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What is an Epsilon-Near-Zero mode?

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Surface Plasmons in Thin Films

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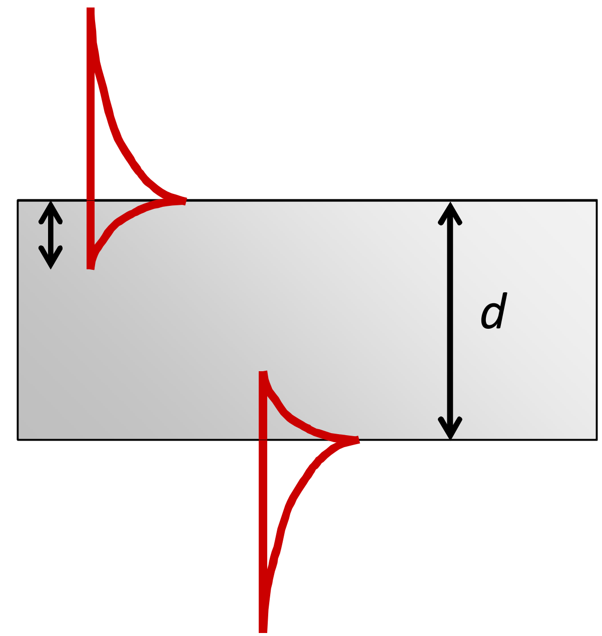
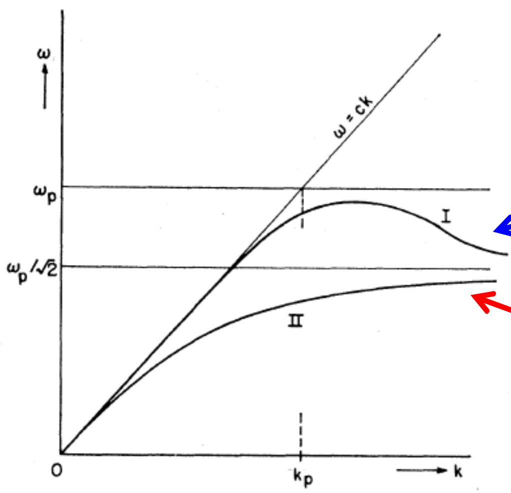
(Received 15 January 1969)

Econoumou, 1969
Burke et al, 1986
etc

"Thin" here: ~20nm for ~400nm plasma wavelength

~ *Skin depth*





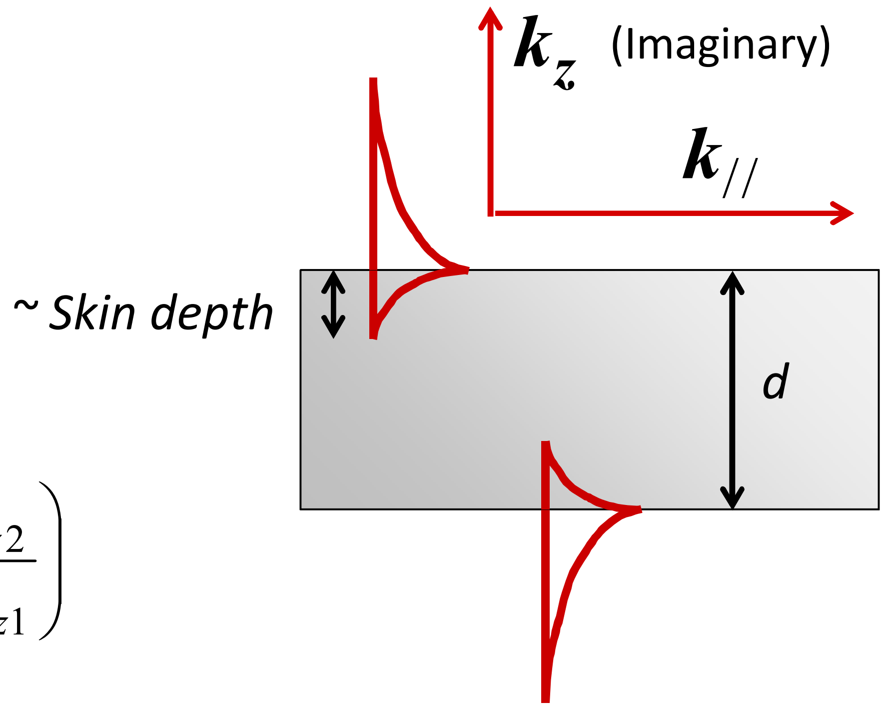
Long range surface plasmon

Short range surface plasmon

FIG. 4. Geometry and the dispersion relations for SPO of a metal film between two semi-infinite insulators ($\epsilon_m = 1 - \omega_p^2/\omega^2$, $\epsilon_i = 1$). The analytical expressions for $k \gg k_p$ or $k \ll k_p$ for the curves shown schematically here are (3.23b) and (3.18).

What happens when the layer becomes much thinner?
(<< skin depth)

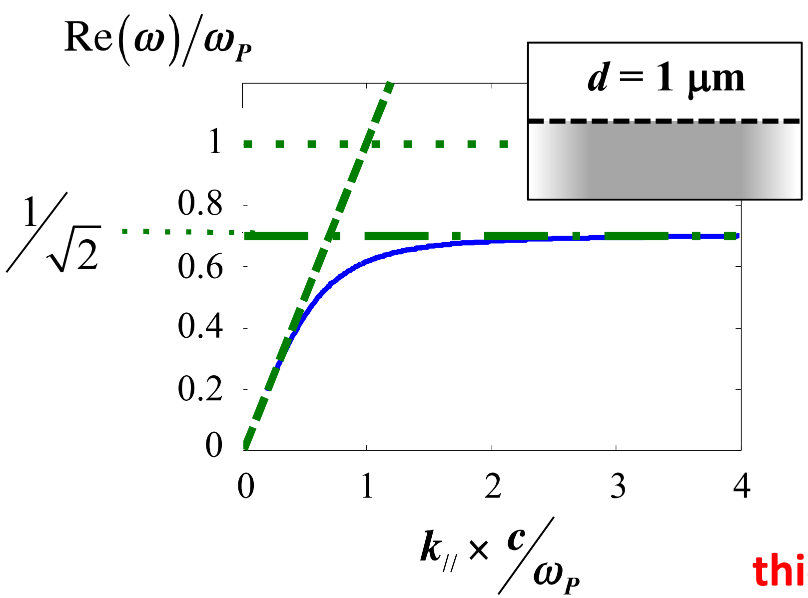
Dispersion relations



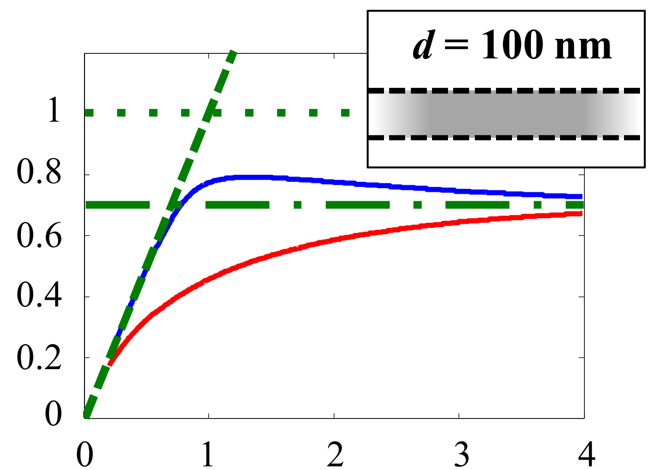
$$1+\frac{\varepsilon_1 k_{z3}}{\varepsilon_3 k_{z1}} = i\tan\left(k_{z2}d\right)\left(\frac{\varepsilon_2 k_{z3}}{\varepsilon_3 k_{z2}}+\frac{\varepsilon_1 k_{z2}}{\varepsilon_2 k_{z1}}\right)$$

