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Plasmonics and Optical Metamaterials: Looking beyond Gold and Silver

EXPLORING AND UTILIZING ALTERNATIVE CONSTITUENT MATERIALS

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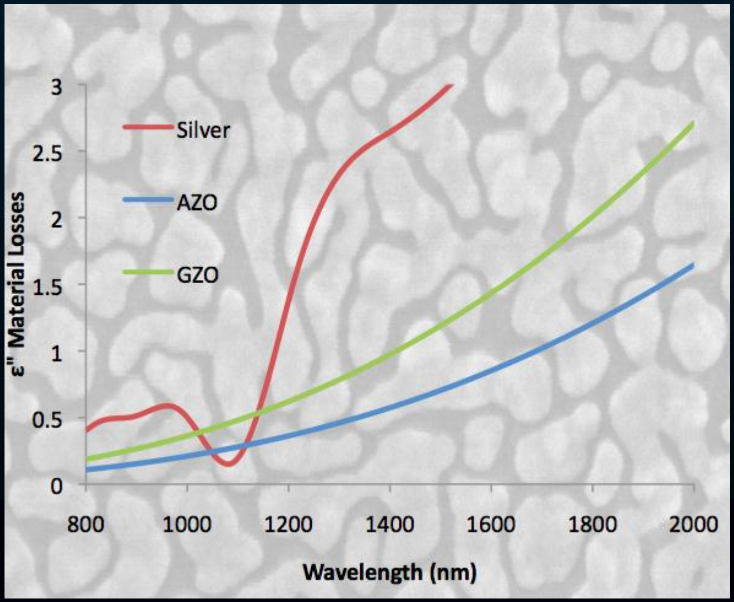
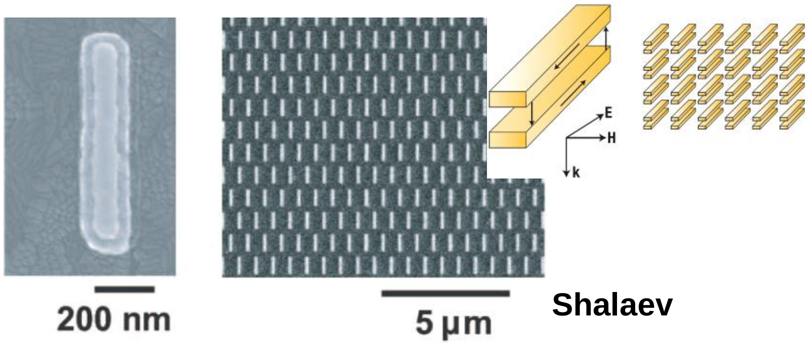
OUTLINE

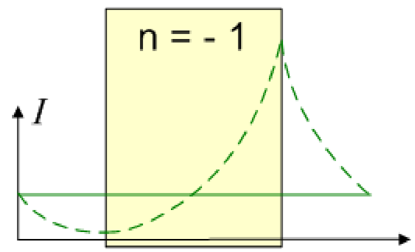
- Introduction: Challenges with Gold and Silver
- Material Requirements: Plasmonics & Metamaterials
- Alternative Materials?
- Transparent Conducting Oxides
- Transition Metal Nitrides
- Figures of Merit
- What is the Right Choice?
- Outlook

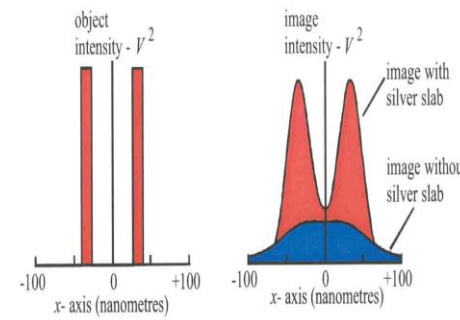


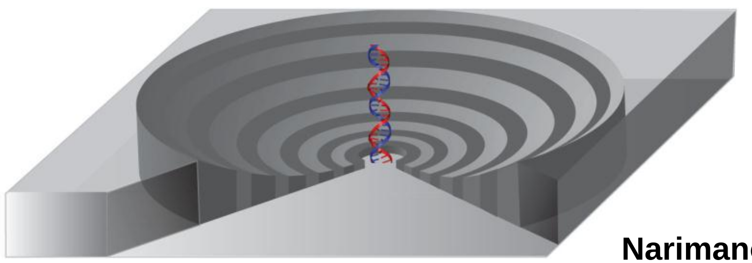
METAMATERIALS/TRANSFORMATION OPTICS



Shalaev

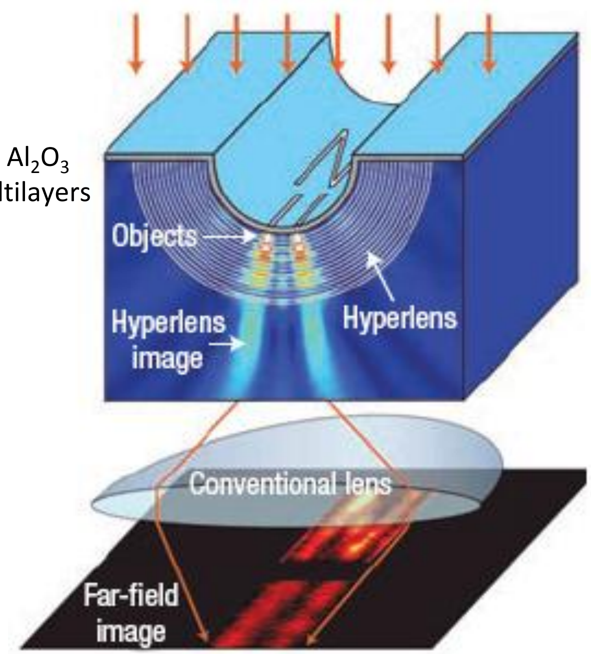


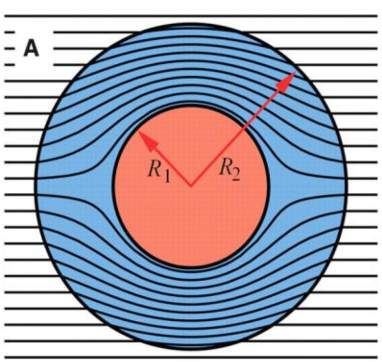


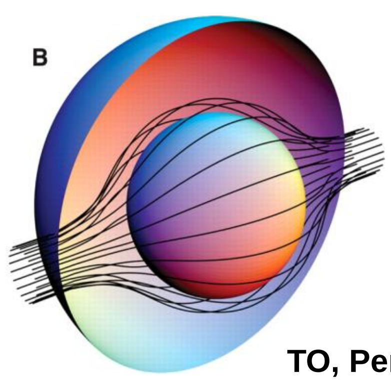


Narimanov, Engheta

Ag/ Al_2O_3 multilayers







TO, Pendry

Z. Liu et. al, Science (2007)

Metamaterials/TO: J. Pendry, X. Zhang, D. Smith, V. Shalaev, E. Narimanov, N. Engeta, M. Wegener, C. Soukoulis and many other groups

CHALLENGES

Conventional plasmonics: Gold and Silver

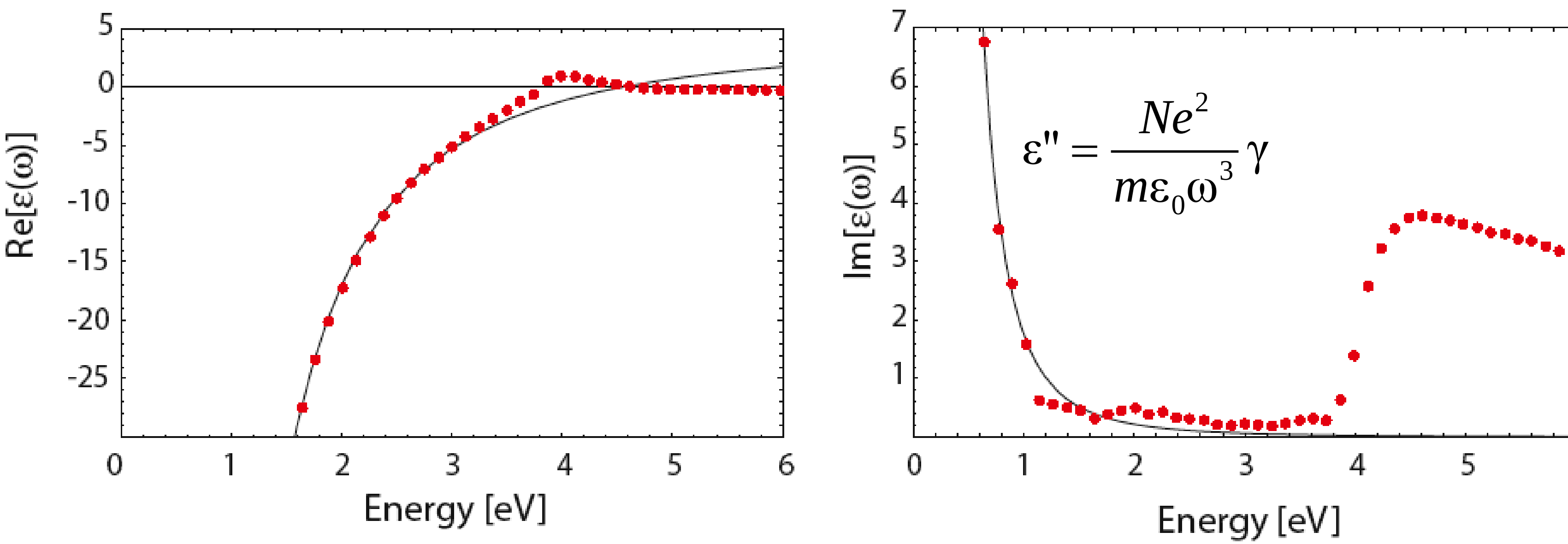
- Large losses in near-IR and visible ranges

Interband transitions

Surface roughness, grain boundaries, etc…

$$\varepsilon(\omega) = \varepsilon_{ib} - \frac{Ne^2 / m\varepsilon_0}{\omega^2 + i\omega\gamma_m(\omega)}$$

Real and Imaginary ε(ω) for Silver (Ag)



Johnson and Christy (dots) (1972)

Stefan Maier, Plasmonic Fundamentals and Applications p. 17 (Drude model fit) (2007)

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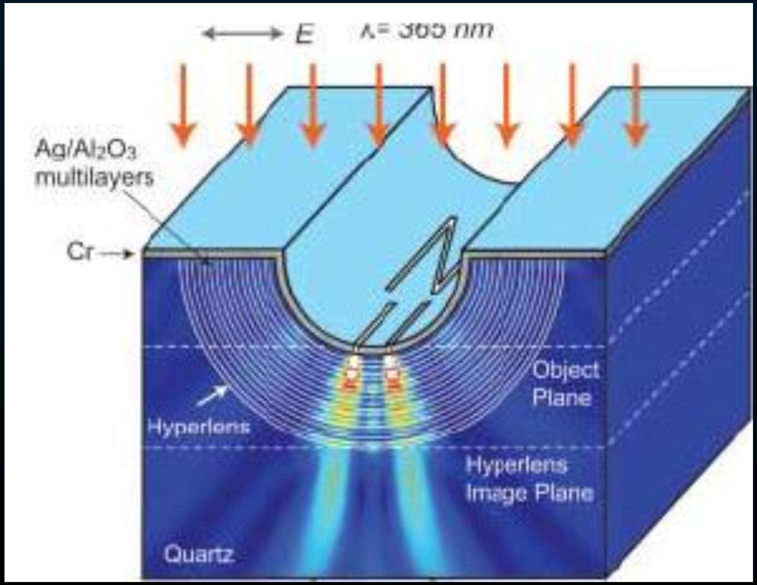
MATERIAL REQUIREMENTS

Emerging innovative fields such as Transformational Optics require comparable magnitudes of ε' of metal and dielectric

- Epsilon-near-zero (ENZ) materials
- Effective permittivity nearly zero: e.g. optical cloaks, hyperlens etc.

Novel devices would require tunable ε'

- Switching and modulation capabilities

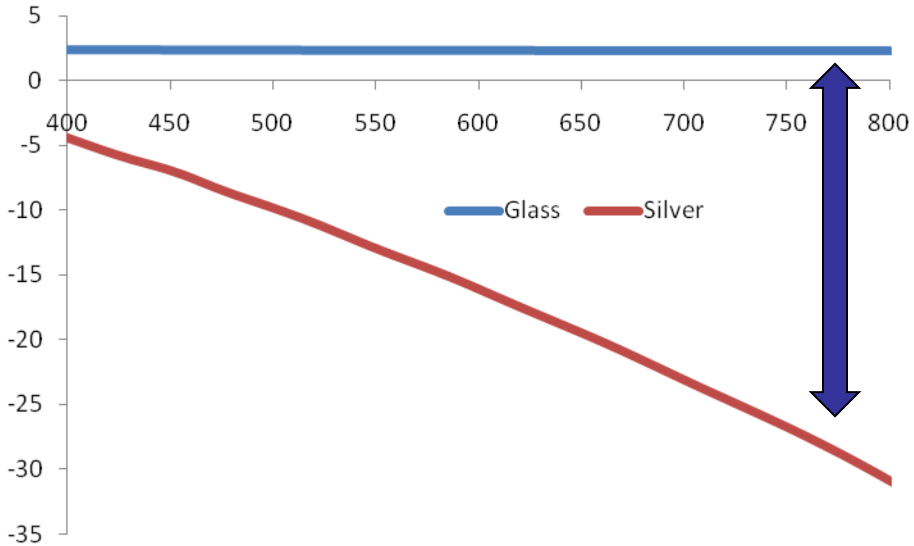


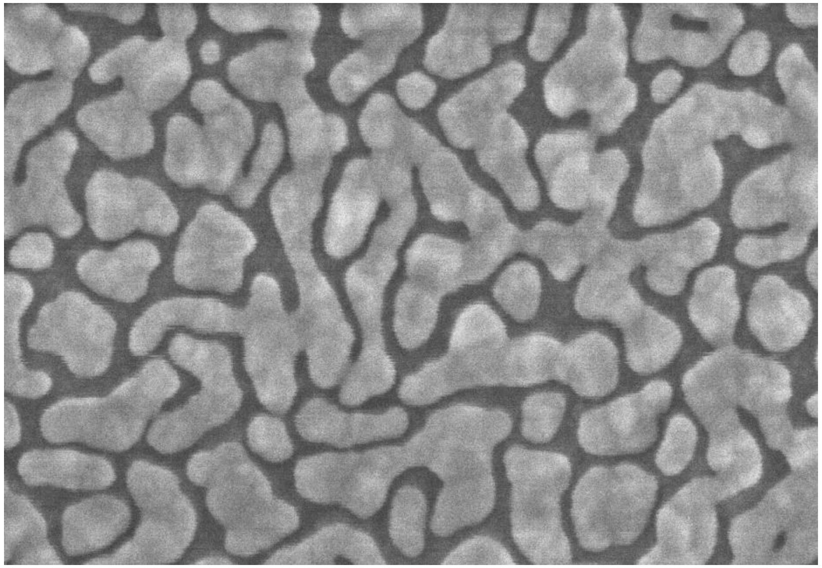
Z. Liu, et al., Science, 2007

MATERIALS FOR TO / ENZ

- Effective permittivity nearly zero $\varepsilon_{effective} \sim 0$: cloaks, hyperlens etc.
- Real permittivity of metals must be comparable to that of dielectrics

(for example, $\varepsilon_{dielectric} \sim 2$ requires $Re(\varepsilon_{plasmonic\ material}) \sim -2$ while $Re(\varepsilon_{Ag}) << -2$...)

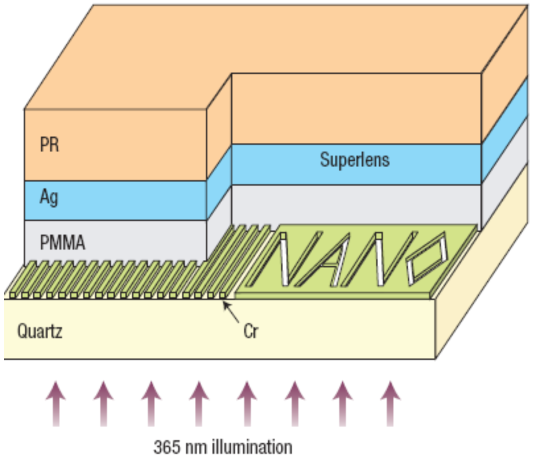




Ag: threshold for uniform continuous films is around 12-23 nm

BEYOND GOLD AND SILVER?

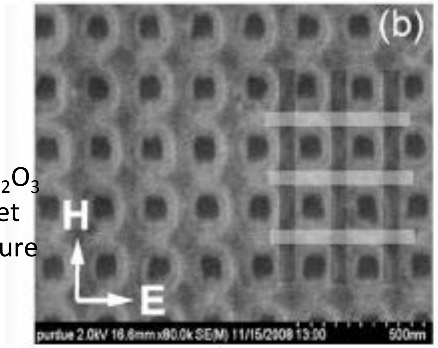
Superlens



N. Fang et. al, Science (2005)

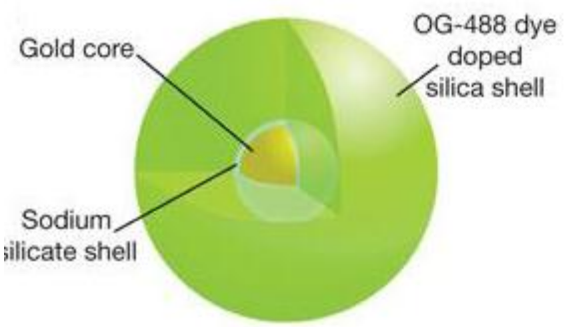
2-D Negative refractive index materials (NIM)

Ag/ Al_2O_3 fish-net structure



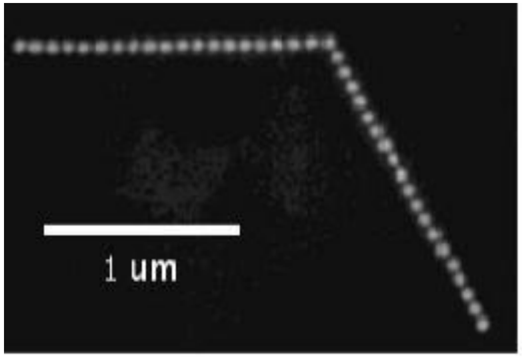
U. K. Chettiar et. al, MRS Bulletin (2008)

Nanolaser



M.A Noginov et. al, Nature (2010)

Plasmonic nanoparticle waveguide



M.L. Brongersma, et al., Phys. Rev. B (2000)

- Too large magnitude of real permittivity
- Large losses (VIS/NIR)
- Optical properties are not tunable
- Fabrication of very thin films/nanostructures is difficult
- Nanopatterning increases losses, grain boundaries, surface roughness…
- **Not CMOS compatible**

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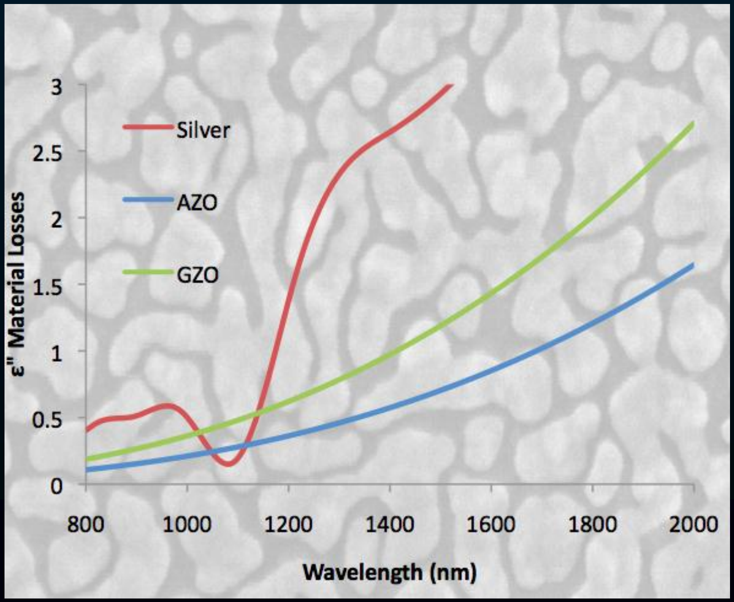

MATERIAL REQUIREMENTS

- Low loss components
  - Dielectrics can be nearly loss-less
  - Metals have large losses

- Adjustable / Tunable optical properties

Some Metamaterial + TO designs require comparable magnitudes of ε’ of metal and dielectric

  - Epsilon-near-zero (ENZ) materials
  - Effective permittivity nearly zero: e.g. optical cloaks, hyperlens etc.

