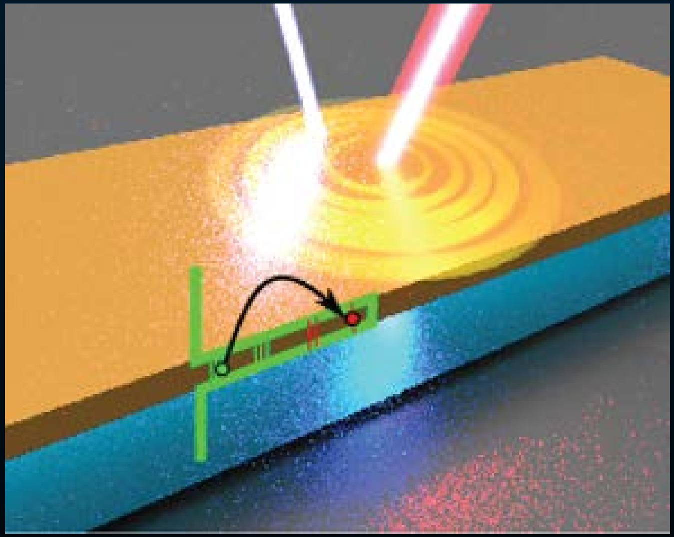
Emerging Materials for Nanophotonics and Plasmonics: Roads Ahead



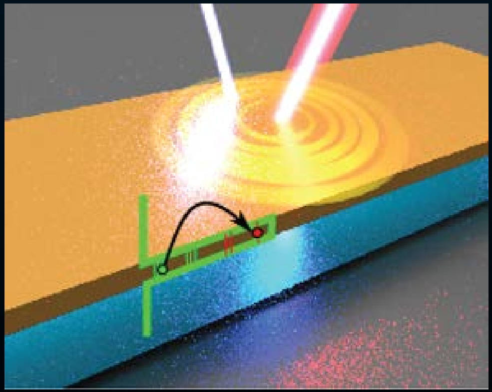
BUILDING NANOSCALE PHOTONIC TECHNOLOGIES OF THE FUTURE

Alexandra Boltasseva

School of Electrical & Computer Engineering
Birck Nanotechnology Center
PURDUE UNIVERSITY

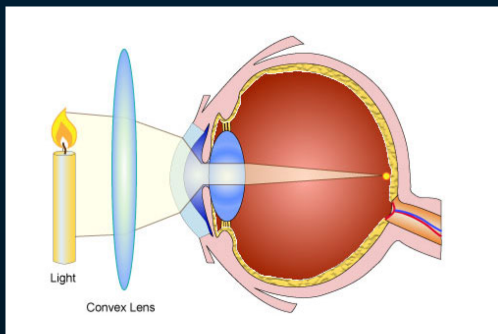
OUTLINE

- Plasmonics: Loss and Gain
- Expanding Materials Playground for Plasmonics and Nanophotonics
- Metal Nitrides
- Transparent Conducting Oxides
- Material Requirements: Tunability & T-Stability
- Ultra-Thin Plasmonic Metal Nitrides
- MXenes: Novel Quasi-2D Materials
- Outlook



BASIC LAWS OF OPTICS

Refraction

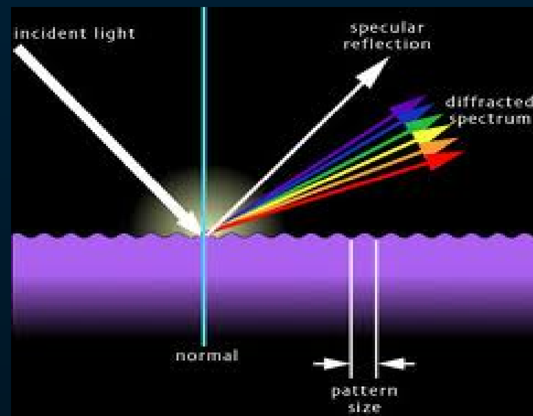


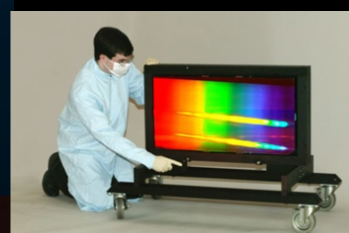
www.passmyexams.co.uk

asvus.it

http://eco-globe.com

Diffraction

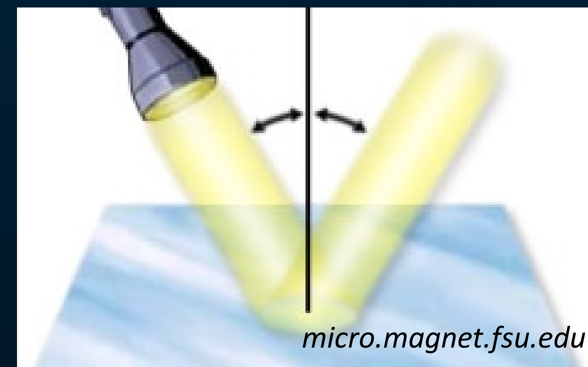




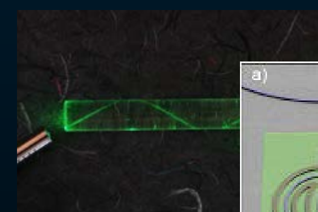
Wikipedia

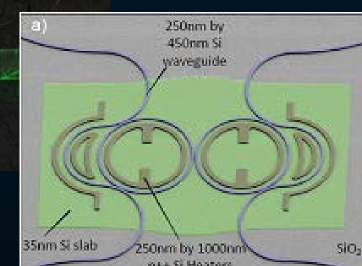
Wikipedia

Reflection



micro.magnet.fsu.edu





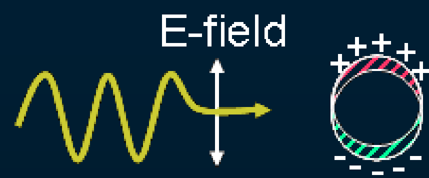
Lipson group

Wikipedia

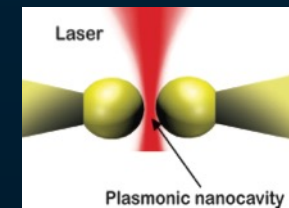
PLASMONICS/NANOPHOTONICS

- Localized Surface Plasmons = Optical Nano-Antenna (imaging, sensing, therapy, energy…)

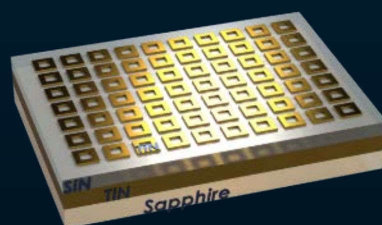
Free – electrons
Negative epsilon



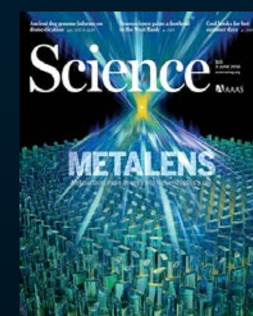

M. Mikkelsen

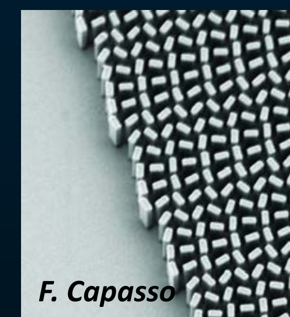


= Optical Metasurfaces/Metamaterials

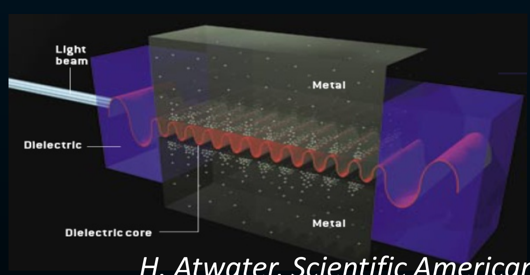



H. Harutyunyan

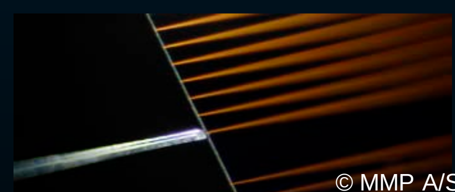


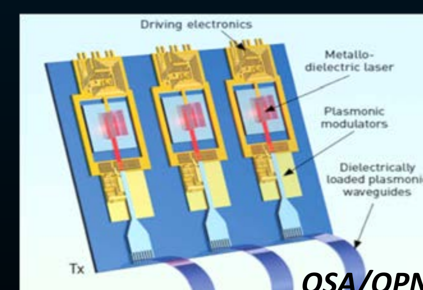

F. Capasso

- Propagating SP = Nano-Waveguide (on-chip photonics/optoelectronics, lab-on-a-chip…)



H. Atwater, Scientific American


© MMP A/S



OSA/OPN

- Epsilon-Near-Zero **= Enhanced nonlinearities, ultra-fast switching, tunnelling, etc**

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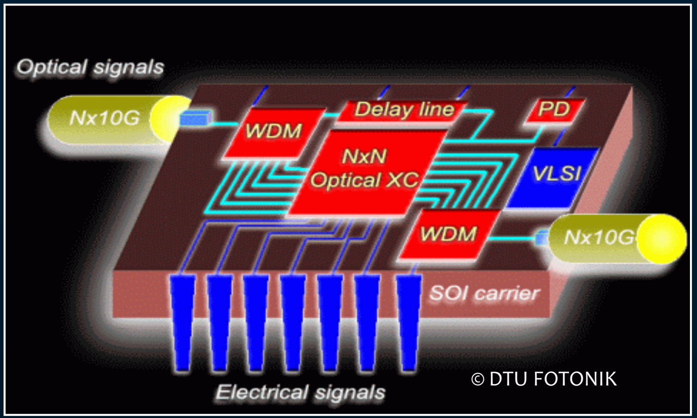
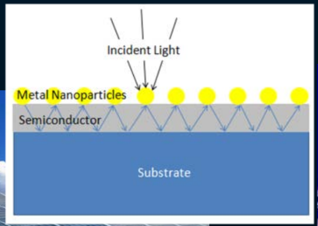
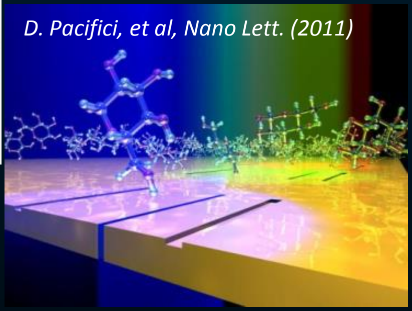
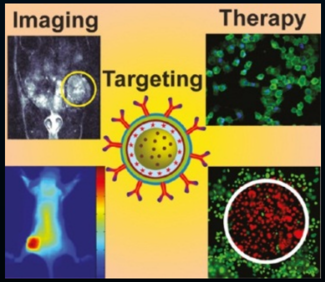
POTENTIAL TECHNOLOGY IMPACT

- On-chip optics/Hybrid photon./electronic circuits
- Sub-λ photodetectors
- Data recording/storage
- Single molecule sensors
- Medical/Drug delivery/Therapy
- Sub-λ imaging
- Optical nanolithography
- Optical nanotweezers
- Solar cells/PV
- Photo-catalysis
- Novel energy conversion schemes
- Quantum information technology









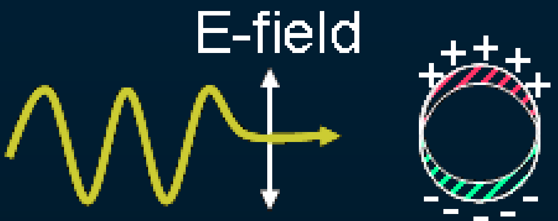
Images from Wikipedia

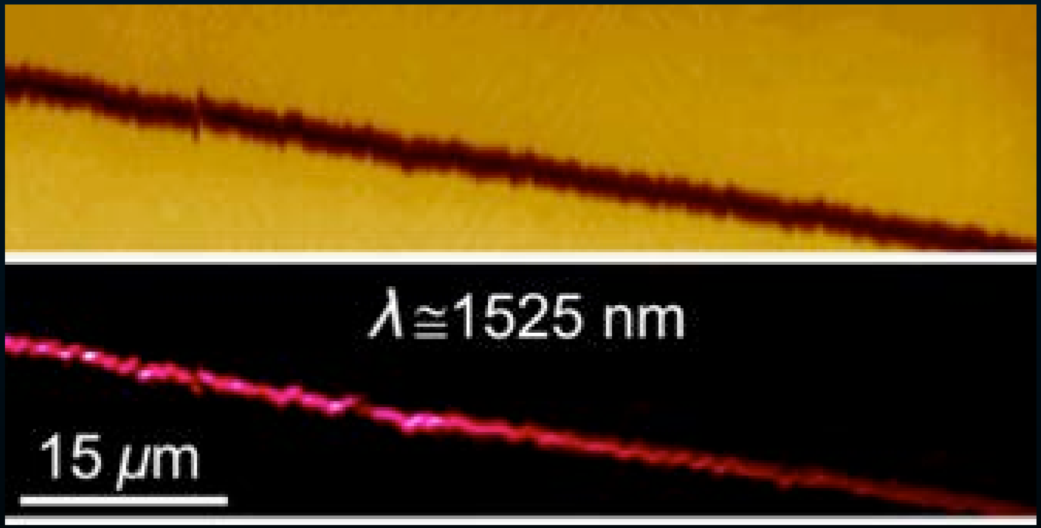
PLASMONICS & LOSS

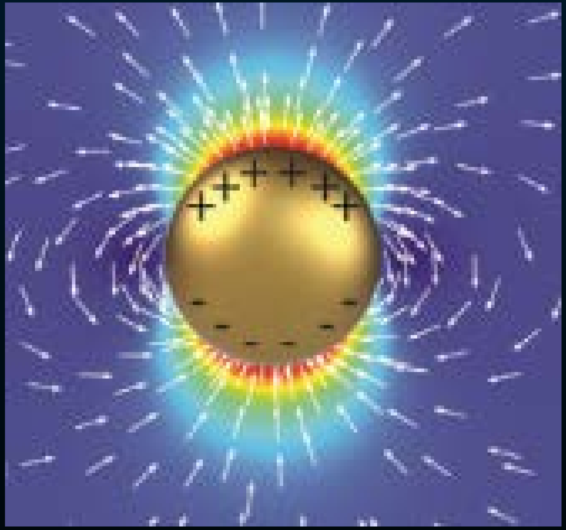
Plasmonic building blocks

NOBLE METALS:

- Much light is absorbed! (Ohmic loss)







LOSS CAN BE USEFUL!

APPLIED PHYSICS

Plasmonics–turning loss into gain

The optical losses usually associated with plasmonic materials could be used in applications

By Justus C. Ndukaife,[1,2] Vladimir M. Shalaev,[1] Alexandra Boltasseva[1]

The light-induced electronic excitations that occur at the surface of metals—plasmons—provide the extraordinary ability to confine electromagnetic energy to the subwavelength scale. Such extreme optical confinement can enhance the light-matter interaction and enable miniaturized optical and optoelectronic devices. However, this confinement requires that plasmonic materials possess free carriers, which unavoidably results in light being lost or absorbed in the system (*1*). This optical loss has hampered the realization of device designs with ultracompact, on-chip optical components and nanometer-scale resolution imaging. Because of the detrimental effects of plasmonic losses, several avenues are being explored to mitigate the high absorption, such as using gain to compensate for the losses, and synthesizing alternative low-loss plasmonic materials (*2*). Rather than continuing to pursue low-loss plasmonics approaches, we draw attention to the benefit of losses by high-

ILLUSTRATION: V. ALTOUNIAN/SCIENCE

334 22 JANUARY 2016 • VOL 351 ISSUE 6271 sciencemag.org SCIENCE

Published by AAAS

W. Li, J. Valentine "Harvesting the Loss: Surface Plasmon-Based Hot Electron Photodetection", Nanophoton. 7, 177, 2017
Ndukaife, Shalaev & Boltasseva. "Plasmonics: Turning Loss into Gain", *Science 351, 6271 (*2016)
See J. Khurgin regarding plasmonic losses
J. B. Khurgin and G. Sun, "In search of elusive lossless metal", APL 96, 181102 (2010)
J. B. Khurgin and A. Boltasseva, MRS Bulletin (2012)

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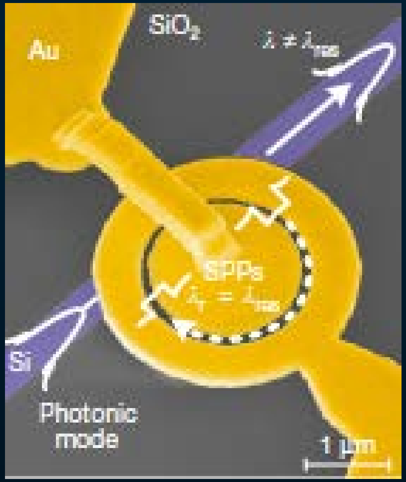
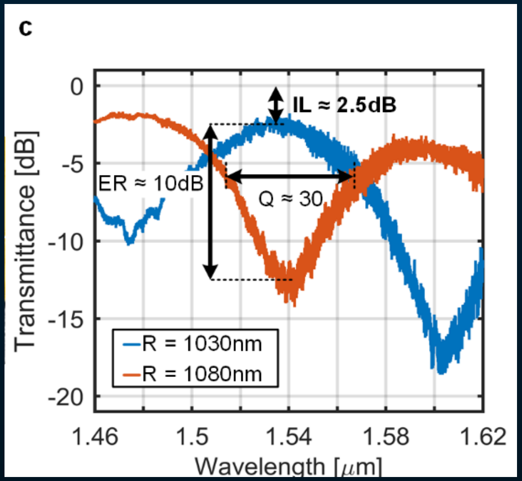
PLASMONICS FOR HYBRID ON-CHIP CIRCUITRY

Low-loss plasmon-assisted electro-optic modulator





SEM image of a plasmonic ring resonator and the corresponding transmittance

Operation

On State (non-resonant)

- Light passes through the WG

Off State (resonant)

- OEO changes refractive index under applied voltage
- Light couples into resonator

Si waveguide mode couple SURFACE PLASMON when **LOSS is ON**!