Dispersion relations

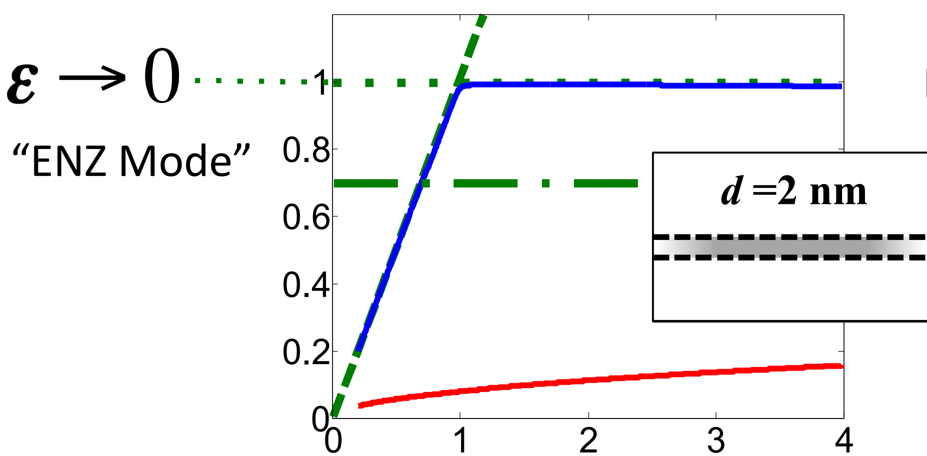
thickness >> skin depth



thickness ~ skin depth



thickness << skin depth



Flat dispersion?

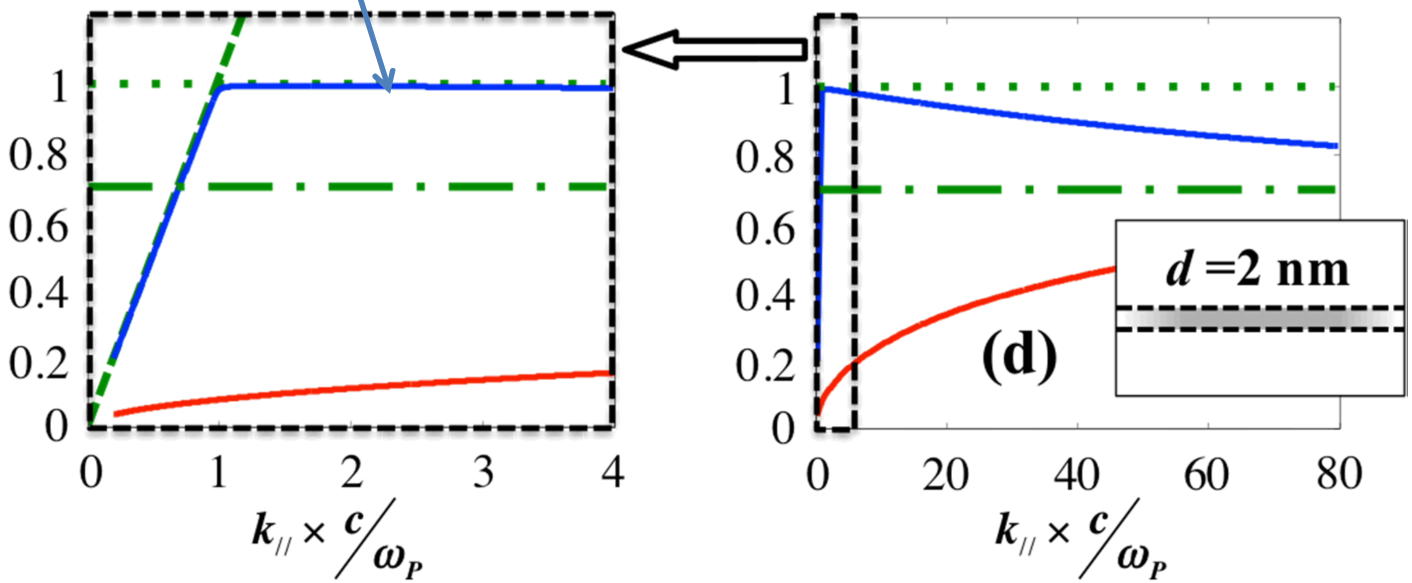
1. Vassant, Marquier, Greffet et al., Phys. Rev. Lett. **109**, 237401 (2012)
2. Vassant, Marquier, Greffet et al., Opt. Express **20**, 23971 (2012)
3. Campione, Brener, Marquier, Phys. Rev. B Rapid Commun. **91**, 121408 (2015)

ENZ mode dispersion

Flat?...

Close to $\omega \approx \omega_P$

$$\omega \approx \omega_P\left[1-\frac{k_{//}d}{4}\right]-i\frac{\gamma}{2}$$



The ENZ mode dispersion is a part of the long-range surface plasmon dispersion that reaches the plasma frequency, where the metal dielectric constant vanishes.

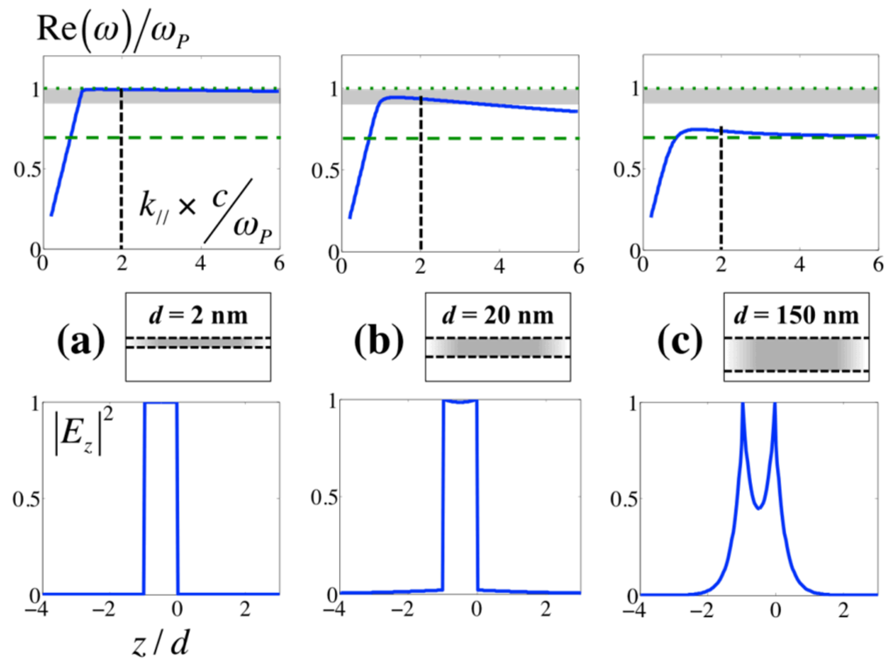
Campione, Brener, Marquier, Phys. Rev. B Rapid Commun. **91**, 121408 (2015)

