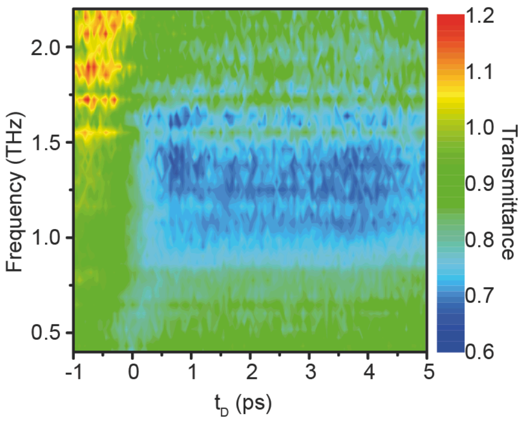
CLEO 2016

SAND2016-5217C

Transient GaAs Plasmonic Metasurfaces at THz Frequencies



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Sandia National Laboratories

Exceptional service in the national interest

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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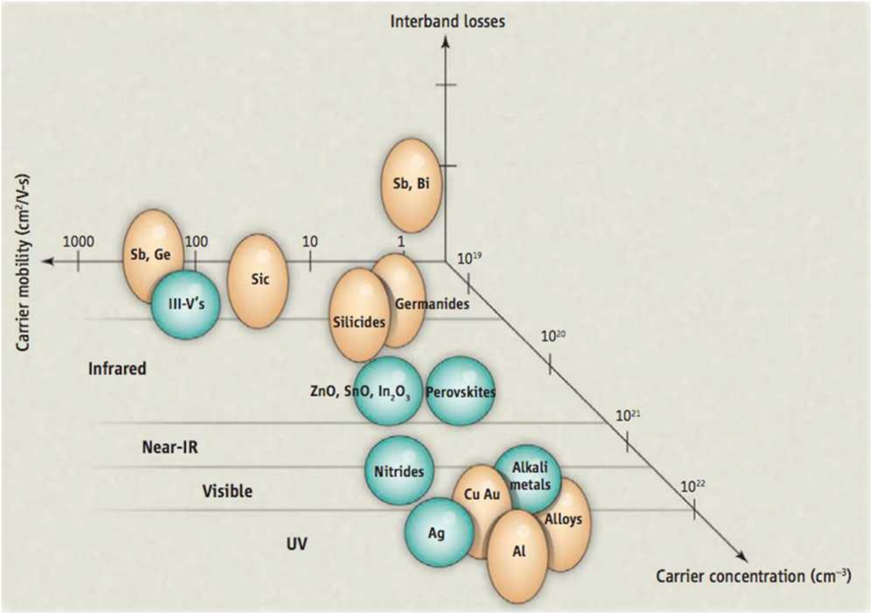
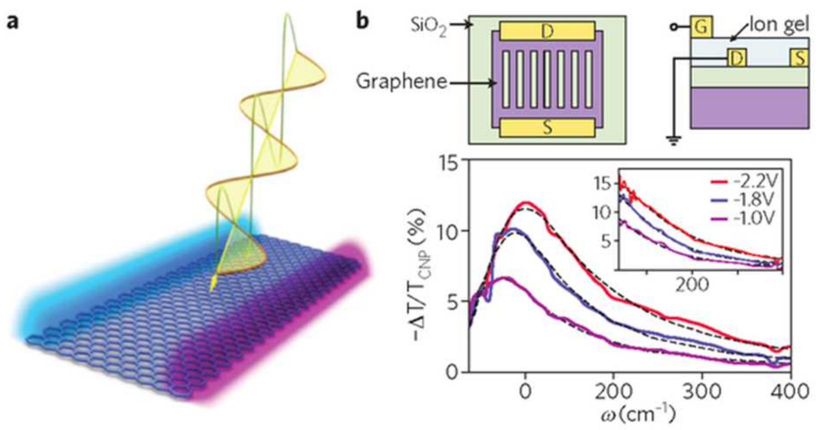
Motivation: Semiconductor Plasmonics

- ***Plasmonics* is a good way to enhance *light matter interactions.***
- **Challenges:**
  - Dissipative loss; Operation bandwidth; Tunability
- **Potential Solution:**
  - Plasmons in doped semiconductors



Boltasseva & Atwater, Science (2011)

