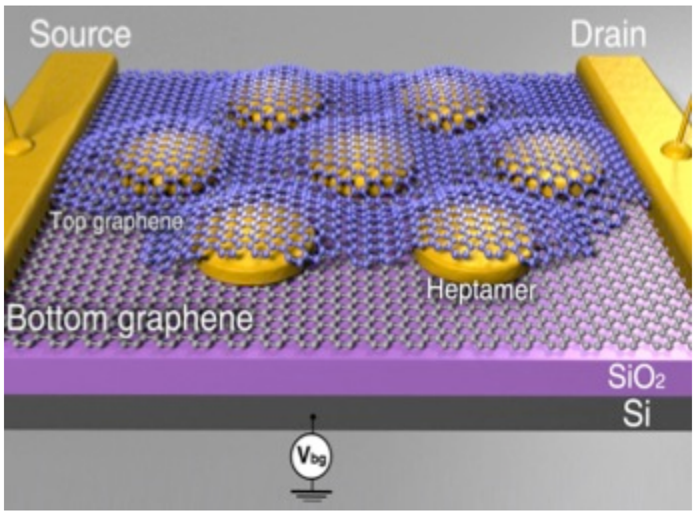
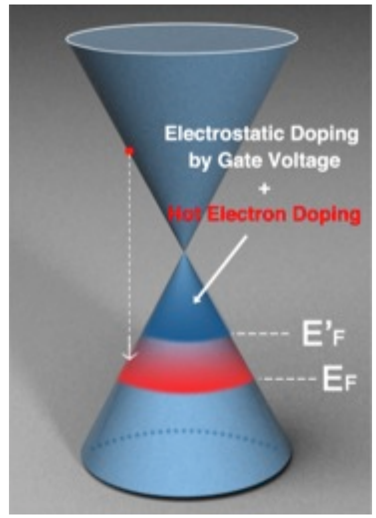
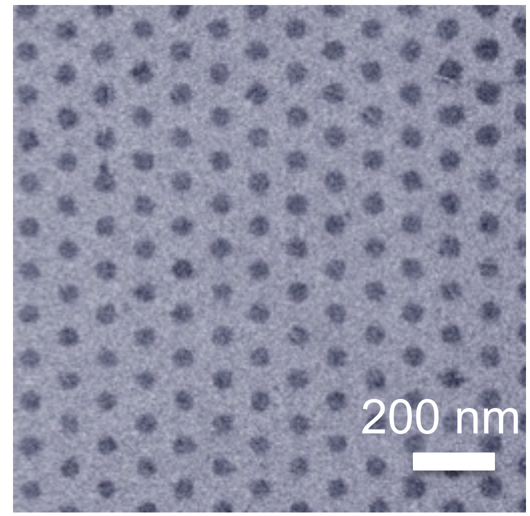
Graphene Plasmonics







Zheyu Fang,

Sukosin Thongrattanasiri (CSIC), Zheng Liu, Yumin Wang, Andie Schlather, Frank Koppens (ICFO), F. Javier García de Abajo (CSIC), Pulickel M. Ajayan, Peter Nordlander, and Naomi J. Halas

LABORATORY FOR NANOPHOTONICS

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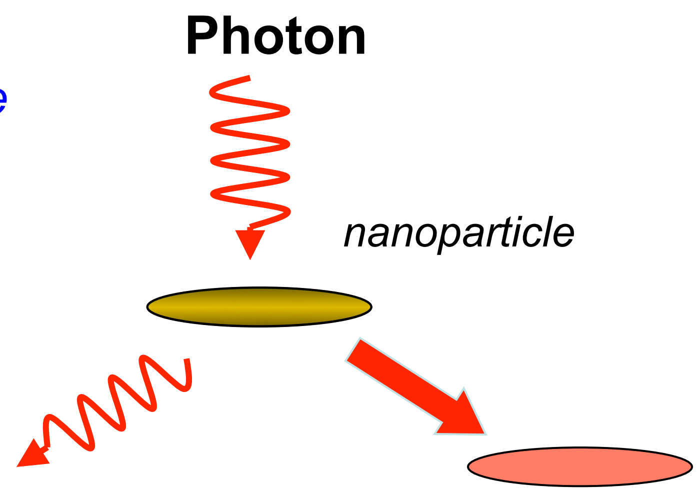
SPIE Optics+Photonics, San Diego
Aug 12-16, 2012

RICE

The plasmon life cycle

Plasmonics:
Surface plasmons are collective oscillations of conduction electrons



Scattering
a.k.a. radiative decay

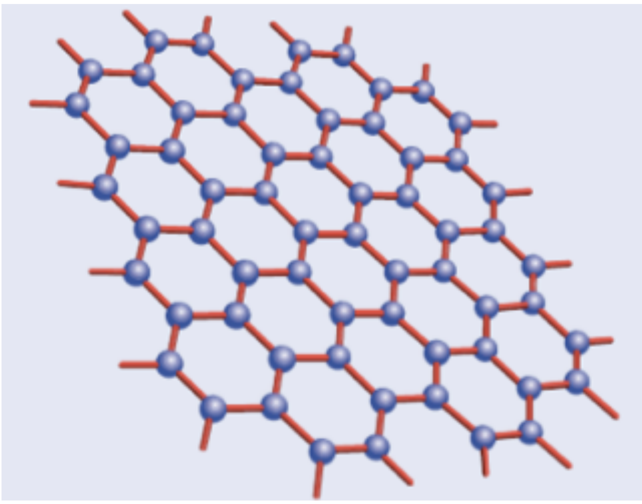
Absorption
'hot' electron-hole pair production

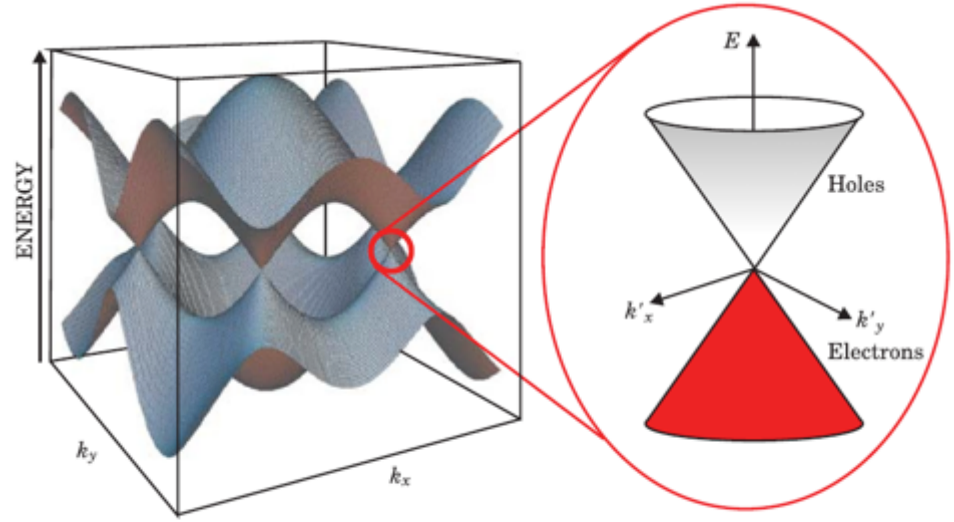
Heating
Result of multiple decay channels (electron-electron scattering, electron-phonon scattering, surface scattering…)

Charge Separation
Conversion of exciton for photocurrent

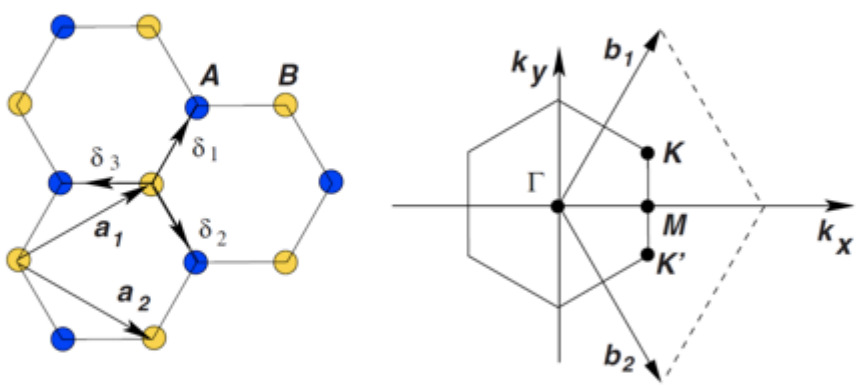
Graphene

A flat monolayer of carbon atoms tightly packed into a 2-dimensional honeycomb lattice





Das Sarma et. al, Rev. Mod. Phys. 2011



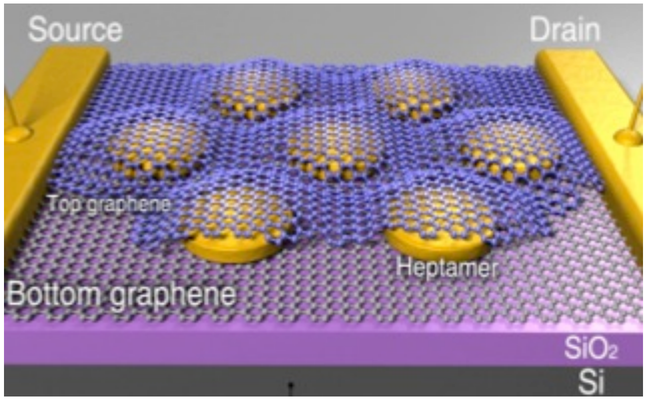
Castro Neto et. al, Rev. Mod. Phys. 2009

- High Mobility: 10000 $cm^2V^{-1}s^{-1}$
- Zero band gap semiconductor
- Poor absorption in visible range

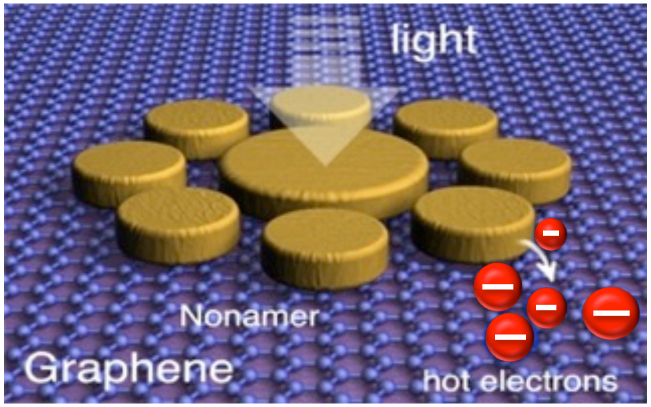
- Improve graphene device optical properties in visible and NIR
- Study graphene semi-metal properties in mid- or far- infrared

Outline

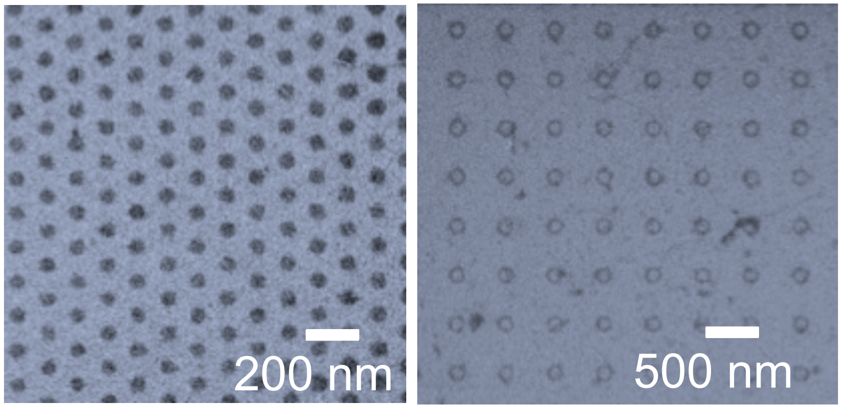
- Graphene-antenna sandwich photodetector



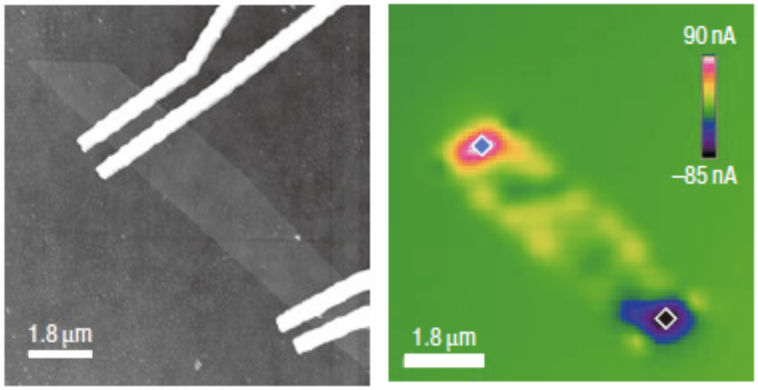
- Doping graphene with plasmonic hot electrons



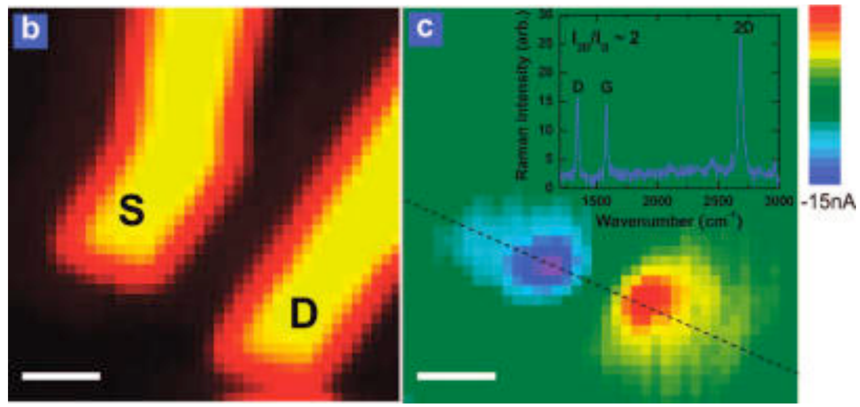
- Graphene nanostructures
  - nanodisk
  - nanoring



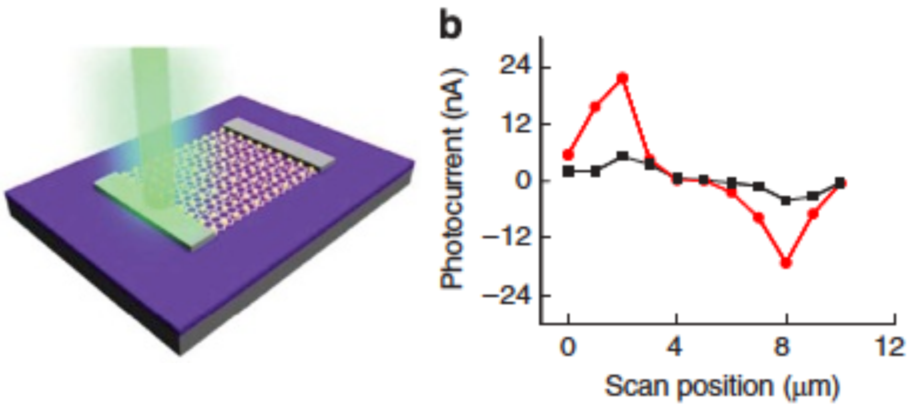
Graphene Photodetector



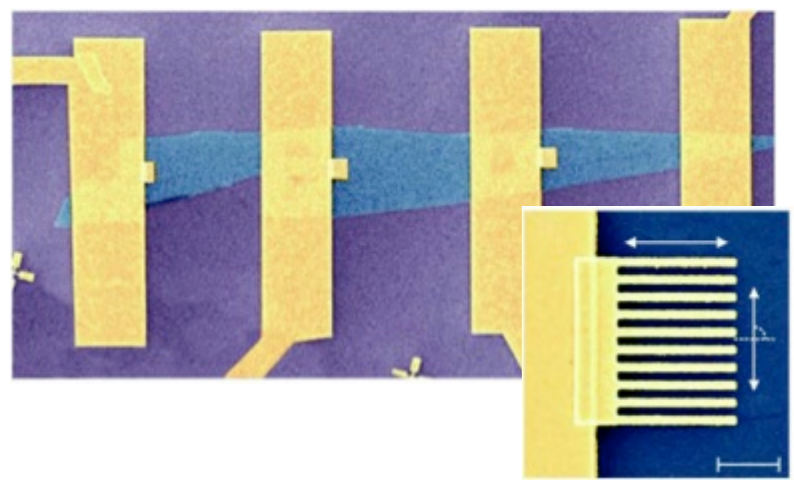
E.J.Lee et.al. *Nature Nano.*,**3**, 488 (2008)



F.Xia et.al. *Nano Lett.*,**9**,1039 (2009)

