Brian Kim — PhD Stanford 2018 E.E. (H. Hwang)
Postdoc Columbia (J. Hone, D. Basov)
Nano plasmonics / oxide heterostructures

Surface plasmon polariton

AC conductivity (Drude model)

$$\dot{\vec{p}} = -\vec{p}/\tau - e\vec{E}$$

Let $p = p(\omega)\, e^{-i\omega t}$, $E = E(\omega)\, e^{-i\omega t}$, $\vec{j} = -ne\vec{p}/m$ $\Rightarrow$

$$-i\omega p(\omega) = -p(\omega)/\tau - eE(\omega)$$

$$j(\omega) = \underbrace{\left(\frac{ne^2\tau}{m}\right)\left(\frac{1}{1-i\omega\tau}\right)}_{\sigma(\omega)} E(\omega)$$

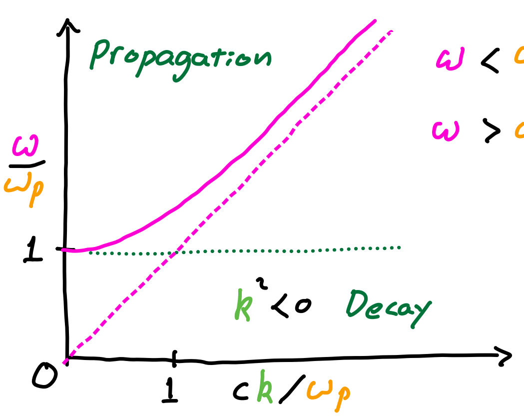
Wave propagation

$$\vec{\nabla}\times\vec{E} = -\frac{1}{c}\frac{\partial\vec{H}}{\partial t}, \quad \vec{\nabla}\times\vec{H} = \frac{4\pi}{c}\vec{j} + \frac{1}{c}\frac{\partial\vec{E}}{\partial t} \quad \Rightarrow \quad -\nabla^2\vec{E} = \frac{\omega^2}{c^2}\left(1+\frac{4\pi i\sigma(\omega)}{\omega}\right)\vec{E}$$

$$\epsilon(\omega) \rightarrow 1 - \frac{\omega_p^2}{\omega^2} \quad (\omega\tau \gg 1), \qquad \omega_p^2 = \frac{4\pi ne^2}{m}$$

Try $E \sim e^{i(\vec{k}\cdot\vec{r}-\omega t)}$

$\Rightarrow$ $k^2 = \epsilon(\omega)\frac{\omega^2}{c^2}$, $\quad \omega = \sqrt{c^2k^2 + \omega_p^2}$, $\quad c^2k^2 = \omega^2 - \omega_p^2$



$\omega < \omega_p$: $\epsilon(\omega) < 0$: k imaginary $\Rightarrow$ exponential decay

$\omega > \omega_p$: $\epsilon(\omega) > 0$: $k \in \mathbb{R}$ $\Rightarrow$ wave propagation

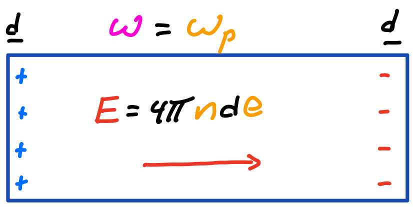
Transverse or Longitudinal?

EM wave in vacuum: $\vec{\nabla}\cdot\vec{E} = 4\pi\rho = 0 \Rightarrow \vec{k}\cdot\vec{E} = 0$ (transverse)

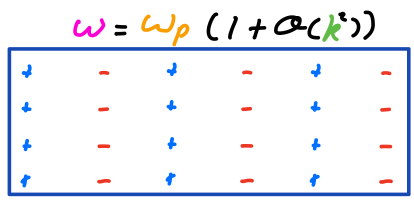
In matter, let $\rho(\vec{r},t) = \rho(\omega)\, e^{i(\vec{k}\cdot\vec{r}-\omega t)}$, $\vec{j}(\omega) = \sigma(\omega)\vec{E}(\omega)$

Continuity $\vec{\nabla}\cdot\vec{j} = -\frac{\partial}{\partial t}\rho = i\omega\rho(\omega) = \sigma(\omega)\, 4\pi\rho(\omega)$

