SAND2018-9602C

Ultrafast Plasmonics and Metasurfaces

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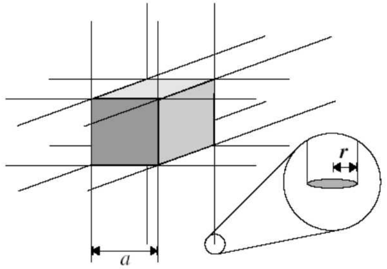
Outline

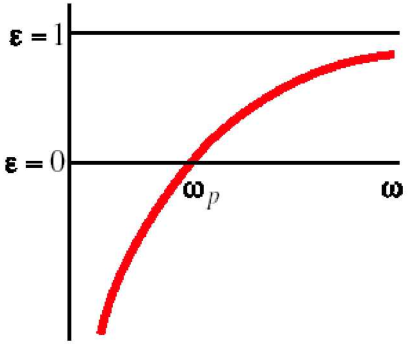
- Ultrafast and Transient Plasmonics/Metasurfaces
  - Optical creation of a plasmonic grating
  - Ultrafast switching using epsilon near zero (ENZ) media
- High Harmonic Generation in ENZ
- Ultrafast switching of dielectric metasurface

Refresher: Metamaterials

Controlling ε

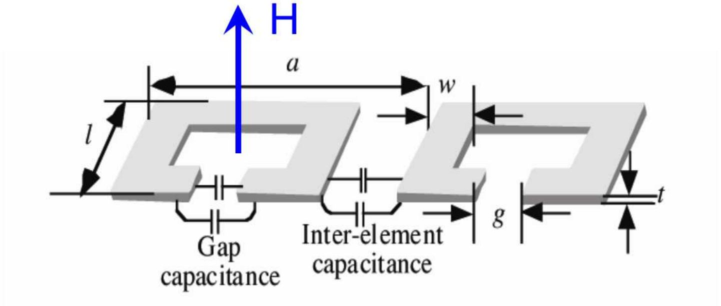
$$\omega_p = \sqrt{\frac{ne^2}{m^*\varepsilon_o}}$$



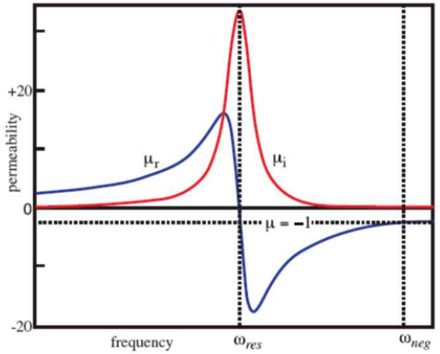


"Diluted Drude" or some electric resonance

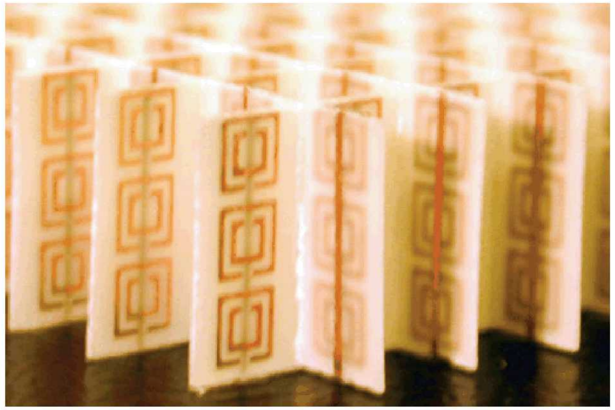
Controlling μ



from; S. McMeekin, Proc. Of SPIE, Vol. 6581



Some magnetic resonance

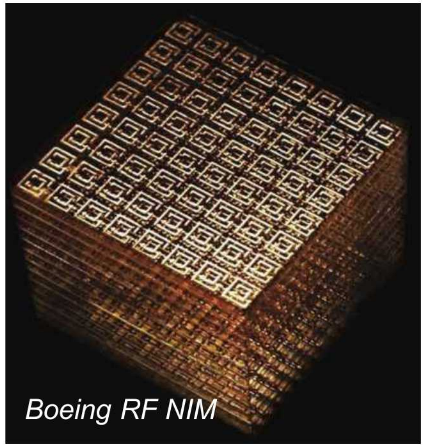


What is a "Metasurface"

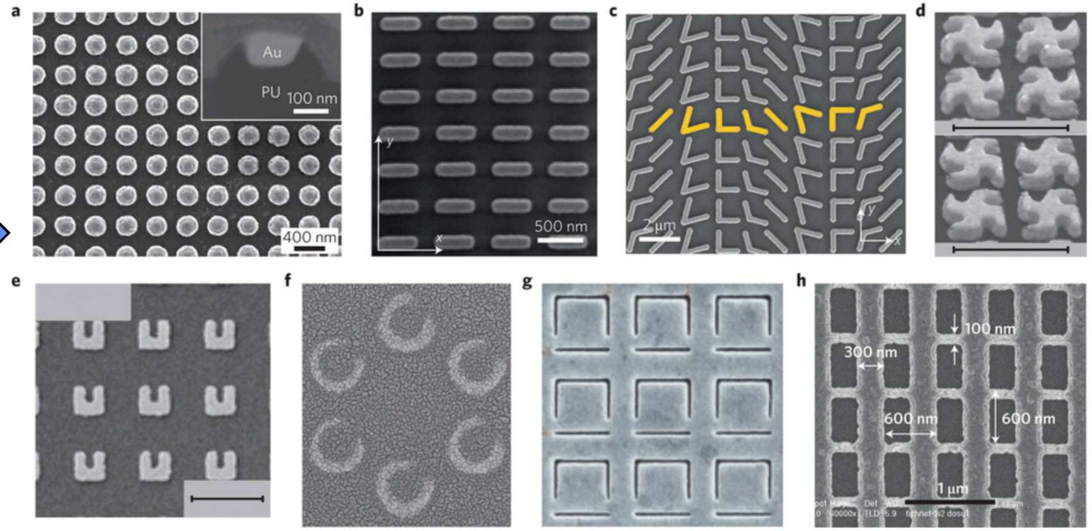
The 2D version of a 3D Metamaterial

- Metallic or Dielectric
- Resonant or non-resonant

3D



2D

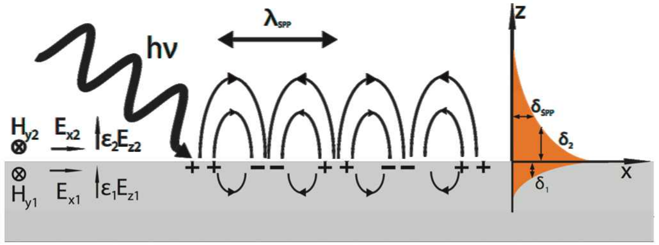


Nature Photonics 8, 889 (2014)

A collection of structures<λ where electric/magnetic reflection, transmission & scattering can be controlled by each element

Transient Plasmonics/Metasurfaces

http://physicsworld.com/cws/article/news/2012/sep/28/

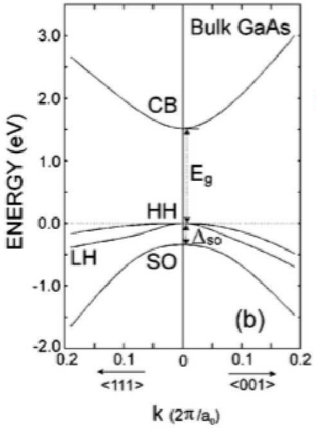


https://en.wikipedia.org/wiki/Surface_plasmons

$$\omega_p = \sqrt{ne^2 / \varepsilon_0 m^*}$$

Static density of electrons

Photo-"create" electrons:

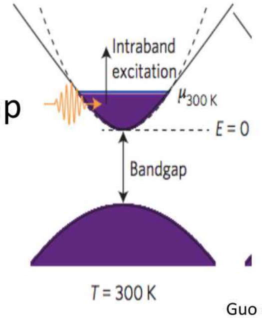


Pump

Vurgaftmana
JAPN (2001)

Photo-"perturb" electrons:

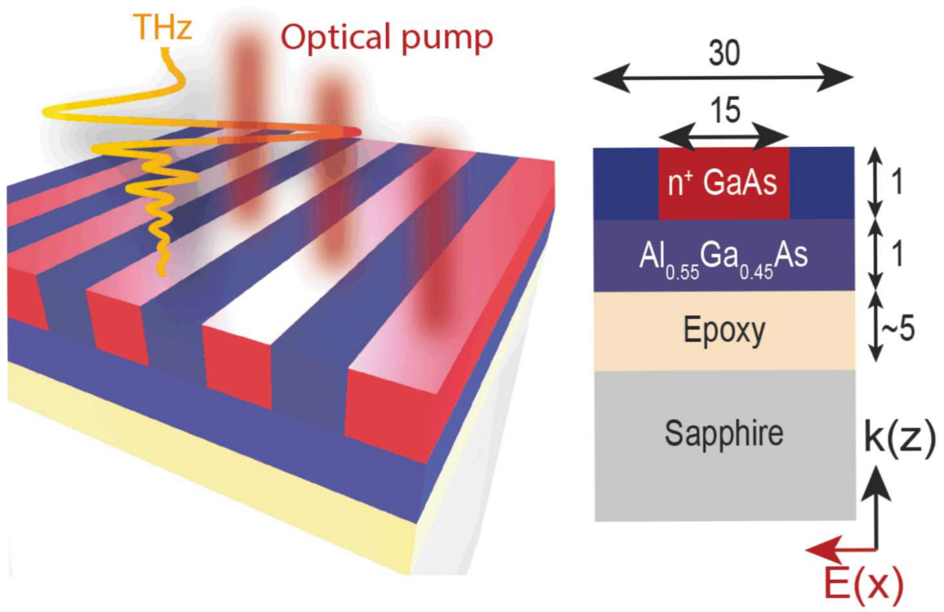
Pump



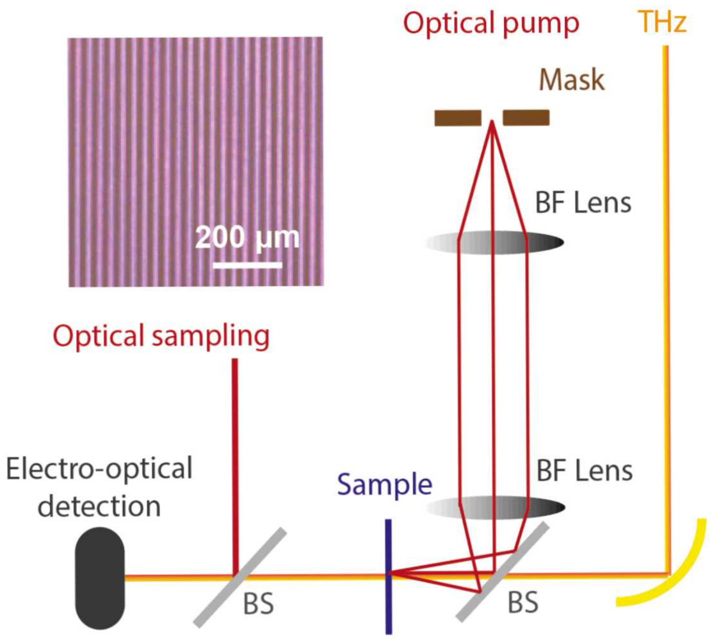
Guo et. al., Nat. Photon, (2016)

- **How does a photoexcited e-plasma behave as a plasmonic material ?**
- **What can we do with transient plasmonics?**

Transient THz GaAs Plasmonic Metasurfaces



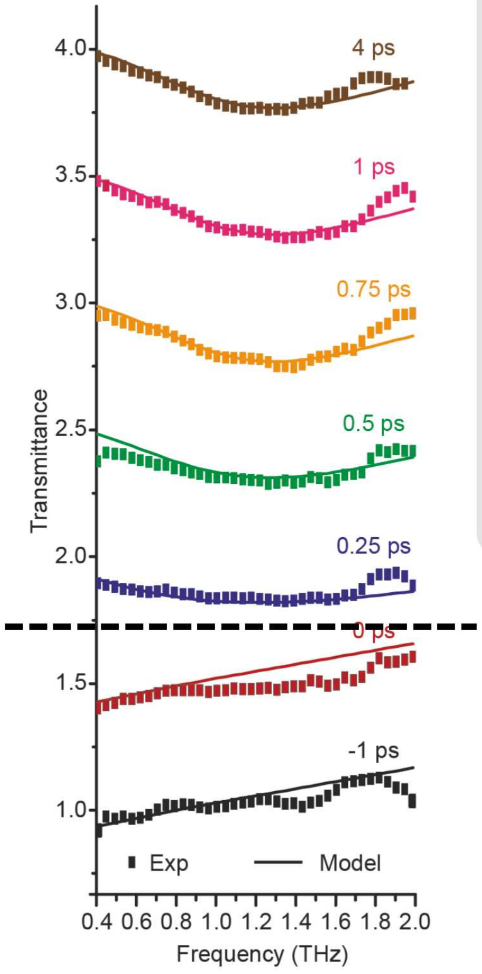
Structured-optical pump THz probe (S-OPTP):



What are the ultrafast dynamics of plasmon formation

Yang et. al., ACS Photonics, **4**, 15 (2017)

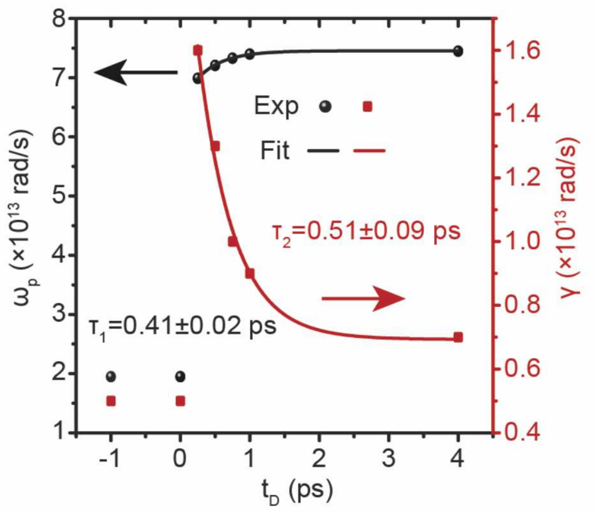
Ultrafast Dynamics of Plasmon Formation



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 coupling. ~500 fs

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

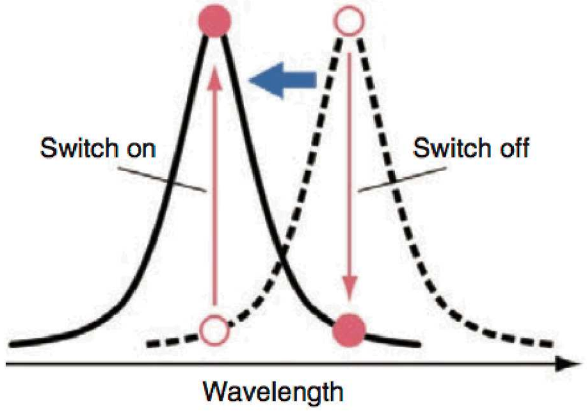


Within the ~500 fs electron-phonon cooling process:

- Plasma frequency increases;
- Plasma damping decreases.

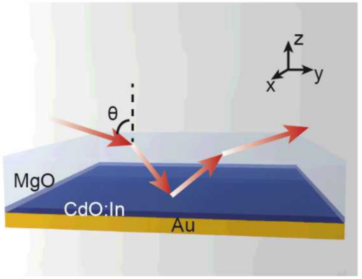
Yang et. al., ACS Photonics, 4, 15 (2017)

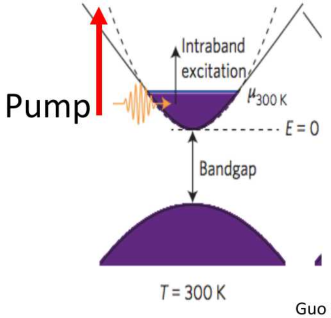
Ultrafast Switching Using Metasurfaces/Plasmonics



NTT Tech. Rev.