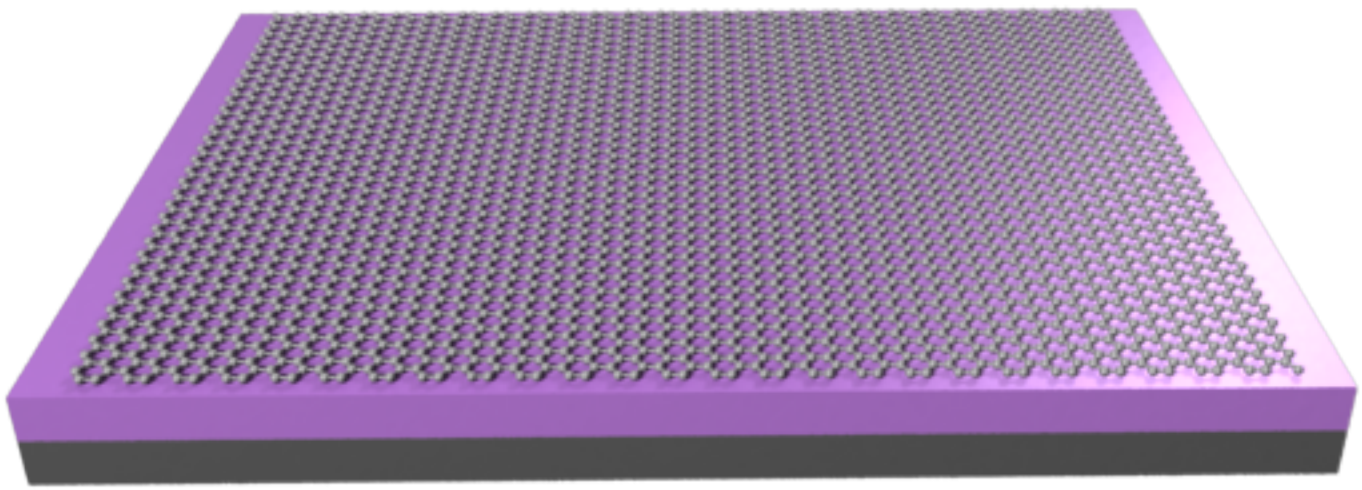


X. Duan et.al. *Nature Comm.*,**2**, 579 (2011)



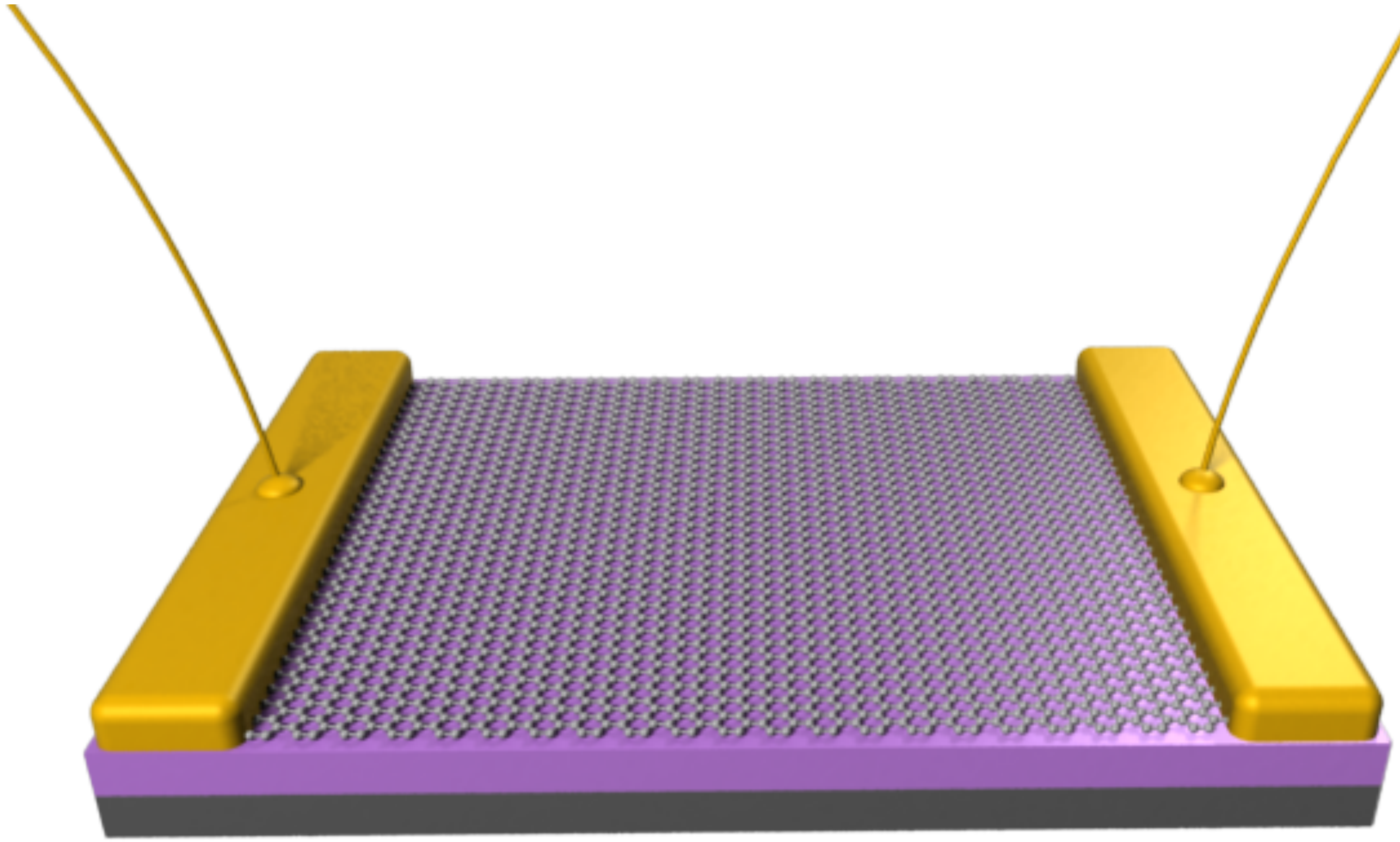
E.J.Lee et.al. *Nature Comm.*,**2**, 458 (2011)

Graphene-Antenna Sandwich Device



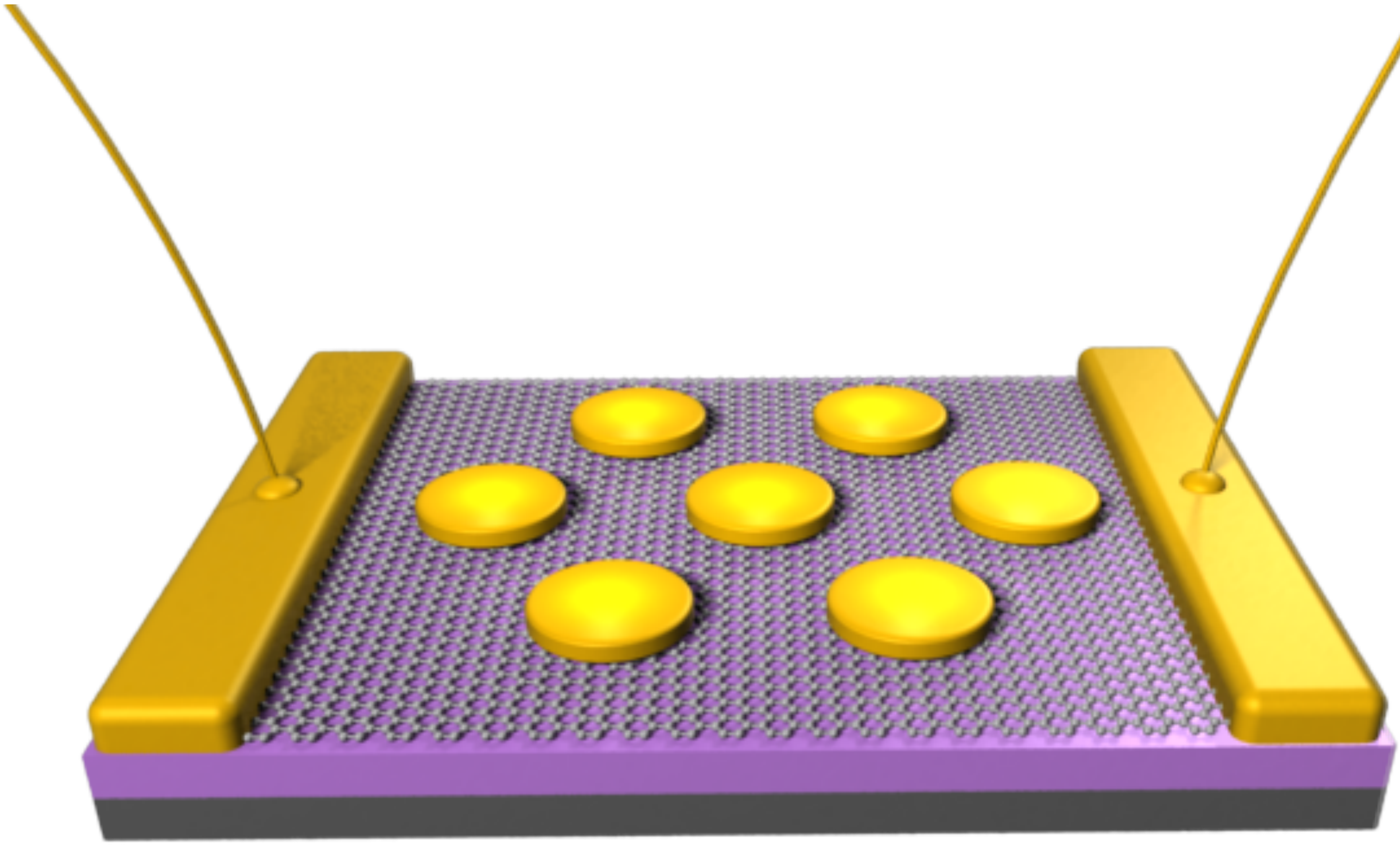
Transfer a graphene monolayer onto a SiO_2/Si substrate

Graphene-Antenna Sandwich Device



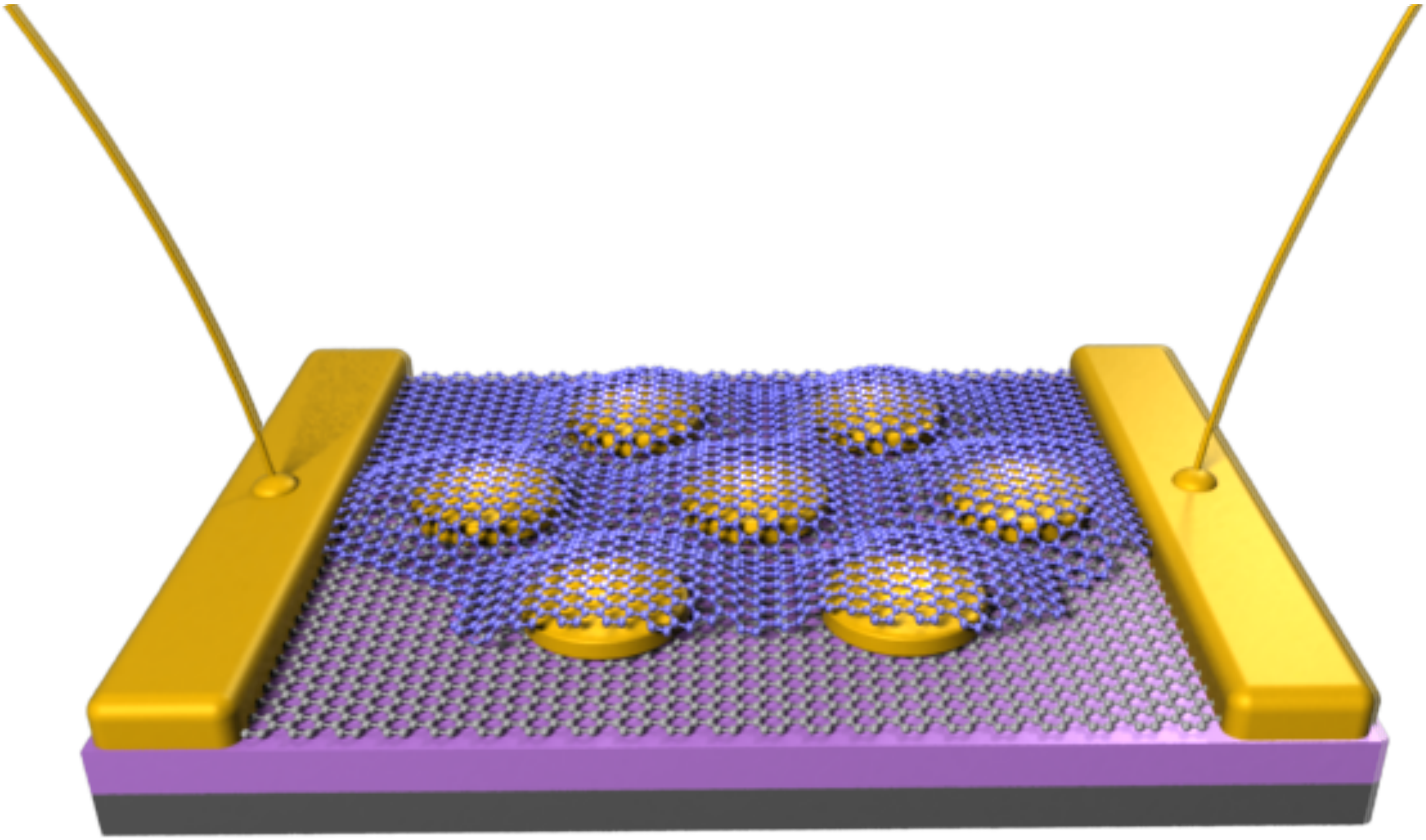
Deposit the source-drain electrodes on the graphene

Graphene-Antenna Sandwich Device



Fabricate heptamer array using two-step E-beam lithography

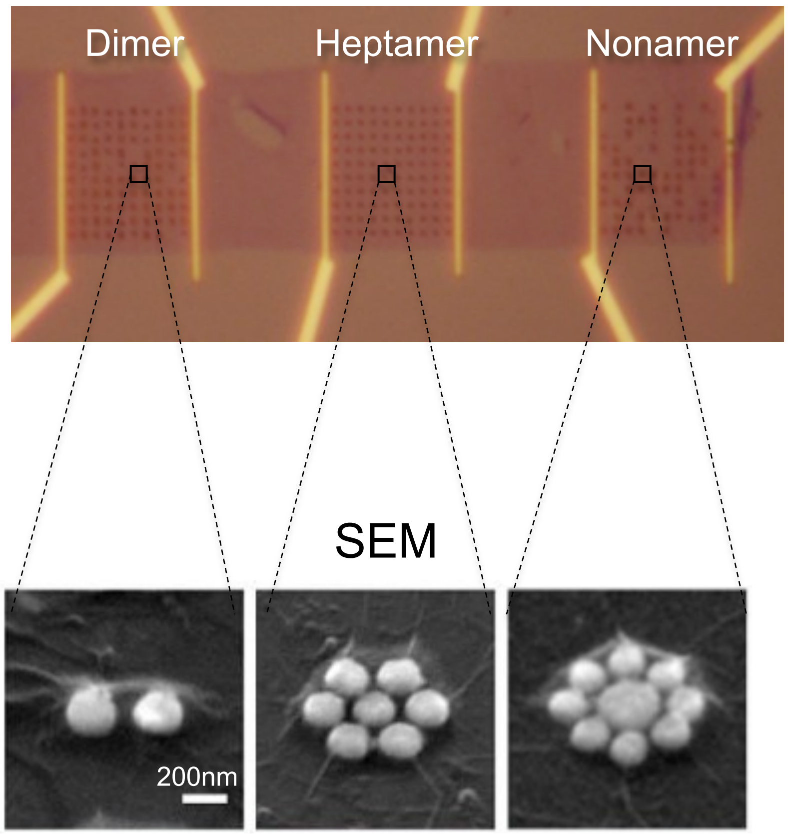
Graphene-Antenna Sandwich Device



Transfer a second graphene monolayer onto the structure to form a sandwich device

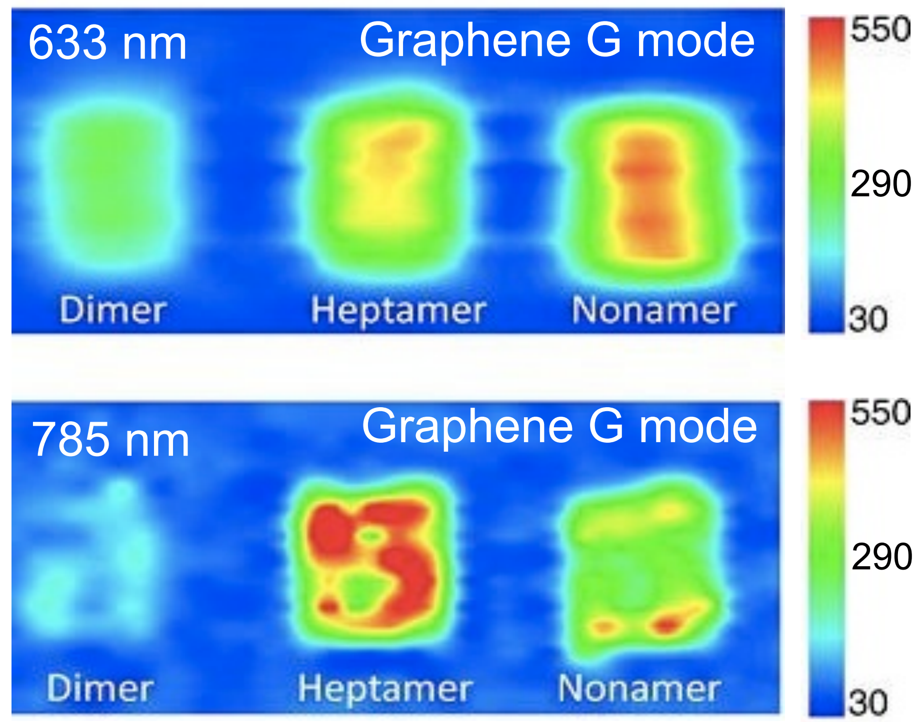
Sandwich Device Characterization

Optical image of the device



Dimer Heptamer Nonamer

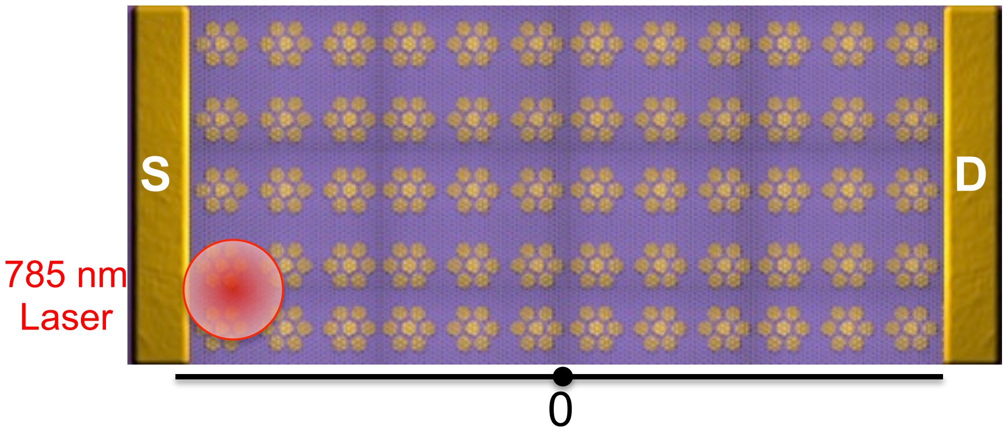
Raman mapping

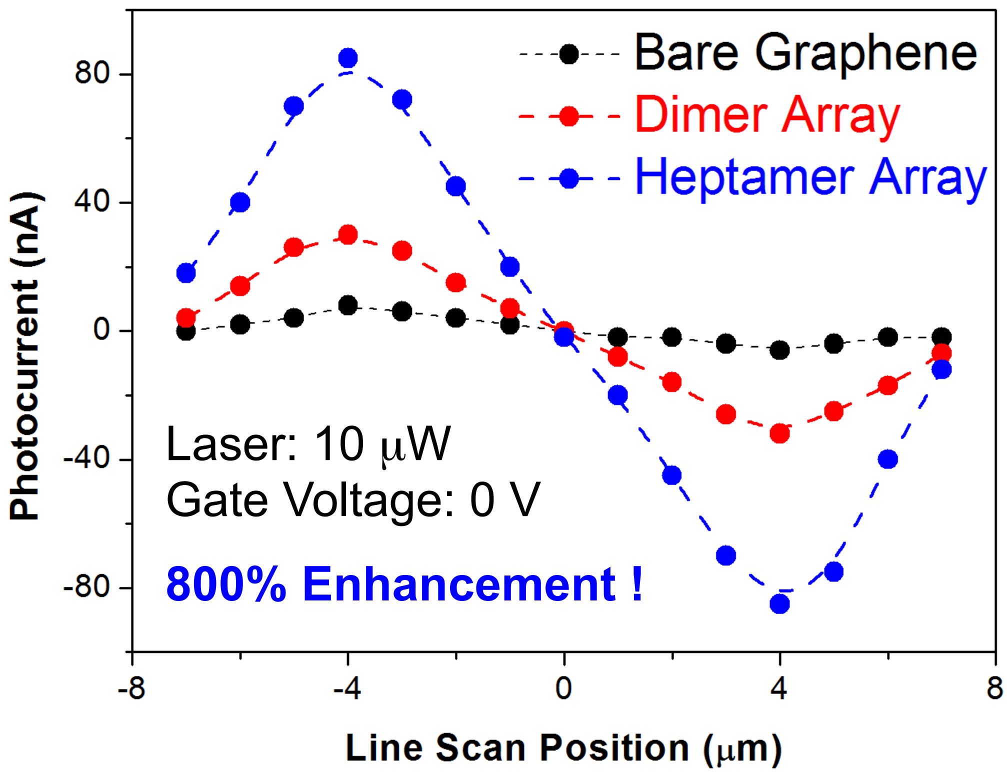


Second graphene on the top is used to capture the hot electrons from the whole *k*-space !

