Universidade do Minho

Excitation of surface polaritons in graphene and other accompanying phenomena

Yuliy V. Bludov, Mikhail Vasilevskiy, Nuno Peres
Centre for Physics, University of Minho, Braga, Portugal

Aires Ferreira
Graphene Research Centre, National University of Singapore

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Outline

- Introduction
- THz switch and polarizer, based on the ATR structure
- Excitation of surface polaritons by diffraction grating
- Conclusions

Introduction

Possibilities to tune SPP modes in plasmonic devices using external control signals:

- Electric field in a liquid crystal

  W. Dickson, *et al.*, Nano Lett. **8**, 281 (2008).
- Magnetic field in a magneto-optically active substrate

  G. A. Wurtz, *et al.*, New J. Phys. **10**, 105012 (2008).
- Thermal heating

  O. Tsilipakos, T. V. Yioultsis, and E. E. Kriezisa, J. Appl. Phys. **106**, 093109 (2009);

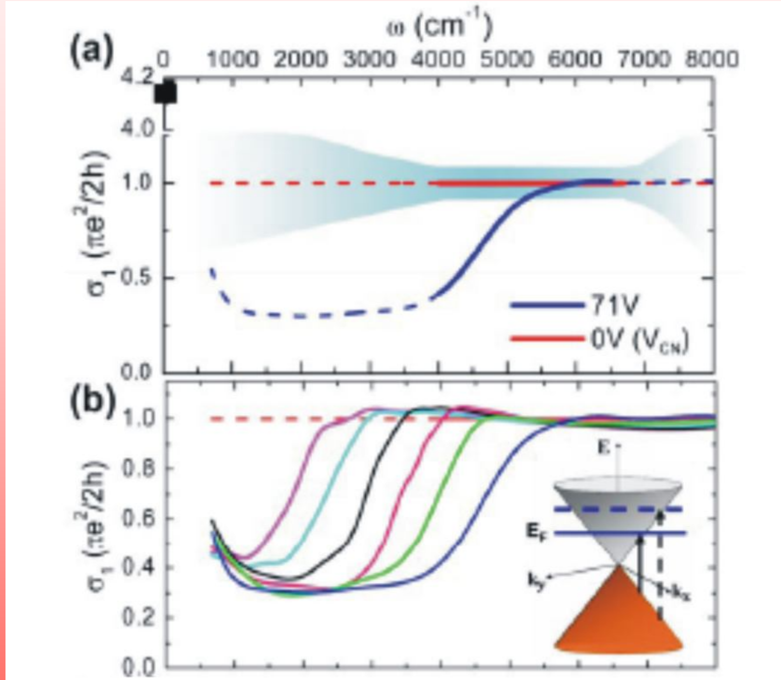
  J. Gosciniak, *et al.*, Opt. Express **18**, 1207 (2010).
- Control of light focused on a nonlinear coating

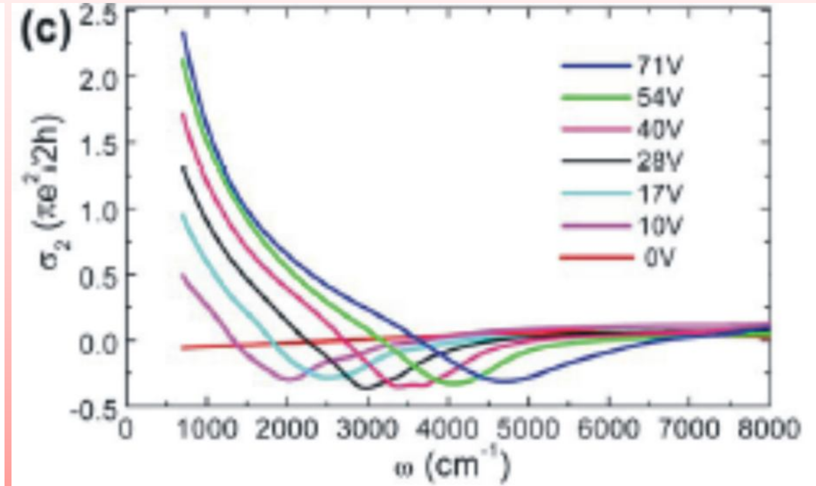
  G. A. Wurtz, R. Pollard, and A. V. Zayats, Phys. Rev. Lett. **97**, 057402 (2006).

Properties of graphene

Graphene chemical potential can be varied by the application of external gate voltage.

K. S. Novoselov, *et al.*, Science **306**, 666 (2004).



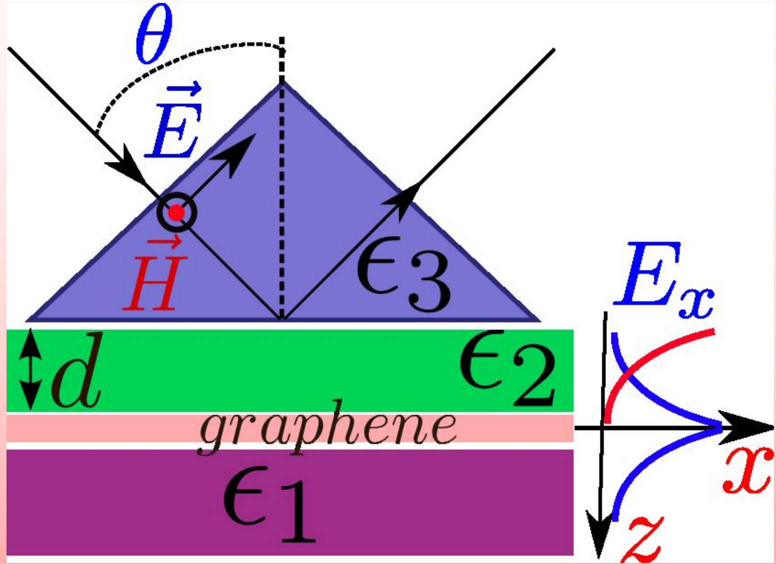


Z. Q. Li, *et al.*, Nature Physics **4**, 532 (2008)

This opens the possibility to tune the SPP parameters by adjusting external gate voltage.

V. Ryzhii, A. Satou, T. Otsuji, J. Appl. Phys. **101**, 024509 (2007).

THz switch, based on the ATR structure



Maxwell equations:

$$
\begin{aligned}
\frac{\partial E_x^{(m)}}{\partial z} - ikE_z^{(m)} &= \frac{i\omega}{c} H_y^{(m)} \\
\frac{\partial H_y^{(m)}}{\partial z} &= \frac{i\omega\varepsilon_m}{c} E_x^{(m)} \\
kH_y^{(m)} &= -\frac{\omega\varepsilon_m}{c} E_z^{(m)}
\end{aligned}
$$

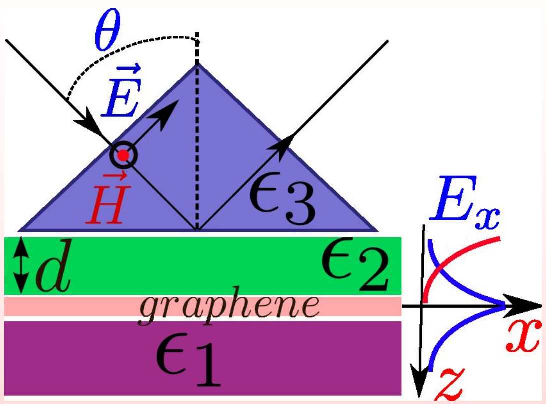
m=1,2,3 is the medium index

Propagating wave in the prism (3), evanescent waves in the capping layer (2) and in the substrate (1)

