PURDUE UNIVERSITY Discovery Park

BIRCK Nanotechnology Center

PURDUE UNIVERSITY

How Plasmonic Materials Make Light Work at Nanoscale

BUILDING NANOSCALE PHOTONIC TECHNOLOGIES OF THE FUTURE

Alexandra Boltasseva

School of Electrical & Computer Engineering
Birck Nanotechnology Center
PURDUE UNIVERSITY

PURDUE UNIVERSITY

THE INTERNATIONAL YEAR OF LIGHT

UNESCO

United Nations Educational, Scientific and Cultural Organization

International Year of Light 2015

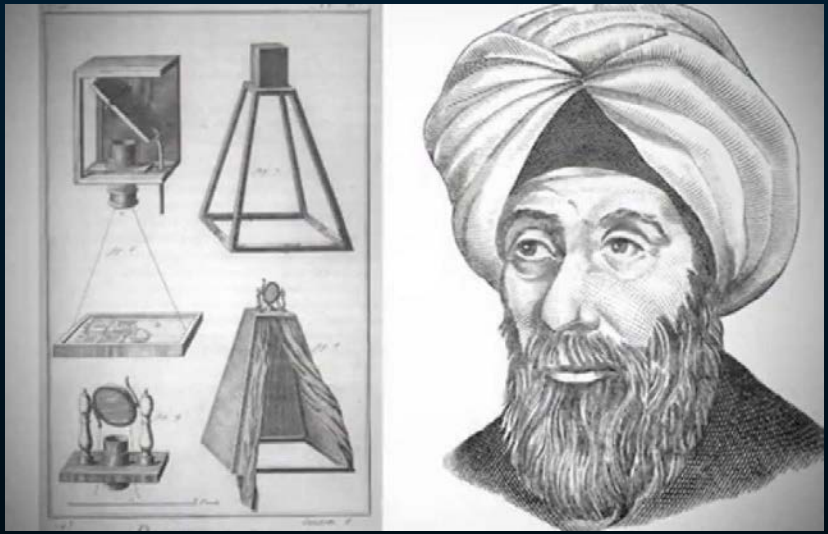
Optical technologies promote sustainable development and provide solutions to worldwide challenges in communication, energy, education, agriculture and health

http://www.light2015.org/Home.html

PURDUE UNIVERSITY

THE INTERNATIONAL YEAR OF LIGHT

1,000-old "Book of Optics" transformed our understanding of optics and light:
Introduction of scientific method!



http://www.muslimsdigest.com

https://www.natureasia.com

1015: Works on optics by Ibn Al-Haytham (965-1039) the Father of Optics

OPTICAL TECHNOLOGIES

Communication

https://www.mpoptical.com

Health

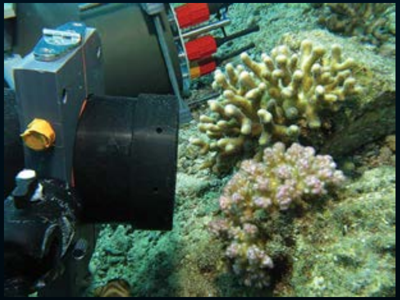
www.universalmedicalinc.com

Energy

https://www.bam.de

Economy

Environment



Scripps Inst. of Oceanography

Agriculture

Consumer Physics

Social

Yui Mok/Zuma Press

IMPACT OF INFORMATION TECHNOLOGIES

The ever-increasing need for faster information processing and exchange is undeniable!

FASTER!

MORE

BANDWIDTH!

ELECTRONICS VS PHOTONICS

Electronics	Nanophotonics
Electrons	Photons
Wires	Waveguides

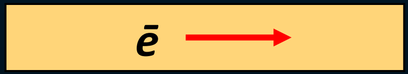
f ~ 10^{10} Hz (GHz) f ~ 10^{15} Hz (THz)

Electronic signal delay is due to resistive-capacitive effects (RC delay) hindering the speed increase in microelectronics

ELECTRONICS VS PHOTONICS

How many audio channels of 64 kbps can be transmitted over a 4G cell phone signal of 1.9 GHz?

How many audio channels of 64 kbps can be transmitted over a fiber optic cable operating at a wavelength of 1.3 µm?



f ~ 10^{10} Hz (GHz)

f ~ 10^{15} Hz (THz)

LET'S JUST REPLACE ALL ELECTRONICS WITH PHOTONICS!

ELECTRONICS VS PHOTONICS

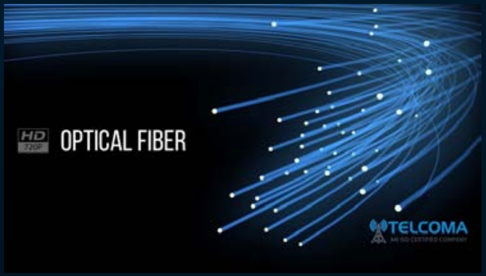
We already replaced coaxial cables with Optical Fibers!

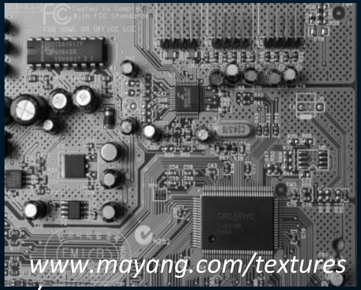
Replacing electronics with on-chip optics

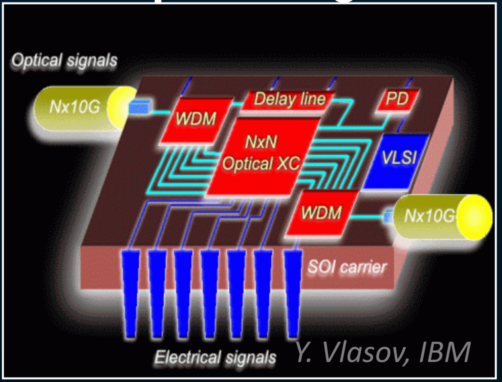
Deep scaling of

<~ 100nm

Wikipedia







Still diffraction limited!

Fiber Optics: Transmitting Information

Integrated Optics/Nanophotonics: Processing Information on a Chip!

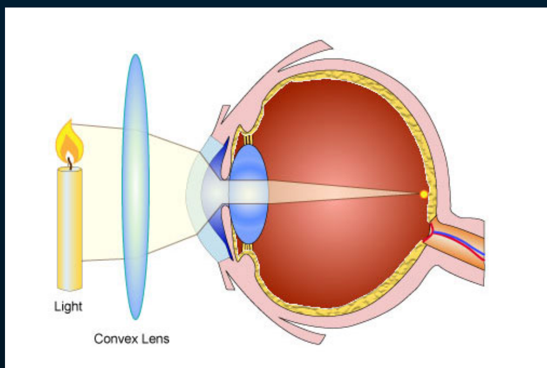
BUT: Diffraction limit sets the minimal waveguide size….

NEED NEW APPROACHES TO MATCH SIZES…

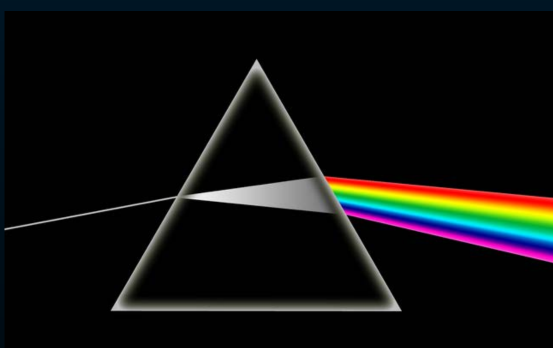
PURDUE UNIVERSITY

NEED FOR NEW APPROACHES

Refraction

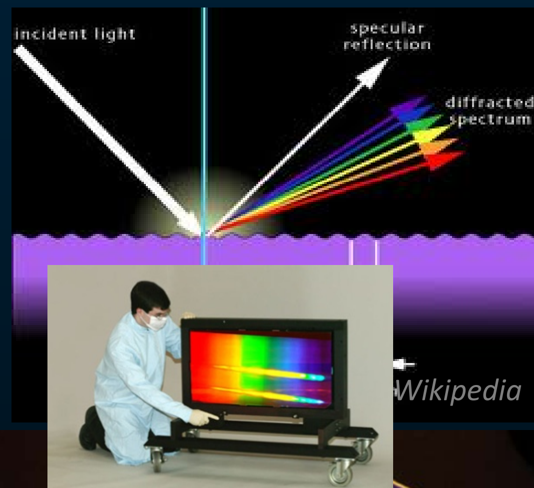


www.passmyexams.co.uk



asvus.it

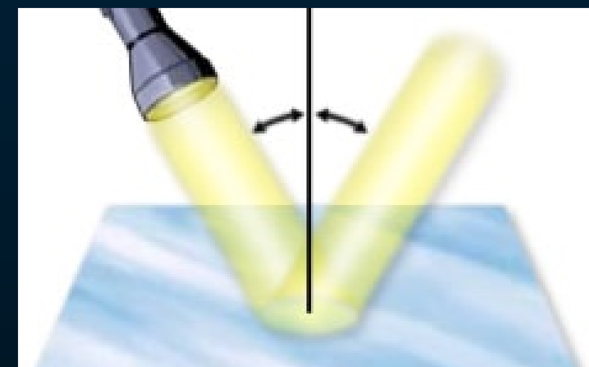
Diffraction



Wikipedia

Wikipedia

Reflection

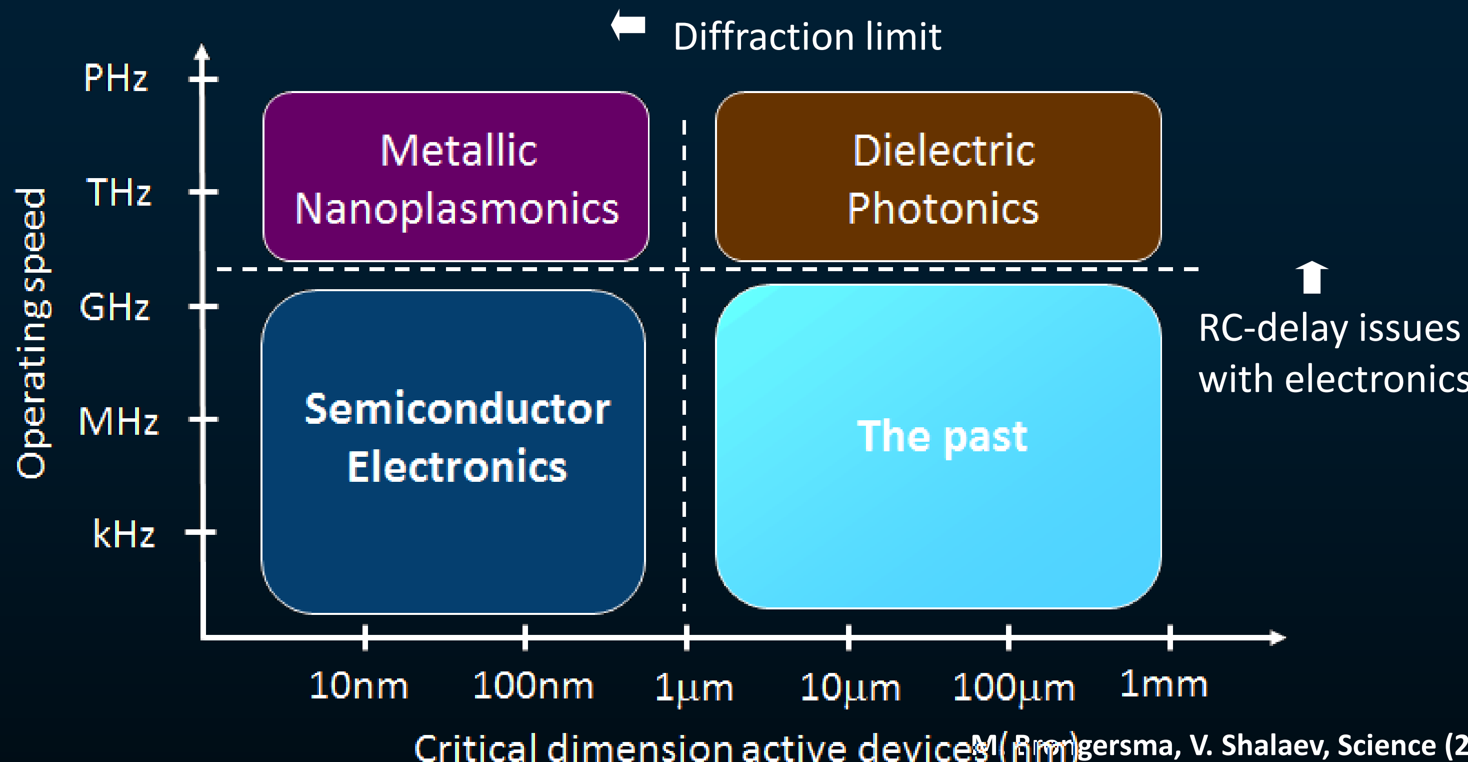


micro.magnet.fsu.edu

Wikipedia

WHAT'S NEXT?

Operating regimes of different technologies



M. Brongersma, V. Shalaev, Science (2010)

- Improved synergy between electronic and photonic devices
- Solution to the size-compatibility problem
  - Plasmonics naturally interfaces with *similar size electronic components*
  - Plasmonics naturally interfaces with *similar operating speed photonic networks*

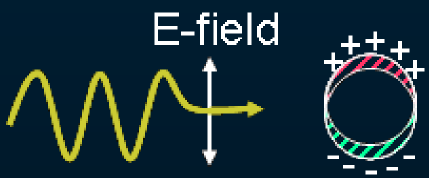
CHALLENGE

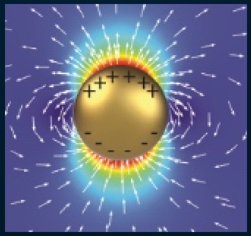
How to couple light down to NANOSCALE?

