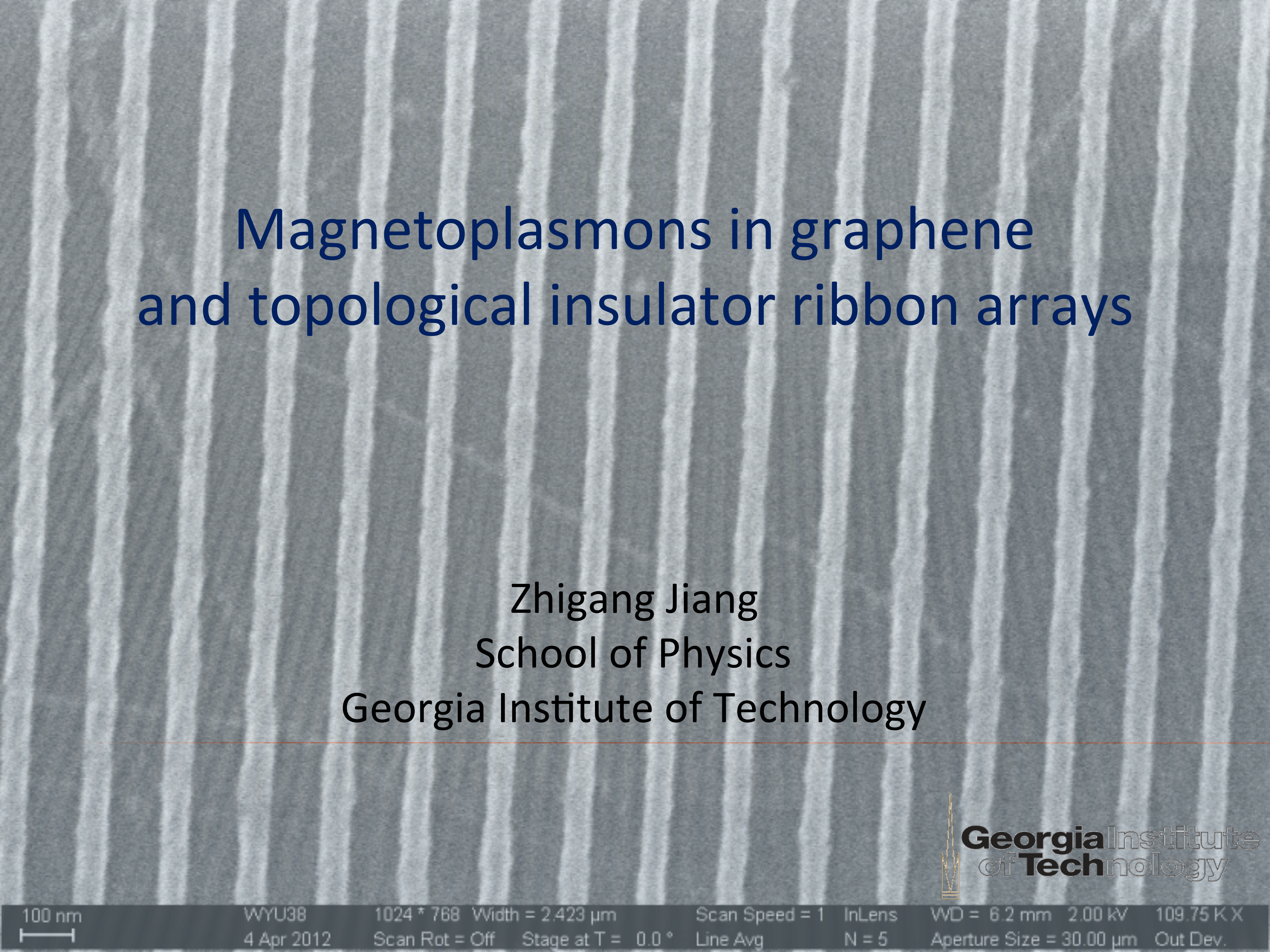
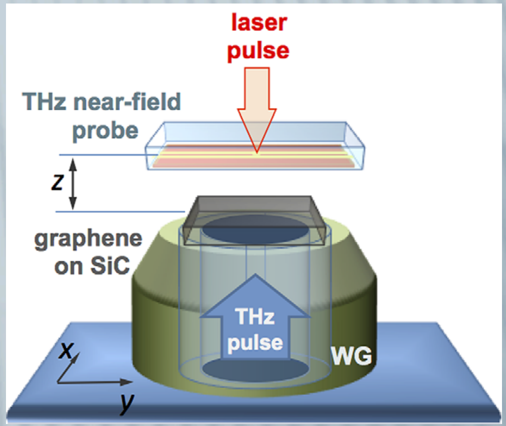
Magnetoplasmons in graphene and topological insulator ribbon arrays

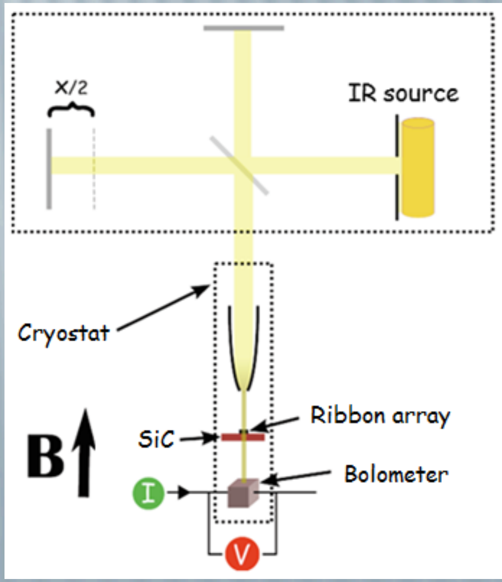
Zhigang Jiang
School of Physics
Georgia Institute of Technology



OUTLINE:

- Introduction to graphene and graphene-based tunable plasmonics and optoelectronics
- THz near-field imaging of surface plasmon waves in graphene micro-structures
- Dirac plasmons in graphene nanoribbons:
  (1) Upper-hybrid mode between cyclotron resonance and plasmon resonance
  (2) Peculiar $\propto(1/WB)$ scaling behavior
- Magnetoplasmons in topological insulators
  (1) Tunable upper-hybrid mode
  (2) Effective mass, $m^* \sim 0.23\ m_e$





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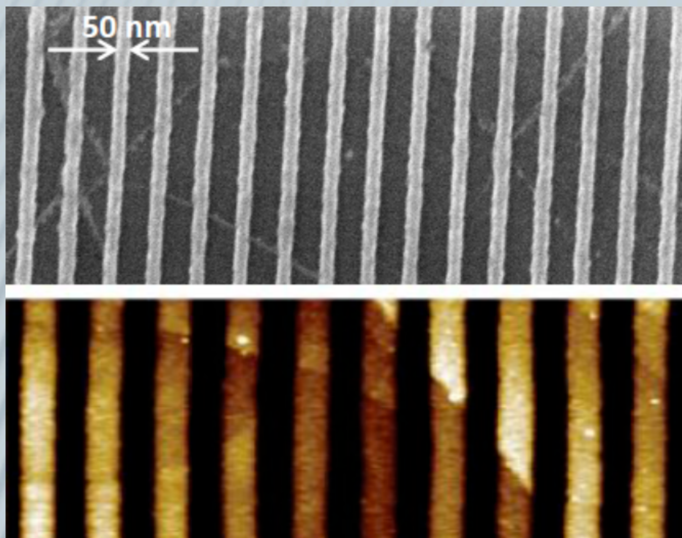
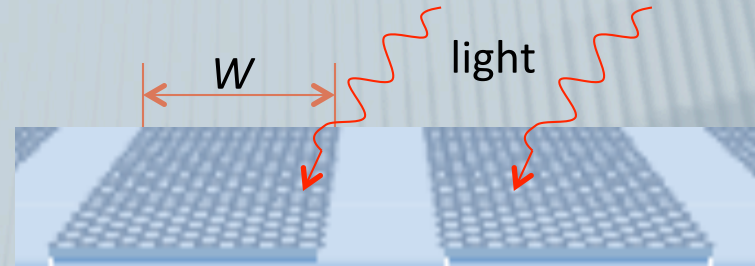
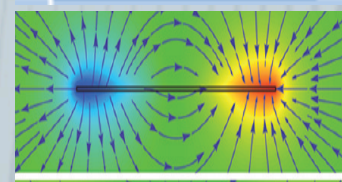
Introduction: Graphene plasmonics







$\lambda_{plasmon} = 2W$ "size" of plasmon

$$q = \frac{2\pi}{\lambda} = \frac{\pi}{W}$$

Why graphene plasmonics?

	Light confinement $\lambda_{IR} / \lambda_{plasmon}$	Propagation loss-length	Tunability
Ag/Si	~20	~0.1 $\lambda_{plasmon}$	Limited
Graphene	~200	~10 $\lambda_{plasmon}$	$\omega_p \propto n^{1/4} W^{-1/2}$

M. Jablan et al. PRB **80**, 245435 (2009)
J. Christensen et al. ACS Nano **6**, 431 (2012)

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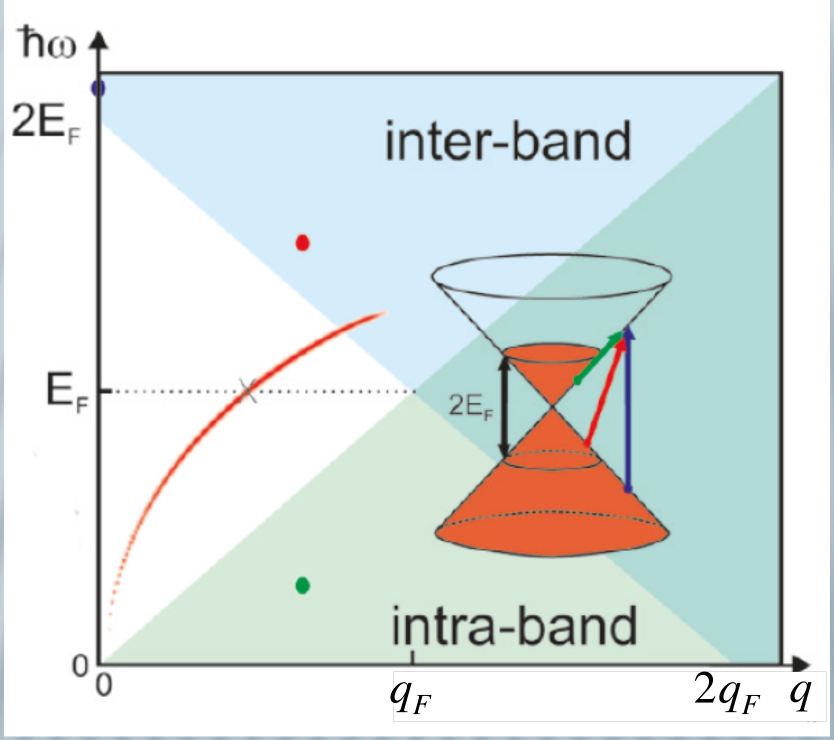
Plasmon dispersion in graphene

$$\omega_p \approx \sqrt{\frac{2e^2 E_F}{\epsilon} q} \quad \text{when} \quad q < q_F \qquad \left(q = \frac{\pi}{W}\right)$$



B. Wunsch et al. New J. of Phys. **8**, 318 (2006)
E.H. Hwang et al. PRB **80**, 205405 (2007)
R. Roldán et al. Semicond. Sci. Technol. **25**, 034005 (2010)