Boundary condition across graphene:

$$H_y^{(1)}(0) - H_y^{(2)}(0) = -(4\pi/c)\sigma(\omega)E_x(0)$$

Reflection coefficient:



$$r = \frac{E_x^{(r)}}{E_x^{(i)}} = \frac{\left[\frac{\varepsilon_1}{p_1} - \frac{4\pi}{i\omega}\sigma(\omega)\right]\chi_1 + \frac{\varepsilon_2}{p_2}\chi_2}{\left[\frac{\varepsilon_1}{p_1} - \frac{4\pi}{i\omega}\sigma(\omega)\right]\overline{\chi_1} + \frac{\varepsilon_2}{p_2}\overline{\chi_2}}$$

$$\chi_1 = \tanh(p_2 d) + \frac{i\varepsilon_2 k_z}{\varepsilon_3 p_2}, \quad \chi_2 = 1 + \frac{i\varepsilon_2 k_z}{\varepsilon_3 p_2}\tanh(p_2 d),$$

$$p_m = (\omega/c)\sqrt{\varepsilon_3 \sin^2\theta - \varepsilon_m}, \qquad k_z = (\omega/c)\varepsilon_3^{1/2}\cos\theta,$$

If $d \to \infty$ the poles of the reflection coefficient yield the SPP modes in graphene.

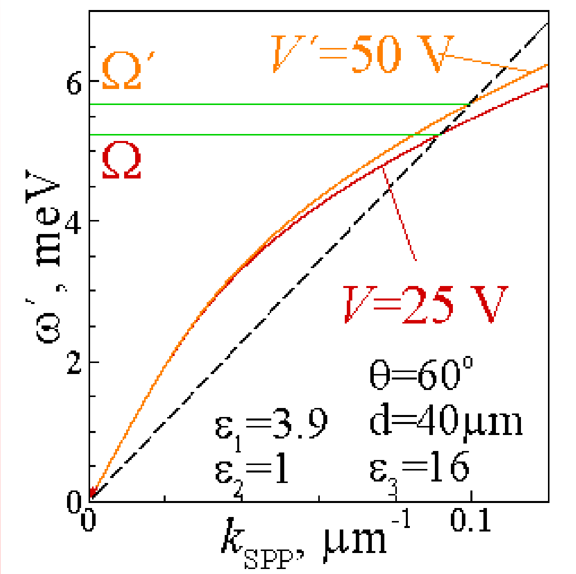
$$\frac{\varepsilon_1}{p_1} - \frac{4\pi}{i\omega}\sigma(\omega) + \frac{\varepsilon_2}{p_2} = 0,$$

$$k_{SPP} = (\omega/c)\varepsilon_3^{1/2}\sin\theta$$

ATR scanline, fixed by the prism

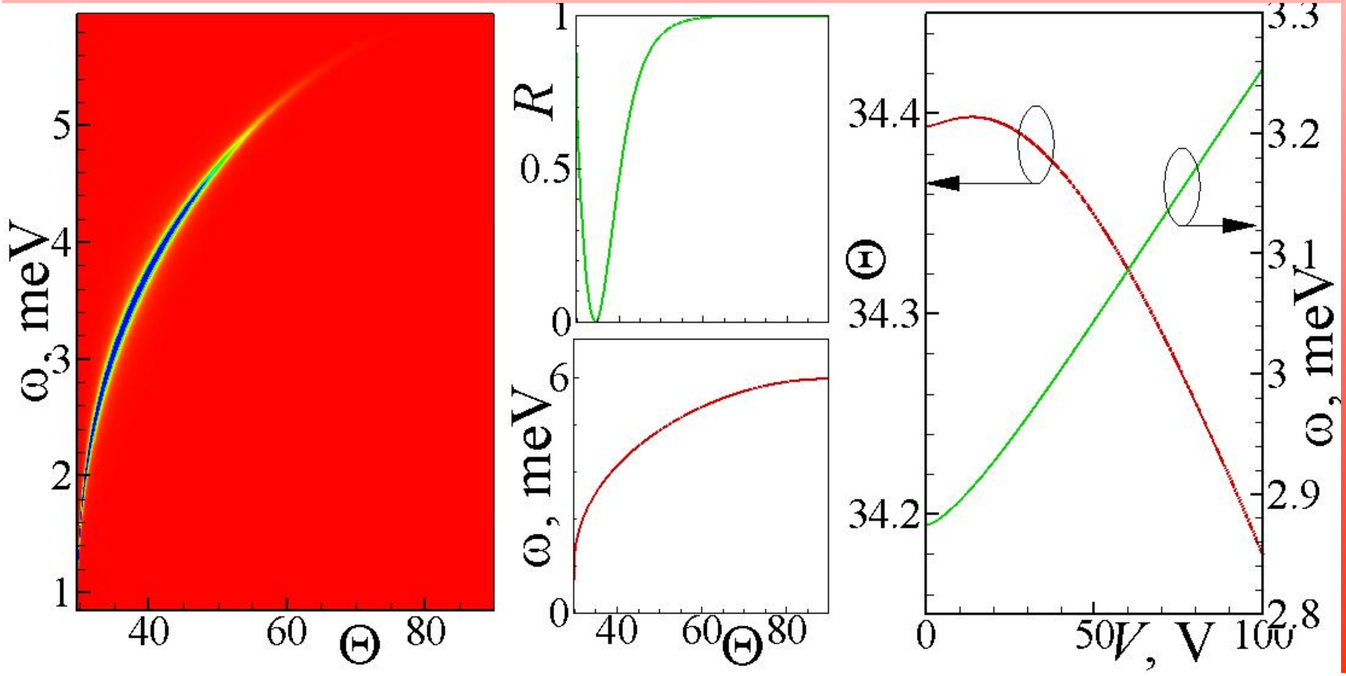
$$\frac{\varepsilon_2}{\sqrt{k_{SPP}^2 - (\omega/c)^2\varepsilon_2}} + \frac{\varepsilon_1}{\sqrt{k_{SPP}^2 - (\omega/c)^2\varepsilon_1}} = \frac{4\pi}{i\omega}\sigma(\omega)$$

The reflectivity minimum is determined by the intersection of the SPP dispersion curve with the ATR scanline

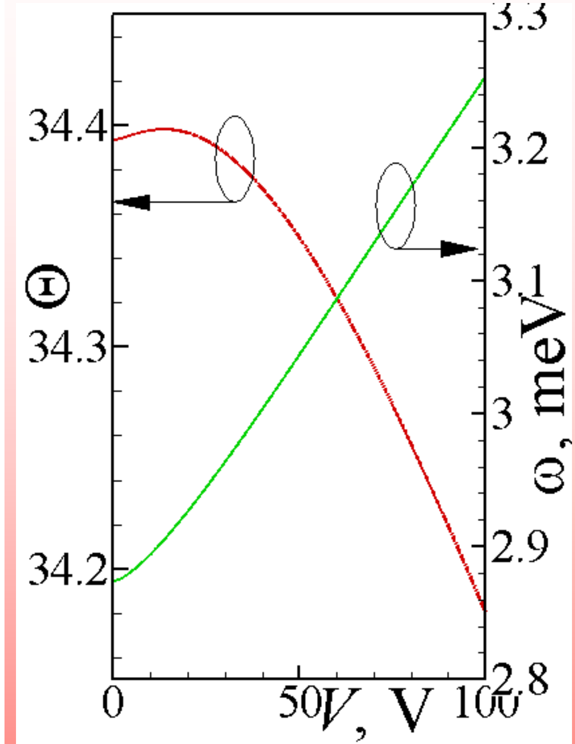


If the gate voltage is changed, the conditions for the SPP resonant excitation are not met any more, and the reflection coefficient will be increased.