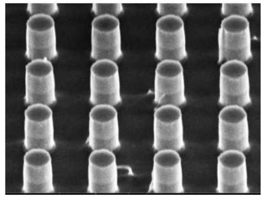
- **Perfect Plasmonic Absorber**

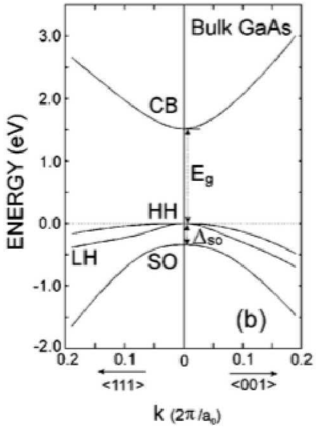




Guo et. al., Nat. Photon, (2016)

- **Dielectric Metasurfaces**

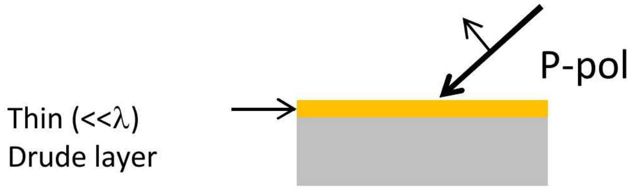


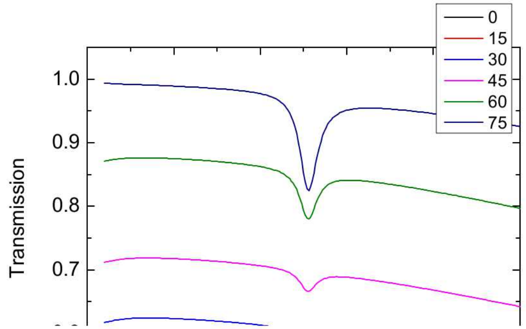


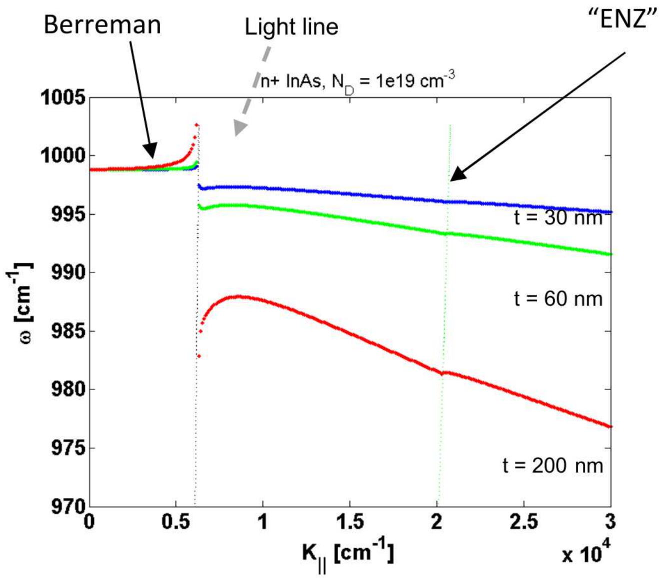
Pump

Vurgaftmana
JAPN (2001)

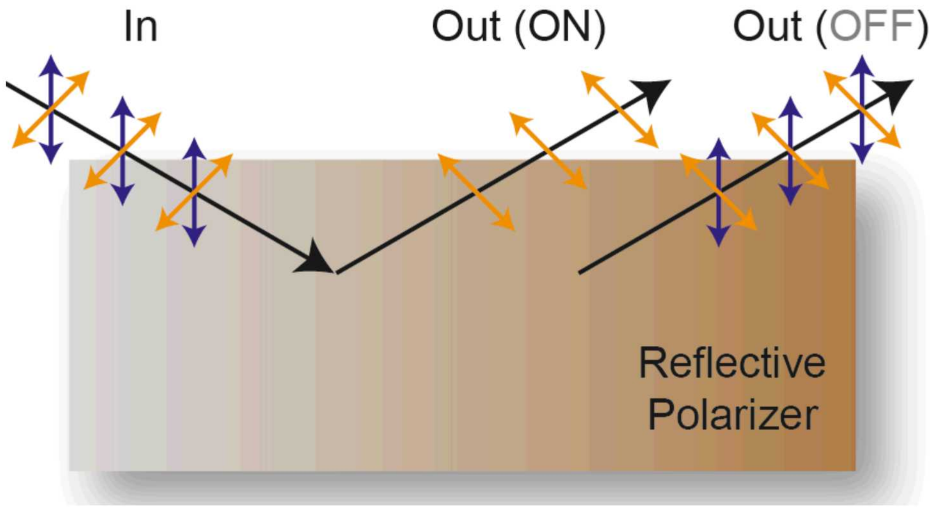
“Perturbing” a Plasmon Mode: Ultrafast Polarizer/Switch Concept

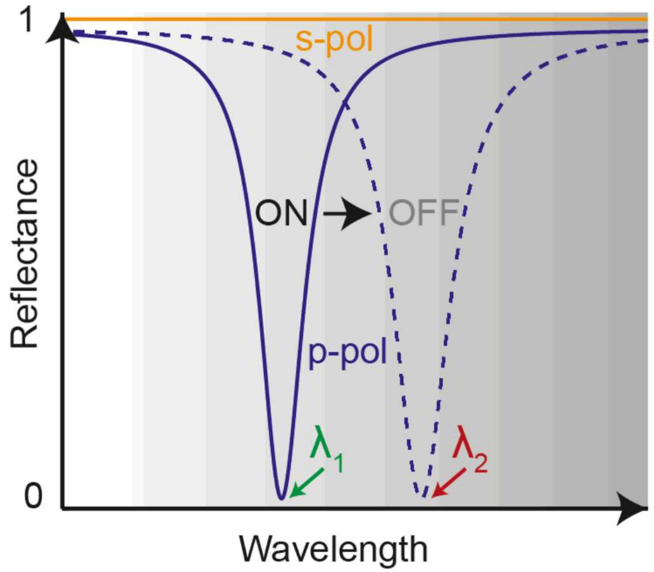






Concept of a switchable reflective polarizer:

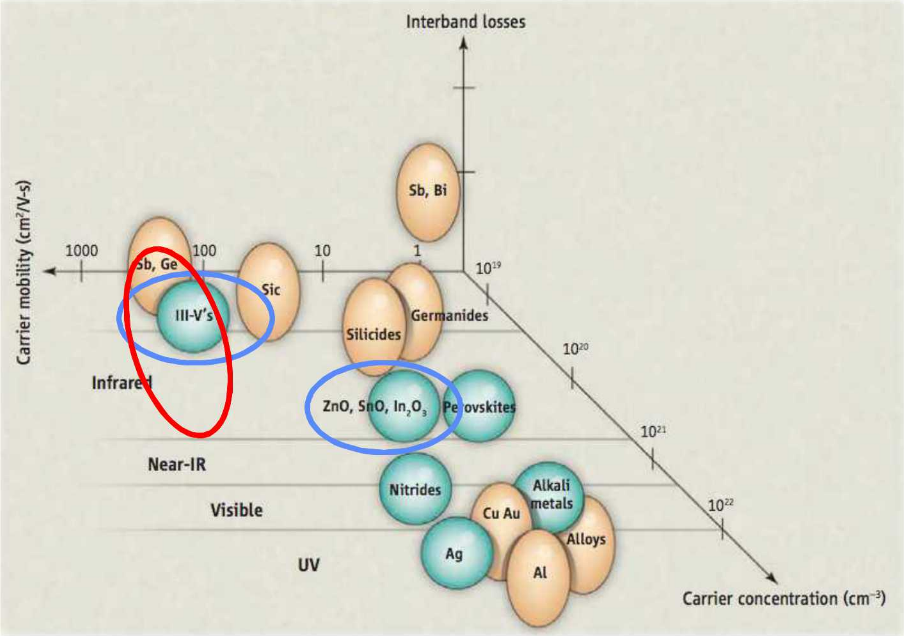




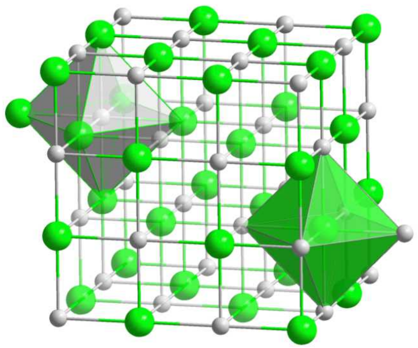
Yang et. al., accepted Nat. Phot. 2017

Doped CdO

An Amazing Plasmonic Material!