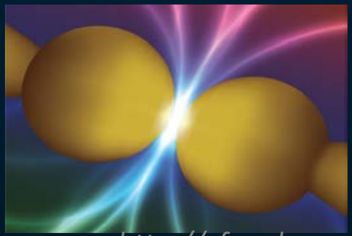
NANOPHOTONICS=PLASMONICS

Localized SURFACE PLASMONS with METALS

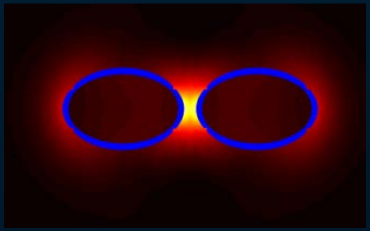
Free – electrons
Negative epsilon



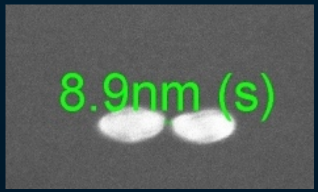




http://cfm.ehu.es

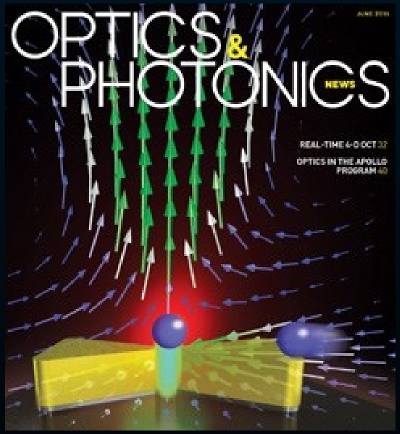


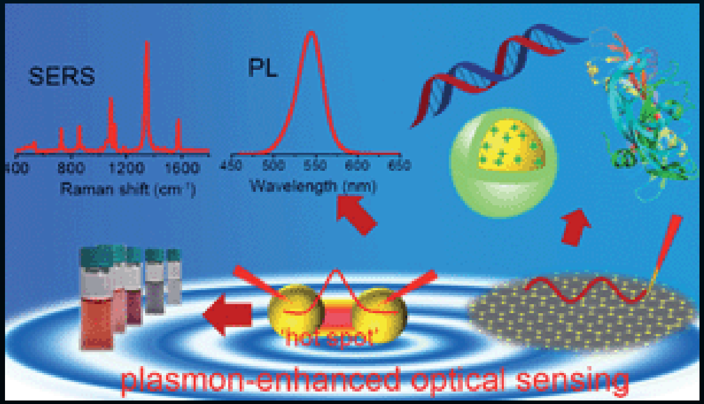
M. Mikkelsen



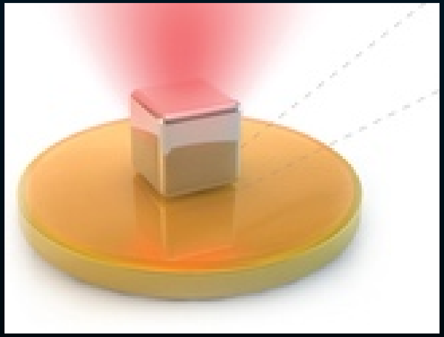
Z. Liu et al, Metamaterials (2008)

Optical Nano-Antenna (Nano Imaging, Sensing, Therapy, Energy, Quantum!...)





Li, Cushing, Wu



M. Mikkelsen

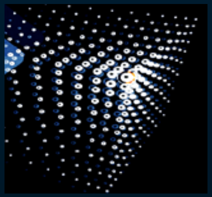
PURDUE
UNIVERSITY

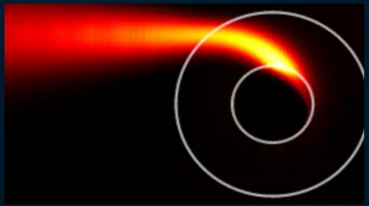
NANOPHOTONICS=PLASMONICS

Localized SURFACE PLASMONS with METALS

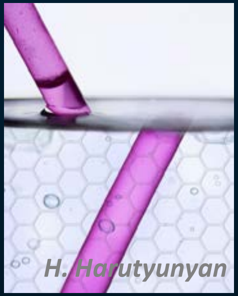
Free – electrons
Negative epsilon

Optical Metamaterials

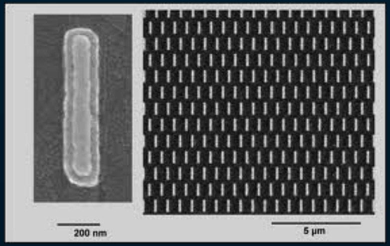




Narimanov, Kildishev groups



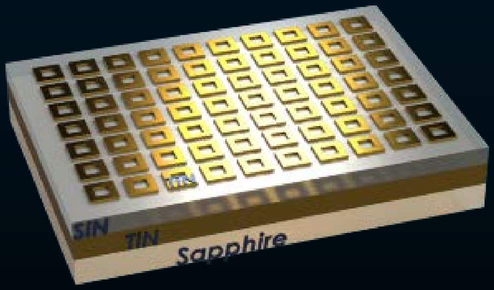
H. Harutyunyan



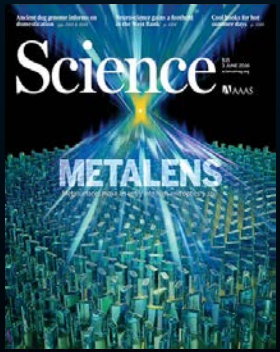
Shalaev group

1-st optical
negative-refractive index material

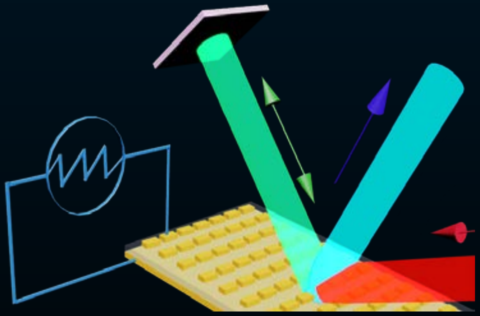
Optical Metasurfaces (ultra-thin/flat optics, sensors, energy…)