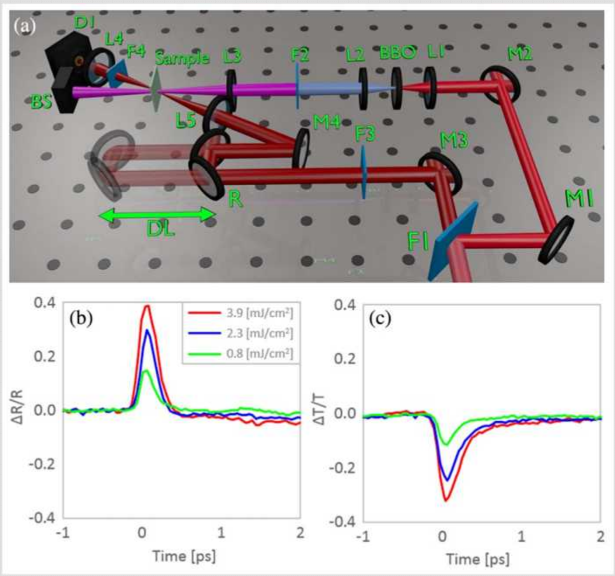


Wang et. al., Nat. Nano. (2011)

Motivation: Transient Plasmonics

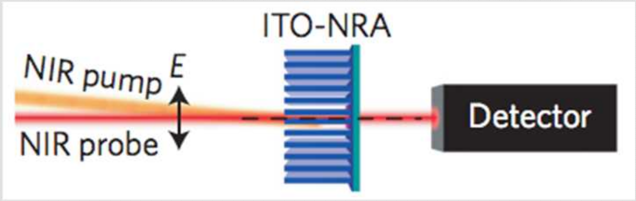
- ***Transient plasmonics: Ultrafast tuning of light.***
- **Physics:**
  - Inter-band excitation (carrier density modulation)
  - Intra-band excitation (hot electron & band non-parabolicity)

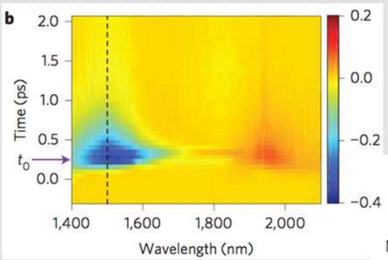
Inter-band excitation in Ga-ZnO ENZ layer

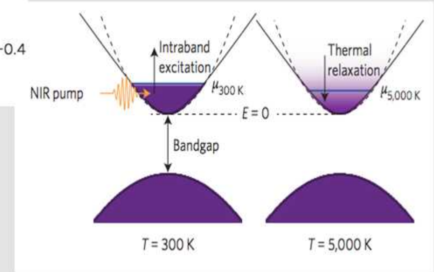


Kinsey et. al., Optica, 2, 616 (2015)

Intra-band excitation in ITO nano-rod array







Guo et. al., Nat. Photon, 10, 1038 (2016)

Transient THz GaAs Plasmonic Metasurfaces

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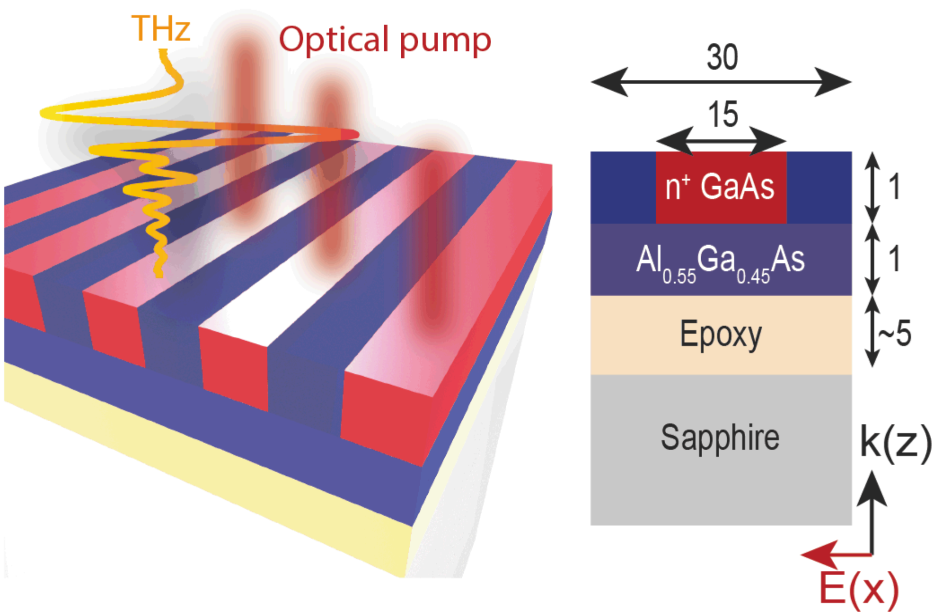