ENZ Modes: E_z is Constant and Large

$$\varepsilon_1 E_{z1} = \varepsilon_2 E_{z2}$$

$$\frac{\varepsilon_1}{\varepsilon_2} E_{z1} = E_{z2}$$

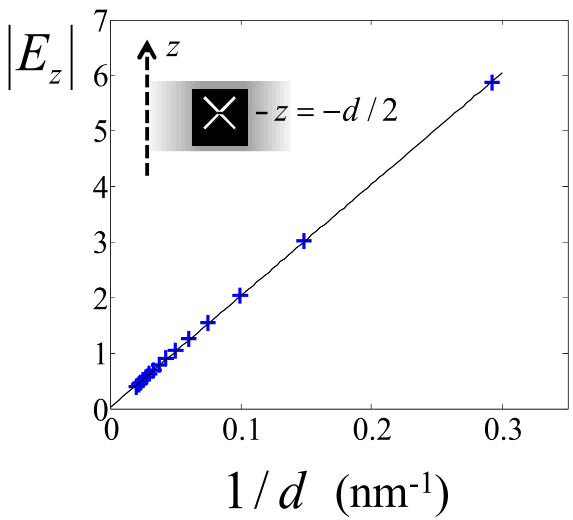
~ 0

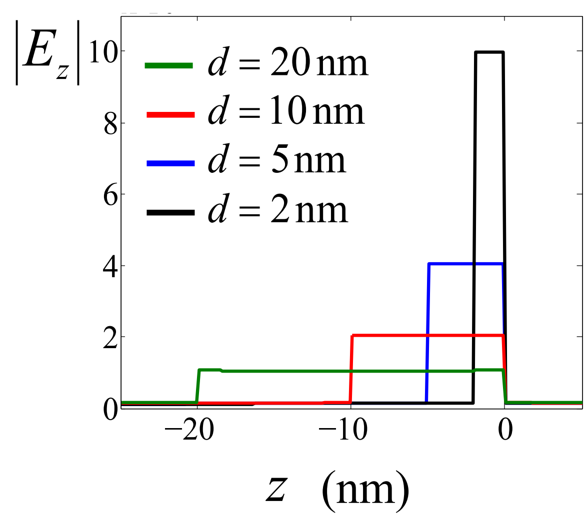


Campione, Brener, Marquier, Phys. Rev. B Rapid Commun. **91**, 121408 (2015)

ENZ Modes: E_z is Constant and Large

Field normalized to its value for *d* = 20nm





$$\boxed{E_z \propto \frac{1}{d}}$$

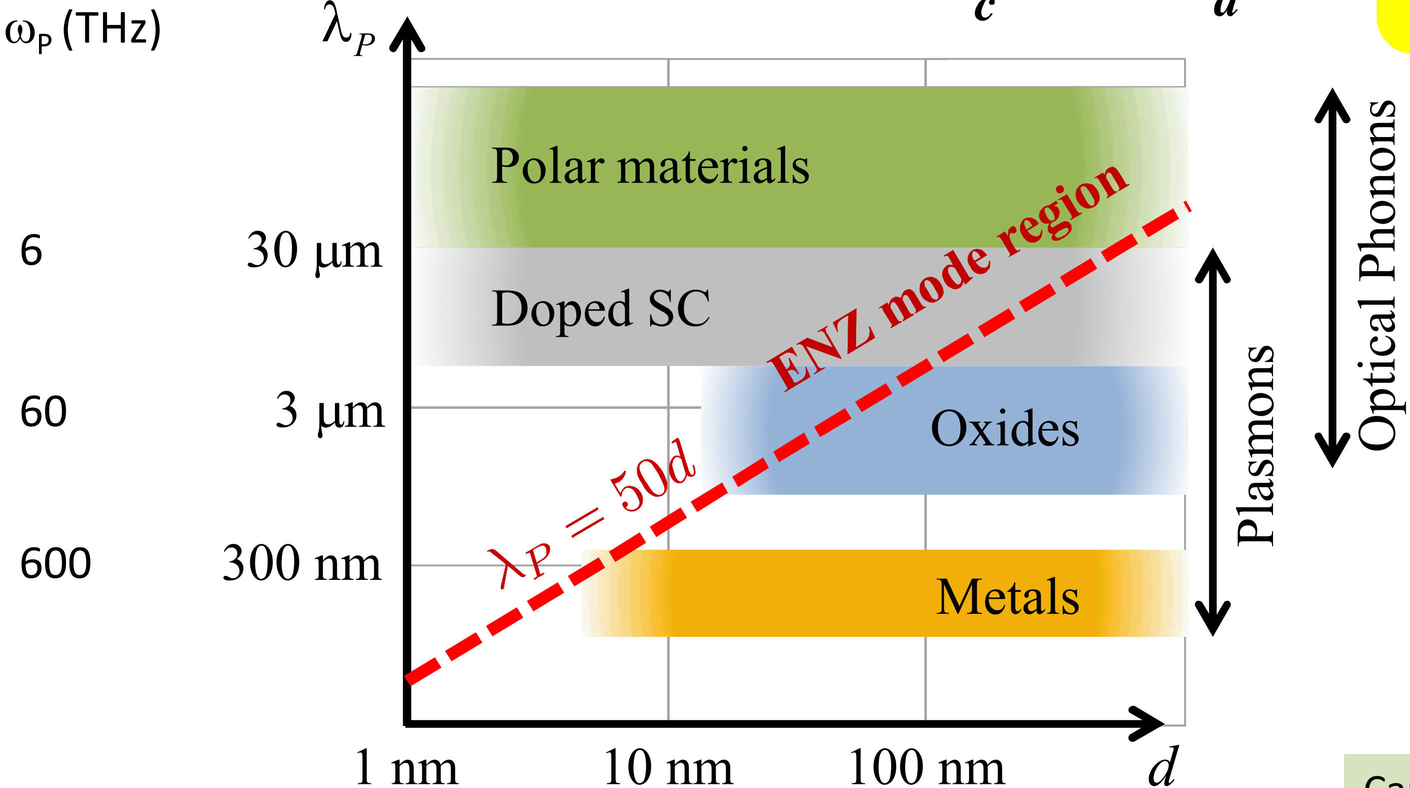
Campione, Brener, Marquier, Phys. Rev. B Rapid Commun. **91**, 121408 (2015)

Where Can We Find ENZ Modes?