COMPACT (footprint of a few square micrometres)

HIGH SPEED (> 100 GHz) and LOW LOSS (< 3 dB)

C. Haffner, et al., *Nature* (April 26, 2018)

In collaboration with ETH, J. Leuthold , VCU, N. Kinsey, & U Wash

Plasmonic circuitry:

Berini, Bozhevolnyi, Zhang, Brongersma, Atwater, Zayats and other

PLASMONICS FOR HYBRID ON-CHIP CIRCUITRY

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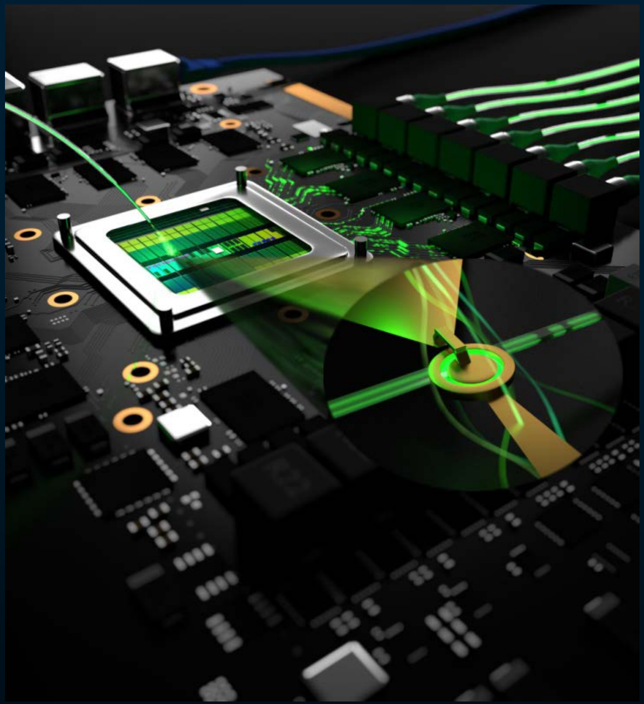
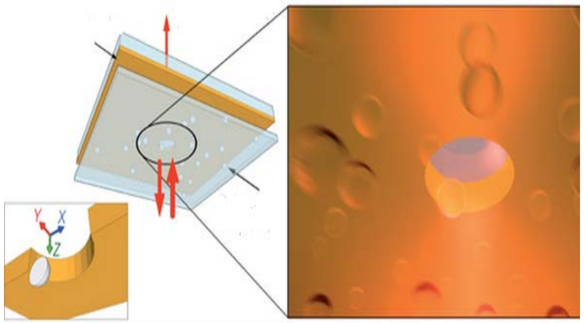
Low-loss plasmon-assisted electro-optic modulator

- Compact footprint (6 µm diameter) smaller than conventional SOI modulators and plasmonic MZIs
- 72Gbps speed demonstrated experimentally
- Low Q (~30) – higher thermal stability
- Low energy consumption (12 fJ bit−1 at 72 Gbit s−1)
- High bandwidth (~100 GHz)

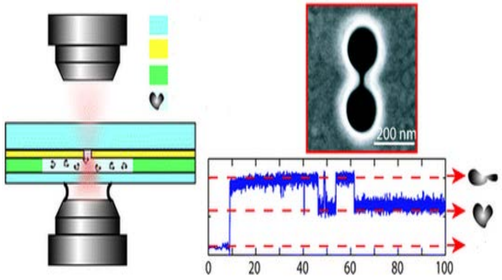


In collaboration with ETH, J. Leuthold and VCU, N. Kinsey
C. Haffner, et al., *Nature* (April 26, 2018)

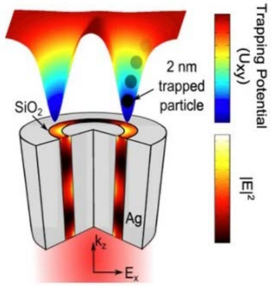
PLASMONIC NANOTWEEZERS



Juan et al. *Nature Physics* (2009)



Yuanjie et al. *Nano letters* (2011)

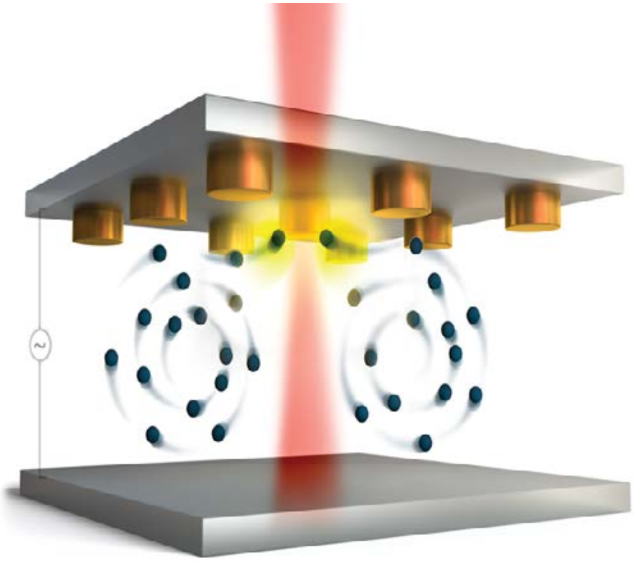


Amr et al. Nano letters (2012)

See also works from the groups of:

R. Quidant, K.Crozier, L. Hesselink, K. Touissaint, X. Zhang, Y. Tsuboi, J. Dionne and other

The Hybrid Electrothermoplasmonic Nanotweezer (HENT)



R. Quidant: ETP- enhanced LSPR chip

HENT Features:

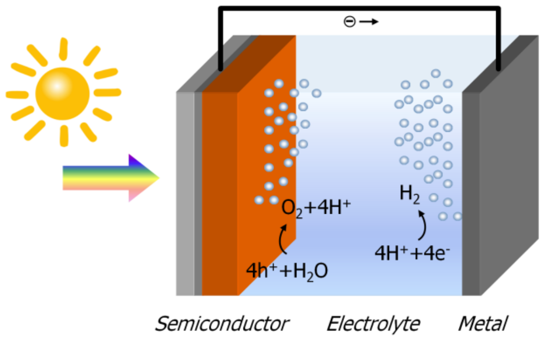
- Laser + AC electric field:
  on-demand fluid flow
- Fast and precise delivery to plasmonic hotspots
- High resolution nanoparticle trapping
- Ability to immobilize trapped object

With S. Wereley, Purdue

Ndukaife *et al., Nature Nanotechnology* (2016)

Ndukaife, Shalaev & Boltasseva. *Science 351, 6271* (2016)

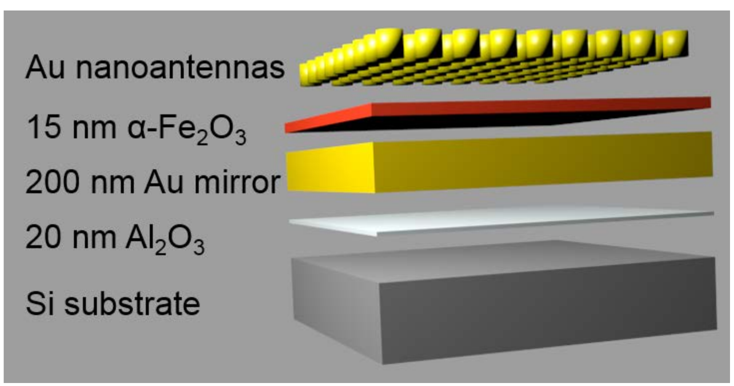
FROM SOLAR STEAM TO WATER SPLITTING

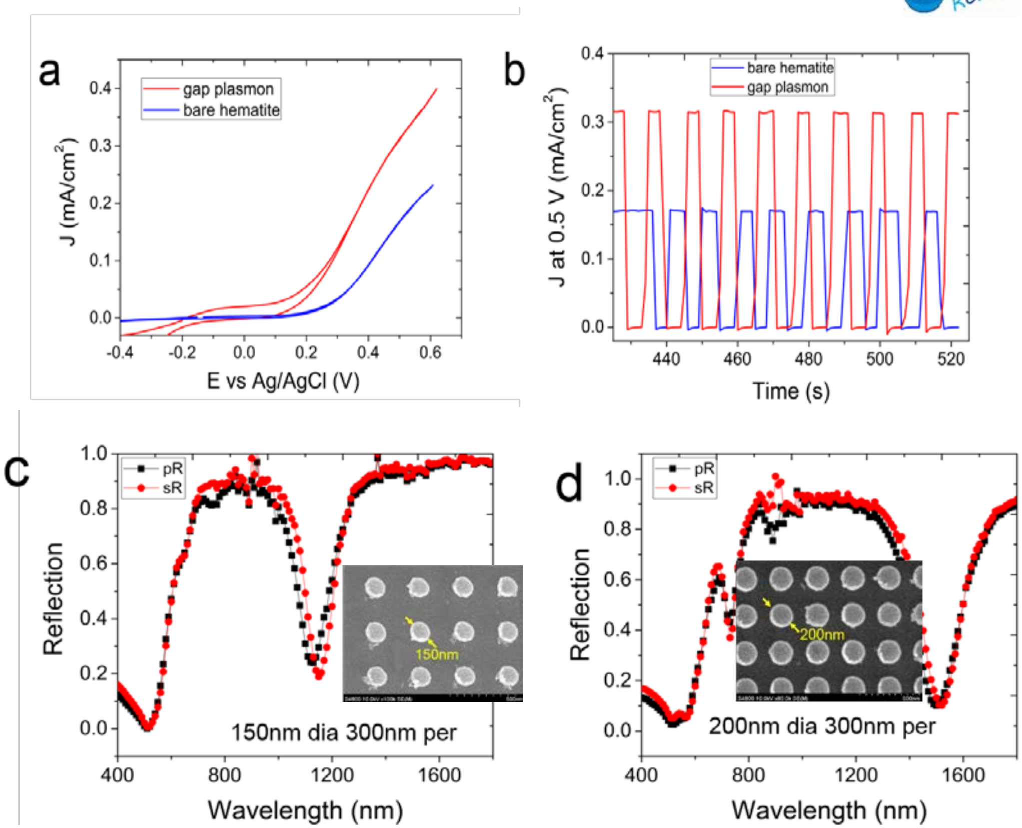


Water splitting with hematite

Collaboration with RCPTM

- Plasmon enhanced solar water splitting
- Hematite bandgap 2.0-2.2eV (solar spectrum)
- Earth abundant/Commercially viable
- Photochemically stable
- Grown with Pulsed Laser Deposition





Photocurrent enhancement with gap plasmons (See work by S. Bozhevolnyi)

With A. Naldoni

See work by N. Halas & P. Nordlander on solar steam, S. Link and other

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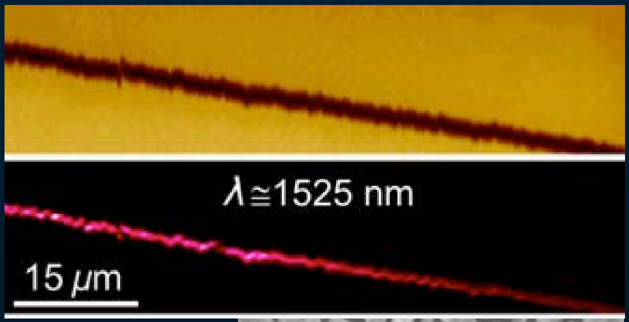
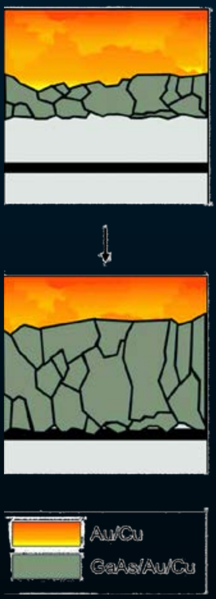
MATERIALS BUILDING BLOCKS

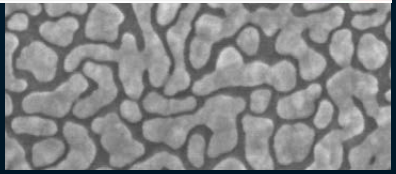
Plasmonic NOBLE METALS:

- Much light is absorbed (Ohmic LOSS)
- Not adjustable optical properties
- Hard to switch/tune
- Challenging fabrication
- Challenging integration
- Not CMOS-compatible
- Soft
- Low melting point
- High cost

TUNABLE/SWITCHABLE response and STABILITY remain a challenge!







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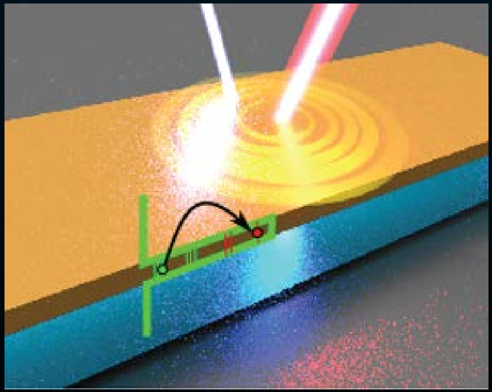

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PLASMONIC MATERIALS RESEARCH

Looking for intermediate carrier density materials

TUNABLE & ROBUST/STABLE & Sustainable

- TiN, TiAlN, Zr_xN_y, HfN, ScN, TaN, YN, VN, NbN, Cu_3N, WN
- SnO_2, In:SnO_2, ZnO, Ga:ZnO, Al:ZnO, InGa:ZnO, CdO, $CdSb_2O_6$, In_2O_3, $GaInO_6$, $MgIn_2O_4$, TiO_2, $SrTiO_3$, $SrSnO_3$, Cd_3TeO_6, $BaSnO_3$, $SrGeO_3$, IrO_2, VO_2, RuO_2
- $CoSi_2$, $CrSi_2$, $FeSi_2$, $HfSi_2$, $IrSi_2$, $NbSi_2$, Ni_xSi_x, Os_2Si_3, Pt_2Si, Pd_2Si, $ReSi_2$, $RhSi_2$, Ru_2Si3, $TaSi_2$, $TiSi_2$, V_xSi_y, WSi_2, $ZrSi_2$, Ca_2Si, Mg_2Si
- Ru_2Ge_3, Os_2Ge_3, $BaGe_3$, $SrGe_2$, Ca_2Ge, Mg_2Ge, $CrGe_2$
- GaAs, AlGaAs, InGaAs, InP, AlInAs
- Graphene
- YH_2
- Li, Na, K
- MgB_2
- Al, Cu, Ag, Au

See work by E. Hu, H. Giessen, L. Dal Negro, M. Brongersma, T. Odom, H. Atwater, N. Zheludev, A. Zayats, M. Ford, M. Blaber, O. Muskens, M. Noginov, R. Soref, M. Wegener, M. Polini and other groups

A. Boltasseva and H.A Atwater, Science **331**, 290 (2011)
G. Naik, V. Shalaev, A. Boltasseva, Advanced Materials 25 (24), 3264 (2013)
C. Zhang et al., Advanced Materials, 1521, 2017; N. Kinsey et al, JOSA B **32**(1), 2015

METALS TO ‘LESS-METALS’

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

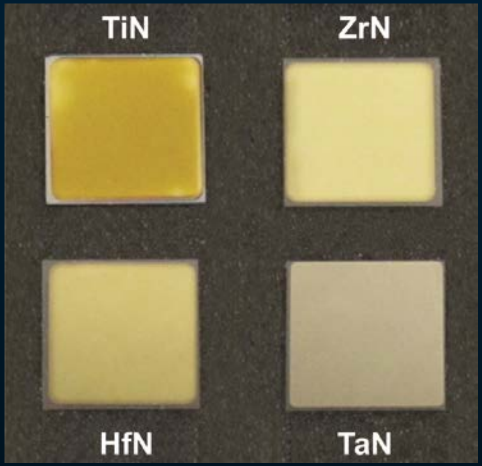
Many compounds:

Intermetallics

Ceramic materials

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

Wiki:
Ceramics = metal + non-metal



Transition metal nitrides
Mimic Au optical properties
High melting point!
REFRACTORY
Hard materials

See work by E. Hu, H. Giessen, J. Dionne, G. Naik, H. Atwater, S. Ishii, M. Blaber, M. Ford, Soref, L. Dal Negro, A. Zayats, A. Calzolari, P. Patsalas and other