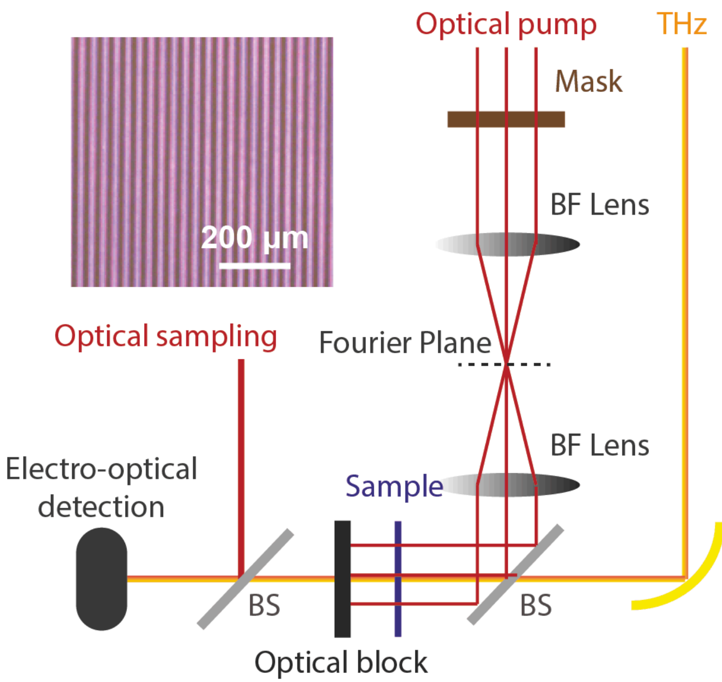
- **Devices:**
  - 1-µm-thick GaAs film on sapphire substrate.
- **Fabrication:**
  - MBE growth
  - Flip-chip bonding
  - Selective wet-etching of the substrate
- **Benefit of no physical pattern:**
  - Non-destructive for pristine samples
  - Dynamic tunability

- **Reveal the ultrafast dynamics of plasmon formation;**
- **Demonstrate a wide-bandwidth frequency tuning;**

Structured-optical pump THz probe (S-OPTP):

Okada et. al., Sci. Rep. (2011);
Chatzakis et. al., Appl. Phys. Lett. (2013);
Kamaraju et. al., Light Sci. App. (2014)

Measurement Schematics



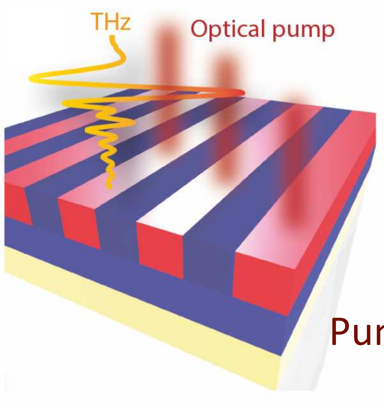
- **Source:** Ti-Sapphire Amplifier, 800 nm, 1 kHz, 6mJ, ~35 fs pulse duration.
- **THz generation:** Optical rectification in a 1-mm-thick <110> ZnTe.
- **THz detection:** Electro-optical sampling in a 1-mm-thick <110> ZnTe.
- **Mask:** 30um period, 50:50 duty cycle Cr mask.
- **Imaging:** 4-f imaging system with two best form lenses (150 mm focal length).