- Switchable devices

- SC-compatible components

M. Ren *et al.*, *Adv. Mater.* 23 (2011) 5540; J.Y. Ou *et al.*, *Nano Lett.* 11 (2011) 2142. (Zheludev’s group)
E. Feigenbaium *et* al., *Nano Lett.* 10 (2010) 2111. (Atwater’s group)

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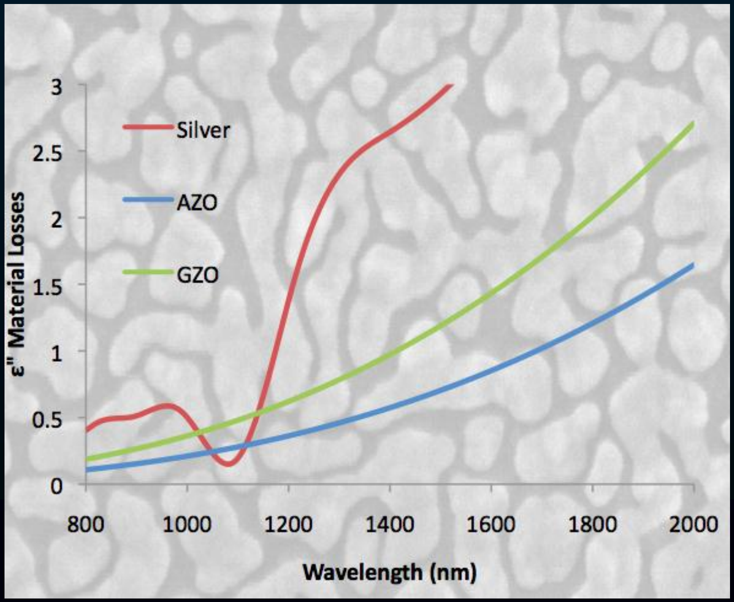
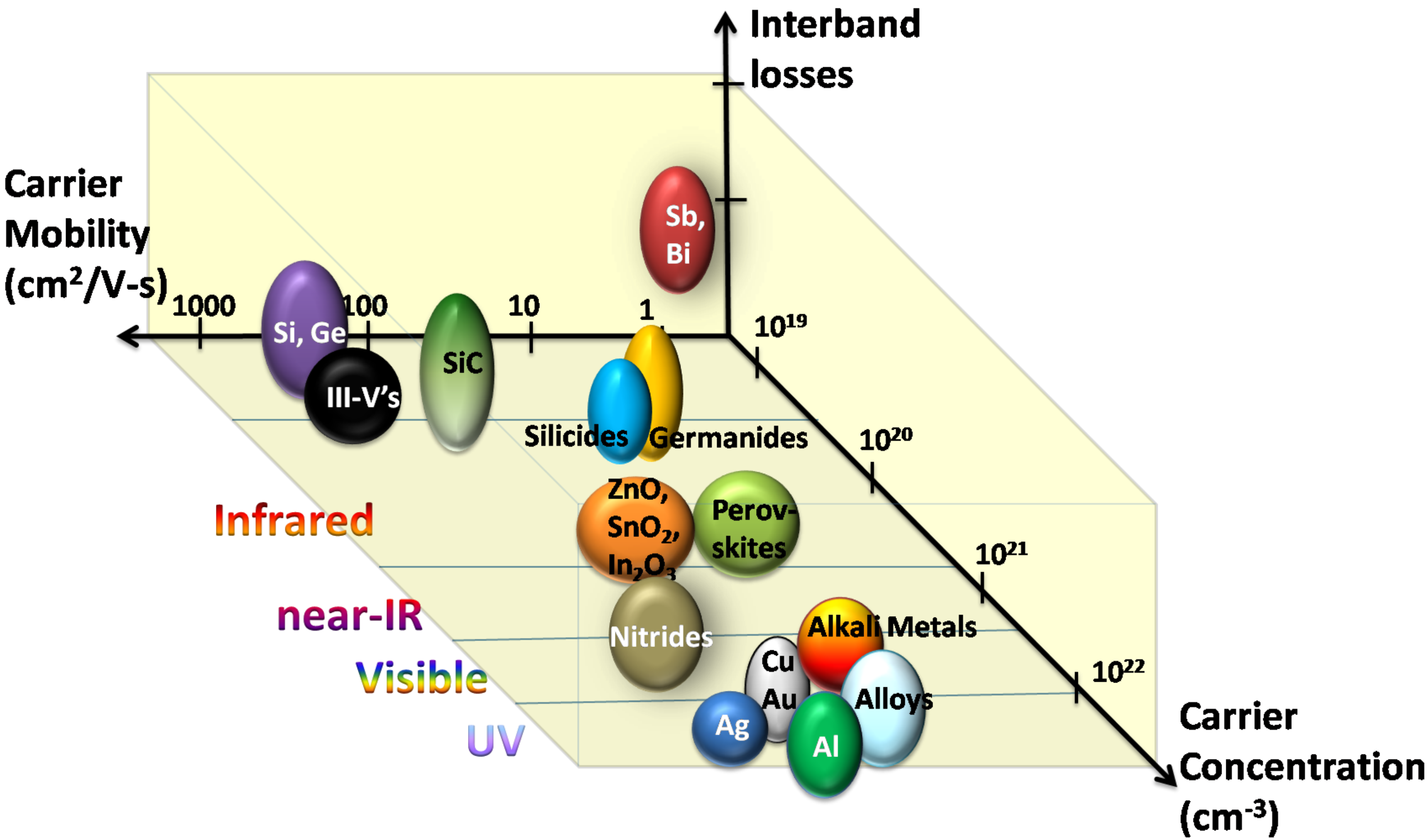


POSSIBILITIES

- Metals (Ag, Au, Cu, Al, Alkali)
- Alloys (Noble-Alkali[1], alloys of noble metals with transition metals like Cadmium and Zinc[2])
- Doped Semiconductors: Highly doped semiconductors[3], doped conducting oxides (ITO[4], Al:ZnO and Ga:ZnO[5])
- Intermetallics (nitrides, germanides, ...)

1:M. G. Blaber et al., J.Phys. Cond. Matter, 21, 144211 (2009),
2:D. A. Bobb et al., Appl. Phys. Lett. 95, 151102 (2009); 3:A. J .Hoffman et al., Nature Mater., 6, 946 (2007)
4:C. Rhodes et al., J. Appl. Phys., vol. 100, 54905 (2008)
5: LPR 4, 795 (2010), Phys. Status Solidi RRL 4, 295 (2010), Metamaterials 5, 1 (2011), OMEx (2011)

ALTERNATIVE MATERIALS



A. Boltasseva and H.A Atwater, Science 331 (2011) 290.

METALS

Ag – Conventional Plasmonics, usual choice

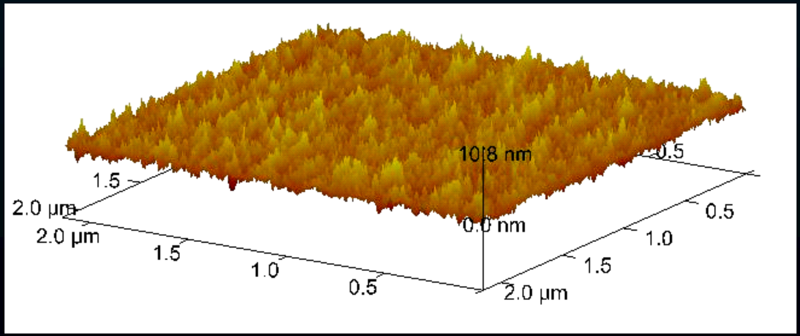
- Low loss
- Standard physical vapor deposition (PVD) methods + chemical methods
- But *degrades* in air

Au – Second Best for VIS, NIR

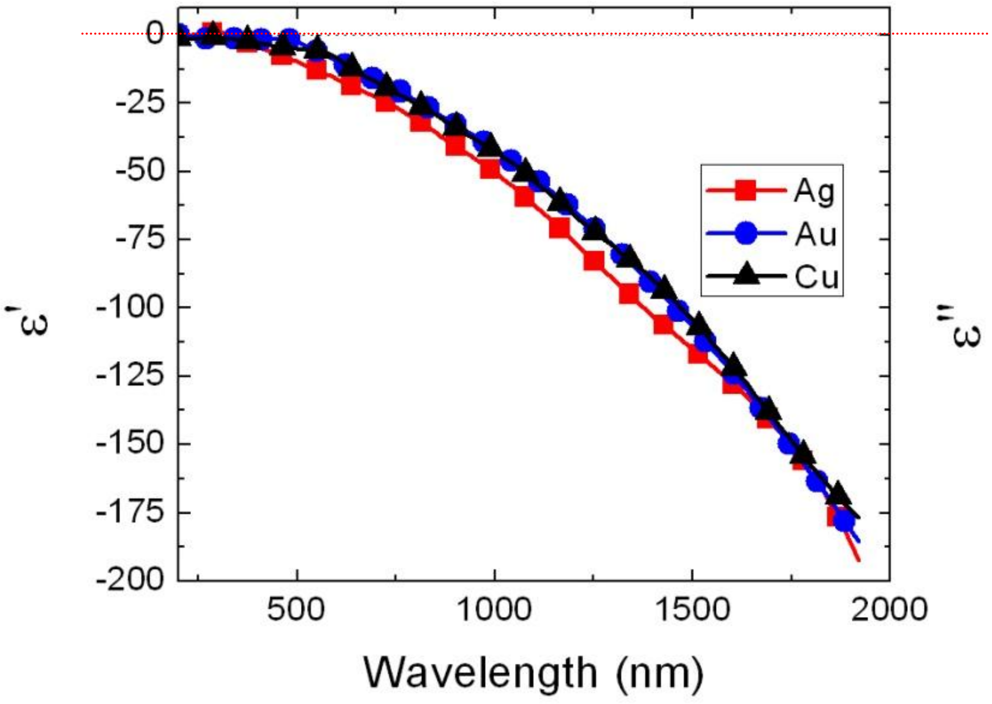
- Acceptable loss but *interband transition* (5d-6p) within VIS range
- Standard PVD methods + chemical methods: Chemically stable
- Continuous film at thickness of 2-7nm

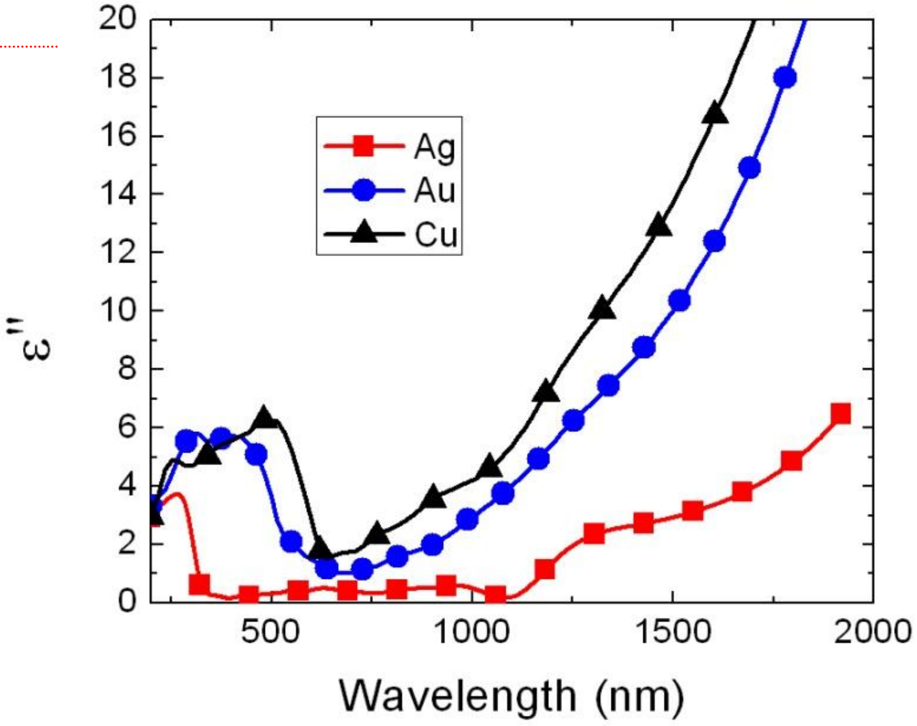
Cu – Ok for VIS (similar to Au)

- High conductivity + low cost
- But prone to surface *oxidation*



Ag, Au, Cu



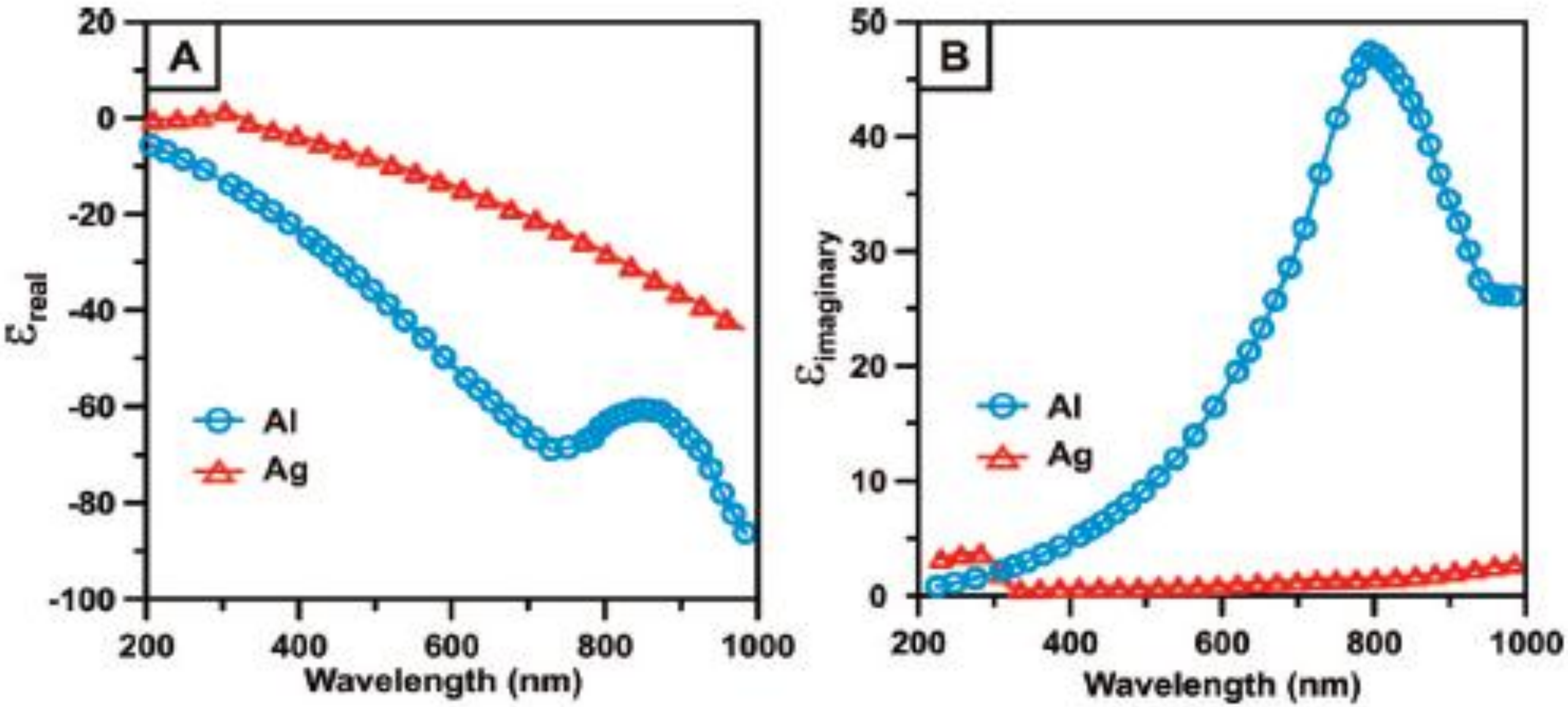


Cu – similar to Au 600-750 nm
fabrication is challenging (easily oxidizes)

ALUMINUM

Al – Higher loss in VIS + NIR

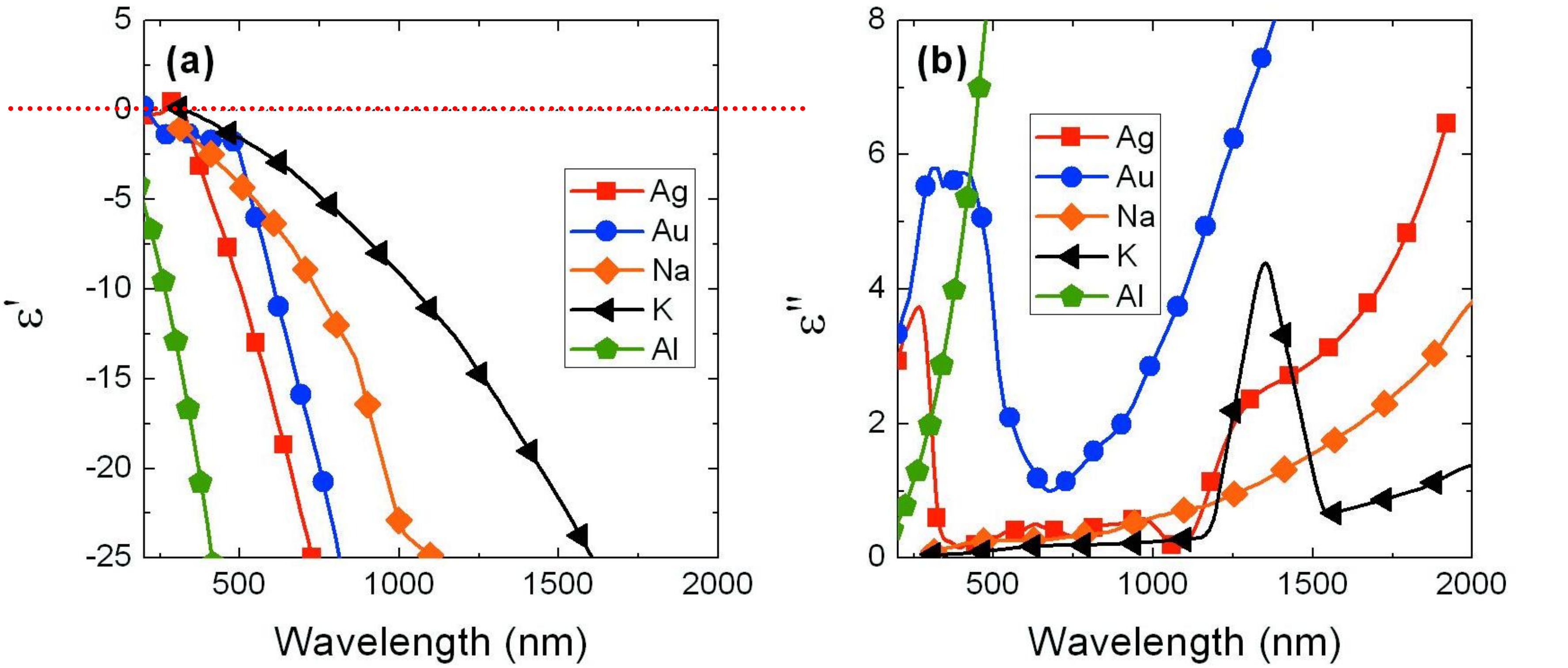
- Best for short wavelengths (still plasmonic below 200 nm)
- Prone to surface *oxidation* (Al_2O_3 2.5~3nm)



G. Chan, et al, J. Phys. Chem. C, 112, 13958 (2008)
C. Langhammer, et al, Nano Letter, 8, 1461 (2008)

ALKALI

Alkali (Sodium, Potassium) – Lowest losses, closest to free-electron gas
- Very *reactive* (ultra-high vacuum 10^{-19} Torr reqiurement, passivation)



Ag, Au: P. B. Johnson and R. W. Christy, Phys. Rev. B 6, 4370-4379 (1972)
Al, Na, K: E. D. Palik, Handbook of Optical Constants of Solids

ALLOYS: IMPROVING METALS

Improving Noble Metals:

- To shift interband transitions to another (unimportant) part of the spectrum

-By alloying two or more elements to create unique band structures that can be fine-tuned by adjusting the proportion of each alloyed material

Noble-Transition Metal Alloys

Bivalent transition metals (Cadmium and Zinc) contribute one extra electron to the free-electron plasma n-type doping $\Rightarrow$

- Increasing of ω_p
- Shifting the threshold for interband transitions
- Reducing the absorption at a specific wavelength

"Band Engineering"

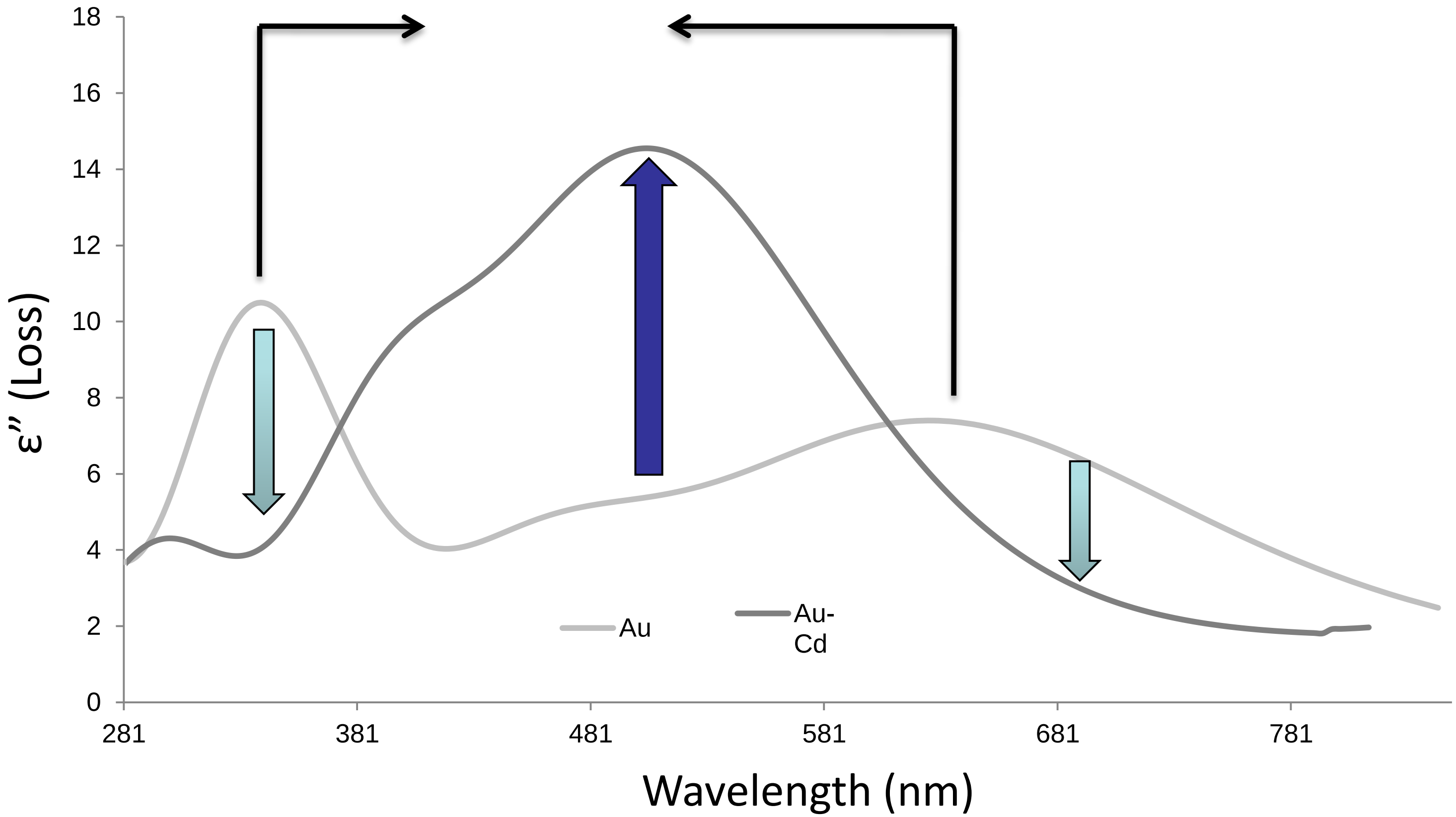
D. A. Bobb, G. Zhu, M. Mayy, A. V. Gavrilenko, P. Mead, V. I. Gavrilenko, and M. A. Noginov, Appl. Phys. Lett. 95, 151102 (2009) - Norfolk University