Condition for ENZ modes $\frac{\omega_P}{c} < k_{//} << \frac{4}{d}$

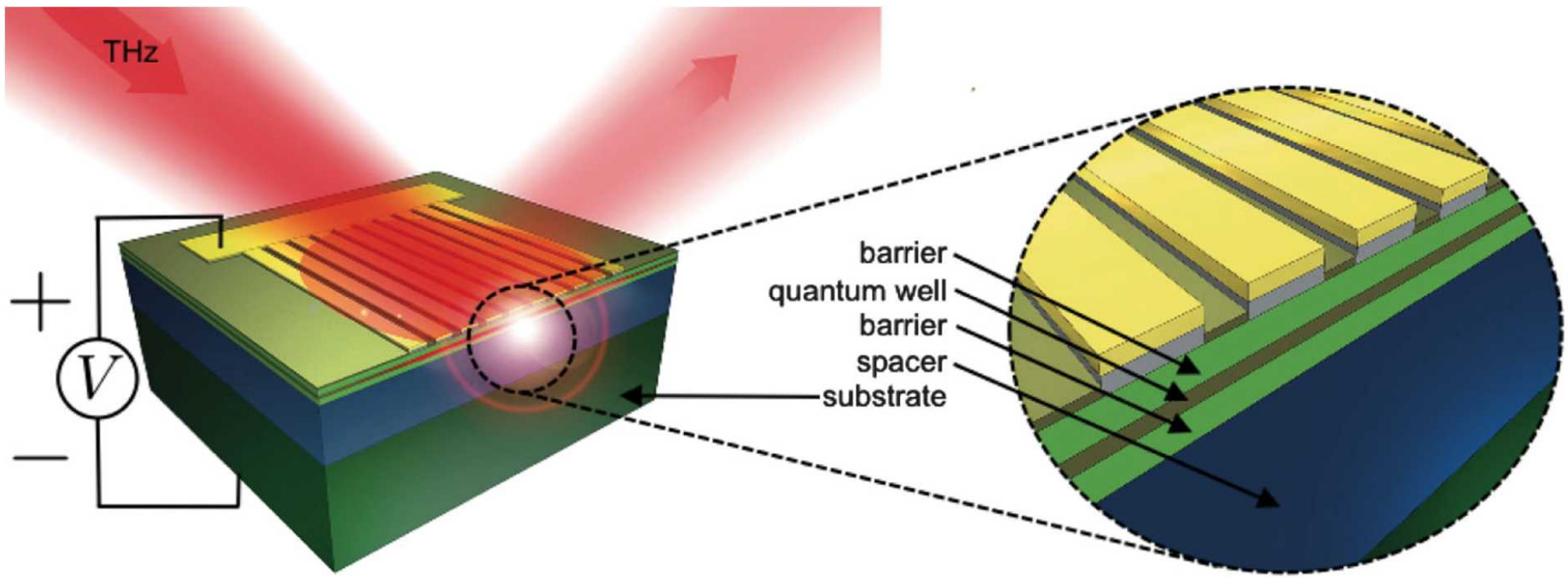
Rule of Thumb:

$$d <\approx \frac{\lambda_P}{50}$$



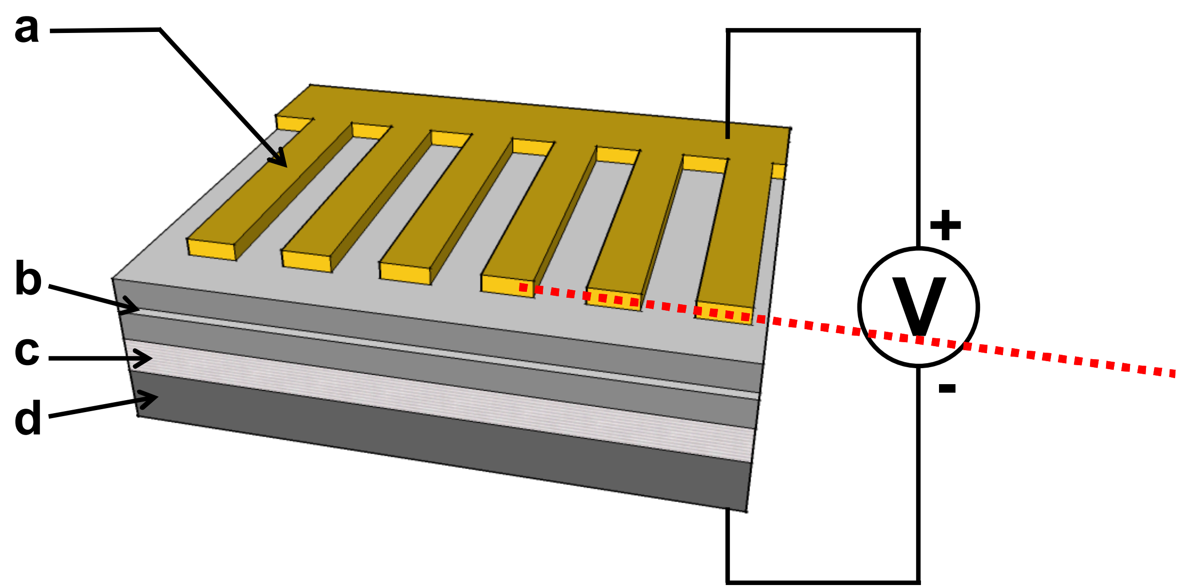
Campione, Brener, Marquier, Phys. Rev. B Rapid Commun. **91**, 121408 (2015)

Electrical control of the absorption



Vassant, Phys. Rev. Lett., **109**, 237401 (2012)

Electrical control of the absorption



$$\epsilon = \begin{pmatrix} \epsilon_{//} & 0 & 0 \\ 0 & \epsilon_{//} & 0 \\ 0 & 0 & \epsilon_z \end{pmatrix}$$

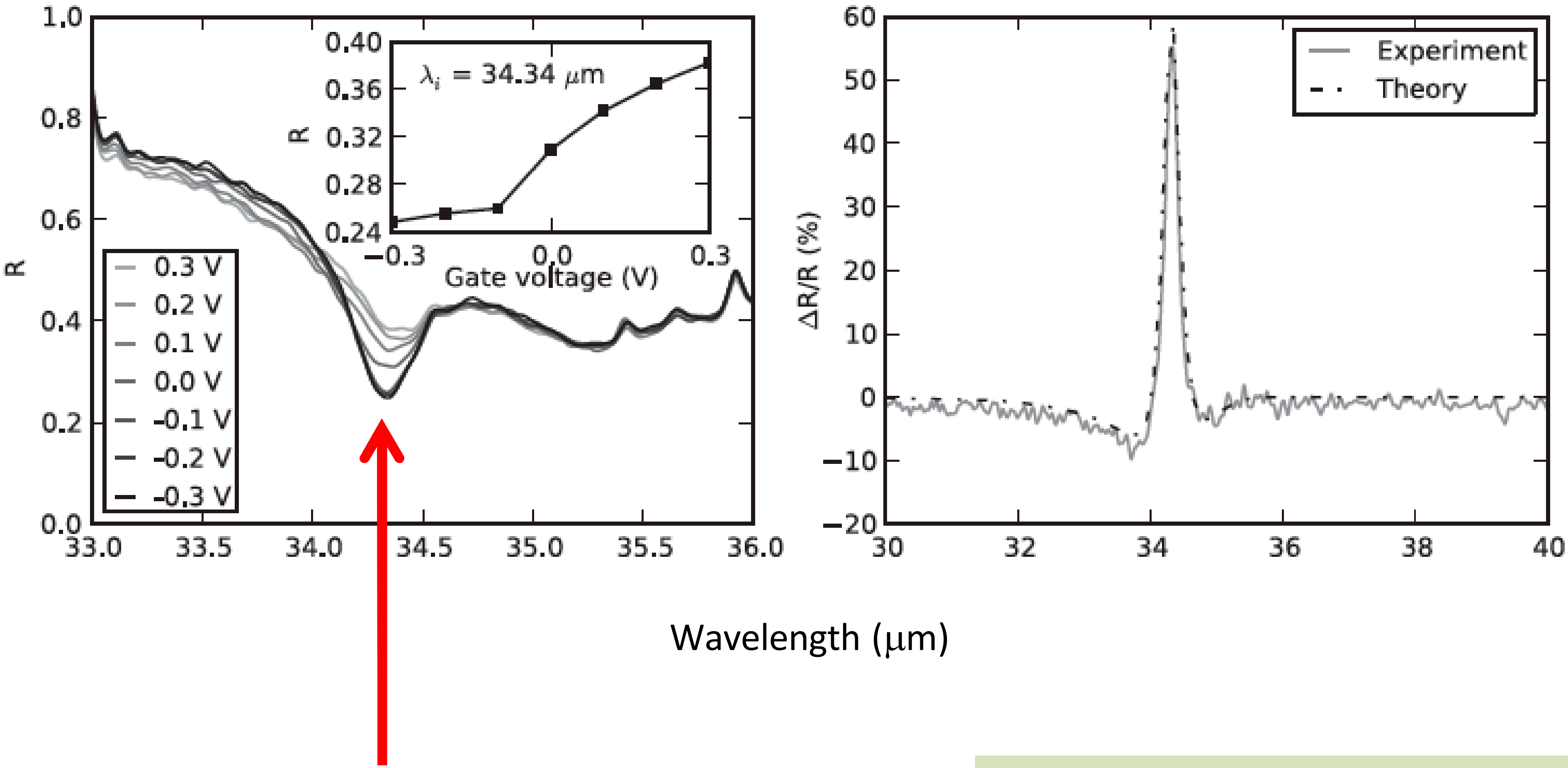
$$\epsilon_{//} = \epsilon_{\mathrm{GaAs}} - \frac{\omega_P^2}{\omega^2 + i\gamma\omega}$$