W. Li et al., Adv. Mater. 26, 7959 (2014)



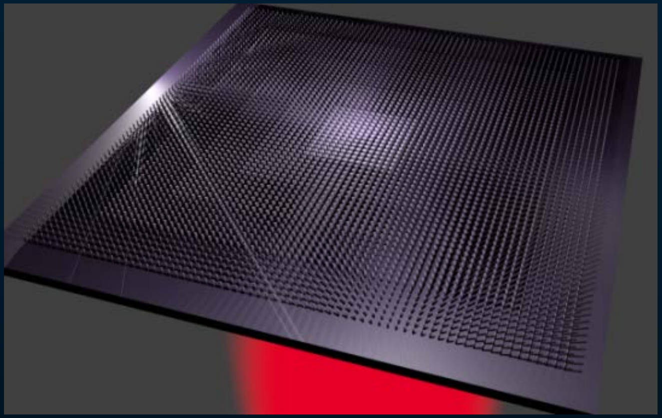
F. Capasso



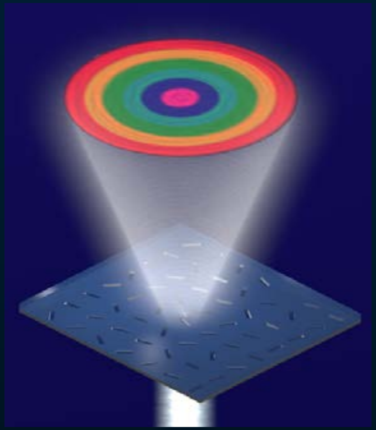
Shalaev group

EMERGING FLAT OPTICS

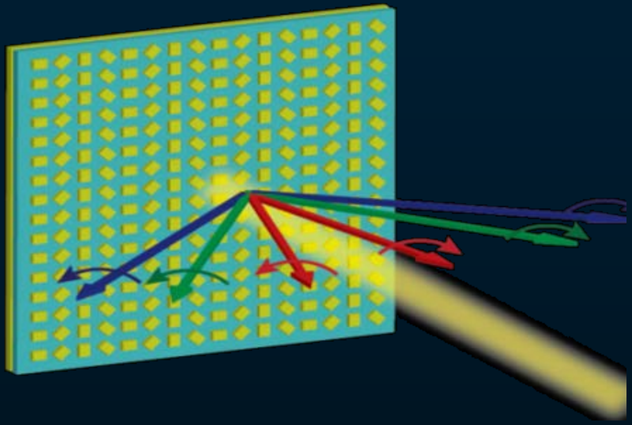
Ultra-Thin Lens



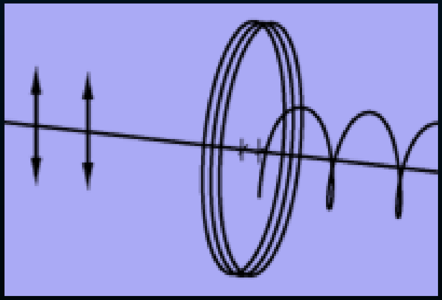
Color Hologram

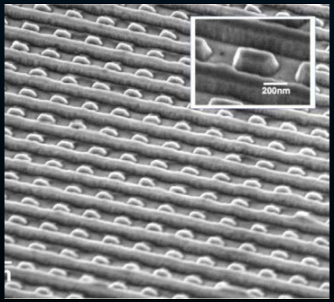


Ultra-Thin CD Spectrometer

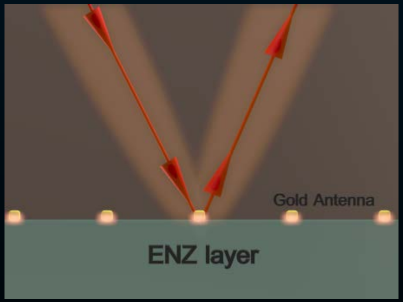


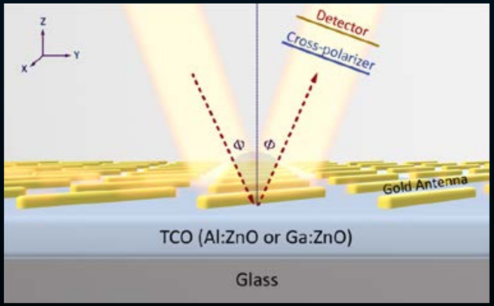
Ultra-Thin Wave Plates



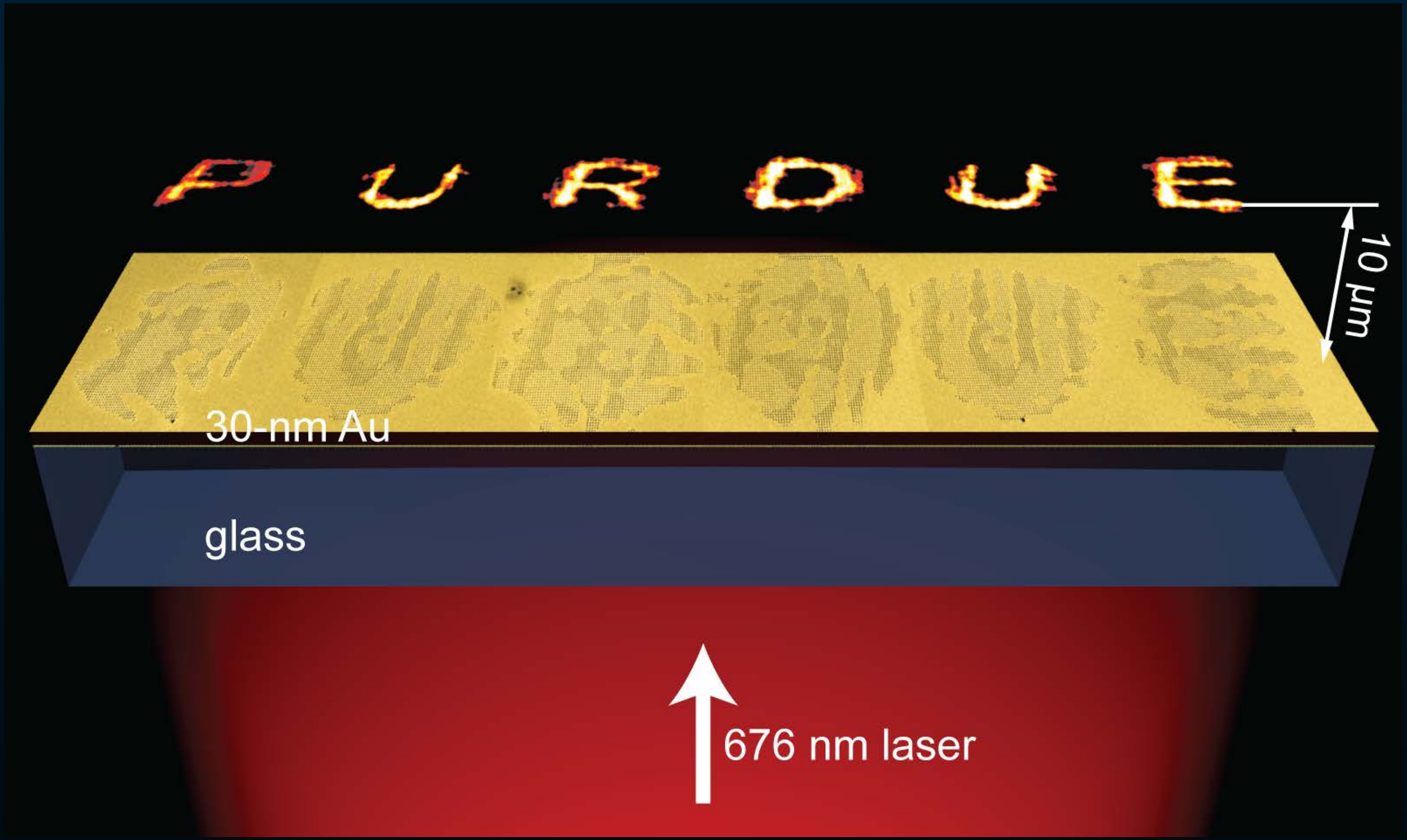


Light Emission Engineering





ULTRA-THIN HOLOGRAM

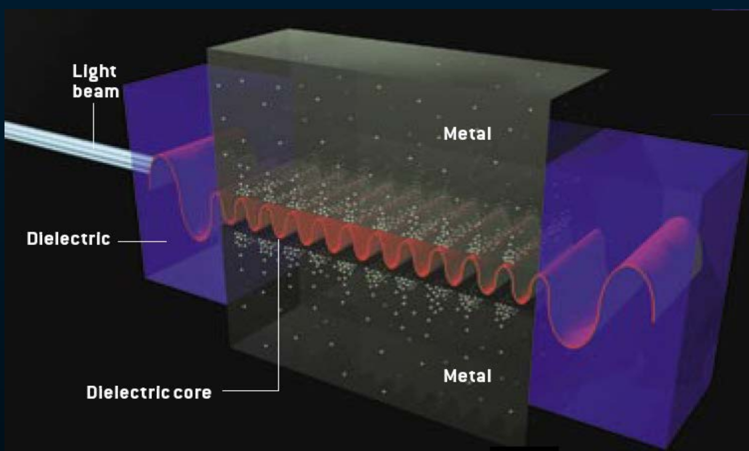


Shalaev group

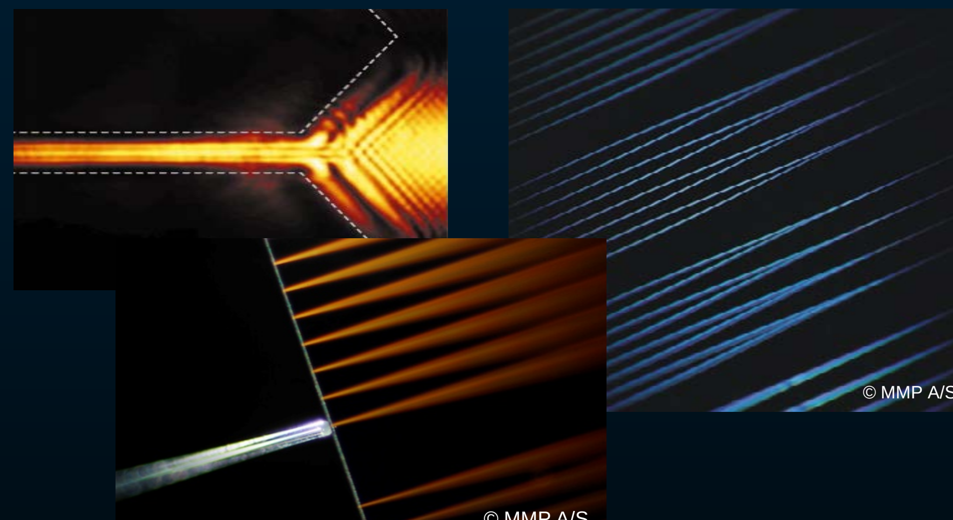
NANOPHOTONICS=PLASMONICS

Propagating SURFACE PLASMONS

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



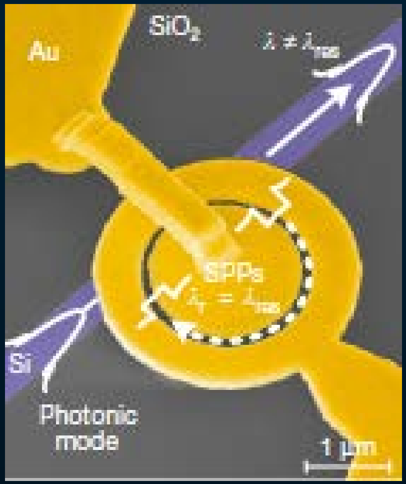
Atwater, Scientific American, 2007

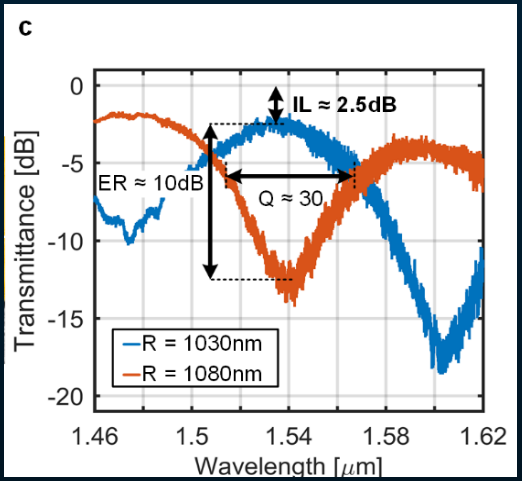


Plasmon Slot Waveguide can squeeze the optical signal by shrinking its wavelength by a factor of 10 or more

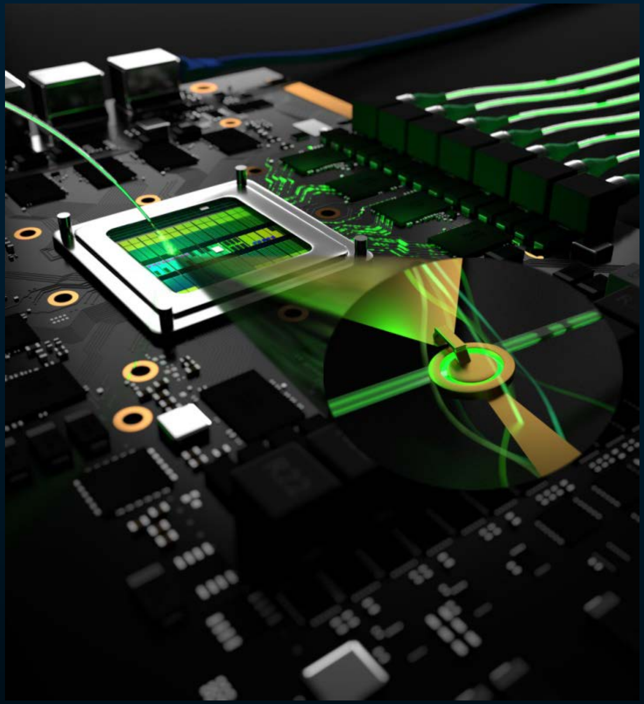
PLASMONICS FOR HYBRID ON-CHIP CIRCUITRY

Low-loss plasmon-assisted electro-optic modulator





SEM image of a plasmonic ring resonator and the corresponding transmittance



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, & L. Dalton, U Wash

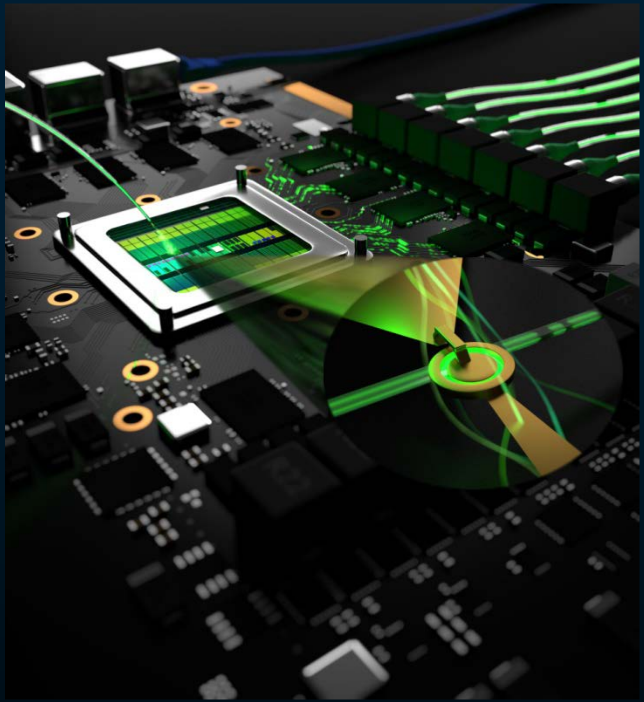
Plasmonic circuitry:

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

PLASMONICS FOR HYBRID ON-CHIP CIRCUITRY

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)

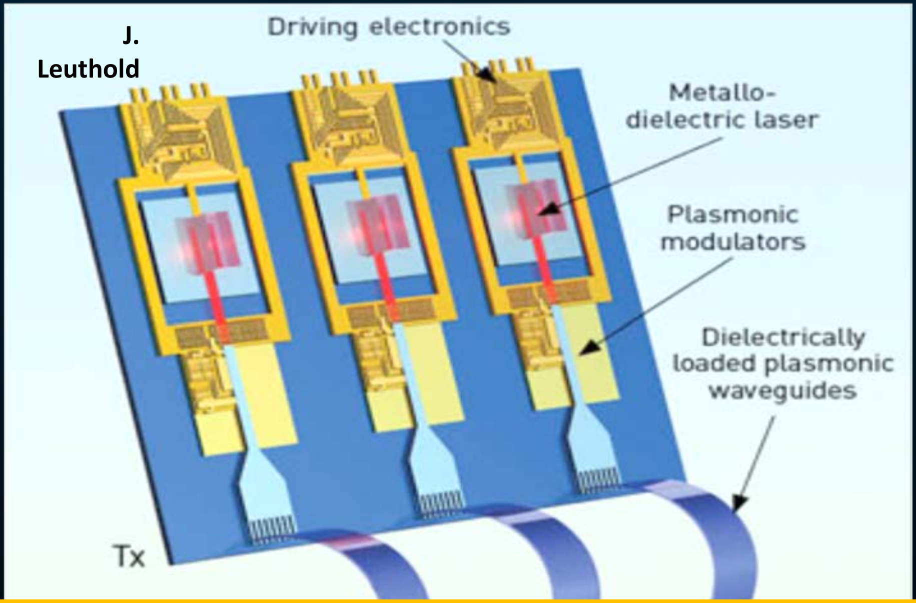


In collaboration with ETH, J. Leuthold and VCU, N. Kinsey
C. Haffner, et al., *Nature* (April 26, 2018)

NANOPHOTONICS=PLASMONICS

Propagating SURFACE PLASMONS

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



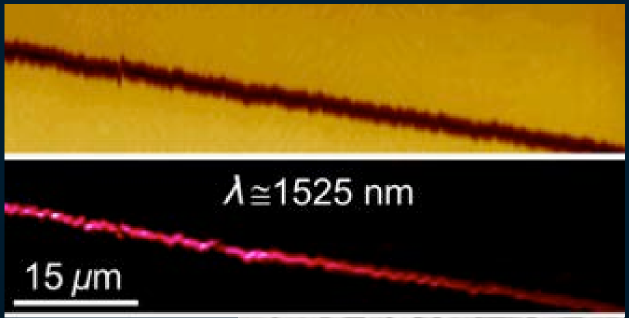
PROBLEM SOLVED?

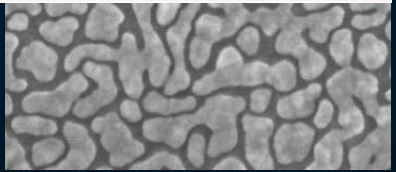
PURDUE
UNIVERSITY

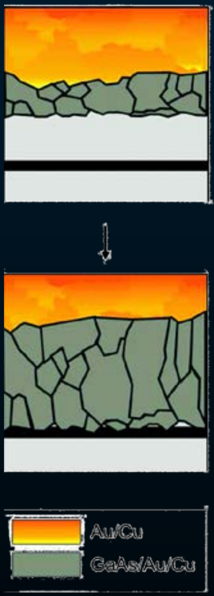
MATERIALS BUILDING BLOCKS

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



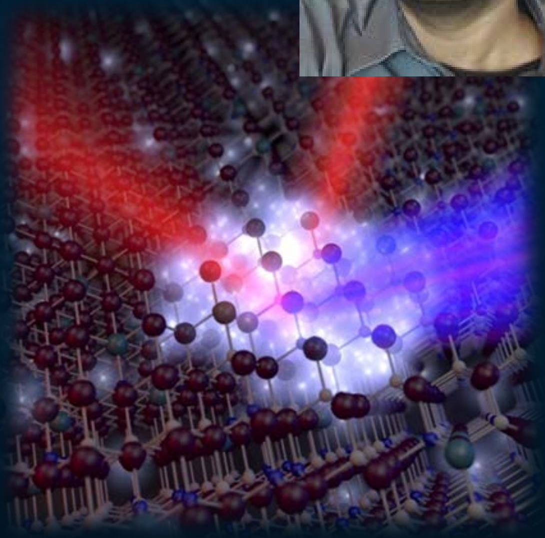


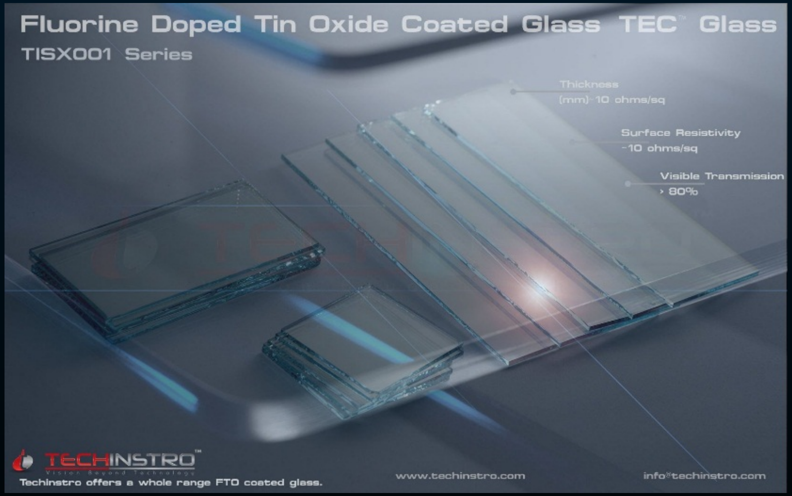


***TUNABLE/SWITCHABLE* response and *STABILITY* remain a challenge!**

NANOPHOTONICS WITH CONDUCTING OXIDES

- Indium Tin Oxide (ITO)/Doped Zinc Oxide, Cd Oxide
- Conducting + Low light absorption!
- **Plasmonic at TELECOM wavelength of 1.5um!**
- **PROPERTIES CAN BE ADJUSTED/TUNED!**
  - ALL-OPTICALLY!
  - Electrically