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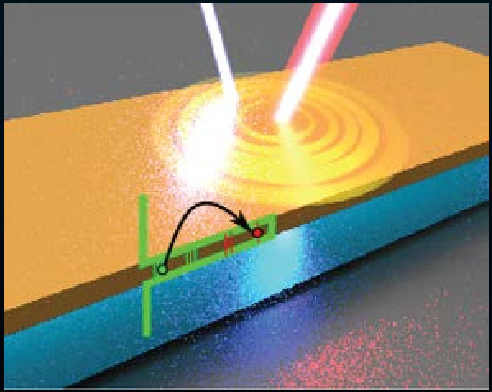

TITANIUM NITRIDE

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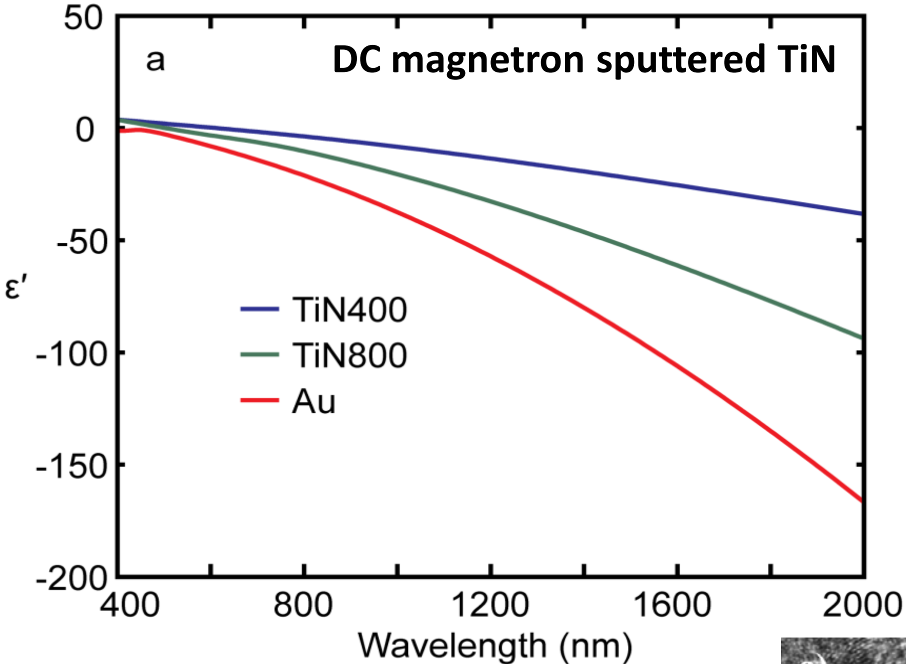
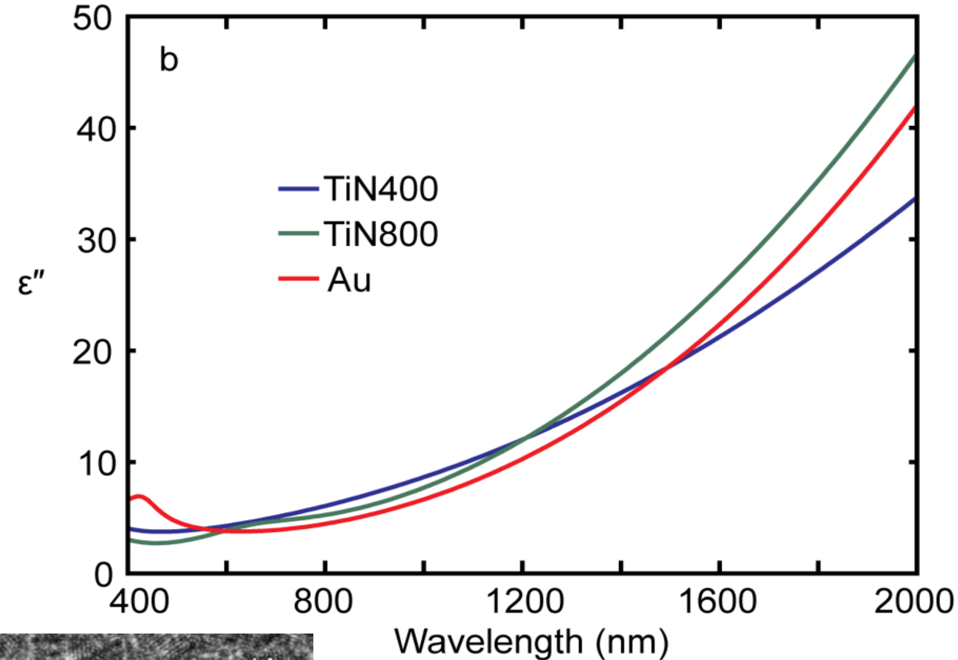
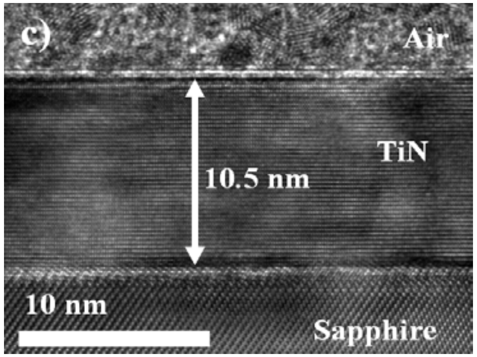
Plasmonic, Tailorable, REFRACTORY

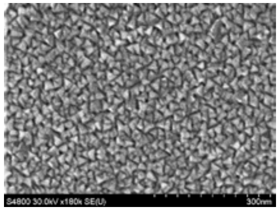




Ultra-thin/Smooth

Epitaxial growth





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

See work by L. Dal Negro, E. Hu, H. Giessen, J. Dionne, G. Naik, H. Atwater, S. Ishii and other

G.V. Naik et al., OMEx 2, 478 (2012), U. Guler et al., Nano Letters 13, 6078 (2013)

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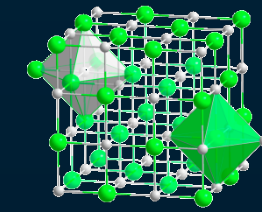
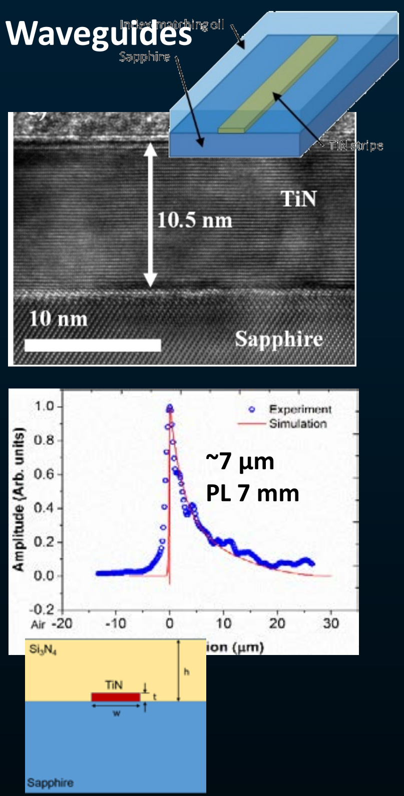
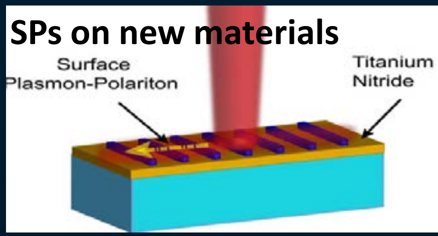
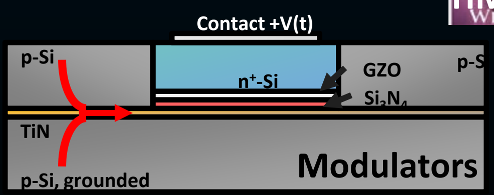
TMNs HIGHLIGHTS/RESULTS

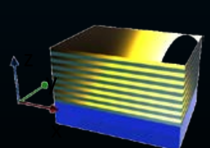
- New functional devices and new physics unlocked by tailorable **TMNs**
  - *Plasmonics/Metamaterials/Metasurfaces in VIS*
  - *Robust/high-T Stable/CMOS, bio-compatibility*



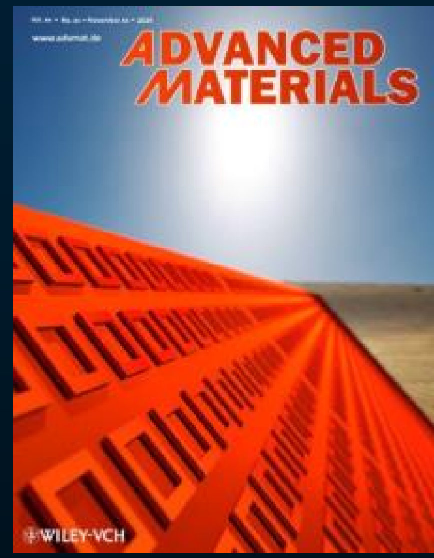


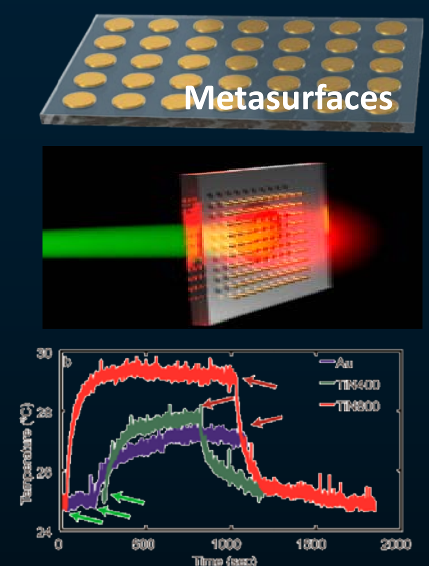




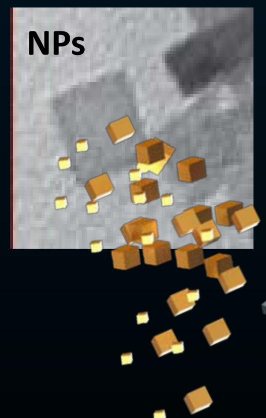


OMEx 2012
PNAS 2014
AdvMat 2013
LPR 2014

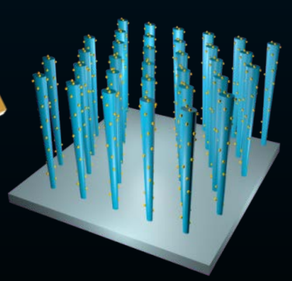




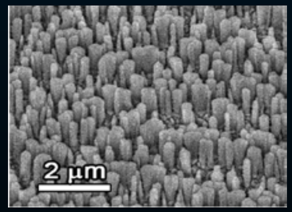
Local heating



TiO_2-TiN



Catalysis



AdvMat 2016
NanoLet 2013
MatToday 2014
AdvOptMat 2017

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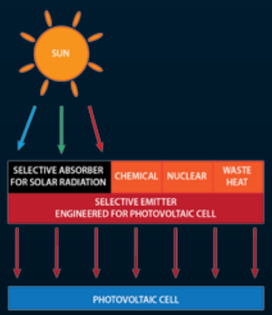
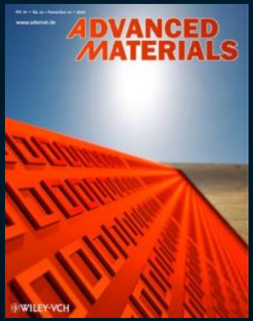
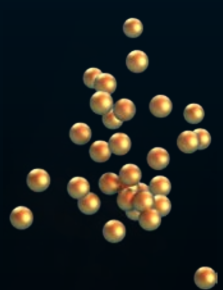
POTENTIAL OF PLASMONIC CERAMIC MATERIALS

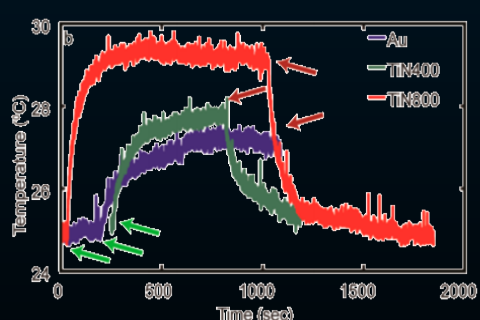
Ceramic (high-T stable) materials with plasmonic properties

- Photothermal biomed apps/therapy/drug delivery
- Heat-assisted magnetic recording
- Harsh environment sensing
- Solar/Thermophotovoltaics (S/TPV)
- Plasmon-assisted photocatalysis
- Optical trapping/nanomanufacturing

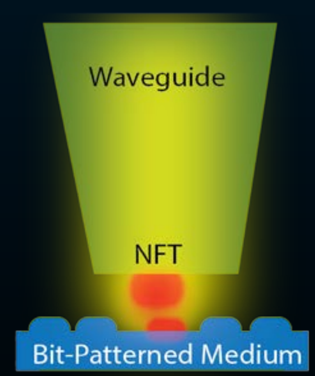




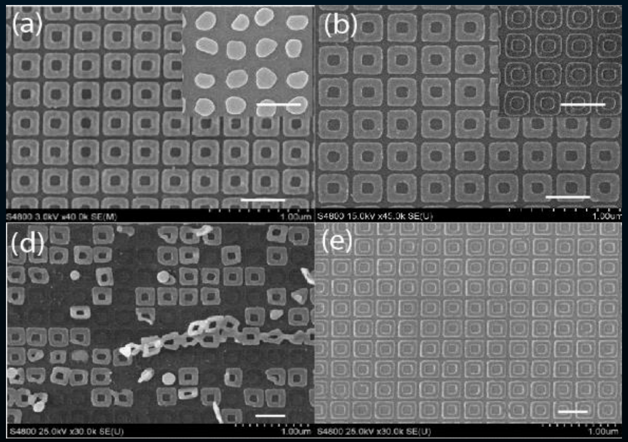




Nano Letters 2013



Faraday Discussions 2014



Mater. Today 2014

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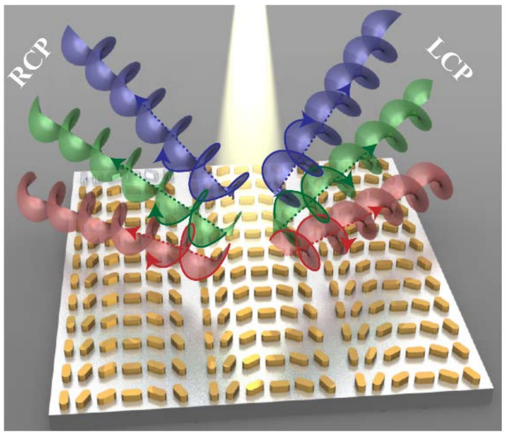
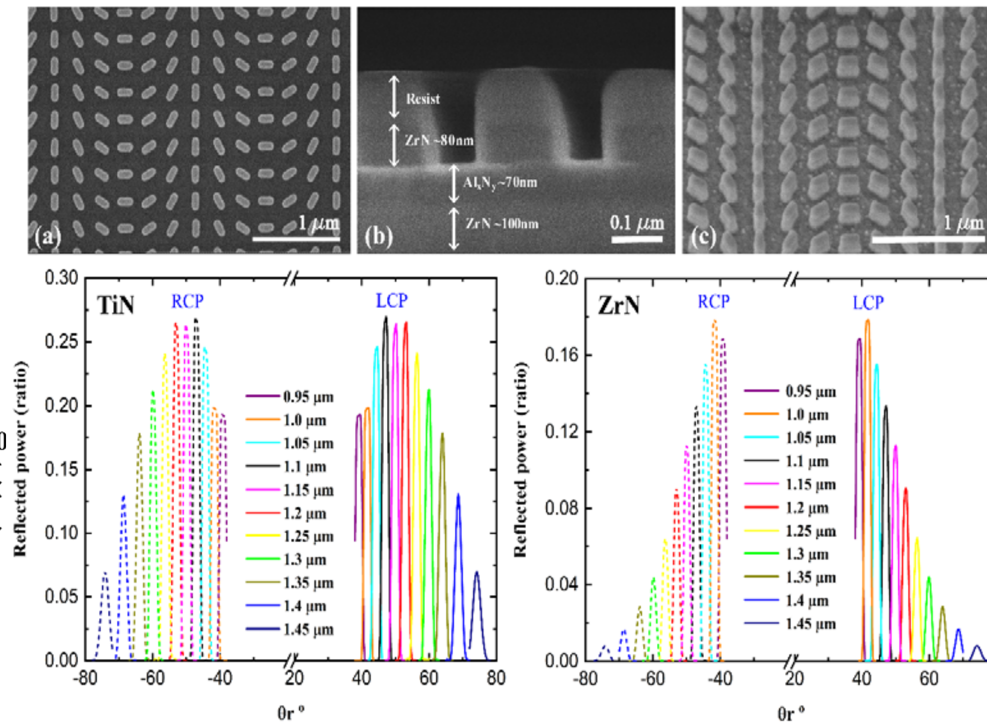
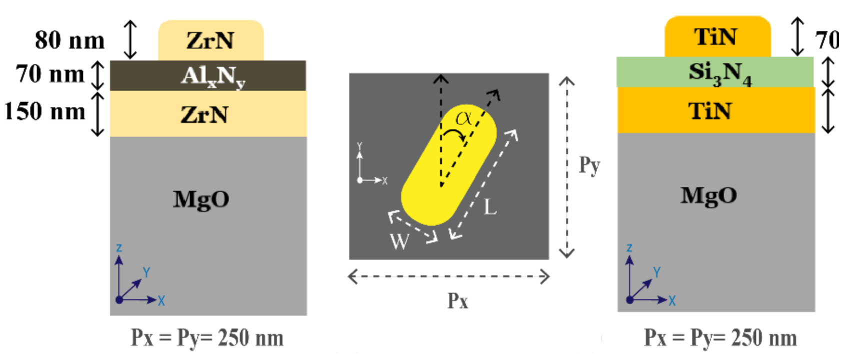
Photonic Spin Hall Effect in TiN Metasurface