Boltasseva & Atwater, Science 331, 290 (2011)



http://chemistry.stackexchange.com/questions/23673/rock-salt-structure

- Cubic rocksalt lattice (similar to NaCl)
- n-doping (In populates the Cd sublattice with a 3^+ charge)

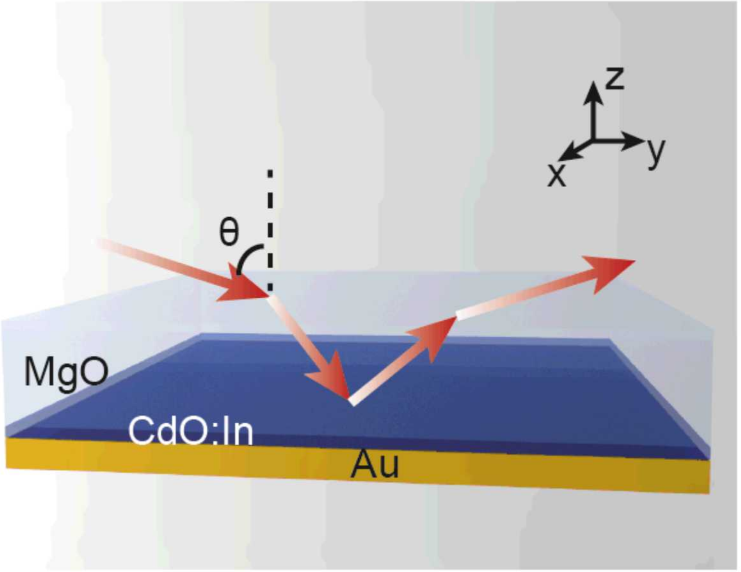
- **Doping density can reach > 10^{20}cm^{-3}**
- **Plasma frequency tunable from near to long IR**
- **Mobilities in the 100's, sometimes comparable with III-V's.**

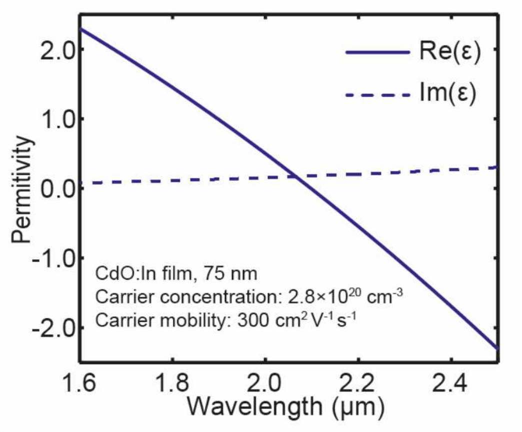
Material	Carriers [cm^{-3}]	Mobility [cm^2/V·s]	ε_1=0 [cm^{-1}]	ε_2 at ε_1=0	ε_2 at ε_1=-2
CdO:Dy	9.94×10^{19}	474	2770	0.19	0.30
CdO:Dy	3.70×10^{20}	359	5350	0.13	0.20
AZO (2 wt%)[4]	7.2×10^{20}	48	6970	0.21	0.39
ITO (10 wt%)[4]	7.7×10^{20}	36	7122	0.69	1.29

Sachet et. al., Nat. Mat (2015)

J-P Maria, NC State

CdO-based Perfect Absorber

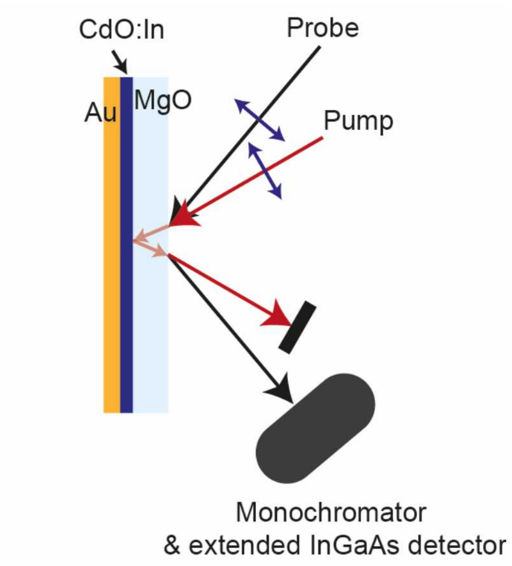


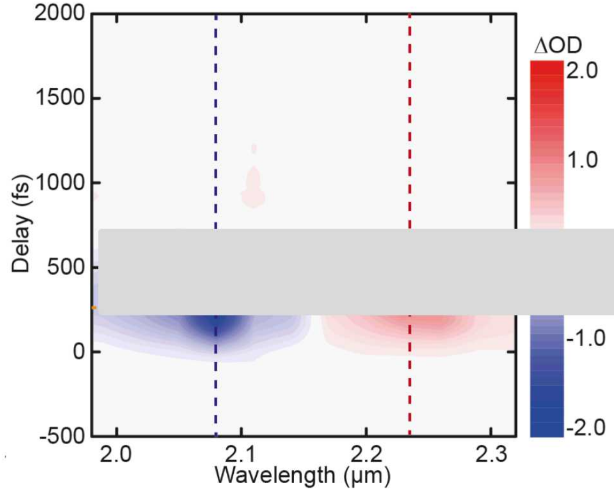


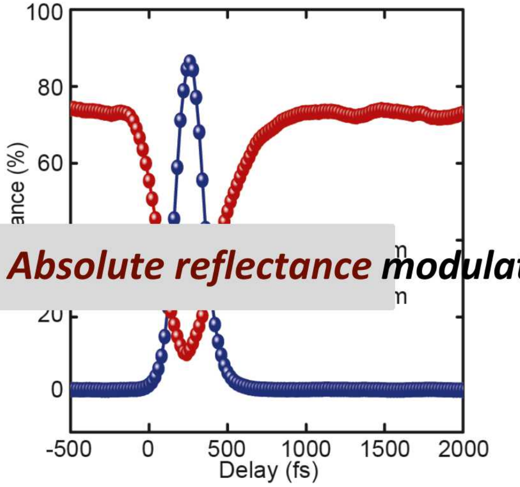
Sachet et. al., Nat. Mat (2016)

- Berreman-type perfect absorber for p-polarized incident light at 50 degrees.
- >90% reflectance for s-polarized light.

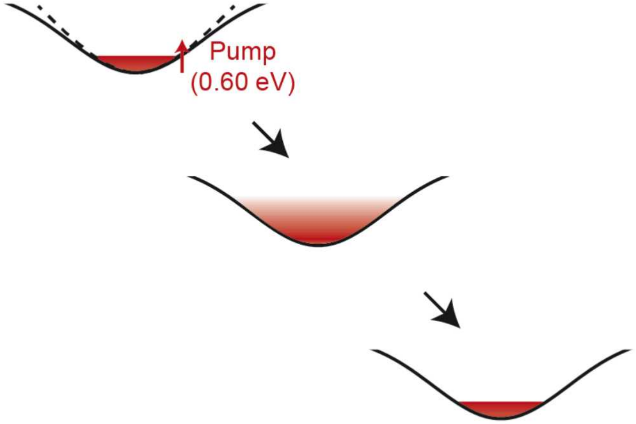
Ultrafast **Amplitude Switching** of the **Perfect Absorber**

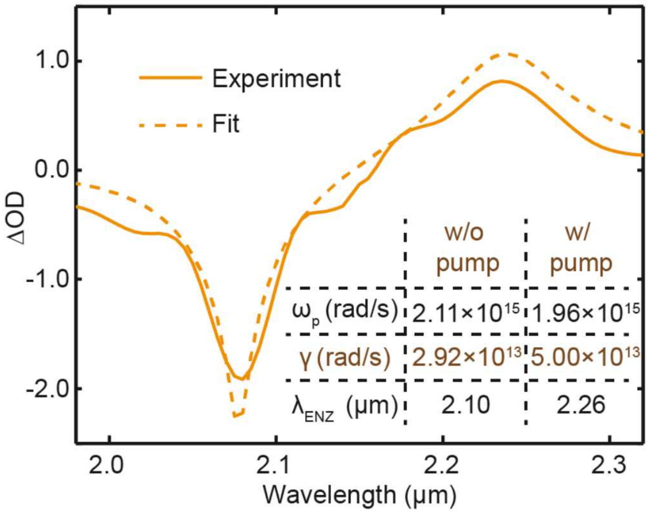






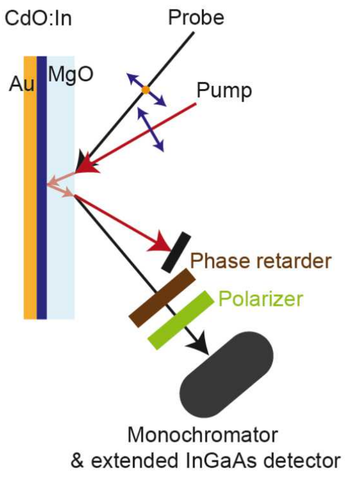
Absolute reflectance modulation from 1% to 86%!



