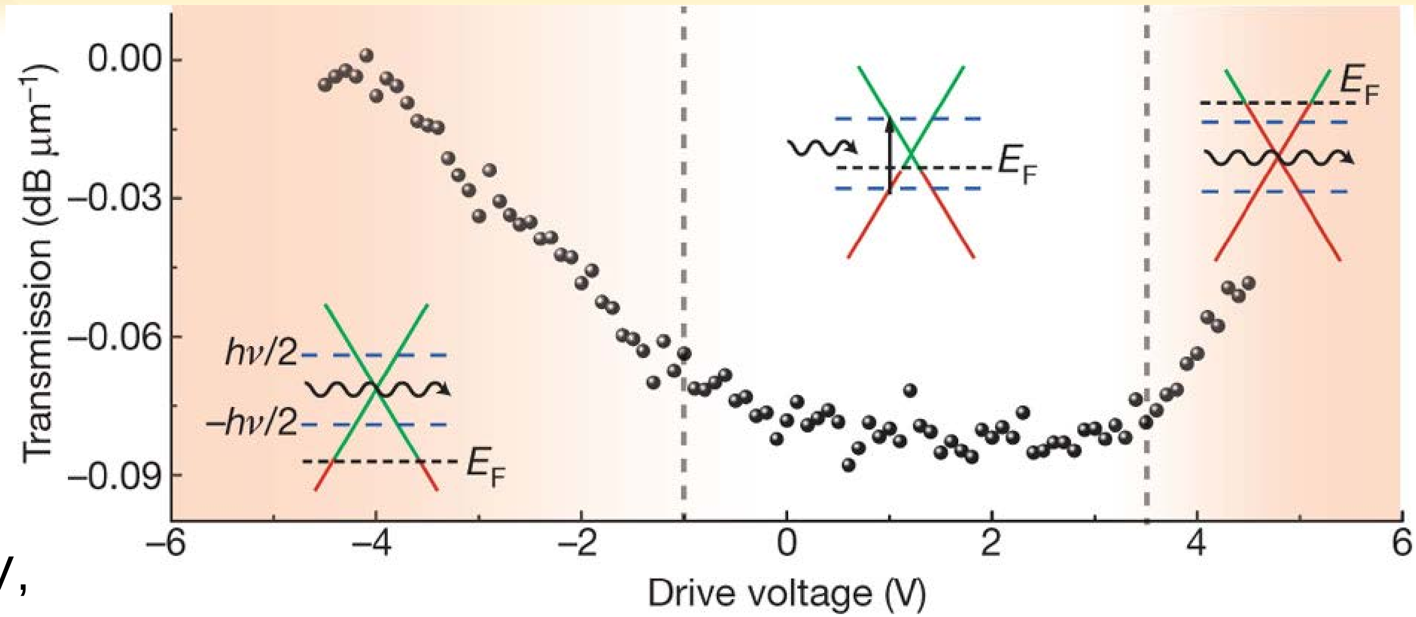
Optical Microscopy and SEM Image of the Modulator

c d



Graphene sheet covers only the wave guide region. (To minimize capacitance)

Static electro-optical response of the device at different drive voltages (Transmission of 1.53µm photon)