Photonic SHE: Reflects the two photonic spins (left and right circular polarizations, LCP and RCP) in opposite directions with ROBUST Nitrides



All-nitride: highly anisotropic, multilayer resonators





Phase gradient for the two opposite polarizations, created by anisotropic antenna unit cells
Reflection mode unit cell supporting gap-plasmon type resonance

See work by X. Zhang, F. Capasso, E. Hasman, and other

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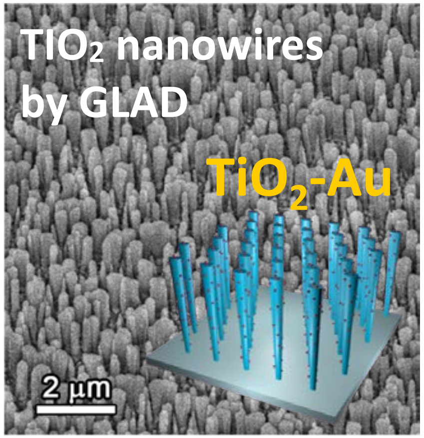
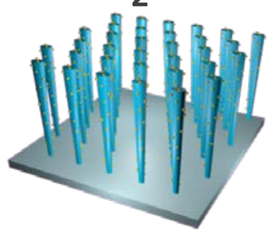
PLASMON-ENHANCED WATER SPLITTING

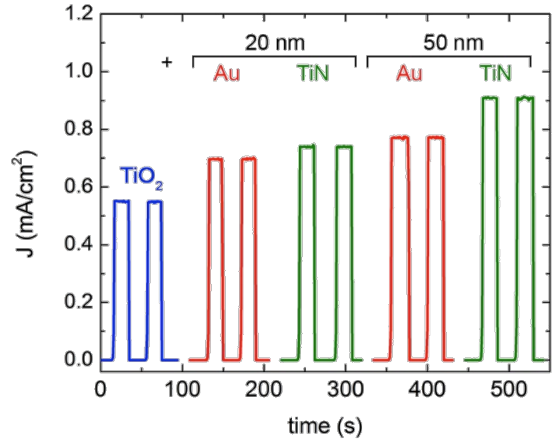
Enhancing hot electron collection with TiN nanoparticles



vs.

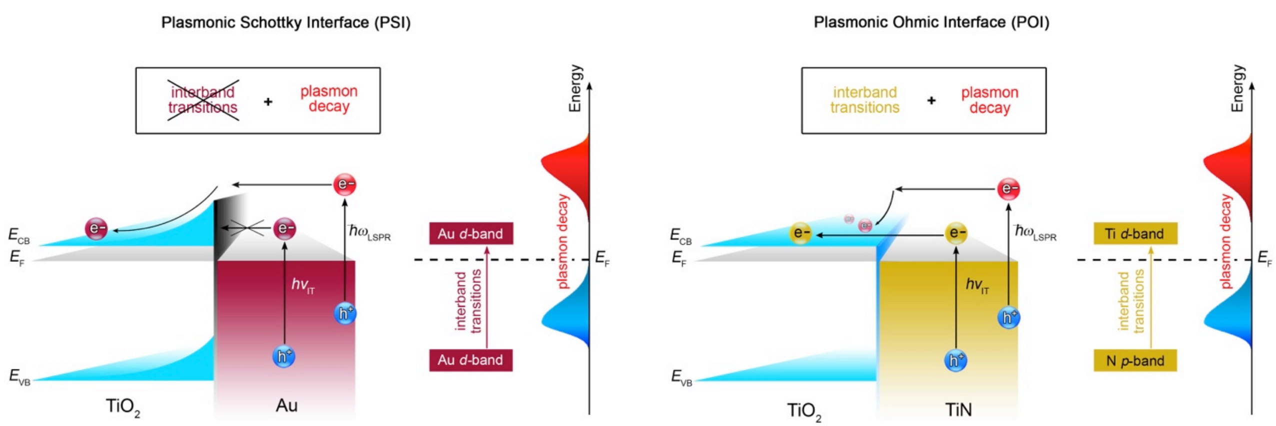
TiO_2-TiN





TiN and Au NPs: TiN produces higher photocurrent enhancement than Au NPs!

TiN has a broader LSPR and produce more hot electrons than Au, higher transmission of hot electrons at the interface with TiO_2



With A. Govorov

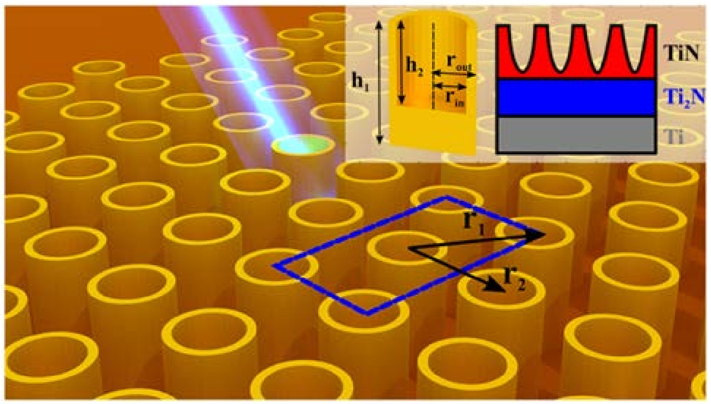
With A. Naldoni

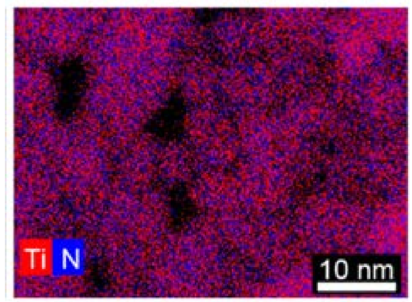
A. Naldoni et. al Nanophotonics 2016 & Adv Opt Mat 2017

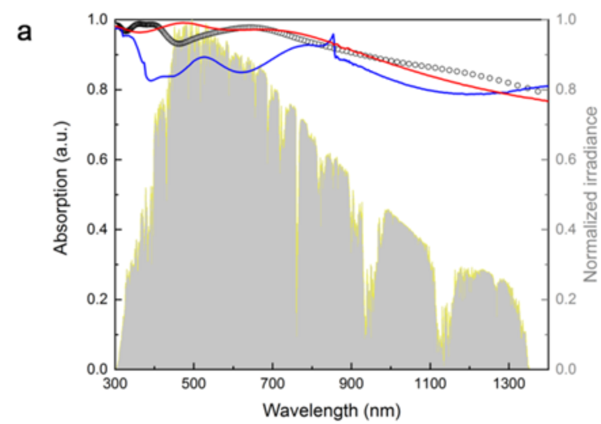
See work by N. Halas, P. Nordlander, P. Christopher, S. Ishii, A. Zayats and other

THERMOPLASMONIC TiN NANOFURNACE

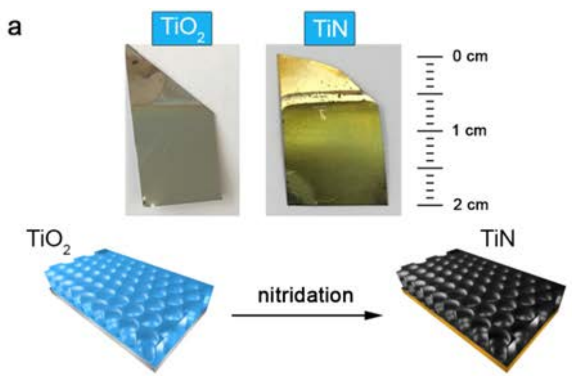
- High temperatures can be obtained using thermoplasmonic TiN nanofurnace under solar illumination
- Enables thermally induced nanochemistry with attolitre volume precision

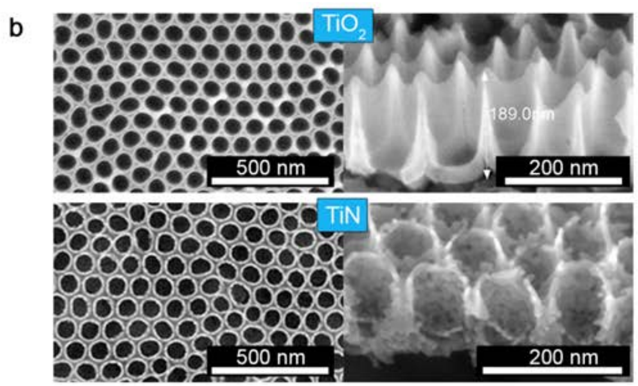


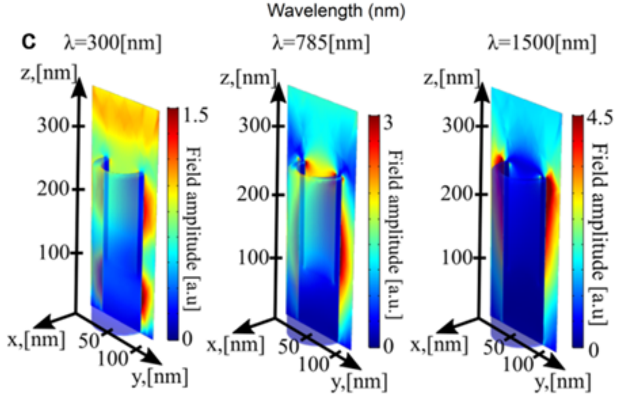




TiN nanofurnace formed by nitridation of TiO_2 at 600^0 C







With A. Naldoni

See work by N. Halas, P. Nordlander, P. Christopher, S. Ishii and other

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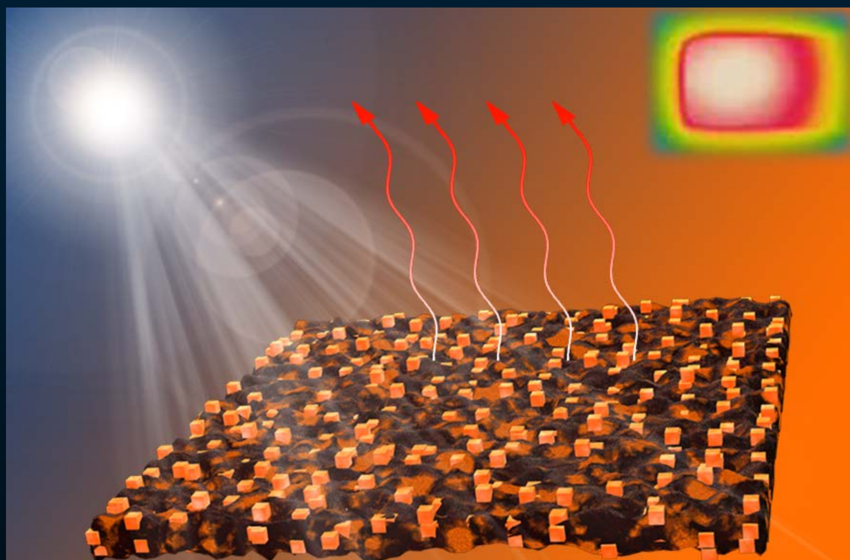
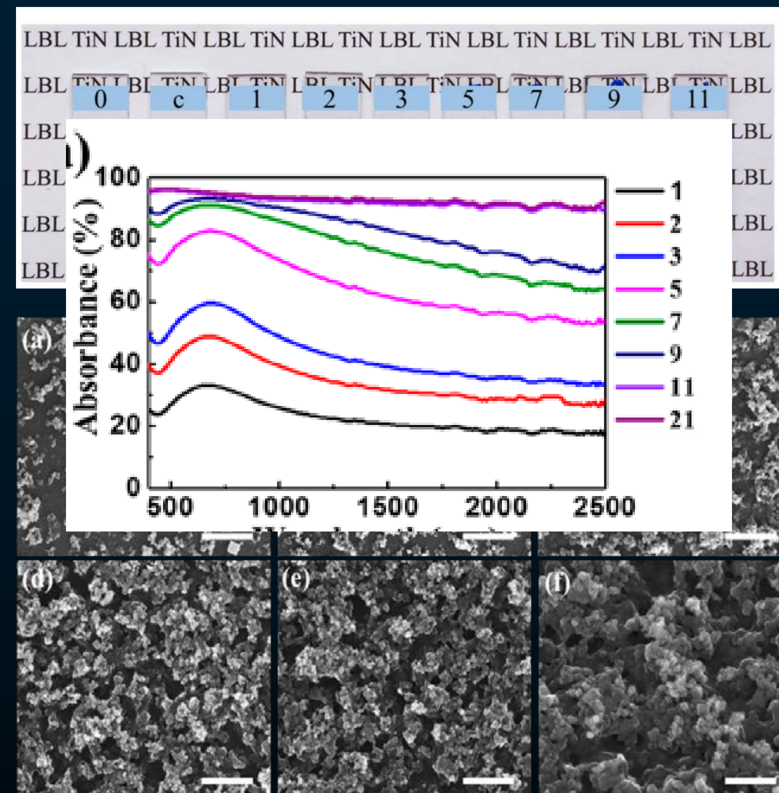
Biomimetic TiN as Broadband Absorbers

Plasmonic Biomimetic Nanocomposite with Spontaneous Subwavelength Structuring as Broadband Absorbers





Corrugated TiN coatings:
Broadband absorption (90%)
FAST, FLEXIBLE, ENVIR. FRIENDLY

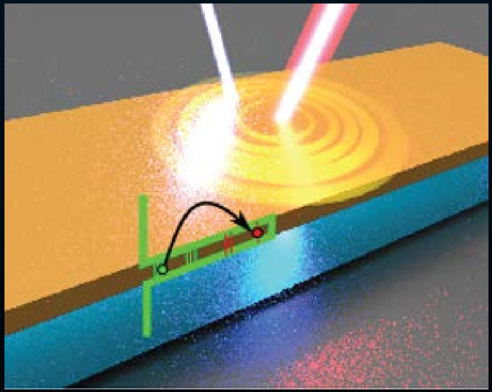
Layer-by-layer assembly of TiN nanoparticles with polyelectrolytes: out-of-plane topography with subwavelength dimensions.

With N. Kotov, UMich

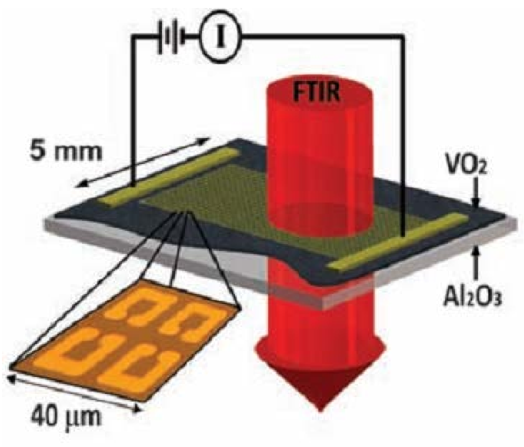
ACS Energy Letter, 2018

OUTLINE

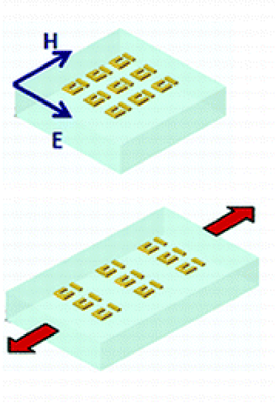
- Plasmonics: Loss and Gain
- Expanding Materials Playground for Plasmonics and Nanophotonics
- Metal Nitrides
- Transparent Conducting Oxides
- Material Requirements: Tunability & T-Stability
- Ultra-Thin Plasmonic Metal Nitrides
- MXenes: Novel Quasi-2D Materials
- Outlook



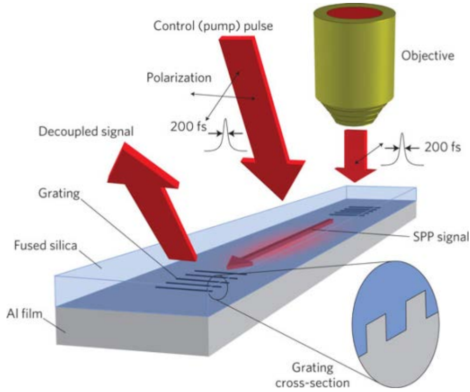
APPROACHES TO SWITCHING/TUNING



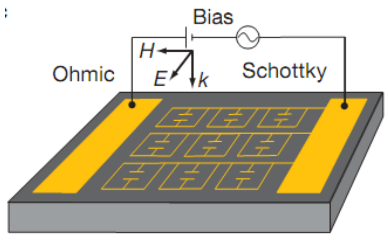
Phase Transition in VO_2[1]