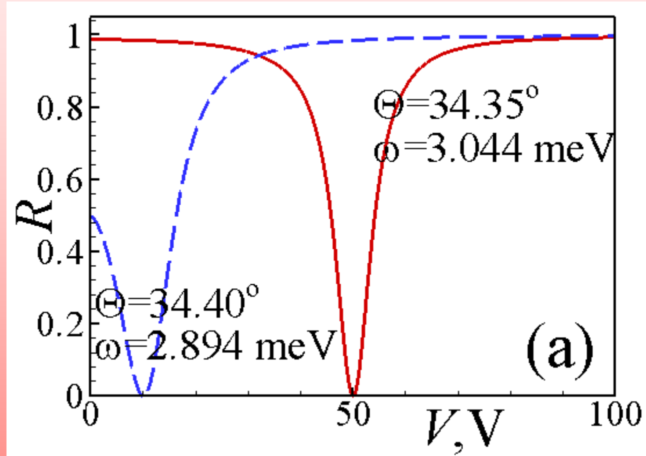
YVB, M. I. Vasilevskiy, N. M. R. Peres, EPL **92**, 68001 (2010)



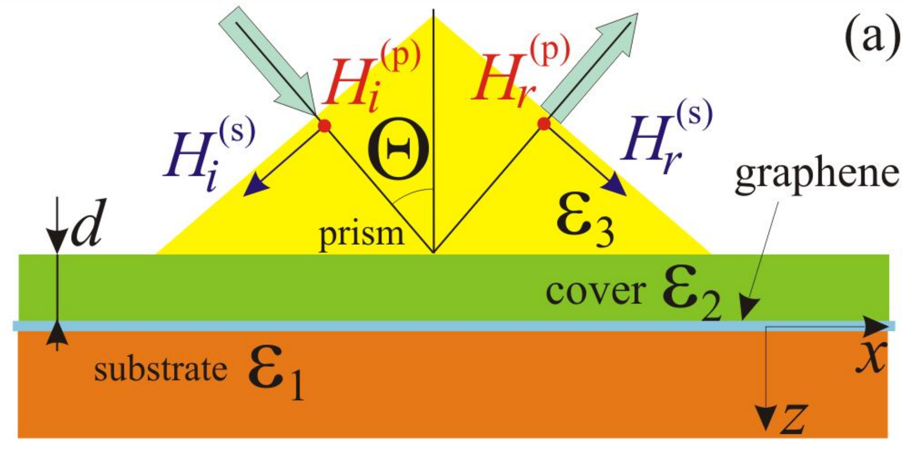
$R(V)$ dependence



Changing gate voltage, one can change the reflectivity from total absorption, R=0, to total reflection, R=1.



Polarizer



YVB, N.M.R. Peres, M.I. Vasilevskiy, J. Appl. Phys. 112, 084320 (2012)

$$H_x^{(3)}(x,z) = -\exp(ik_x x)\cos\theta\{H_i\exp(ik_z z)\cos\varphi - H_r^{(s)}\exp(-ik_z z)\},$$
$$H_y^{(3)}(x,z) = \exp(ik_x x)\{H_i\exp(ik_z z)\sin\varphi + H_r^{(p)}\exp(-ik_z z)\},$$
$$H_z^{(3)}(x,z) = \exp(ik_x x)\sin\theta\{H_i\exp(ik_z z)\cos\varphi + H_r^{(s)}\exp(-ik_z z)\}$$

$\varphi = 0$ purely s-polarized wave

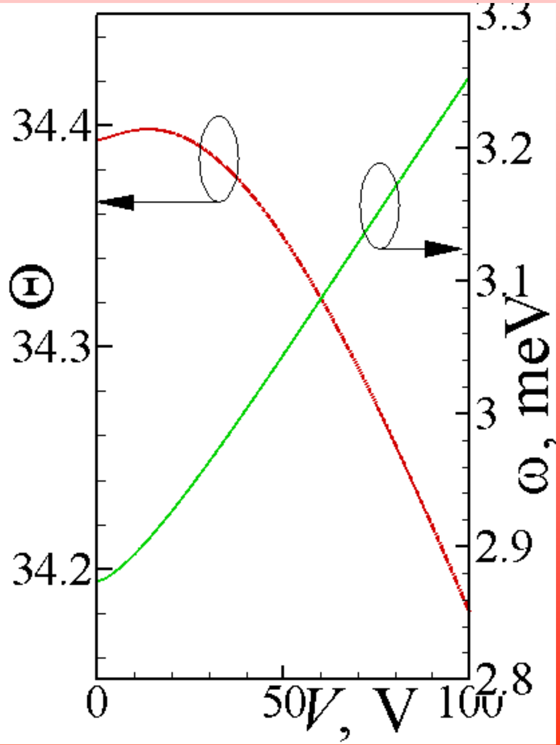
$\varphi = \frac{\pi}{2}$ purely p-polarized wave

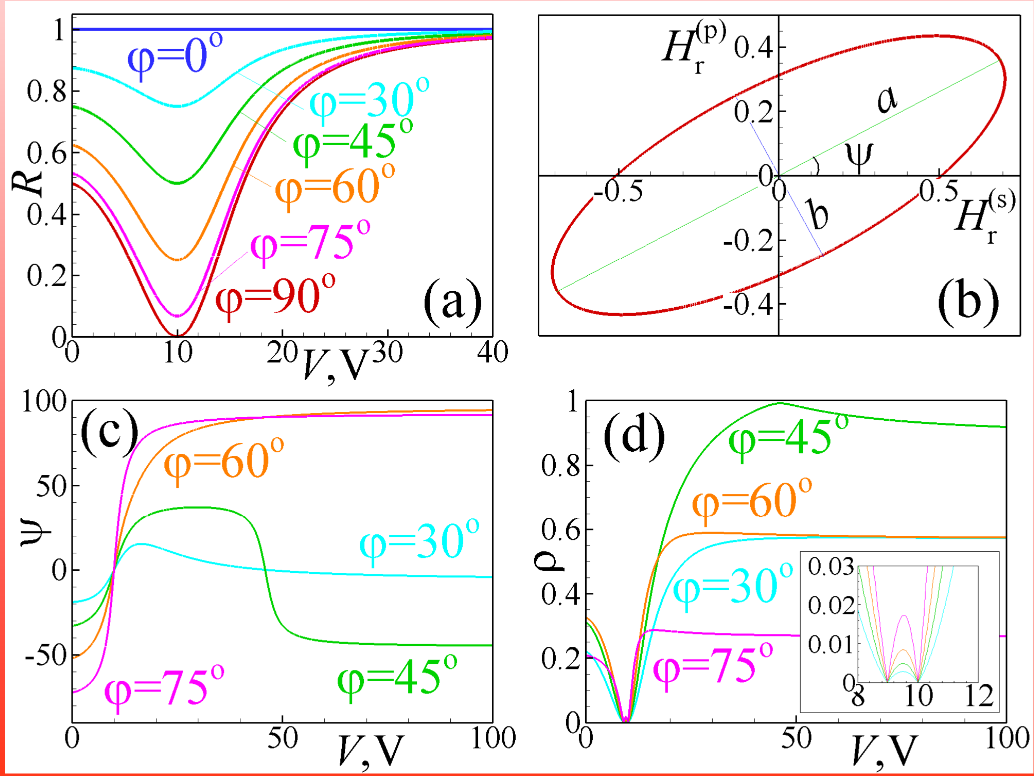
If zero-point conditions are met, and incident wave are linearly polarized, reflected wave will be purely s-polarized