Solvability $1 + \frac{4\pi i\sigma(\omega)}{\omega} = \epsilon(\omega) = 0 \Rightarrow \omega = \omega_L = \omega_p$



$k=0$ plasmon



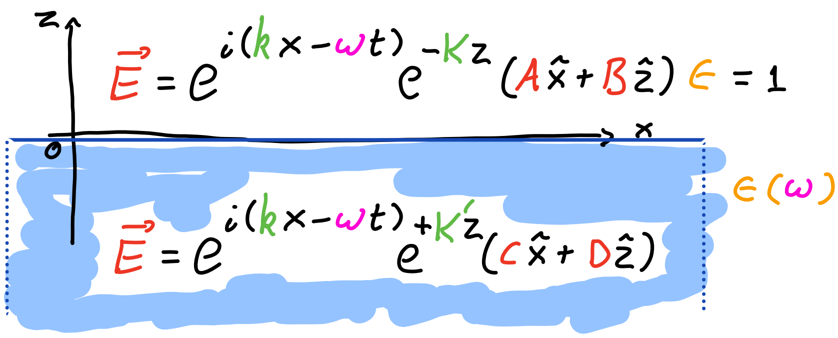
$k>0$ plasmon

Surface plasmon

Boundary Conditions:

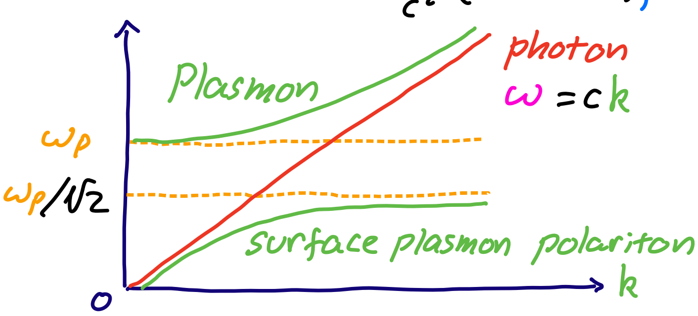
$[E_x] = [\epsilon E_z] = 0$

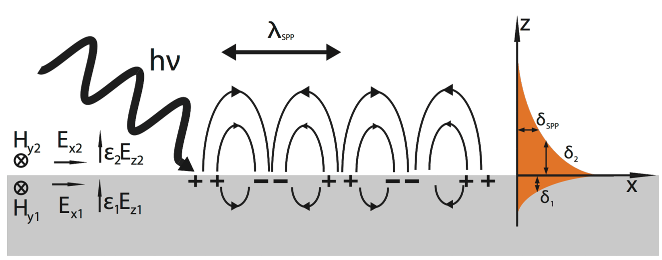
Gauss' Law: $\vec{\nabla}\cdot(\epsilon\vec{E}) = 0$



Wave equation: $-\nabla^2\vec{E} = \frac{\omega^2}{c^2}\epsilon\vec{E}$

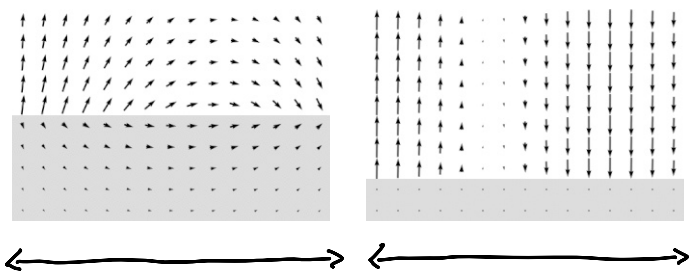
Solve: $K'^2 - K^2 = \frac{\omega^2}{c^2}(1-\epsilon(\omega))$, $K'/K = -\epsilon(\omega)$, $K^2 - k^2 = \frac{\omega^2}{c^2}$