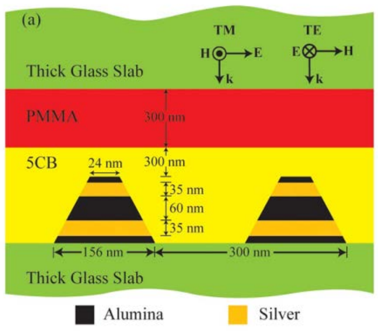
Mechanical Stretching[2]
“Plasmomechanics”
Electromechanical



Optical Control[3]



Electrical Injection
in Semiconductors[4]



Liquid Crystals[5]

Key issues

- **Speed vs Magnitude**
- **Electrical control**
- **Modulation in VIS/NIR**
- **Tunable plasmonic materials**

[1]T. Driscoll et. al., Science (2009)
[2]I. M. Pryce et. al., Nano Lett. (2010)
[3]K. F. MacDonald et. al., Nat. Phot. (2008)
[4]H. T. Chen et. al., Nature (2006)
[5]S. Xiao et. al., APL (2009)
Zheludev, Atwater, Brongersma, Mortensen, other

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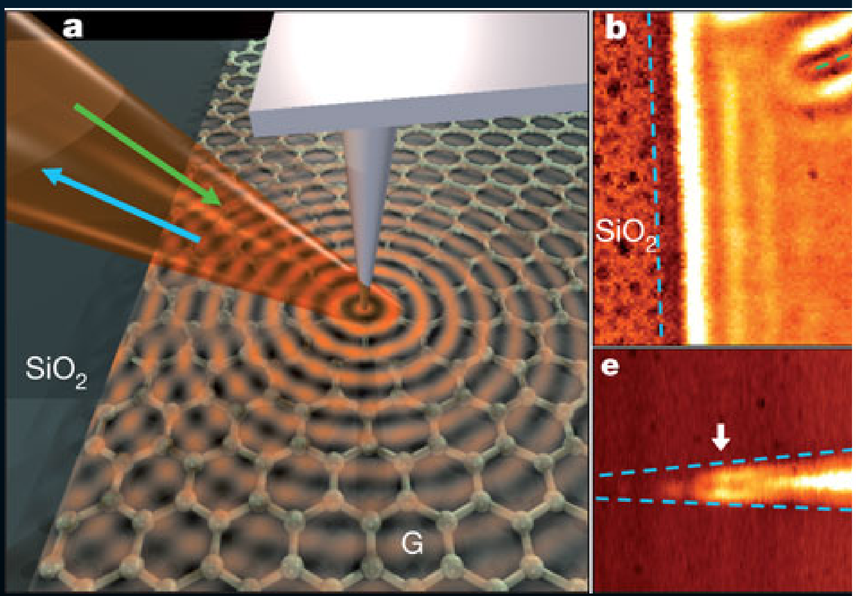
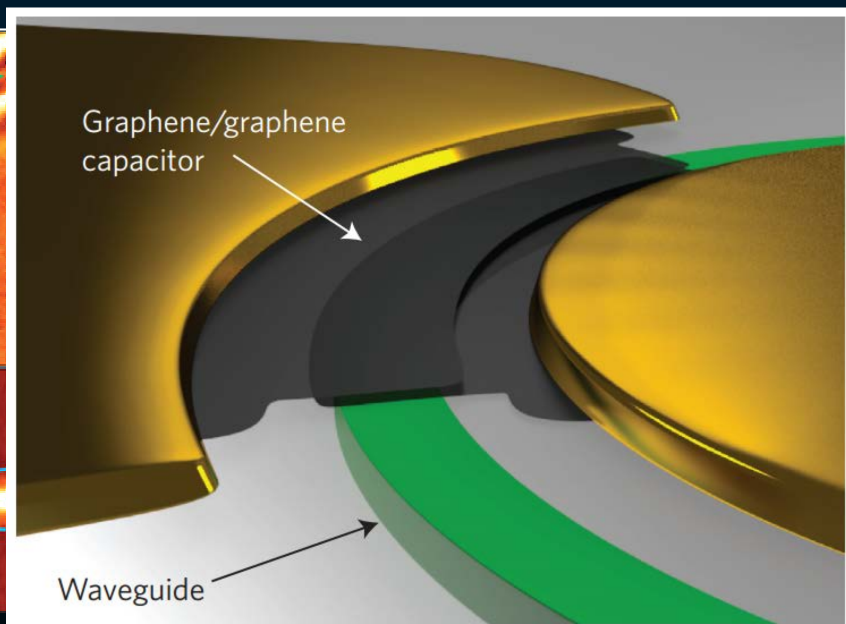
GRAPHENE AS TUNABLE PLATFROM

- High degree of optical confinement – PLASMONIC MATERIAL
- Easy and high dynamic tunability – TUNABLE PLATFORM
- Stackable with other 2D materials for new properties
- Zero bandgap, uniform optical absorption – a promising material for photodetection



Graphene plasmons in IR
Z. Fei et al, Nature (2012)

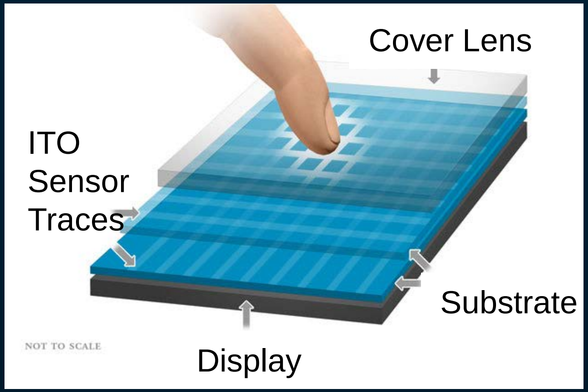


C.T. Phare, …& M.Lipson, Nature Photonics (2015)

D. Basov, X. Garcia de Abajo, F. Koppens, M. Lipson, N. Halas, N. A. Mortensen, H. Altug, N. Zheludev and other

TCOs AS DYNAMIC MATERIALS

- Transparent Conducting Oxides with extremely high dopant solubility (10^{21} cm^{-3})
- Indium Tin Oxide (ITO)/Doped Zinc Oxide/Vanadium Oxide/Cadmium Oxide
- Numerous advantages for photonics
- Mature fabrication processes
  - Sputtering, PLD, ALD, CVD, etc.
- Non-stoichiometric materials
  - Plasma frequency highly tunable from VIS to NIR
- Ultra-fast response
- Electrical- and all-optical switching



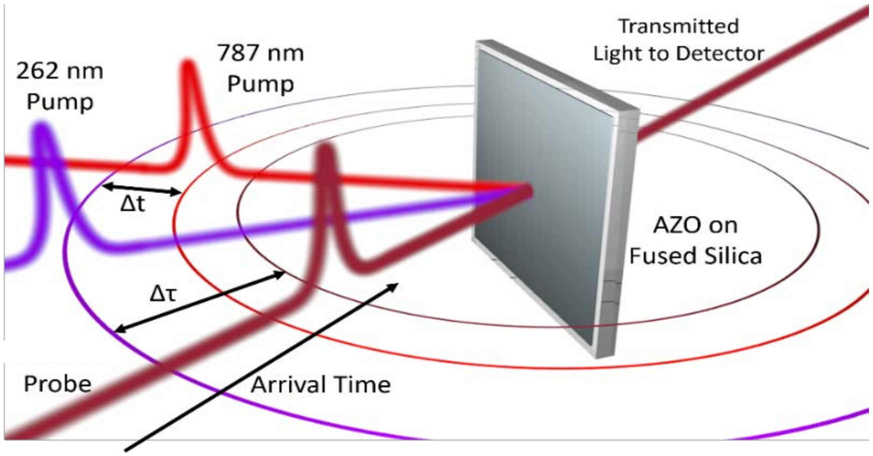
ITO-based touch screens

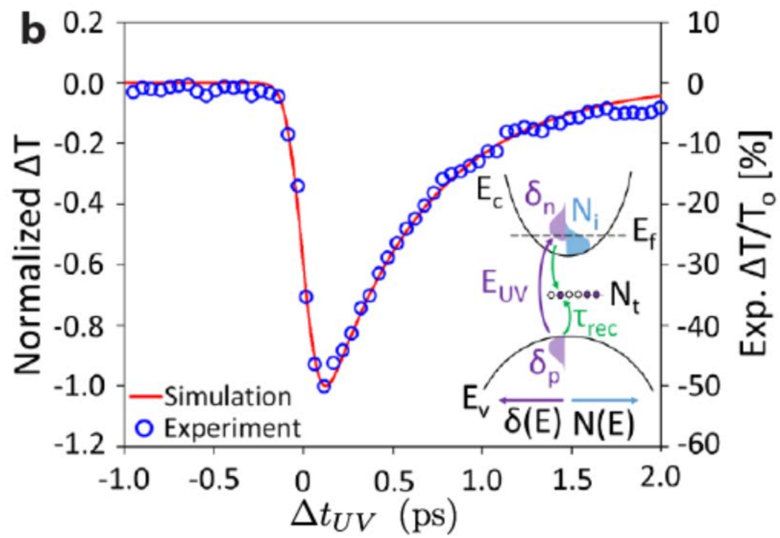
IGZO-based highly resolved flexible screen

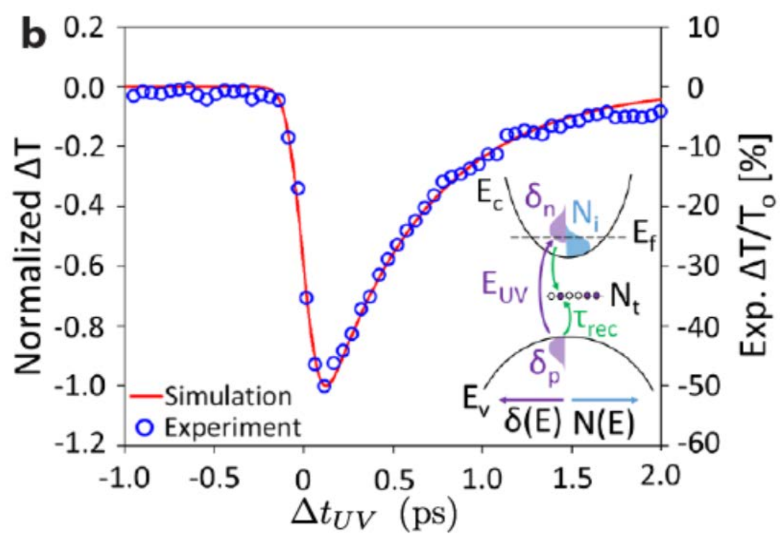
G.V. Naik et al, Opt. Mater. Express **1**(6), 2011

Also work by H. Atwater, R. Boyd, H. Li, O. Muskens, M. Brongersma, I. Brener, H. Li, N. Zheludev and other

ULTRAFAST NONLINEARITIES







Engineered nonlinearities by controlling delay between two pumps: UV (262nm) and IR (787 nm)

Strong modulation with change in T/R ~ 100%
With ultrafast response ~ 100 fs

fast NLOs – see also work by Zheludev group
NLO in TCOs – see also work by Muskens group

M. Clerici, et al. Nat. Comm (2017)

ENZ ENHANCED NONLINERITIES

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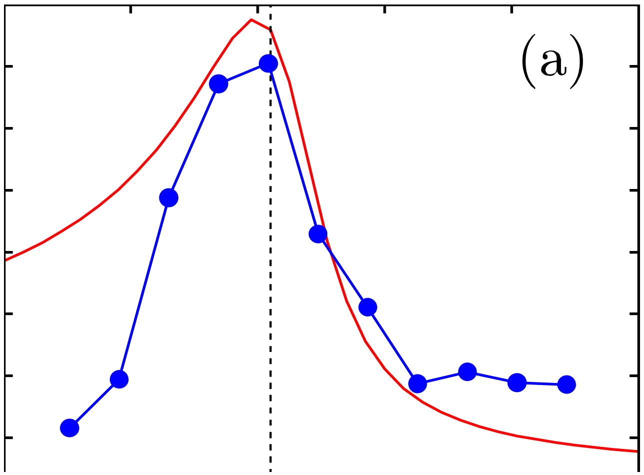
$$n = n_0 + \Delta n = n_0 + n_2 I$$

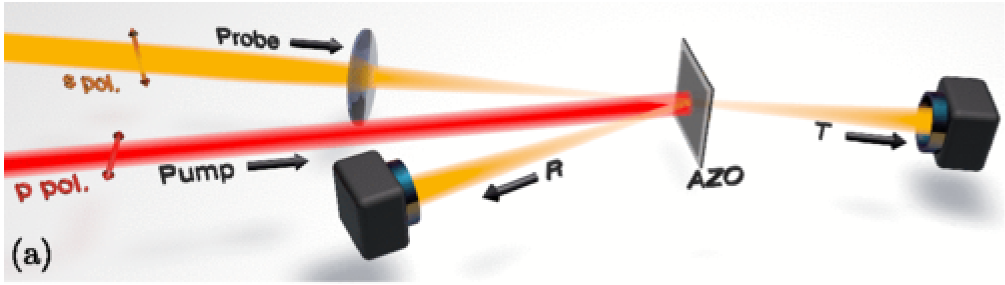
$$n_2 = n_{2r} + i\beta_2 \sim \frac{\chi^{(3)}}{n_0}$$

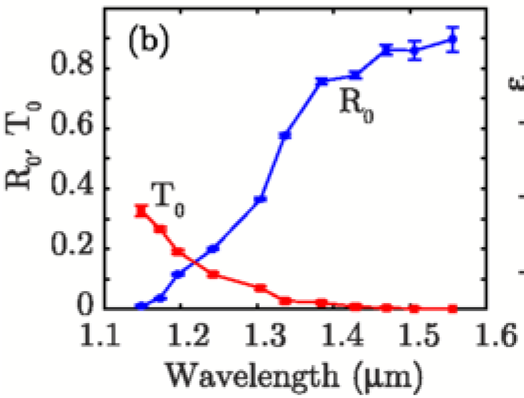
Kerr index is dependent on refractive index

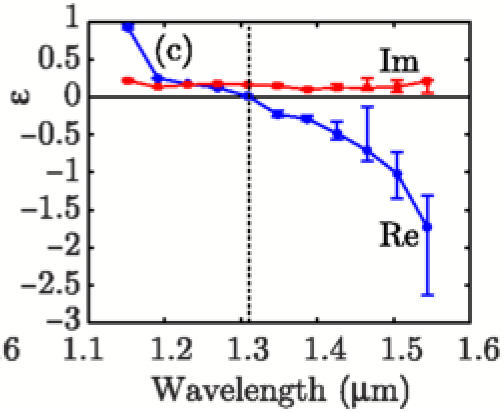
- $n_2 \sim \chi^{(3)}/n_{probe}$ (non-degenerate)
- $n_2 \sim \chi^{(3)}/n_{probe}^2$ (degenerate)

Collaboration with Heriot-Watt Univ.