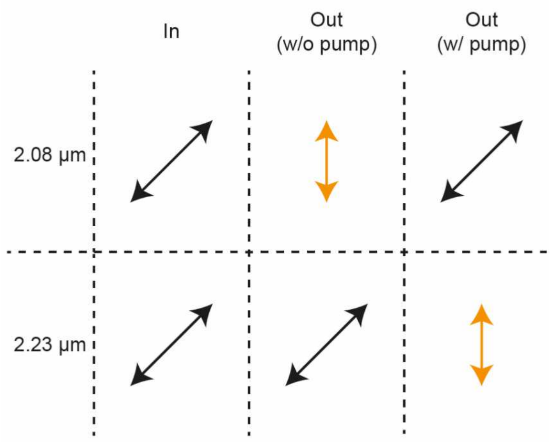


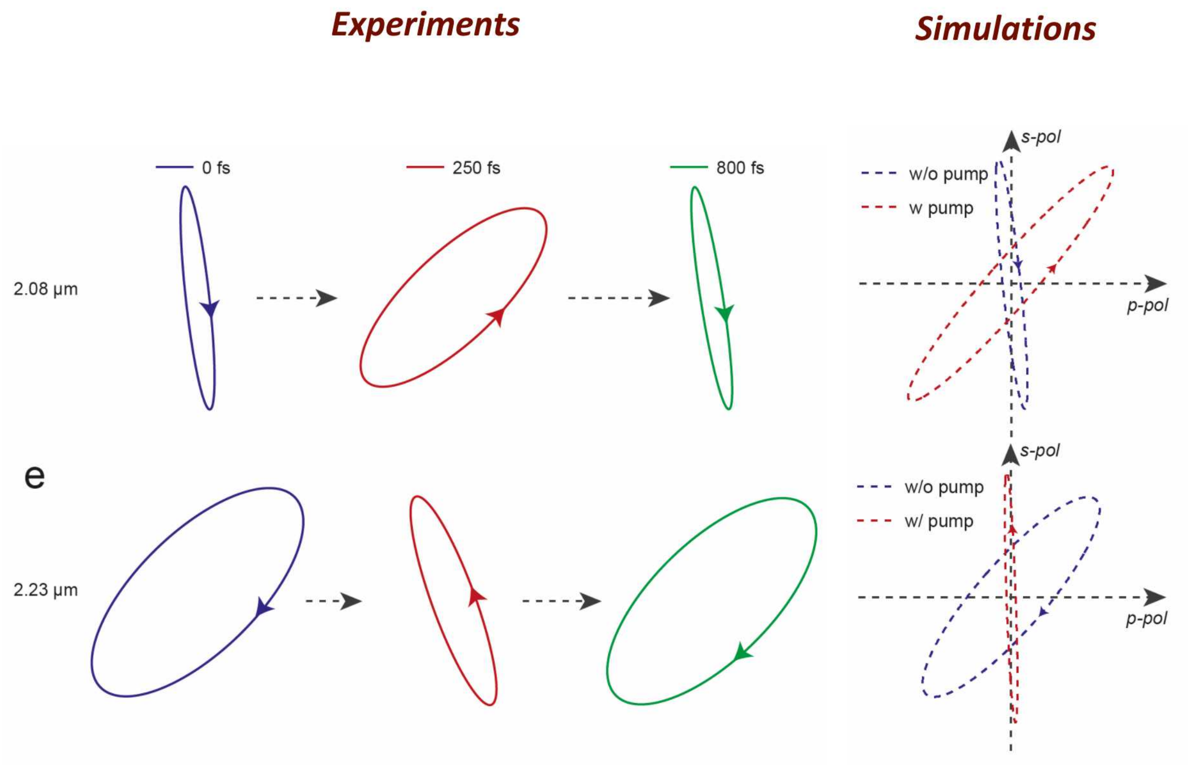
Yang et. al., Nat. Phot. 2017

Ultrafast Polarization Switch



Predicted polarization input/output:

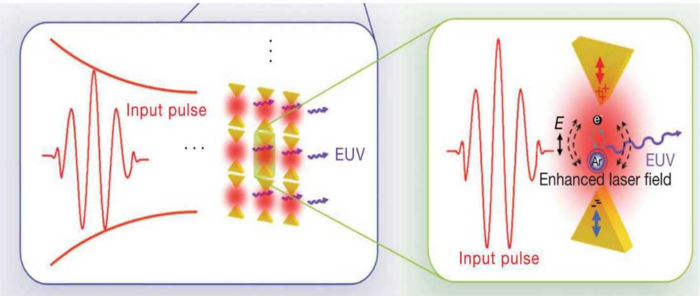


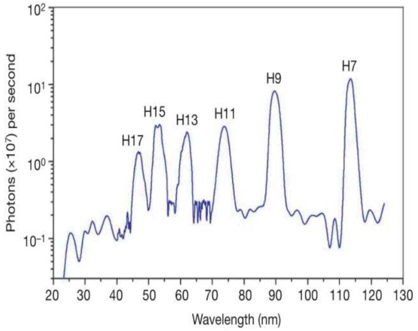


Nat. Phot. 2017

High Harmonic Generation (HHG) enhanced by Plasmonics

Gas-phase HHG enhanced by plasmonics:

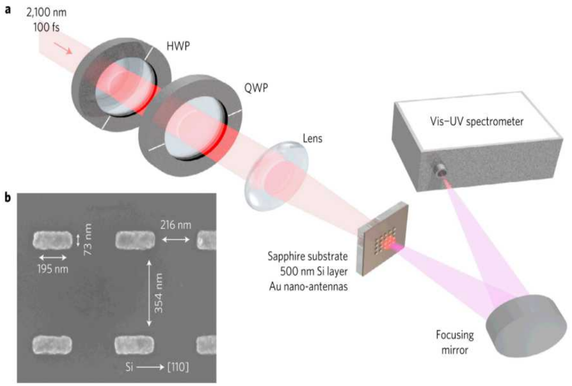


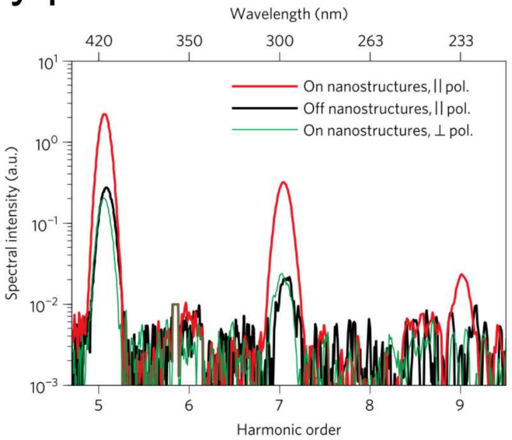


S. Kim et al, ***Nature***, 453, 757(2008)

Low damage threshold

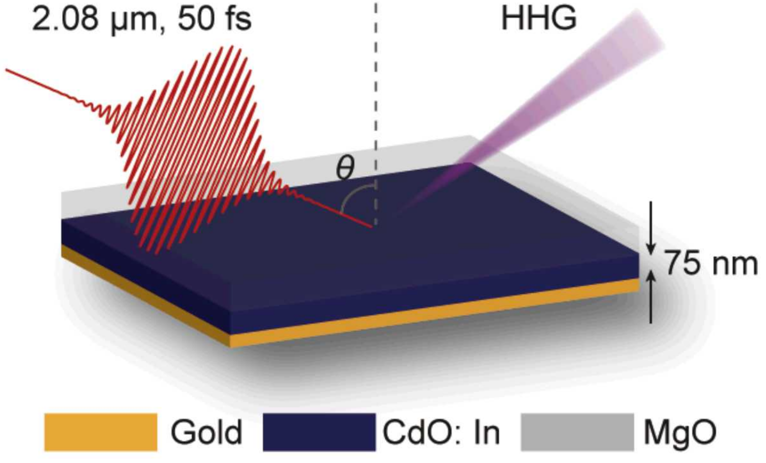
Solid-phase HHG enhanced by plasmonics:



