Light-matter interaction phenomena using subwavelength engineering of material properties

Igal Brener and Michael B. Sinclair
Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185, USA

U.S. DEPARTMENT OF ENERGY
Office of Science
Sandia National Laboratories
cint.lanl.gov

Program Scope

- The overarching goal of this project is to achieve fundamental understanding and control of light–matter interaction through engineering material properties at the subwavelength scale. We use localized and propagating metamaterial photon modes (to tailor the photonic mode properties) coupled to semiconductor heterostructures (to enable the production of electronic and vibrational transitions with desired characteristics)

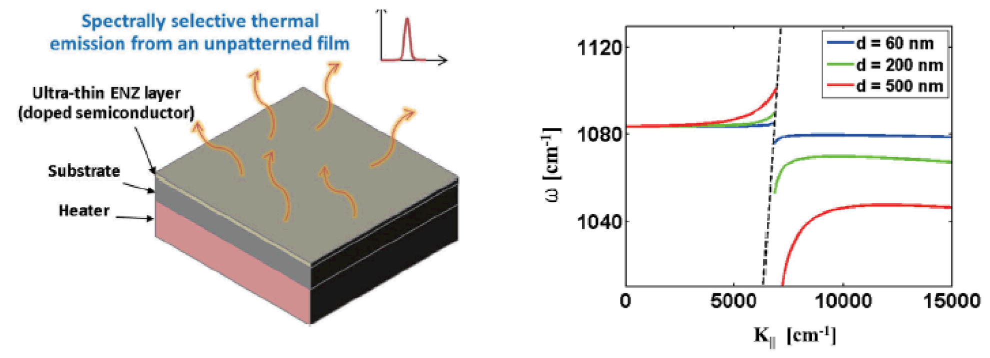
Thrust I
Investigate strong coupling of the localized modes of planar metamaterial nanocavities to semiconductor transitions

Thrust II
Explore the coupling of the propagating modes of hyperbolic metamaterials to semiconductor transitions

- The ultimate goal is to control the flow of energy between photons, phonons, and electrons in ways that are not possible with natural materials

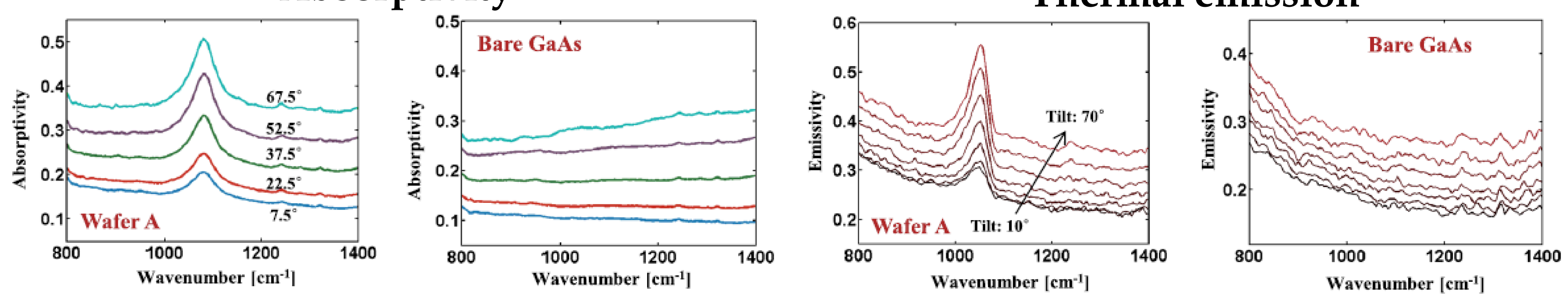
Thermal emission through epsilon-near-zero (ENZ) modes in doped semiconductors

- We use Berreman modes in ENZ films to naturally out-couple thermal emission into free space **without** any surface patterning [1]