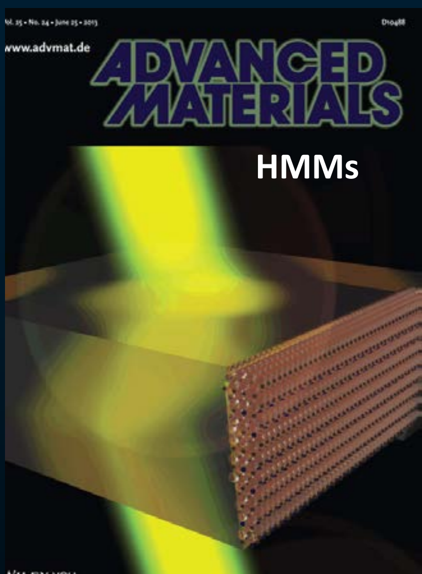


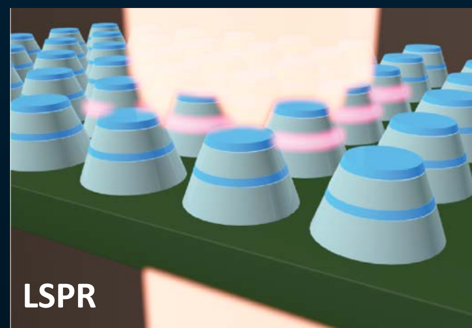


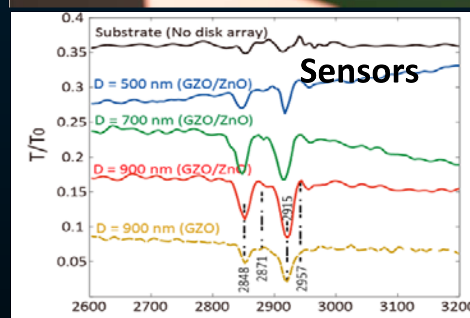
L. Caspani, et al Phys. Rev. Lett. 116, 233901 (2016); see also work on ITO by Boyd group, Science (2016)

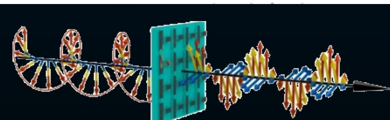
TCO HIGHLIGHTS/RESULTS

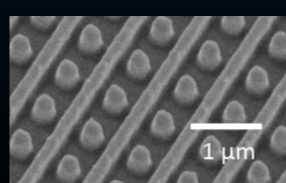
- New functional devices and new physics unlocked by LOW-LOSS **TCOs**
  - *Plasmonics/Metamaterials/Metasurfaces in NIR*
  - *Ultra-fast switching/Enhanced Nonlinearities*

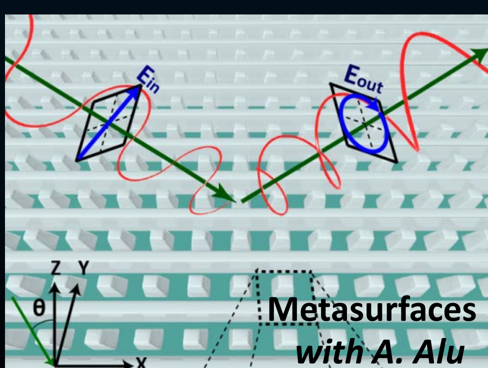




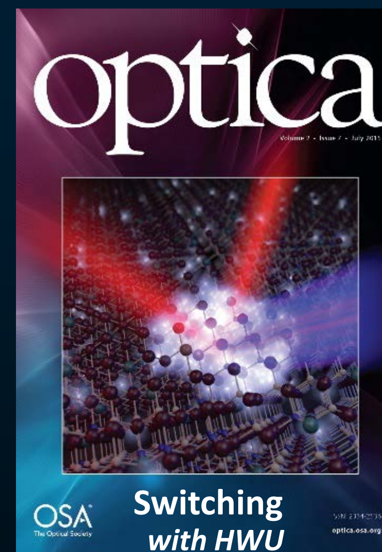


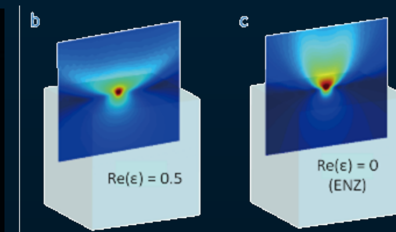


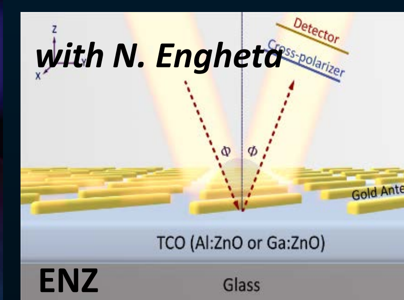


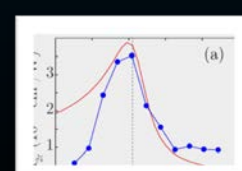


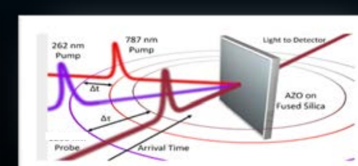
IEEE-JSTQE 2013
PNAS 2012
AdvMat 2013
ACS Ph 2015
ACS Nano 2016











with HWU

Optica 2016
Optica 2016
PRL 2016
NatCom 2017

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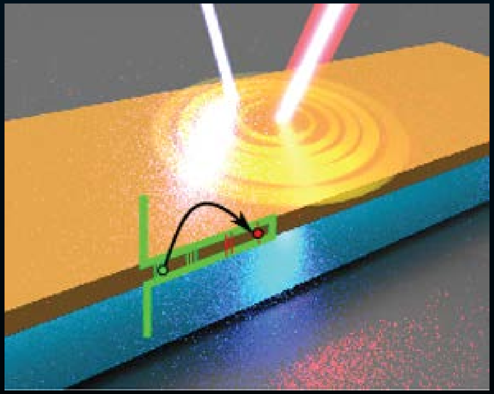
OUTLINE

- Plasmonics: Loss and Gain
- Expanding Materials Playground for Plasmonics and Nanophotonics
- Metal Nitrides
- Transparent Conducting Oxides
- Material Requirements: Tunability & T-Stability
- Ultra-Thin Plasmonic Metal Nitrides
- MXenes: Novel Quasi-2D Materials
- Outlook

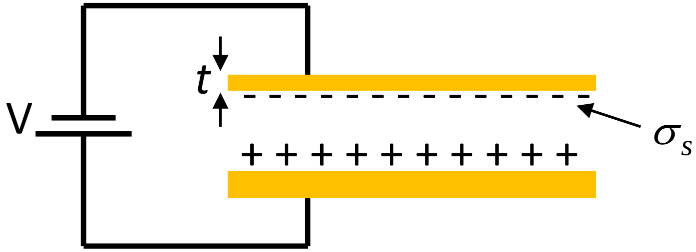


TUNING THE PROPERTIES OF METALS?

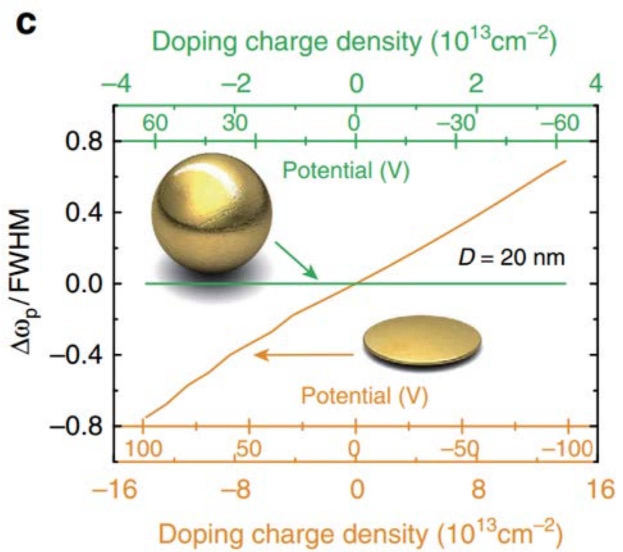
- High carrier density in metals: no appreciable tuning

- Change in the carrier density

$$\Delta n = \frac{\sigma_s}{t}$$



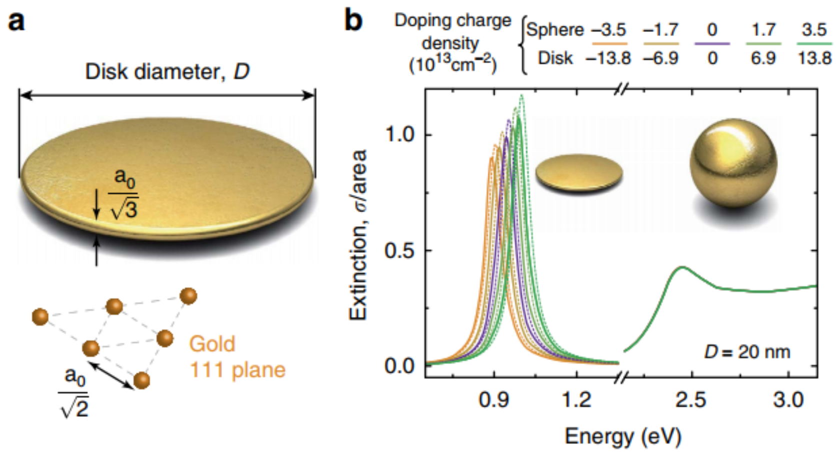
- Thinner the film larger the tunability!



- Tuning of carrier density close to 15-20% has been theoretically predicted in atomically thin films

ULTRA-THIN PLASMONIC FILMS

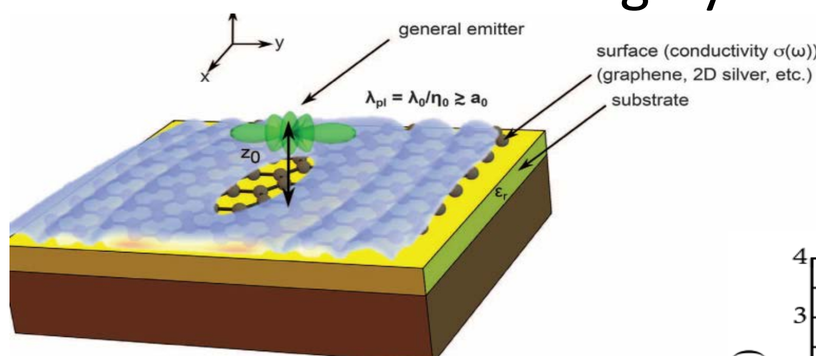
- Electrical (optical) control over the properties



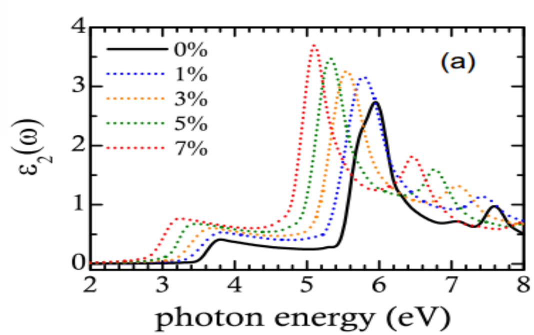
J. Garcia de Abajo's group
Nature Communications, 2014

- Unique light-matter interactions in highly confined light regime

M. Soljacic's group
Science 2016

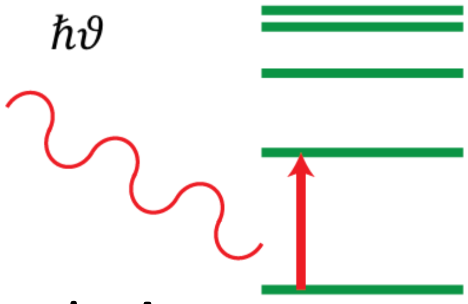


- Control the optical properties
  by adjusting strain/stress



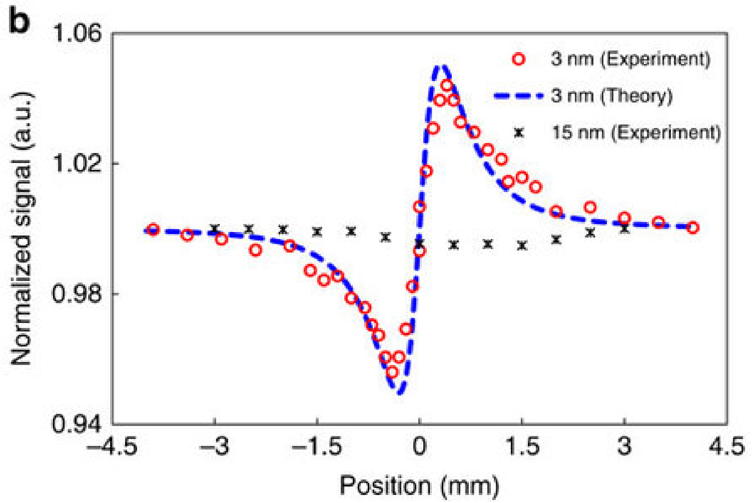
QUANTUM CONFINEMENT ENHANCED NONLINEARITIES

- Energy level discretization enhanced nonlinearities

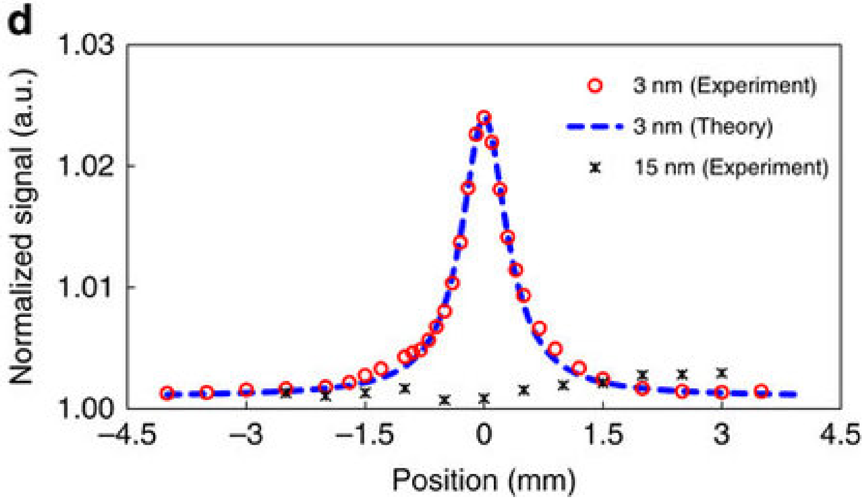


- Enhanced nonlinear properties have been shown in Au quantum wells

Closed Aperture



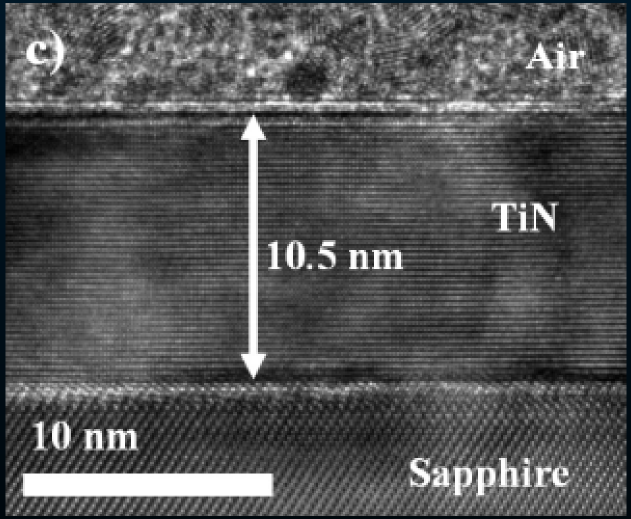
Open Aperture

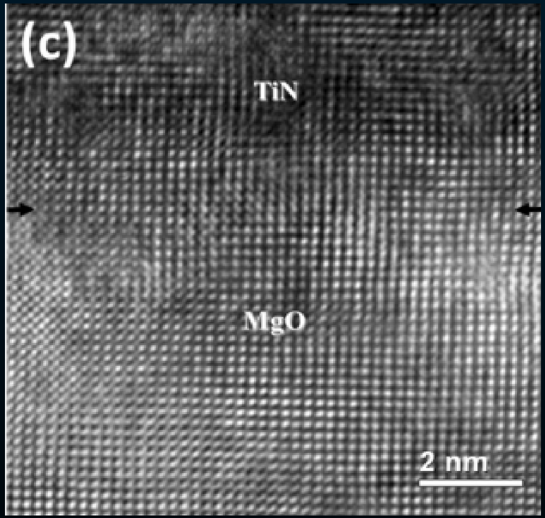


Zhaowei Lu's group, Nat. Comm (2016)

PLASMONIC ULTRATHIN TiN FILMS

- Plasmonic noble metals
  - Difficult to grow smooth, continuous films <7-10nm
- Titanium Nitride
  - *Epitaxial growth* on c-sapphire and MgO
  - Potentially epitaxial growth of *ultrathin* (~1-2nm) films on Si
  - Enhanced nonlinearities
  - *High T- and High-Intensity Stability* and Robustness