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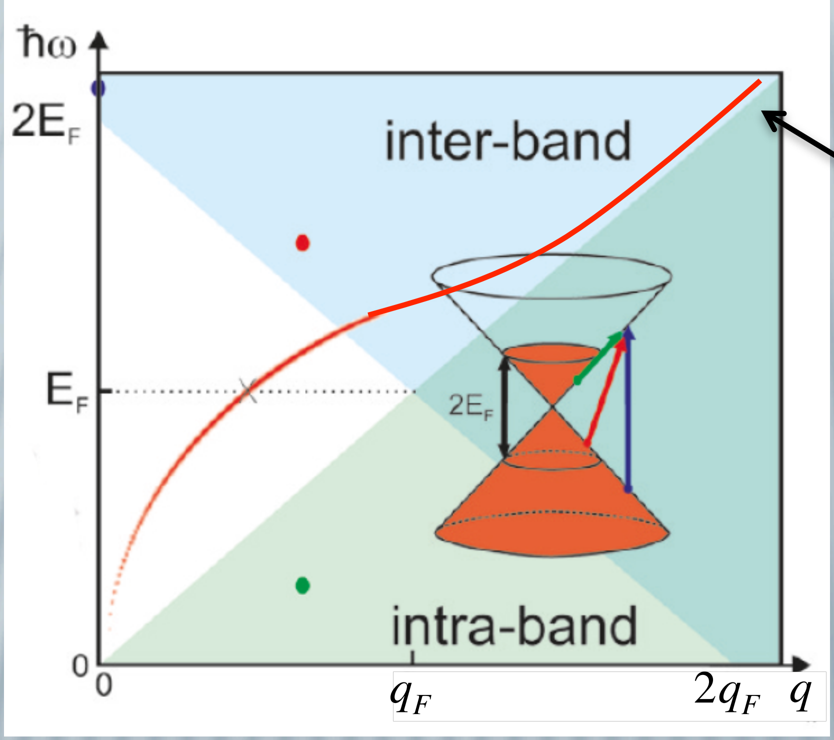
Plasmon dispersion in graphene

$$\omega_p \approx \sqrt{\frac{2e^2 E_F}{\epsilon} q + \gamma v_F^2 q^2}$$

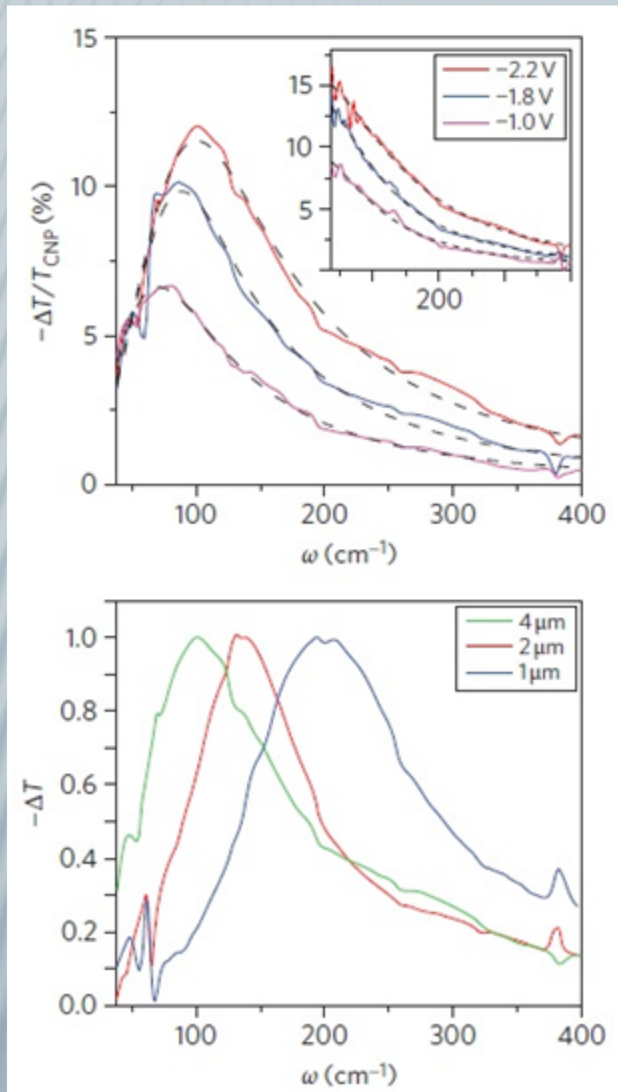


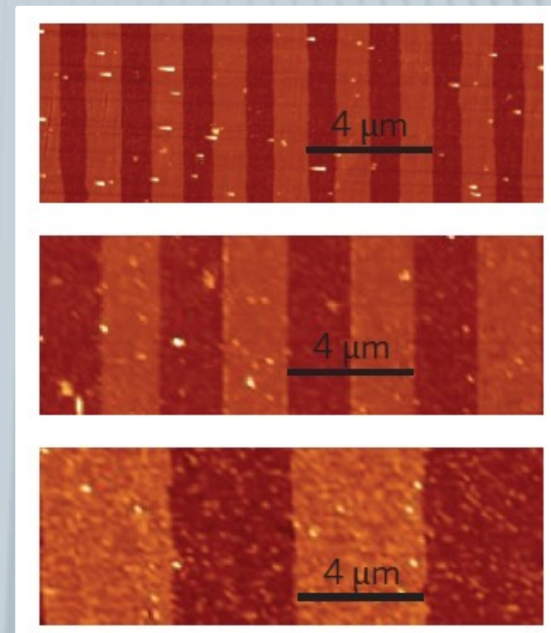
Approaching

$\omega = v_F q$

B. Wunsch et al. New J. of Phys. **8**, 318 (2006)
E.H. Hwang et al. PRB **80**, 205405 (2007)
R. Roldán et al. Semicond. Sci. Technol. **25**, 034005 (2010)

Tunable plasmons in graphene





$$\omega_p \; \alpha \; n^{1/4}.w^{-1/2}$$

(1) tunability
(2) long lifetime
(3) confinement: λ_{IR} / λ_{pl} ~50

L. Ju et al. Nat. Nanotechnol. **6**, 630 (2011)

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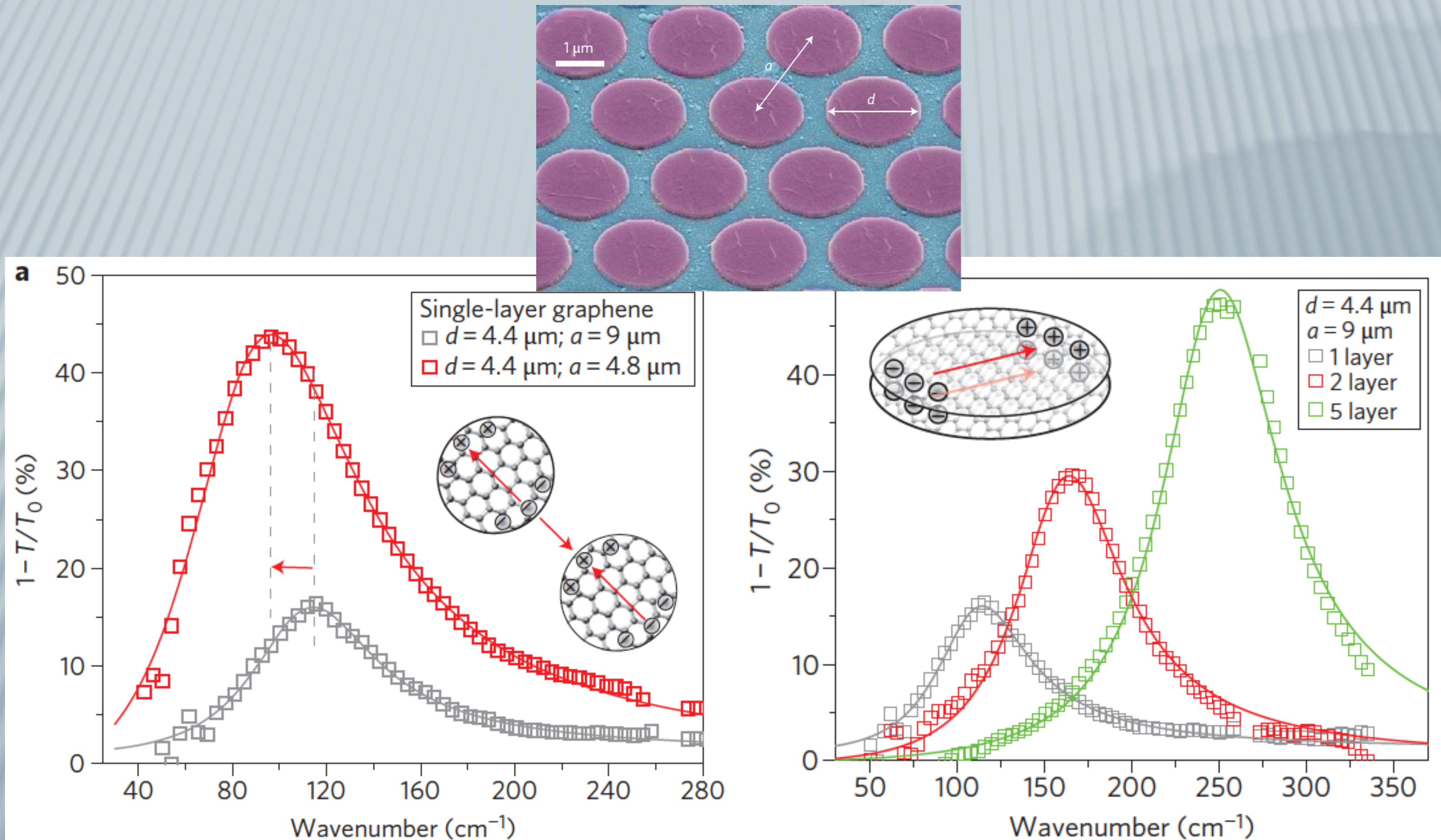
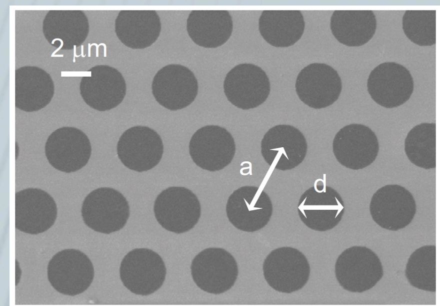
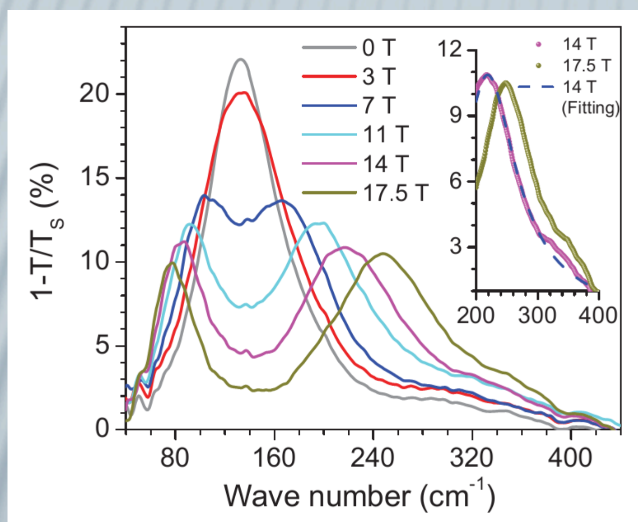
Tunable plasmons in graphene

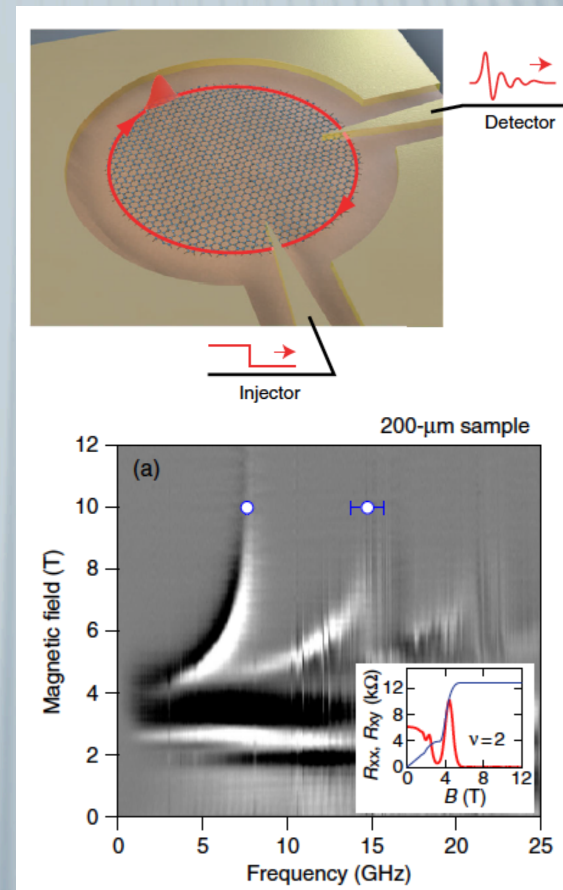


H. Yan et al. Nat. Nanotechnol. **7**, 330 (2012)

Tunable plasmons in graphene







H. Yan et al. Nano Lett. **12**, 3766 (2012)
I. Crassee et al. Nano Lett. **12**, 2470 (2012)
I. Petković et al. PRL **110**, 016801 (2013)
N. Kumada et al. PRL **113**, 266601 (2014)