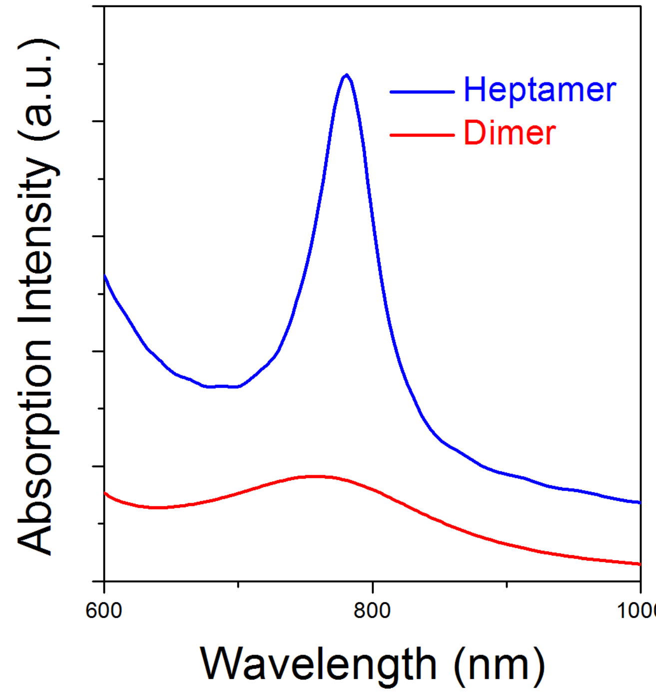
Z. Fang, *et.al. Nano Lett.* **12**, 3808, 2012

Photocurrent Detection

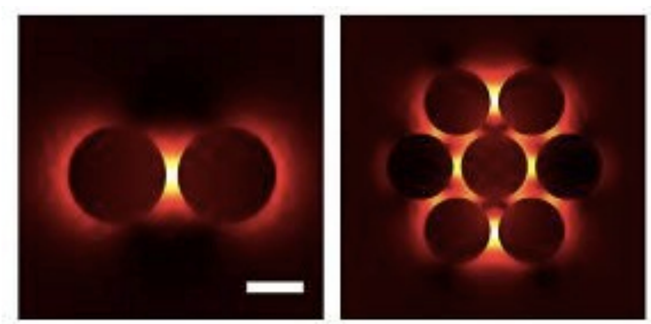




Simulated Absorption Cross Section

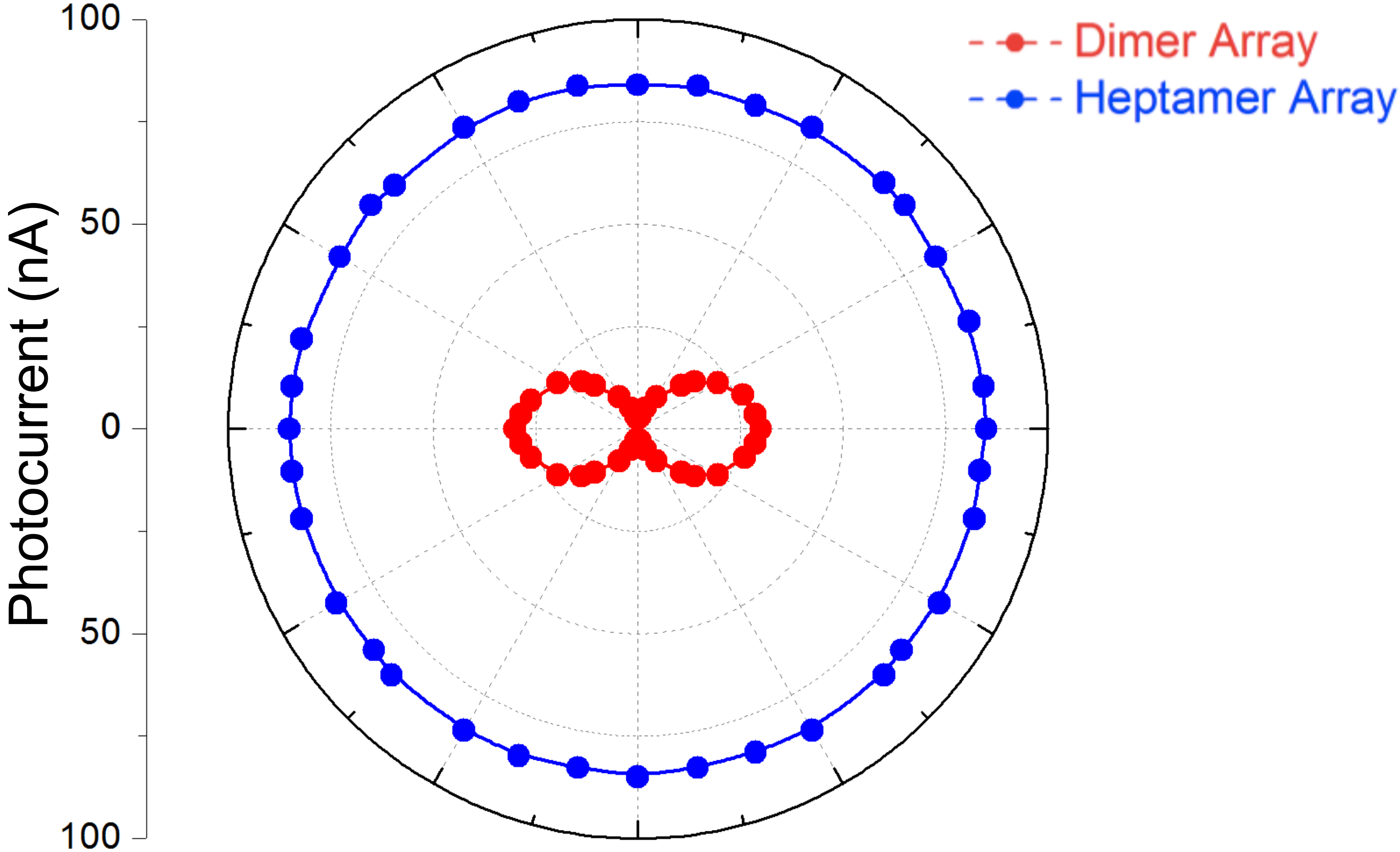


Strong Electric-field Enhancement



Z. Fang, *et.al. Nano Lett.* **12**, 3808, 2012

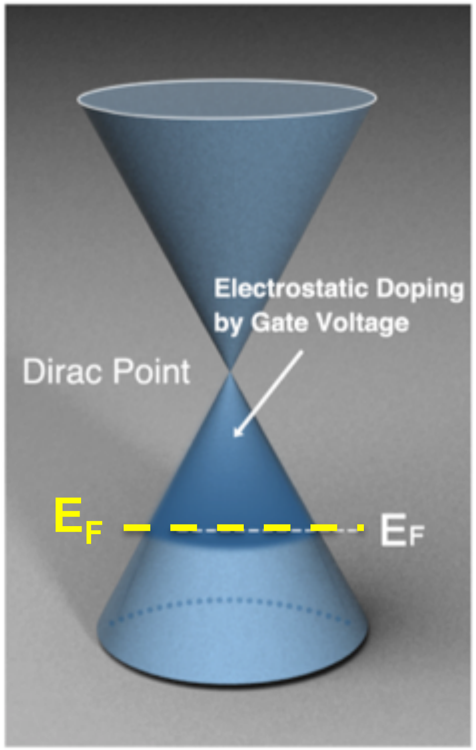
Polarization Dependence

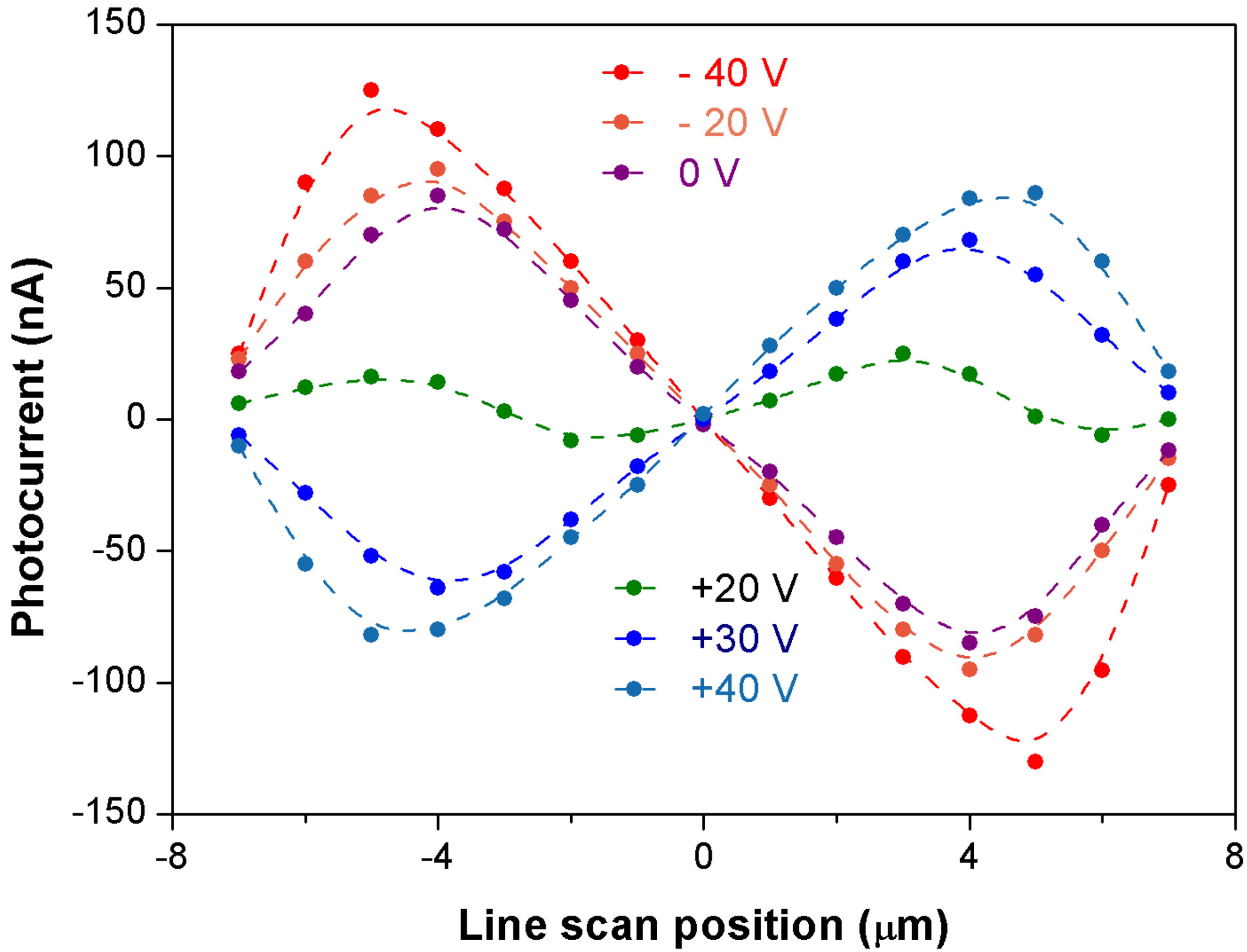


By choosing a different geometry, we can make either polarization dependent or independent photodectector

Z. Fang, *et.al. Nano Lett.* **12**, 3808, 2012

Gate Voltage Control



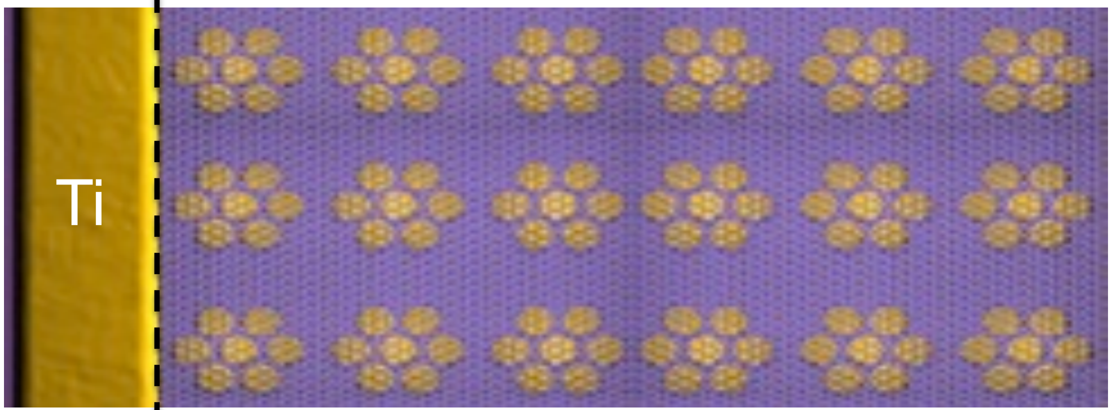


By tuning the gate voltage from -40 to +40 V, we can actively control the photocurrent

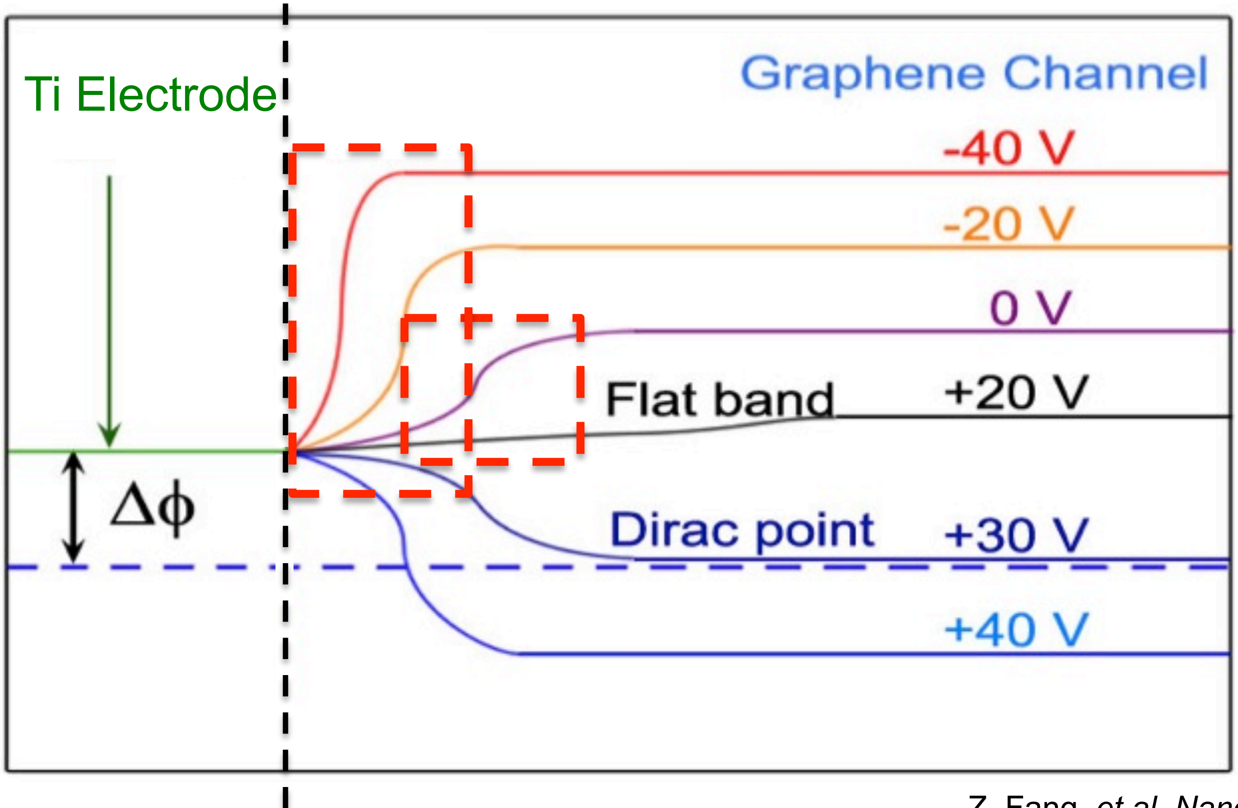
Z. Fang, *et.al. Nano Lett.* **12**, 3808, 2012