$$T = \left| \tilde{E}_{sample} / \tilde{E}_{sapphire} \right|^2$$

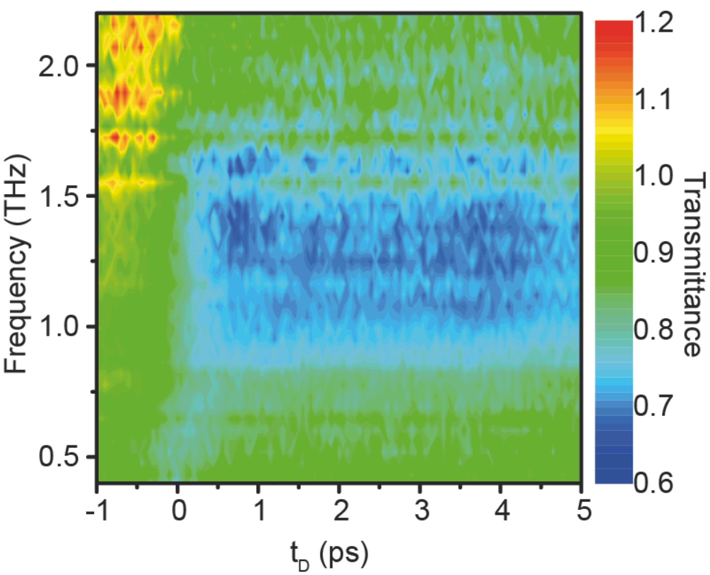
- **OPTP experiments:** to ensure the entire THz transient to experience the **same optical pump delay**, the **delay line** is located at the **THz generation arm**.

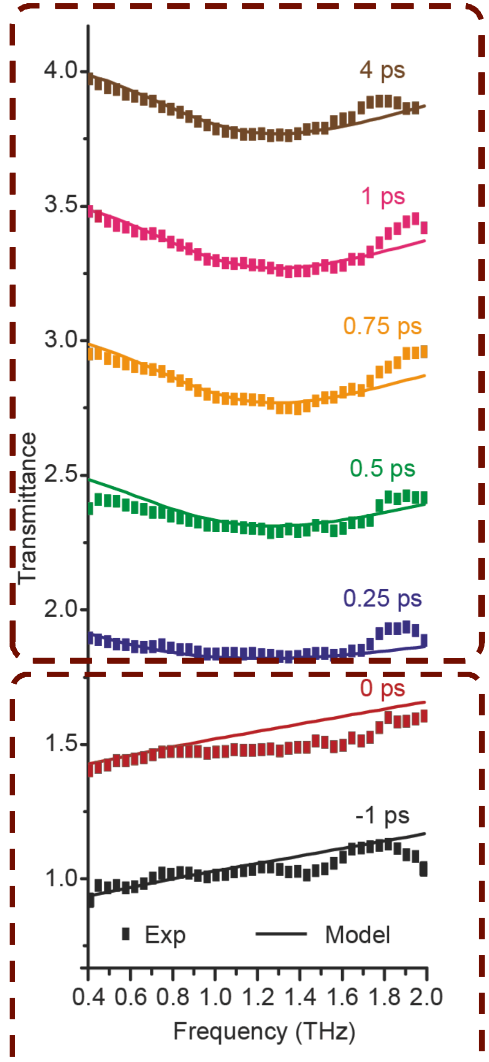
Beard et. al., Phys. Rev. B 62, 15764 (2000)