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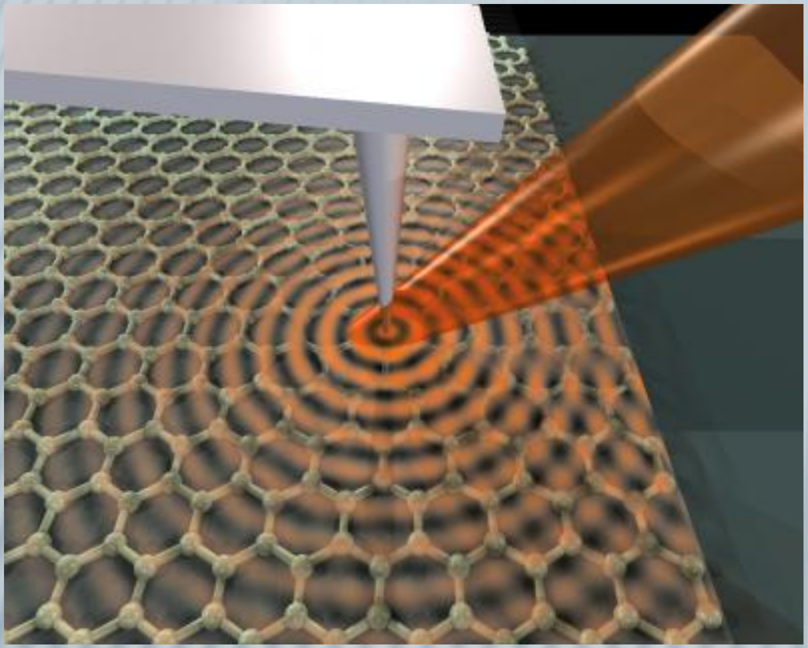
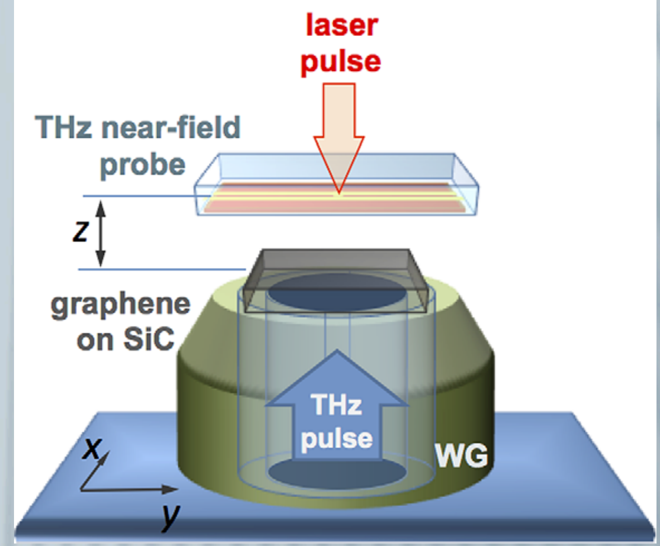
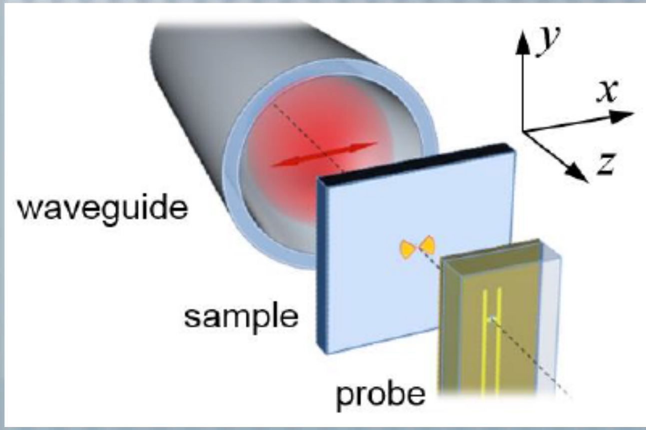
Near-field study of graphene plasmons

@ mid-IR spectral range

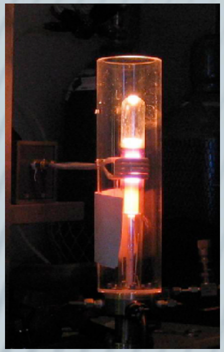


J. Chen et al. Nature **487**, 77 (2012)
Z. Fei et al. Nature **487**, 82 (2012)





Epitaxial graphene grown on SiC

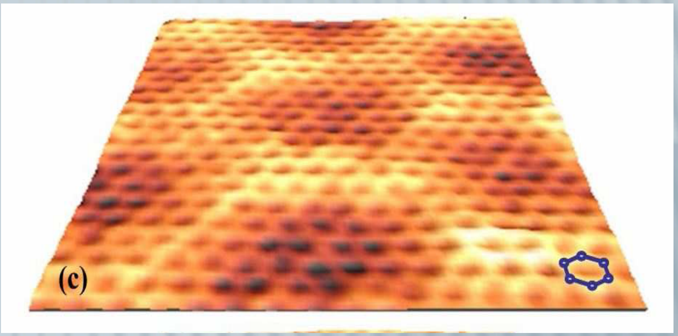


Induction furnace

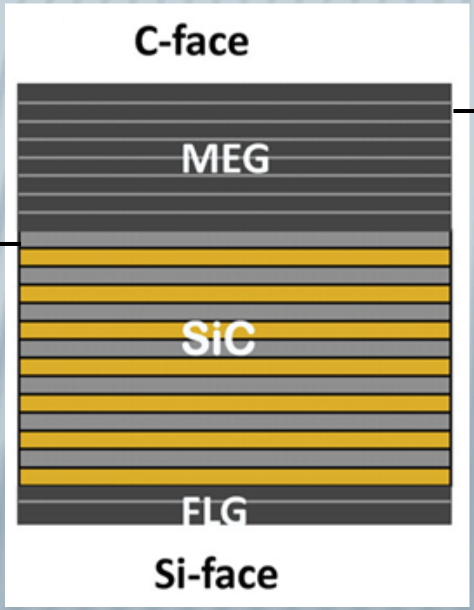
+

SiC substrate

=



Epitaxial graphene



E_F ~17 meV n ~1.9 x 10^{10} /cm^2
μ ~50,000 cm^2/Vs
v_F ~1.02(3) x 10^6 m/s

E_F > 200 meV
μ ~1,000 cm^2/Vs

C. Berger et al. JPCB **108**, 19912 (2004)
W.A. de Heer et al. PNAS **108**, 16900 (2011)

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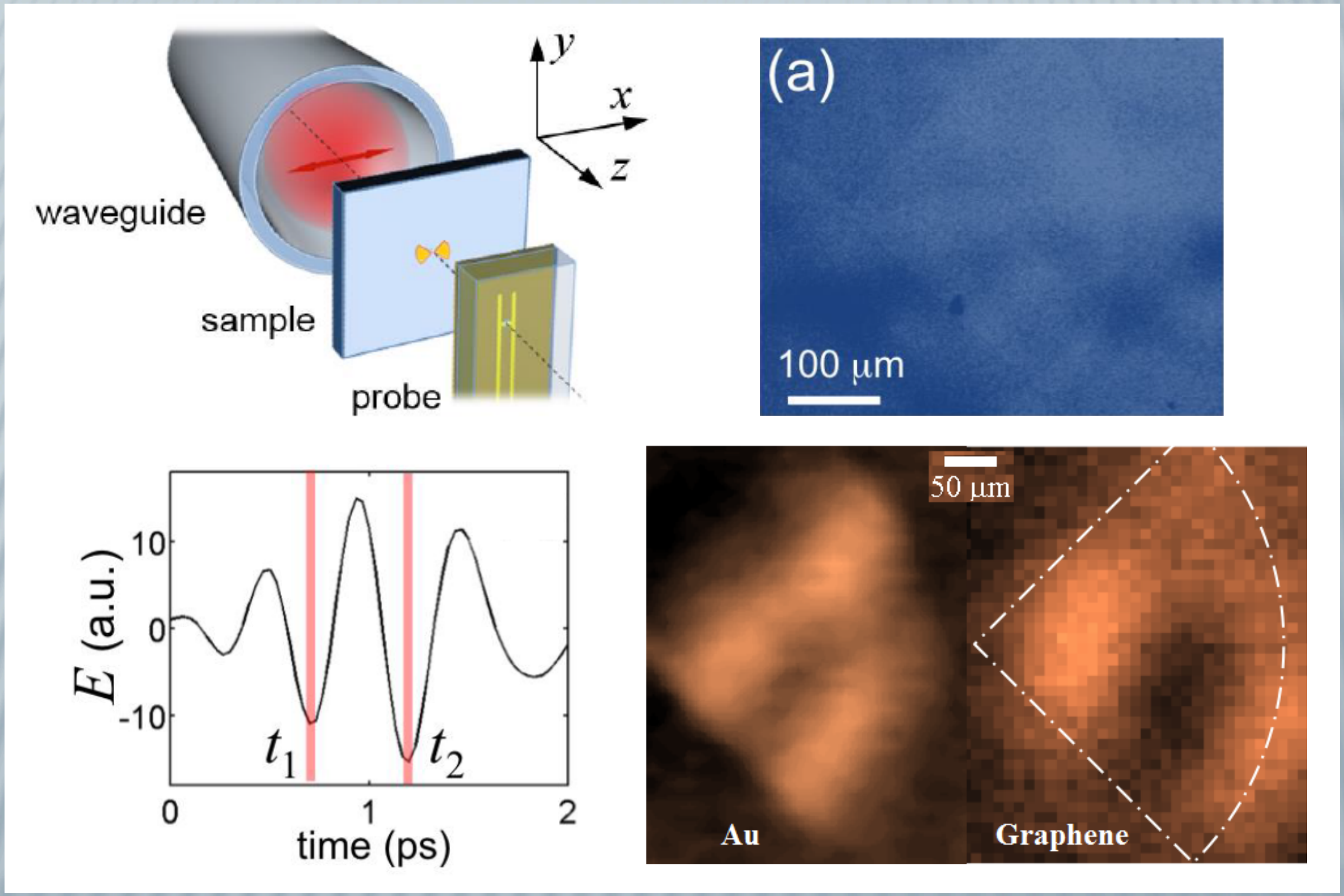
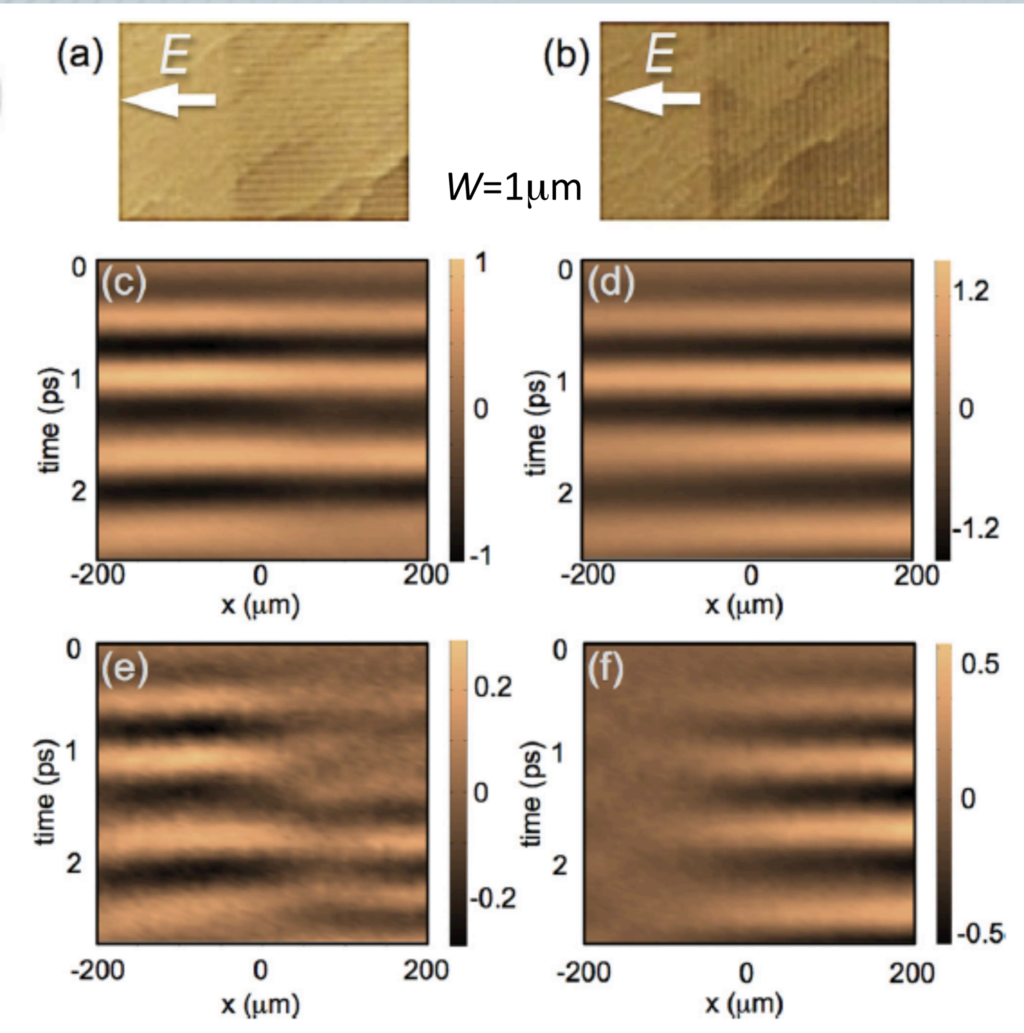
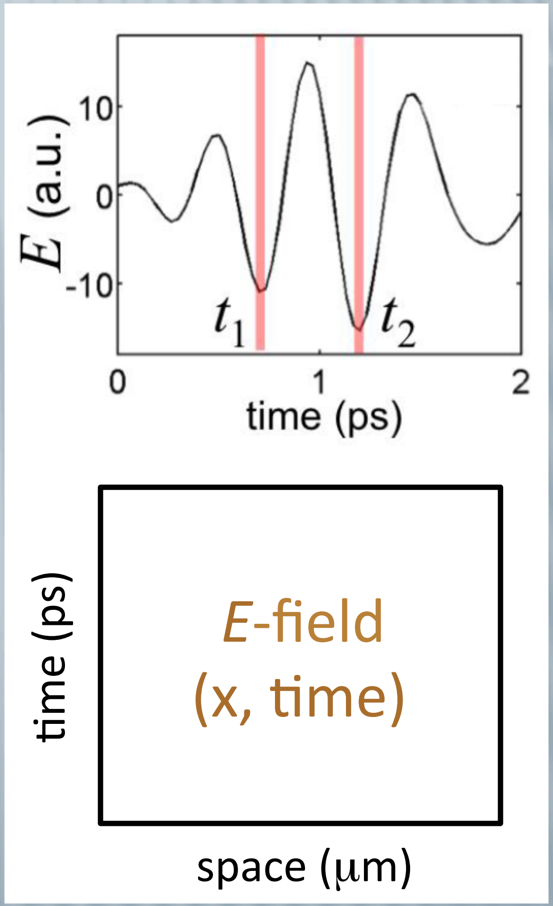
THz near-field imaging