NOBLE-TRANSITION ALLOY

Cadmium + Gold ⇒ Additional electron to free electron gas

Shift of the Lorentz resonance peaks ⇒ Tuning of the optical parameters

Optimum – 3.3% Cadmium in Gold



D. A. Bobb, G. Zhu, M. Mayy, A. V. Gavrilenko, P. Mead, V. I. Gavrilenko, and M. A. Noginov, Appl. Phys. Lett. 95, 151102 (2009) - Norfolk University

ALKALI-NOBLE COMPOUNDS

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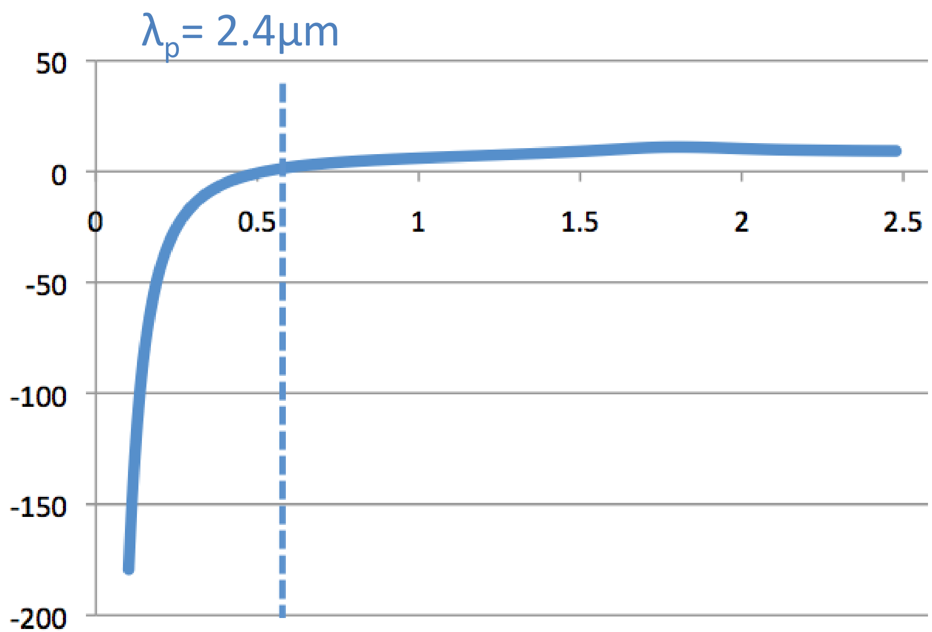
Alkali-Noble Metal: Intermetallic Compounds

Group I alkali metals: Strongest free-electron-like behavior

Most promise: Potassium Gold (KAu)



KAu:
Crossover point is 0.5 eV (2.4 μm)

⇒ KAu does not have negative ε' values in the NIR and VIS ranges

M. G. Blaber, M. D. Arnold, and M. J. Ford, J. Phys. Condens. Matter 21, (2009)

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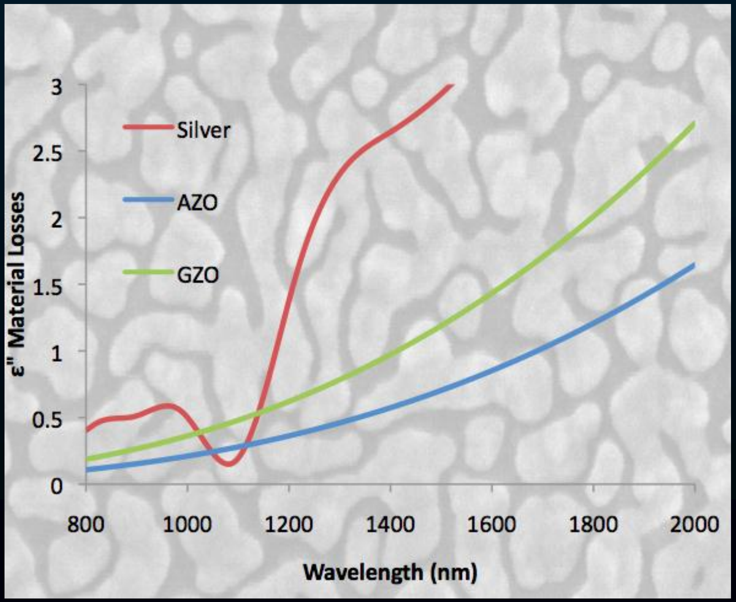


SEMICONDUCTORS AS "METALS"

- Metals: Too large carrier concentration
  - Large plasma frequency (ω_P)
    - $\omega_P \alpha \sqrt{n}$: n ~ 10^{22} cm^{-3} in metals
  - Large loss ($\varepsilon'' \alpha \omega_P^2$) + large magnitude of ε'

METALS ARE TOO METALLIC…

- Semiconductors: Doping can control carrier concentration
  - Conventional semiconductors: too low carrier concentration (dielectrics)
  - Doping density of $10^{21} cm^{-3}$ could produce ε'<0 in NIR

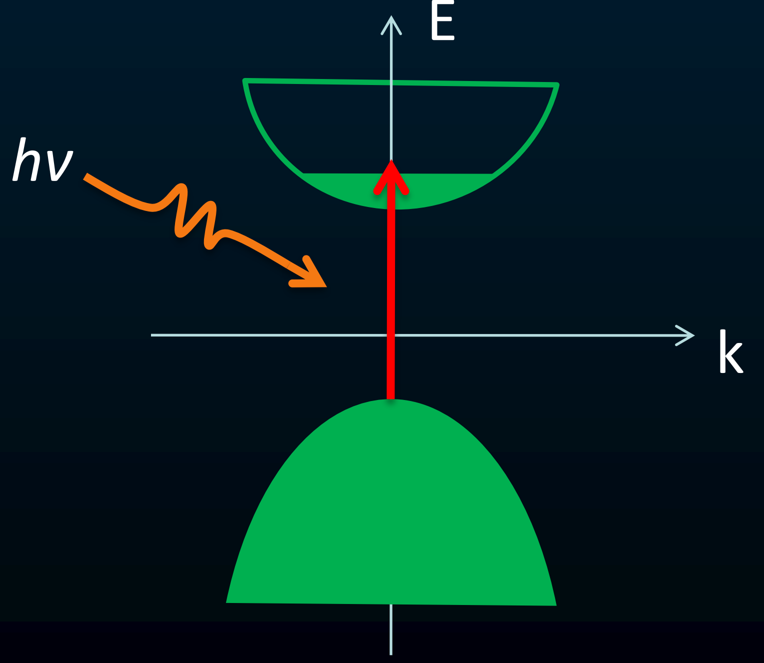
MAKE SCs MORE METALLIC…

METALS AS "LESS-METALS"

- Lower carrier concentration in metals
  - Abstract electrons by non-metal inclusions
  - Non-stoichiometric: controllable properties

SEMICONDUCTOR-BASED “METALS”

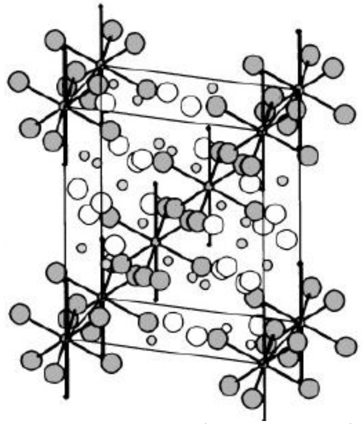
- Make semiconductors more metallic:
  Increase carrier concentration to 10^{21} cm^{-3}
- Wide Bandgap Semiconductors:
  Negligible interband transition losses
- Bandgap should be larger than frequency of interest
  Material Bandgap (eV):
  Si - 1.12, GaAs - 1.42, SiC - 2.36-3.05
- Large carrier mobility:
  Low damping losses



SEMICONDUCTORS

- Semiconductors
  - A lot of potential candidates like GaAs, GaN, Zn and Cd compounds (Oxides, Sulphides, Selenides, Tellurides), In_2O_3, SnO_2, SiC, etc.
  - Bandgap should be larger than frequency of interest (Material Bandgap (eV): Si - 1.12, GaAs - 1.42, SiC - 2.36-3.05)
  - Negative ε at IR: heavy doping or resonance *(Hoffmann et. al: Alternating layers of InGaAs and InAlAs; Doping 7x10^{18} cm^{-3} to achieve negative epsilon at ~ 10 µm)*

- **Transparent Conducting Oxides**
  - Tune plasma frequency by doping
  - Great switching opportunities
  - **Indium Tin Oxide (ITO), Al doped Zinc Oxide (AZO)** and **Ga doped Zinc Oxide (GZO)**



Solieman et al., Thin Solid Films, 502, 205 (2006)

TCO for switching: group of H. Atwater

SEMICONDUCTORS AS "METALS"

NIR: Transparent Conducting Oxides

- **Tune plasma frequency by doping**
- **Great switching opportunities**

- Gallium doped zinc oxide (GZO)
- Aluminum doped zinc oxide (AZO)
- Tin doped indium oxide (ITO)

C. Rhodes, *et* al., J. *Appl. Phys.* 100, 054905 (2006); P. R West *et* al., *Laser & Photonics Reviews* (2010);
M.A. Noginov *et* al.*, Appl. Phys. Lett.* 99 (2011) 021101.
E. Feigenbaium *et* al., *Nano Lett.* 10 (2010) 2111. (Atwater's group)

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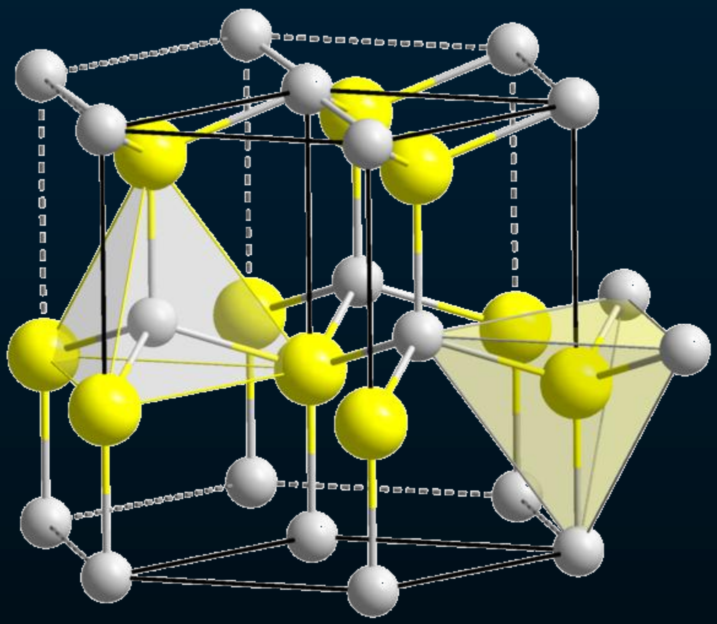
ZINC OXIDE

- II-VI semiconductor
- Wide band-gap of 3.37 eV at 300 K
- Applications:
  - Display panels
  - Piezo-electric devices
  - Paints, anti-corrosive coatings
  - Bio-compatible devices



DOPING ZnO

- By substituting a fraction of the Zn^{2+} ions by Al^{3+} ions, which serve as electron donors, ZnO is turned into a n-type semiconductor

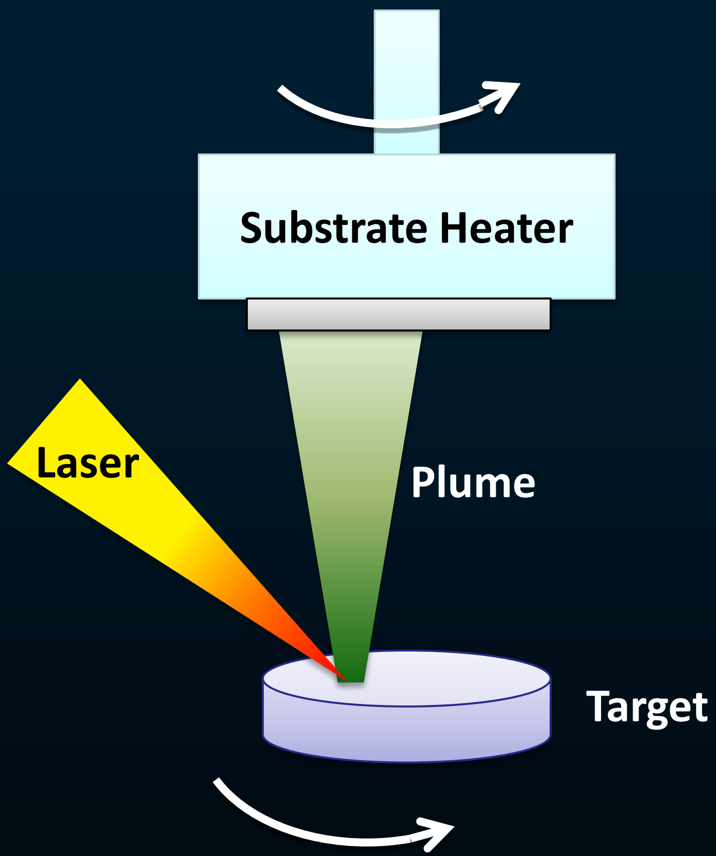
Ultra-High Doping Challenges

- Solid solubilities (maximum concentrations) of Ga and Al in ZnO are high (2-4 wt%)[1]
- High carrier concentration[1] ~ 10^{21} cm^{-3} (close to solid solubility limit)
- Very heavy doping lowers mobility of carriers due to increased impurity scattering
- Properties depend largely on the deposition method and the deposition conditions

1: M. H. Yoon, et al., J. Mater. Sci. Lett. 21, 1703-1704 (2002)

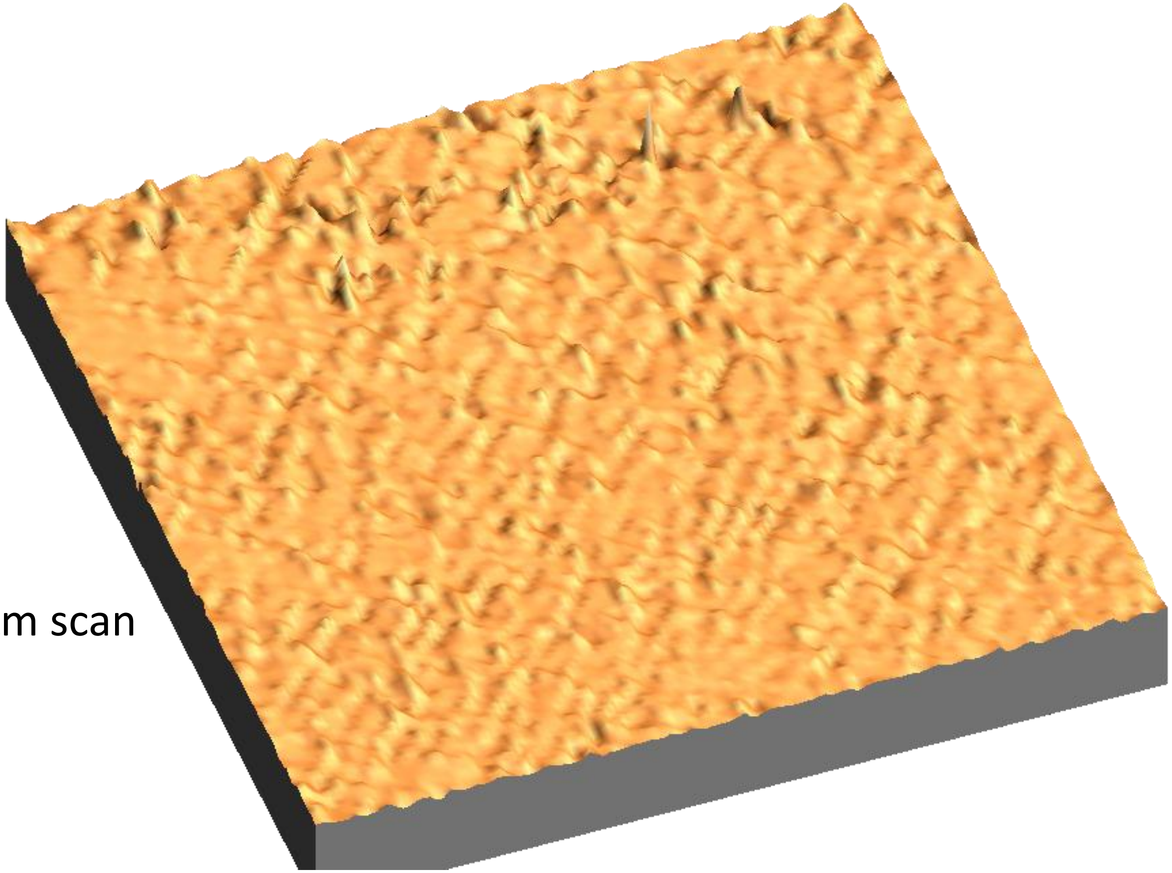
PULSED LASER DEPOSITION (PLD)

- Pulsed LASER Deposition (PLD)
  - Excimer laser pulses ablate the target of desired material
  - Ablation of more than one targets can deposit material with mixed composition
- Optical Characterization: Ellipsometry
  - Spectroscopic ellipsometer (J.A. Woollam Co.)
  - Drude-Lorentz model to extract the dielectric function