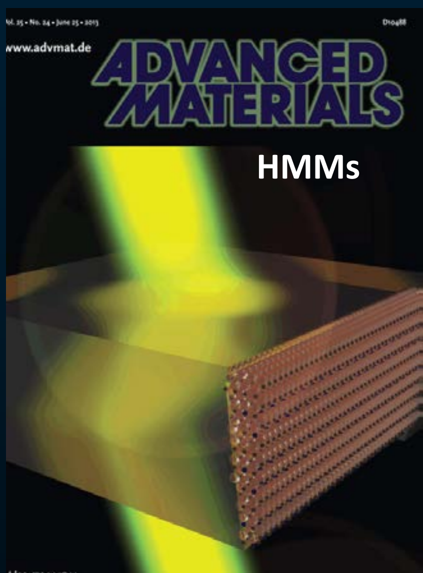


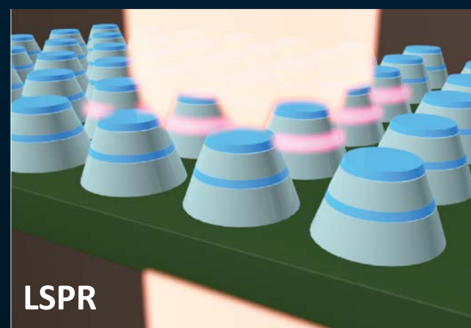


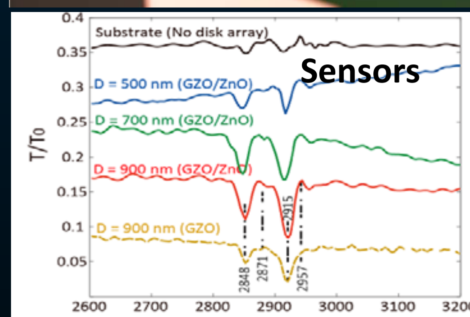
IGZO-based flexible screen

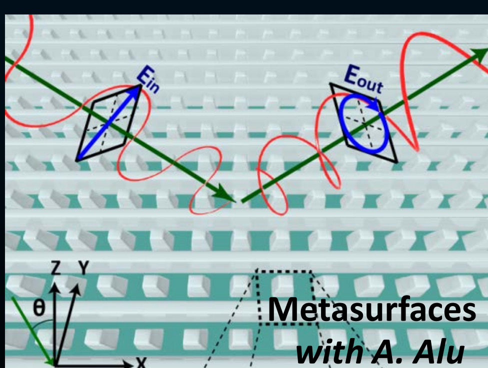
TCO HIGHLIGHTS/RESULTS

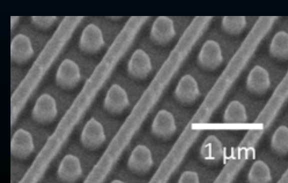
- New functional devices and new physics unlocked by LOW-LOSS **TCOs**
  - *Plasmonics/Metamaterials/Metasurfaces in NIR*
  - *Ultra-fast switching/Enhanced Nonlinearities*



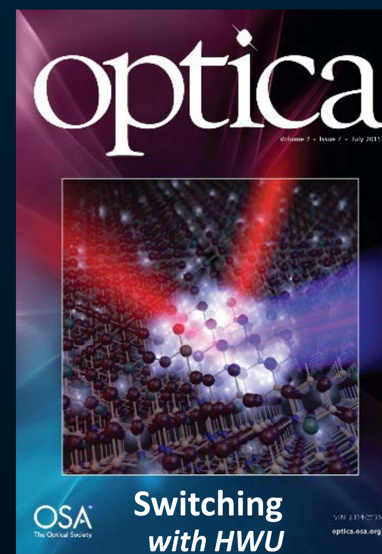


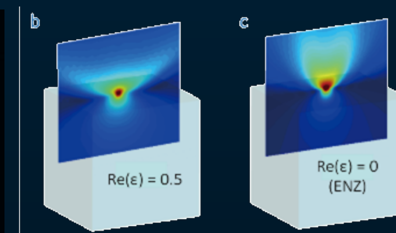


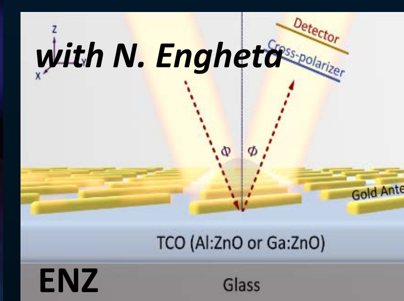


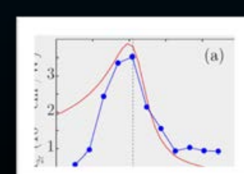


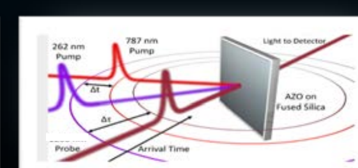
IEEE-JSTQE 2013
PNAS 2012
AdvMat 2013
ACS Ph 2015
ACS Nano 2016









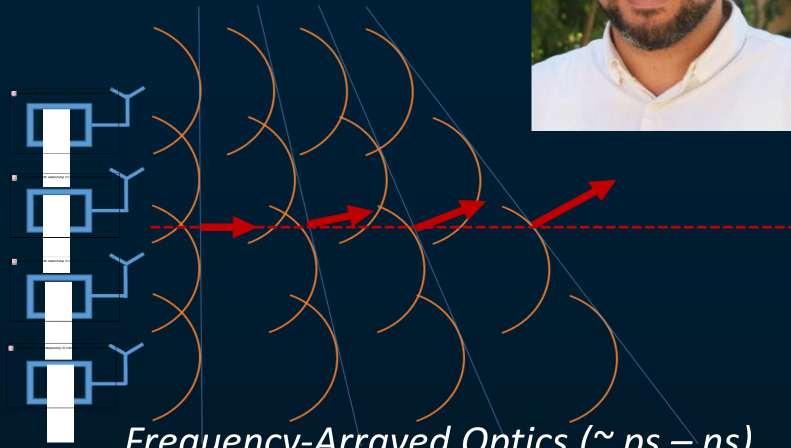


with HWU

Optica 2016
Optica 2016
PRL 2016
NatCom 2017

METASURFACES FOR LIDAR AND SECURITY

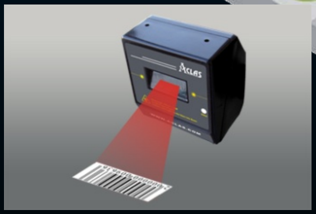
Ultrafast Laser Beam Steering Using Frequency-Arrayed Optics



Frequency-Arrayed Optics (~ ps – ns)

Non-mechanical Steering
Lighter, Faster , More Compact

- Scanners
- 3D printing
- Remote Sensing
- Geographic mapping
- Biology
- Autonomous Vehicles



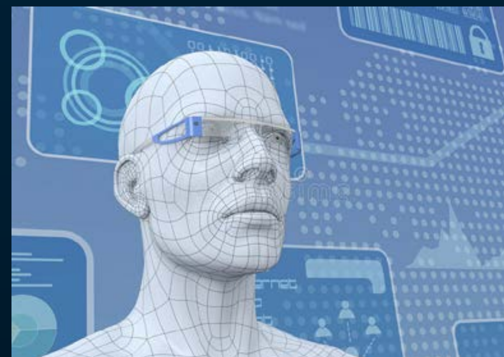
Continuous Angle Steering
Angle of View ~ 25^0
Steering Time ~ 10 ps (order of magnitude less)

Purdue-Stanford
Shalaev, Brongersma groups

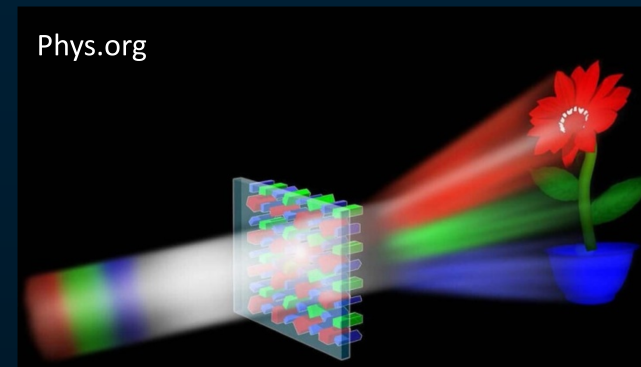
PURDUE
UNIVERSITY

FUTURE FLAT/CONFORMAL OPTICAL TECHNOLOGIES

Lightweight Optical Wearables



Smart Glasses/Night Vision



Augmented Reality/Real-Time Holograms

Smart Windows/Thermal Control/Holograms/Transparent Screen

Smart Windows/Skins for Vehicles

Images from Dreamstime.com/Phys.org/Hight3ch.com

PURDUE UNIVERSITY

METALS TO 'LESS-METALS'

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

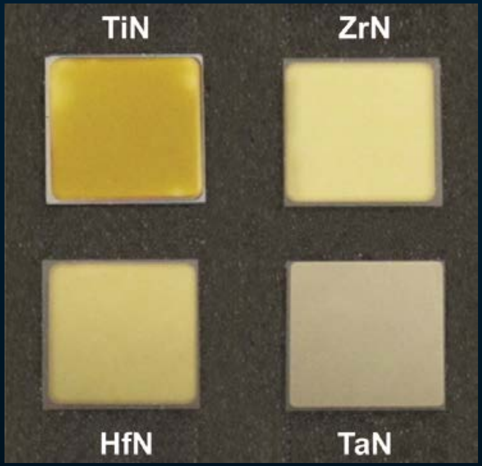
Many compounds:

Intermetallics

Ceramic materials

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

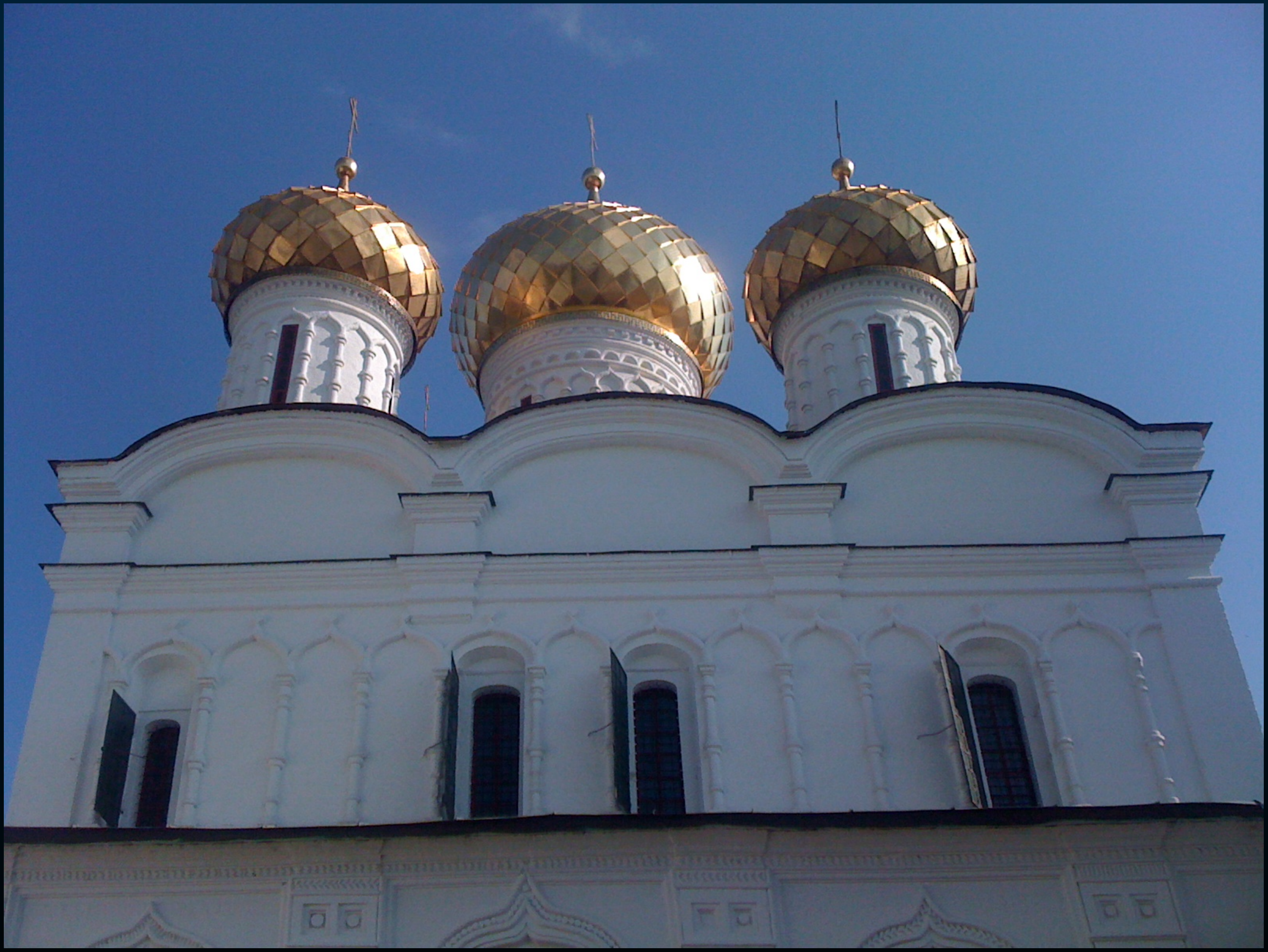
Wiki:
Ceramics = metal + non-metal



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

See work by E. Hu, H. Giessen, M. Blaber, M. Ford, Soref, L. dal Negro, A. Zayats, A. Calzolari and other

ALL THAT GLITTERS NEED NOT BE GOLD!