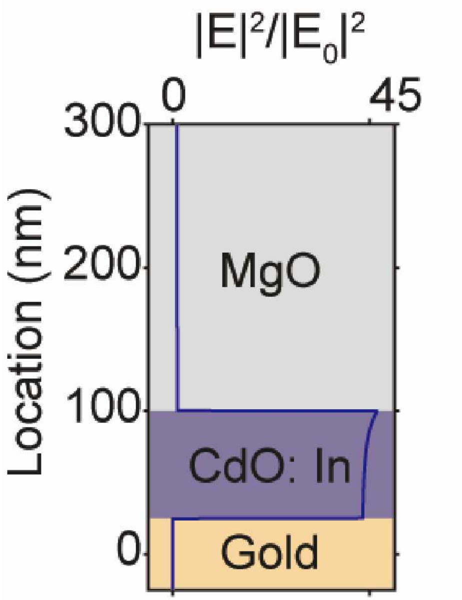


G. Vampa et al, ***Nature Physics***, 13, 659(2008)

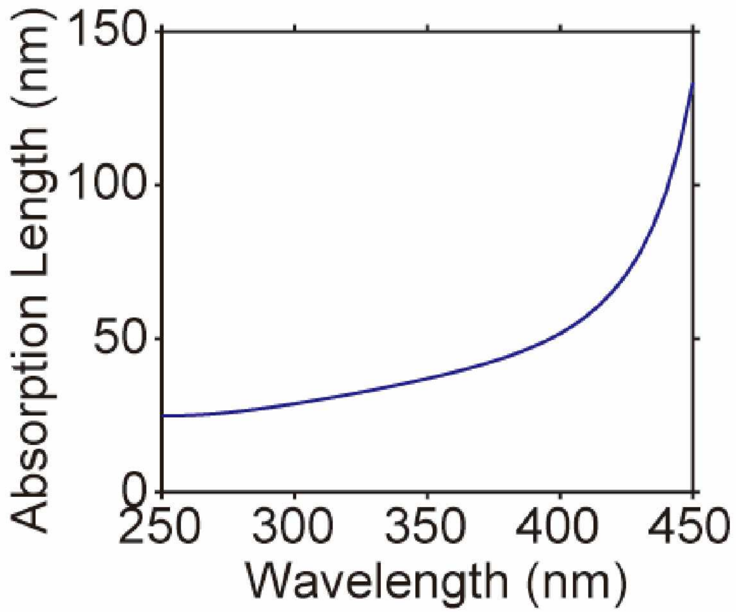
HHG in an ENZ Material



Robust structure

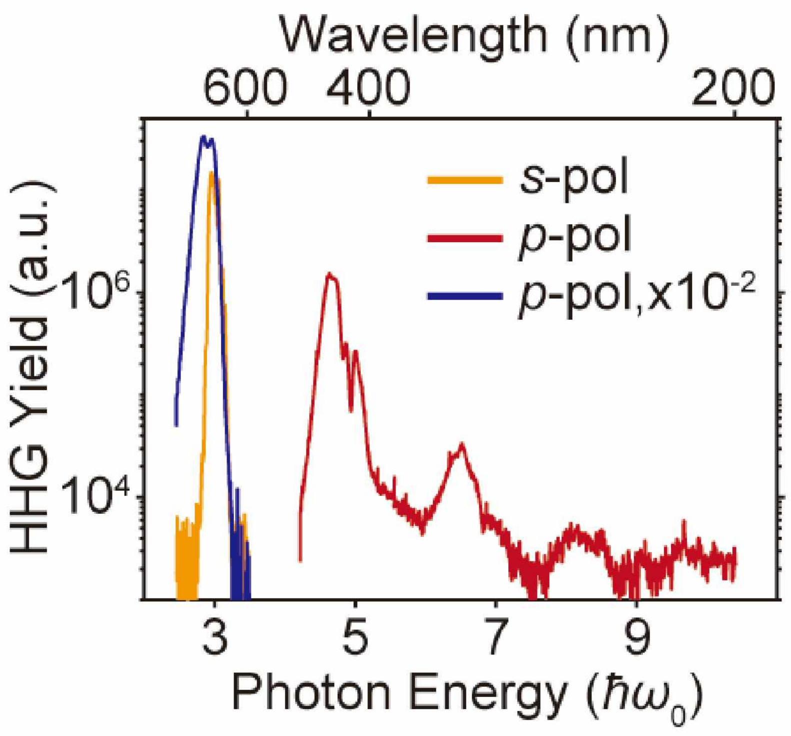


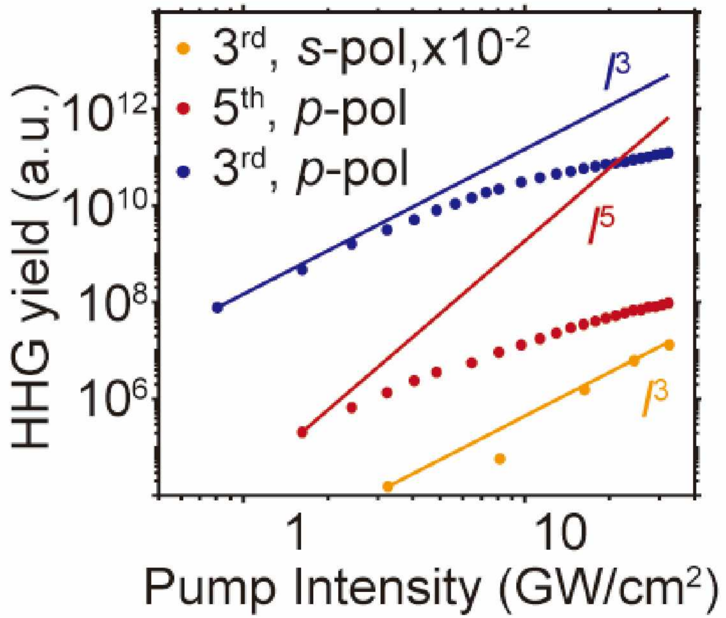
High field enhancements



Moderate absorption length

HHG Spectrum

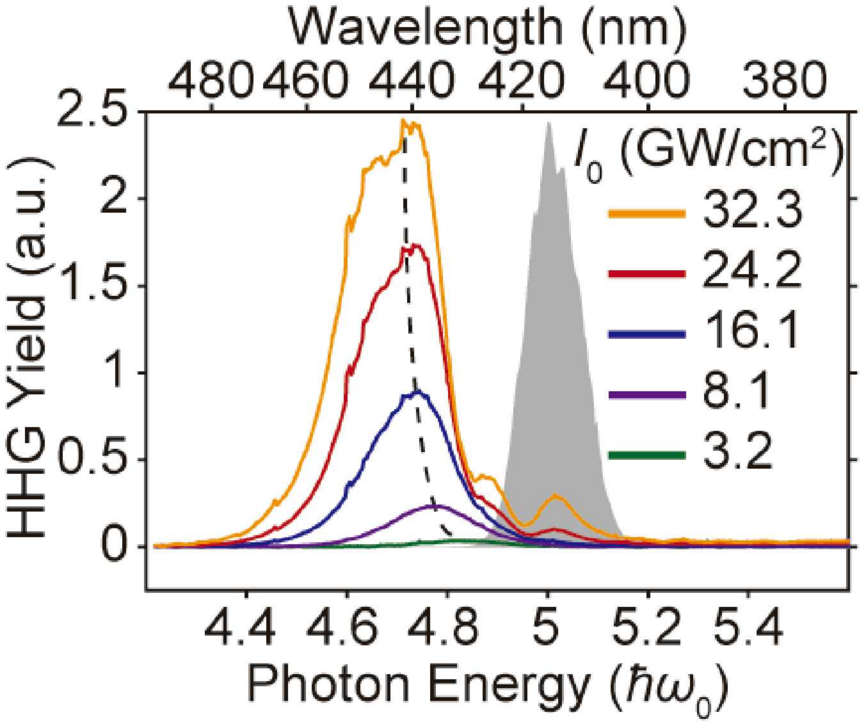




HHG from 3rd to 9th order

Nonperturbative HHG

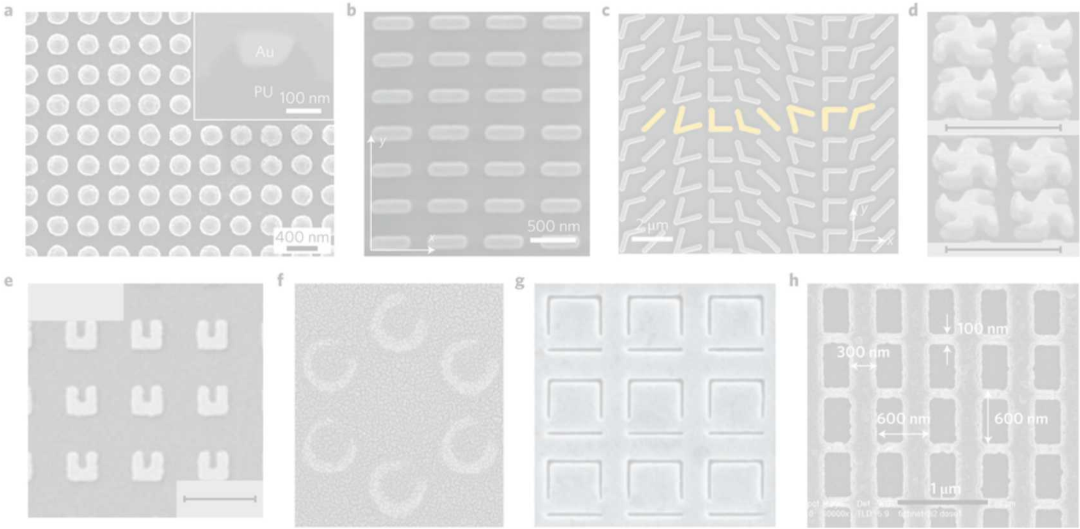
HHG Spectral Shift and Broadening



Harmonic shift and broadening:
- Rapidly evolving cavity--unique hot electron dynamics
- Reduced HHG temporal pulse duration

Metasurfaces

Metallic

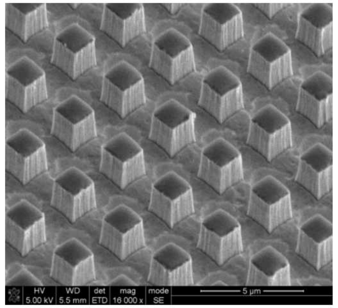


Nature Photonics 8, 889 (2014)

- Strong field confinement
- Small mode volume
- Low damage threshold
- Loss

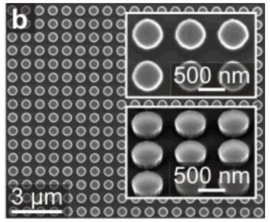
Dielectric

Tellurium

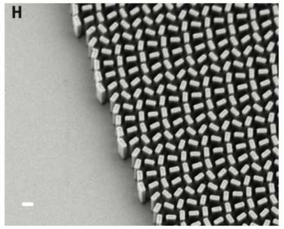


PRL 2012

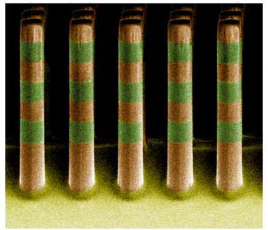
Silicon



Adv. Opt. Mat. 2015, NL 2015, ACS Phot. 2016



GaAs



Adv. Opt. Mat. 2016, NL 2016

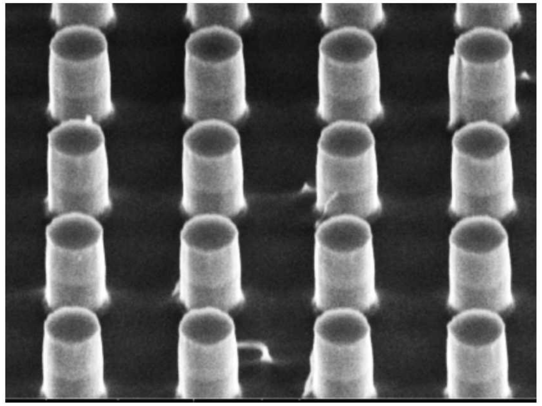
- Large mode volume
- More flexibility with electric and magnetic polarizabilities
- Higher damage threshold