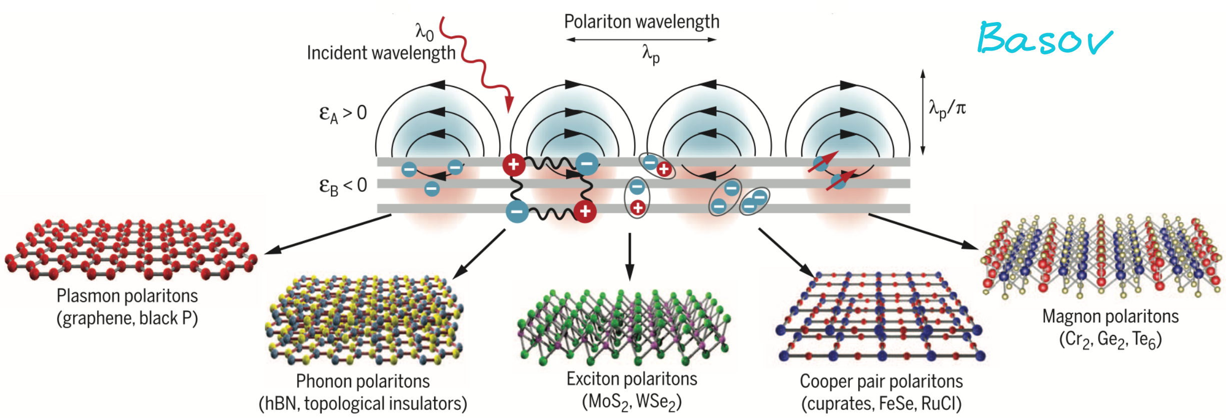
Air

Silver

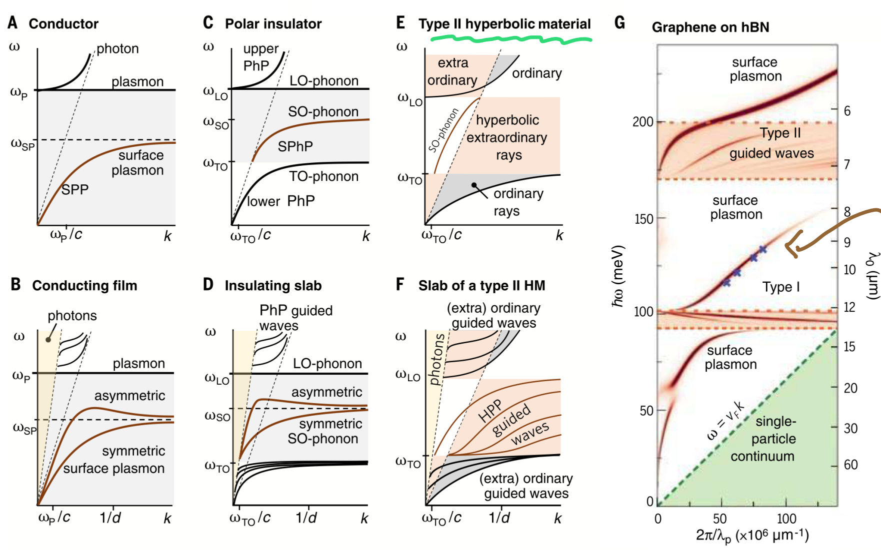


$\lambda = 370$ nm $\qquad \lambda = 6\ \mu m$

Wikipedia

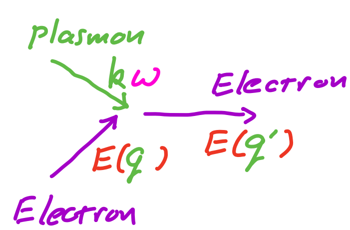


Basov



hyperbolic material: $\varepsilon_{\parallel} > 0 \quad \varepsilon_{\perp} < 0$

spectral function $A(k, \omega)$



Plasmon dispersion $\omega(k) \Rightarrow \mathrm{Im}\ \sigma(k,\omega)$

Plasmon decay length $\delta_{spp} \sim \dfrac{\mathrm{Im}\ \sigma}{\mathrm{Re}\ \sigma} \dfrac{2\pi}{k}$

Plasmon scattering rate $\dfrac{1}{\tau_p} \sim \dfrac{\mathrm{Re}\ \sigma}{\mathrm{Im}\ \sigma}\ \omega$

Measurements yield optical conductivity $\sigma(k,\omega)$

Near-field Scanning optical microscope (NSOM AKA SNOM)