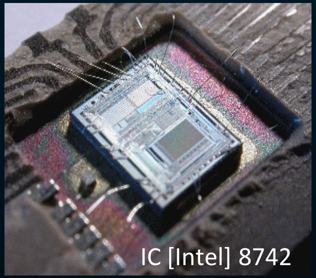
Images from Wikipedia

PURDUE UNIVERSITY

TITANIUM NITRIDE

- **Metallic/Plasmonic:** Golden luster
- Hard & tough: high speed drill-bits, coatings
- Deposition: CVD, sputtering, evaporation…
- **Epitaxial growth** on c-sapphire, MgO, and silicon *(2nm layer)*
- Mechanically, chemically stable
- **BIOCOMPATIBLE** high biostability
  - BioMEMS
  - Medical implant
- **CMOS-**compatible (silicon ICs):
  - Gate metal
  - Barrier layer
- **REFRACTORY** (melting point **2900 °C**)

http://www.harborfreight.com



U. Guler et al., Mater. Today 18 (4), 227-237 (2015)

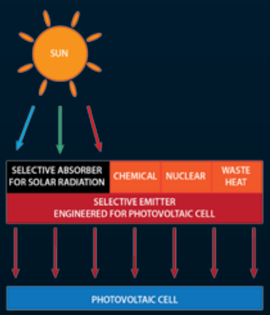
G. Naik, et al. Adv. Mater. 25 (24), 3264 (2013)

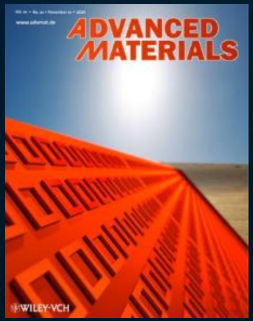
PURDUE UNIVERSITY

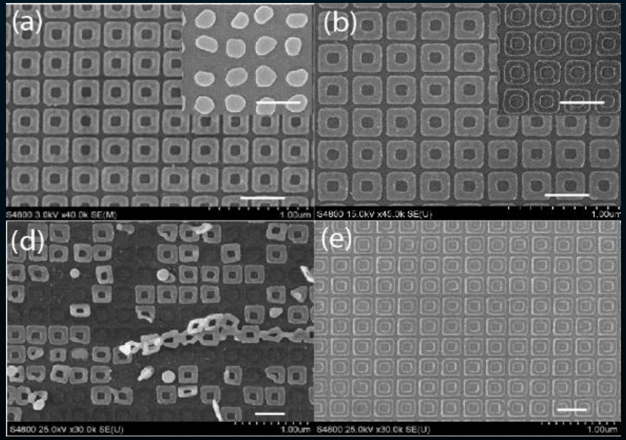
POTENTIAL OF PLASMONIC CERAMIC MATERIALS

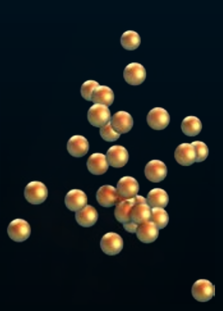
Ceramic (high-T stable) materials with plasmonic properties

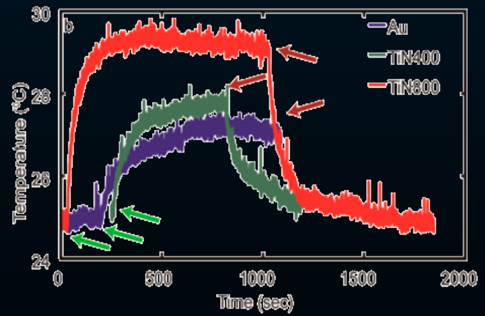
- Photothermal therapy
- Heat-assisted magnetic recording
- Harsh environment sensing
- Solar/Thermophotovoltaics (S/TPV)
- Plasmon-assisted photocatalysis
- Optical trapping/nanomanufacturing



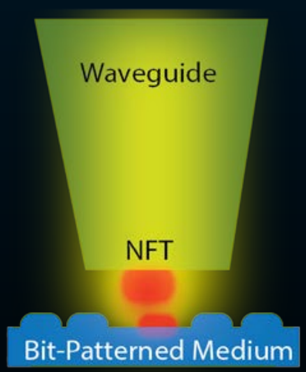








Nano Letters 2013

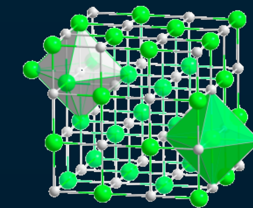


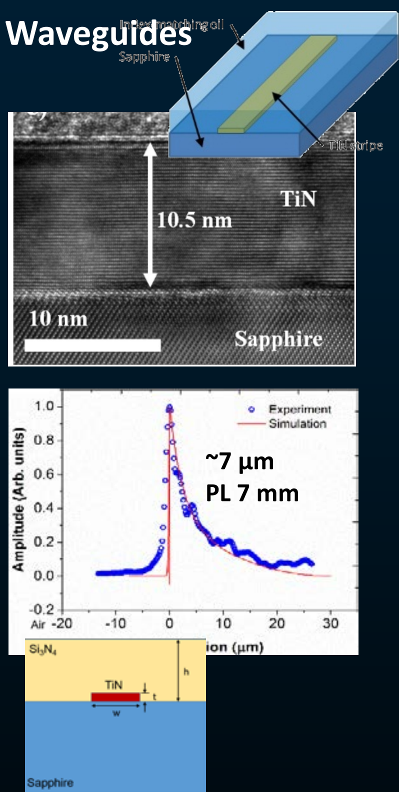
Faraday Discussions 2014

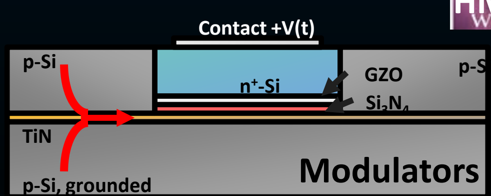
Mater. Today 2014

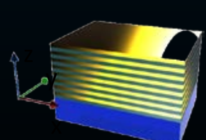
TMNs HIGHLIGHTS/RESULTS

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

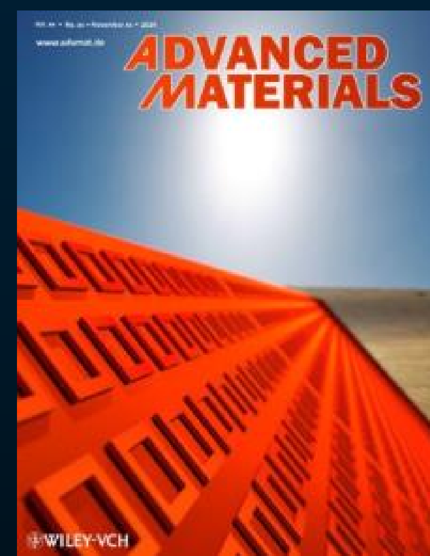


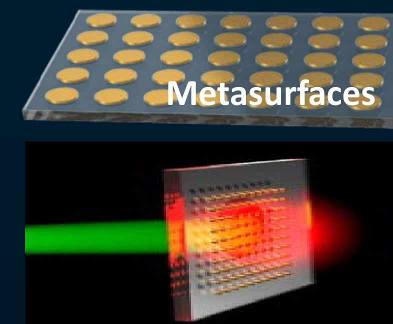


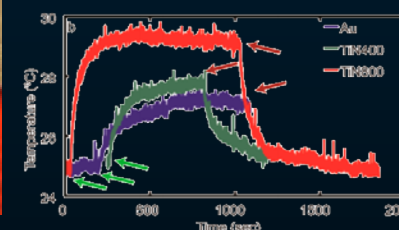




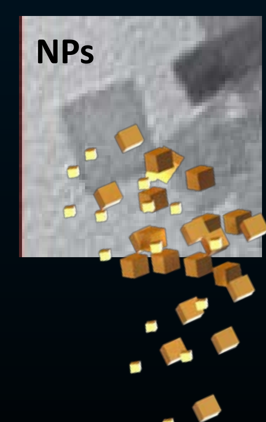
OMEx 2012
PNAS 2014
AdvMat 2013
LPR 2014

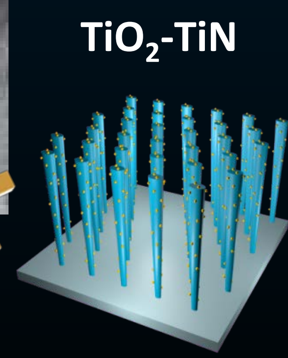


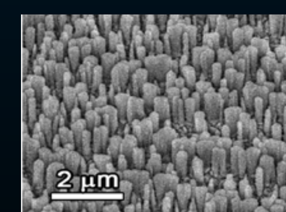




Local heating

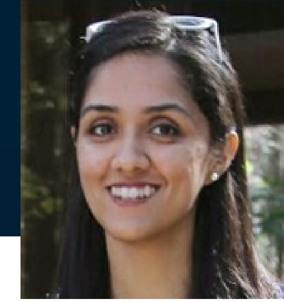




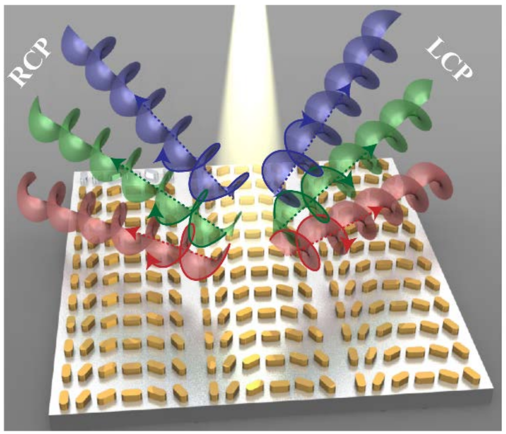


AdvMat 2016
NanoLet 2013
MatToday 2014
AdvOptMat 2017

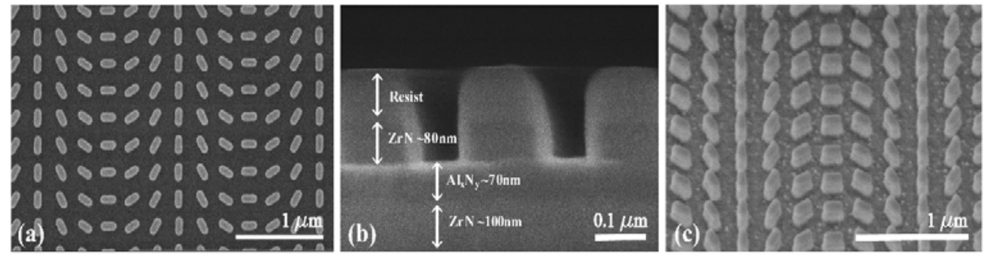
Photonic Spin Hall Effect in TiN Metasurface

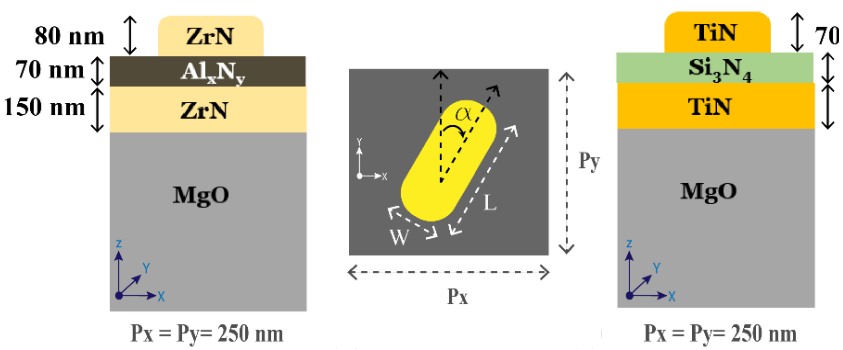


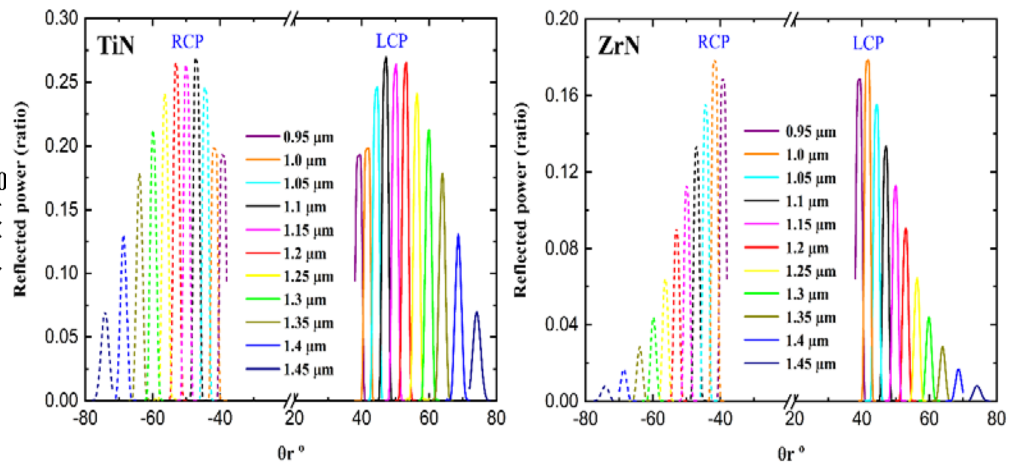
Photonic SHE: Reflects the two photonic spins (left and right circular polarizations, LCP and RCP) in opposite directions with ROBUST Nitrides