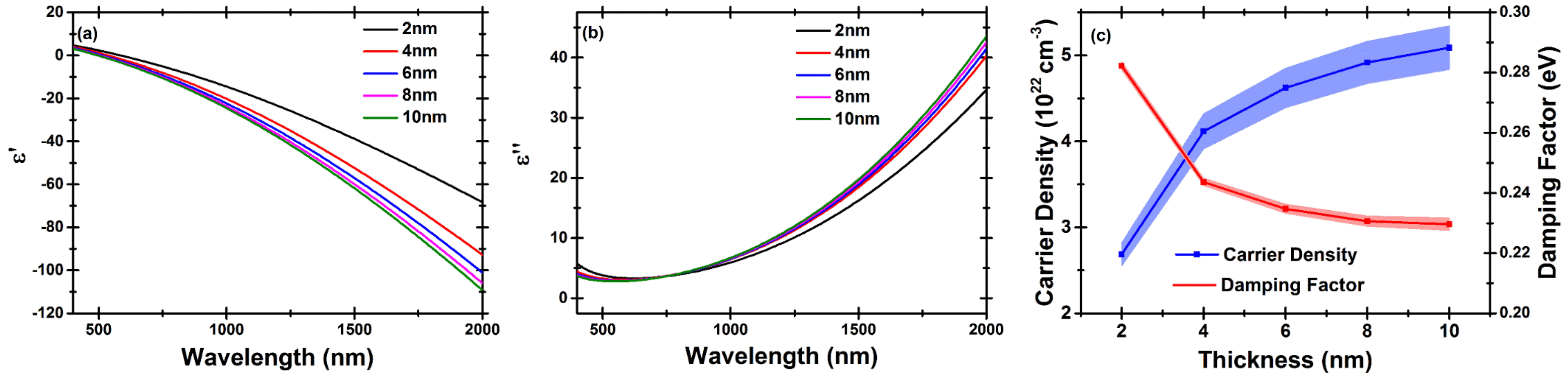


N. Kinsey et al., Opt. Express (2014)

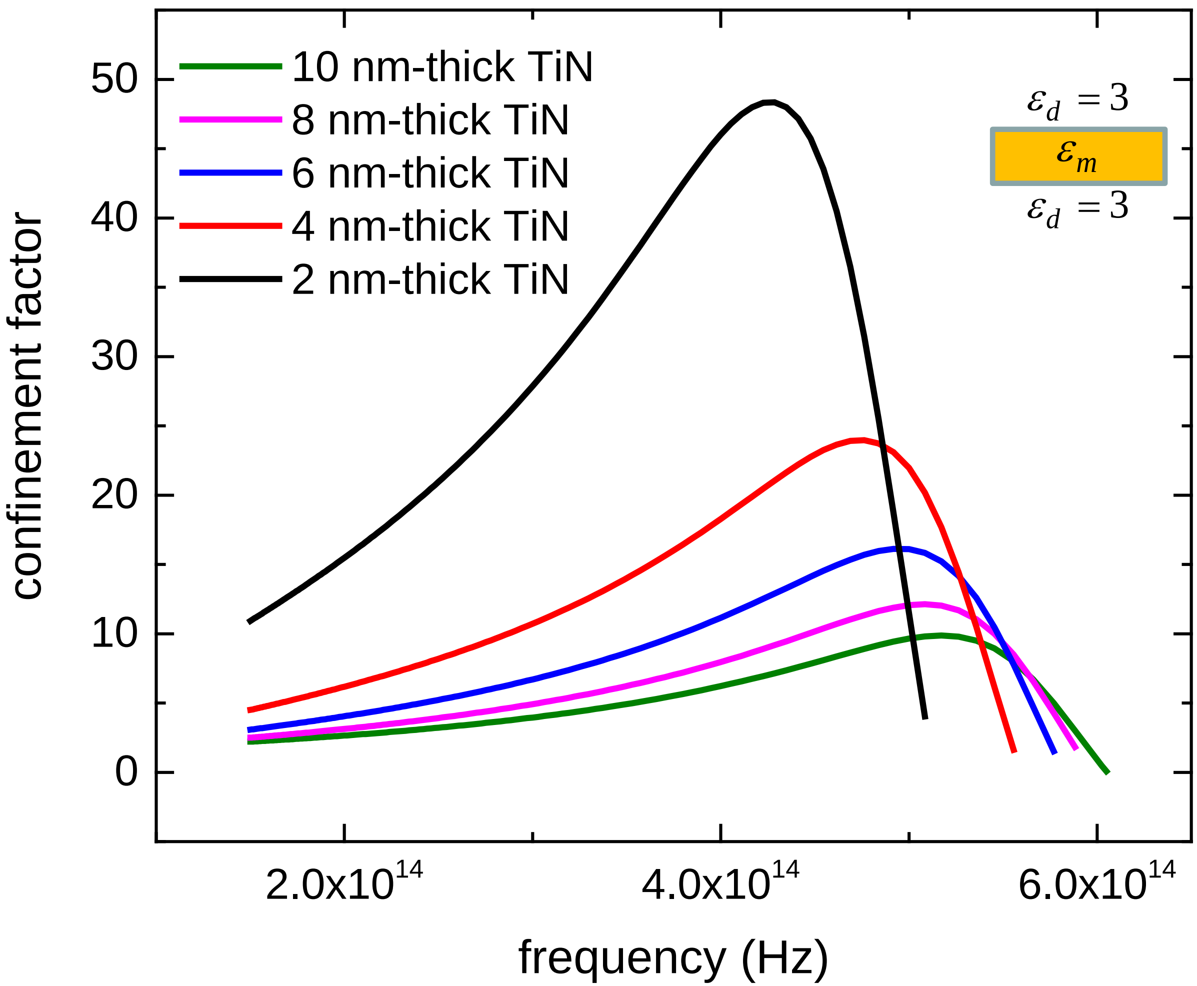
Chen et al., Nanoscale Research Letters (2014)

OPTICAL PROPERTIES OF ULTRATHIN TiN

- Lower metallicity (~2-nm-thick TiN_xO_y layer on the surface)
- Agrees with theory; plasma frequency acquires the spatial dispersion (~ 2D)
- Films remain highly metallic, even at a thickness of 2 nm ($n \approx 10^{22}$ cm^{-3})
- Higher losses in thinner films
- Increase in scattering rate
  - Defect scattering: TiN_xO_y layer
  - Surface scattering rate, $\Gamma_{ss} \sim 1/t$, t = film thickness



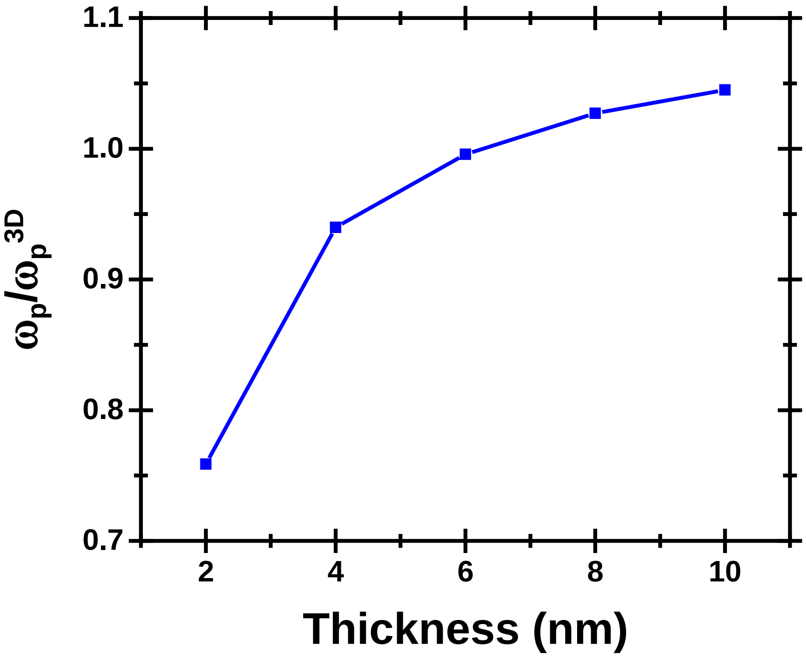
CONFINEMENT FACTOR CALCULATIONS

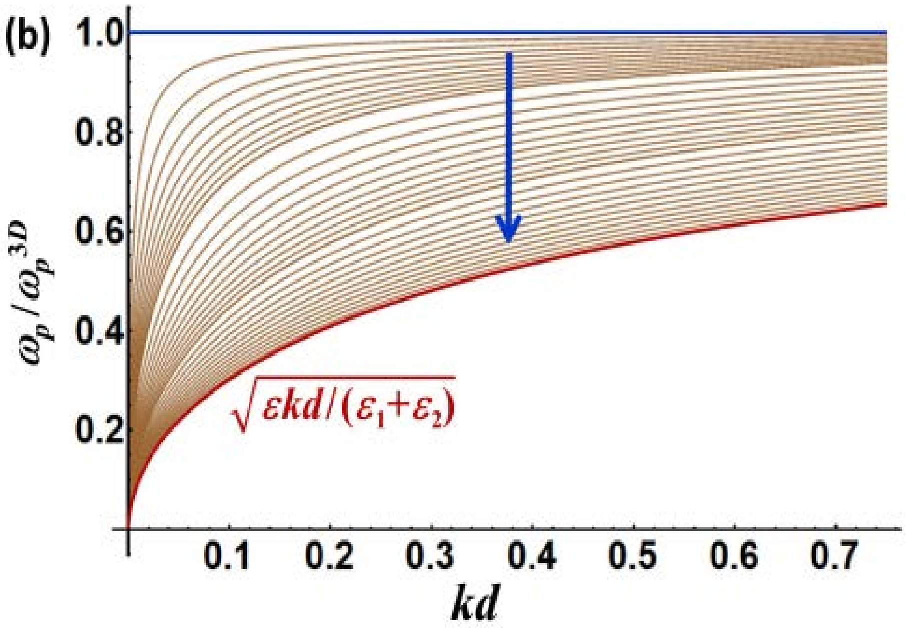


- Computed confinement factor of tightly confined plasmons λ_0/λ_p
- Maximum confinement of close to 50 in 2 nm films

With M. Soljacic

EFFECT ON PLASMA FREQUENCY





The plasma frequency acquires the spatial dispersion ~ typical for 2D materials: shifted to the red at all fixed k with dielectric losses enhanced as the film thickness d ⬇

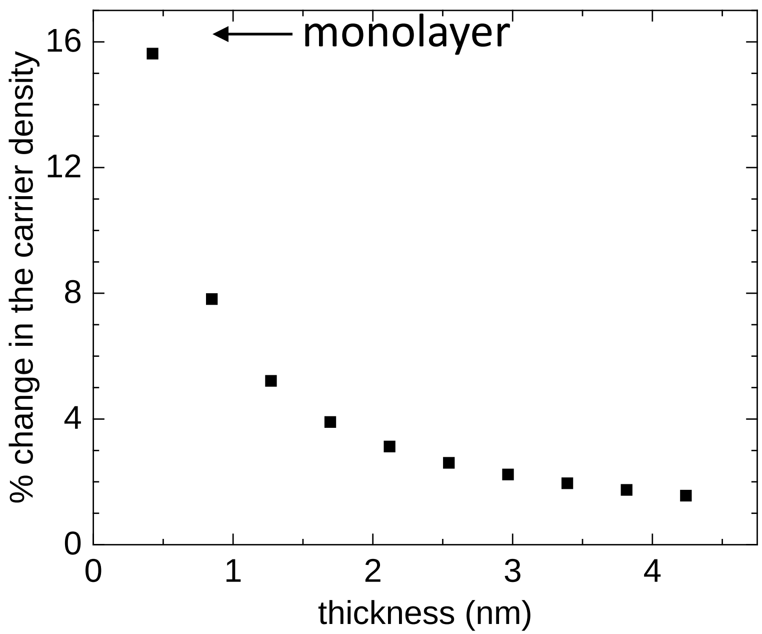
$$\omega_p = \omega_p(k) = \frac{\omega_p^{3D}}{\sqrt{1 + (\varepsilon_1 + \varepsilon_2)/\varepsilon k d}}$$

D. Shah, et al, Adv Opt Mat (2017)
Bondarev et. al, OMEx (2016)

ULTRATHIN TiN: TUNABLE METAL?!

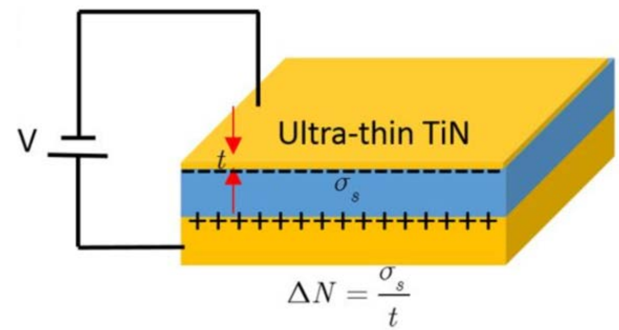
- Epitaxial quality films with thicknesses down to 1 nm are fabricated

Calculation

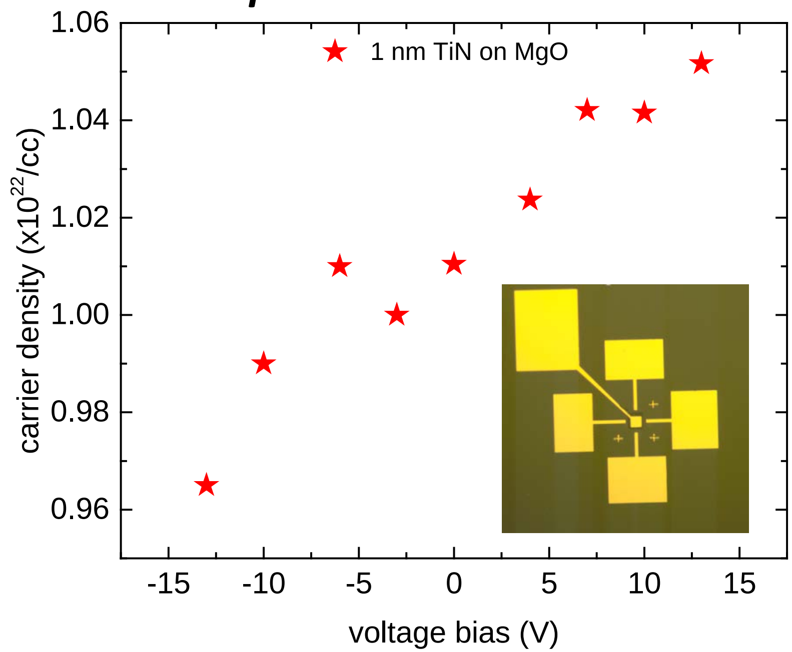


- Close to 16% relative change in the carrier density is expected in monolayer TiN film

- Inversely proportional to film thickness



Gate dependent Hall measurements



8.5% change in 1nm TiN films!

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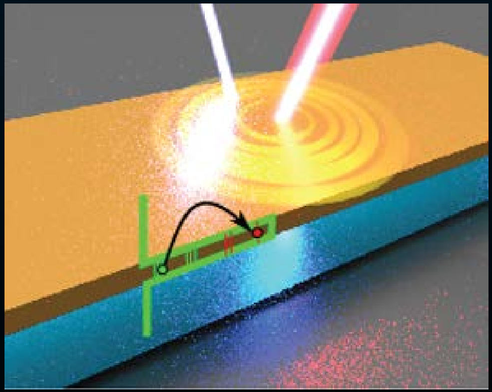
- Ultra-Thin Plasmonic Metal Nitrides
- MXenes: Novel Quasi-2D Materials
- Outlook



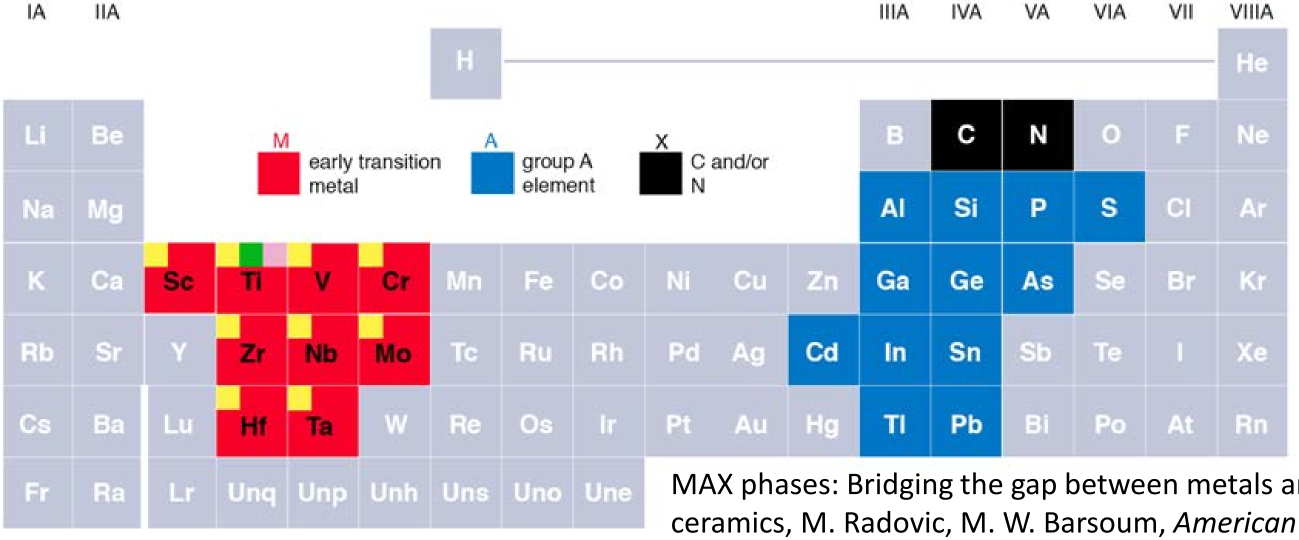
MAX Phases

The MAX Phases: a family of ternary carbides with the general formula $M_{n+1}AX_n$

M is an early transition metal

A is an A-group element (mostly IIIA and IVA),

X is C and/or N



MAX phases: Bridging the gap between metals and ceramics, M. Radovic, M. W. Barsoum, *American Ceramic Society Bulletin* (2013)

→ Unique, combination of properties: **METALS & CERAMICS**

→ **Conduct heat and electricity** like metals

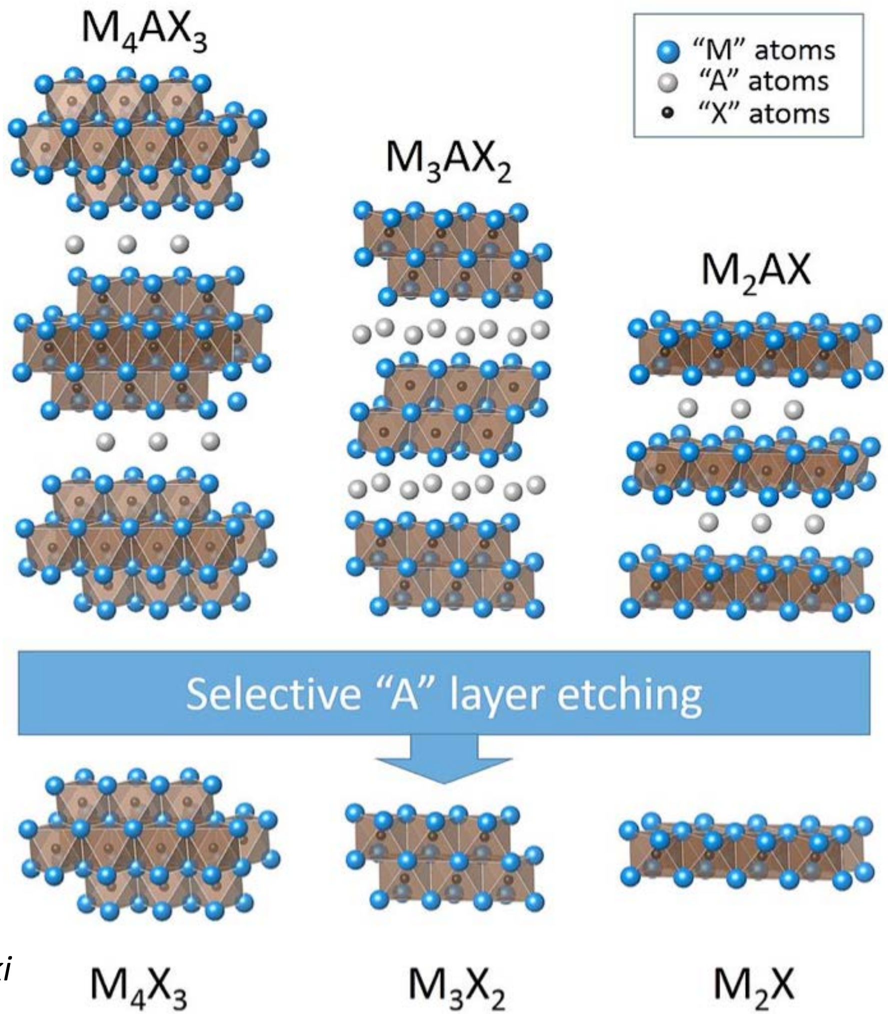
→ **Elastically stiff, strong, brittle, and heat-tolerant** like ceramics

→ Chemically-, thermally stable, readily machinable, damage tolerant

→ Fatigue, creep, and oxidation resistant

MAX/MXenes

The next generation of sustainable, cost-effective materials for technological use



Wiki

2D materials: unique properties!
Graphene – just Carbon!