$\varphi = 0$ purely s-polarized wave

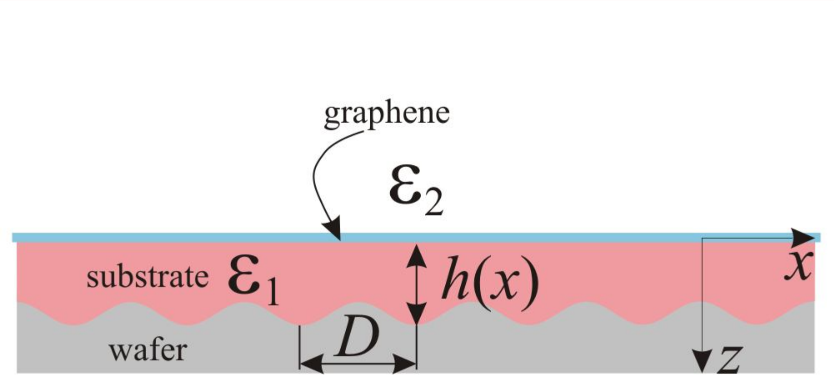
$\varphi = \frac{\pi}{2}$ purely p-polarized wave

$\rho = b/a$





Excitation of surface polaritons by diffraction grating



For uniform $h(x)=h_0$

carrier density $n_0 = \varepsilon_0 \varepsilon_1 V / e h_0$

chemical potential

$$\mu_0 = \hbar v_F \{\pi n_0\}^{1/2}$$

E. V. Castro, et al., Journal of Physics: Condensed Matter **22**, 175503 (2010).

For nonuniform $h(x)$ when $D >> h(x)$

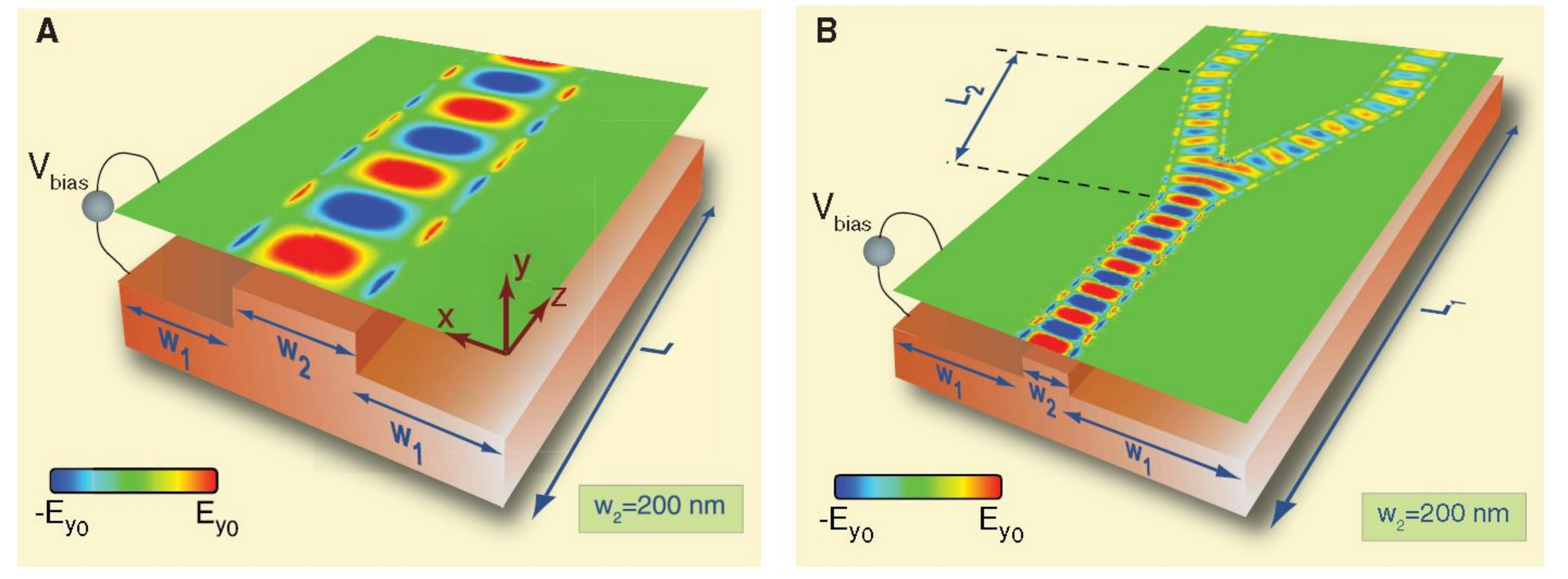
$$n(x) \approx \varepsilon_0 \varepsilon_1 V / e h(x)$$

$$\mu(x) = \hbar v_F \{\pi n(x)\}^{1/2}$$

As a result, conductivity of graphene is periodic in direction *x*

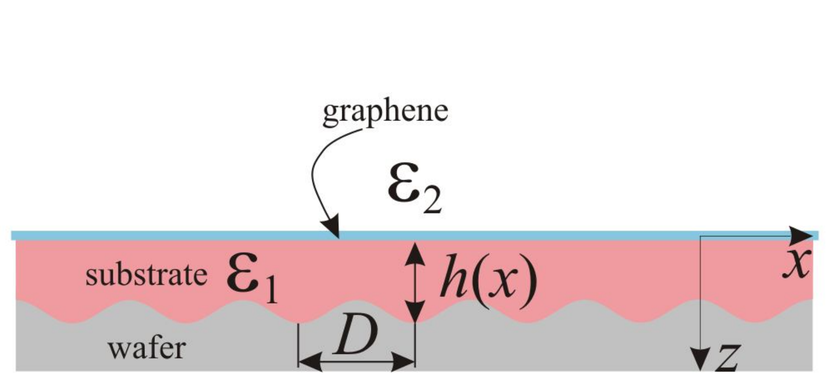
Example of plasmonic waveguide, based on nonuniform wafer

A.Vakil, N. Engheta, Science **332**, 1291-1294 (2011).



Nonuniform (but not periodic) substrate allows creation of plasmonic waveguide and splitter in graphene