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

SOLAR/THERMOPHOTOVOLTAICS (S/TPV)

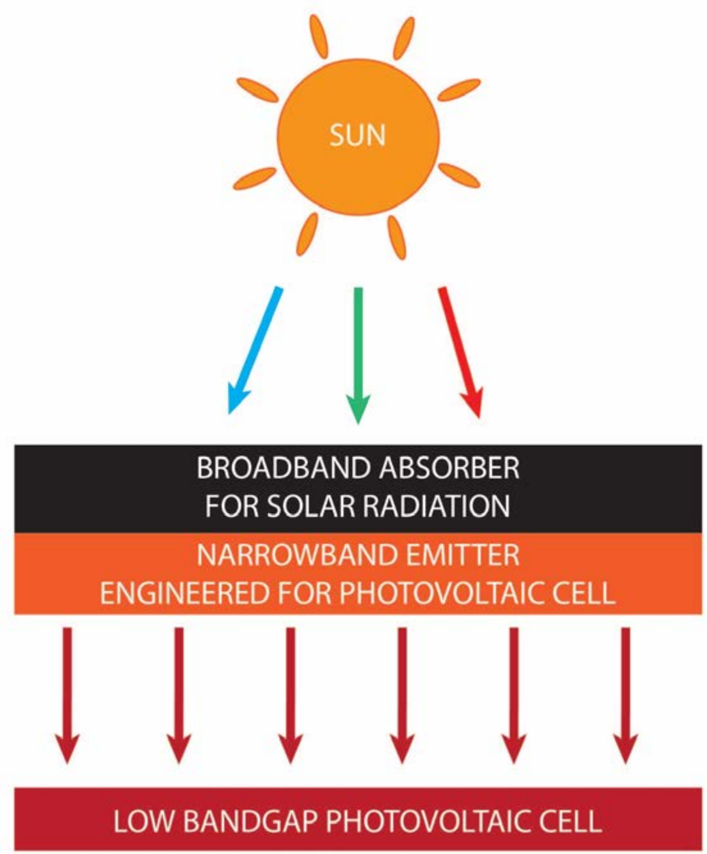
SOLAR/TPV

- **BROAD light ABSORPTION**
- **SELECTIVE “in-band” EMISSION**
- **“Human-made sun”**

85%

High operation temperatures: Above 1000°C

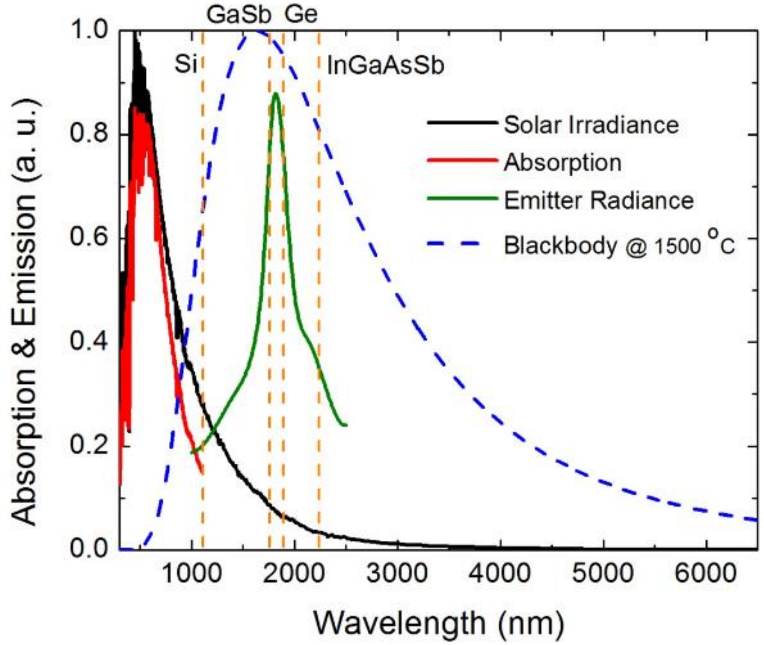
CERAMICS IS NEEDED!

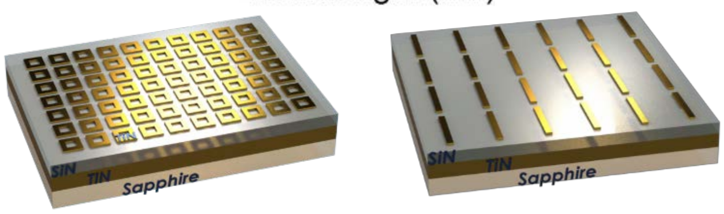


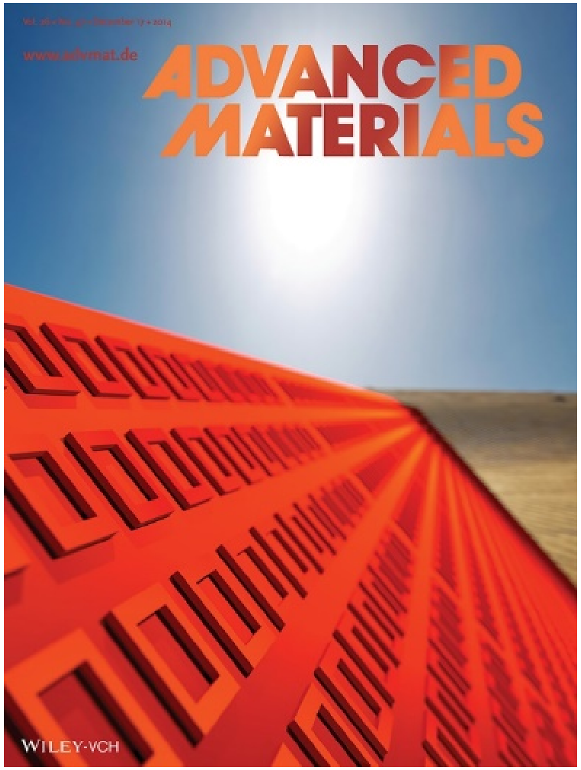
NMTI, Inc

PURDUE UNIVERSITY

TiN for SOLAR/THERMOPHOTOVOLTAIC

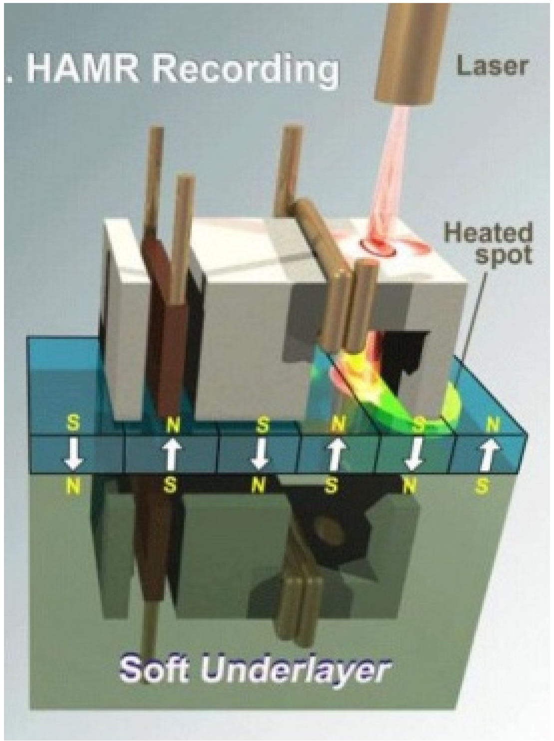






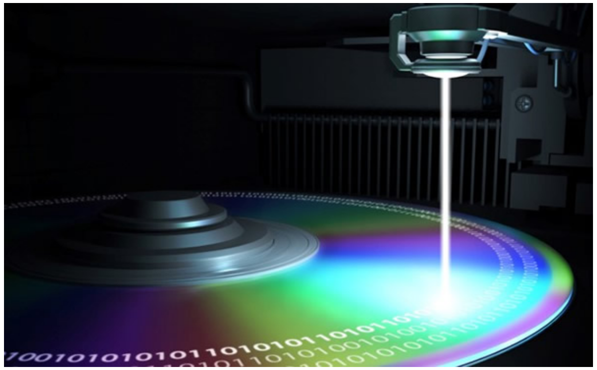
Kildishev, Shalaev, Boltasseva groups
W. Li et al., Adv. Mater. (2014)

HEAT ASSISTED MAGNETIC RECORDING



Western Digital

HAMR promises 10 – 16X greater Hard Disk Drive (HDD) storage densities!



iNTEVAC, INC.

Denser storage **- *SMALLER bit sizes***

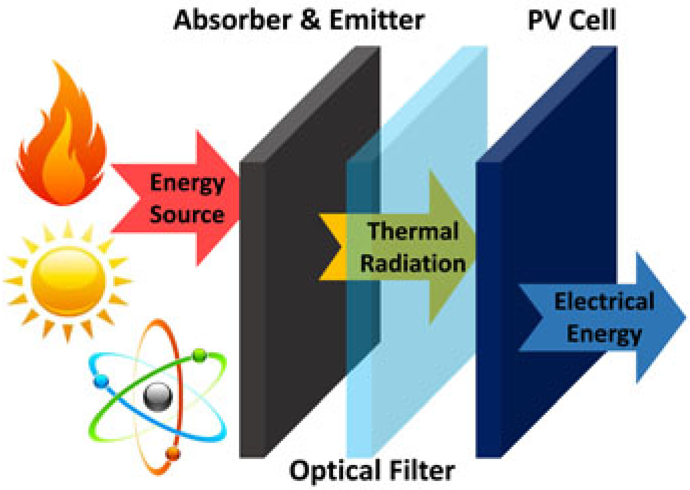
Smaller bit sizes bring instabilities **- *higher coercivity materials***

Higher coercivity material requires ***HIGHER writing T***

Nanoscale heating with light **- *NANOANTENNAE!***

Temperatures up to 500 °C:
Refractory plasmonic antennas needed!

THERMOPHOTOVOLTAIC GENERATOR



Thermophotovoltaic(TPV) System

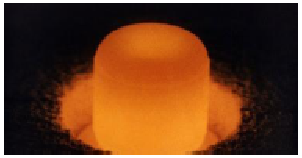
http://mel.khu.ac.kr/

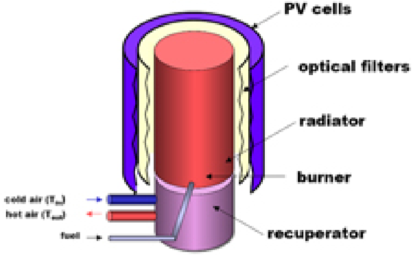
Waste heat harvesting
TPV is capable of waste heat recovery in various applications such as metal casting and fossil-fuel based power generation, including various diesel- and gas powered engines.

Fuel-fired cells
TPV is well-suited for fuel-based power generation for military needs or as a backup energy source. They can also complement solar TPV devices.

Portable generators
1-3KW power generators are typically 15-20% efficient, which can be matched or exceeded in TPV. No-moving-parts TPV devices will be cheaper and easier to maintain.

Radioisotopic cells
use arrays of thermo-couples to convert heat released by radioactive decay into electricity. Their energy efficiency, about 10%, can be surpassed using TPV.