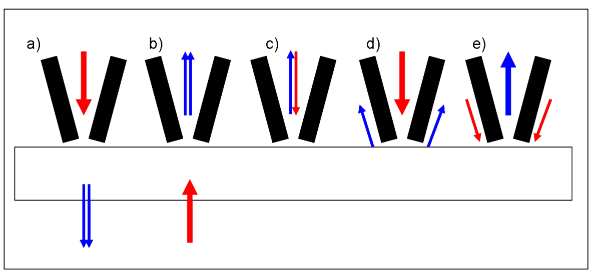
Radiation zones

Source size d	$d \ll r \ll \lambda$	Near-field
Wavelength λ	$d \ll r \sim \lambda$	Induction zone
	$d \ll \lambda \ll r$	Far-field

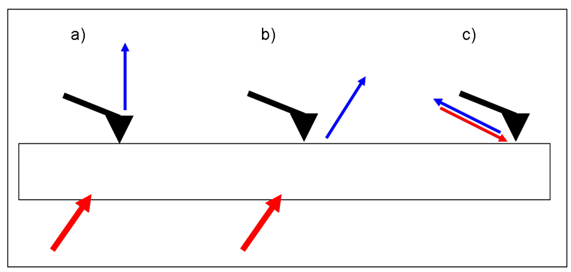
Multipole expansion: $A(\vec{r}) = \frac{1}{c} \sum_{\ell m} \frac{1}{r^{\ell+1}} Y_{\ell m}(\theta, \varphi) \int d\vec{r}' \vec{J}(\vec{r}') Y_{\ell m}(\theta', \varphi')$