Can be made from semiconductors >> optical generation of carriers

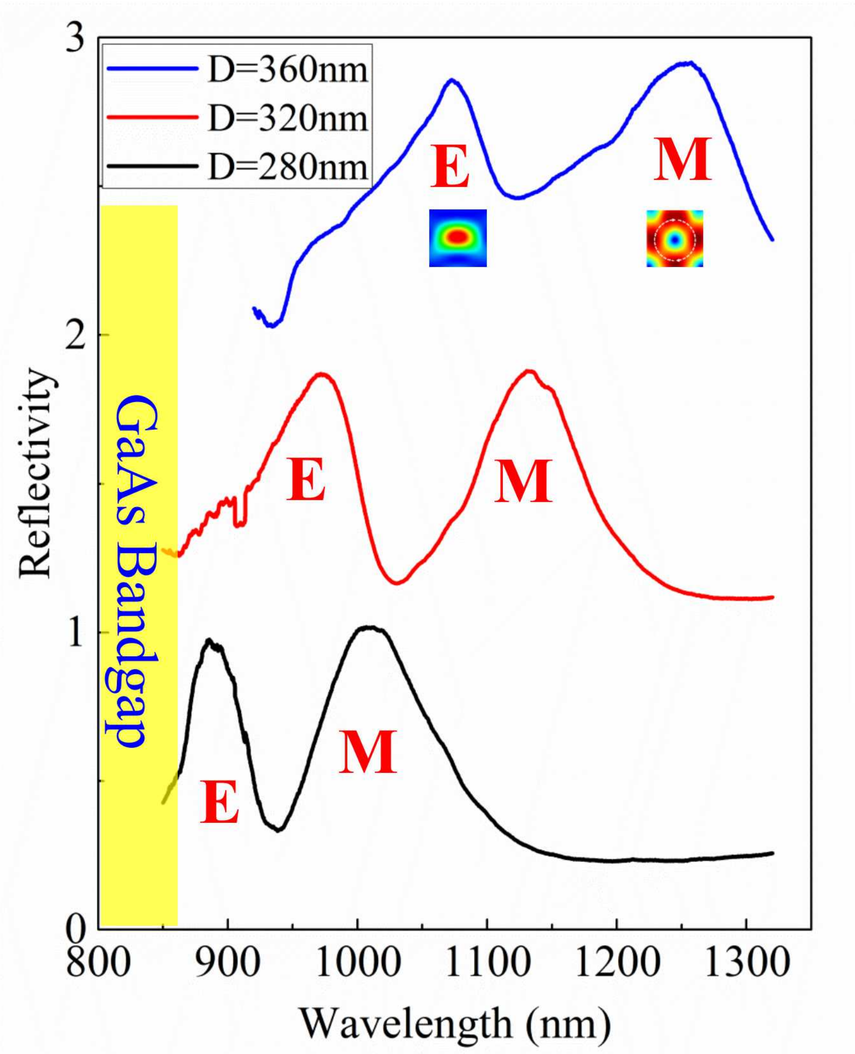
GaAs Dielectric Metasurface

GaAs disk height ~300nm

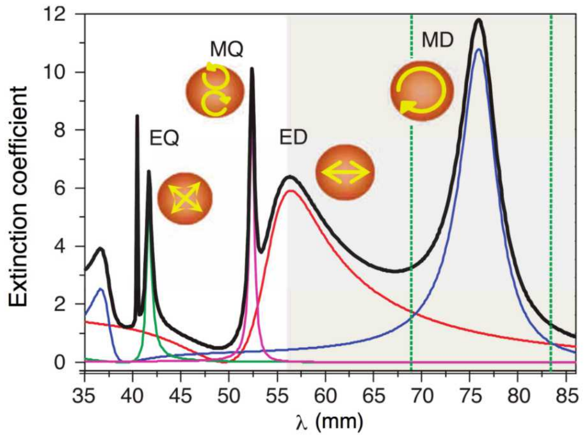
Different diameters



- Extremely low loss below bandgap
- Crystalline



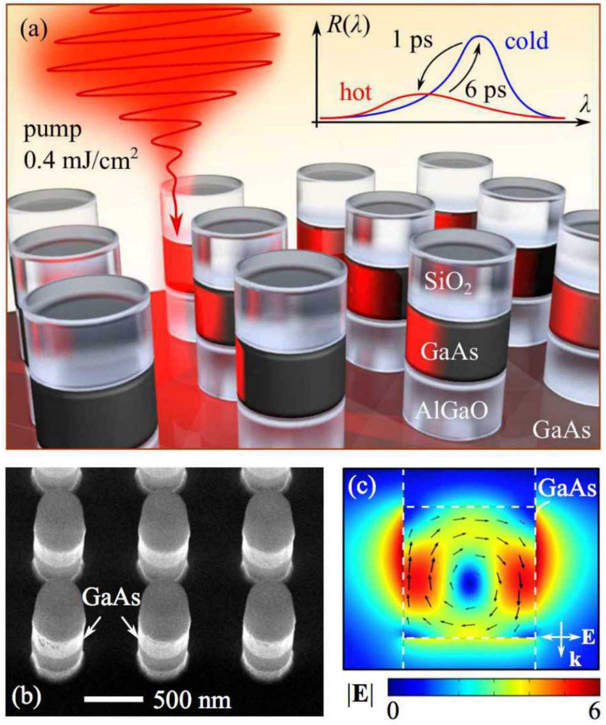
Mie resonances in Dielectric spheres



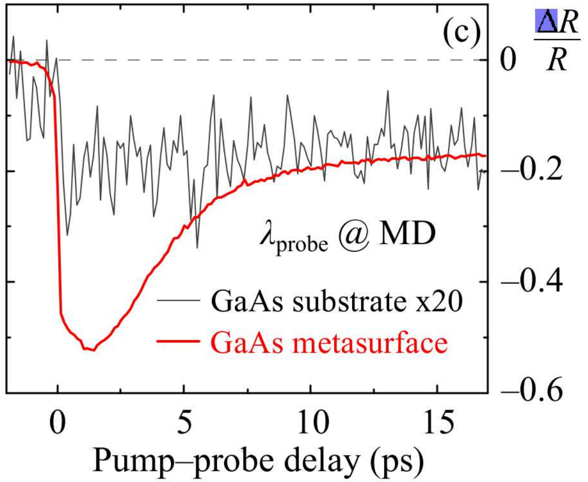
Geffrin, J.-M., et al. *Nat. Commun.* 3, 1171, **2012**

Advanced Opt. Mat 2016

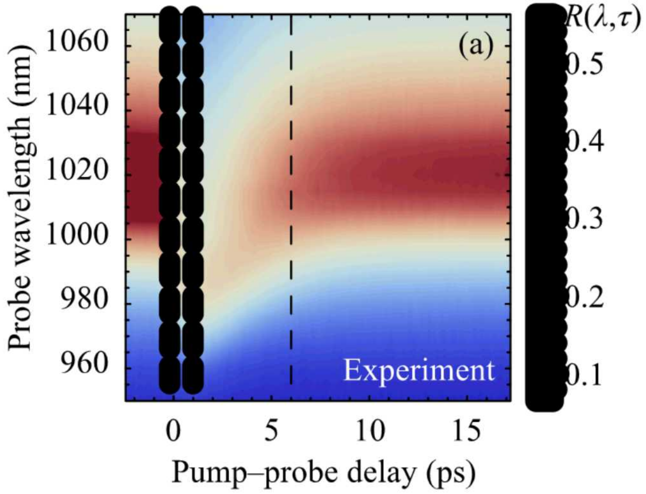
Dielectric Metasurface: Ultrafast Tuning of Magnetic Dipole Mode

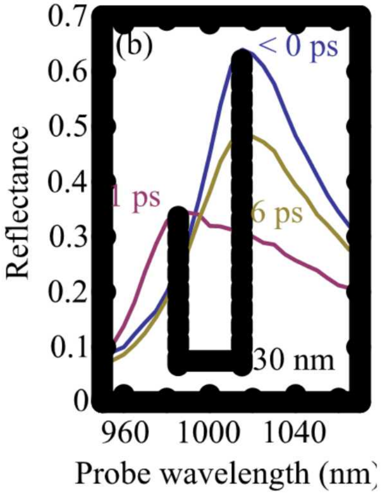


Modulation 50x of substrate



Resonance tuning by 30 nm





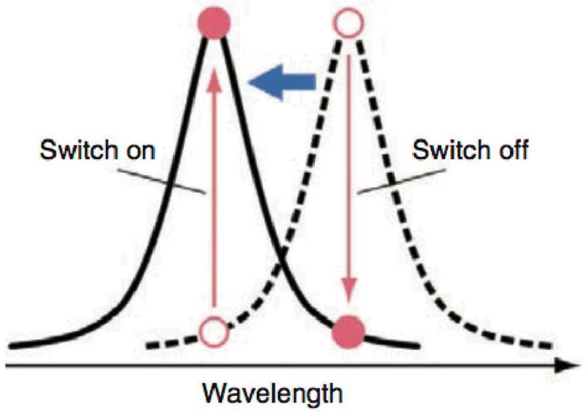
- **Fast recovery due to surface recombination (~2.5 ps from low power expts)**
- **Maximum index modulation is –0.14 due to Drude dispersion and band filling effects**

Nat. Comm. 2017

Summary

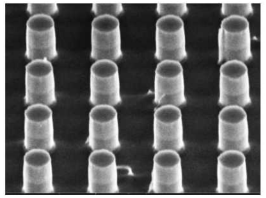
- Ultrafast and Transient Plasmonics/Metasurfaces