"MAX" & "Graphene" = "MXene"

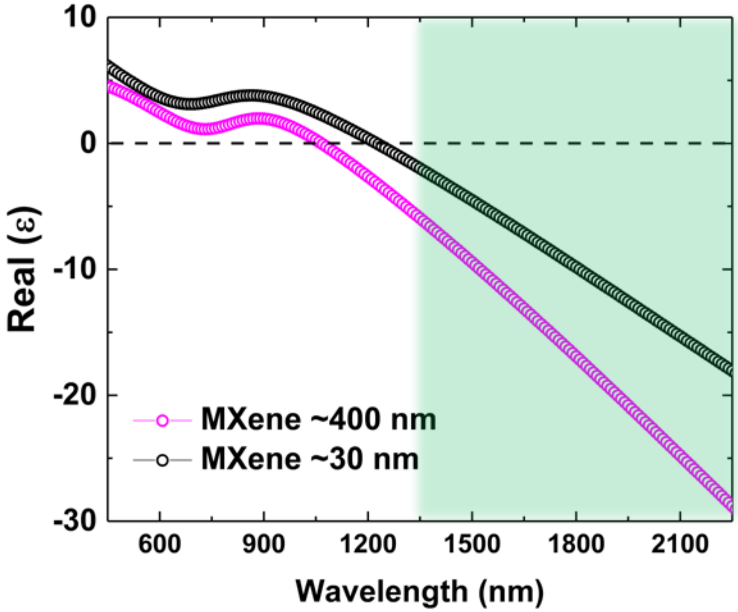
MAX Layered structure → Kink and delaminate during deformation → 2D early TM carbides/carbonitrides

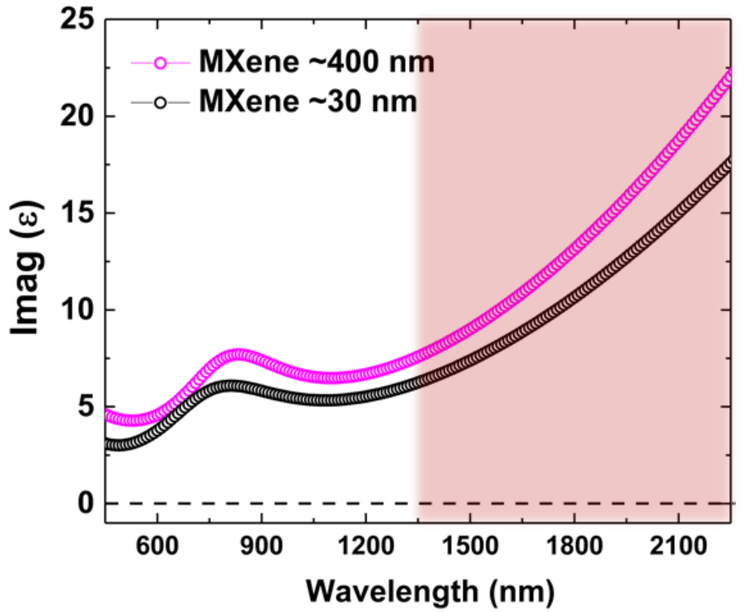
MXenes: M_2X, M_3X_2, and M_4X_3

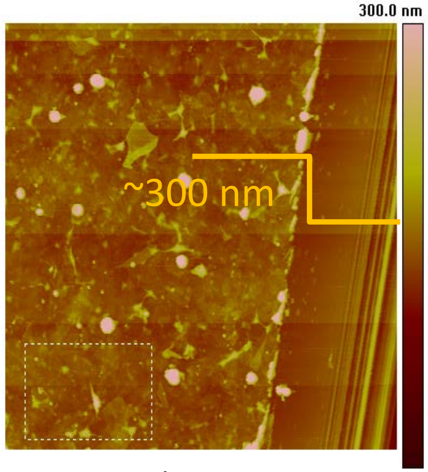
- Bare: metallic (similar to multilayer graphene)
- OH or F terminated: semiconductors with small band gap
- Can be intercalated

With Y. Gogotsi, Drexel

$Ti_3C_2T_x$ MXene thin FILMS







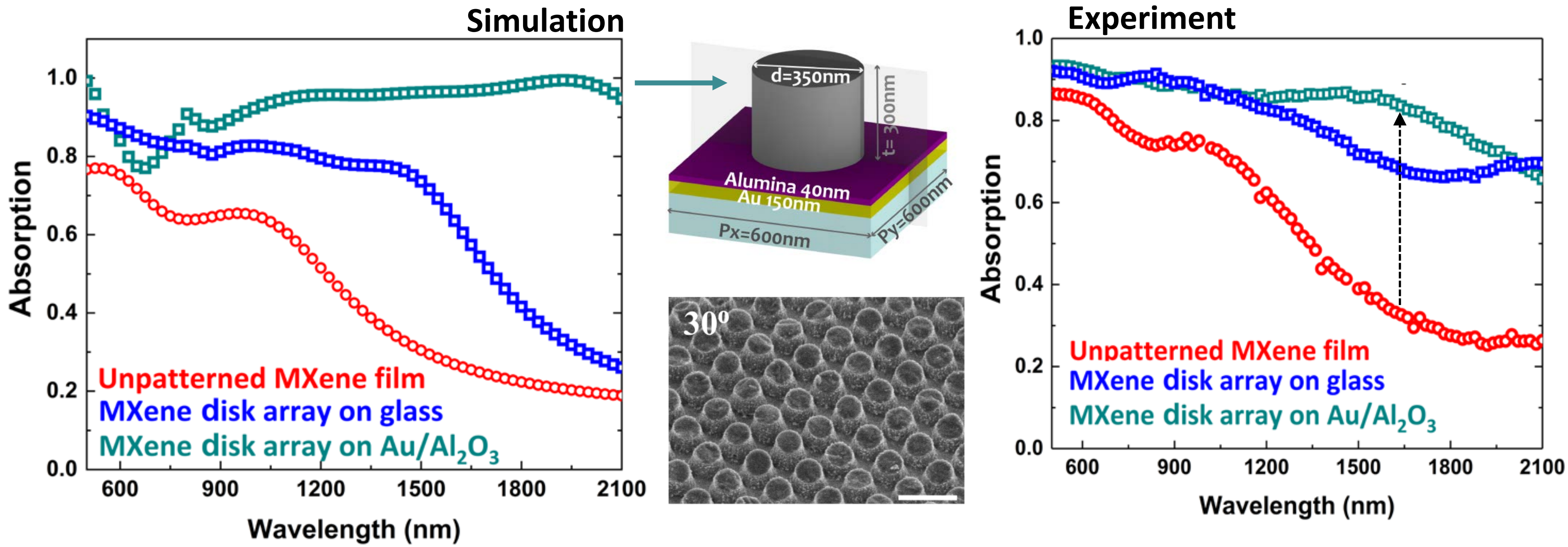
RMS roughness ~ 15 nm

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\Gamma_p)} + \frac{f_1\omega_1^2}{\omega_1^2 - \omega^2 - i\omega\Gamma_1} + \frac{f_2\omega_2^2}{\omega_2^2 - \omega^2 - i\omega\Gamma_2}$$

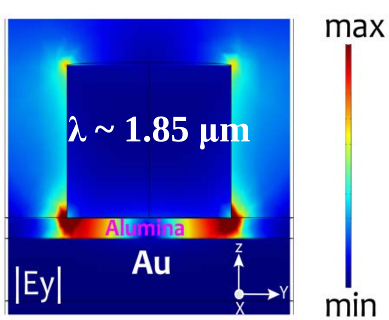
Optical losses

- Inter-band transitions
- Scattering in the rough/disordered structure

MXene BROADBAND ABSORBER



Ti_3C_2 disks/pillar-like structures:
LSPR in NIR

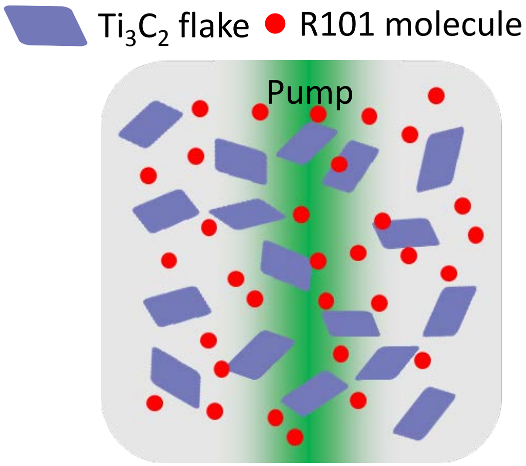


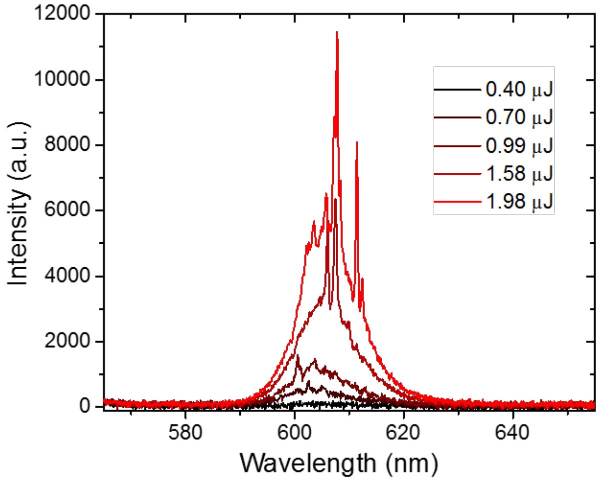
- **The first experimental exploration of MXene $Ti_3C_2T_x$ as a functional plasmonic broadband absorber**
- **Simple design** of the absorber: utilizes both the inherent absorption in MXene, as well as the scattering enhancement at the plasmonic resonances at longer wavelength
- Optimized to design: **efficiency in NIR >80% in λ~0.5-1.6um**

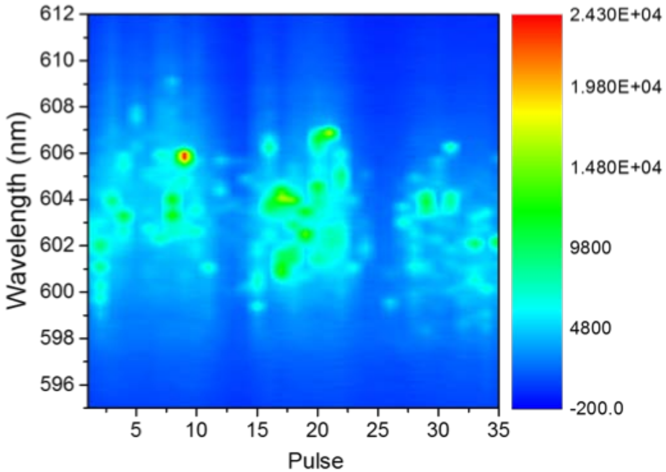
With Y. Gogotsi, Drexel

K. Chaudhuri, … Y. Gogotsi, A. Boltasseva, ACS Photonics (2018)

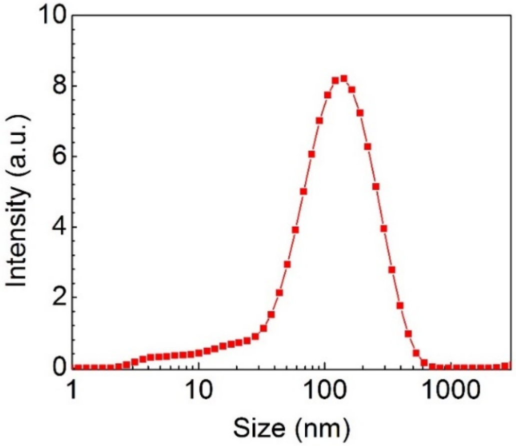
MXenes FOR RANDOM LASING







Size distribution of Monolayer $Ti_3C_2T_x$ flakes in water



- Active system composed of 2D graphene nanoflakes can operate as cavity-free random lasers due to the ultra low threshold of saturable absorption of graphene. Phys. Rev. Lett. 116, 217401 (2016)
- Experimentally demonstrated random lasing with $Ti_3C_2T_x$ nanoflakes (diameter ~ 85 nm) and dye molecules
- The lasing effect can be tunable by varying the concentration of $Ti_3C_2T_x$ nanoflakes

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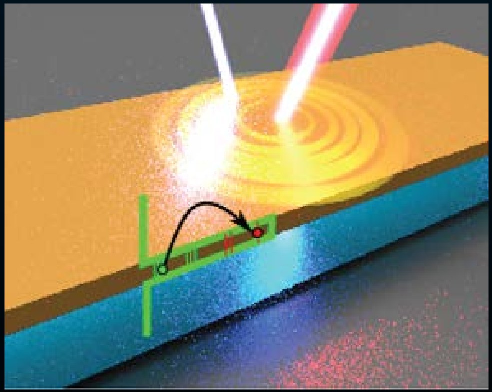
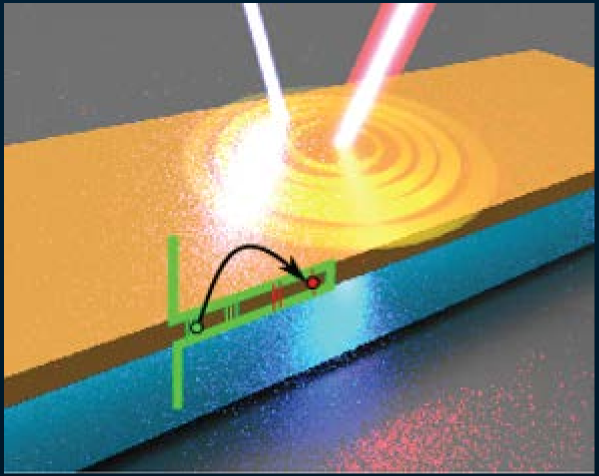


SWITCHABLE/DURABLE/FLEXIBLE PHOTONICS

PLASMONIC CERAMICS

- *Durable//high-T/intensity stable/nonlinear*
- *Ultra-thin/CMOS-compatible*

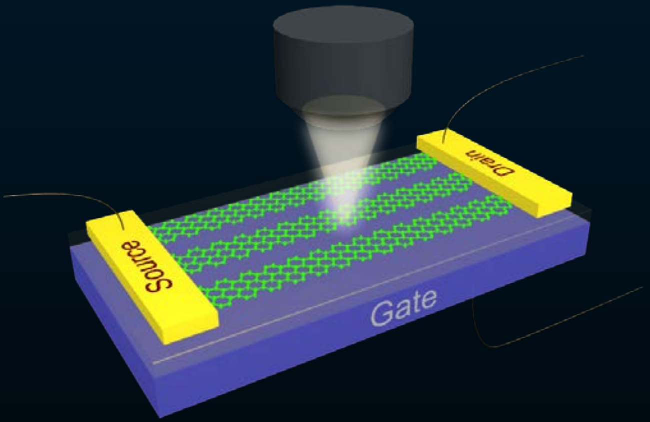


CONDUCTING OXIDES

- *Plasmonic materials in NIR*
- *Great switching opportunities*

Ultra-Thin Plasmonic Films

- *Quantum confinement enhanced nonlinearities*
- *Dynamic control over optical response*
- *Highly confined plasmons*



GRAPHENE/2D/MXenes

- *Strong electrical tunability/Highly confined SPs*

Applications

- *Flat Optics, Flexible/Conformal Optics, TPV*
- *Optical Modulators, NIR/VIS photodetectors, Lasers, THz polarization controllers*

Groups of N. Halas, H. Giessen, H. Atwater, N. Zheludev, M. Brongersma, L. dal Negro, O. Muskens, D. Basov, J. Garcia de Abajo, F. Koppens, and other

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PURDUE UNIVERSITY

TEAM AND SUPPORT

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- Office of Naval Research (ONR-MURI N00014-10-1-0942, N00014-16-1-3003)