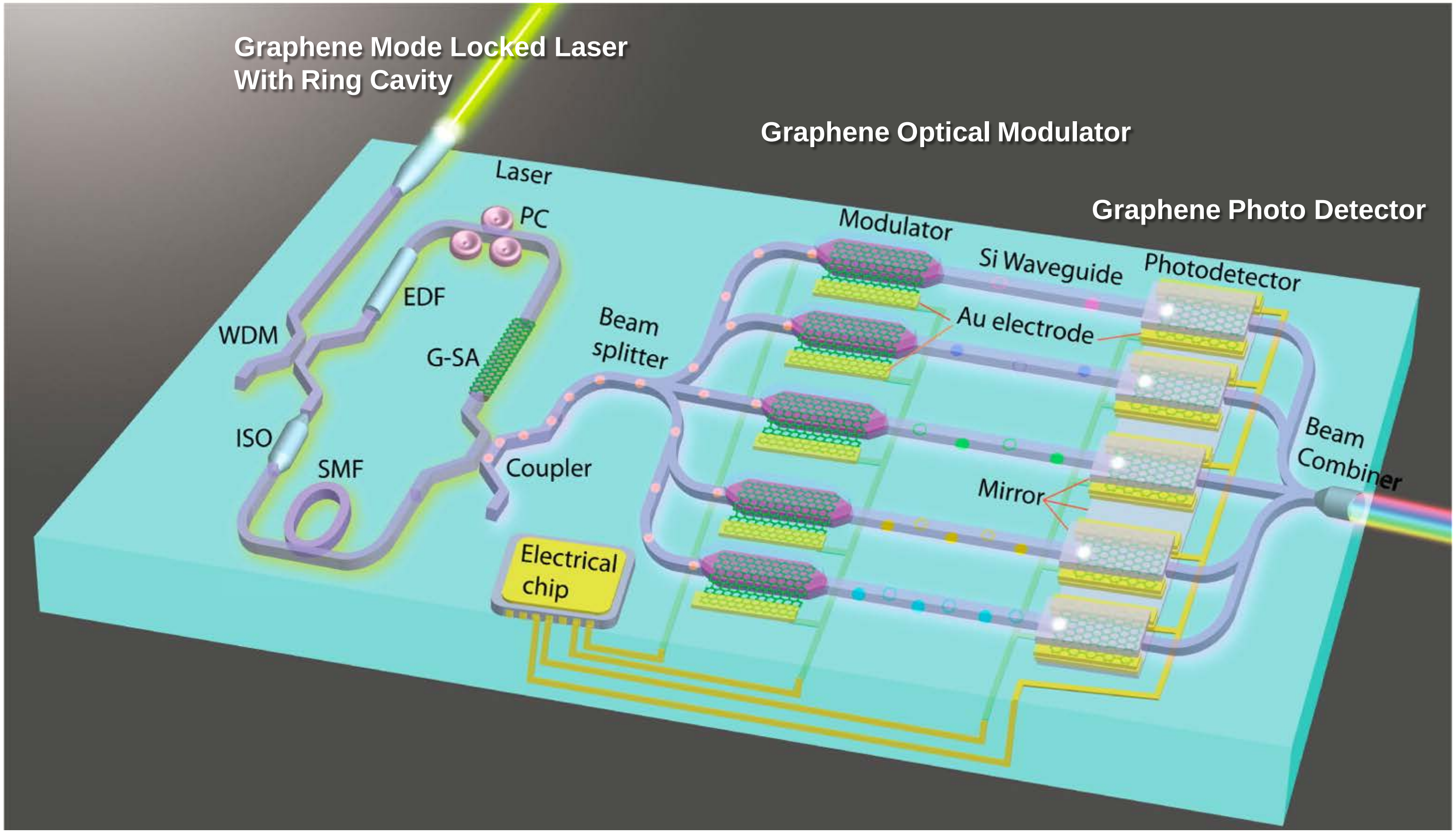


$V_D < -1V$,
Fermi Level $E_F(V_D)$
Lowered below transition threshold, due to +ve charge accumulation. **No e^- for interband transition.**
Graphene appears transparent

$-1V < V_D < 3.8V$,
Fermi Level $E_F(V_D)$
Close to Dirac Point.
Interband Transition when electron excited by incoming Photon