- For ENZ ultra-thin films, the dispersion of the Berreman mode on the left of the light line gets flatter
- We measure both absorptivity with hemispherical directional reflectometer measurements at room temperature and calibrated thermal emission spectra at 140°C as a function of angle

Absorptivity **Thermal emission**

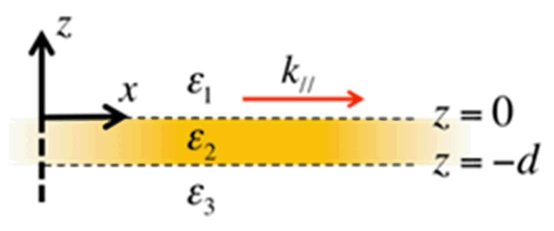


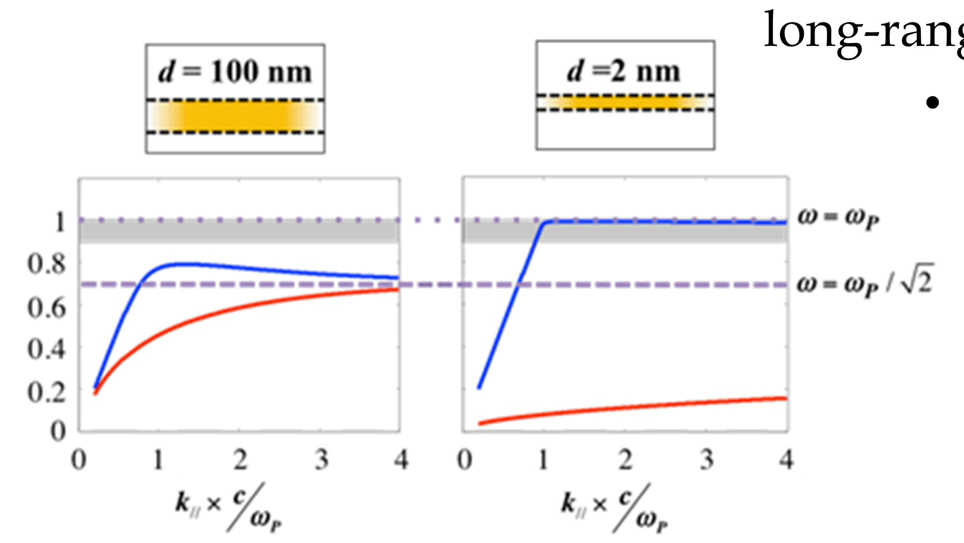
- For p-polarized light only, a relatively sharp peak appears in the spectra near the ENZ point. This corroborates the flat dispersion of Berreman modes for ultra-thin ENZ layers

Physics of ENZ modes

- We investigated and clarified the physics of the ENZ mode [3], providing its main characteristics and its domain of existence

Ultrathin ENZ layer

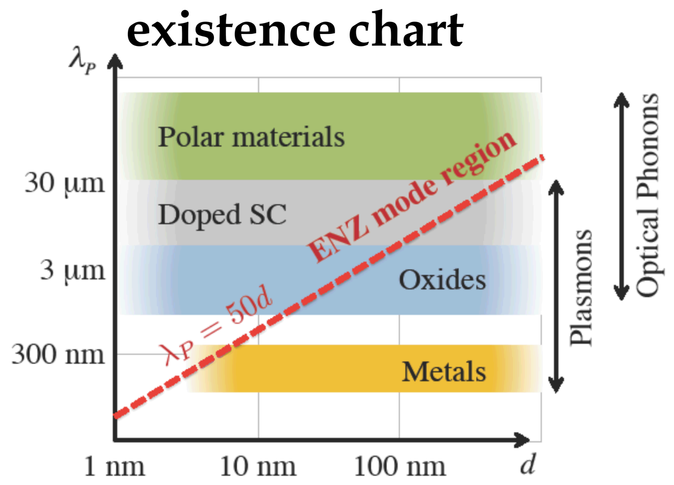




- The ENZ mode is a part of the long-range surface plasmon mode
  - For d much smaller than the skin depth, the dispersion relation can reach the plasma frequency w_P and can be approximated as