Solution of problem



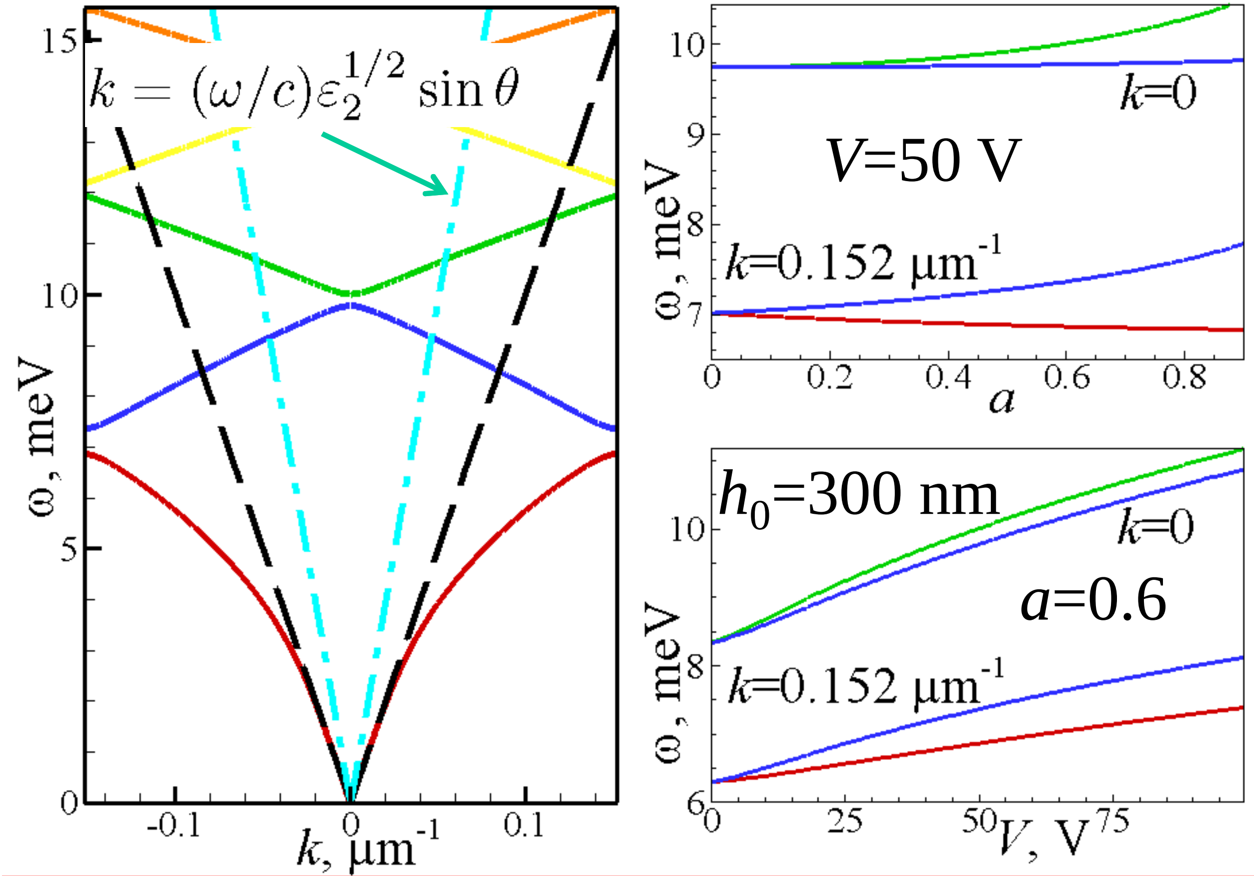
$$\sigma(x,\omega)=\sum_{n=-\infty}^{\infty}\sigma_n\exp(ingx),\qquad \sigma_n=D^{-1}\int_0^D\sigma(x,\omega)\exp(-ingx)dx$$

$$H_y^{(2)}(x,z)=H_i\exp[ikx]\exp(ik_z z)+\sum_{n=-\infty}^{\infty}A_n^{(2)}\exp(p_n^{(2)}z)\exp[i(k+ng)x],$$
$$H_y^{(1)}(x,z)=\sum_{n=-\infty}^{\infty}A_n^{(1)}\exp(-p_n^{(1)}z)\exp[i(k+ng)x],$$

$$p_n^{(m)}=\sqrt{(k+ng)^2-\omega^2\varepsilon_m/c^2}\qquad p_0^{(2)}=-ik_z$$

$$k=(\omega/c)\varepsilon_2^{1/2}\sin\theta$$

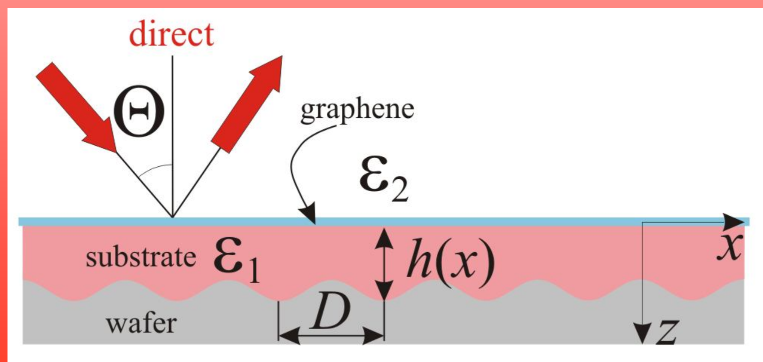
$$H_y^{(1)}(0)-H_y^{(2)}(0)=-(4\pi/c)\sigma(x,\omega)E_x(0)$$



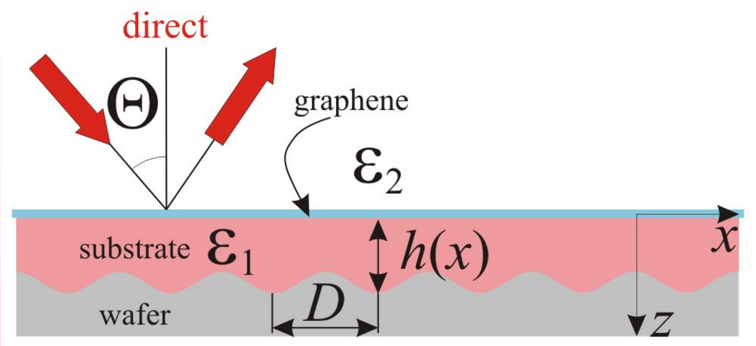
$h(x)=h_0[1+a\cos(2\pi x/D)]$

YVB, N. M. R. Peres, M. I. Vasilevskiy, PRB 85, 245409 (2012)

Spectrum exhibits band-gap structure, where values of the gaps can be tuned by external gate voltage *V*



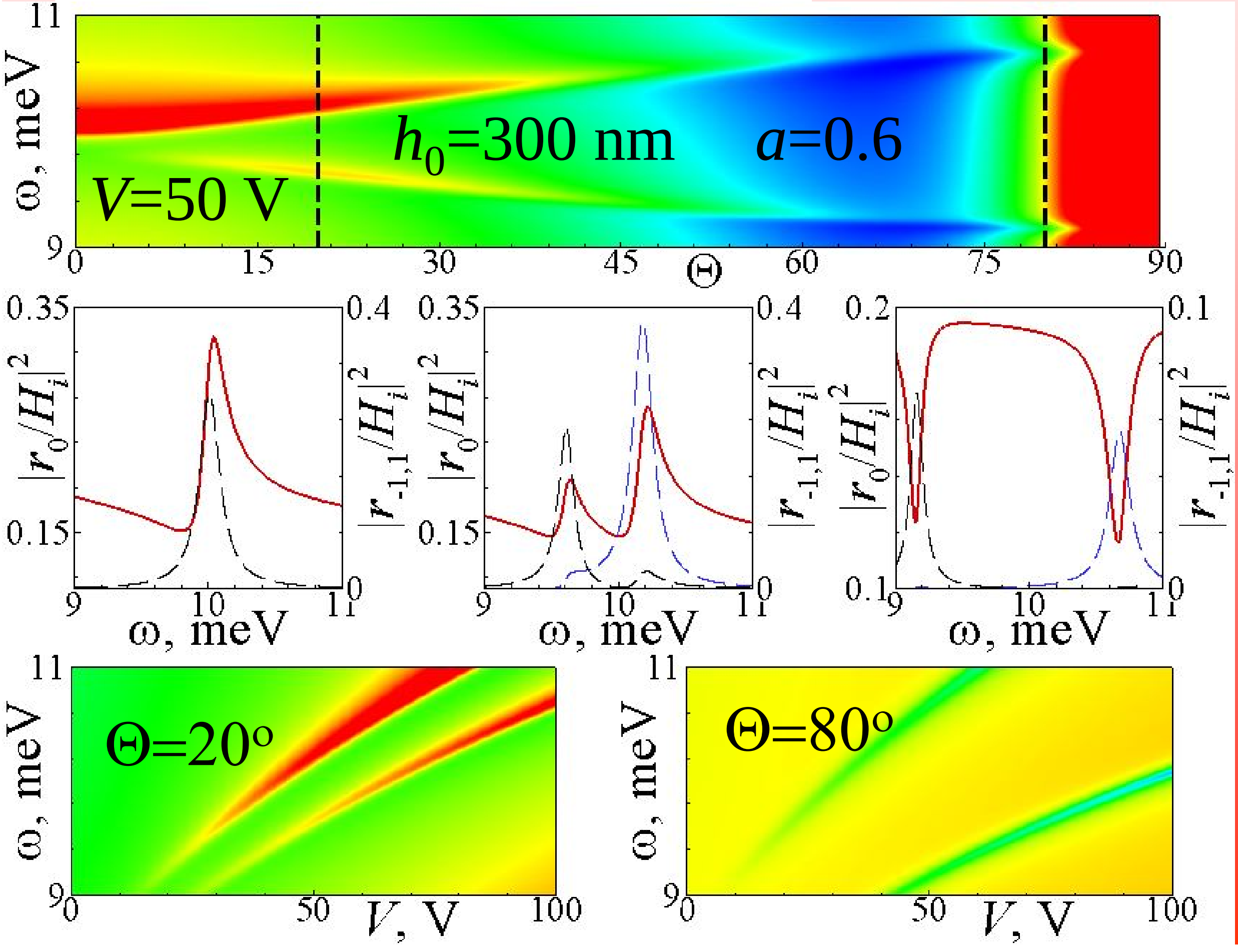
Direct excitation of surface polaritons in graphene