O. Mitrofanov et al. invited paper to Solid State Commun. (2015)

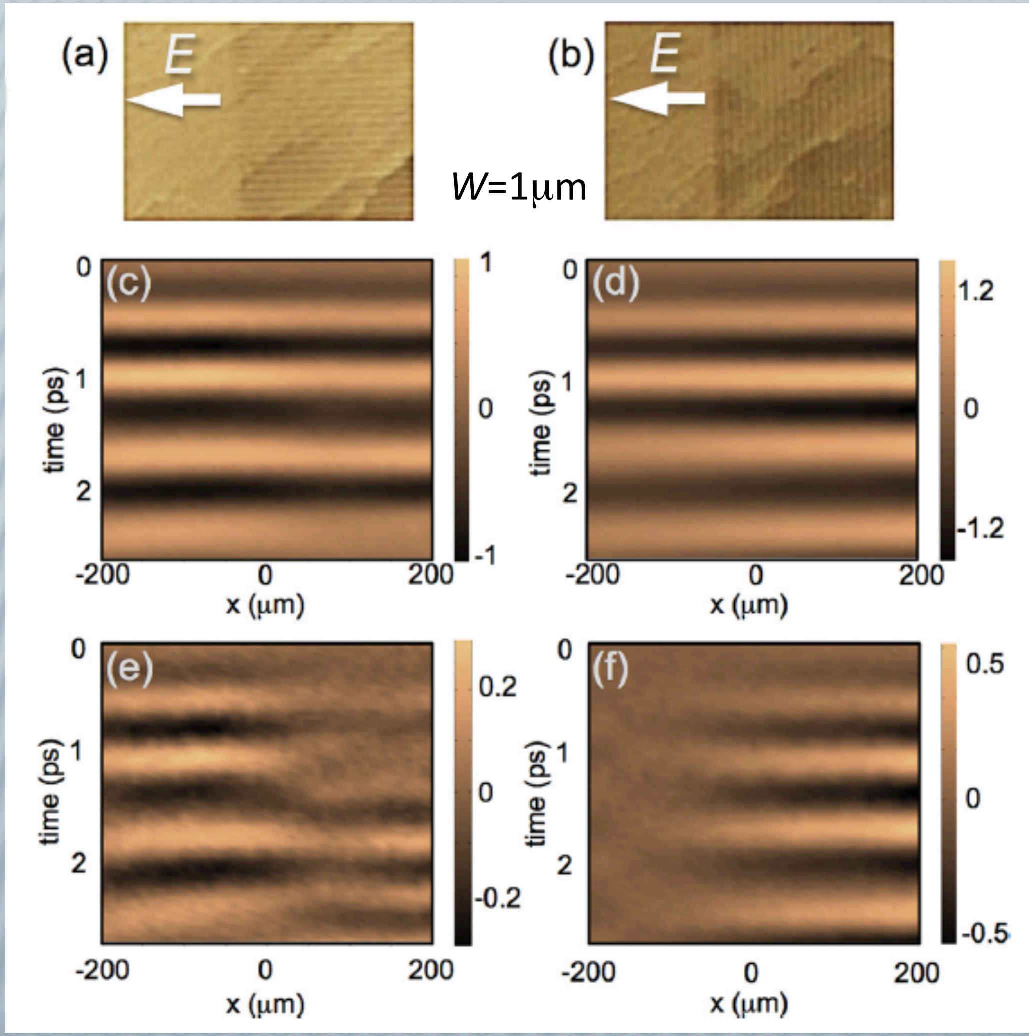
THz near-field imaging

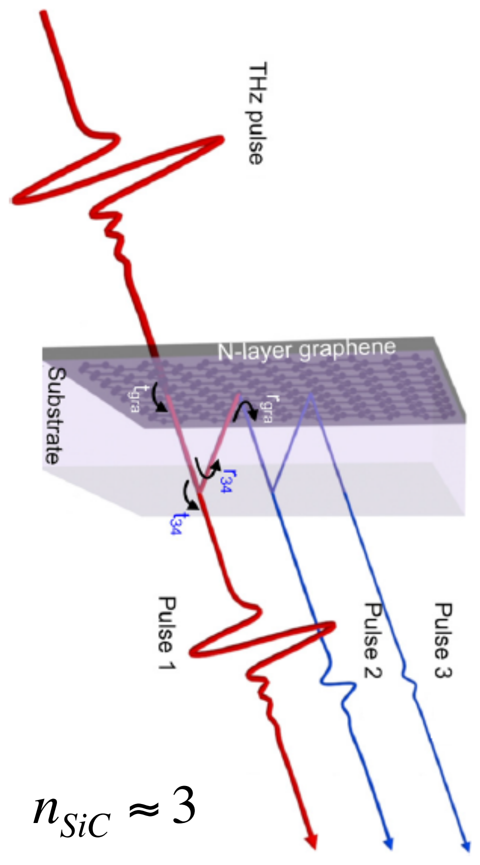




O. Mitrofanov et al. invited paper to Solid State Commun. (2015)
O. Mitrofanov et al. APL **103**, 111105 (2013)

THz near-field imaging





Y. Zhou et al. APL **104**, 051106 (2014)

O. Mitrofanov et al. invited paper to Solid State Commun. (2015)
O. Mitrofanov et al. APL **103**, 111105 (2013)

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Charge neutral top layers on C-face

E_F ~17 meV n ~1.9 x 10^{10} /cm^2
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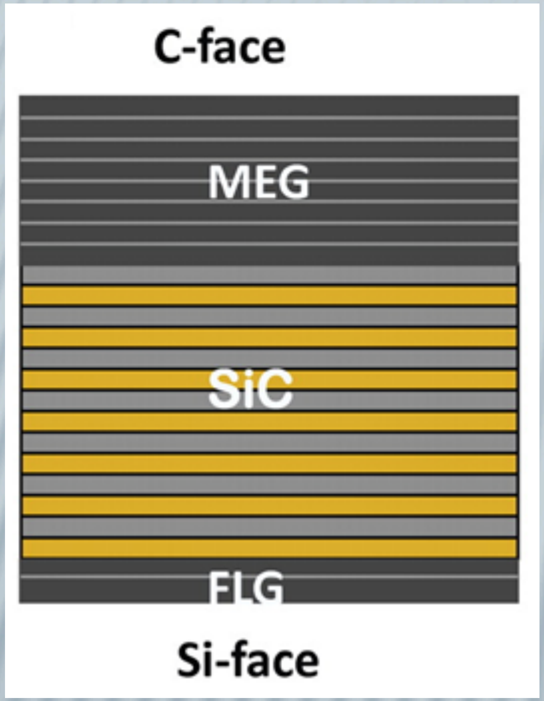
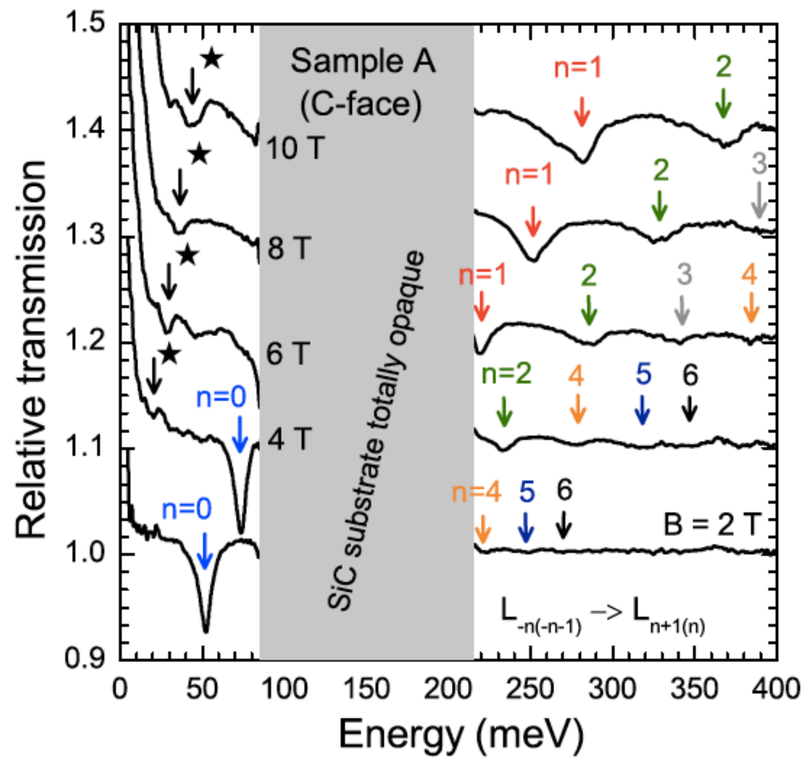
v_F ~1.02(3) x 10^6 m/s