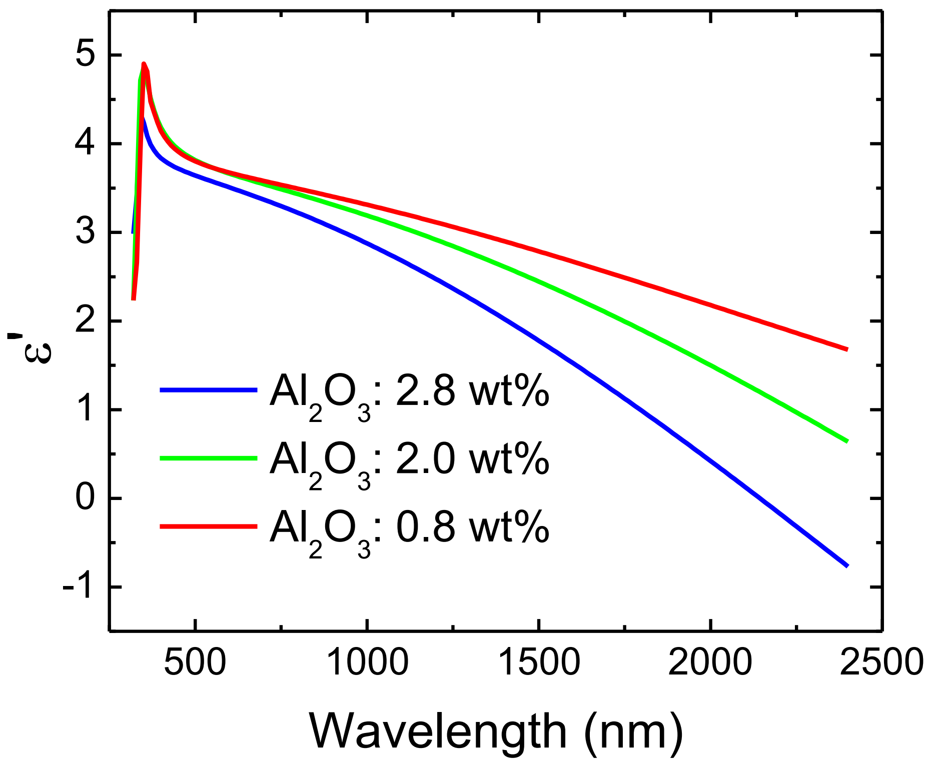
AFM OF AZO FILMS

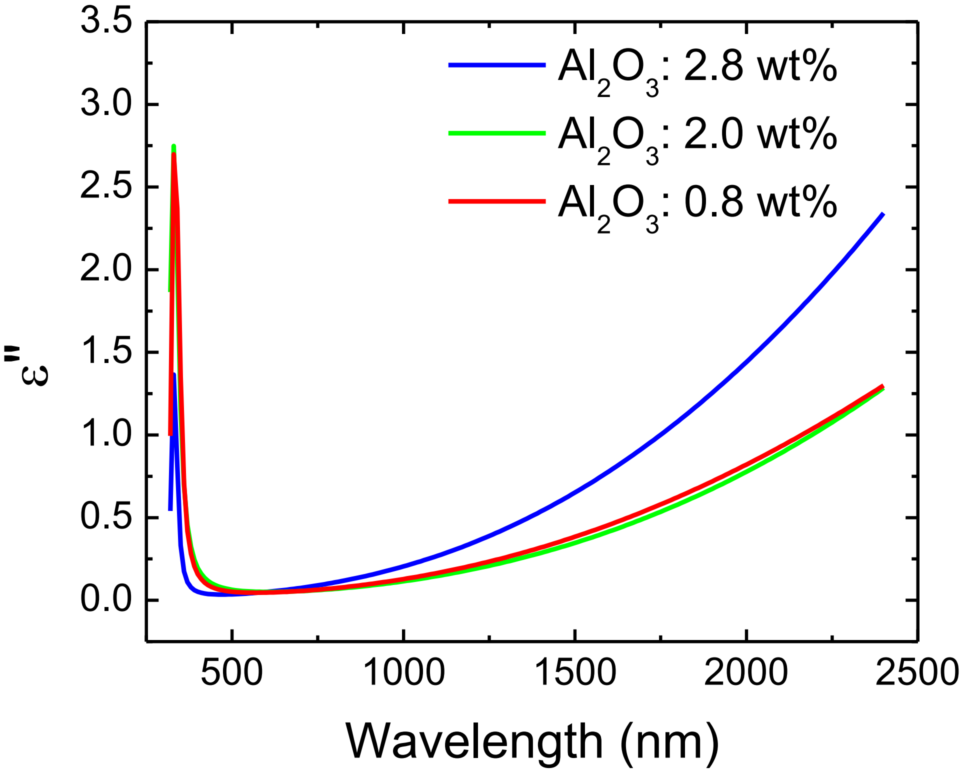
1 µm X 1 µm scan



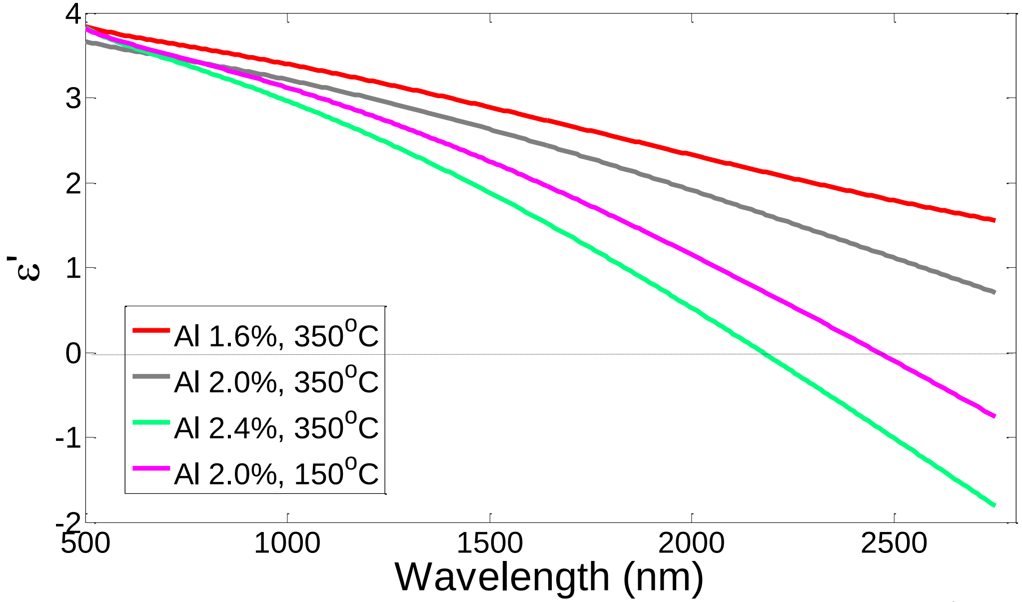
Mean grain size: 8 nm; Roughness (rms): 1.3 nm; Thickness 62 nm

AZO THIN FILMS

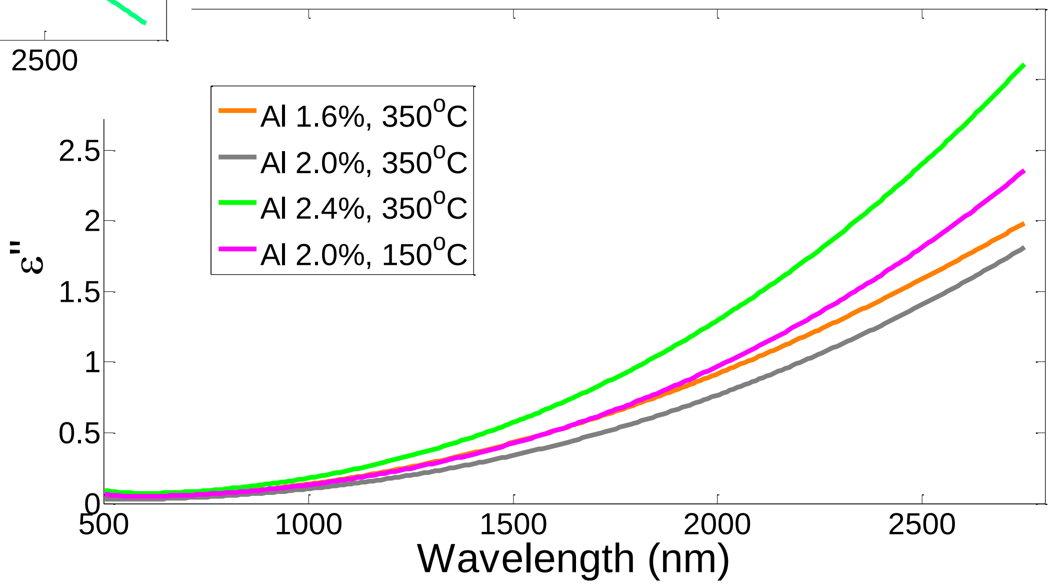




OPTICAL PROPERTIES



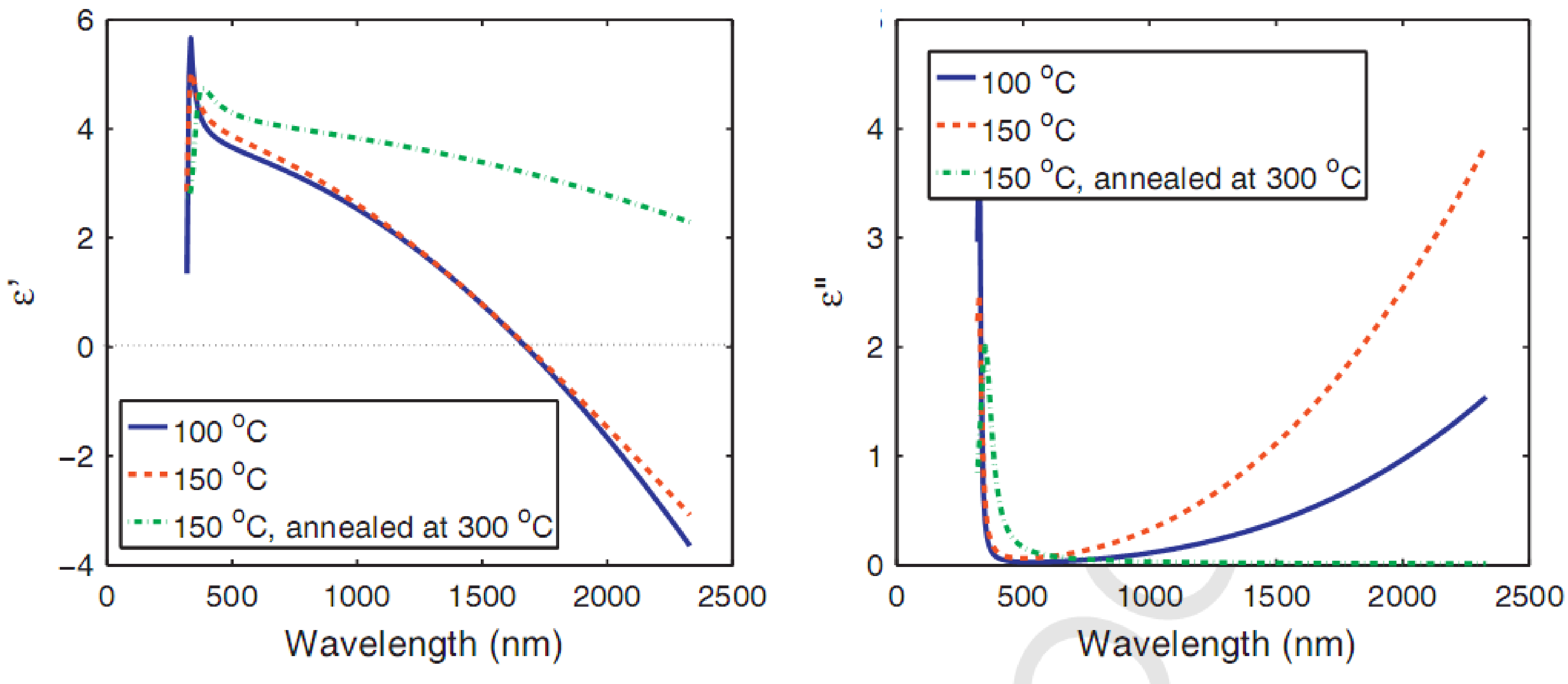
Permittivites for AZO films deposited at 350°C with 2.4, 2, 1.6% Al and AZO film deposited at 150°C with 2% Al



The cross-over frequency increases with larger Al

Film deposited at 150°C has higher cross-over frequency owing to larger efficiency of doping

OPTICAL PROPERTIES

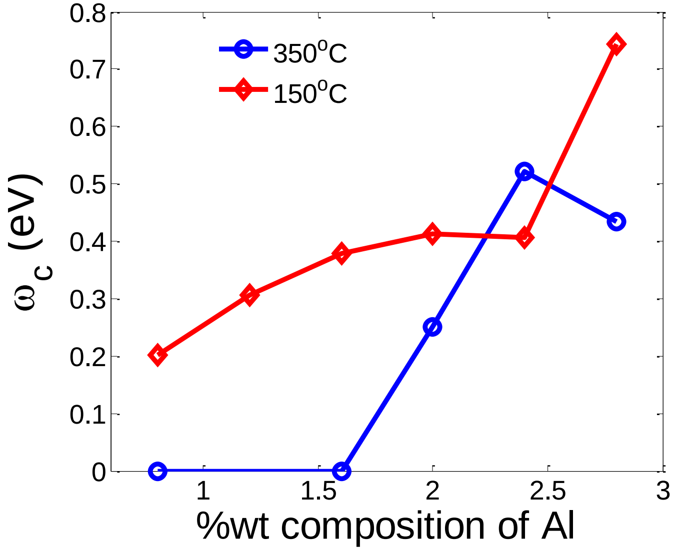


AZO films on c-sapphire substrates: Al doping 3.0 wt%

One of the films deposited at 150 ◦C was subjected to forming gas anneal at 300 ◦C for 2 h.

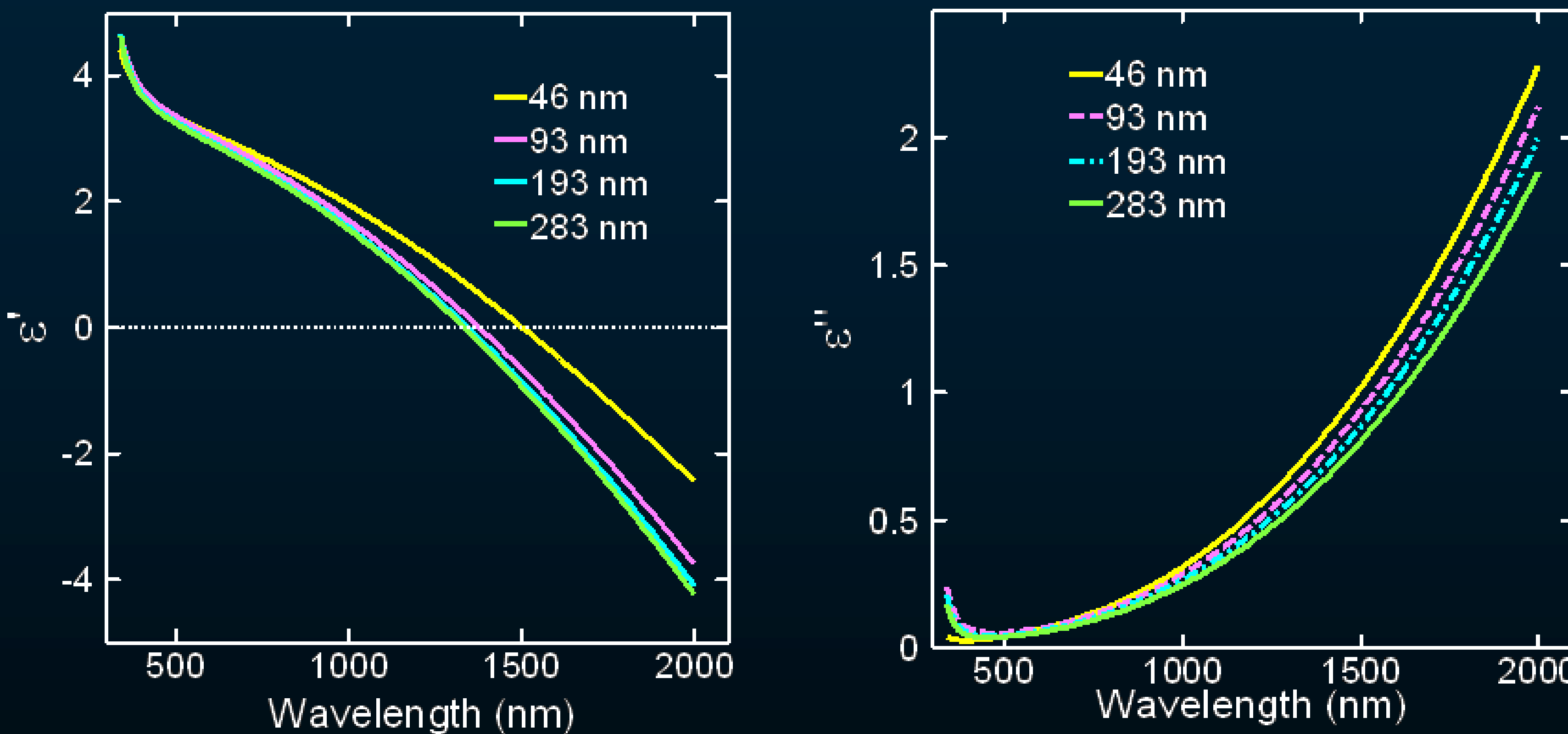
ZnO DOPING

- Larger doping does not necessarily mean larger cross-over frequency
- Trend shows that lower temperature deposition can produce larger cross-over frequency with larger doping



PLD AZO – lowest cross-over wavelength 1720 nm on this slide

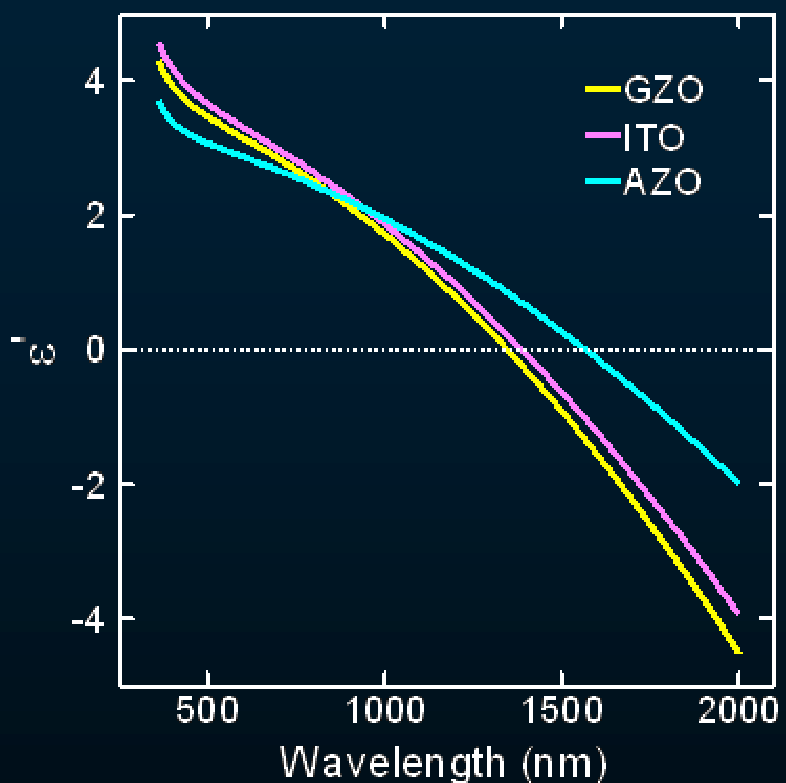
THICKNESS-DEPENDENT PROPERTIES

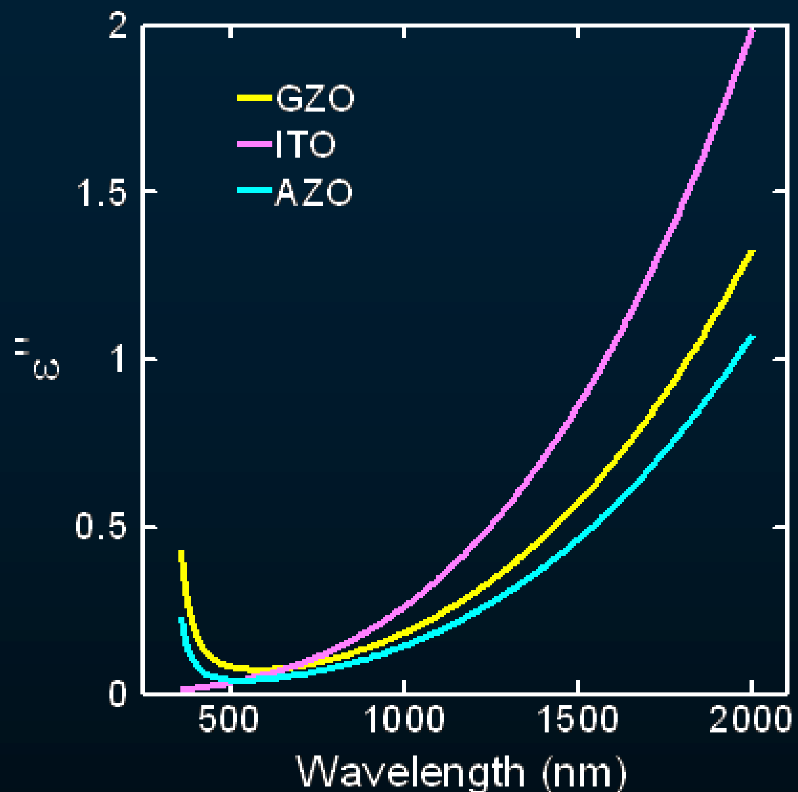


- GZO films deposited on glass under identical condition except film thickness
- Understanding thickness-dependent properties is essential for device fabrication