Gate Voltage Control

Source Electrode

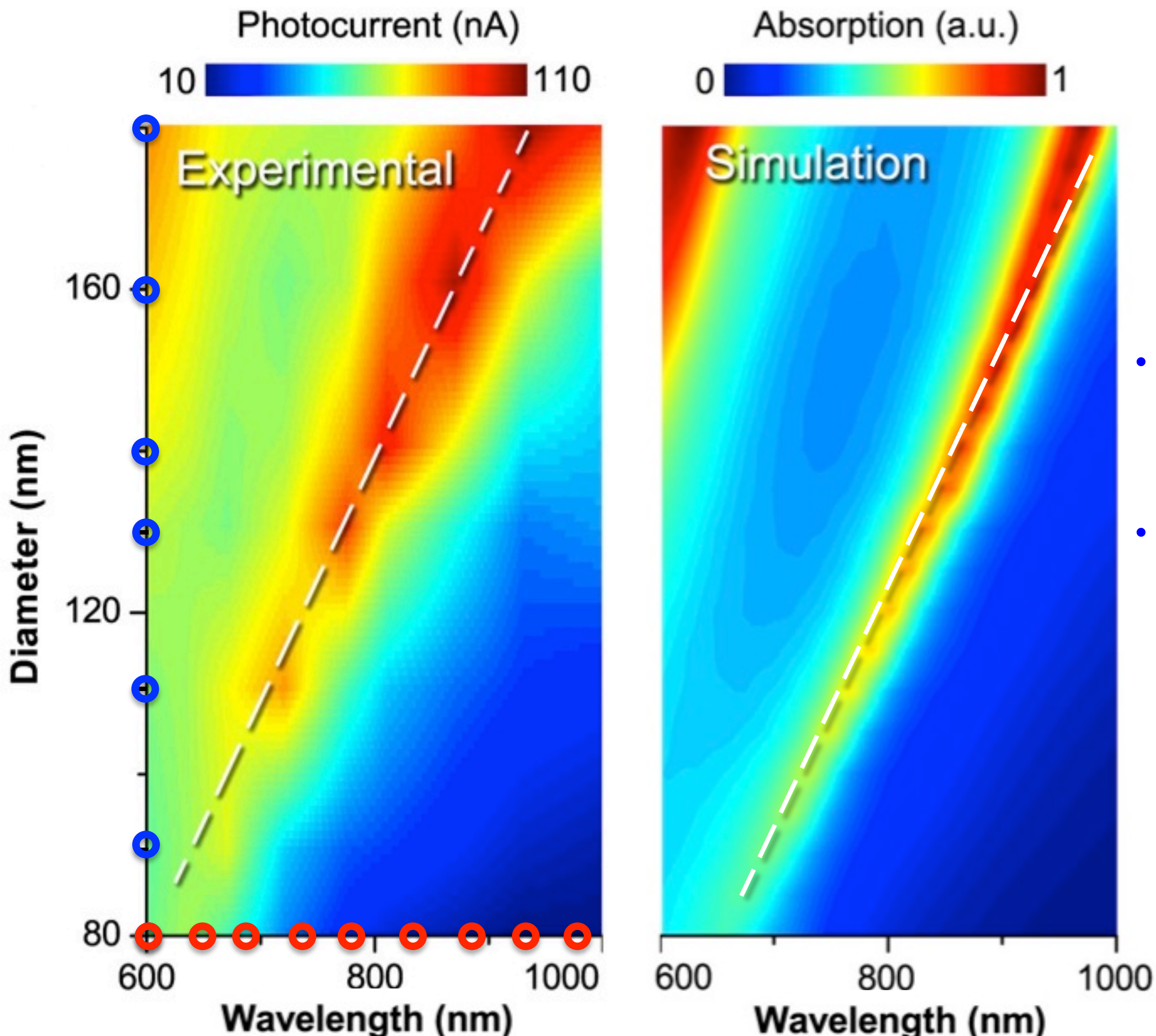


Surface Potential Diagram



Z. Fang, *et.al. Nano Lett.* **12**, 3808, 2012

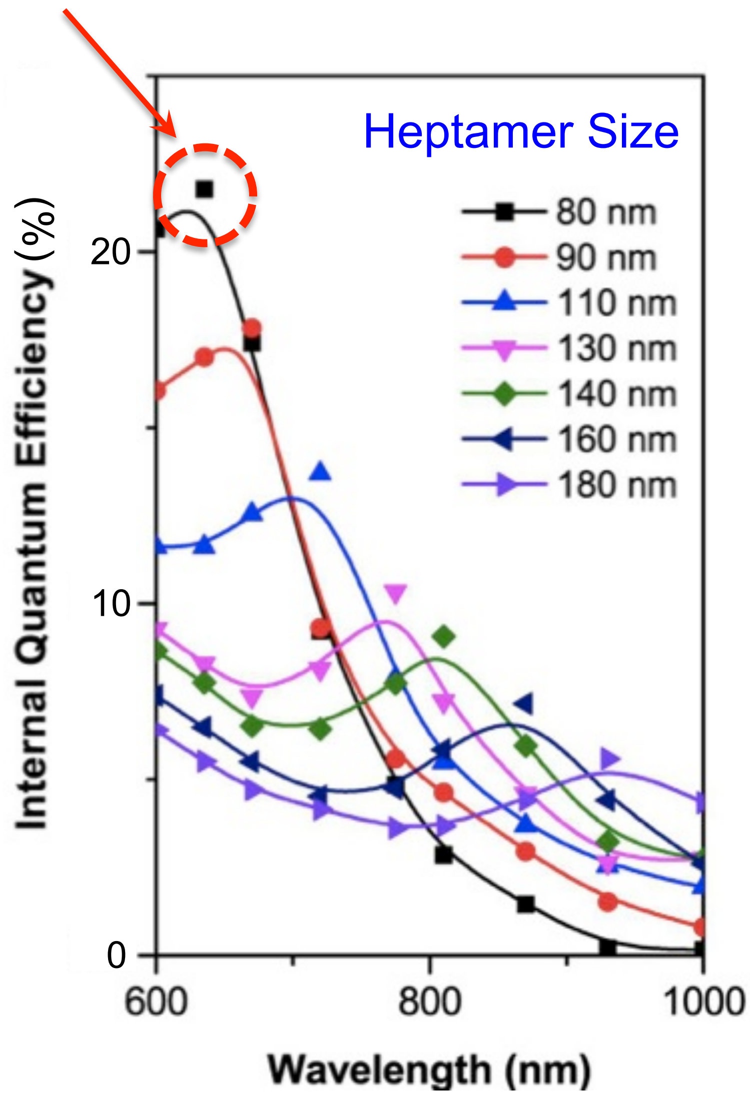
Selective Resonance Detection

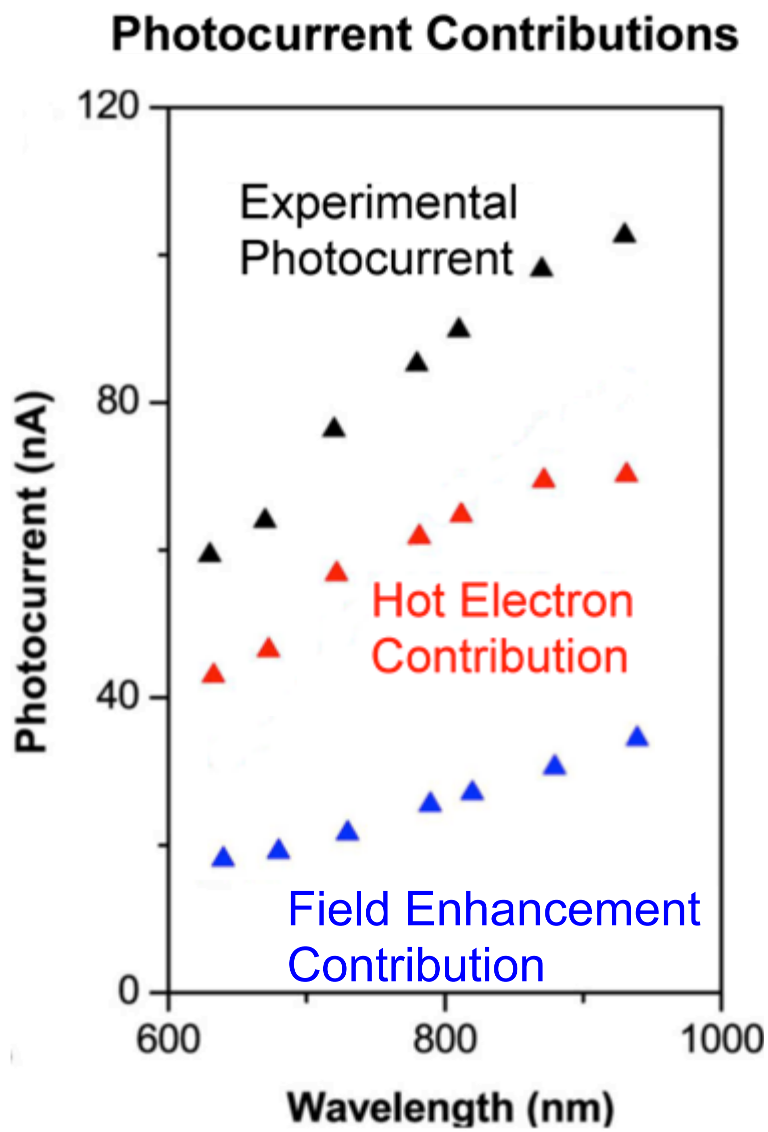


- Realize the tuning of resonance wavelength from visible to NIR
- Have a good agreement between the simulation and experiment

Z. Fang, *et.al. Nano Lett.* **12**, 3808, 2012

Internal Quantum Efficiency



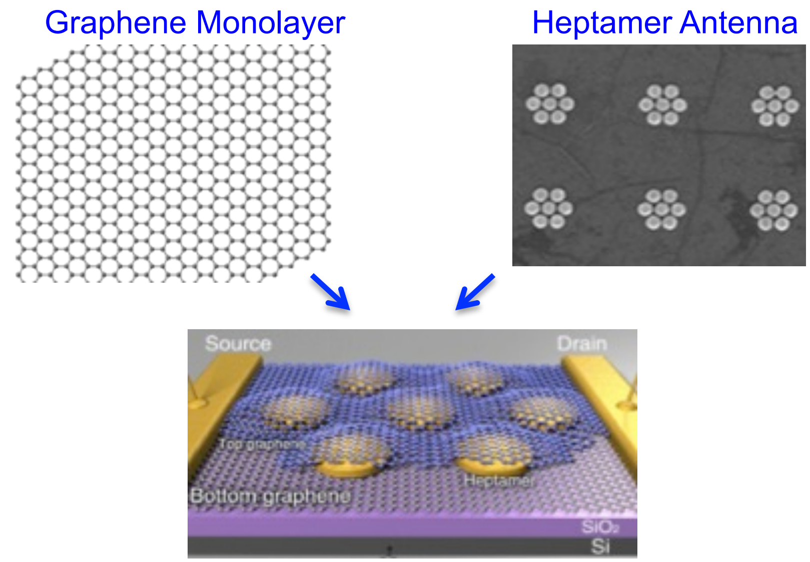


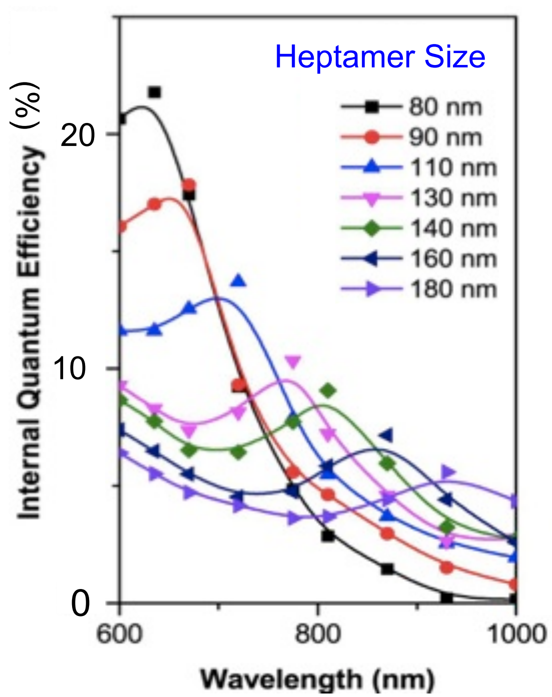
Z. Fang, *et.al. Nano Lett.* **12**,3808 ,2012

Summary: graphene photodetector

Sandwich photodetector:

Fabricate antenna between two monolayer graphene, maximize signal from the whole *k*-space

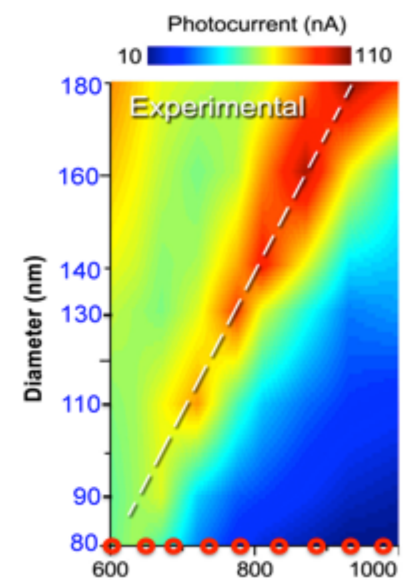




Enhancement:

800% photocurrent enhancement,

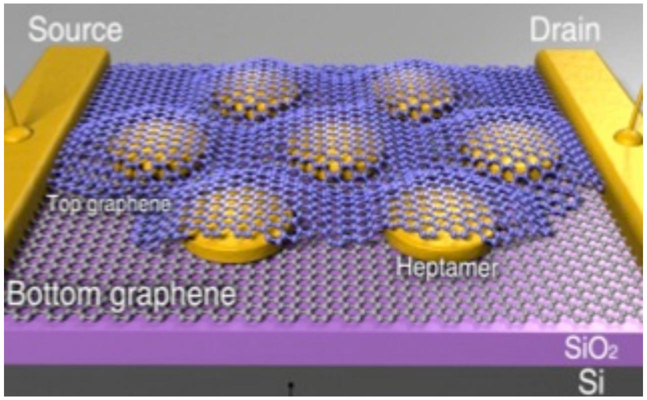
20% internal quantum efficiency!



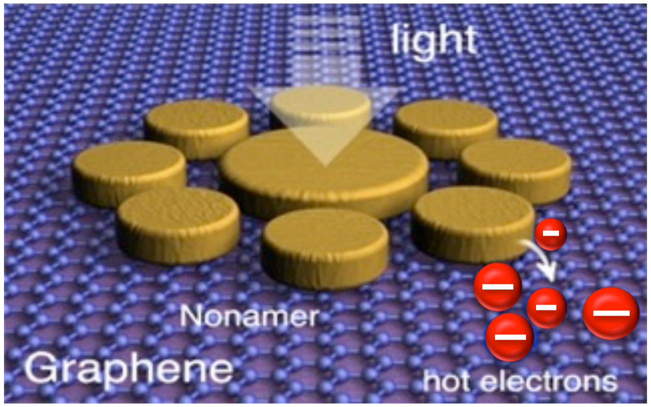
Controllable: polarization, size, resonance frequency (visible to near infrared), gate voltage tuning

Outline

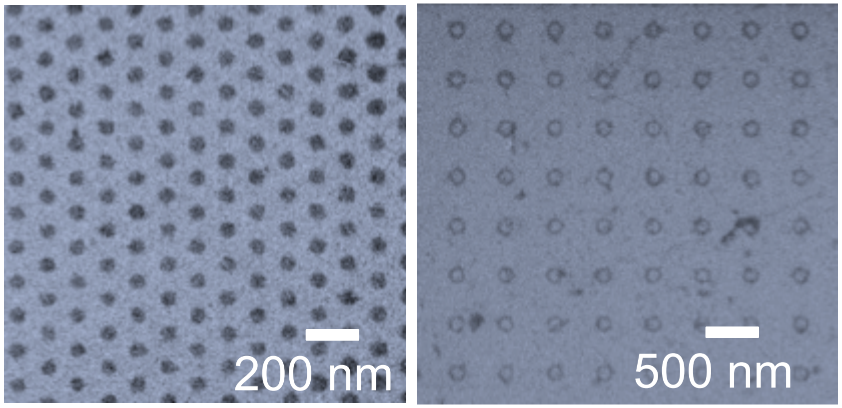
- Graphene-antenna sandwich photodetector



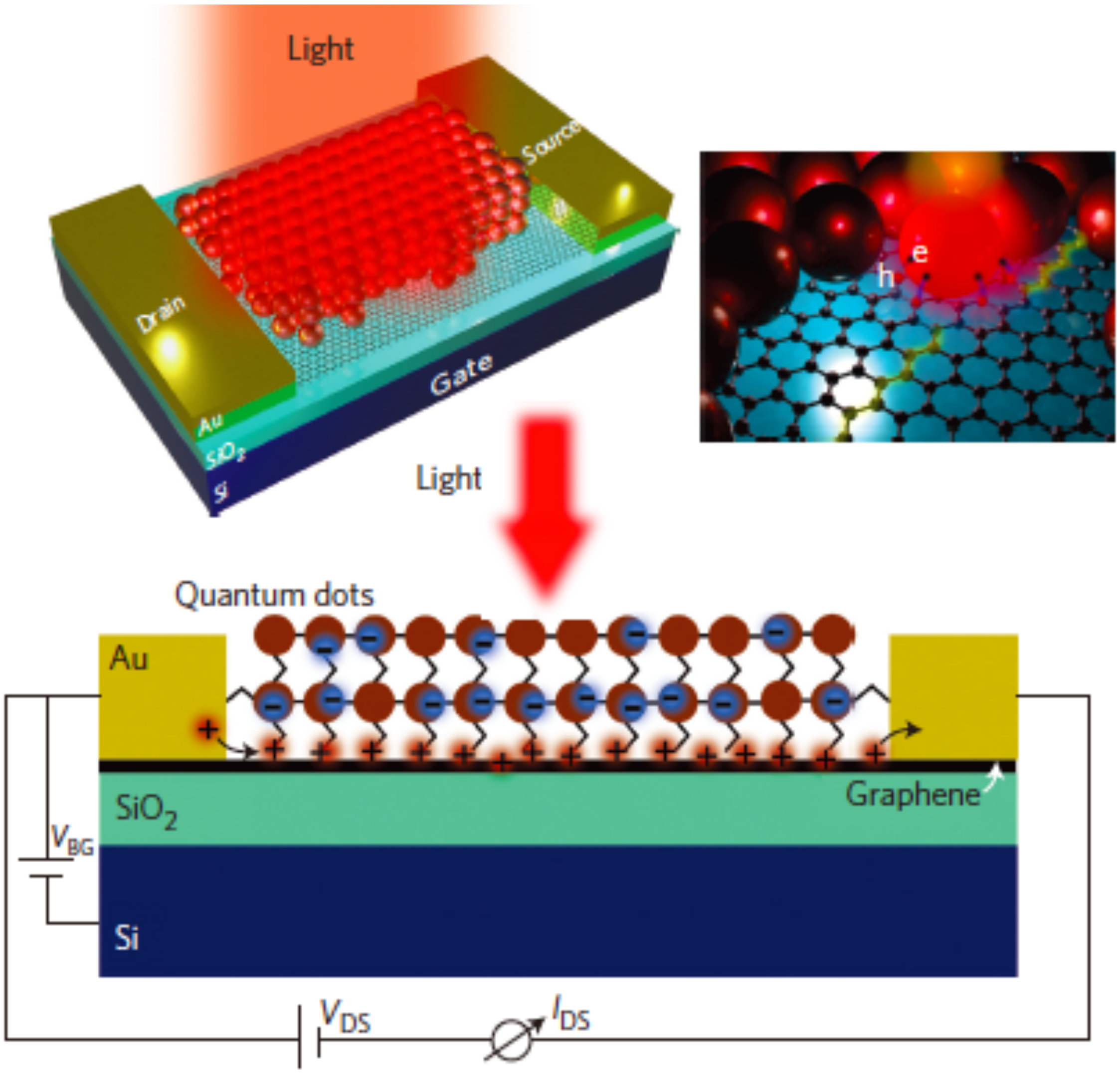
- Doping graphene with plasmonic hot electrons



- Graphene nanostructures
  - nanodisk
  - nanoring



Hole doping graphene



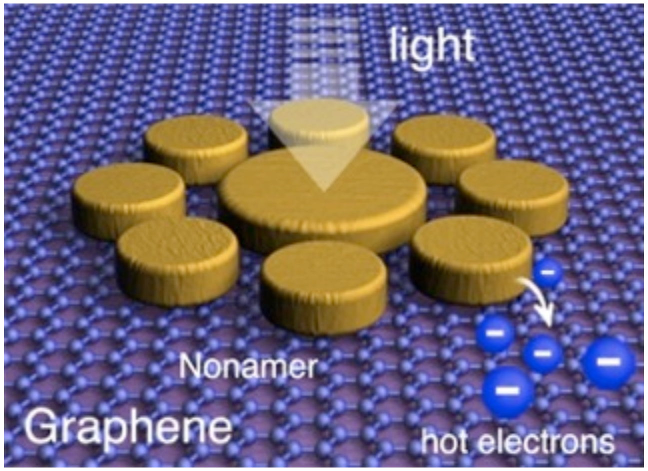
p-type doping graphene with quantum dots

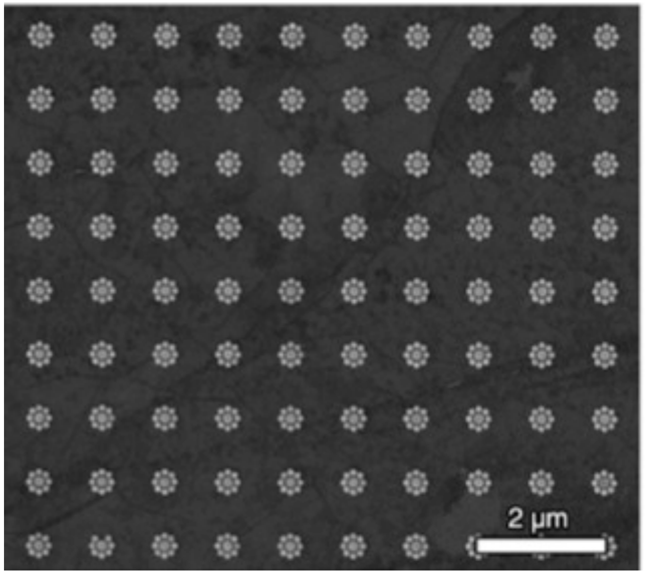
Hole injection!

Can we realize *n*-type doping graphene by plasmonic hot electrons?