W.A. de Heer et al. PNAS **108**, 16900 (2011)

M.L. Sadowski et al. PRL **97**, 266405 (2006)
A.M. Witowski et al. PRB **82**, 165305 (2010)

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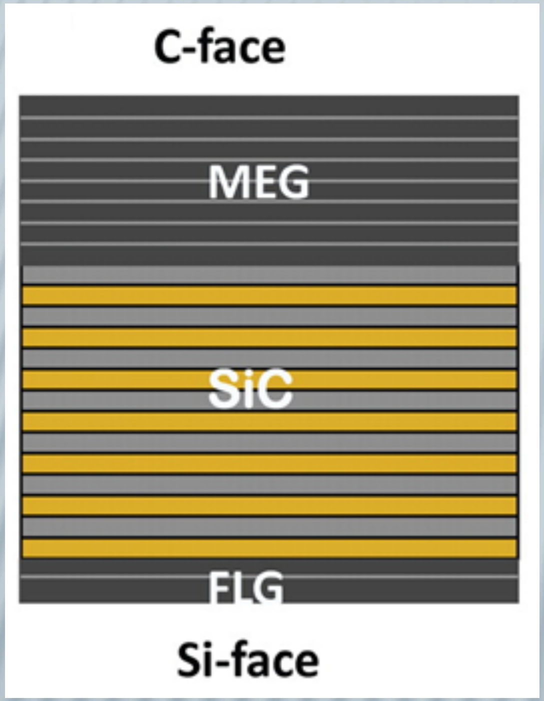

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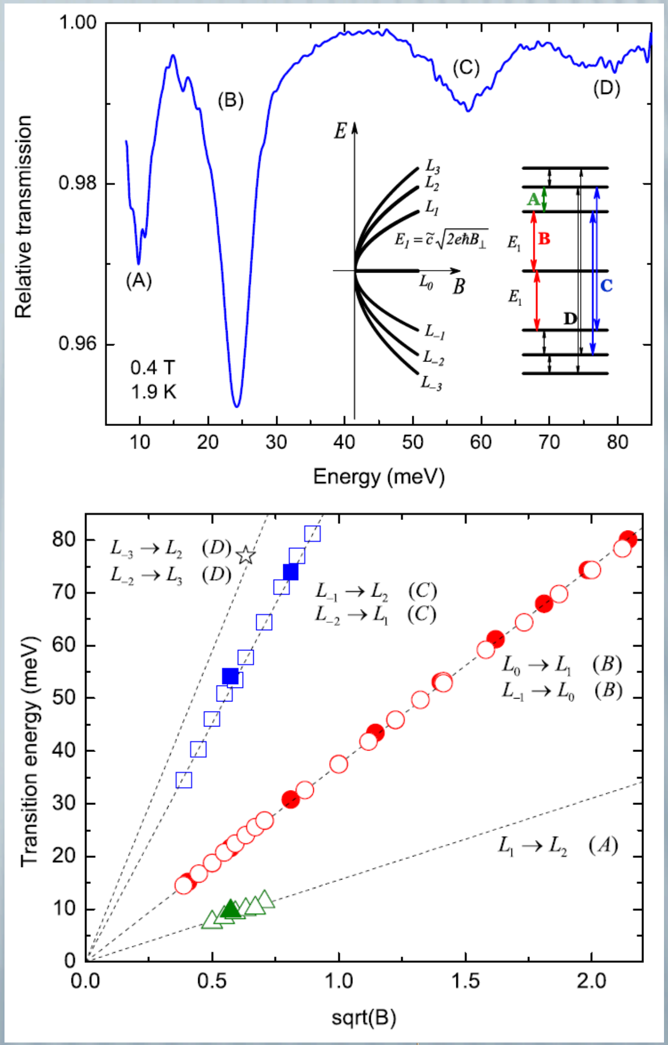

M.L. Sadowski et al. PRL **97**, 266405 (2006)
A.M. Witowski et al. PRB **82**, 165305 (2010)

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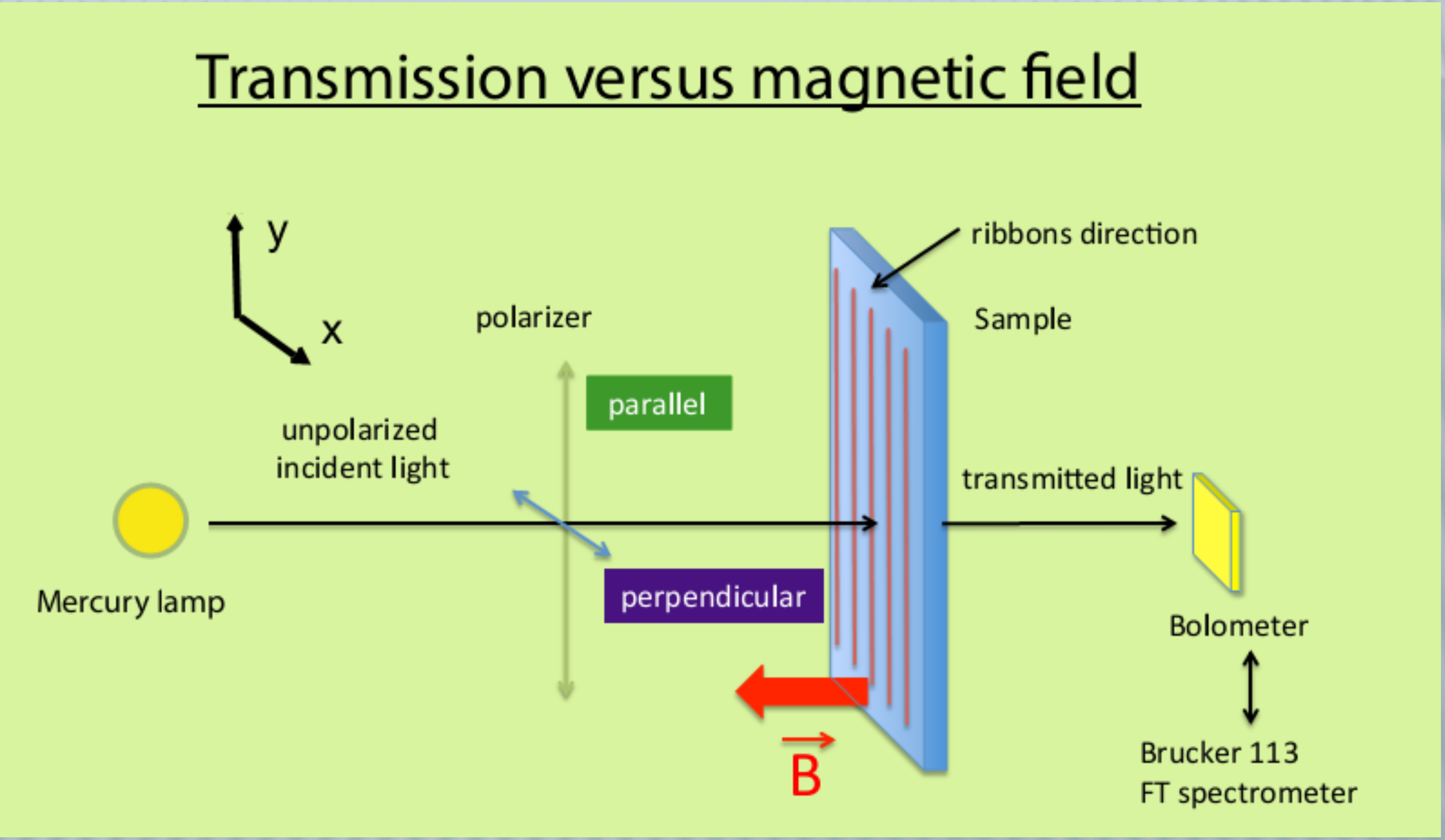
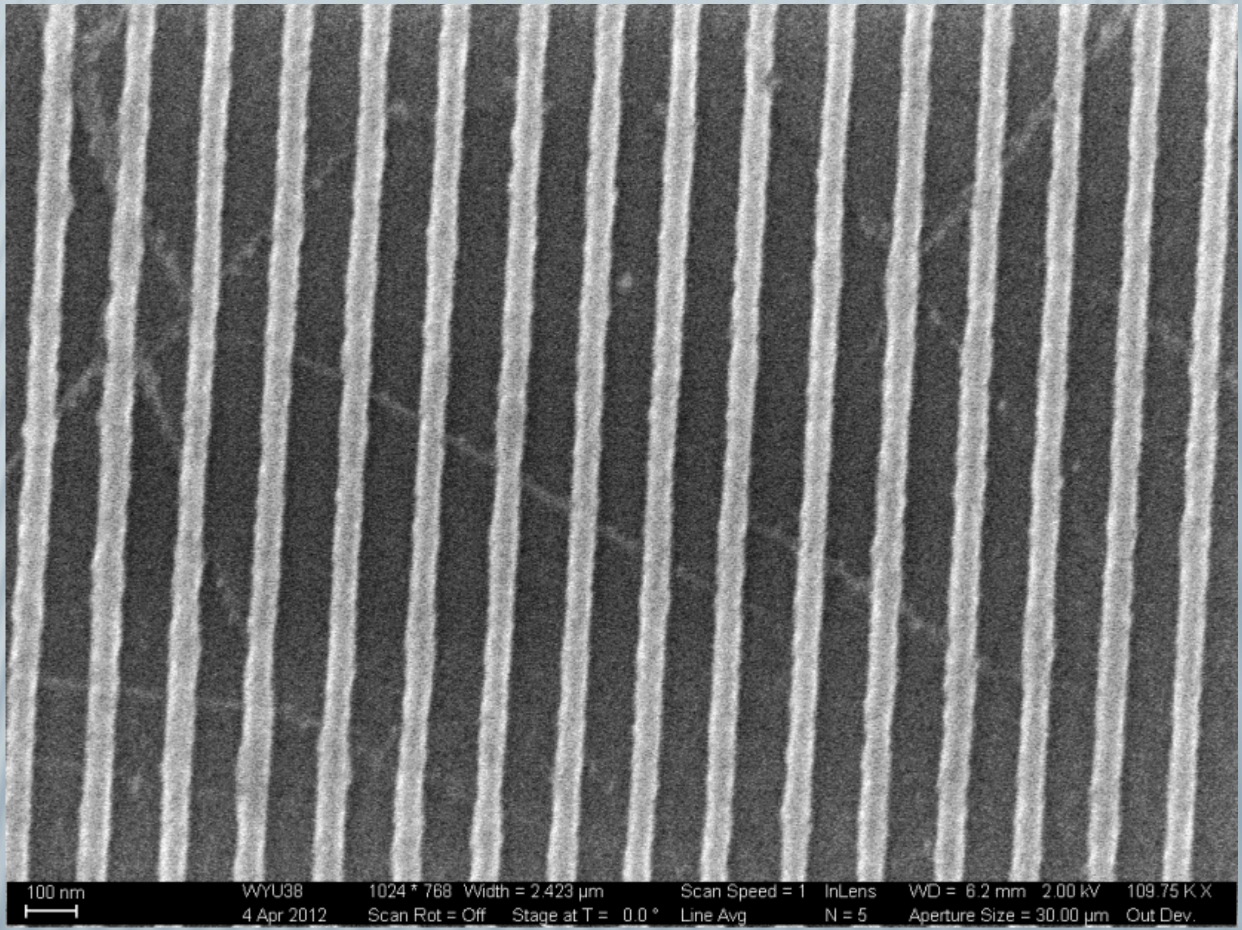
Experimental setup