Modulated interface between substrate and wafer allows one to excite polaritons directly.

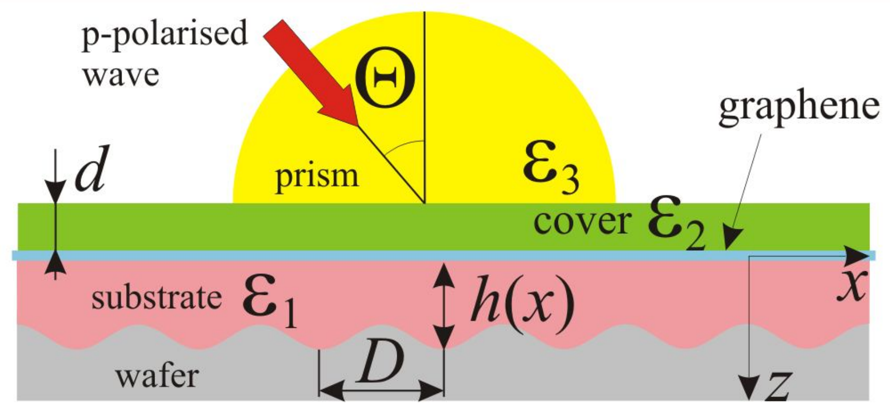
Brewster angle

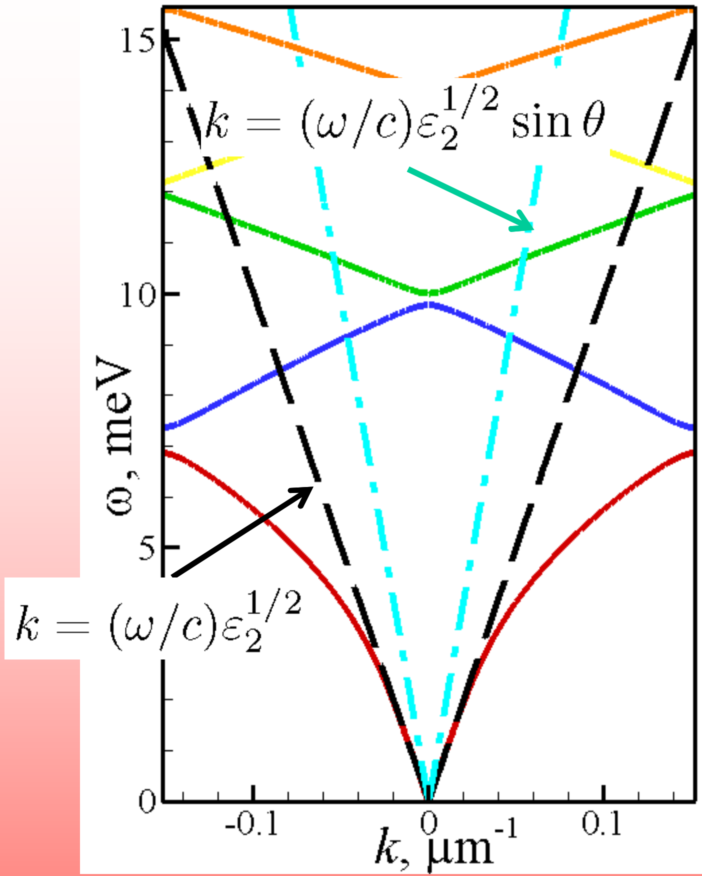
$$\Theta_b = \operatorname{atan}(\sqrt{\varepsilon_1/\varepsilon_2}) \approx 63^o$$



Excitation of surface polaritons reviels itself in reflection peak or deep, depending upon angle of incidence.