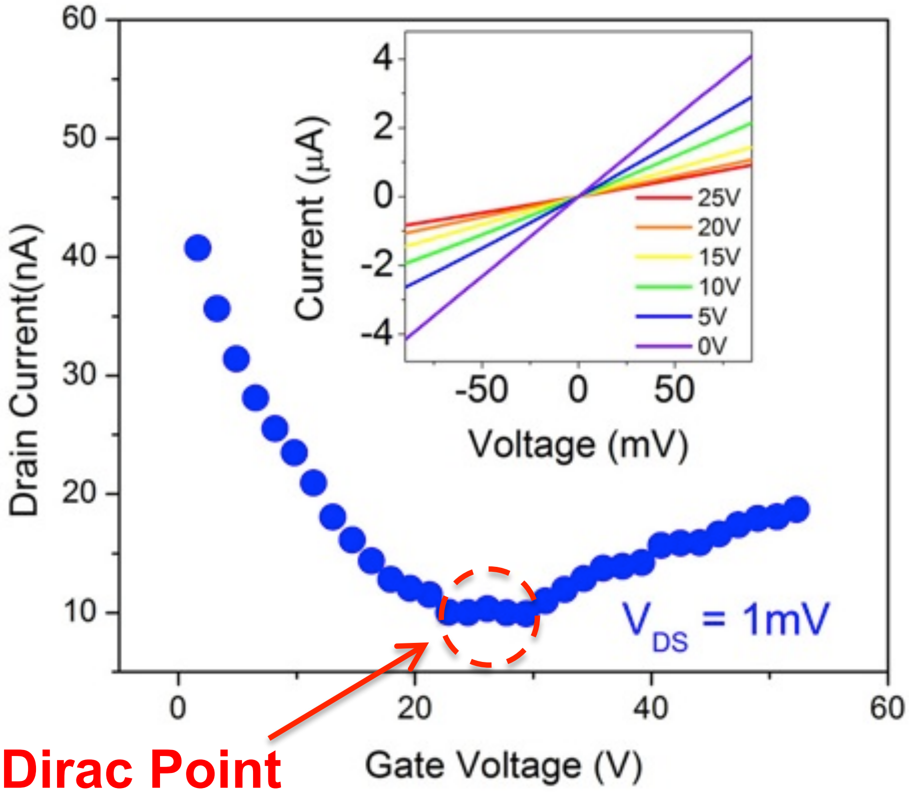
F. Koppens et.al. *Nature Nano*. **7**,363 (2012)

Graphene-Antenna Device





SEM image for the nonamer fabricated on graphene using E-beam lithography



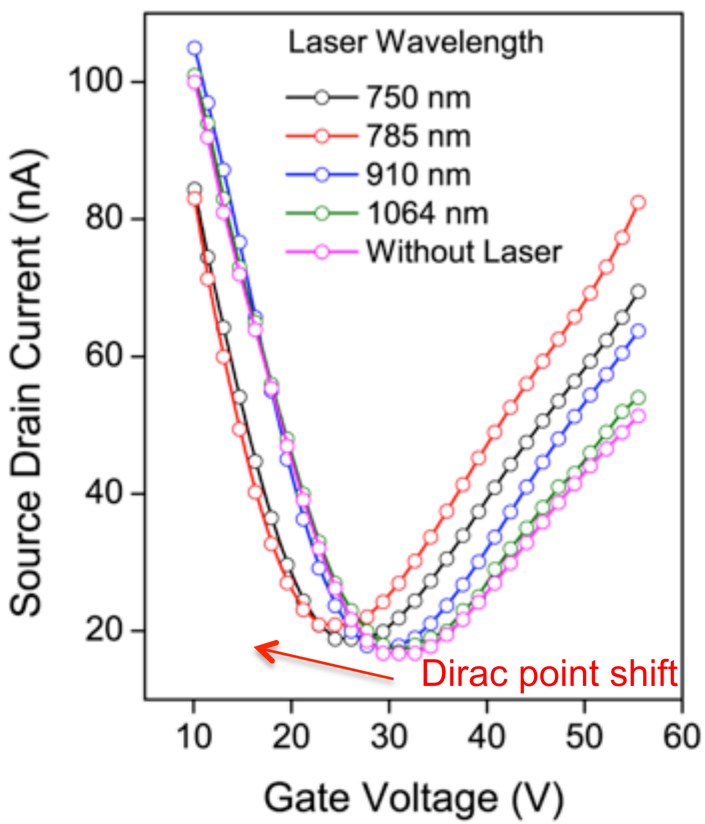
Dirac Point

Electrical Transport Characteristic
at a source-drain bias of 1 mV
Inset: *I-V* plots for various gate voltages V_G from 0 to 60V

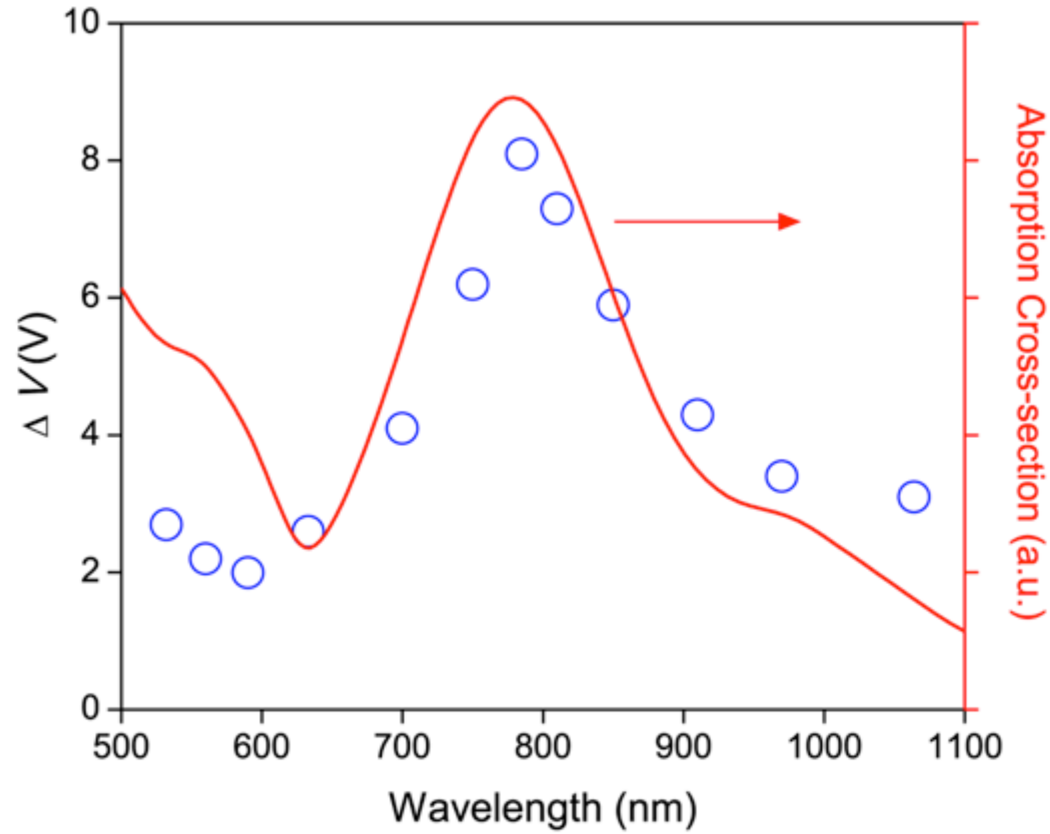
Z. Fang, F. Koppens, et. al. *ACS Nano*

Dirac point shift with absorption

Constant power and antenna size



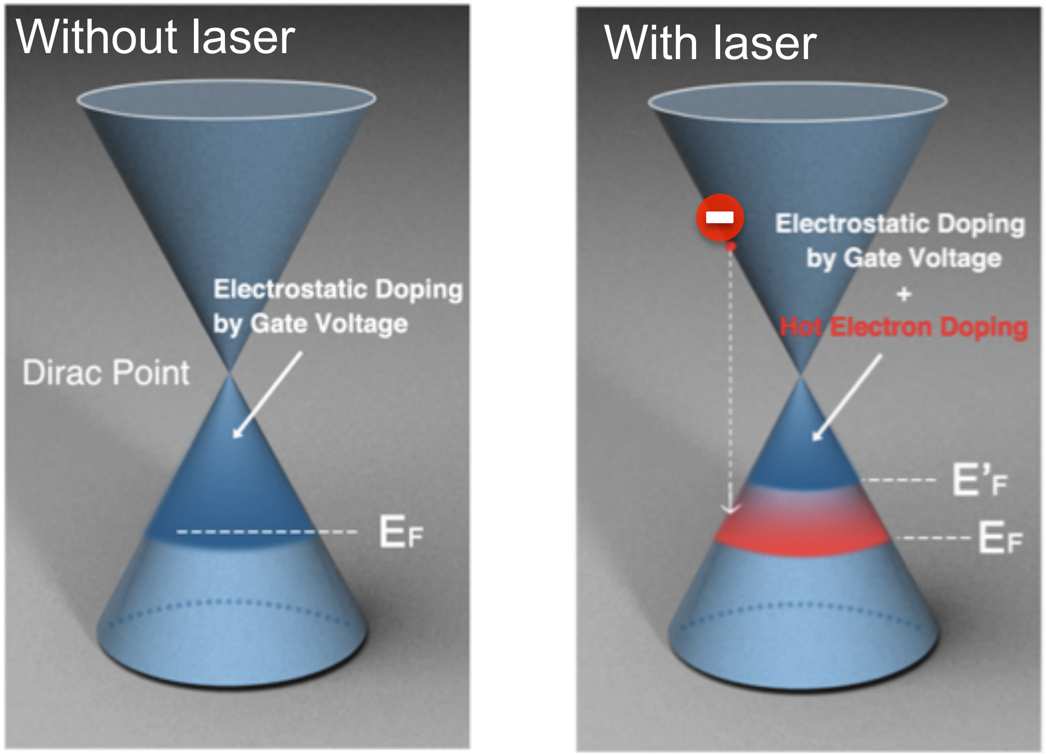
Incident Wavelength Dependence



- Electrical transport characteristic (I-V_G curves) of the nonamer antenna-graphene phototransistor

Z. Fang, F. Koppens, et. al. *ACS Nano*

Dirac point shift with absorption



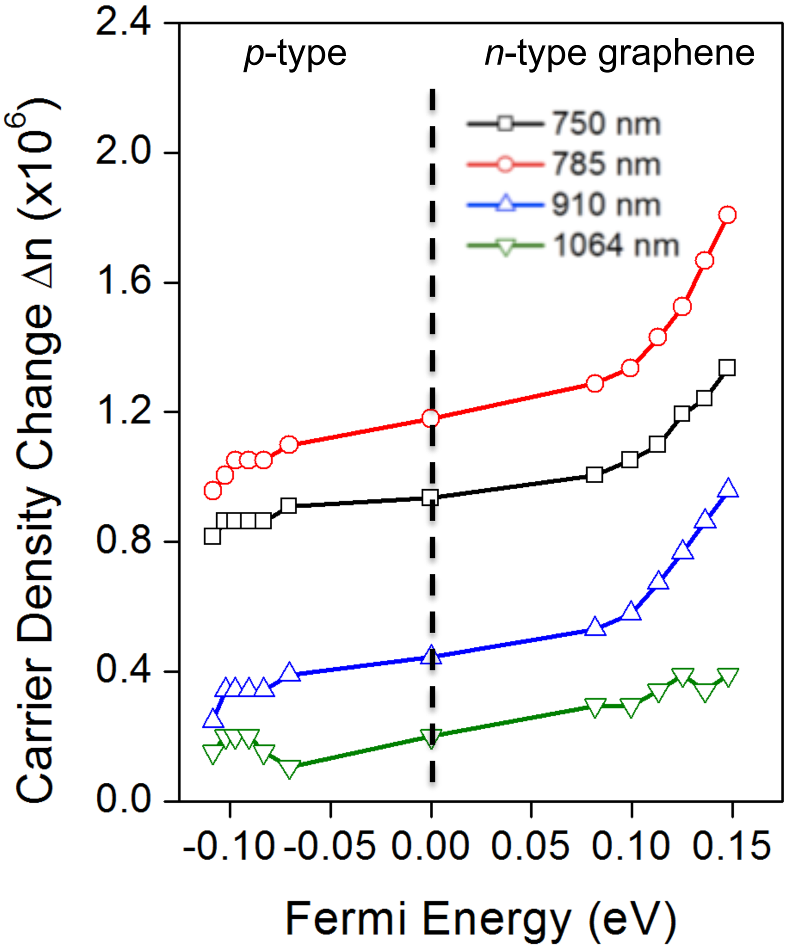
$N_{ES}=Q/e=C_g V/e$ $\quad$ $N=N_{ES}+N_{HE}=C_g V'/e+\alpha N_{HE}$

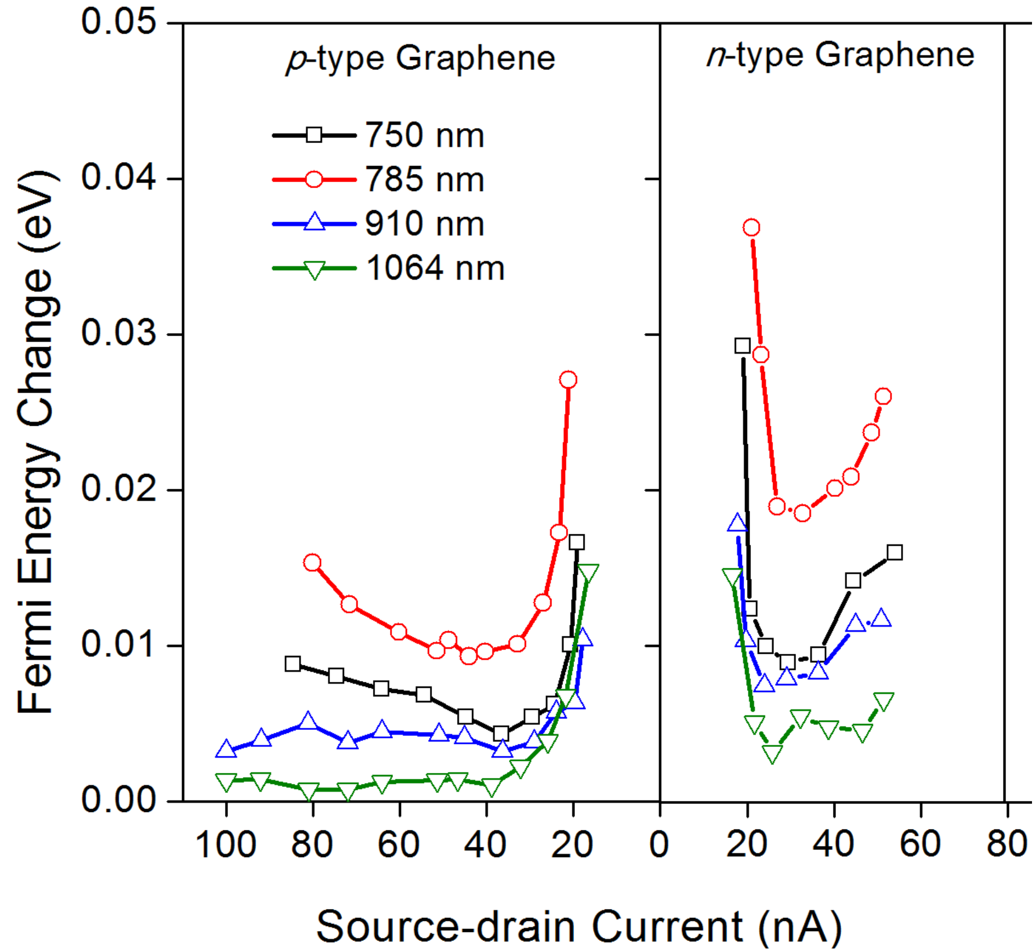
The recorded Dirac point shift $\Delta V=|V-V'|$ is proportional to the nonamer absorption cross-section $\Delta V \propto \sigma_{abs}$

$$E_F = \hbar v_F \sqrt{\pi C_g (V_g - V_D) / eA}$$

Z. Fang, F. Koppens, et. al. *ACS Nano*

Dirac point shift with absorption





- Dependence of E_F with photogenerated carrier density change
- Dependence of Source-drain current on photogenerated E_F change

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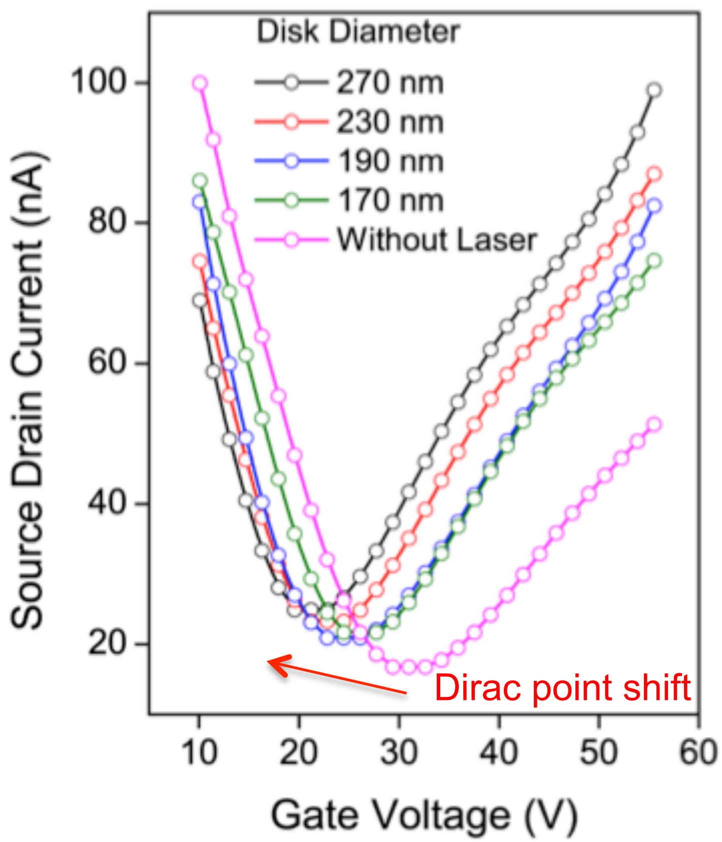
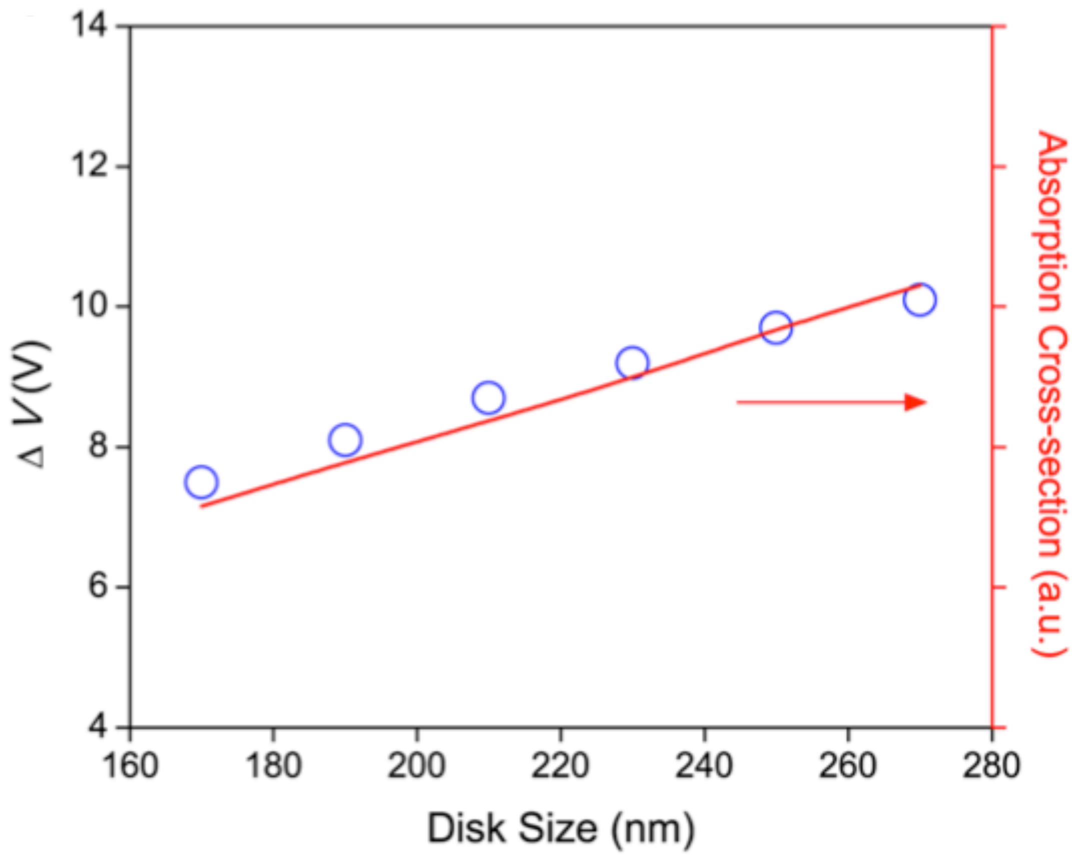
Antenna size control