$$\epsilon_z = \epsilon_{\mathrm{GaAs}} - \sum_{n,n'} \frac{f_{nn'}\omega_P'^2}{\omega^2 - \omega_{nn'}^2 + i\gamma_{\mathrm{isb}}\omega}$$

≈ 0

Vassant, Phys. Rev. Lett., **109**, 237401 (2012)

Electrical control of the absorption

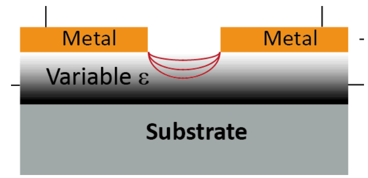


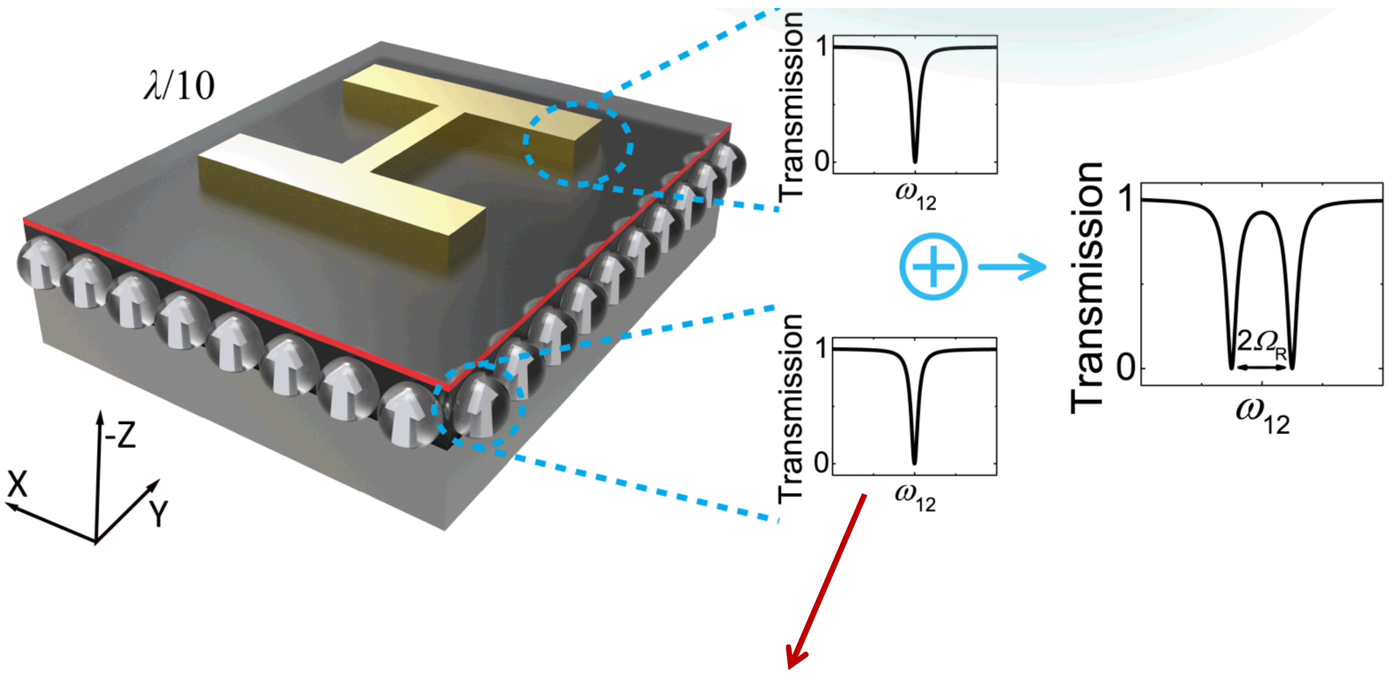
Wavelength (μm)

Vassant, Phys. Rev. Lett., **109**, 237401 (2012)

What Can We Do With ENZ Modes: Coupling to Planar Metamaterials

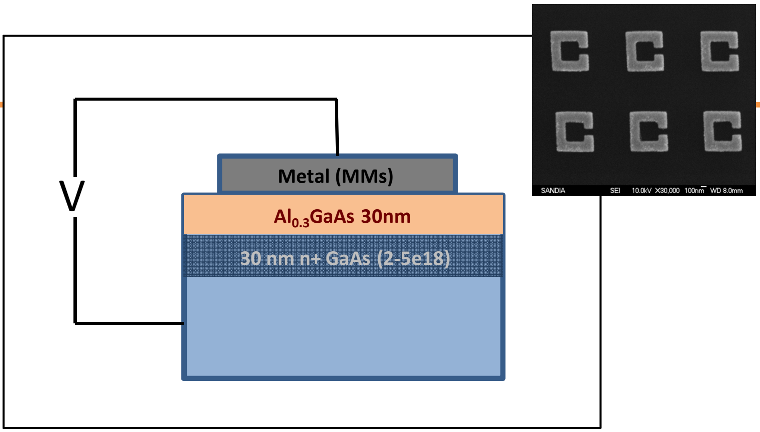
MM resonators create strong optical fields that lead to strong coupling