G.V. Naik, J. Kim and A. Boltasseva, *Optical Mater. Exp.* **1** (2011) 1090

OPTICAL PROPERTIES: TCOs

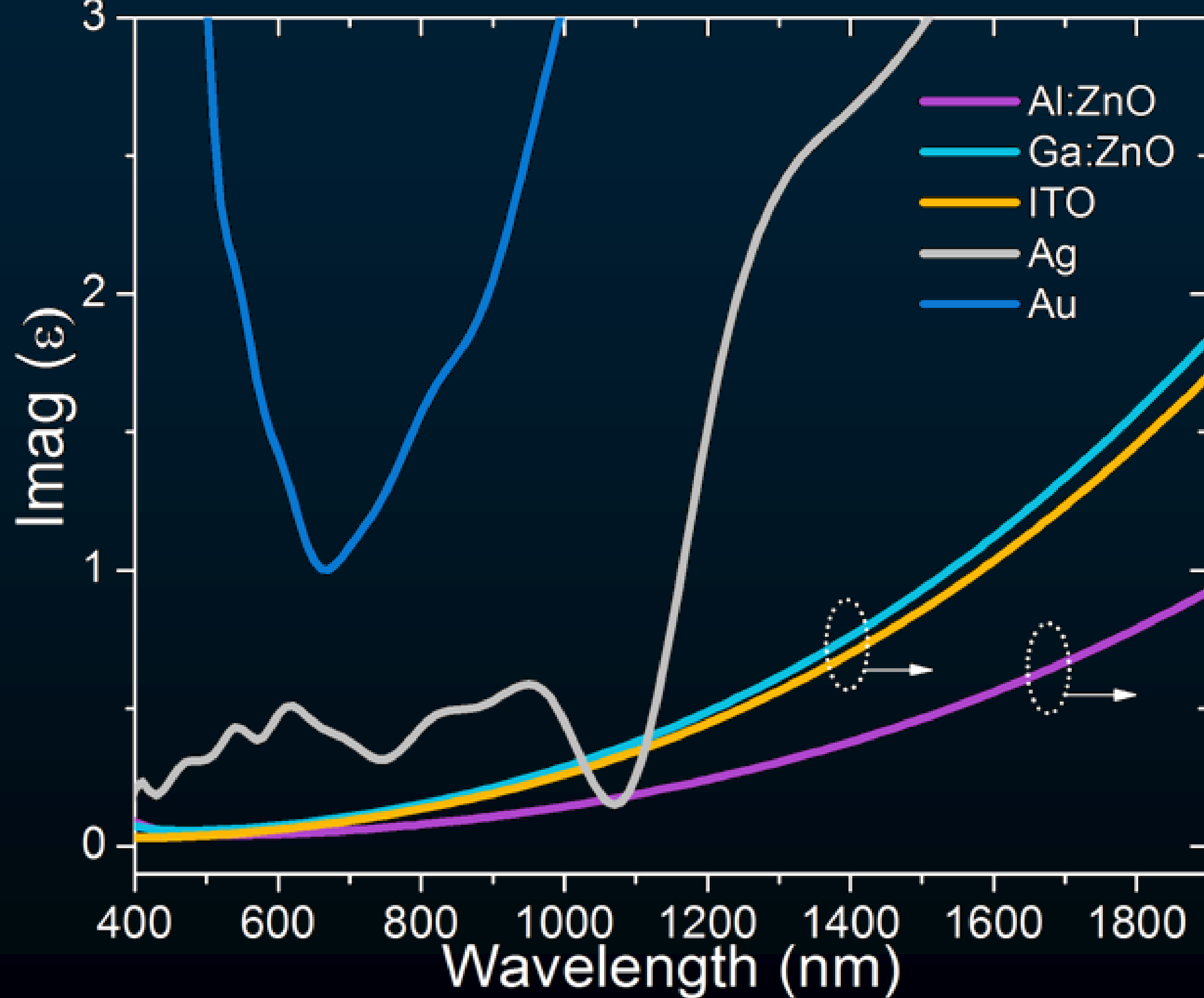




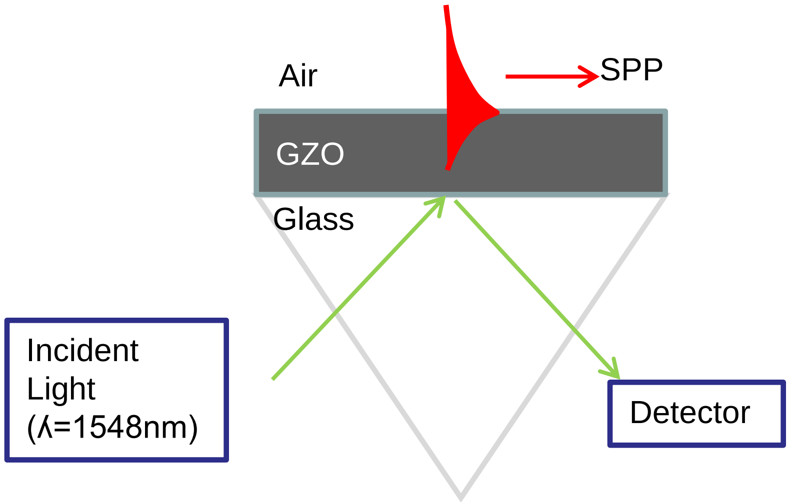
- TCOs films deposited on glass substrate
- AZO: Lowest Drude damping, Longest cross-over wavelength
- GZO, ITO: Cross-over wavelength as low as 1.2 µm
- Drude damping in GZO is slightly higher than that in AZO and lower than that in ITO

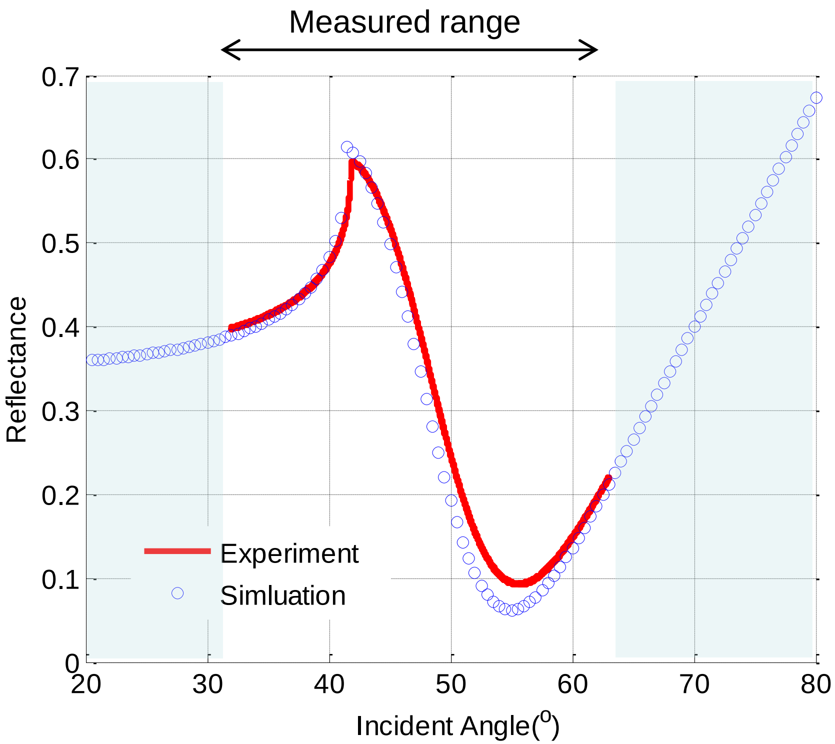
G.V. Naik, J. Kim and A. Boltasseva, *Optical Mater. Exp.* 1 (2011) 1090

TCOs COMPARED TO GOLD/SILVER



SPPs ON GZO FILMS at 1.55um





- GZO is deposited onto glass prism.
- ε_{GZO}=-2.12+1.2i (at 1.55um)
- Angular reflectance shows dip at angles corresponding to excitation of SPPs

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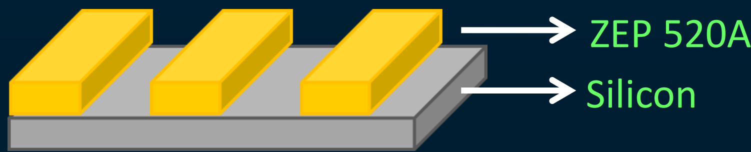
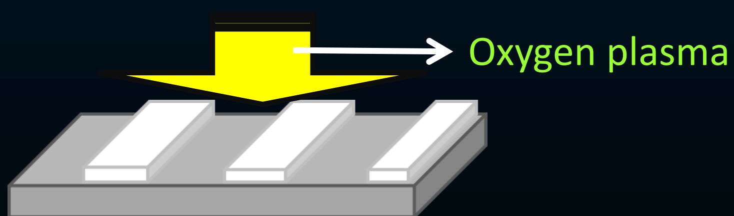
NEXT STEP: PATTERNING



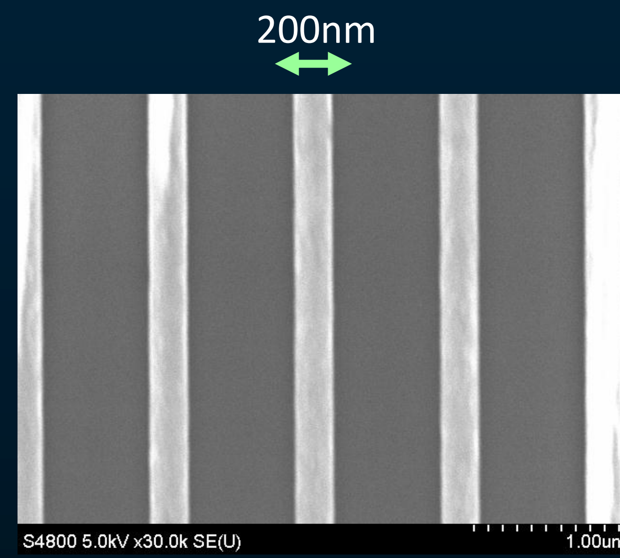
Patterning ZEP 520A using E-beam lithography

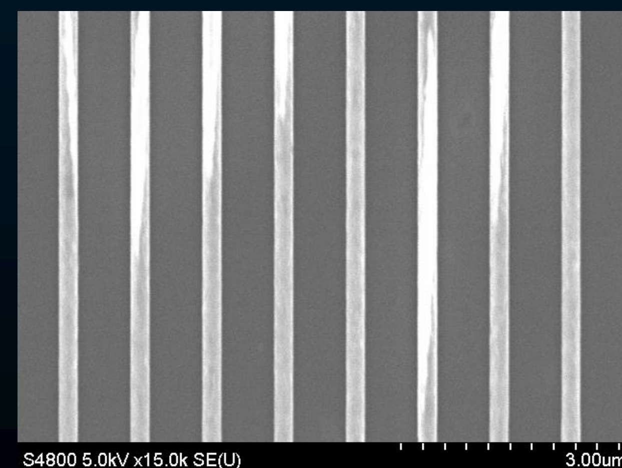
Depositing GZO thin film onto patterned ZEP 520A

Lift-off ZEP 520A by soaking in ZDMAC

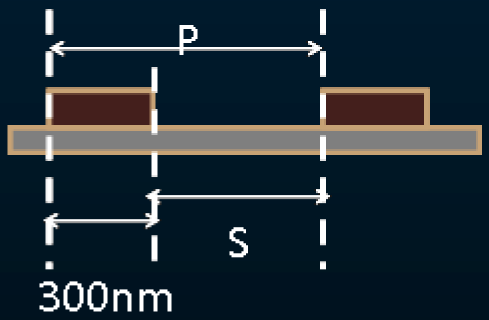


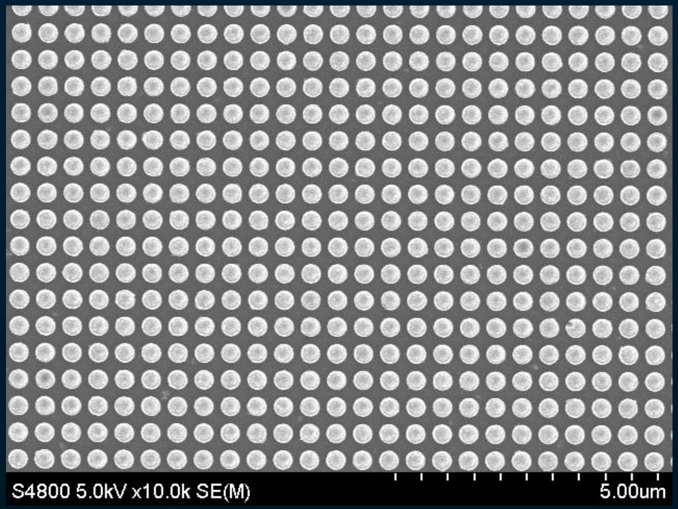
Removing residual ZEP 520A and cleaning a surface with oxygen plasma

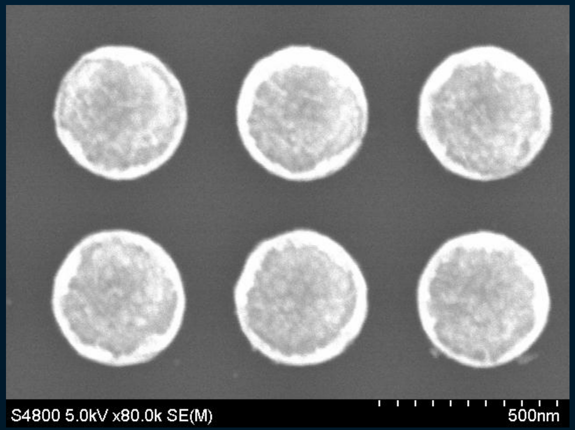




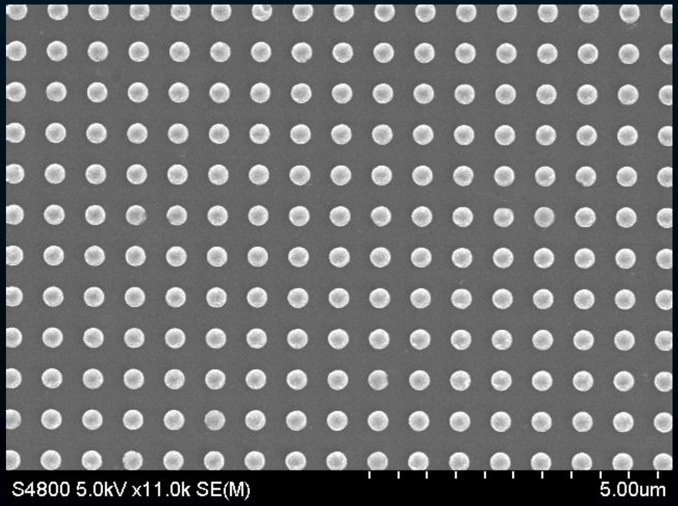
TCO LSPR STRUCTURES FABRICATION

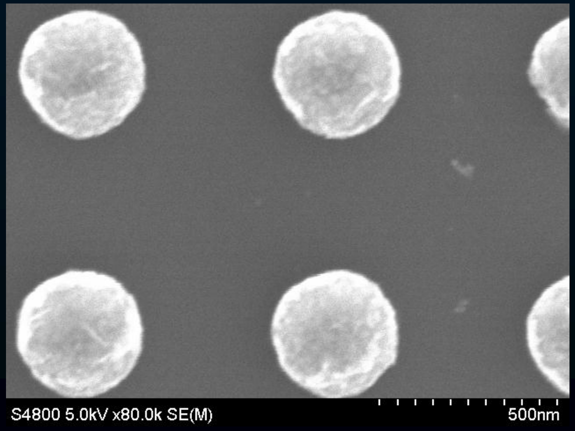






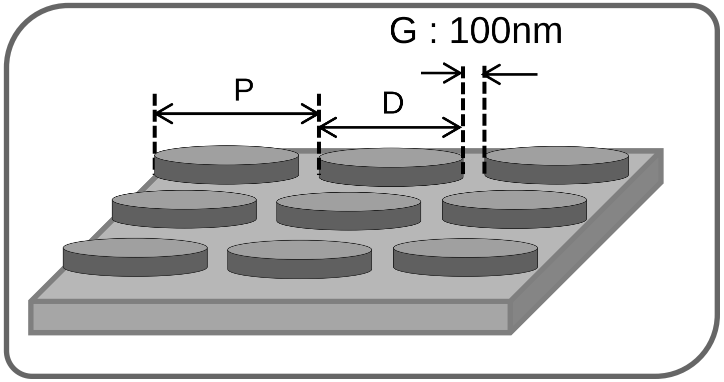
P : 500nm, S : 200nm

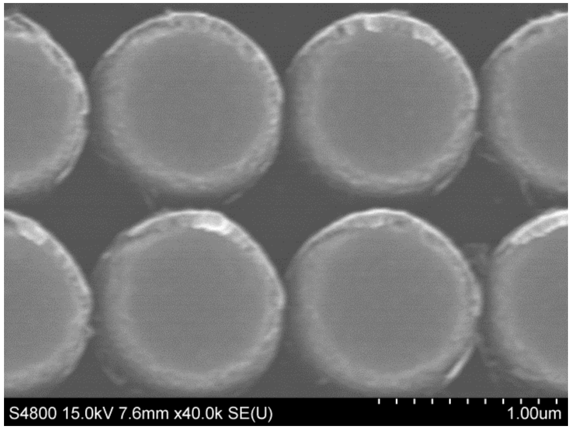


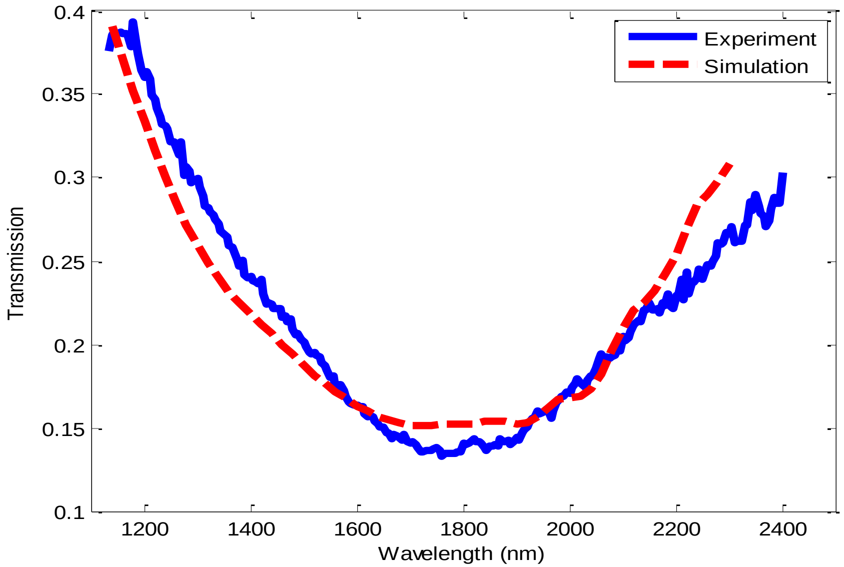


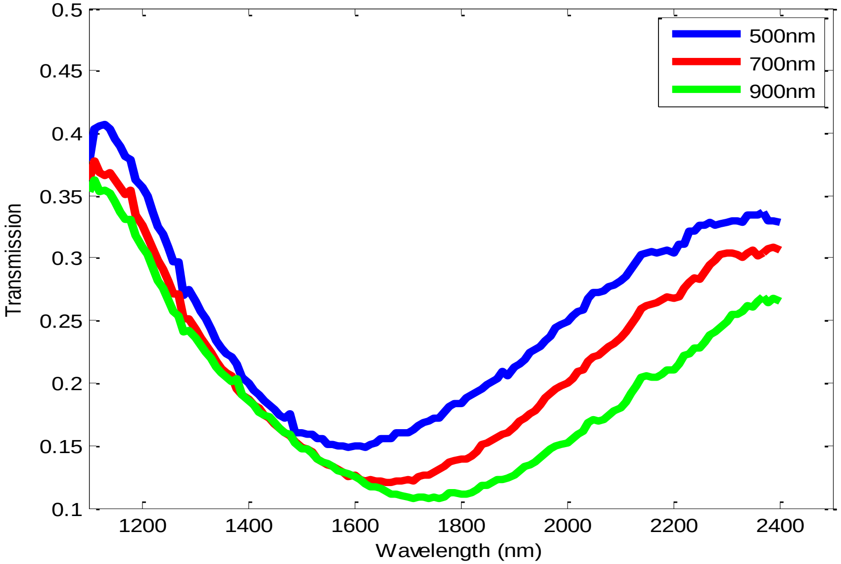
P : 700nm, S : 400nm

TCO LSPR STRUCTURES



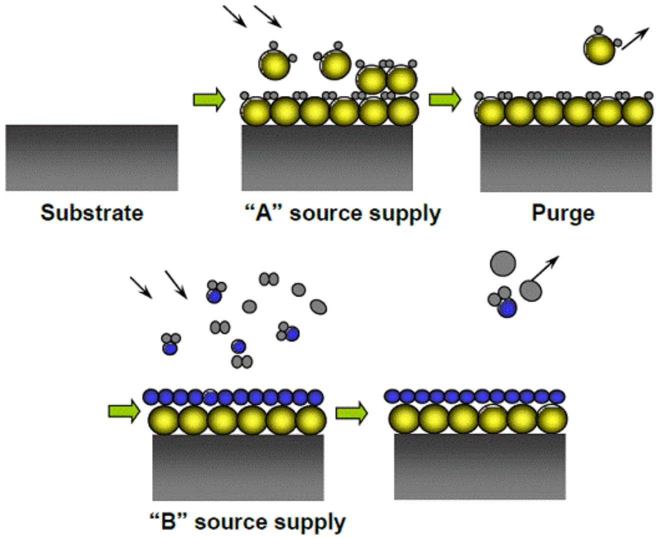






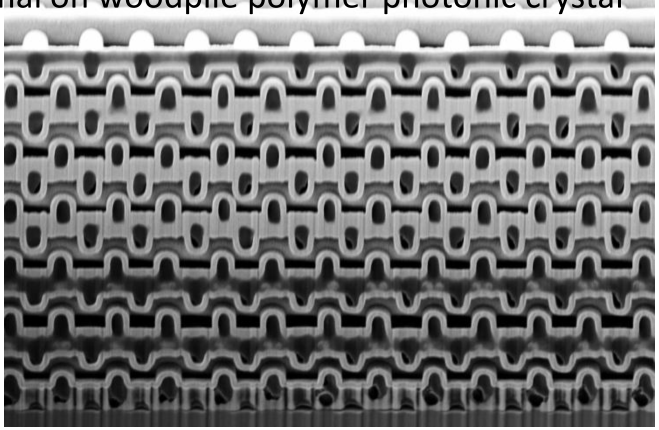
ATOMIC-LAYER-DEPOSITION OF AZO

- Diethyl zinc and oxygen as precursors to deposit ZnO
- Al or Ti dopants are introduced during deposition
- Smallest cross-over wavelength: 1.6 µm
- Drude-damping loss ≈ 0.2 eV
- Smooth films: rms roughness ~ 0.59 nm