Constant laser wavelength (785 nm) and power





- *I*-V_G curves for different sized nonamer array
- Dirac point shift data and the fitting curve simulated from structure absorption

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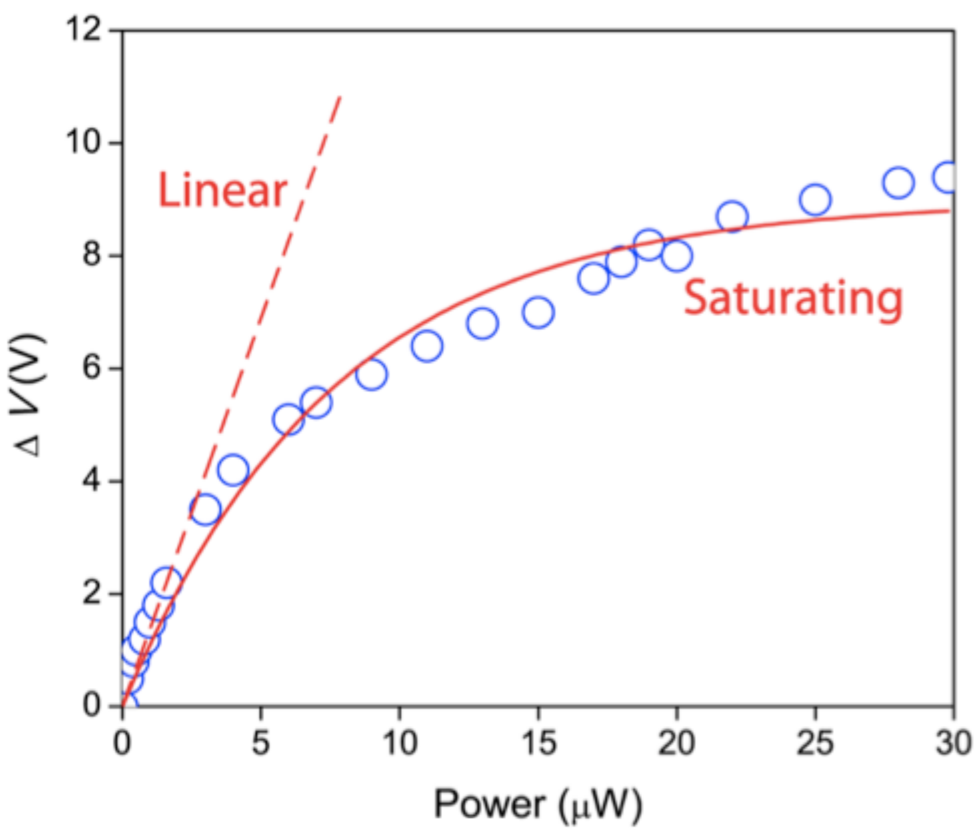
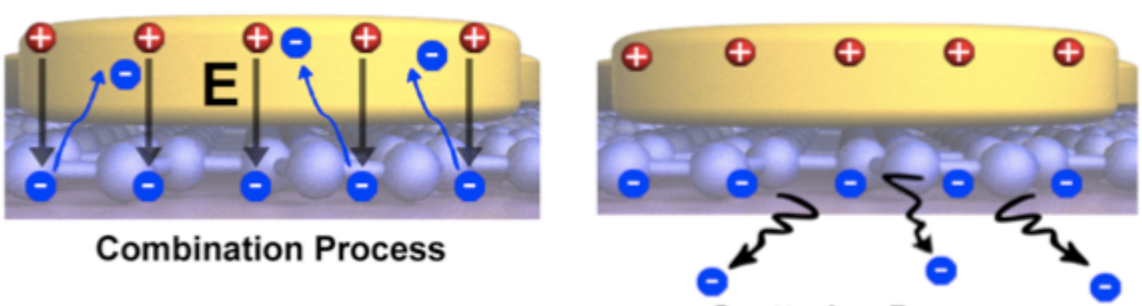
Hot electron recombination and scattering

Constant laser wavelength and antenna size





Recombination:
The internal electrostatic field drives a portion of the electrons back to the antenna

Scattering:
Injected hot electrons with the excessive electrons in graphene induced by Coloumbic interactions

Doping timescale:
estimated as 10^{-6} s for the case ΔV= 4V (under 5 μW incident laser power)

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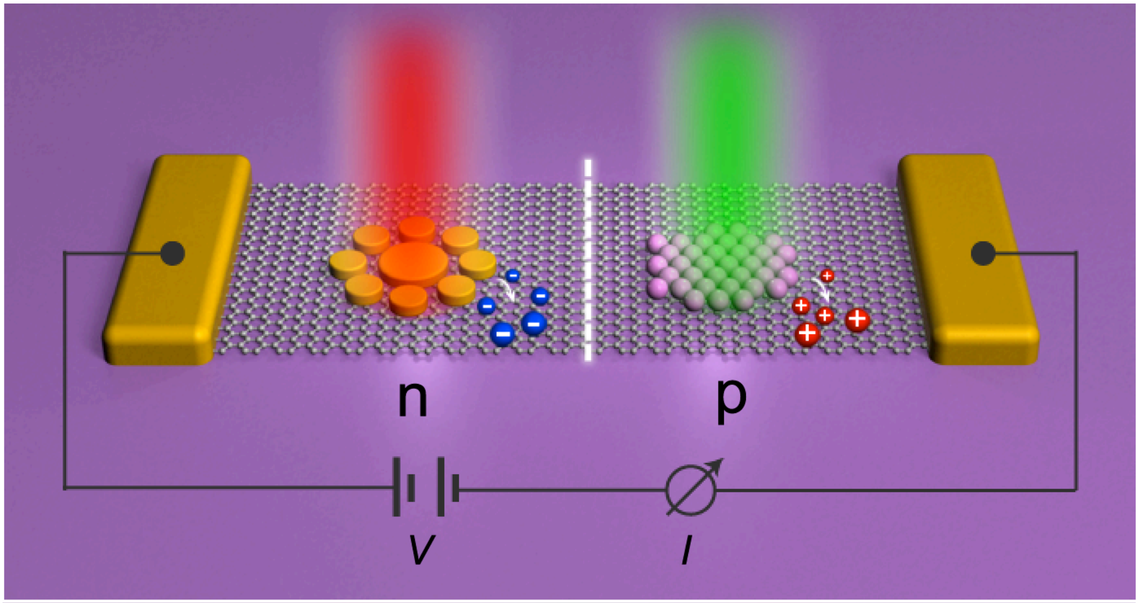
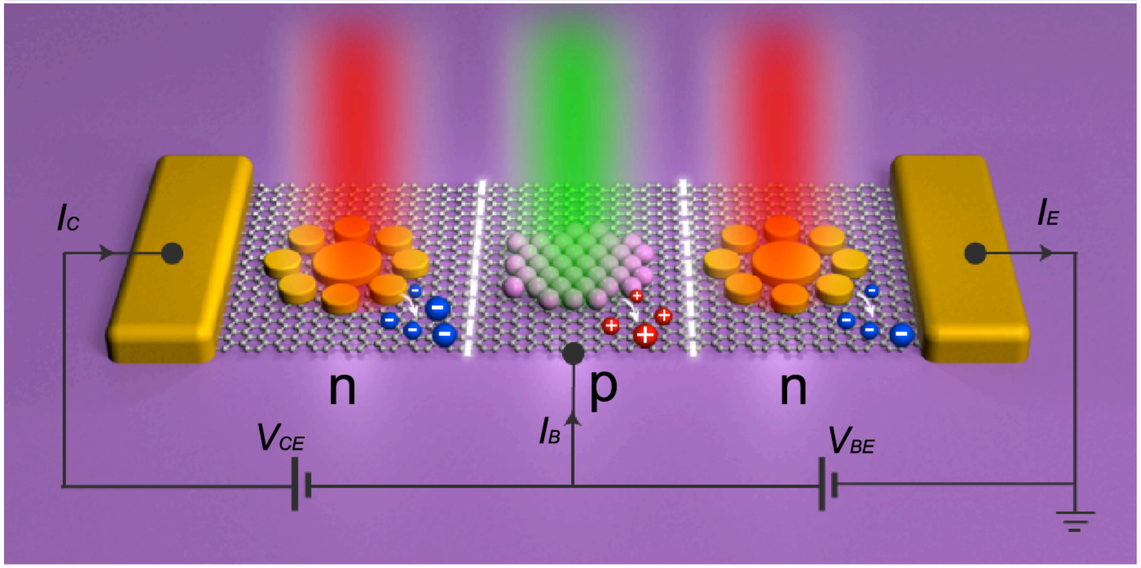
Optical Induced Circuitry



Optical Induced graphene *p-n* junction



Optical Induced graphene *n-p-n* transistor

Z. Fang, F. Koppens, et. al. *COVER ACS Nano*

Summery: hot electron doping graphene

Plasmonic hot electron doping graphene:

Different incident laser, antenna size, and incident laser power

Nonlinear saturating trend:

Hot electron recombination in Au antenna, and electron scattering in graphene

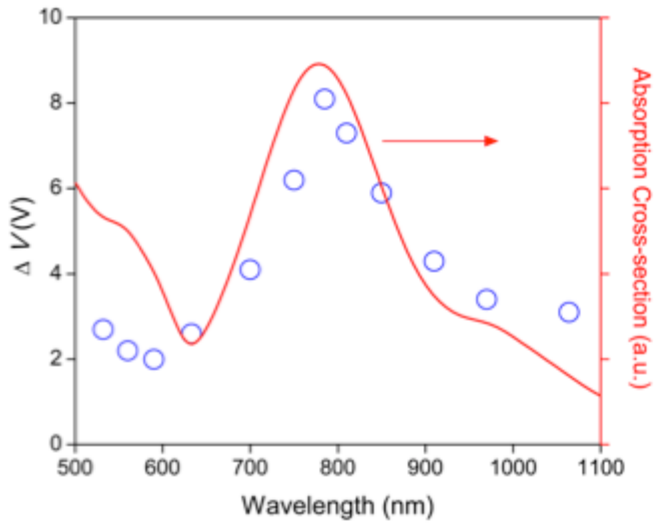
Time scale:

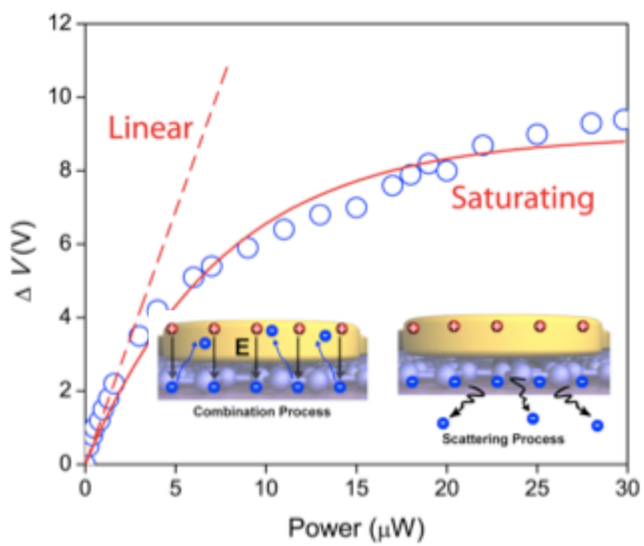
Hot electron doping (10^{-6} s) is much faster then *p*-type doping by using quantum dots

Optical Induced Circuitry:

p-n junction;

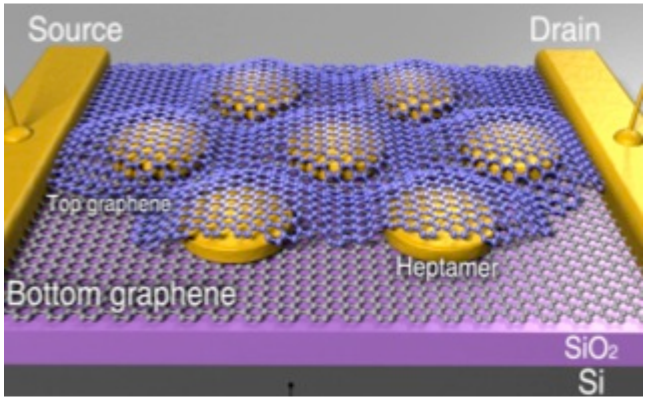
n-p-n transistor



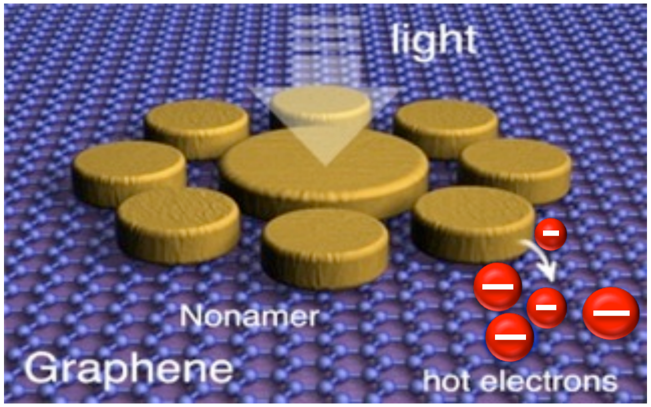


Outline

- Antenna-enhanced graphene sandwich photodetector



- Plasmonic hot electrons doping graphene



- Graphene Nanostructures
  - nanodisk
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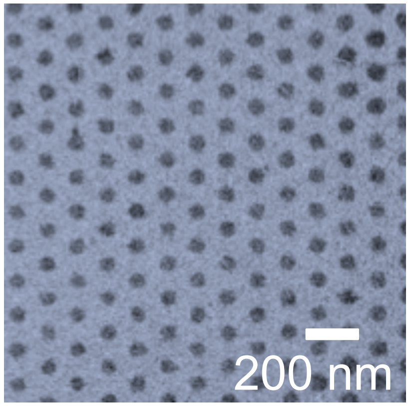
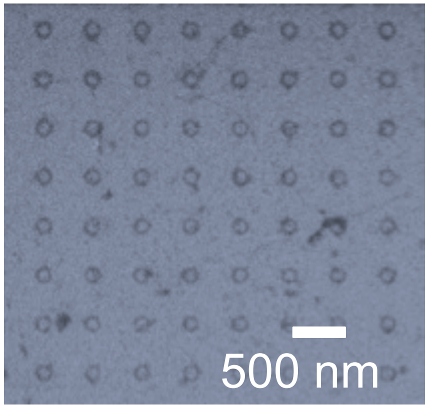
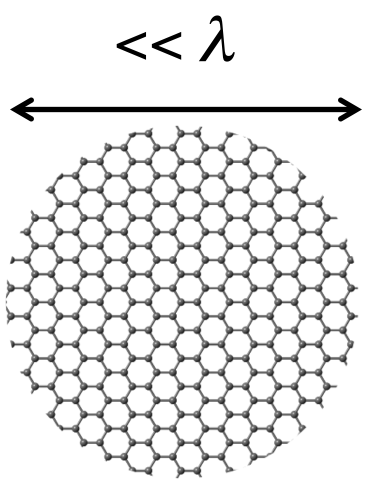