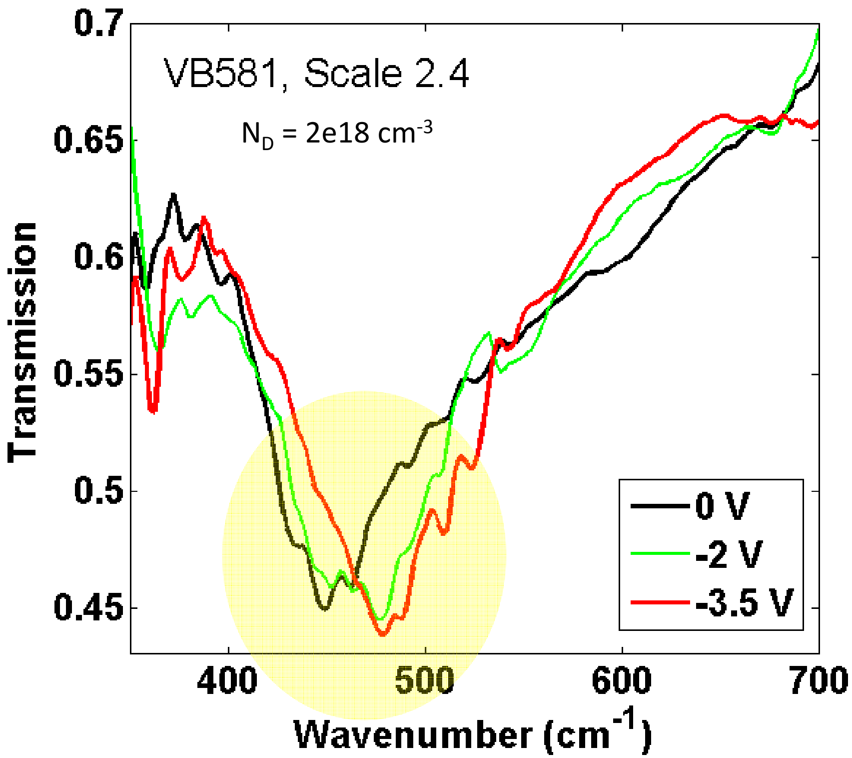


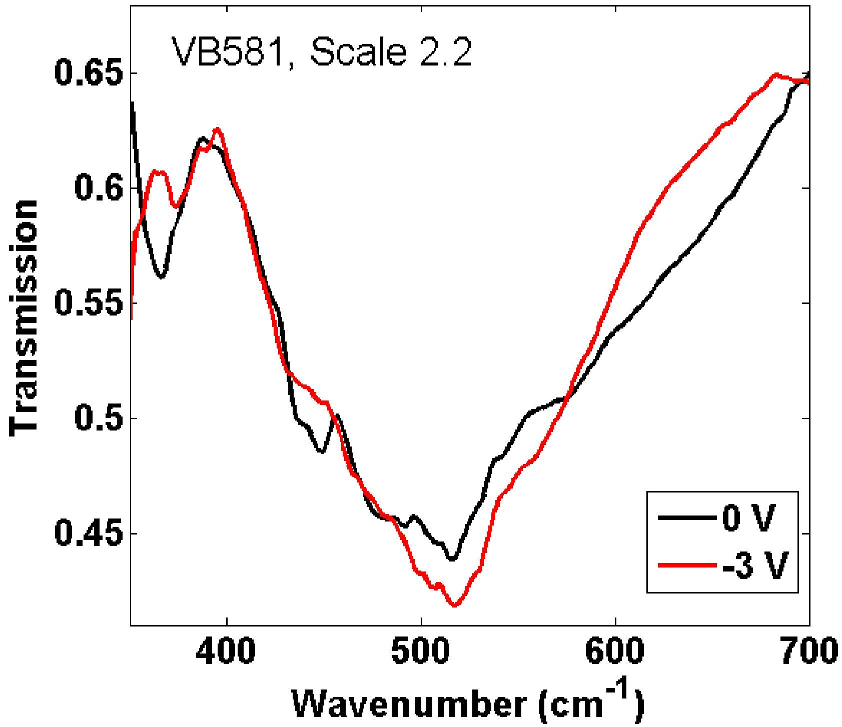
Optical Phonons: Nano Letters 11, 2104 (2011)
Intersubband Transitions: Nature Communications 4, (2013)
Epsilon Near Zero modes: Nano Letters **13**, 5391 (2013)

Electrically Tuning the Coupling to the ENZ Mode



Fundamentally different than tuning just by changing a local permittivity!
Removal of carriers -> removal of ENZ mode



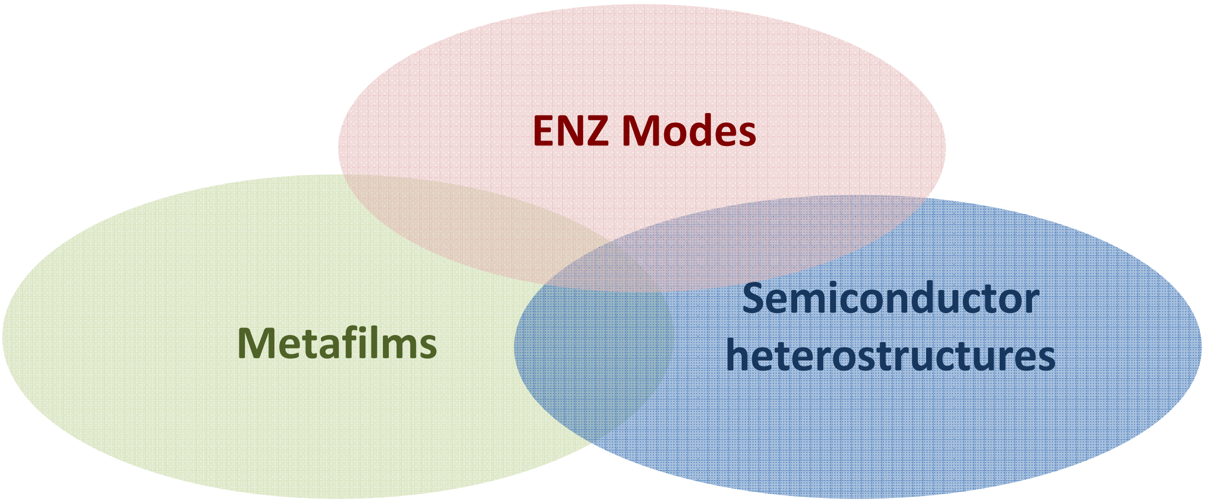


Nano Letters **13**, 5391 (2013)

Summary

"Epsilon-Near-Zero" mode:

- Transverse surface mode. Close to the plasma frequency (or longitudinal phonon…)
- Linear, almost flat, dispersion relation
- Large electric field: opportunity for enhancement of light-matter interactions



Metamaterial resonators + semiconductor heterostructures + ENZ modes : platform for tunable spectral behavior and variable coupling, enhanced nonlinearities etc.