  - Optical creation of a plasmonic grating
  - Ultrafast switching using epsilon near zero (ENZ) media
- High Harmonic Generation in ENZ
- Ultrafast switching of dielectric metasurface

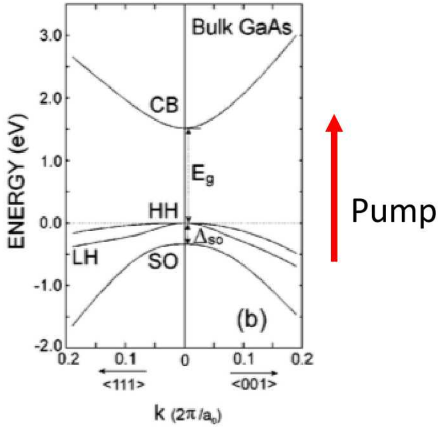
Ultrafast Switching Using Metasurfaces/Plasmonics



NTT Tech. Rev.

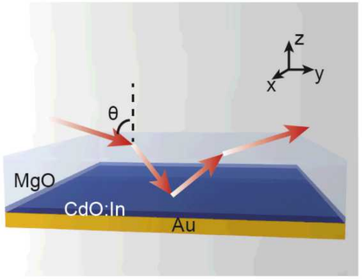
- **Dielectric Metasurfaces**

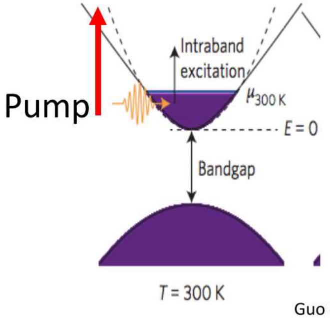




Vurgaftmana
JAPN (2001)

- **Perfect Plasmonic Absorber**



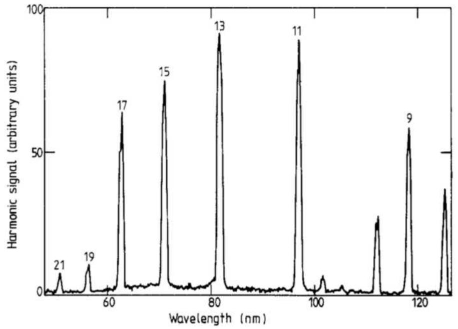


Guo et. al., Nat. Photon, (2016)

High-harmonic Generation (HHG)

Gas-phase HHG:

HHG in Xenon gas:



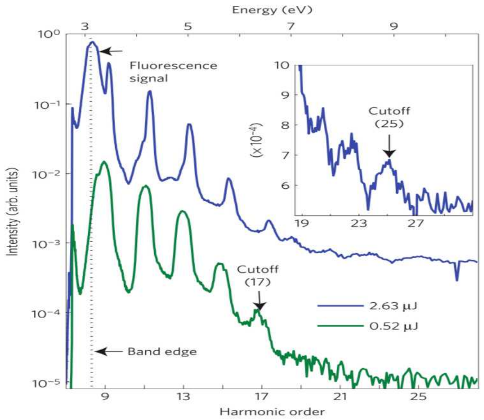
Pros:
- **Virtually no damage threshold**

Cons:
- **Low efficiency**

M. Ferray et al, ***Journal of Physics B***, 453, 757(1988)

Solid-phase HHG:

HHG in ZnO:



Pros:
- **High efficiency (high atom density)**
- **Low pump threshold**

Cons:
- **Difficult phase-matching**
- **Absorption above bandgap**

S. Ghimire et al, ***Nature Physics***, 7, 138(2010)