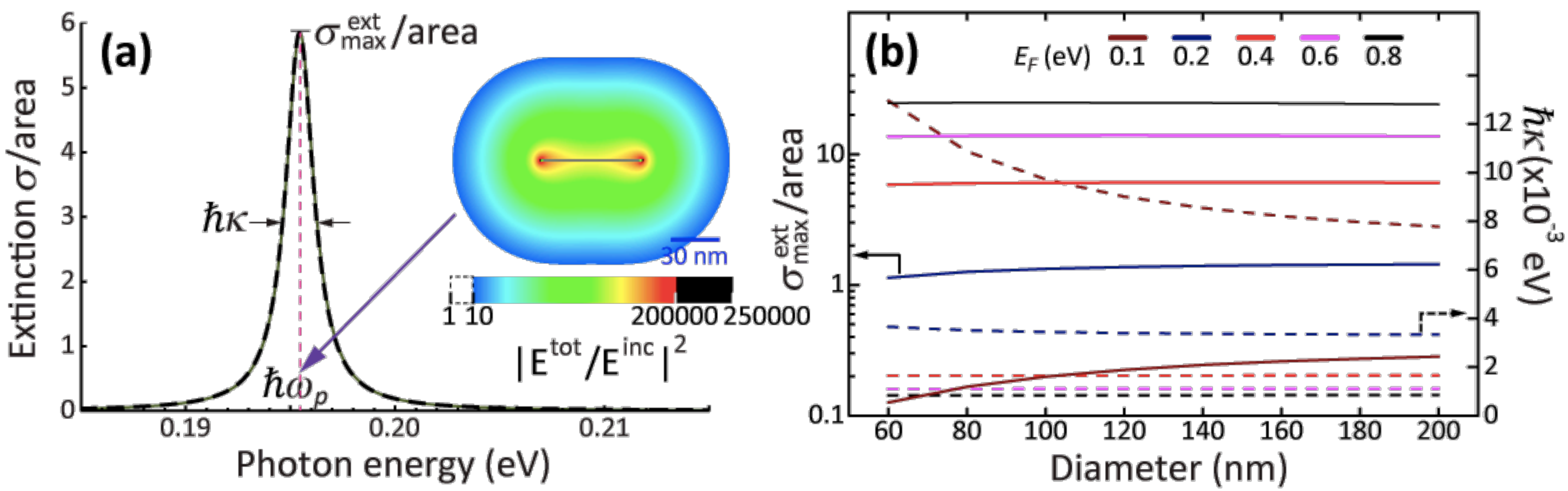


Graphene nanodisk: plasmonic dipolar mode



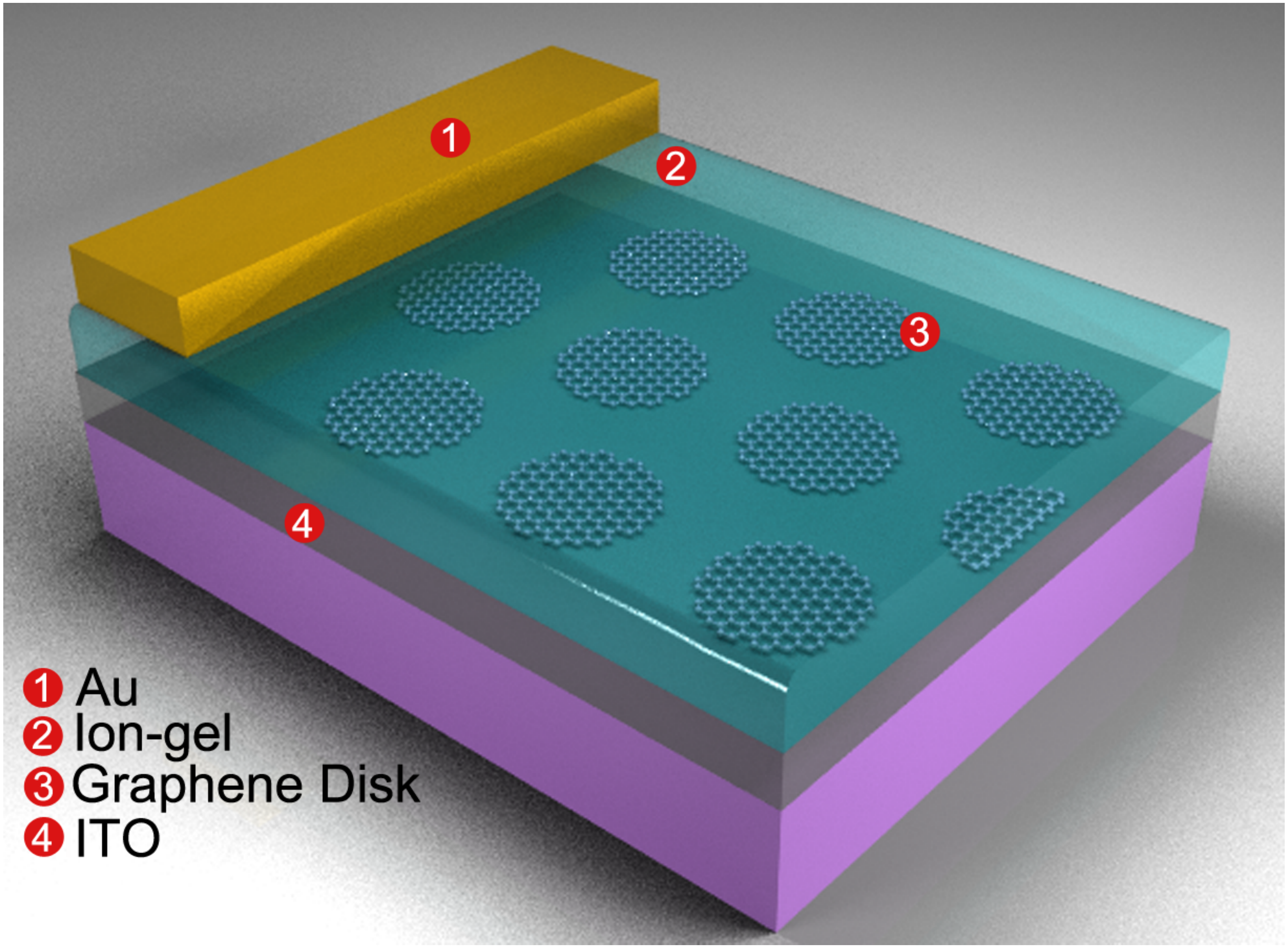
$$\alpha(\omega) = \frac{3c^3}{4\omega^3} \frac{\kappa_r}{\omega_p - \omega - i\kappa/2}$$

$$\sigma^{\mathrm{ext}}(\omega) = \frac{4\pi\omega}{c} \mathrm{Im}\{\alpha\} \approx \frac{3\lambda^2}{2\pi} \frac{\kappa_r}{\kappa}, \qquad \kappa_r << \kappa$$



S. Thongrattanasiri *et al*., Phys. Rev. Lett. (2012)

Device Schematic



Ion Gel Top Gating Method

Start with SiO_2 substrate

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Ion Gel Top Gating Method

Deposit ITO layer

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Ion Gel Top Gating Method

Transfer Graphene Monolayer

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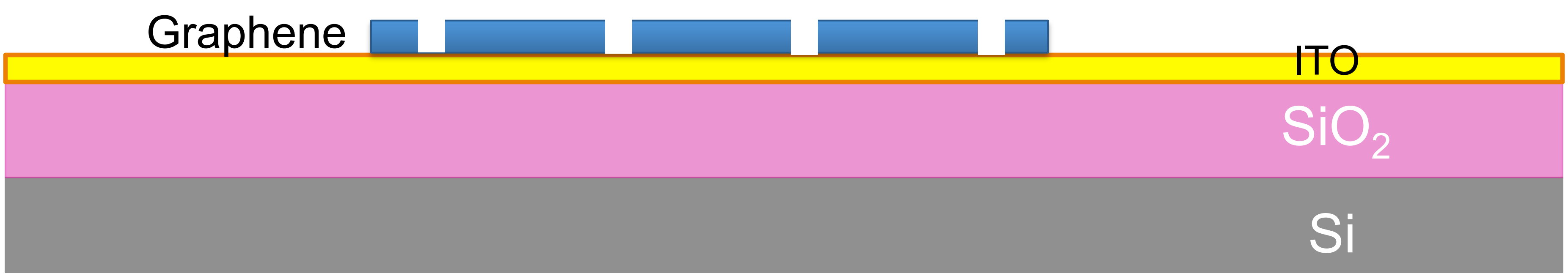
Ion Gel Top Gating Method

Pattern graphene with nanodisk array



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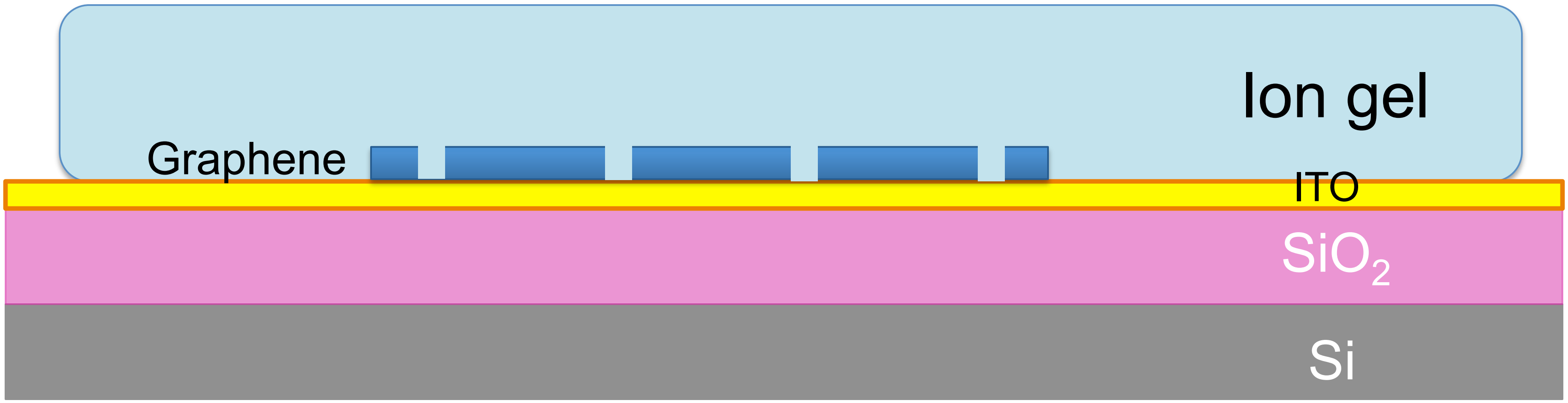
Ion Gel Top Gating Method

Spin-coating Ion gel



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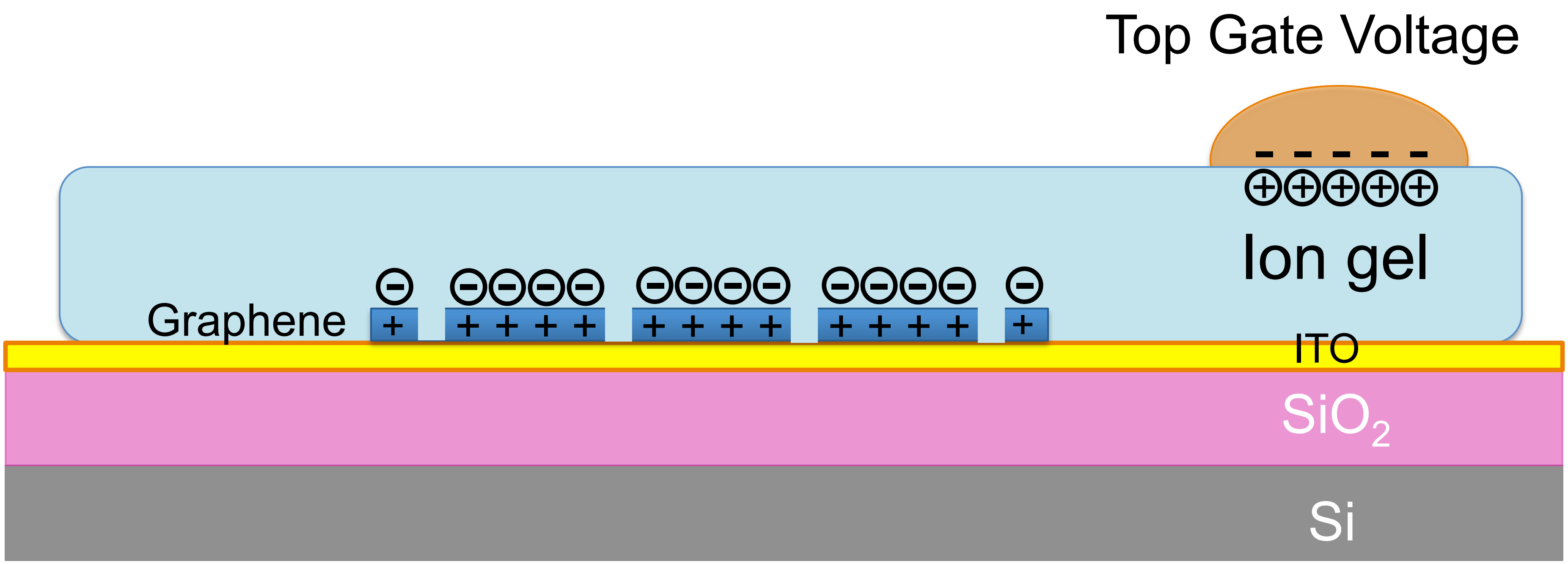
Ion Gel Top Gating Method

Apply gate voltage



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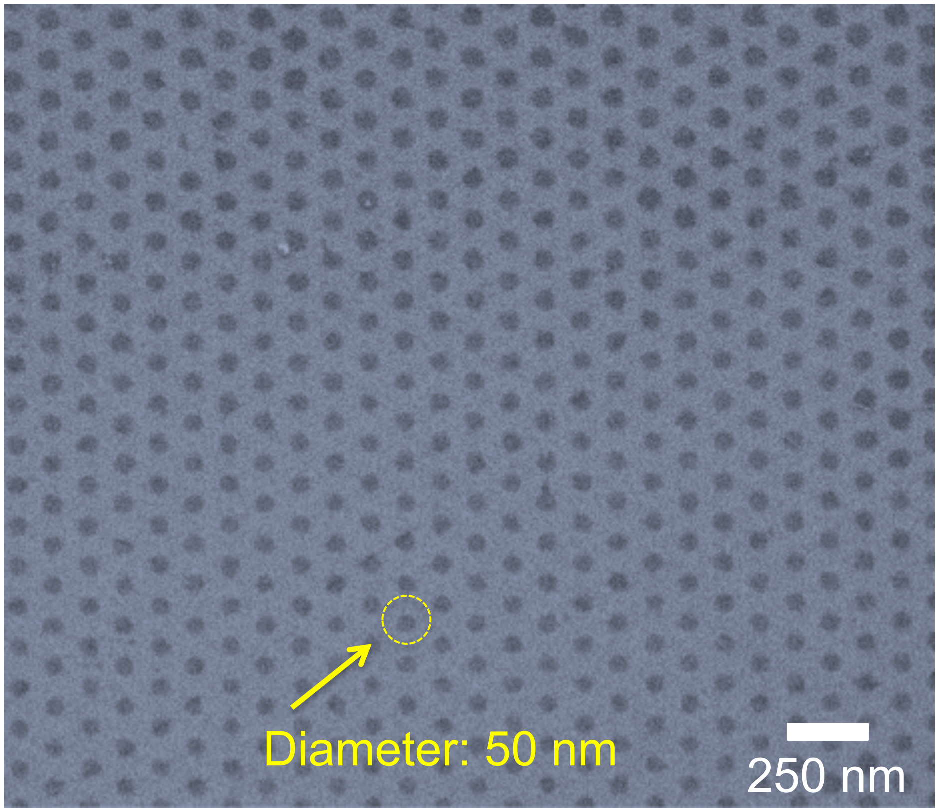
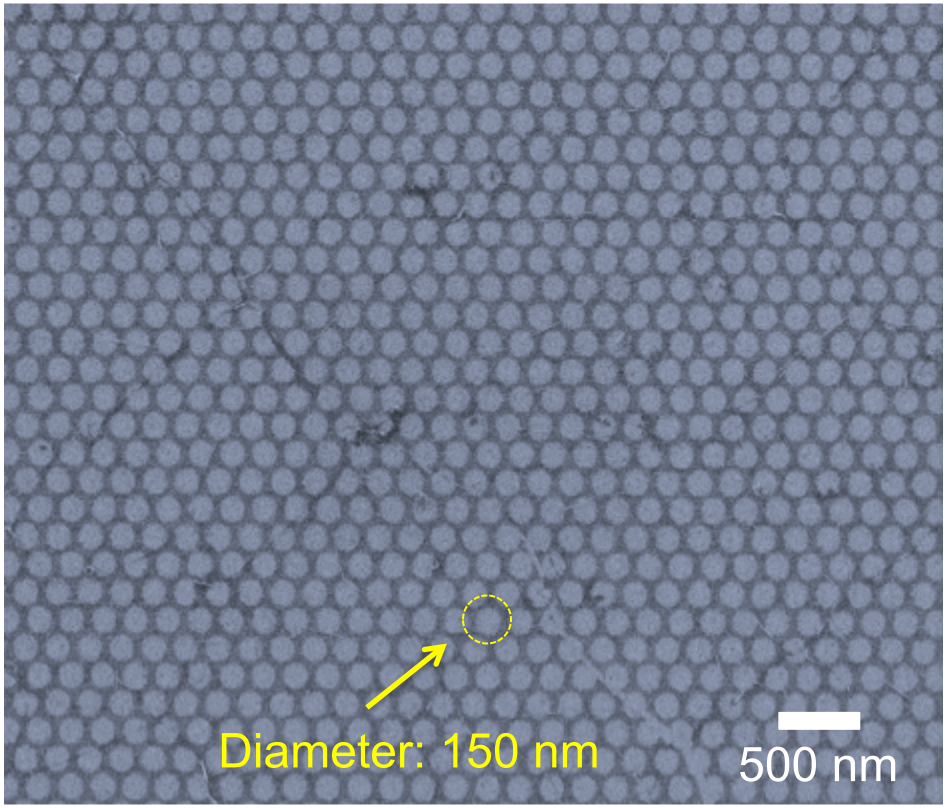
Graphene Nanodisk (D=50 nm) and Nanohole Array

Graphene Nanodisks



Graphene Nanoholes



Center to center distance: 120 nm
SiO_2 thickness: 285 nm
ITO thickness: 50 nm
Ion gel thickness: 100 nm

Center to center distance: 250 nm

We can see the graphene wrinkle

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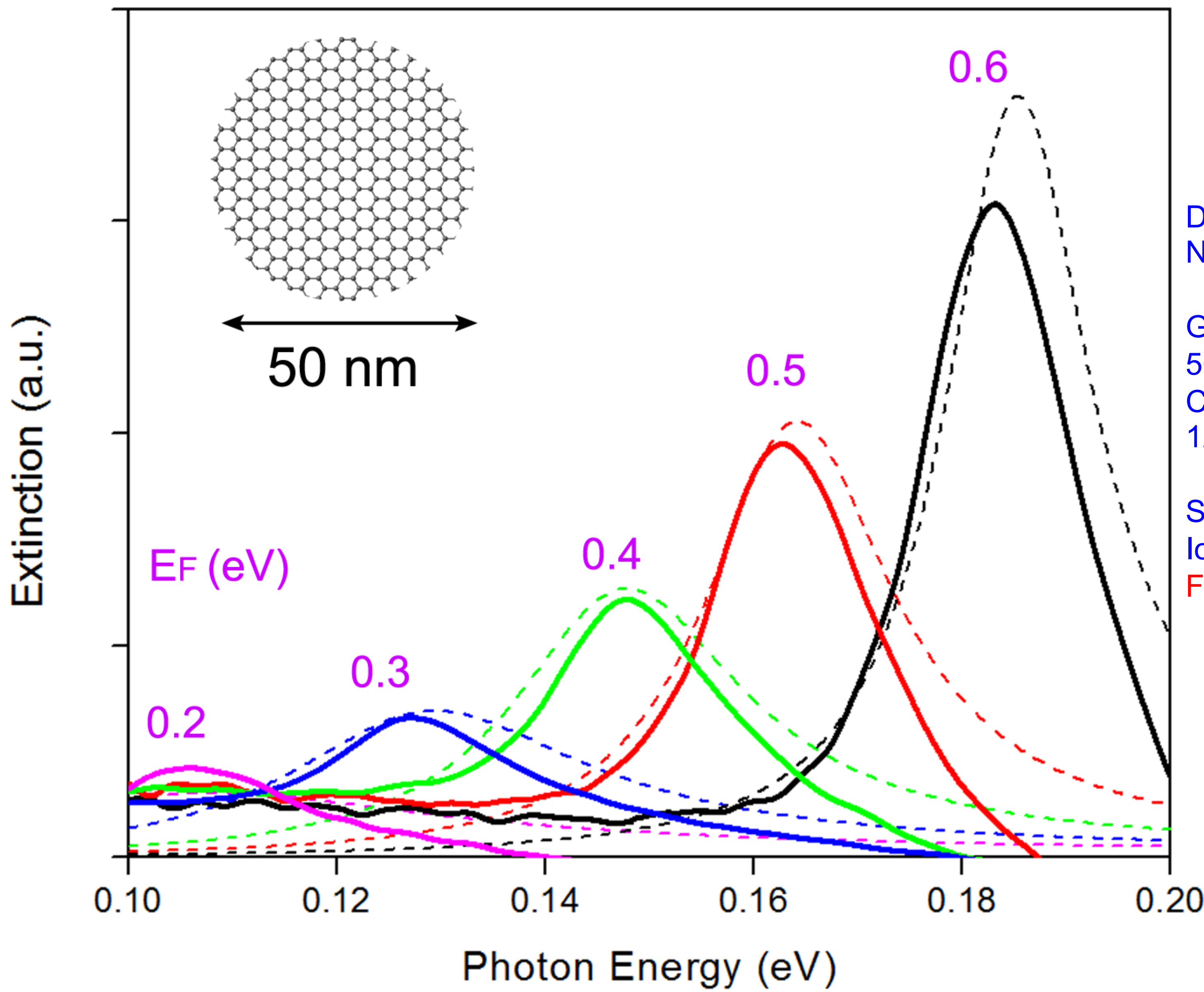
Graphene nanodisk plasmon dipolar mode