Acknowledgements

Igal Brener

Salvatore Campione

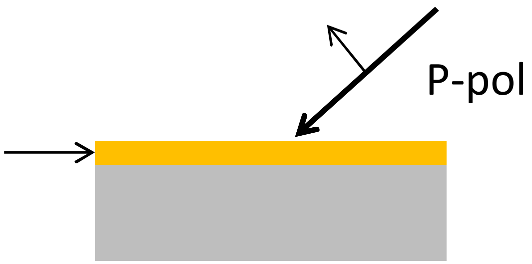
Young Chul Jun

Jean-Jacques Greffet

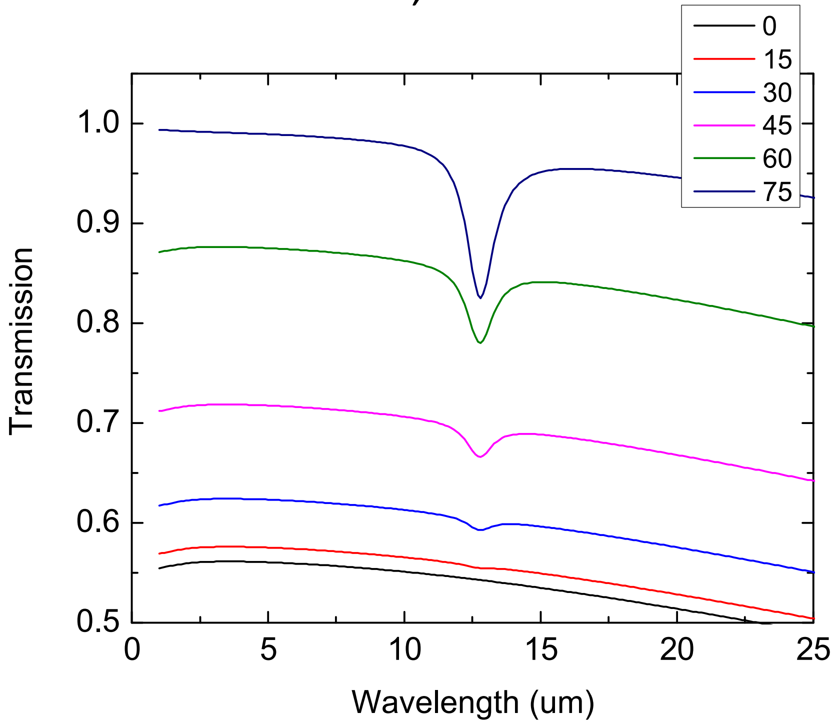
Simon Vassant

Coupling to Berreman Modes From Free Space

Thin (<<λ) layer where ε crosses 0 (Drude, phonon, etc)



Transmission vs angle (p-pol): A sharp dip is observed in transmission, where ε~0

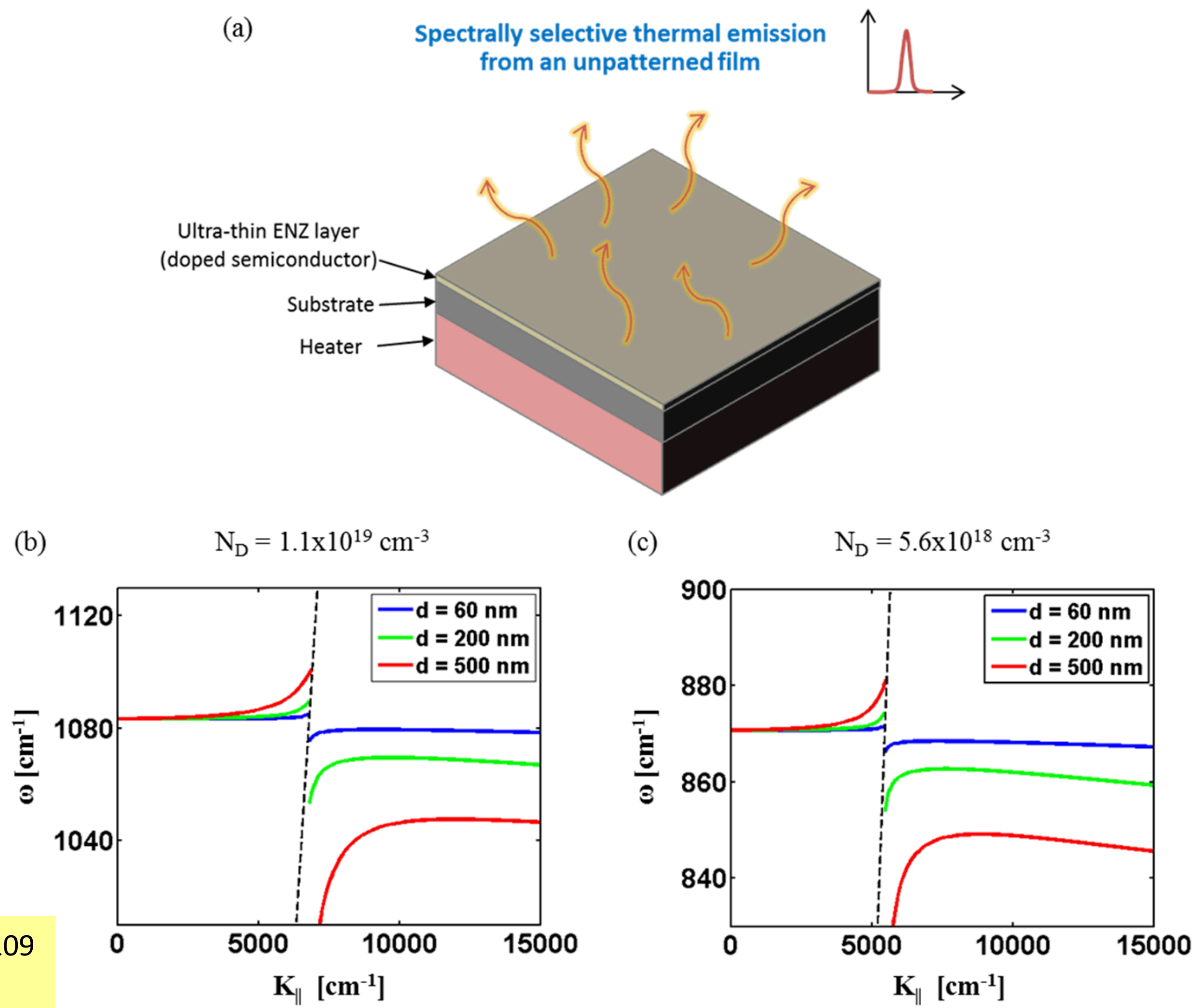


("Berreman" dip)

Berreman, Physical Review 130 (6), 2193 (1963).
McAlister and Stern, Physical Review 132, 1599 (1963).

Thermal Emission: Berreman Modes

Kirchhoff's law of thermal radiation: the absorptivity of an object should be equal to its emissivity ($A = \epsilon$)