Courtesy: Google images

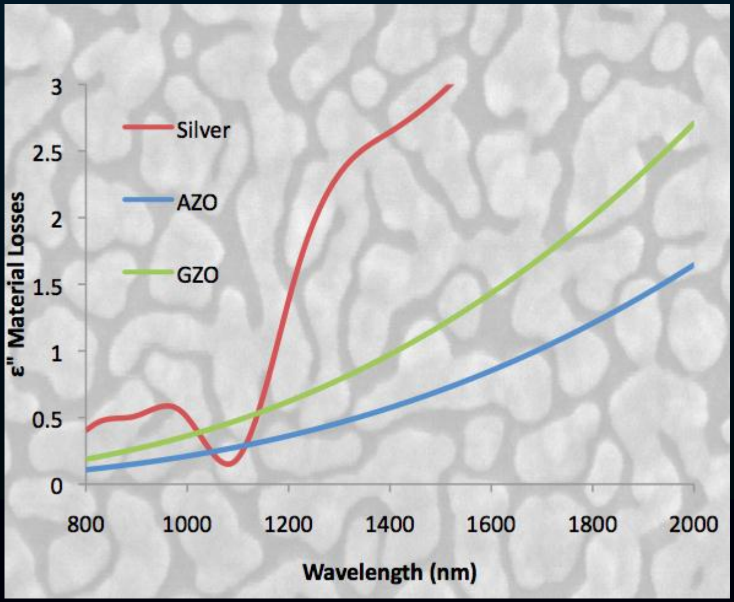
conformal on woodpile polymer photonic crystal



A. Frolich and M. Wegener, *Optical Mater. Exp.* 1 (2011) 883

OUTLINE

- Introduction: Challenges with Gold and Silver
- Material Requirements: Plasmonics & Metamaterials
- Alternative Materials?
- Transparent Conducting Oxides
- **Transition Metal Nitrides**
- Figures of Merit
- What is the Right Choice?
- Outlook



METALS TO 'LESS-METALS'

- Reduce carrier concentration:
  Mixing them with non-metals ⇒

  Intermetallics

  Ceramics

  - Silicides
  - Germanides
  - Borides
  - Nitrides
  - Oxides
  - Metallic alloys

A. Boltasseva and H.A. Atwater, Science 331 (2011)

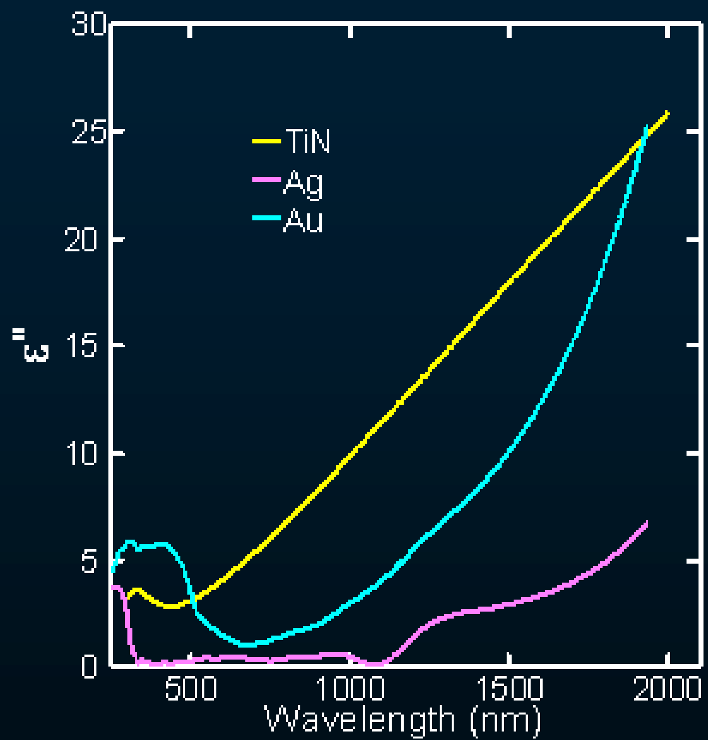
TITANIUM NITRIDE

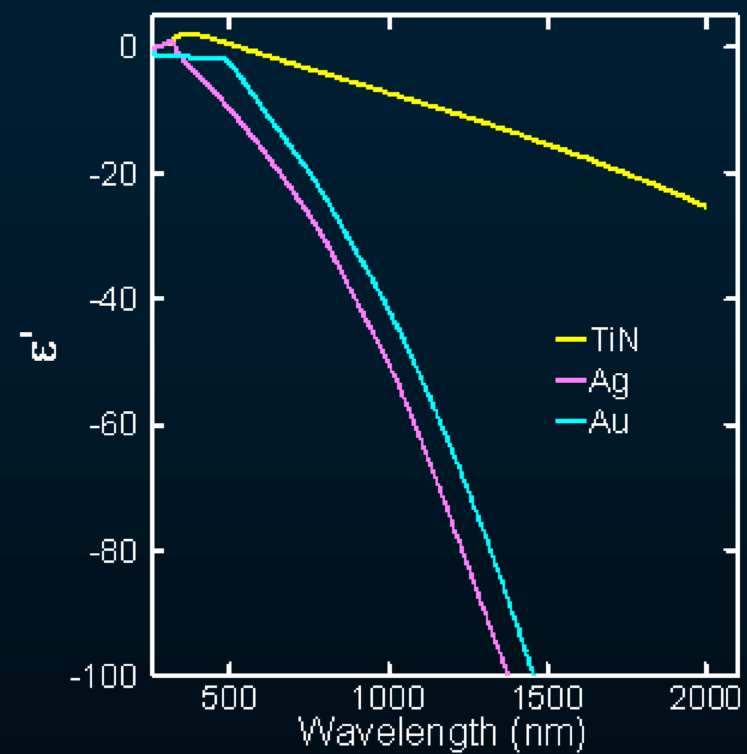
- Metallic: Golden luster
- Hard & tough: high speed drill-bits
- Deposition: CVD, sputtering, evaporation…

CMOS COMPATIBLE

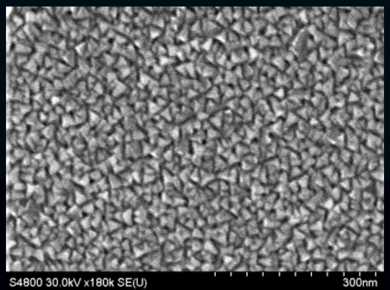
TITANIUM NITRIDE

TiN comparison with Ag and Au



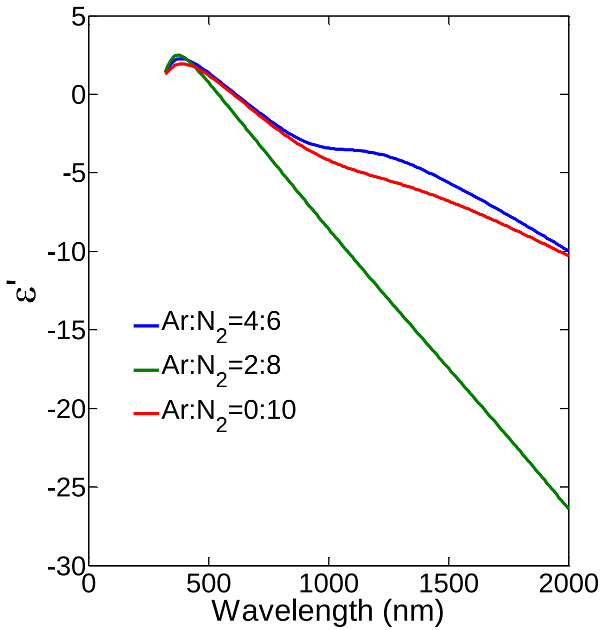


Crystalline TiN on c-Sapphire
(rms roughness 0.5 nm)

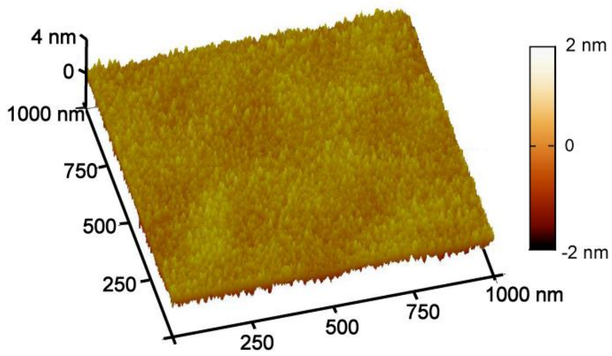


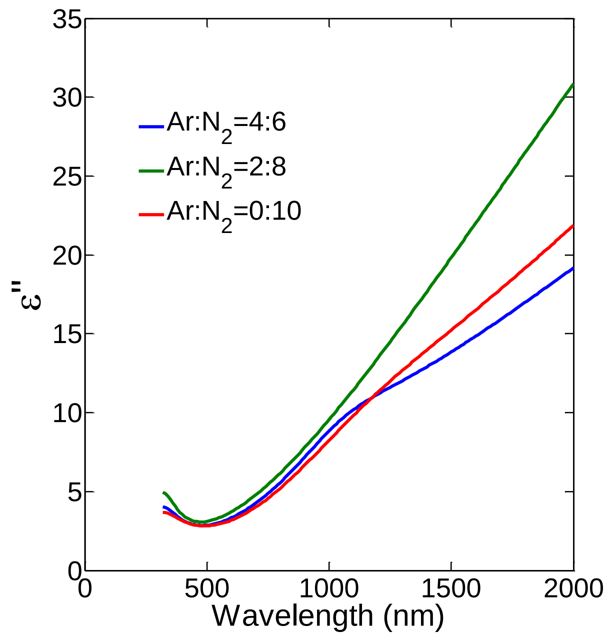
G.V. Naik *et al.*, Optical Materials Express 2 (2012) p. 478

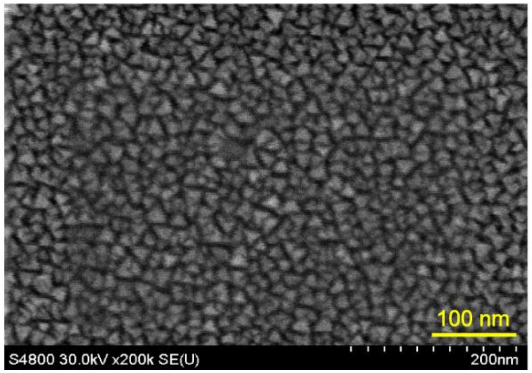
TITANIUM NITRIDE: OPTIMIZATION



Changing optical properties

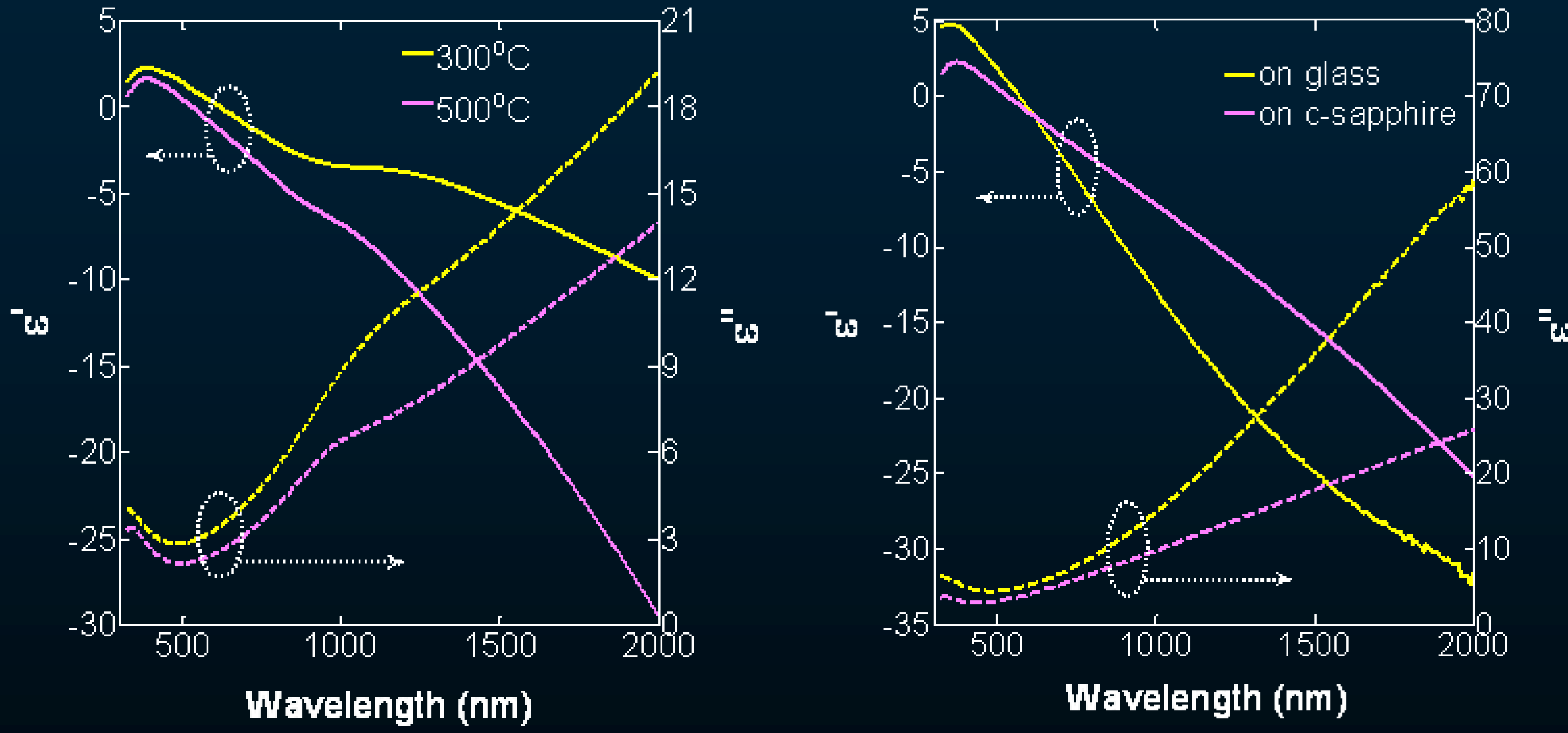






Ultra-thin and smooth films; epitaxial growth

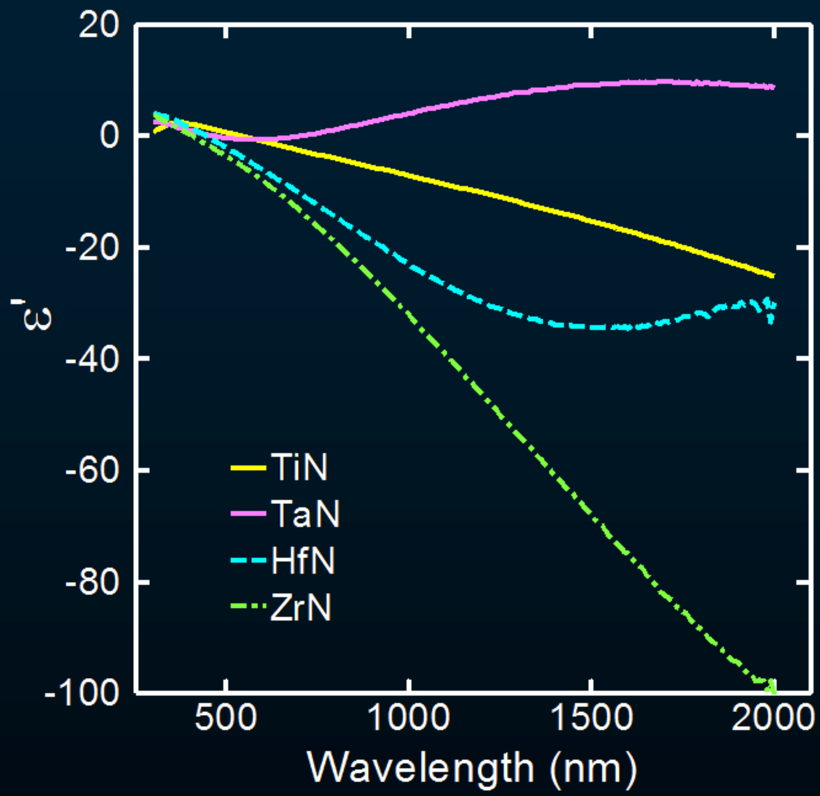
TITANIUM NITRIDE

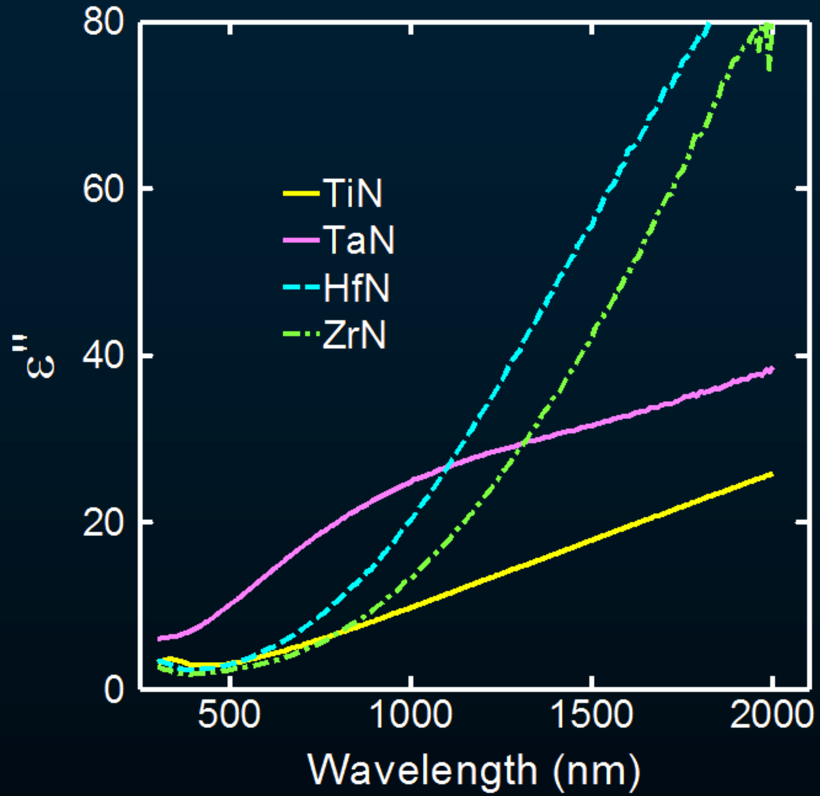


- TiN films deposited at 300$^o C$ and 500$^o C$ (left)
- TiN films deposited on different substrates (right)
- The films were deposited with the flow ratio of Ar and N set to 4:6