OPTP Measurements



Pump fluence: 6 μJ/cm^2

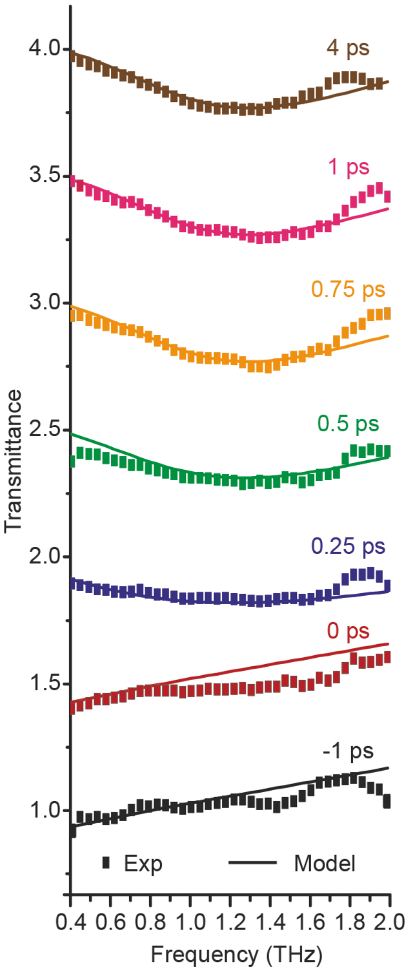




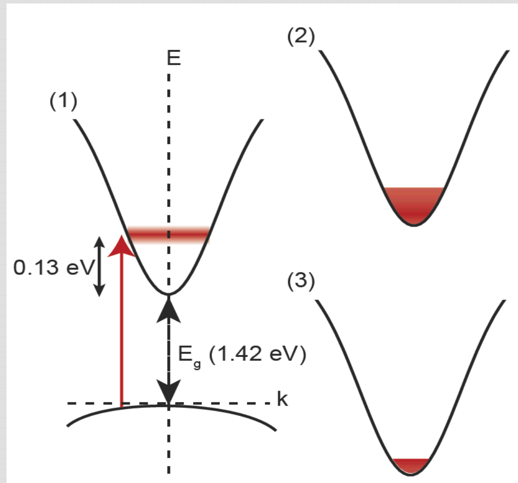
After photoexcitation:
- Interband process
- Intraband process

Prior to photoexcitation:
- Drude behavior
  (free carrier absorption)

Physical Interpretation



Processes involved:

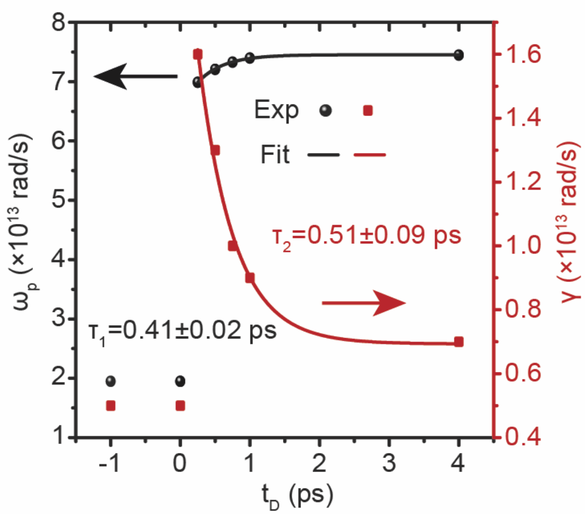


(1). Creation of non-equilibrium hot electron distribution by the optical pump;

(2). Hot electron thermalization (equilibrium within themselves & Fermi Dirac distribution); <100 fs

(3). Electron-phonon cooling. ~500 fs

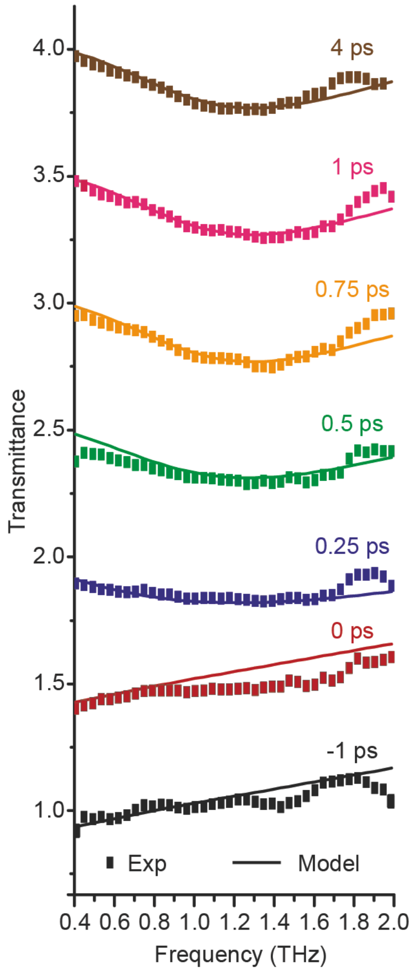
$$m^* = \frac{1}{\int f(E,t)\frac{1}{\hbar^2}\frac{d^2E}{dk^2}dk}, \quad \omega_p = \sqrt{ne^2/\varepsilon_0 m^*}$$



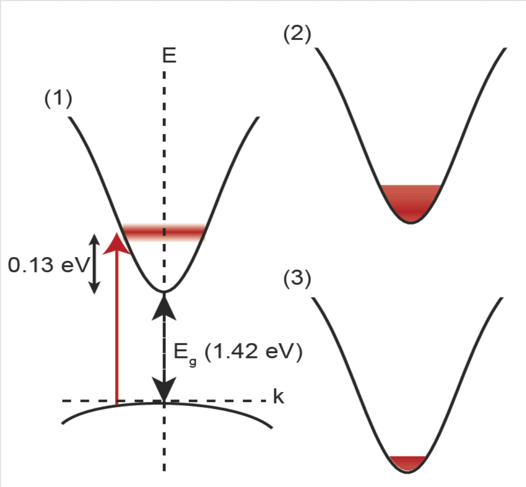
Within the ~500 fs electron-phonon cooling process:

- Plasma frequency increases;
- Plasma damping decreases.