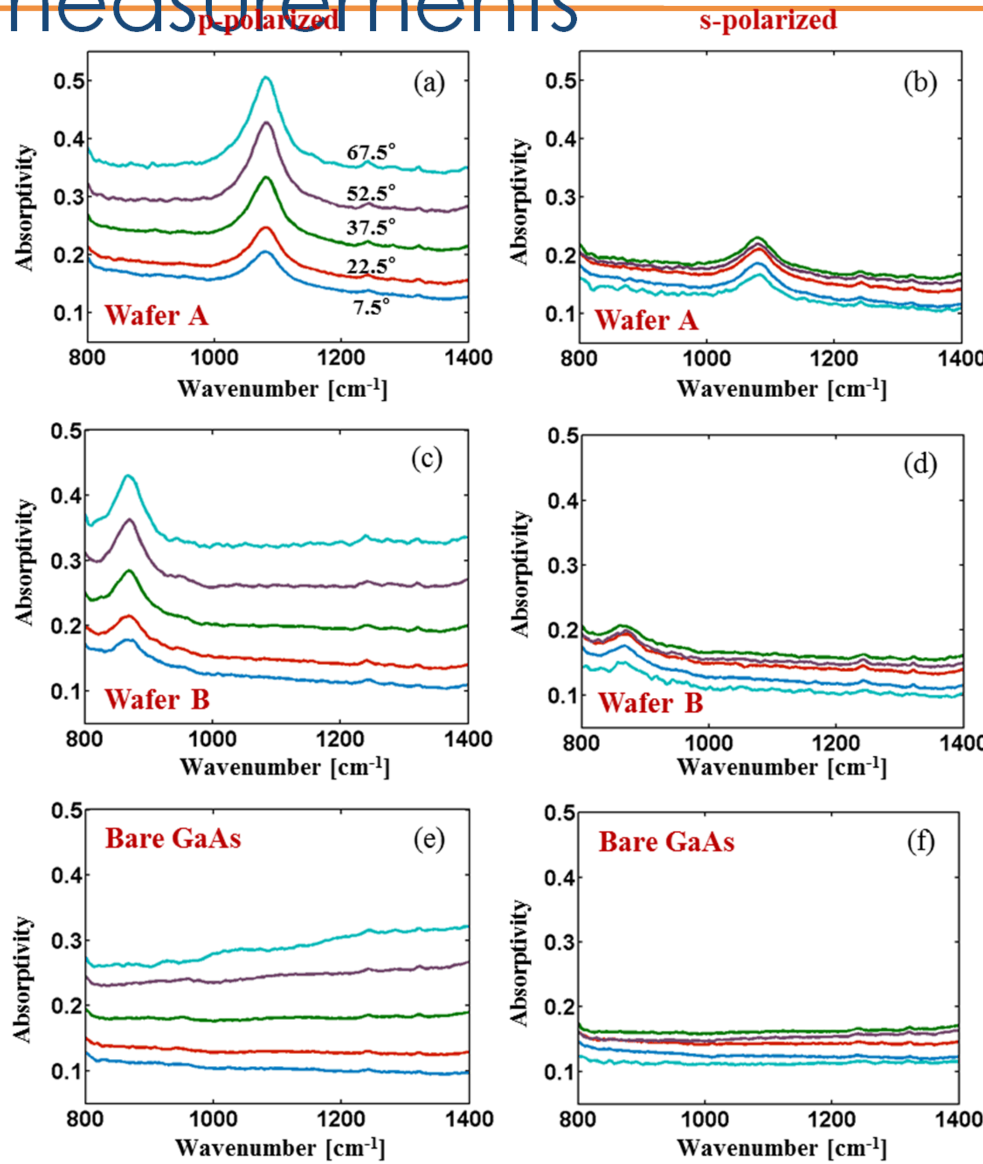
Appl. Phys. Lett. **105**, 131109 (2014)

Angle-resolved, polarization-dependent absorptivity measurements

$N_D = 1.1 \times 10^{19}\ cm^{-3}$

$N_D = 5.6 \times 10^{18}\ cm^{-3}$

Bare GaAs

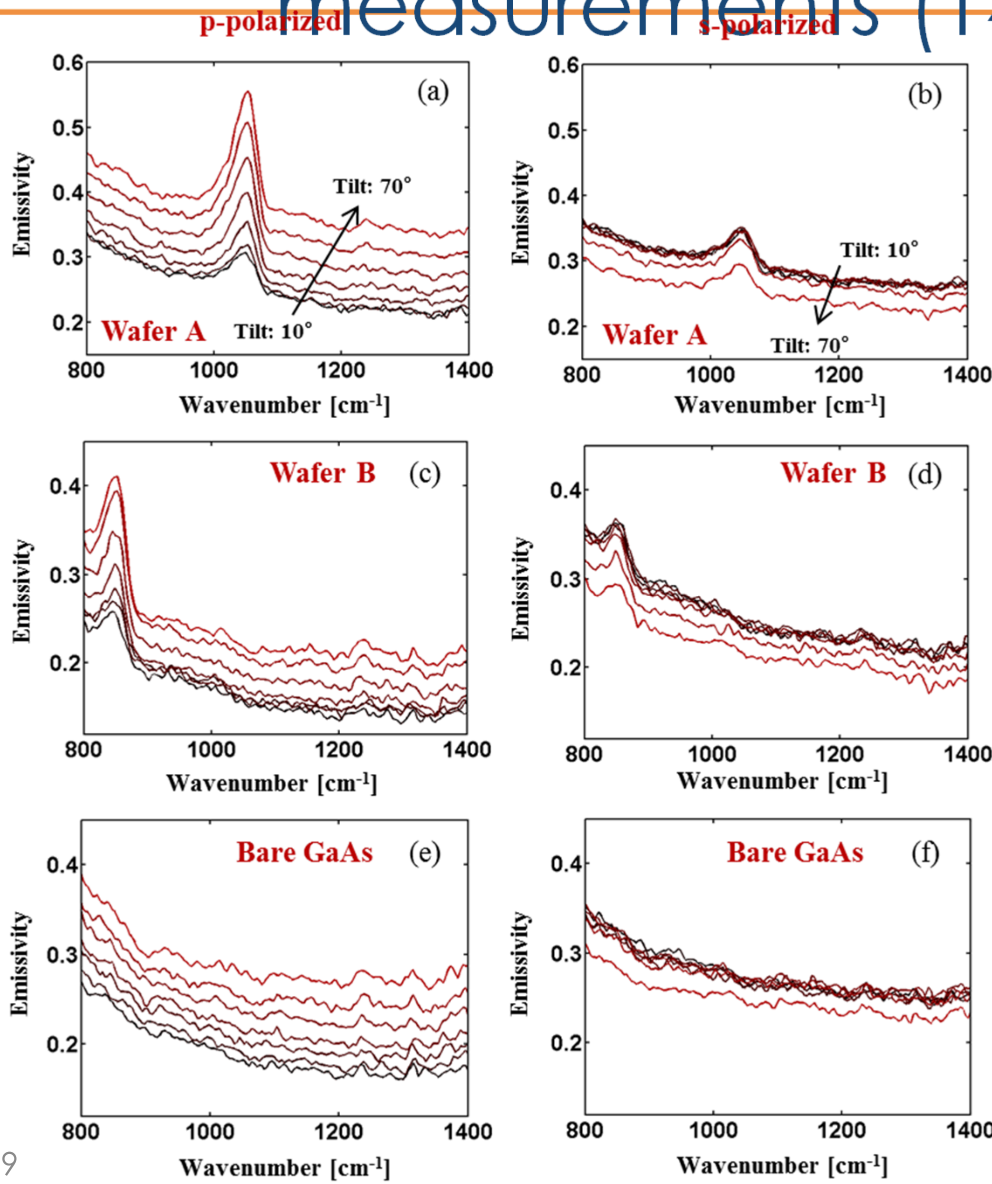


60nm InAs

Hyperhemispherical Directional Reflectomete

$\boldsymbol{A = 1 - R - T}$

Angle-resolved, polarization-dependent emissivity measurements (140°C)



- **Unpatterned semiconductor thin films generate spectrally selective thermal emission near the ENZ frequencies.**
- **Wavelength determined purely by doping densities**
- **An ENZ film works as a “leaky wave antenna”**

Appl. Phys. Lett. **105**, 131109 (2014)
See also recent wotk by Z. Jacob

Outline

- What are Berreman and Epsilon Near Zero (ENZ) modes, what can we do with them?
  - Fundamentals
  - ENZ modes: coupling to metamaterial resonators
  - Berreman modes: Thermal emission