G.V. Naik *et al.*, Optical Materials Express **2** (2012) p. 478

OTHER METAL NITRIDES

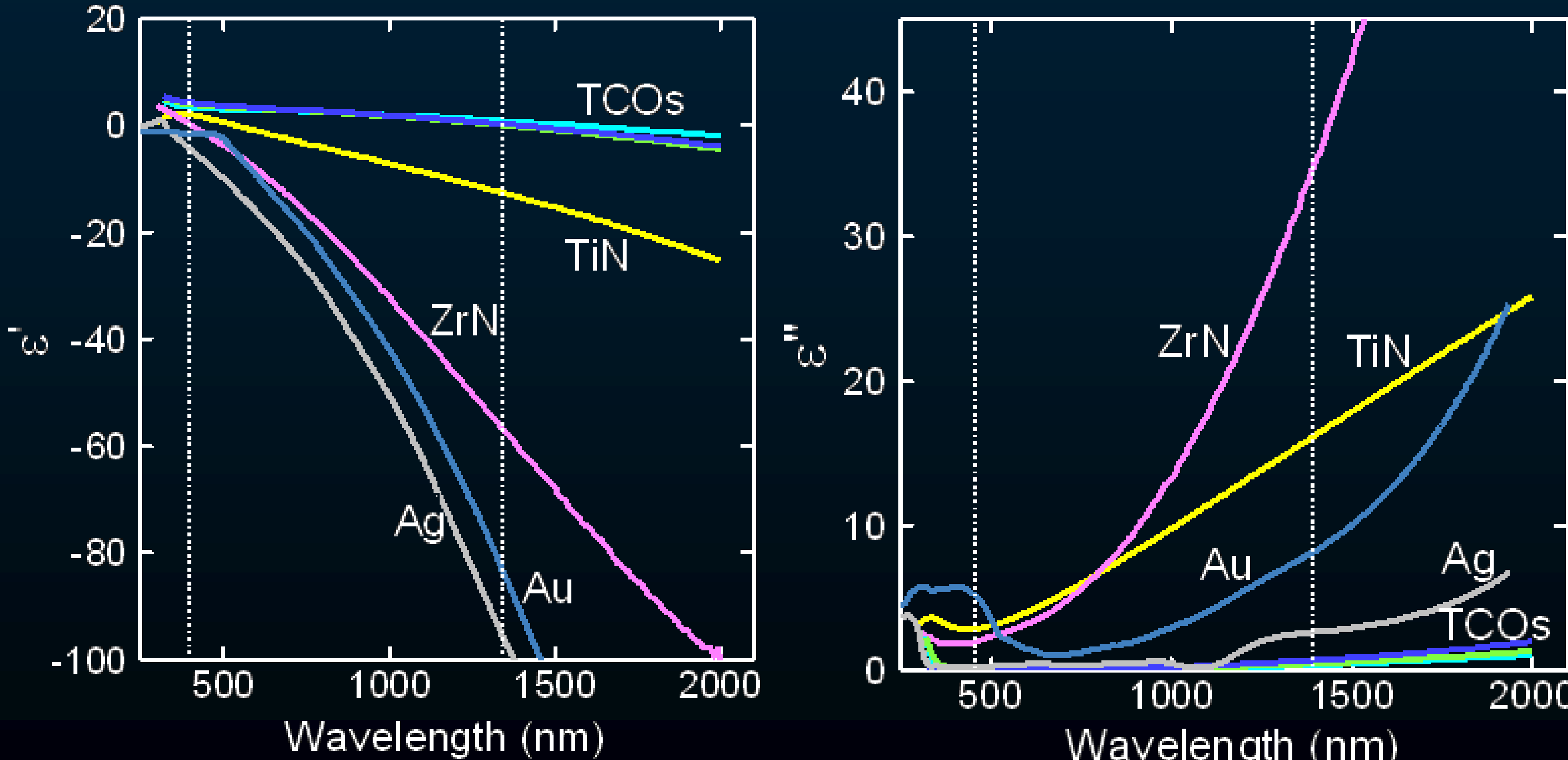




G.V. Naik, J. Kim and A. Boltasseva, *Optical Mater. Exp.* 1 (2011) 1090

COMPARISON WITH SILVER/GOLD

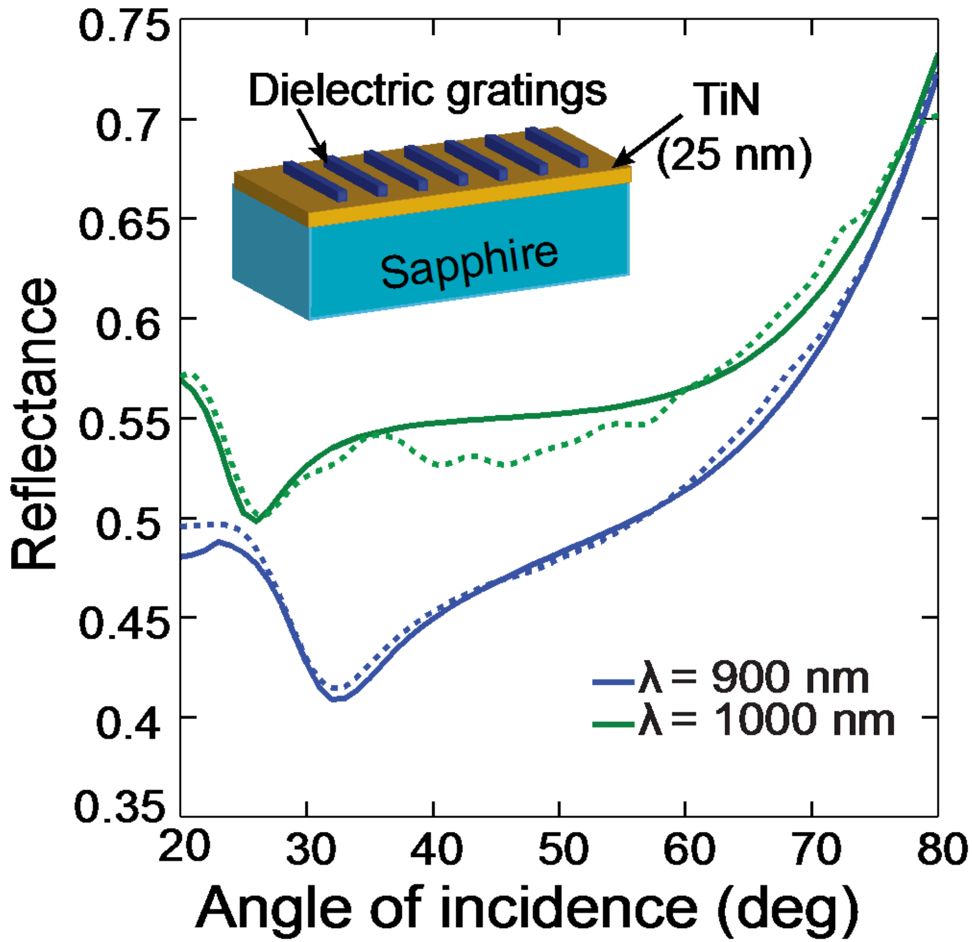
TaN, HfN, ZrN also exhibit metallic properties in the visible!



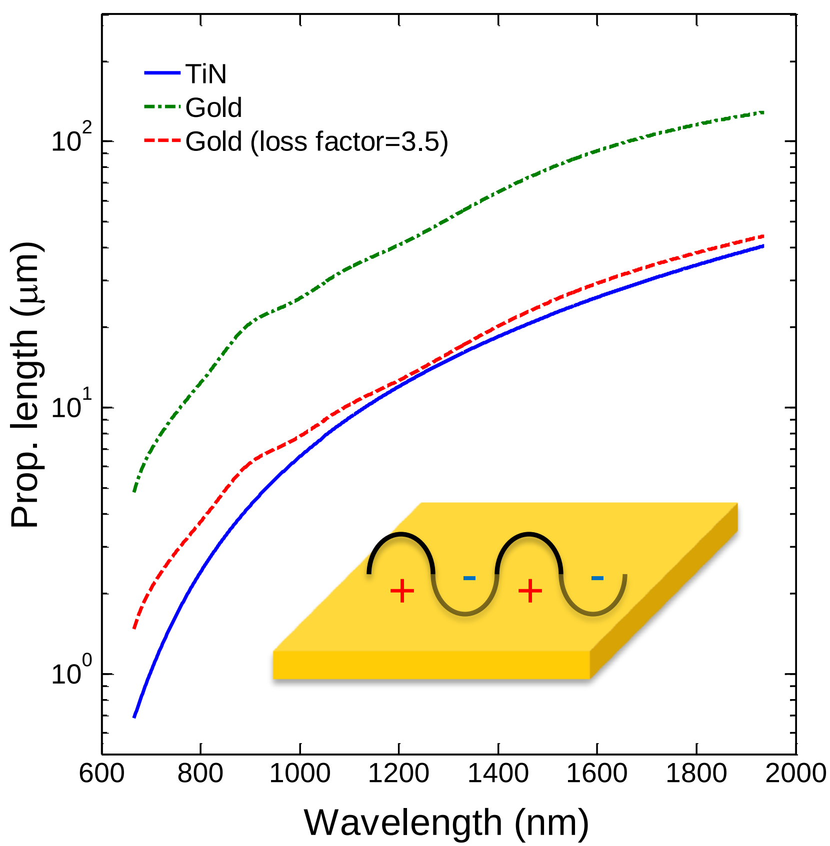
G.V. Naik, J. Kim and A. Boltasseva, *Optical Mater. Exp.* 1 (2011) 1090

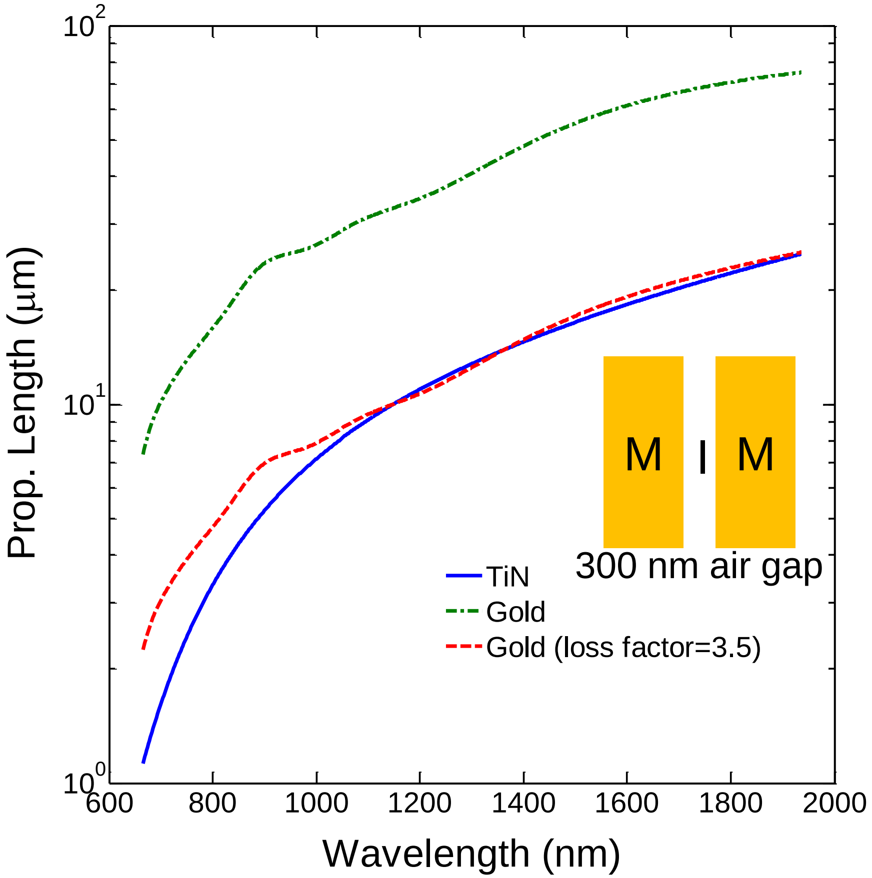
SPP ON TiN FILM

- Dielectric gratings are used to couple SPPs
- Electron-beam resist is patterned into gratings on top of 25 nm thin TiN film
- Angular reflectance shows dip at angles corresponding to excitation of SPPs



SPPs ON TiN FILM





G.V. Naik *et al.*, Optical Materials Express 2 (2012) p. 478

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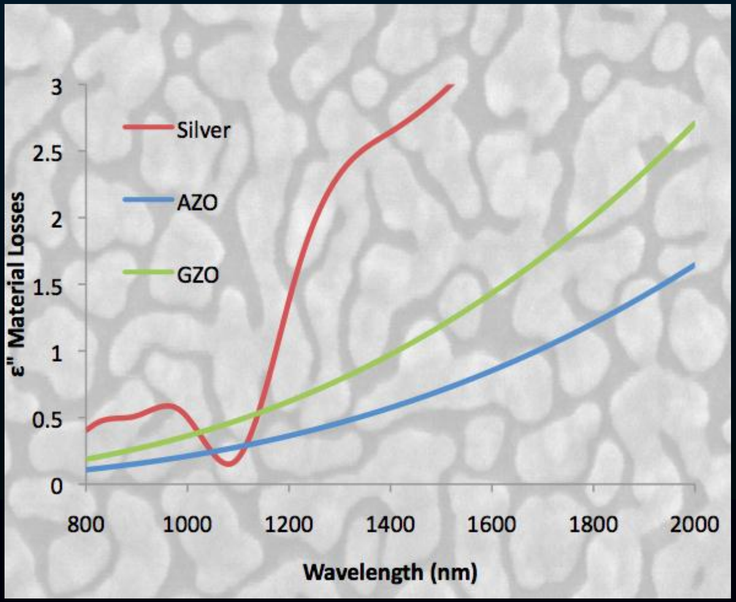

QUALITY FACTORS

- **Im(ε) = ε'' is a necessary indicator of performance *but***
- **Re(ε) = ε' is also important** in quantifying the overall material quality in devices

Metrics/Figures-of-Merit/Quality Factors

are to be estimated for each

- Material
- Application
- Wavelength range…

QUALITY FACTOR FOR SP

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LSPR and SPR systems: Local-field enhancement

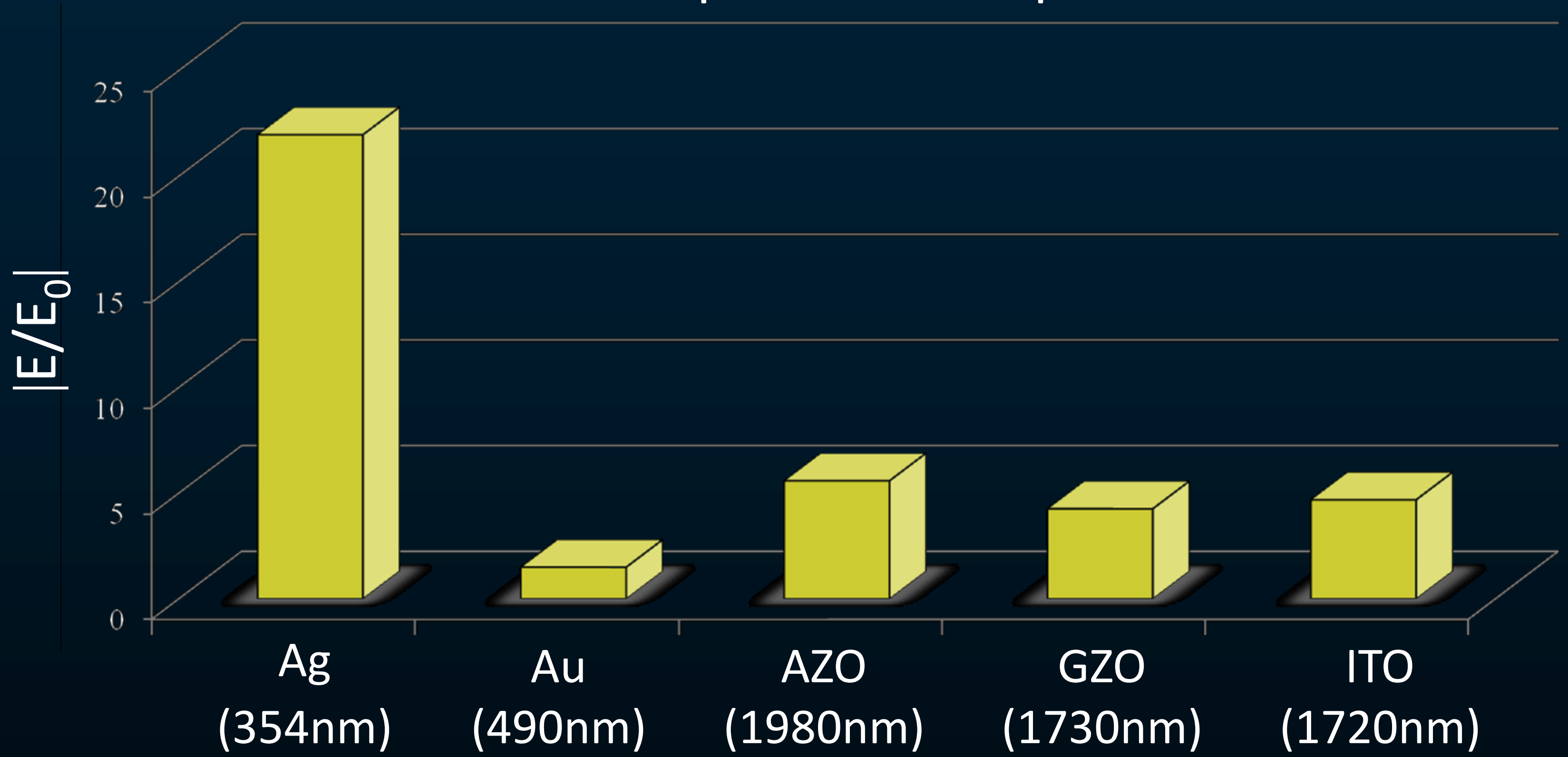
Q_{LSPR} = (Enhanced local-field)/(Incident field)
(depends on the shape)

$$Q_{\mathrm{LSPR}}(\omega)=\frac{-\varepsilon'(\omega)}{\varepsilon''(\omega)}$$

(sphere)

COMPARISON: LSPR

LSPR field enhancement for spherical nanoparticles in air



LSPR occurs at $\varepsilon_{metal}' = -2\varepsilon_{dielectric}$ (dipolar):

- Cannot be satisfied in Ag and Au in NIR
- Need other geometries (core-shells): more challenging to fabricate
- TCOs produce strong LSPR in the near and farther IR

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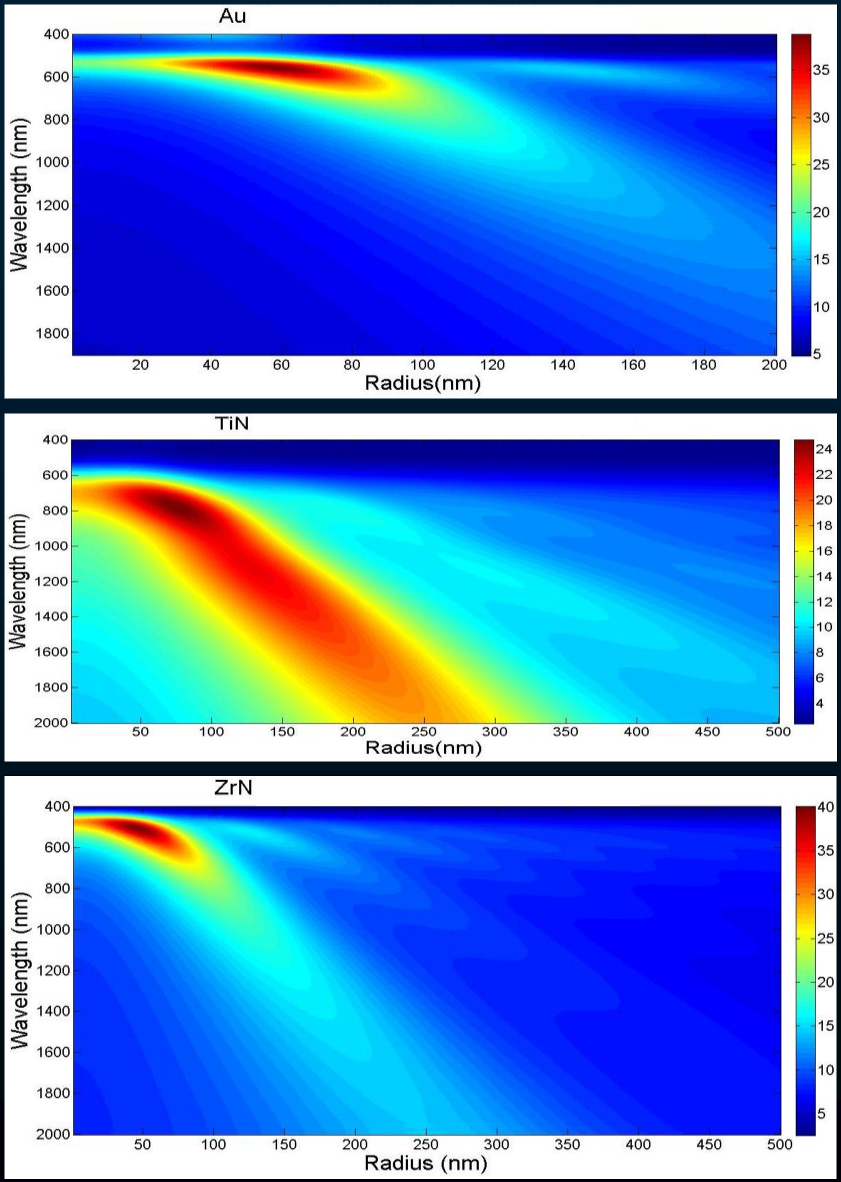
COMPARISON: LSPR

- Field enhancement of metal nanospheres at the surface calculated using Mie theory
- ZrN and TiN nanospheres: Field enhancement comparable to that of Au
- TiN has good performance over broadband in the visible and near-IR

near field intensity enhancement

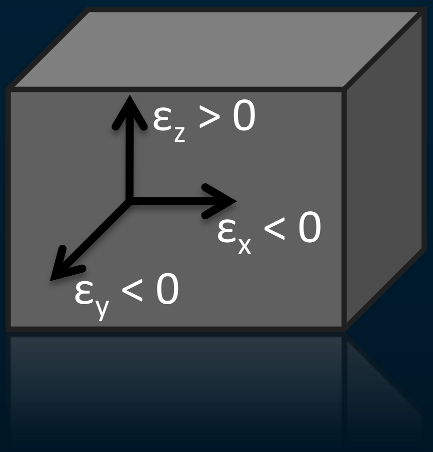


U. Guler *et al.*, Appl. Phys. B , DOI:10.1007/s00340-012-4955-3

HYPERBOLIC METAMATERIALS

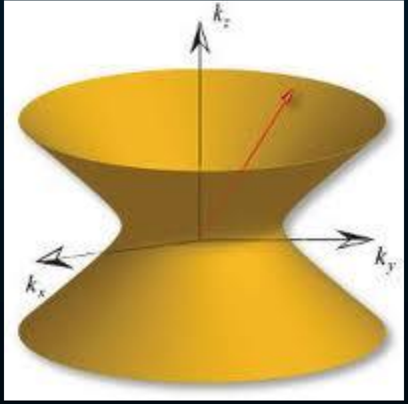
Extremely anisotropic materials

- Extremely large effective index
- Extremely high photonic density of states



Applications

- Quantum optics with metamaterials
- Tailor mechanical, thermal and electromagnetic properties for interesting physics and devices



Designing a material which is metallic in one direction but dielectric in the another

D.R. Smith and D. Schurig, Phys. Rev. Lett. **90** (2003); V.A. Podolskiy and E.E.Narimanov, Phys. Rev. B **71** (2005); C. L. Cortes et al., arXiv:1204.5529v1 (2012); E.E. Narimanov and I.I. Smolyaninov, arXiv:1109.5444v1 (2011).