Physical Interpretation



Processes involved:



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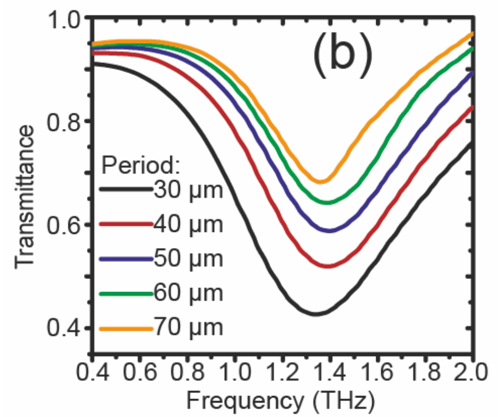
Processes ruled out:

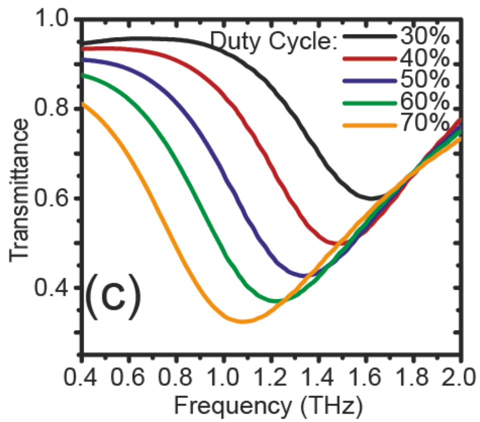
- Velocity overshoot; (Photon energy insufficient)
- Gunn effect; (3 kV/cm intensity needed)
- Hot holes. (large effective mass & low mobility)

Localized Resonance (Electric Dipole)

- vary period



- vary duty cycle



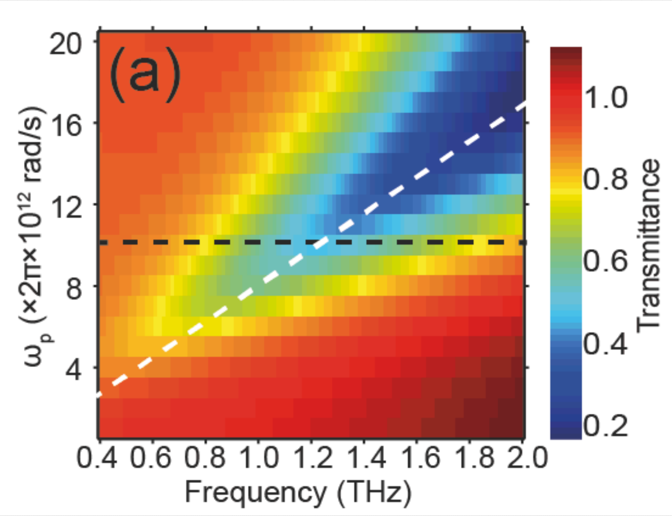
Abs(E) :

Electrical dipole (localized):

$$L = \frac{\lambda_{eff}}{2} = \frac{a_1 + a_2 \frac{\omega_p}{\omega_{res}}}{2},$$

L: length of the dipole antenna;
a_1, a_2: geometric parameters;
ω_{res}: resonant frequency.

Novotny, Phys. Rev. Lett. 98, 266802 (2007)

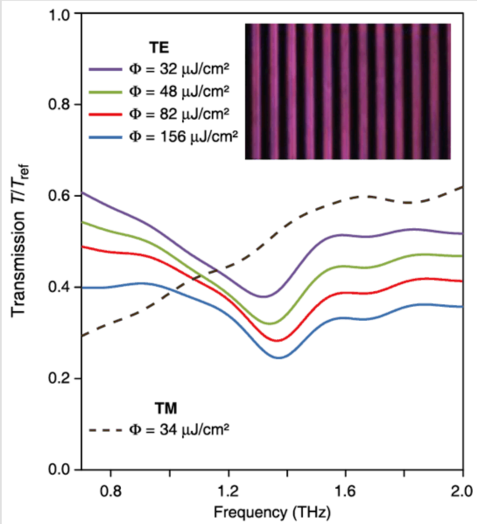


Plasmonic grating (non-local):

$$\lambda_{SP}^{m,n} = \frac{L}{\sqrt{m^2+n^2}} \mathrm{Re}\left(\sqrt{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}}\right),$$