Far field: $B \sim E \sim k^2 \frac{e^{ikr}}{r}$

Near field: $E \sim \frac{1}{r^3}$ $B \sim (kr) E \ll E$

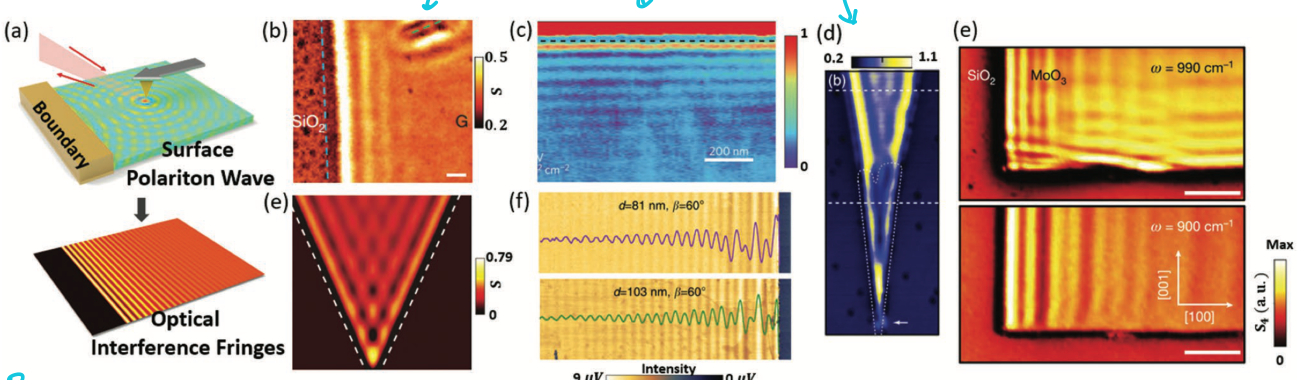


Apertured



Apertureless

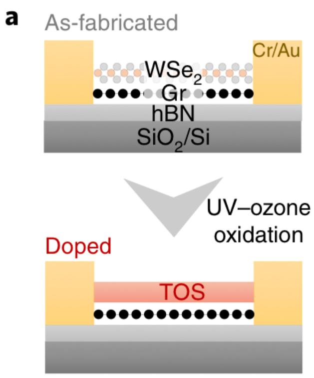
Graphene surface plasmon

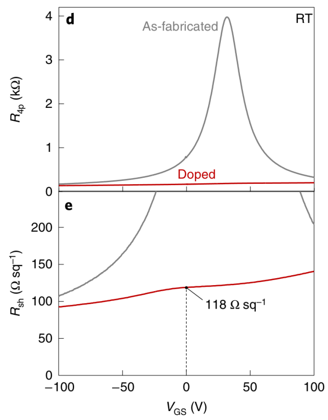


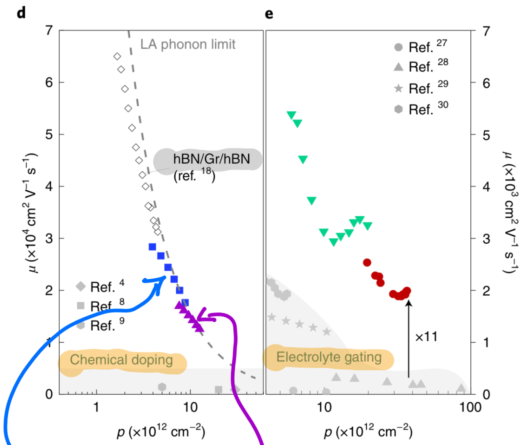
Basov

hBN surface phonon MoS_2 waveguide MoO_3 anisotropy

Charge transfer doping (Choi, 2021)







WSe_2 → TOS

increased electro-negativity

=> hole doping

Resistance drops 10x

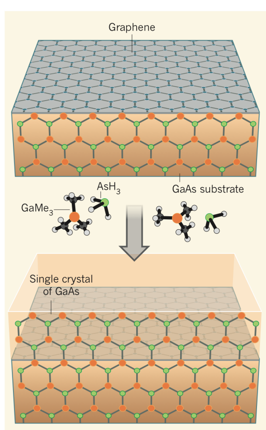
4 WSe_2 interlayers

3 WSe_2 interlayers

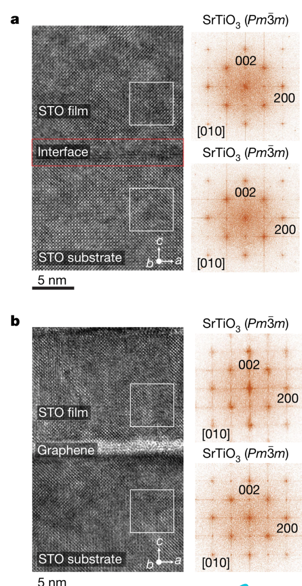
↑

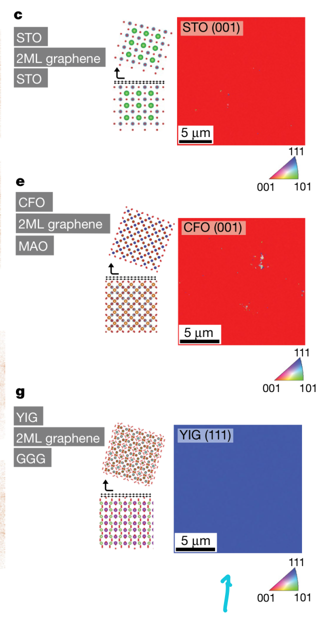
Mobility at phonon limit

Remote epitaxy



Kim (2017)





↑ FFTs of regions

↑ Electron back-scatter

Complex oxide heterostructures

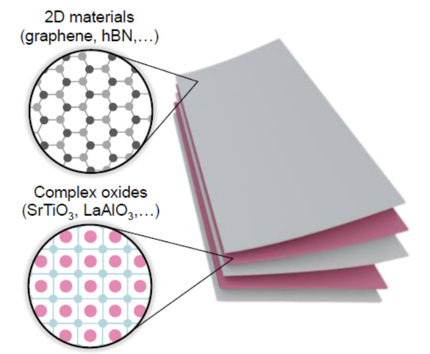


Fig. 2. Layer-by-layer vdW assembly of 2D/oxide heterostructures.

Complex oxides:

$Ba_2Sr_2CaCu_2O_{8+x}$ High T_c superconductor

$In_{2-x}Sn_xO_3$ transparent conductor

$BaTiO_3$ ferroelectric

$SrTiO_3$ incipient ferroelectric and insulating superconductor

2DEGs form at interfaces