MIT Technology Review, 2006

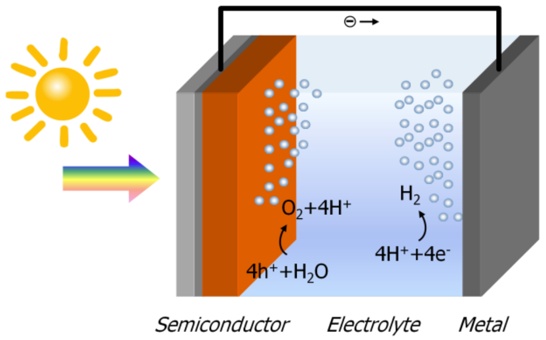
NMTI, Inc

08/22, 4:10pm, S. Azzam

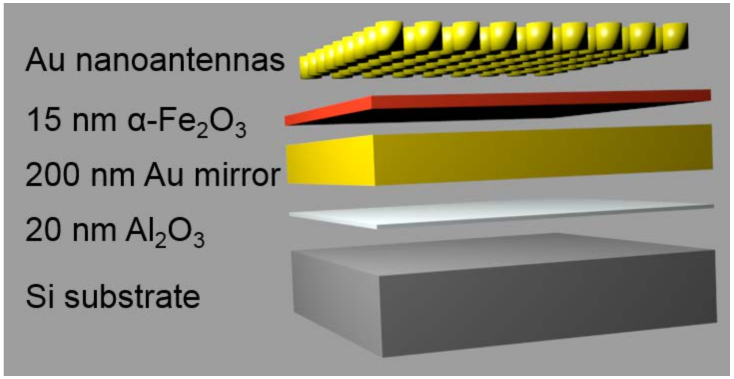
FROM SOLAR STEAM TO WATER SPLITTING

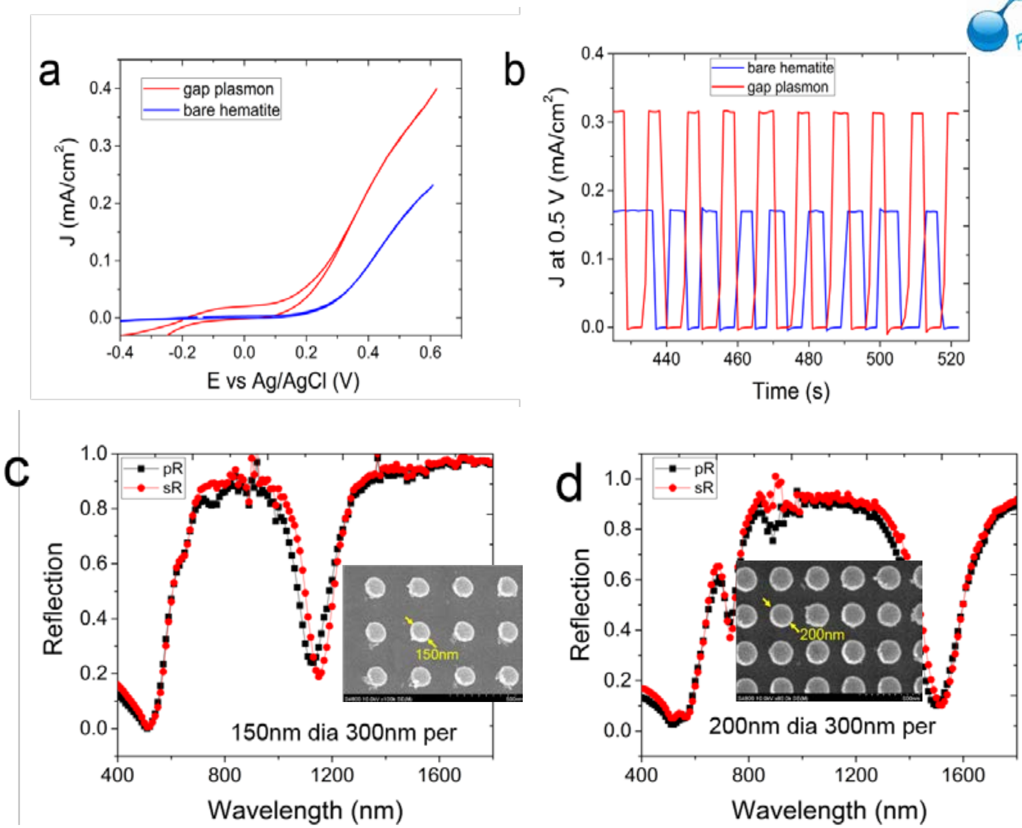
Water splitting with hematite

Collaboration with



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



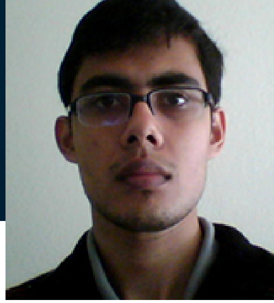


Photocurrent enhancement with gap plasmons (See work by S. Bozhevolnyi)

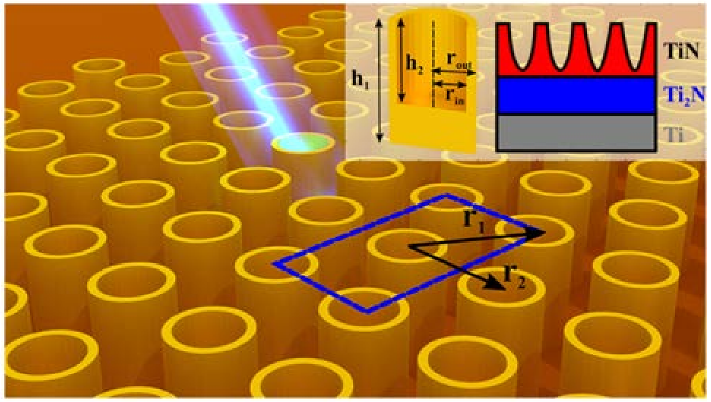
With A. Naldoni

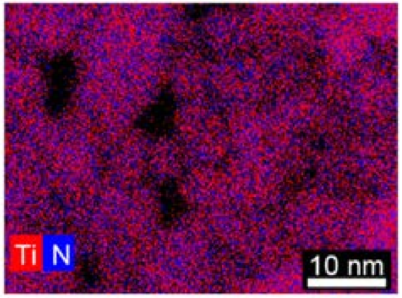
See work by N. Halas & P. Nordlander on solar steam, S. Link and other

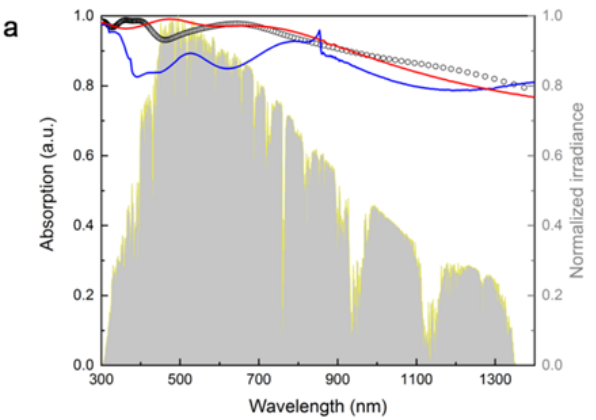
THERMOPLASMONIC TiN NANOFURNACE



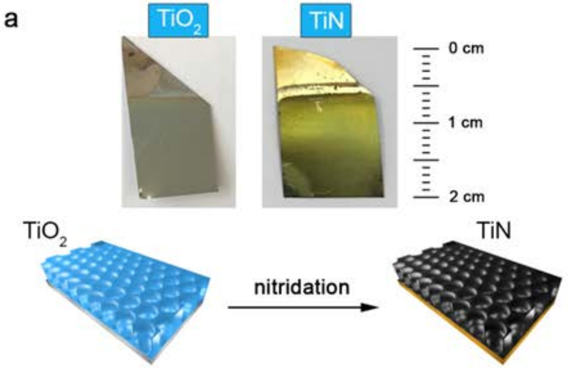
- High temperatures can be obtained using thermoplasmonic TiN nanofurnace under solar illumination
- Enables thermally induced nanochemistry with attolitre volume precision

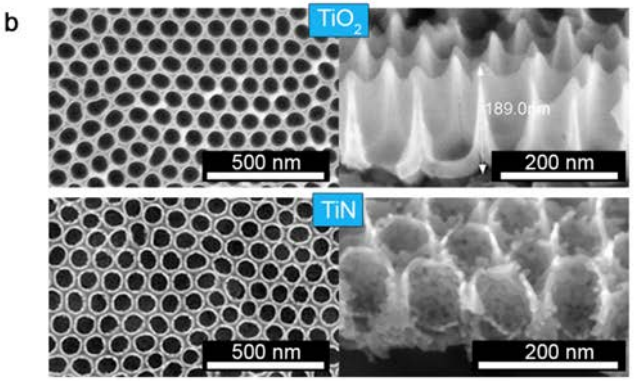


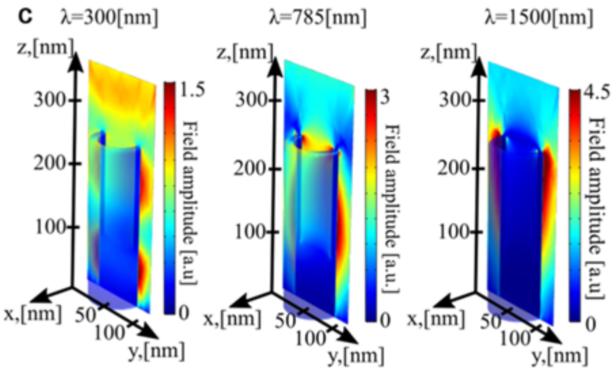




TiN nanofurnace formed by nitridation of TiO_2 at 600^0 C



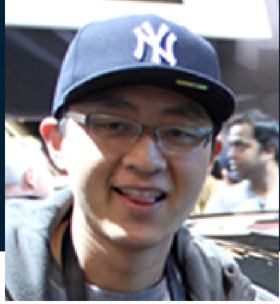




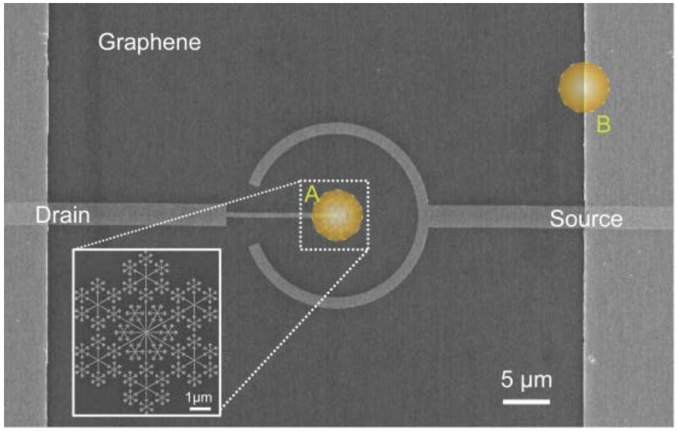
With A. Naldoni

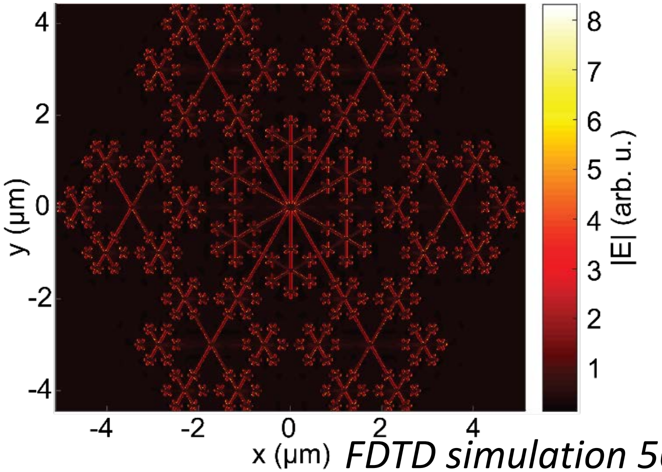
See work by N. Halas, P. Nordlander, P. Christopher, S. Ishii and other

GRAPHENE FRACTAL PHOTODETECTOR



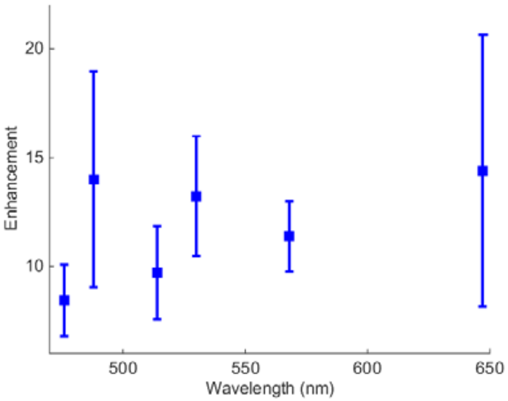
Cayley tree metasurface

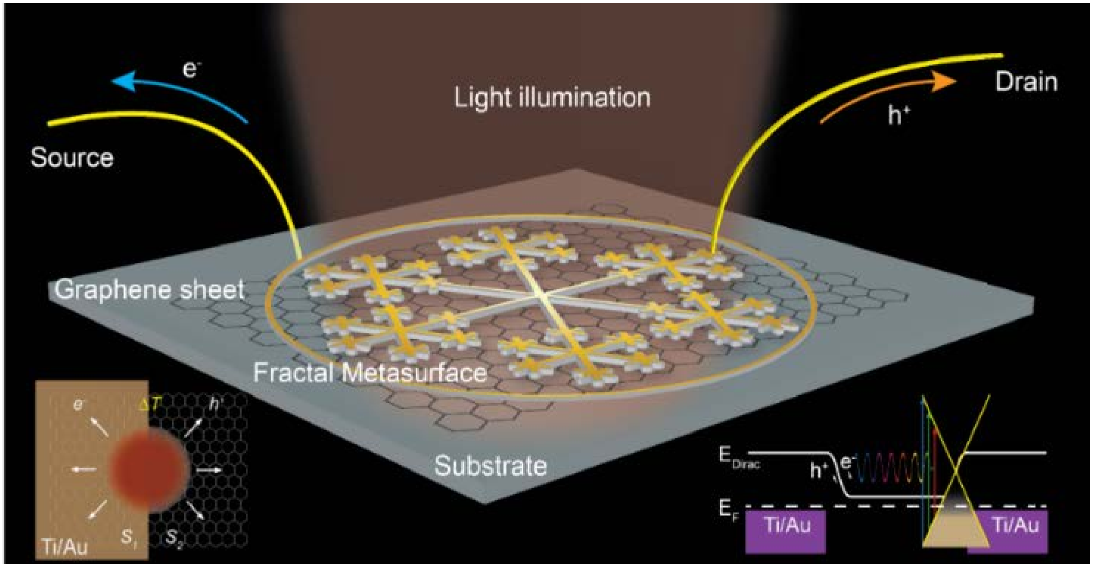




FDTD simulation 568 nm

Photocurrent generation enhancement A/B





Nano Letters 17 (1), 57-62 (2017)

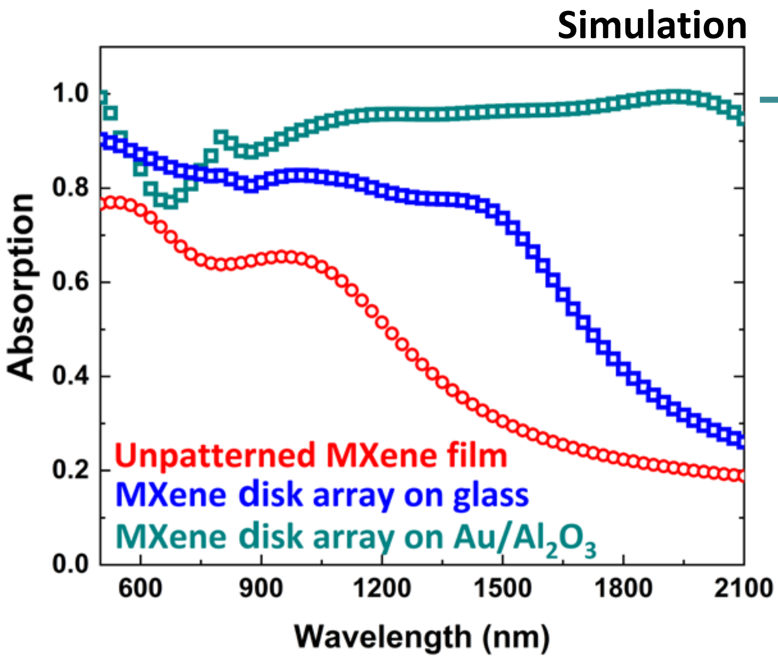
MAX/MXenes

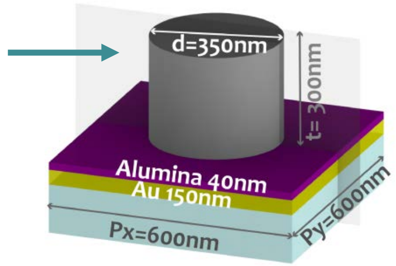
New class of solution dispersible, 2D nanomaterials formed from transition metal carbides and nitrides such as Ti_3C_2