Graphene nanoribbons



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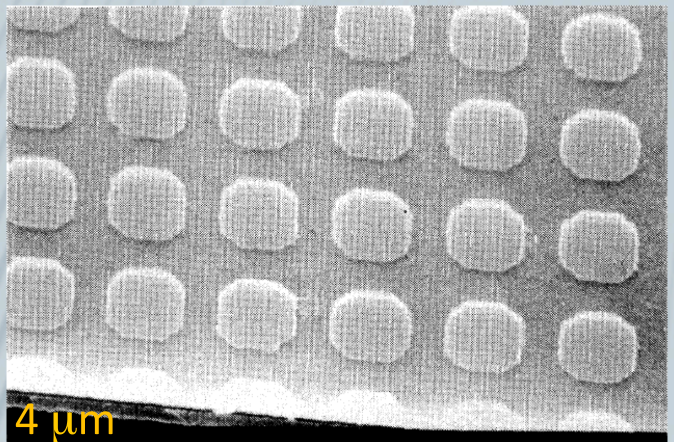
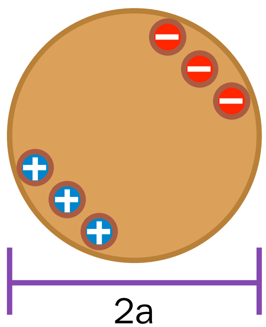
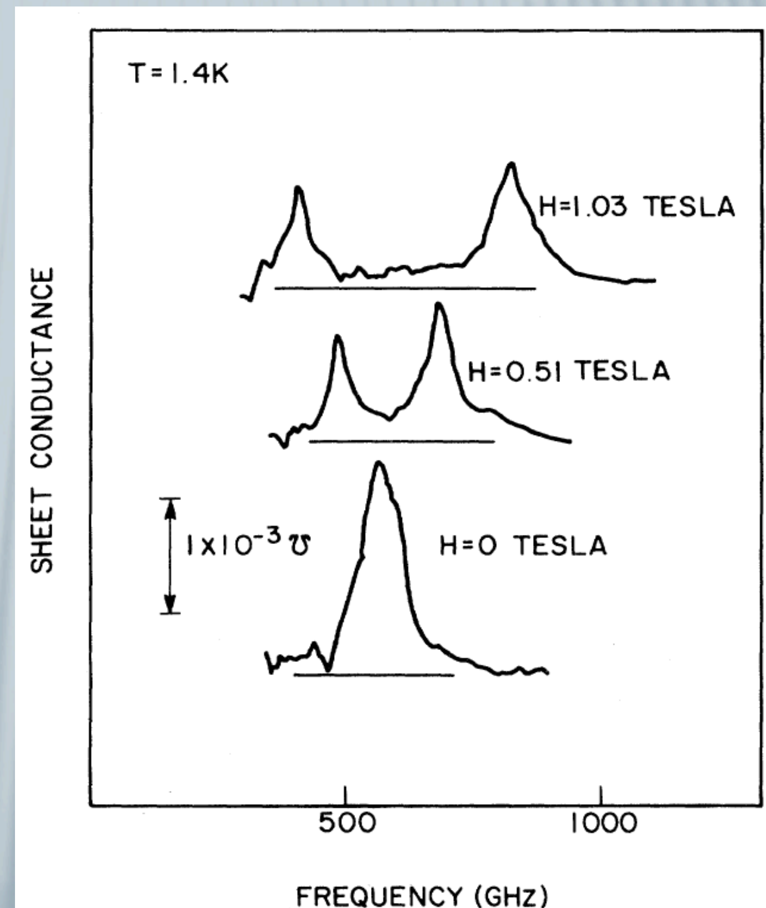
Plasmons in conventional 2D systems

Plasmons in disks





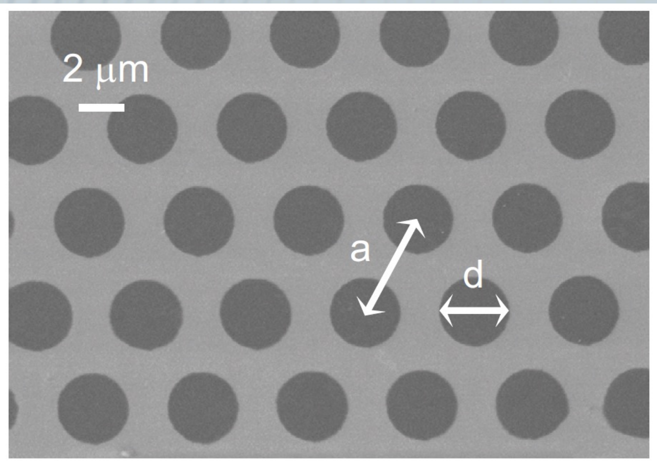
$$\omega_0^2 = \frac{n_s e^2 \pi}{a m^* 2(\epsilon_0 + \epsilon_1)}$$

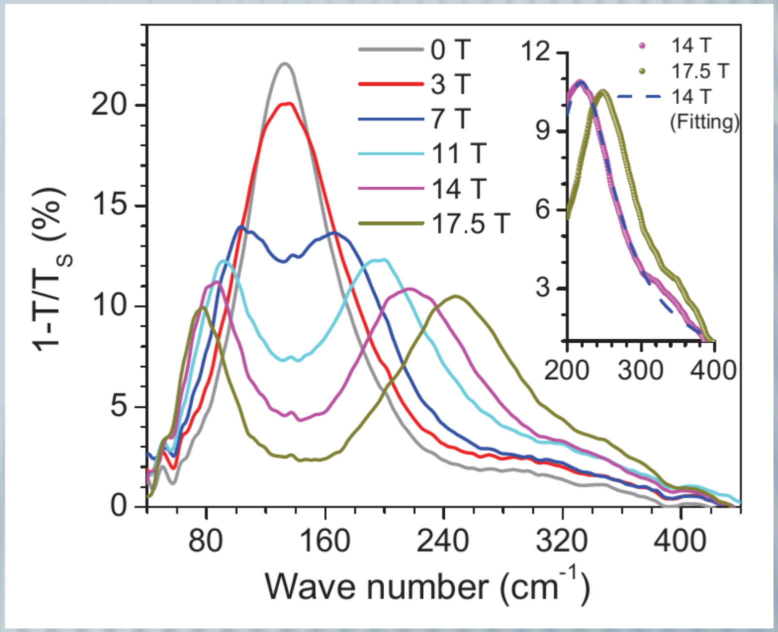


S.J. Allen et al. PRB **28**, 4875 (1983)

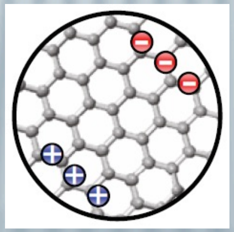
Plasmons in doped graphene disks

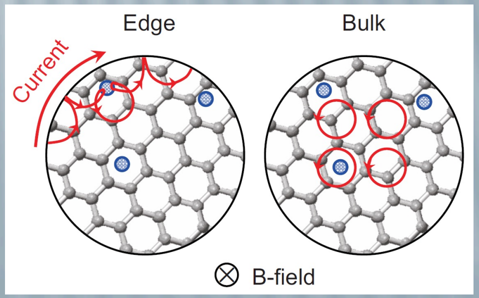
Plasmons in graphene disks





$$\omega^{\pm} = \sqrt{\omega_0^2 + \omega_c^2 / 4} \pm \omega_c / 2$$





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I. Crassee et al. Nano Lett. **12**, 2470 (2012)

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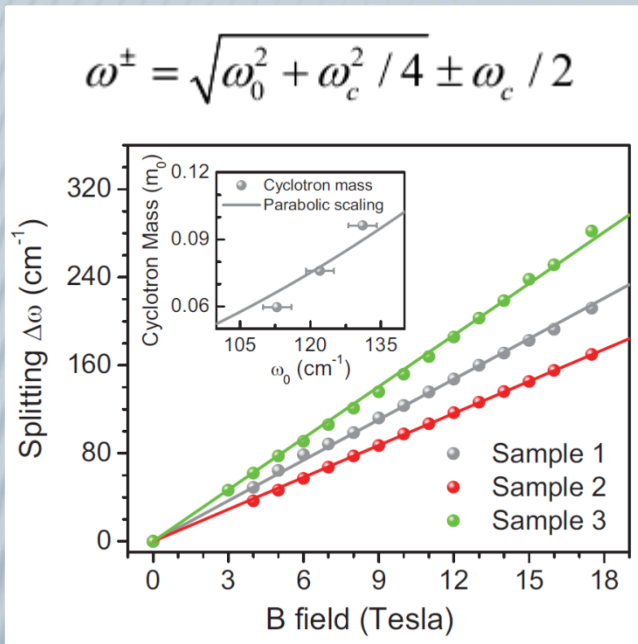
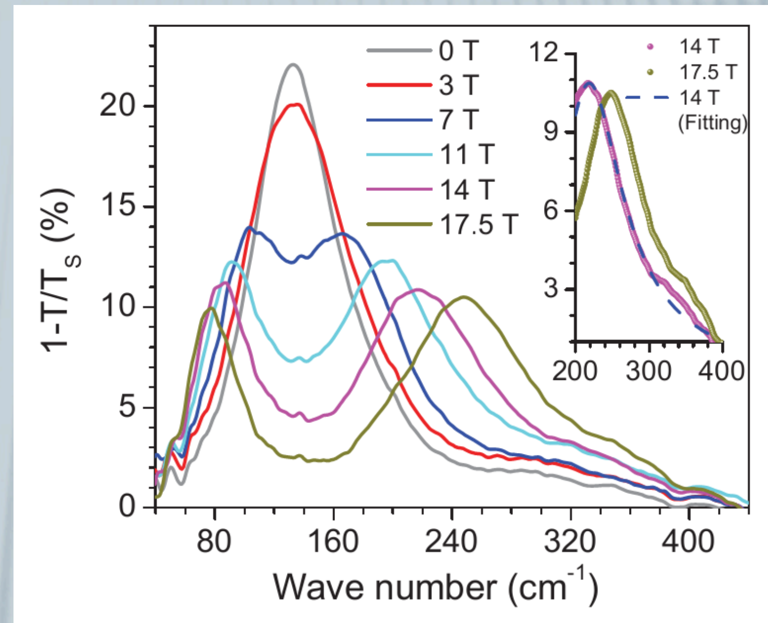
Plasmons in doped graphene disks





Heavily doped graphene in classical limit:

Cyclotron resonance frequency (ω_c) is linear-in-*B*-field

H. Yan et al. Nano Lett. **12**, 3766 (2012)

I. Crassee et al. Nano Lett. **12**, 2470 (2012)

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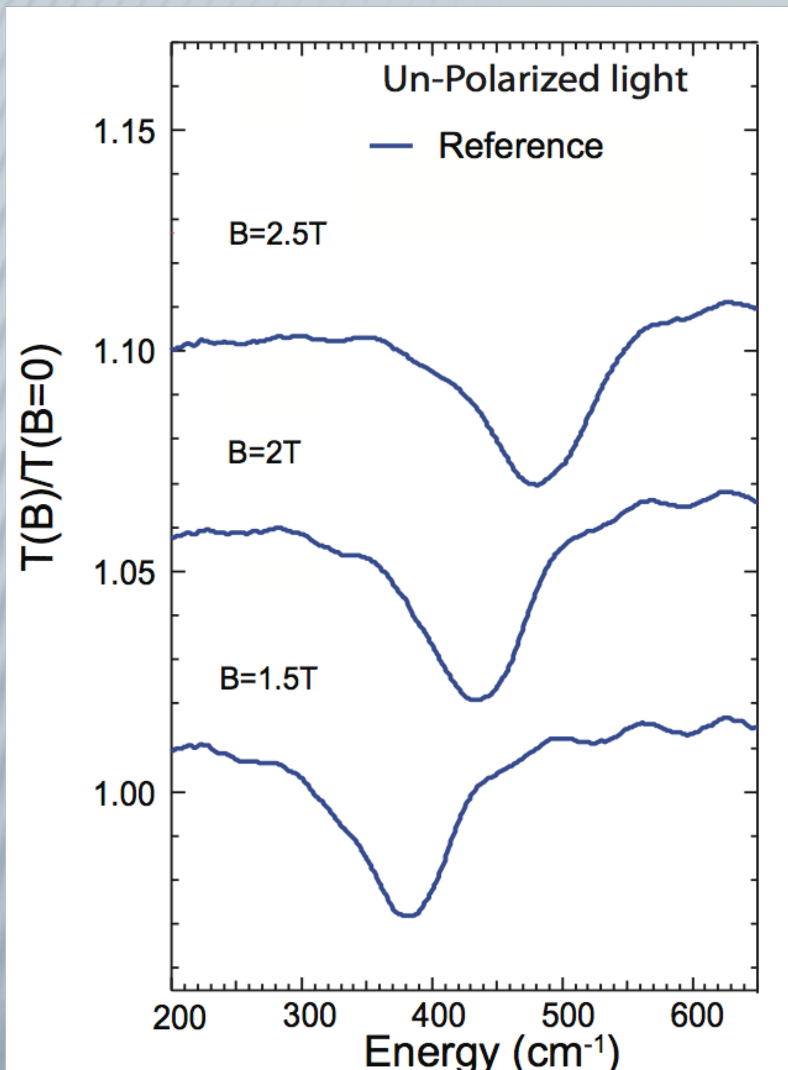
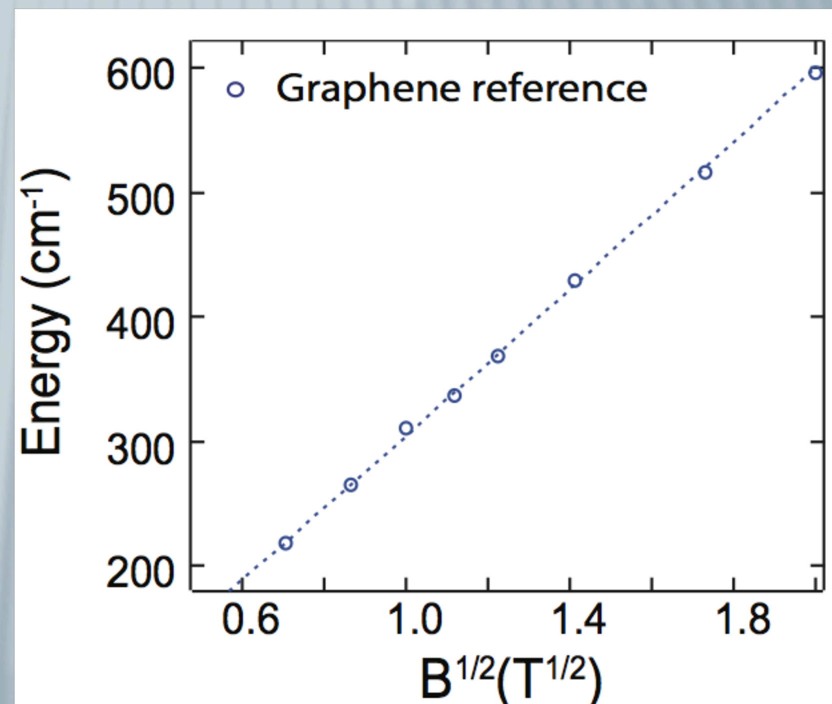
Upper-hybrid mode (UHM) in graphene



Cyclotron resonance
in 2D graphene



J.M. Poumirol et al. PRL **110**, 246803 (2013)

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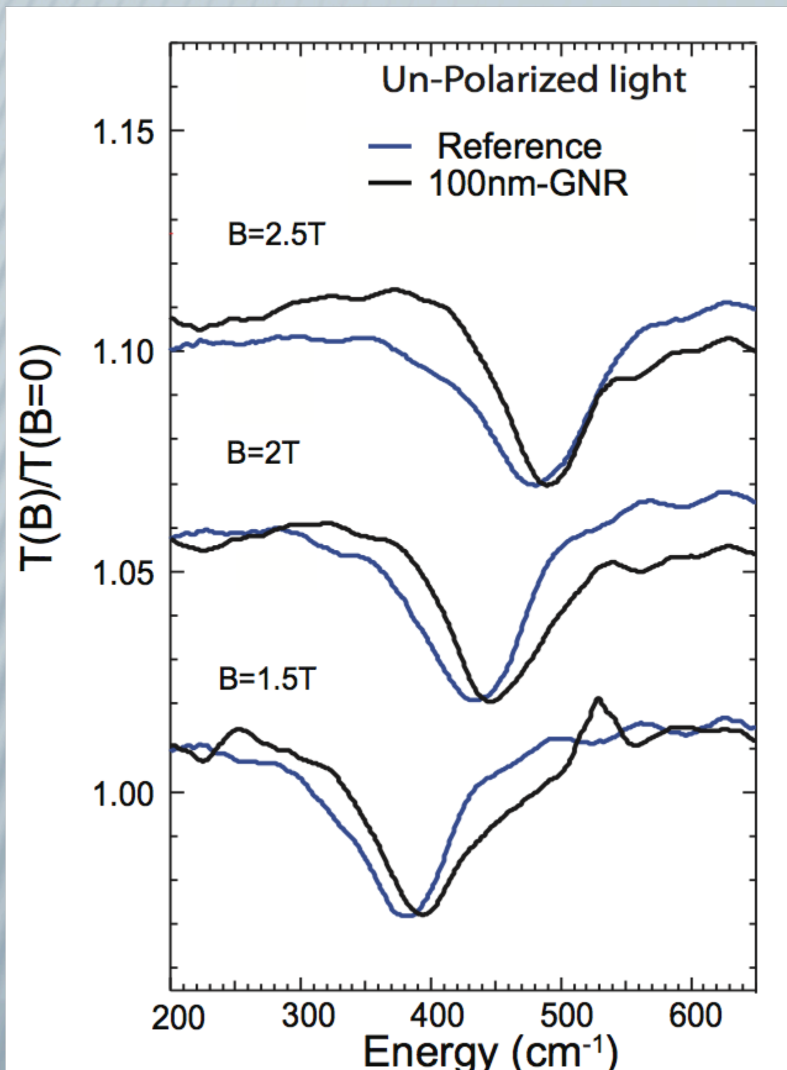
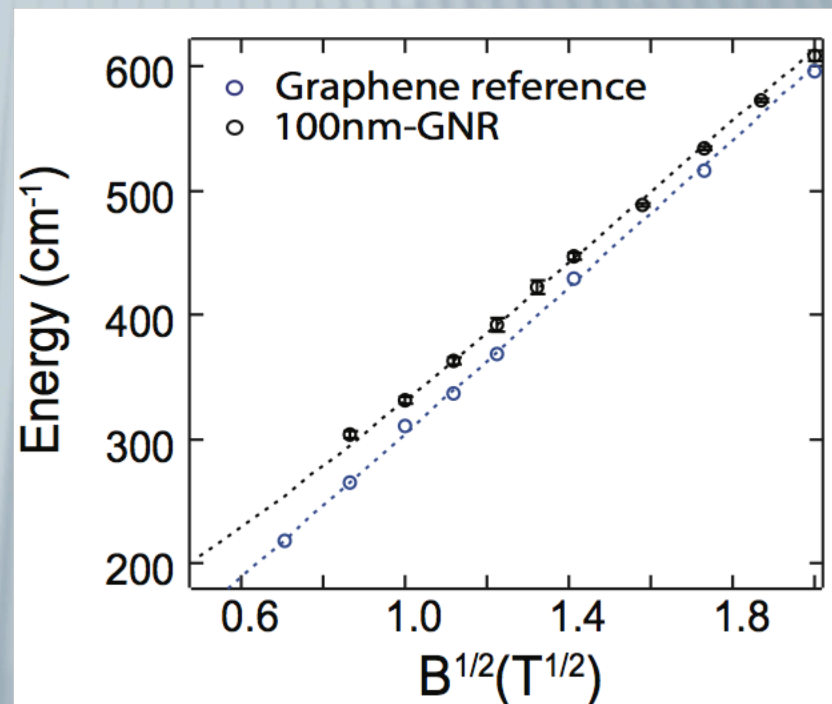


$$\omega_{uh}^2 = \omega_p^2 + \omega_C^2$$



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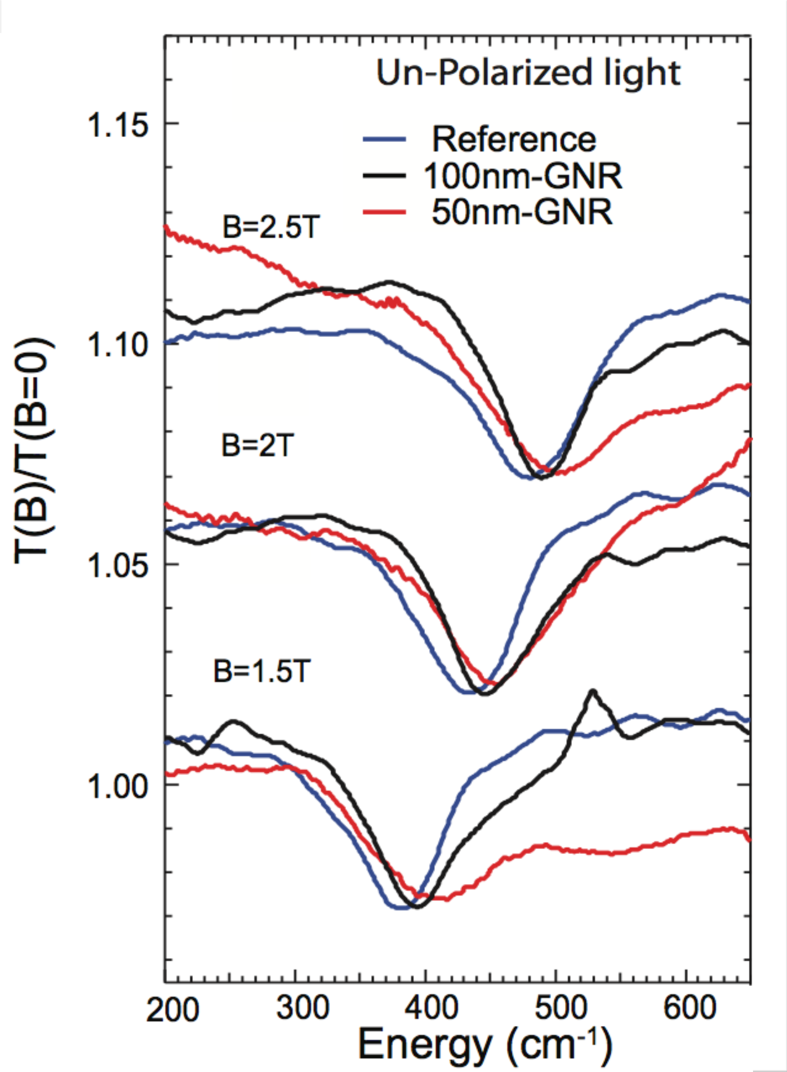