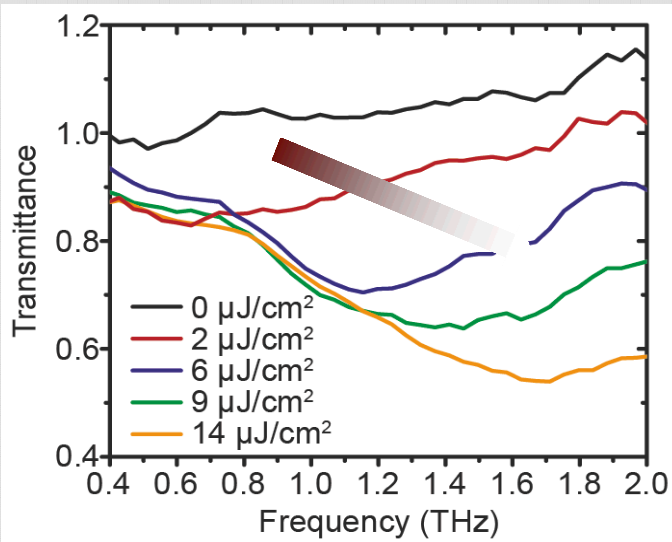
m, n: grating orders;
ε_1, ε_2 : permittivity of metal and surrounding dielectrics;
λ_{sp}: resonant wavelength.

Chatzakis et. al., Appl. Phys. Lett. 103, 043101 (2013)



Demonstration of THz Wave Modulation

Pump fluence-dependent transmittance (Experiments)

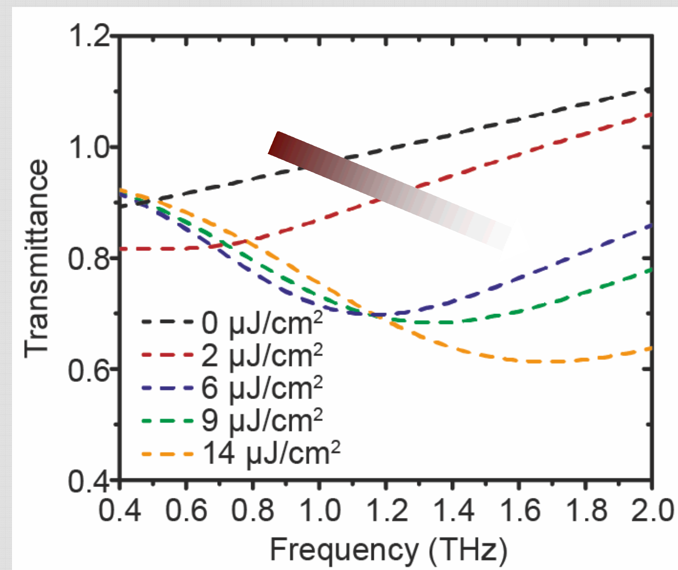


Modulation from 0.5 THz to 1.7 THz!

- One of the widest dynamic modulation bandwidth demonstrated (to the best of our knowledge)

Simulations agree with experiments

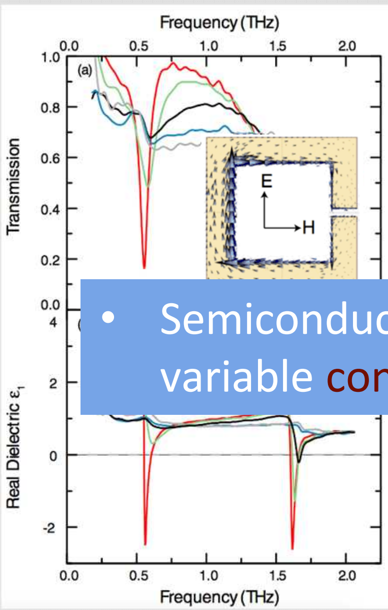
- Assuming gradient carrier density distributions in the GaAs layer.