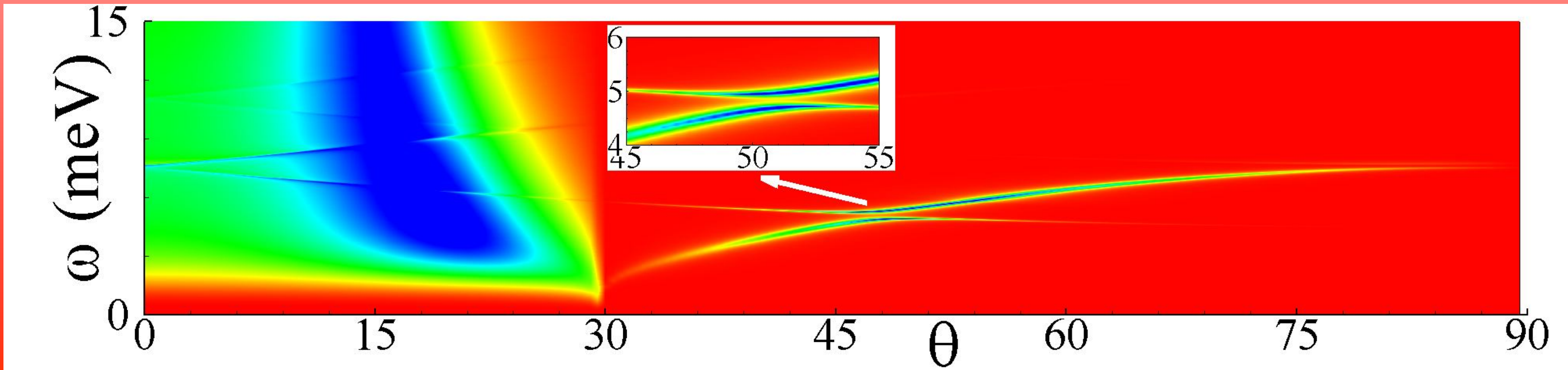
Excitation with prism



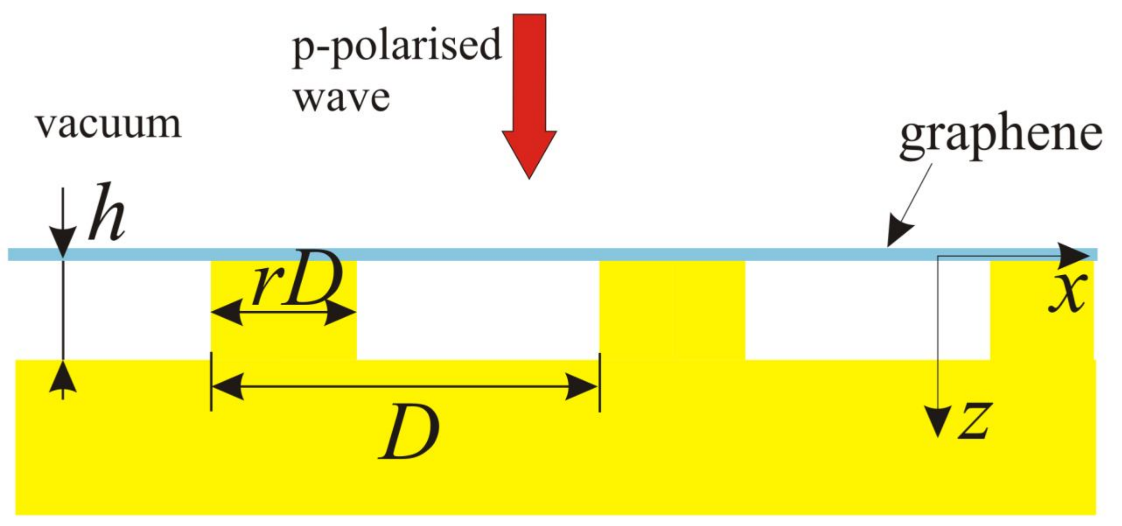


The mode anticrossing, corresponding to the edges of the gap, is clearly seen

d = 10 μm, V=90 V



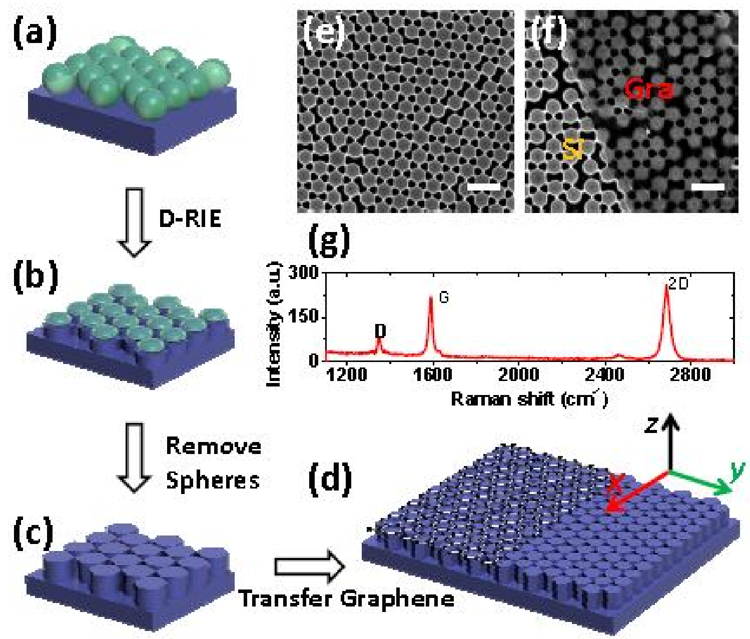
Square-wave grating covered with graphene



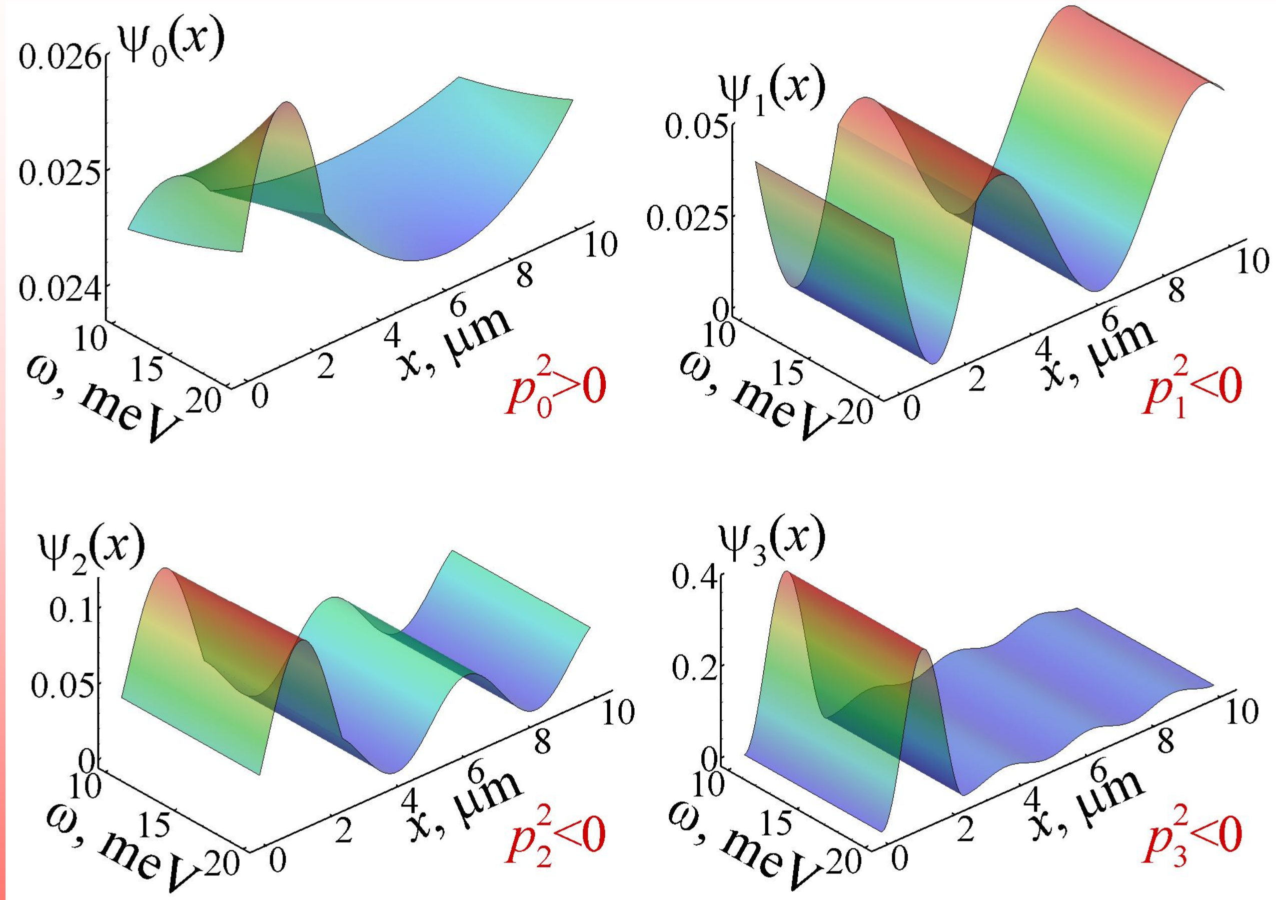
N.M.R. Peres, YVB, A. Ferreira, M.I. Vasilevskiy, J. Phys.: Condens. Matter **25**, 125303 (2013).