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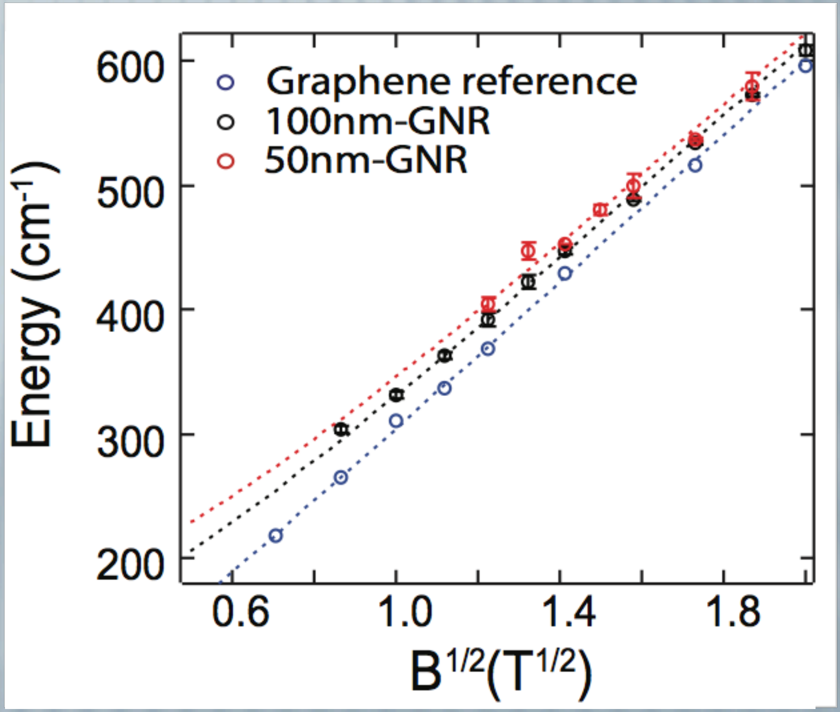

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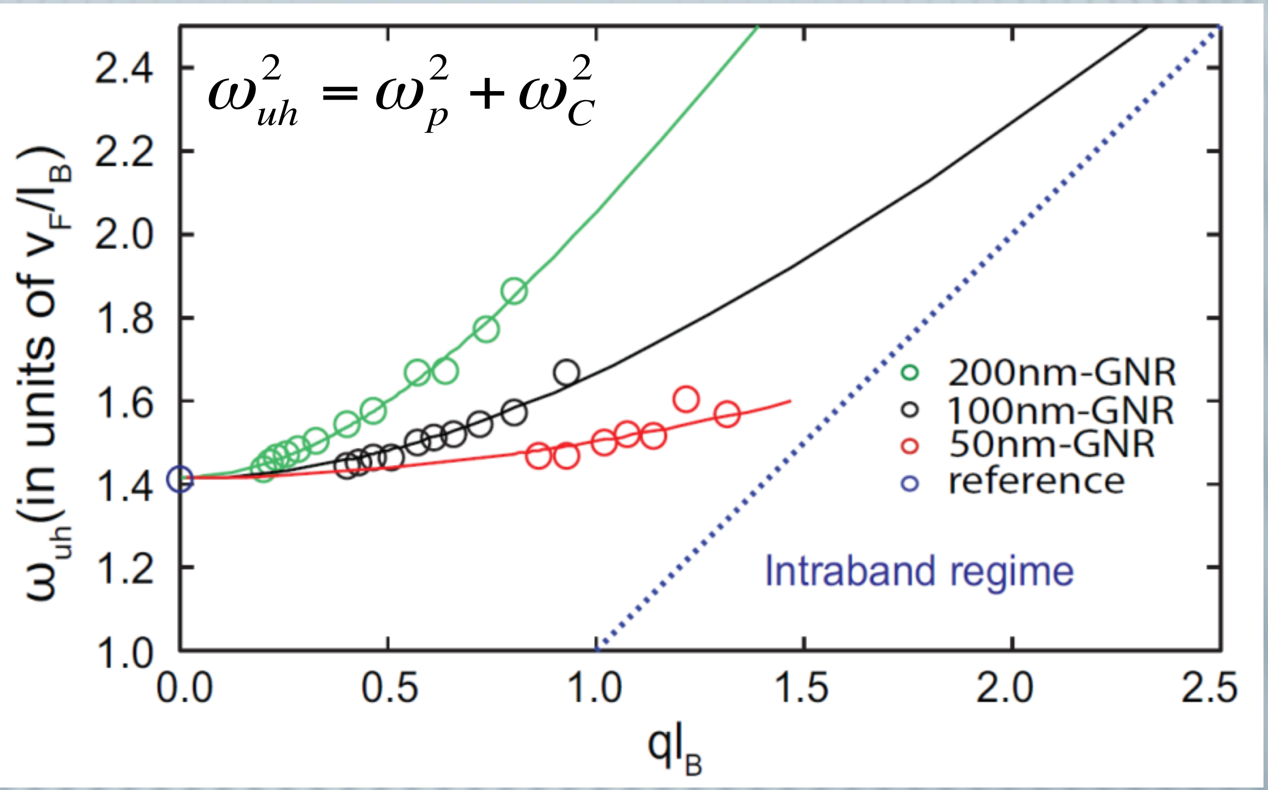
Magneto-plasmon dispersion



$$\omega_C = \sqrt{2}\frac{v_F}{\sqrt{\hbar / eB}} = \sqrt{2} v_F / l_B \qquad (l_B = \sqrt{\hbar / eB}, q = \pi / W)$$

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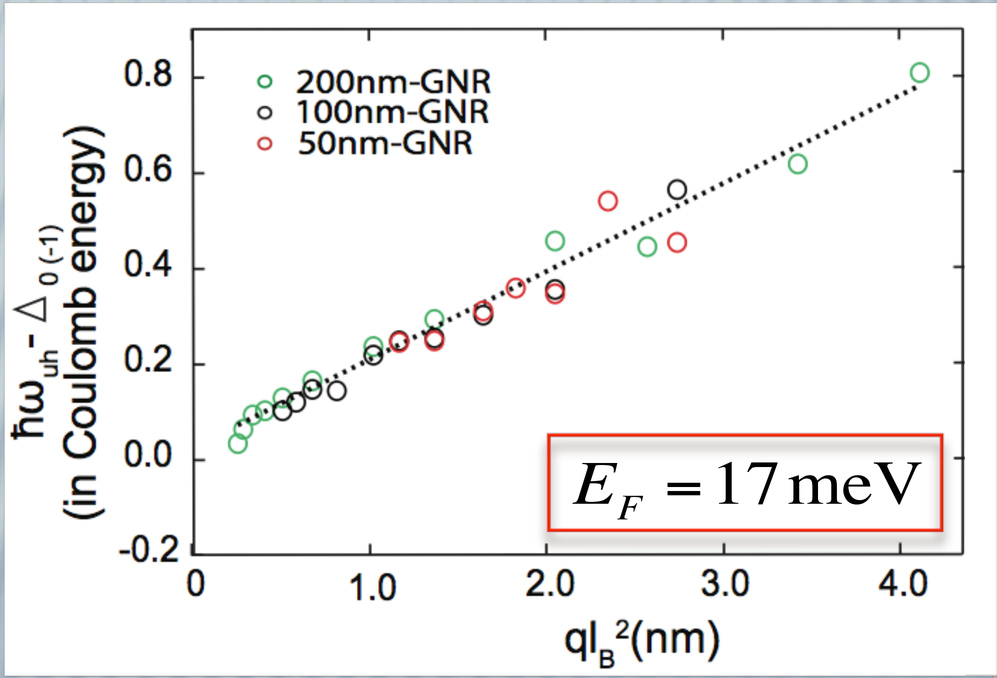
Magneto-plasmon dispersion

UHM in quasi-neutral graphene

$$\frac{\hbar\omega_{uh} - \hbar\omega_C}{e^2 / 4\pi\varepsilon_0 \varepsilon l_B} \cong \frac{E_F}{\sqrt{2}\hbar v_F} q l_B^2 \propto \frac{1}{WB}$$

Magneto-excitons

$$\frac{E_{shift}}{e^2 / 4\pi\varepsilon_0 \varepsilon l_B} \propto q l_B$$



J.M. Poumirol et al. PRL **110**, 246803 (2013)

SUMMARY I:

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- THz near-field imaging of surface plasmon waves in graphene micro-structures
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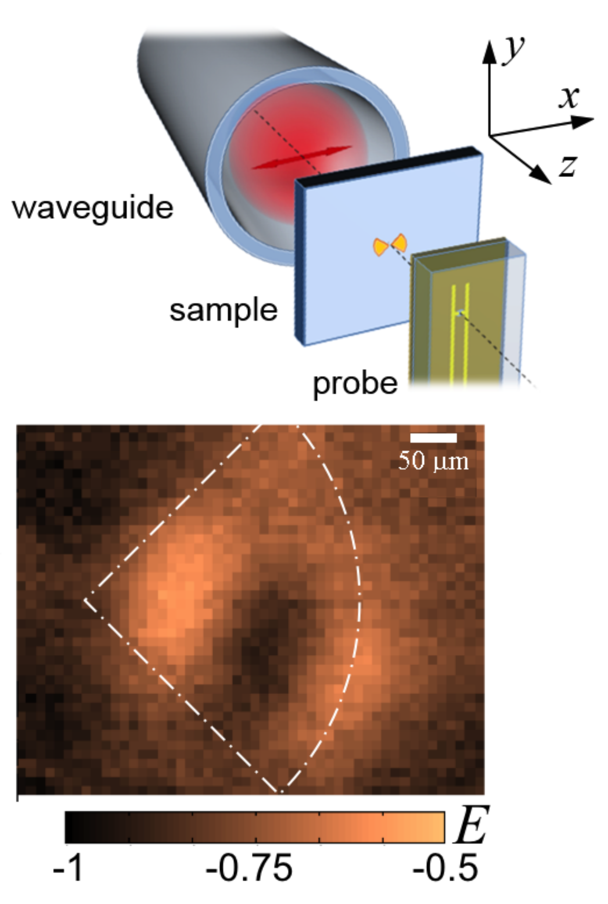
  (2) Effective mass, $m^* \sim 0.23\, m_e$



SUMMARY II:

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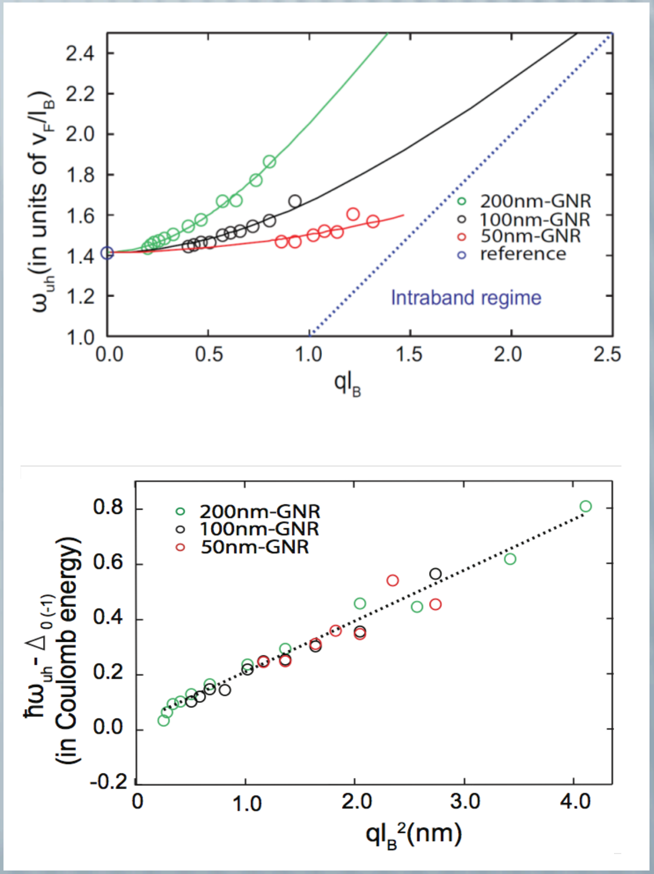

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GaTech:	W. Yu, Y. Jiang, X. Chen, C. Berger, W.A. de Heer, ZJ
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UCL:	O. Mitrofanov
U. Paris-Sud:	M.O. Goerbig
Rutgers:	M. Brahlek, M.Koirala, S. Oh

Thank You !