Outlook

Previous work
-revisited

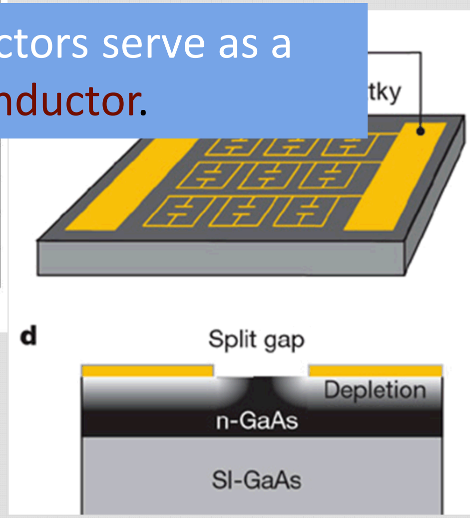
- Optical excitation



Padilla et. al., PRL (2006)

- Electrical excitation

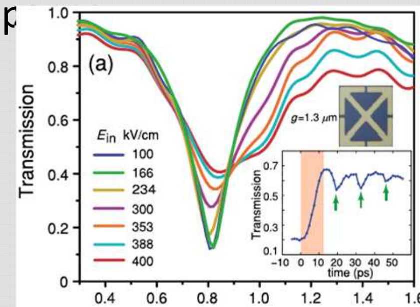
- Semiconductors serve as a variable conductor.



Chen et. al., Nature (2008)

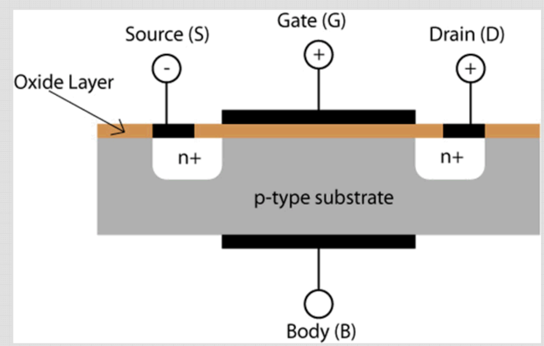
Future vision
-based on semiconductor plasmonics

- Nonlinear THz plasmonic resp



Averitt et. al., PRL (2013)

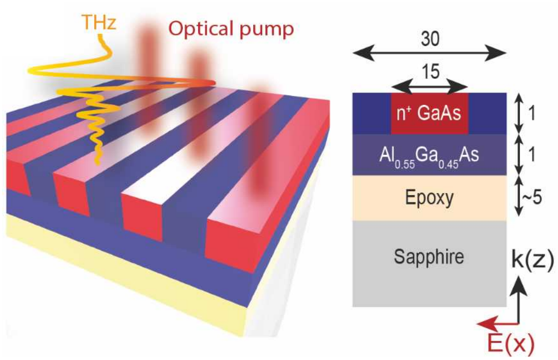
- MOS transistor-type THz plasmonic modulator

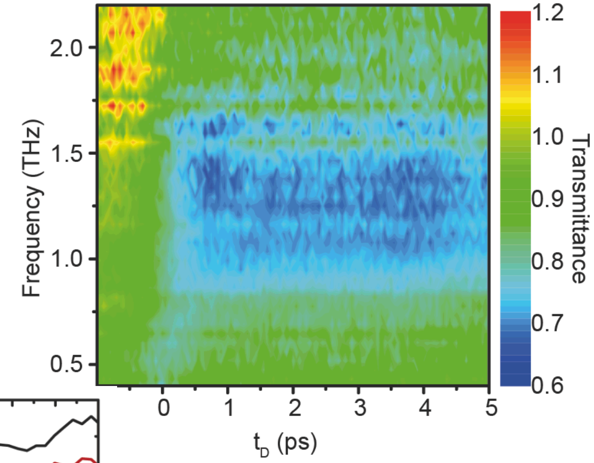


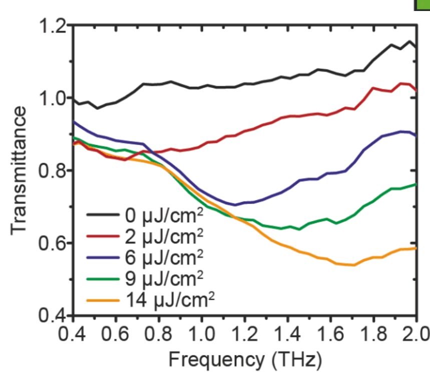
Conclusions

❖ Transient GaAs metasurface

- Demonstrated:
  - Ultrafast dynamics of plasmon formation revealed;
  - Wide frequency tuning range;
- Future:
  - Nonlinear THz response;
  - THz modulators;
  - Extension to the mid- & near- IR.







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