X. Zhu, et al, arXiv: 1301.3250

$$H_y^{(2)}(x,z) = \sum_{n=0}^{\infty} A_n^{(2)} \exp(ip_n z)\psi_n(x)$$

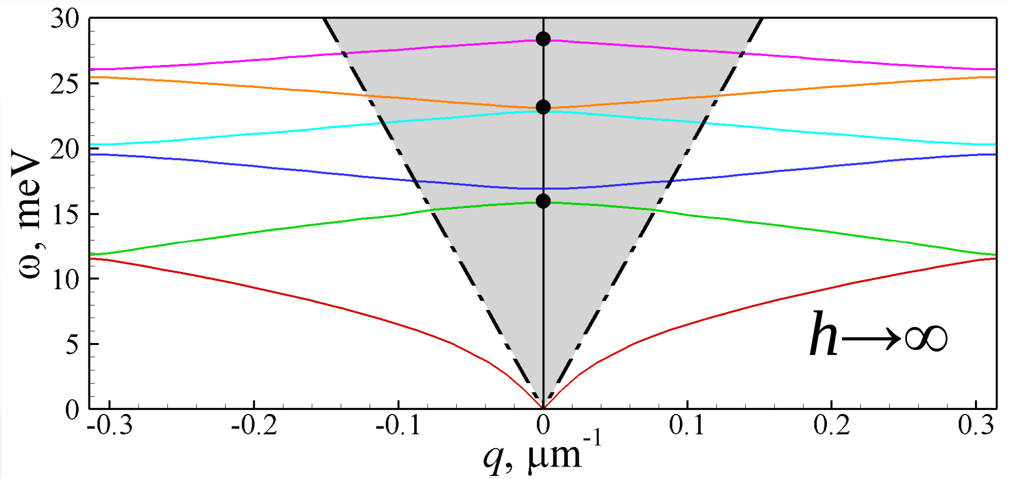


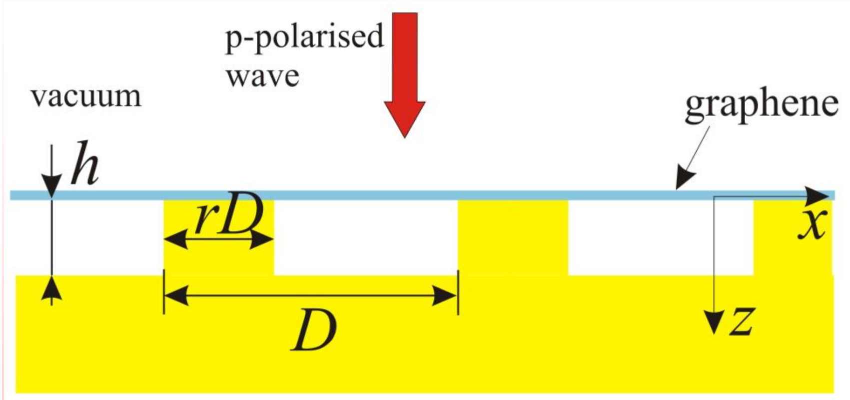
$$H_y^{(2)}(x,z) = \sum_{n=0}^{\infty} A_n^{(2)} \exp(ip_n z)\psi_n(x)$$

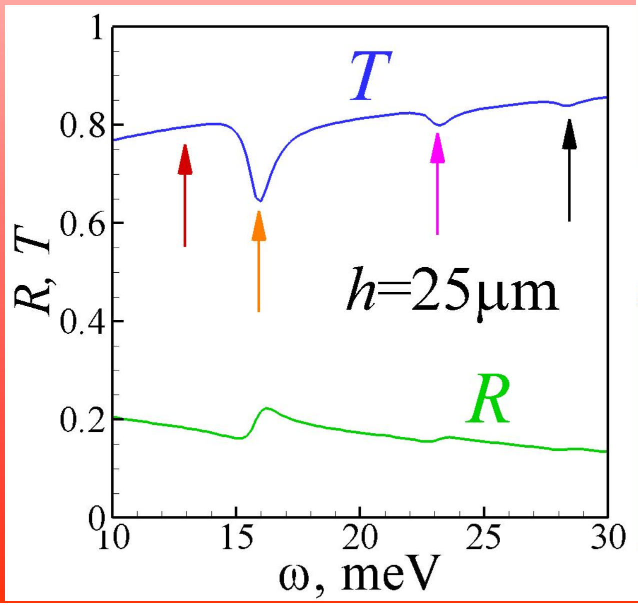


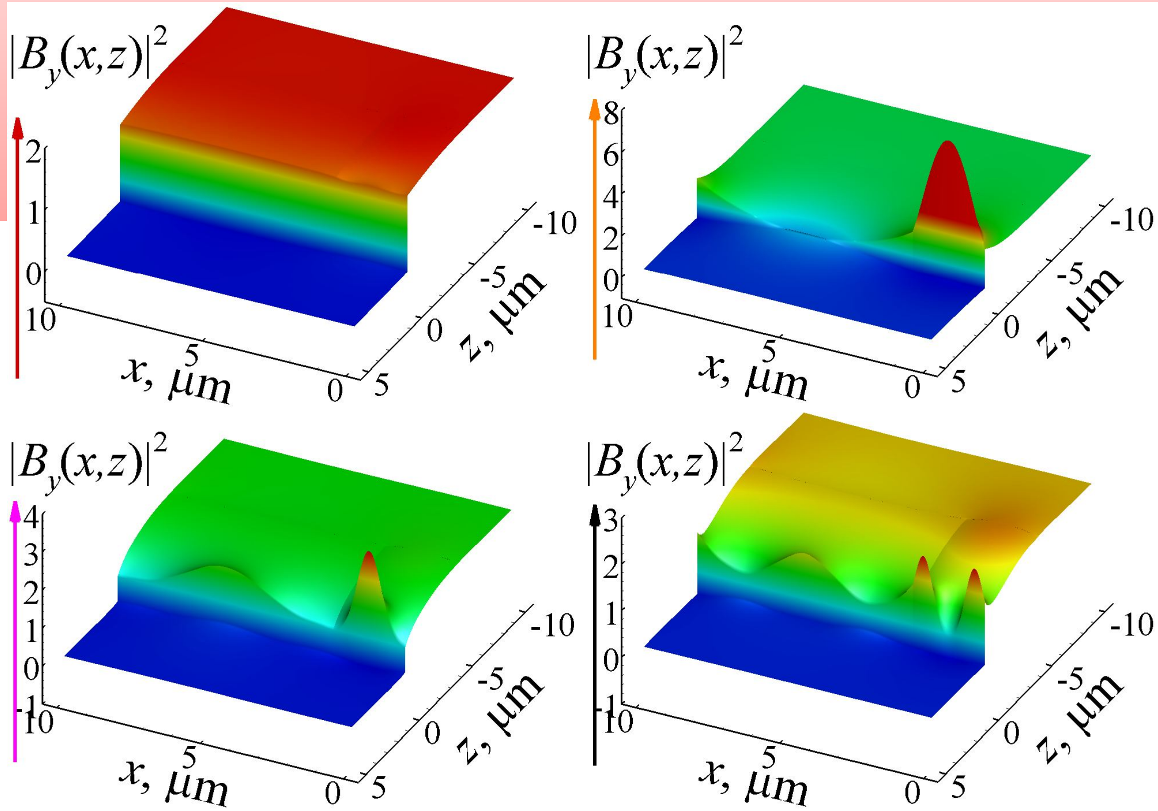
r=0.25,
d=10μm, ε=4

In THz range one square-wave harmonic is propagating, others are evanescent spectrum


ω, meV
q, μm^{-1}
h→∞


p-polarised
wave
vacuum
graphene
h
rD
x
D
z


T
R
R, T
h=25μm
ω, meV


$|B_y(x,z)|^2$
$|B_y(x,z)|^2$
$|B_y(x,z)|^2$
$|B_y(x,z)|^2$
x, μm
z, μm

Conclusions

1. By adjusting the external gate voltage of ATR structure with graphene layer, it is possible to tune the reflectance of the incident electromagnetic wave from total absorption to total reflection.
2. Graphene layer deposited on substrate with periodically modulated thickness or dielectric constant demonstrates band-gap structure of the spectrum (where positions of gap edges can be tuned by external gate voltage).

YVB, M.I. Vasilevskiy, N.M.R. Peres, EPL **92**, 68001 (2010)
YVB, N.M.R. Peres, M.I. Vasilevskiy, PRB **85**, 245409 (2012)
YVB, N.M.R. Peres, M.I. Vasilevskiy, JAP **112**, 084320 (2012)
N.M.R. Peres , YVB, A. Ferreira, M.I. Vasilevskiy, JPCM **25**, 125303 (2013).

COMPETE
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