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

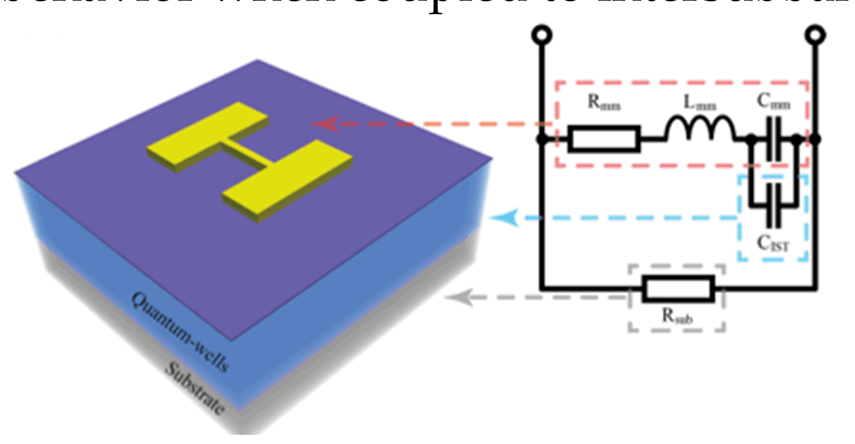
Domain of existence chart



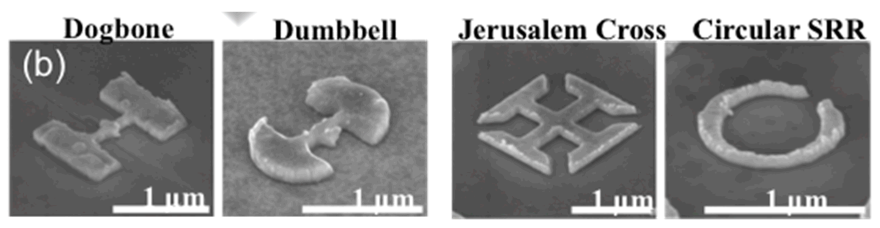
- Domain of existence of the ENZ mode: A good rule of thumb is $d < \lambda_P/50$ where $\lambda_P = 2\pi c/w_P$ is the wavelength for which the film dielectric constant vanishes
- This can guide towards the understanding of which material systems can support an ENZ mode

Control of strong light-matter coupling using the capacitance of metamaterial nanocavities

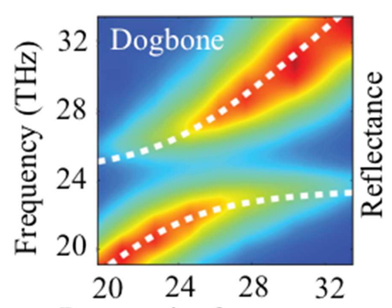
- Metallic nanocavities with subwavelength mode volumes can exhibit strong coupling behavior when coupled to intersubband transitions in semiconductor quantum wells



- We model the bare cavity as an RLC resonant circuit [2]
- The strong light-matter coupling is modeled as a dispersive capacitor (no free fitting parameters) [2]
- Our model shows that the electrostatic capacitance of the metamaterial resonator is the key parameter that controls the light-matter coupling (or Rabi frequency).