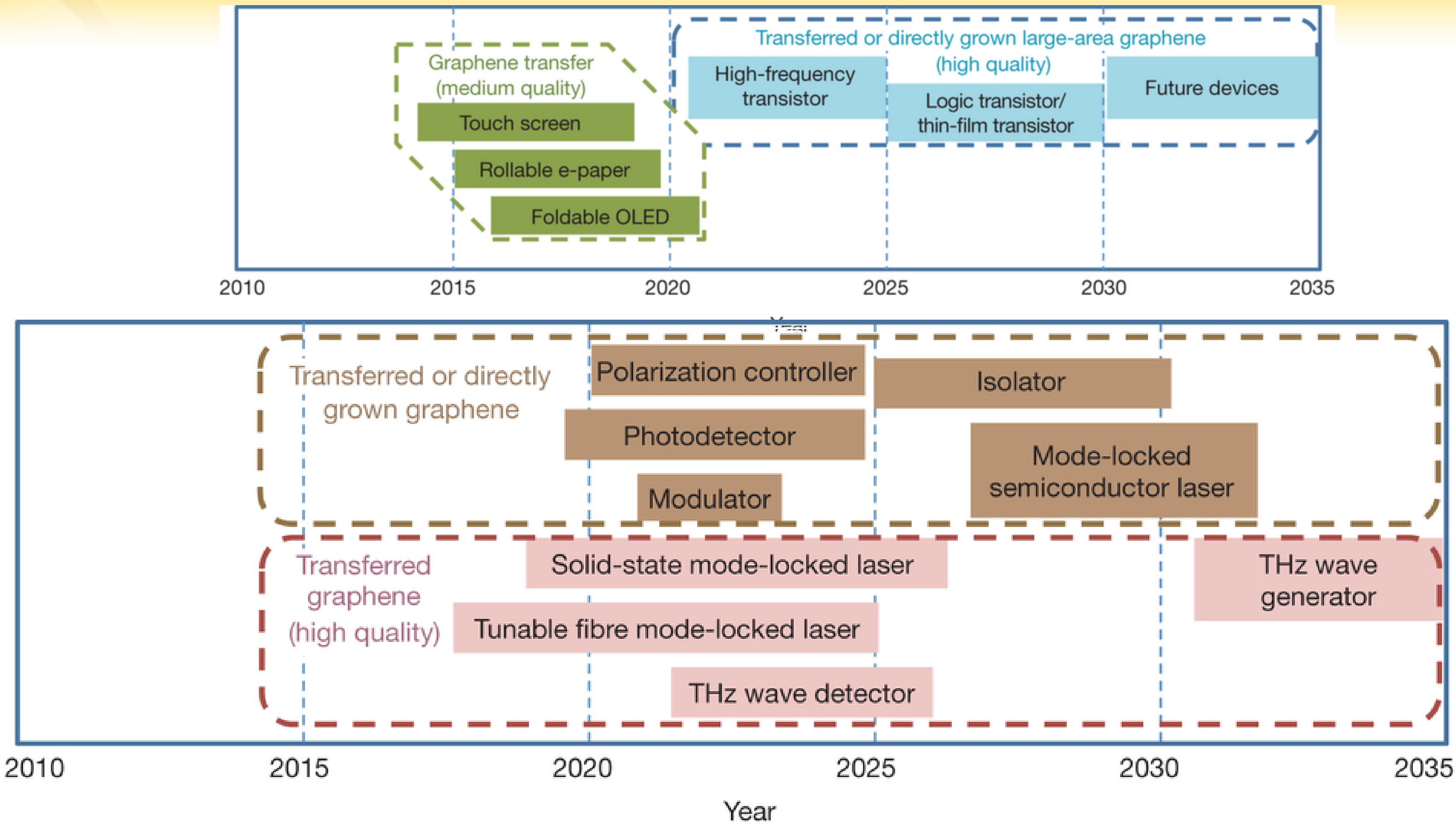
$V_D > -3.8V$,
All e- states filled up,
No interband transition

Integrated Graphene



Bao & Loh *ACS Nano* 2012

Conclusion: Graphene Roadmap



K. S. Novoselov et al. “A roadmap for graphene” Nature 2012

Thank You