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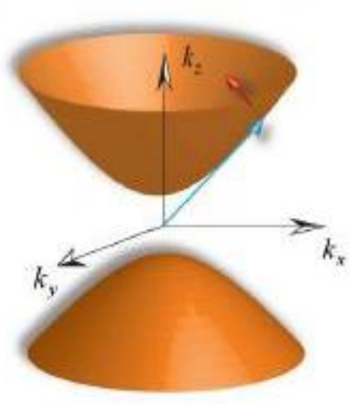
HYPERBOLIC METAMATERIALS

A metamaterial has hyperbolic dispersion relation



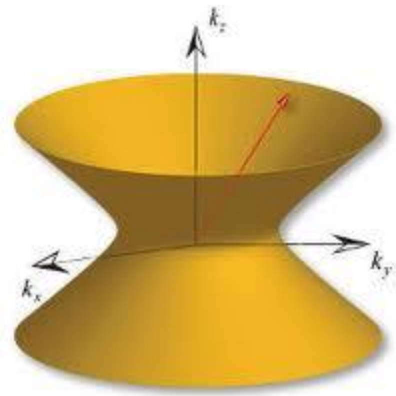
Hyperbolic dispersion

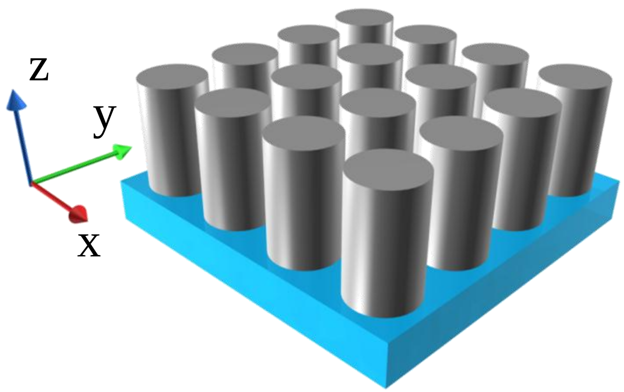
$\varepsilon_{x,y} > 0$; $\varepsilon_z < 0$

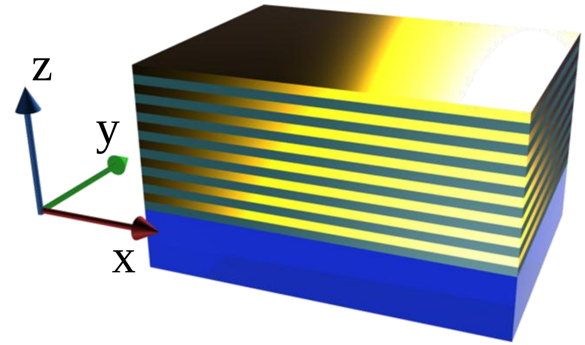
Transverse positive

$\varepsilon_{x,y} < 0$; $\varepsilon_z > 0$

Transverse negative







C. L. Cortes et al., arXiv:1204.5529v1 (2012) (Z. Jacob group)

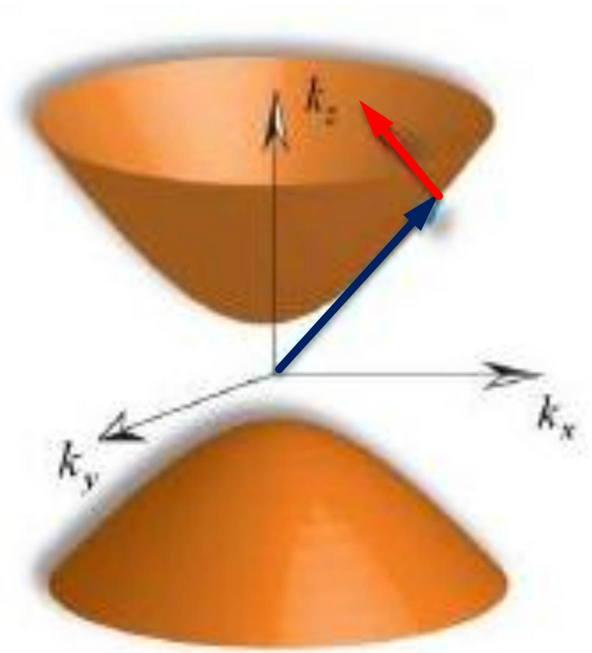
NEGATIVE REFRACTION IN HMMs

- Only transverse-positive HMM can exhibit negative refraction.
- Only transverse-positive HMM produces measurable transmission.
- Only transverse-positive HMM can produce hyperlensing.
- Figure-of-merit[1]: $\mathrm{Re}\{\beta_z\}/\mathrm{Im}\{\beta_z\}$

[1]A. Hoffman et. al, Nature Materials **6** (2007);

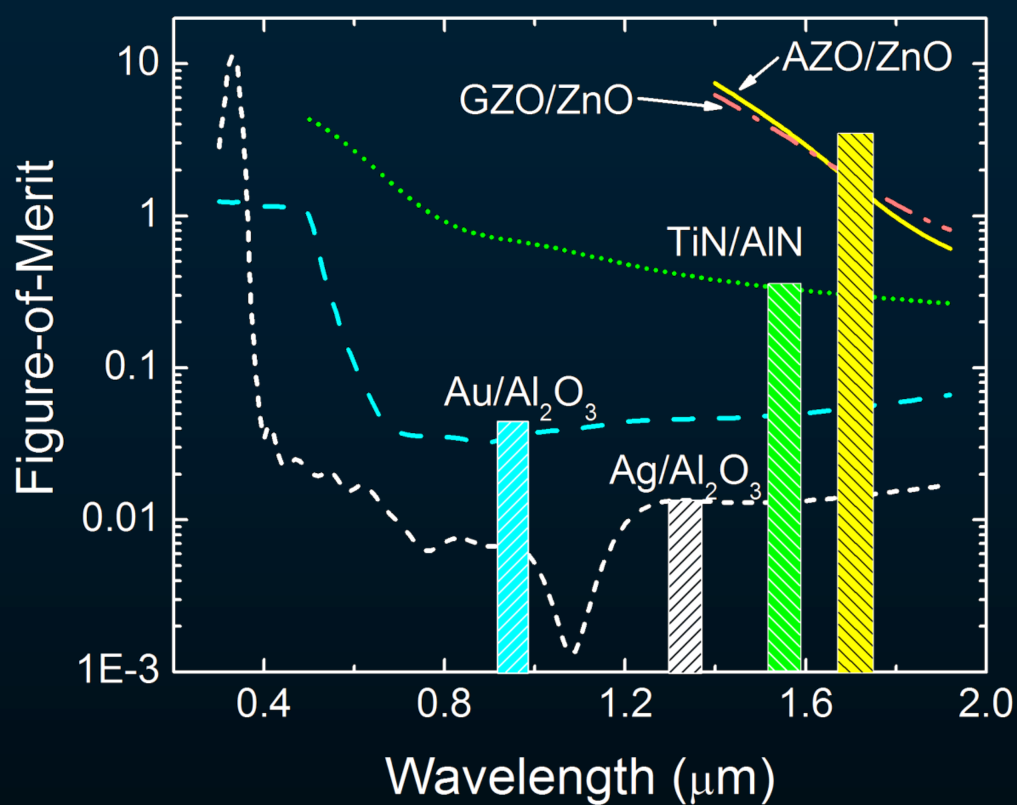
$\varepsilon_{x,y} > 0$; $\varepsilon_z < 0$

Transverse positive



Z. Jacob and V.M. Shalaev, Science **334** (2011)

HMM PERFORMANCE: TCOs / NITRIDES



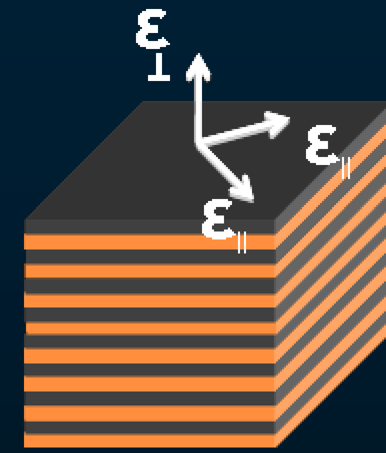


Figure-of-Merit = $Re\{\beta_\perp\} / Im\{\beta_\perp\}$

$\beta_\perp$ – propagation vector in $\perp$ - direction

Polycrystalline AZO/ZnO, single crystal AZO/ZnO, Au/Al_2O_3 and Ag/Al_2O_3

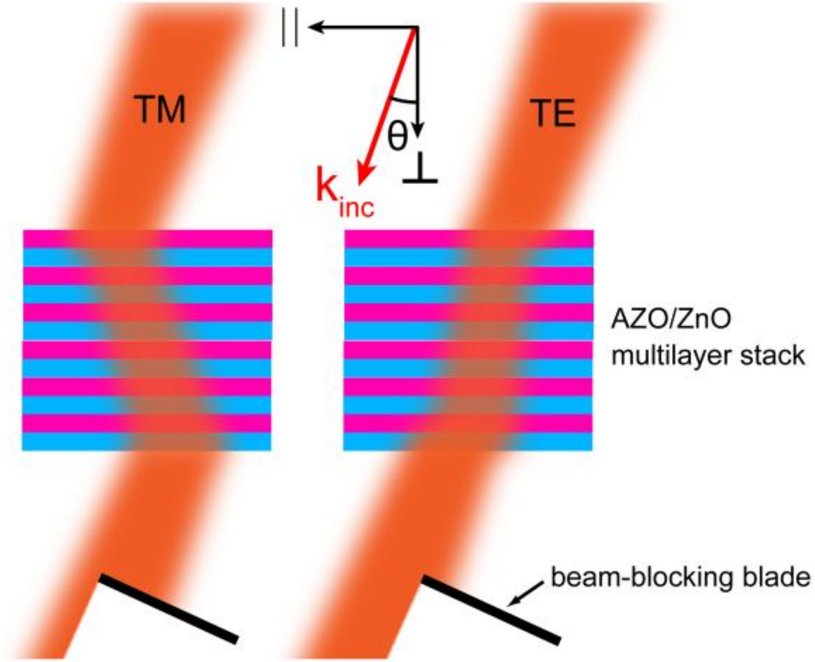
AZO/ZnO - Figure-of-Merit of 11 at 1.8 μm

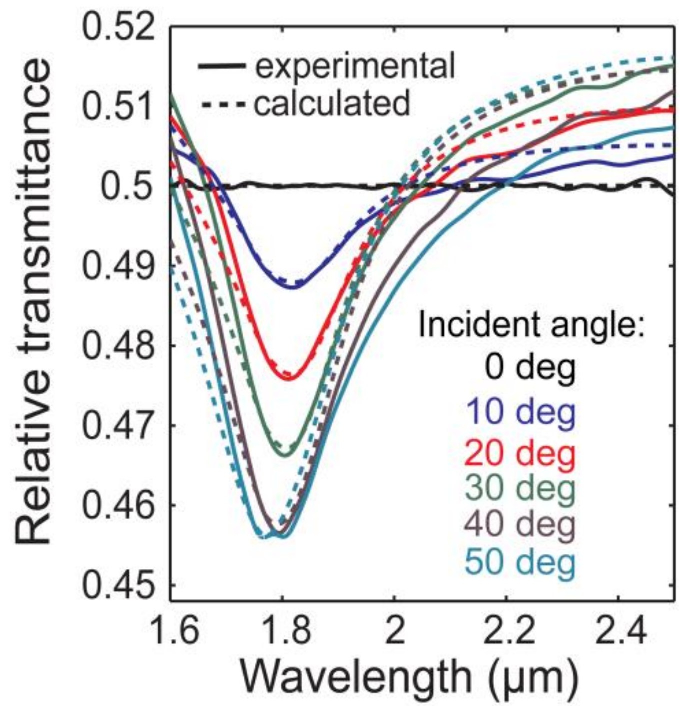
G.V. Naik and A. Boltasseva, SPIE Newsroom (2012)

G.V. Naik and A. Boltasseva, *Metamaterials* 5 (2011) 1-7

A. Hoffmann *et al.*, *Nat. Mater.* 6 (2007) 946

NEGATIVE REFRACTION EXPERIMENT





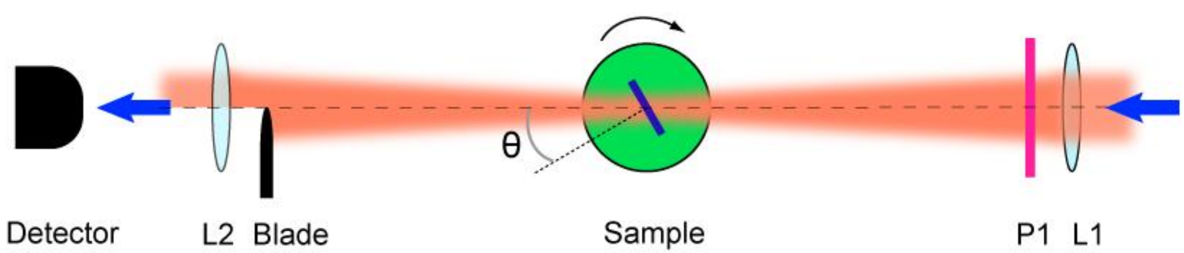


Figure-of-merit (FoM) : 11
at 1.8 μm wavelength
Highest FoM demonstrated
in NIR

G.V. Naik, J. Liu, A.V. Kildishev, V.M. Shalaev and A. Boltasseva, Proc. Natl. Acad. Sci. (2012)

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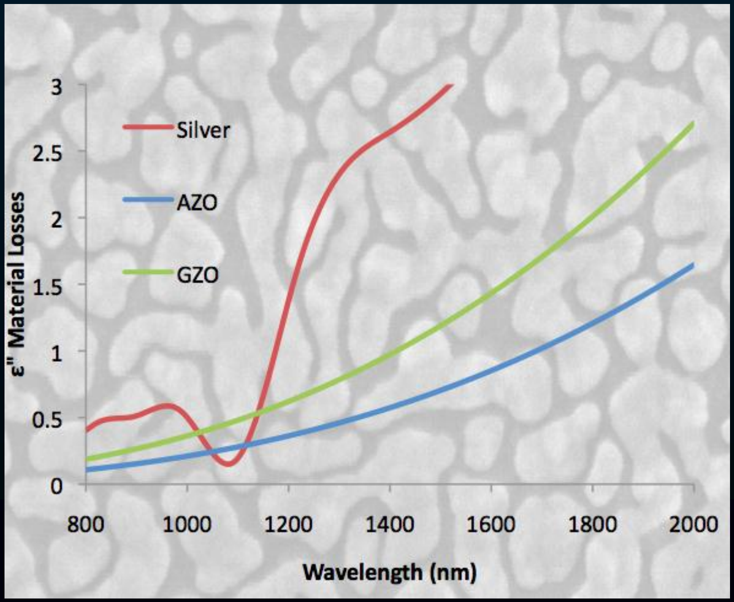

WHAT IS THE BEST MATERIAL FOR…

Applications

LSPR, SPPs & Waveguides, NIMs, TO, ENZ…

Materials

Noble Metals, Metal Nitrides, TCOs, Noble Alkali Alloys, Alkali Metals, Graphene, Other Metals…

What is the Best Plasmonic Material For…

	LSPR	SPPs & Waveguides	NIMs	TO	ENZ	Switchable MMs
Noble Metals	✓	✓	✓	✗	✗	✗
Transition Metal Nitrides	✗	✓	✗	✓	✗	✗
TCOs	✓	✗	✗	✓	✓	✓
Intermetallics	✗	✗	✗	✓	✓	✗
Alkali Metals	✓	✓	✓	✗	✗	✗
Graphene	✗	✗	✗	✗	✗	✓
Other Metals	✗	✗	✗	✗	✗	✗

MATERIAL CHOICES: OUTLOOK

- Infrared:
  - Silicides, Germanides, GaAs, SiC
- Near-infrared:
  - TCOs: AZO, GZO, ITO
  - Perovskites: Heavily doped barium tin oxide, strontium titanate, cadmium tellurium oxide, calcium titanate, strontium tin oxide
  - *Tune plasma frequency by doping*
  - *Great switching opportunities*
- Visible:
  - Intermetallics: Silicides, Germanides, Nitrides…
  - Titanium nitride, tantalum nitride

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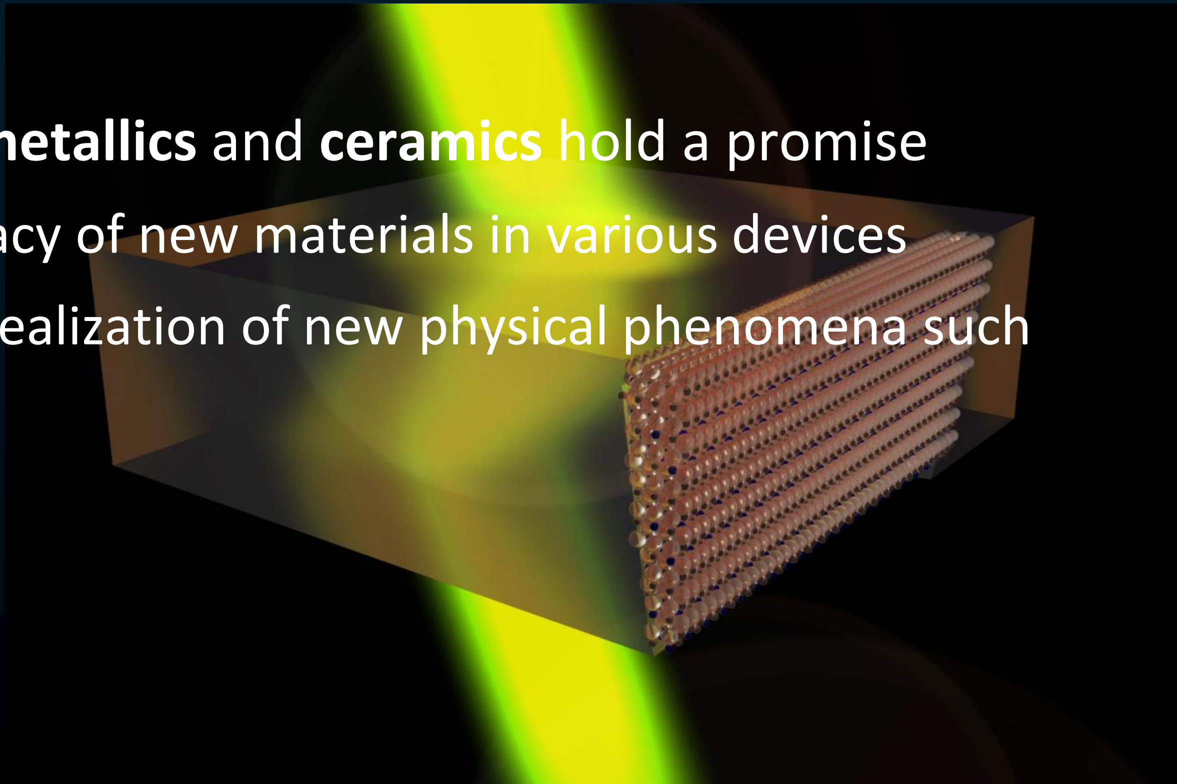
SUMMARY

- There is not a single choice for the best low-loss plasmonic material for all applications and all wavelength
- **At 1.5-μm TCOs** (**AZO, ITO, GZO**) may be the best materials for **TO devices** and **NIR applications** providing low loss and not that negative ε'
- At **visible** range **intermetallics** and **ceramics** hold a promise
- Demonstration of efficacy of new materials in various devices
- New materials enable realization of new physical phenomena such as ENZ properties



PLASMONIC MATERIALS RESEARCH

- Laser & Photonics Reviews 4, 795–808 (2010)
- Phys. Status Solidi RRL 4, 295–297 (2010)
- Metamaterials 5, 1–7 (2011)
- Science 331, 290 (2011)
- Optical Materials Express 1 (6), 1090–1099 (2011) MM and Plasmonics Focus Issue, Invited
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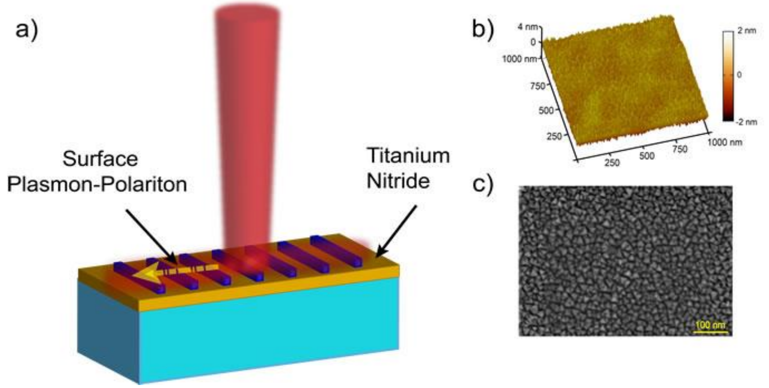

OSA press release March 27, 2012

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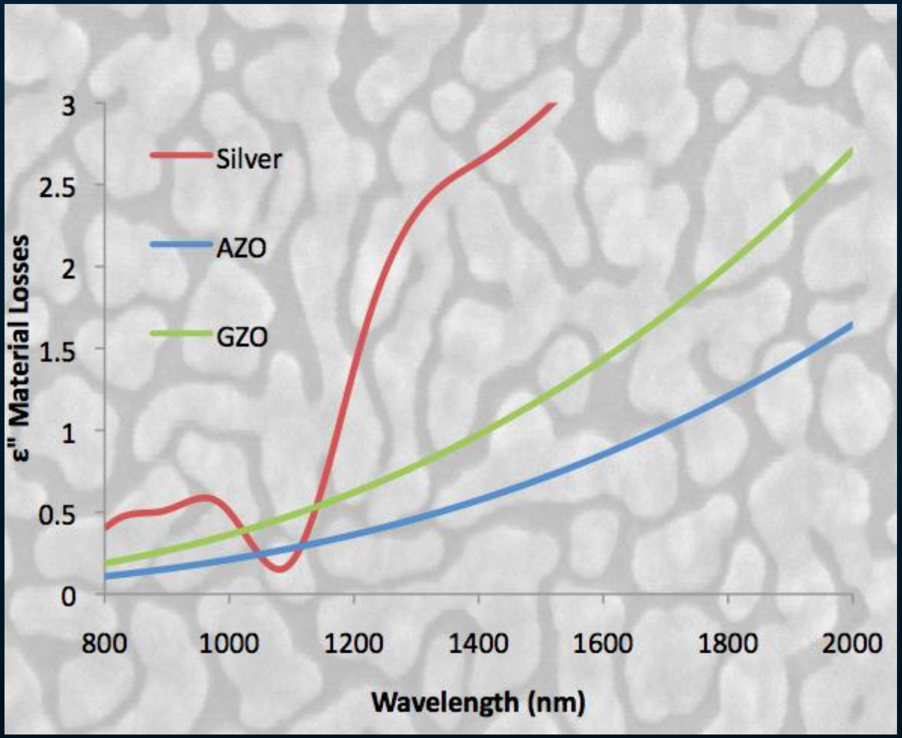

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