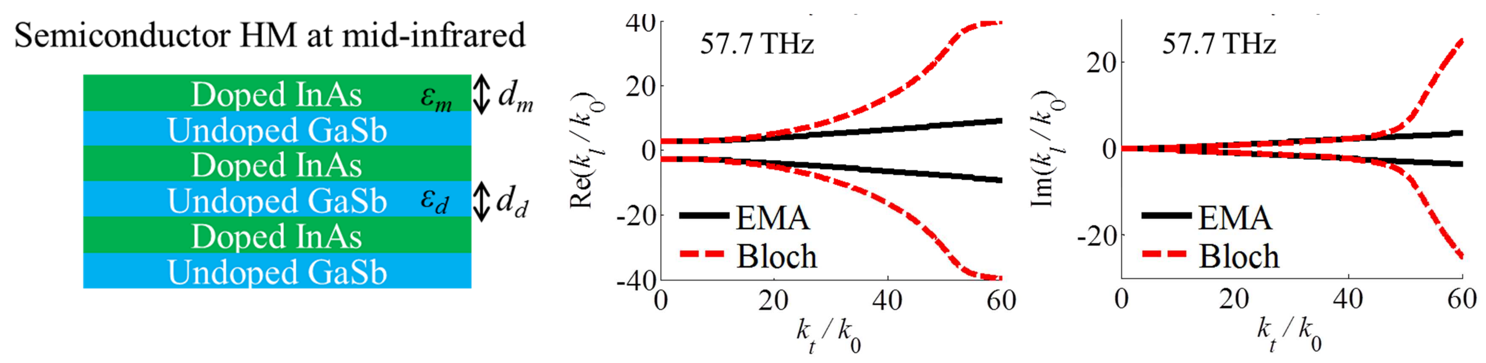
Reflectance



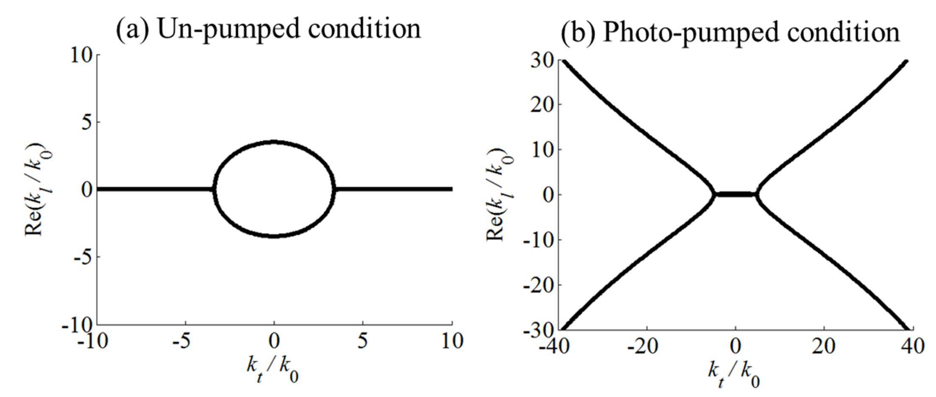
- The same conclusion is observed experimentally using four metamaterial nanocavity geometries

High-quality ultra-large momentum states using semiconductor hyperbolic metamaterials for ultrafast topological transitions

- At mid-infrared frequencies, highly doped semiconductor materials behave like metals and can be used to fabricate semiconductor hyperbolic metamaterials (SHMs)



- Good agreement between effective medium approximation and Bloch theory up to transverse wavenumbers of about $k_t / k_0 = 20$
- SHMs exhibit superior properties when compared to metallic HMs, e.g. SHMs support high-quality, ultra-large photon momentum states [4]



- SHMs offer opportunities for improved properties and can also allow for new phenomena such as *ultrafast transient creation of the hyperbolic manifold through optical pumping* [4]

Publications

[1] Y.C. Jun, T.S. Luk, A.R. Ellis, J.F. Klem, and I. Brener, Appl. Phys. Lett. **105**, 131109 (2014)
[2] A. Benz, S. Campione, J.F. Klem, M.B. Sinclair, and I. Brener, Nano Lett. **15**, 1959-1966 (2015)
[3] S. Campione, I. Brener, and F. Marquier, Phys. Rev. B, Rapid Communications, **91**, 121408 (2015)
[4] S. Campione, S. Liu, T.S. Luk, and M.B. Sinclair, submitted (2015)

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