Detected by using FTIR:
Normal incidence

Graphene disk diameter:
50 nm
Center to center distance:
120 nm

SiO2 thickness: 285 nm
Ion gel thickness: 100 nm
Fermi energy: 0.2 to 0.6 eV

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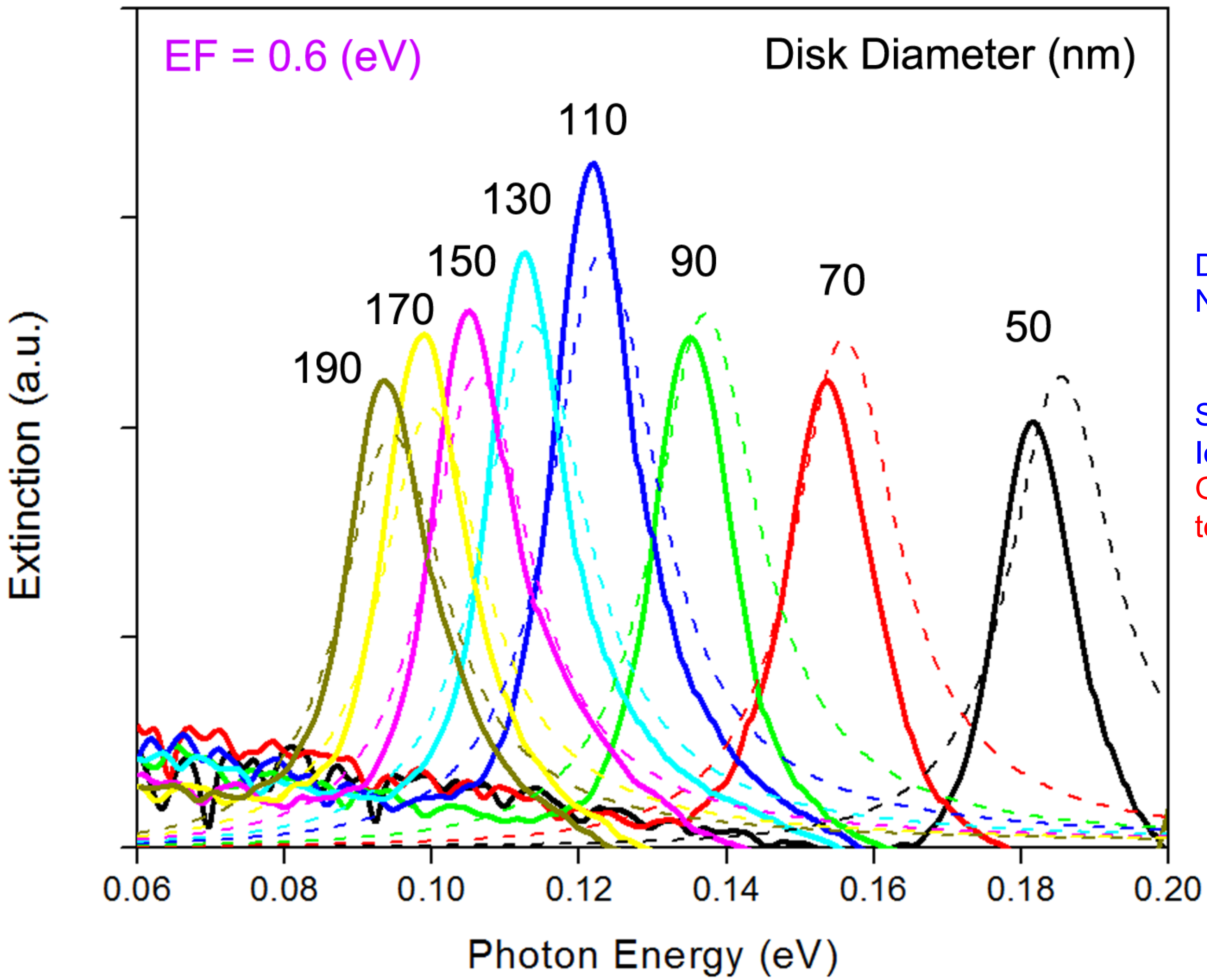
Graphene nanodisk size control



Detected by using FTIR:
Normal incidence

SiO_2 thickness: 285 nm
Ion gel thickness: 100 nm
Graphene disk diameter: 50 to 190 nm

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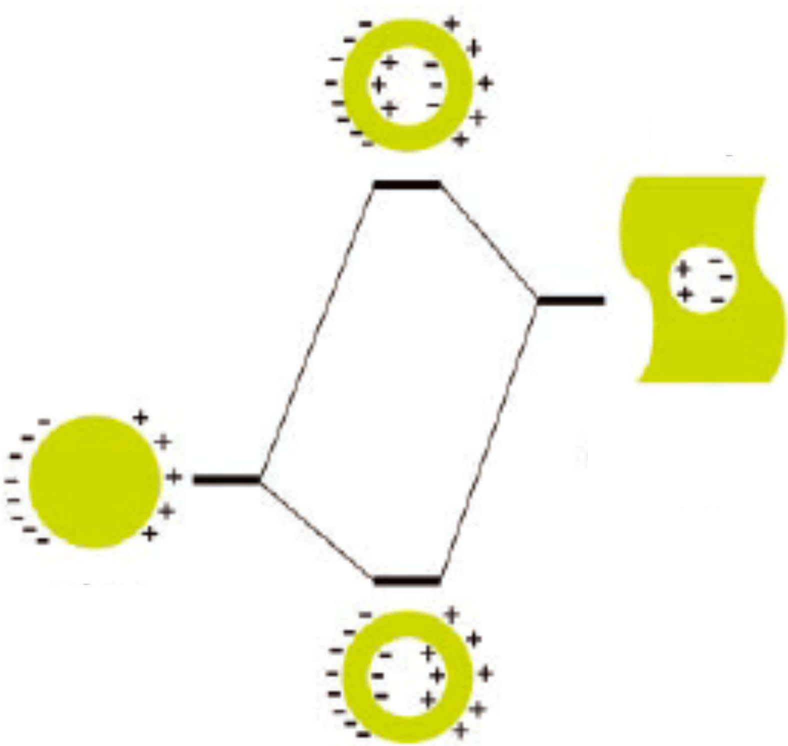
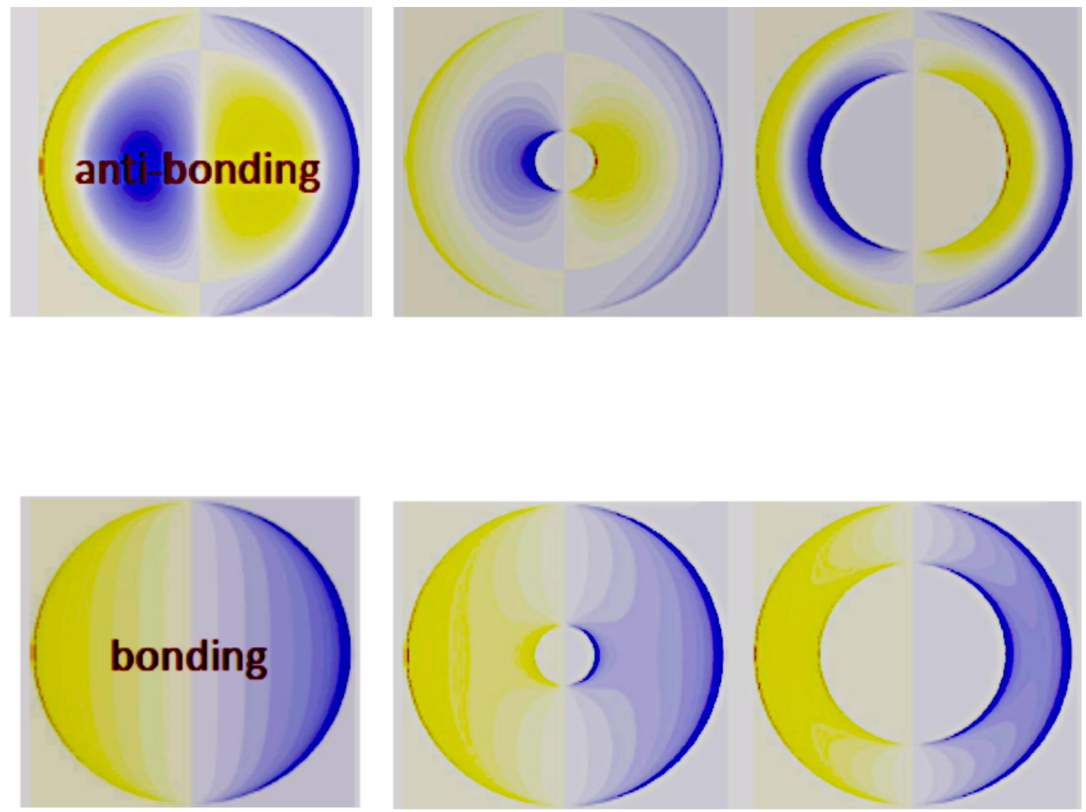
Plasmon hybridization for metallic nanorings



E. Prodan, et al, Science, 419, 2003

Graphene nanorings



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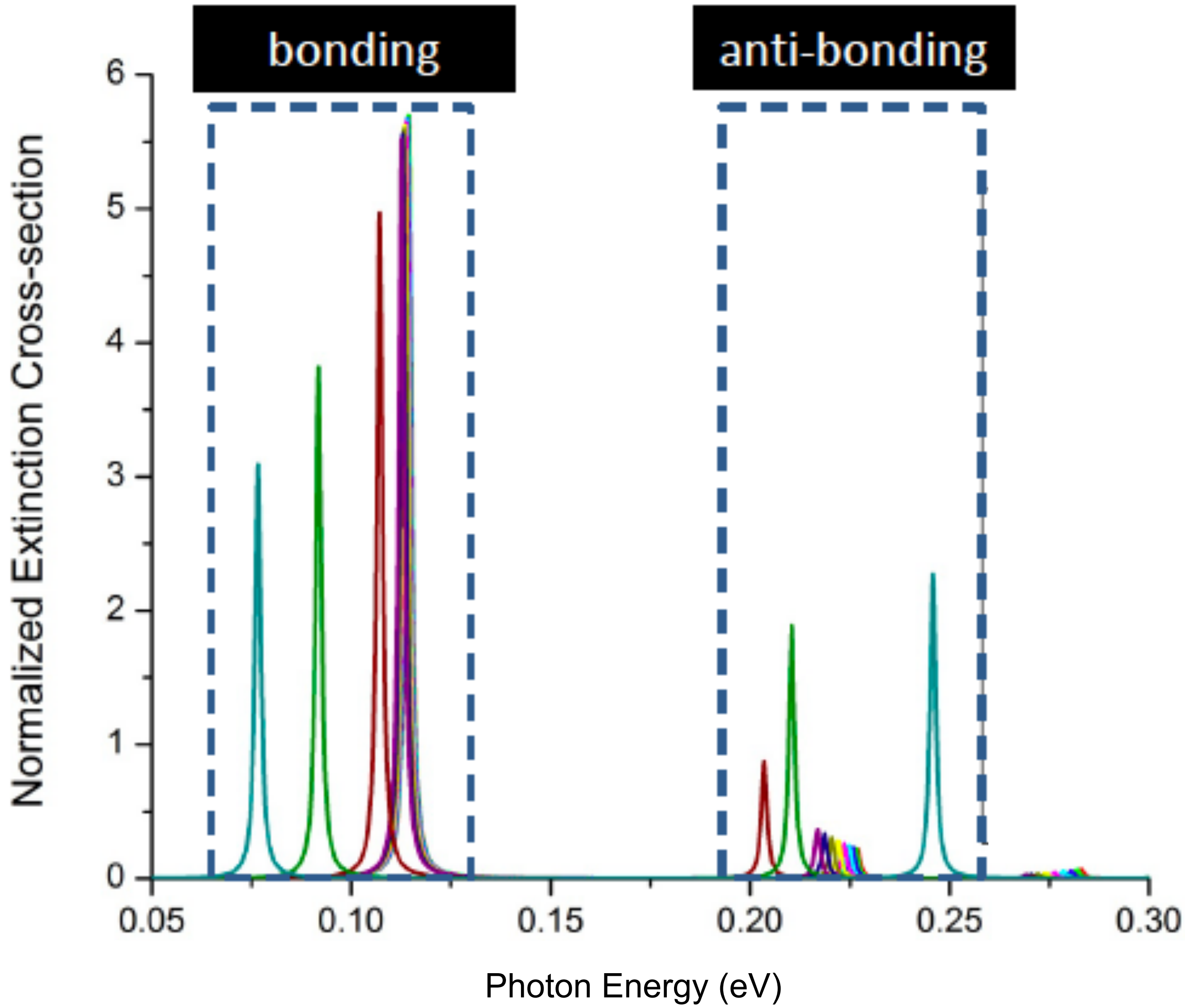
Theoretical Prediction



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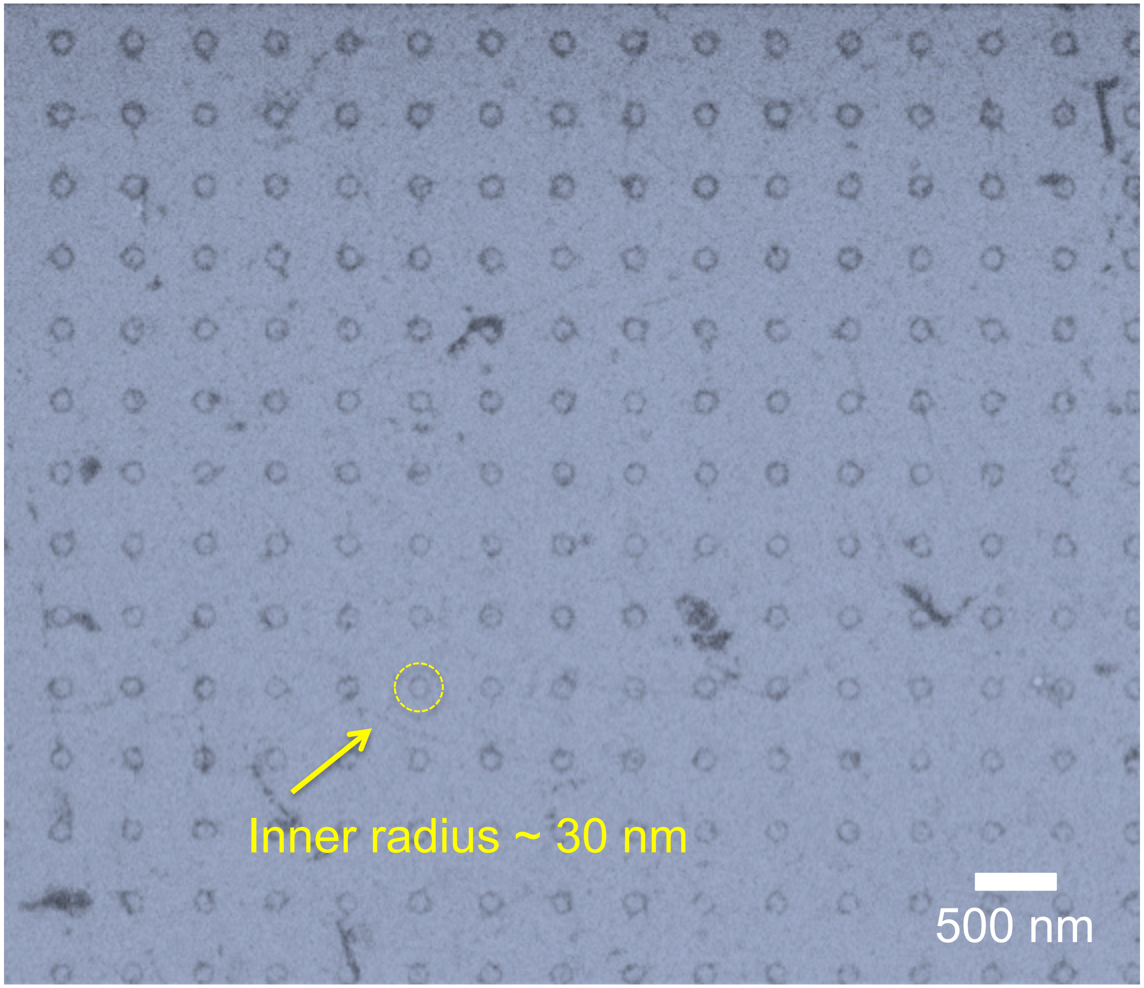
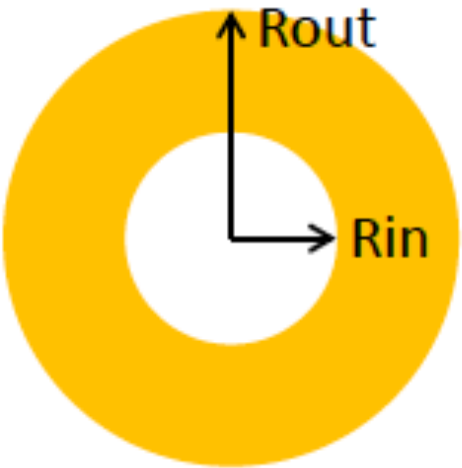
Graphene Nanoring Structure





R_{out}= 50 nm
R_{in}=30 nm

Period=500 nm

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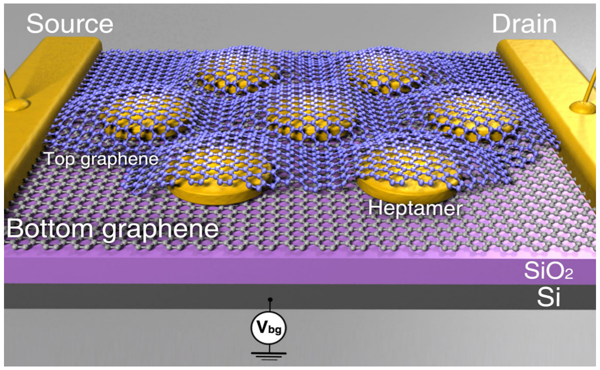
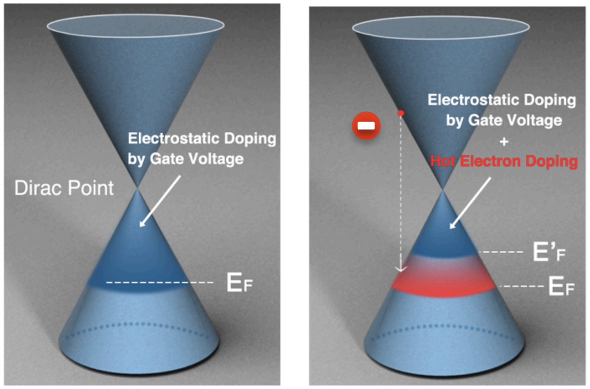
Conclusion

- Graphene-antenna photodetector
  - Sandwich structure
  - high enhancement in visible and NIR
  - High controllable device



- Plasmonic hot electrons doping graphene
  - Incident laser wavelength, power, antenna size
  - Hot electron recombination and further scattering
  - Doping time scale (10 μs)



- Graphene nanostructure
  - Nanodisk plasmonic dipoler resonance
  - Tuning with disk size and Fermi energy
  - Nanoring plasmonic bonding and anti-bonding modes