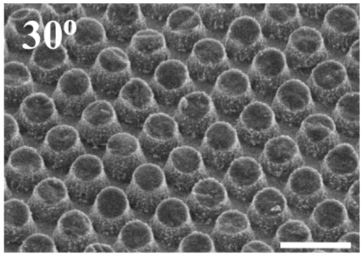
- 60+ varieties of $M_{n+1}X_n$ compounds M: Transition metals Ti, Mo, Nb etc. X: C or N
- Metallic conductivity
- Mechanically robust
- Controllable surface hydrophilicity (surface termination)
- ‘Conductive clays’: Easy intercalation etc.
- Outstanding electrical energy storage
- *Sustainable, cost-effective*

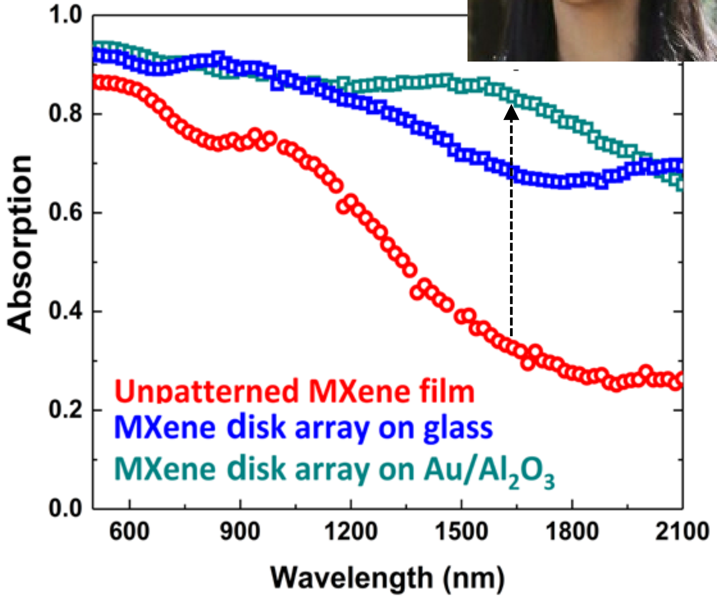
Y. Gogotsi, *Adv. Mat.* 26, 982, 2014); M. Naguib, et al. *Adv. Mat.* 23, 4248 (2011); B. Anasori et al., *ACS Nano* 9, 9507 (2015)
F. Shazad et al., *Science* 353, 1137 (2016); E. Satheeshkumar et al., *Scienctific Reports* 6, 32049 (2016)

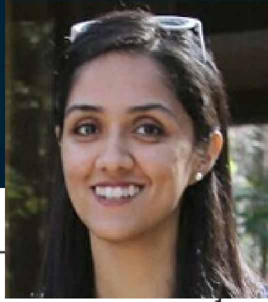
MXene BROADBAND ABSORBER



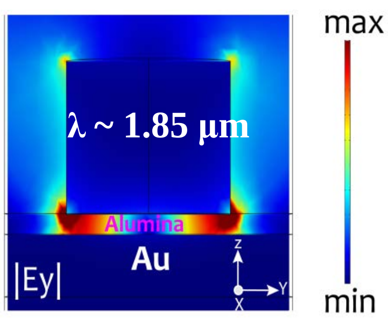








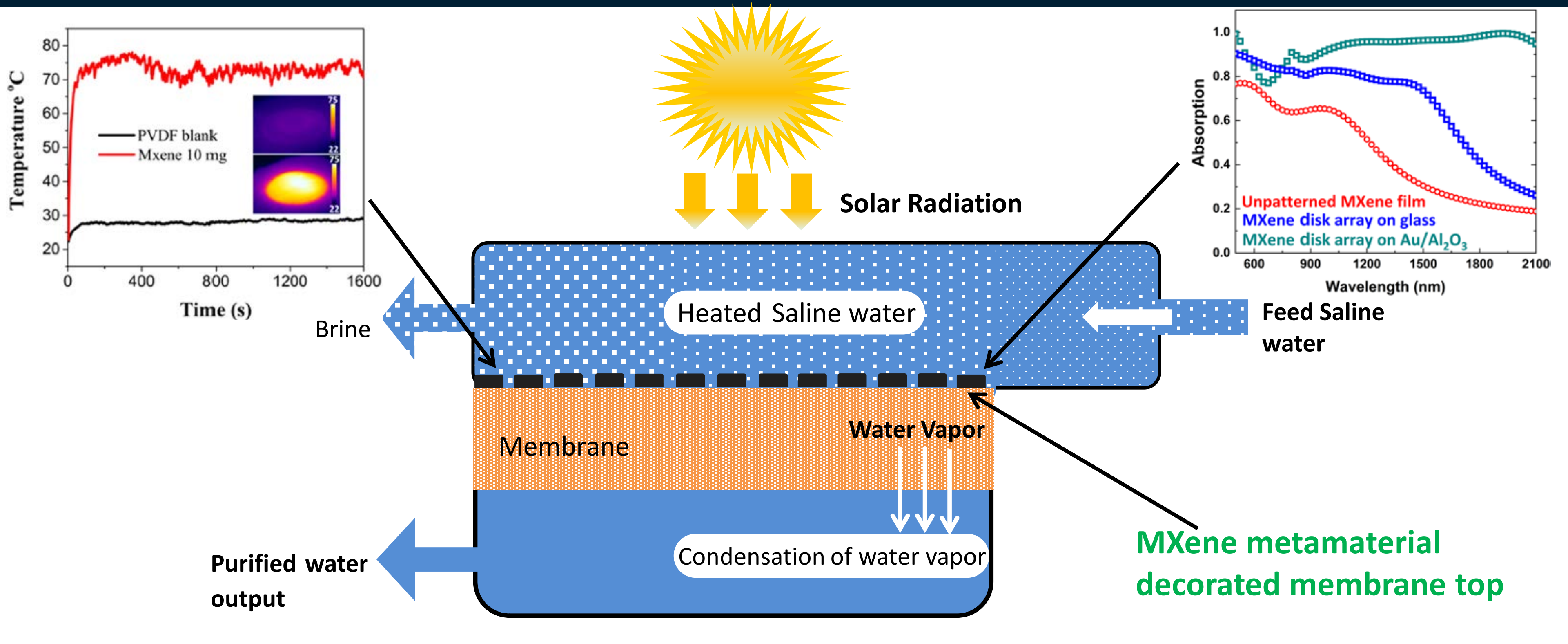
Ti_3C_2 disks/pillar-like structures:
LSPR in NIR



- **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**

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

MXene for WATER DESALINATION



- MXenes with exceptionally high photothermal conversion efficiency- Nb_2C, Ta_4C_3
  - Theranostics, Photothermal Therapy applications
- Optimized meta-structuring for enhanced energy harvesting
  - Broadband perfect absorption of the solar spectrum

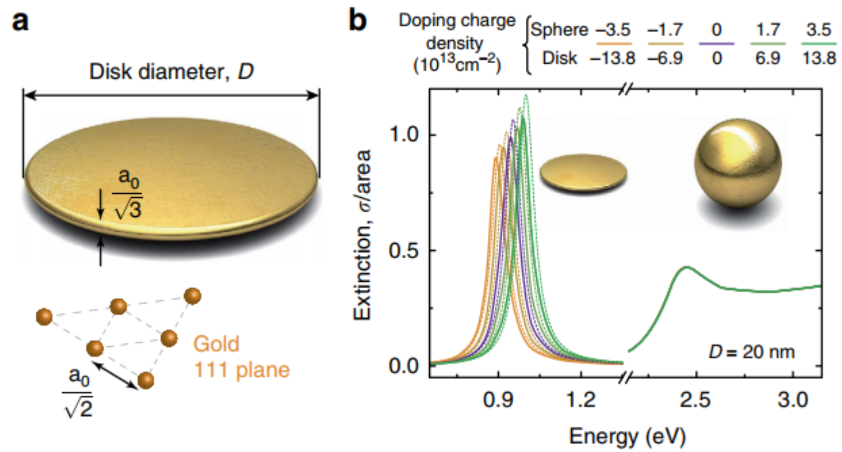
With prof Warsinger

R. Li et. al., *ACS Nano*, 2017
K. Chaudhuri et. al., *ACS Photonics*, 2018

ULTRA-THIN PLASMONIC FILMS


Z. Kudyshev H. Reddy

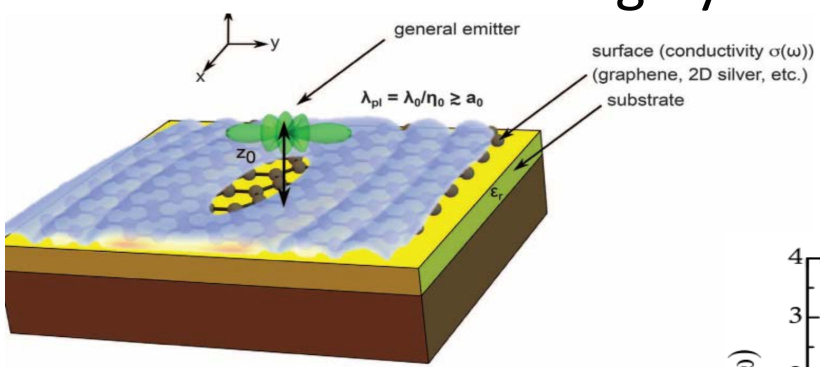
- Electrical (optical) control over the properties



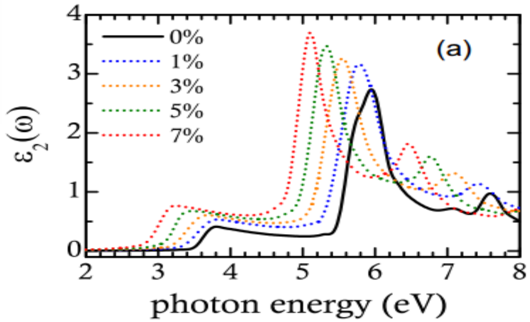
J. Garcia de Abajo's group
Nature Communications, 2014

- Unique light-matter interactions in highly confined light regime

M. Soljacic's group
Science 2016



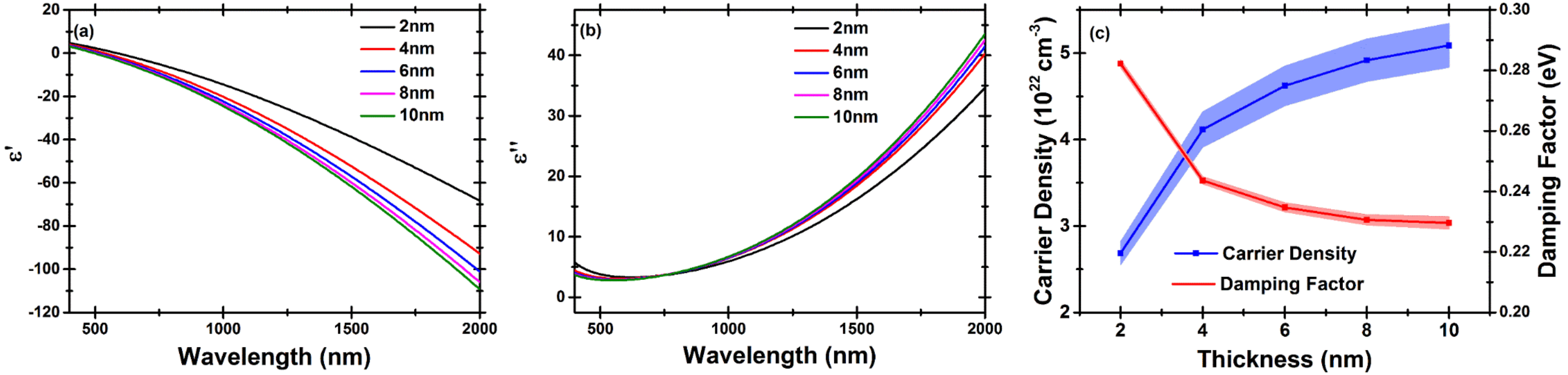
- Control the optical properties by adjusting strain/stress



OPTICAL PROPERTIES OF ULTRATHIN TiN

D. Shah

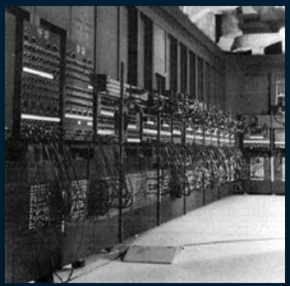
- Lower metallicity (~2-nm-thick TiN_xO_y layer on the surface)
- Agrees with theory; plasma frequency acquires the spatial dispersion (~ 2D)
- Films remain highly metallic, even at a thickness of 2 nm ($n \approx 10^{22}$ cm^{-3})
- Higher losses in thinner films
- Increase in scattering rate
  - Defect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

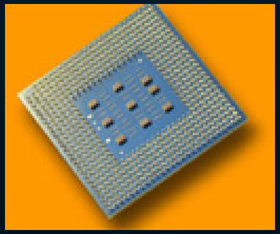


D. Shah, H. Reddy, N. Kinsey, V. Shalaev, A. Boltasseva, Advanced Optical Materials (2017)

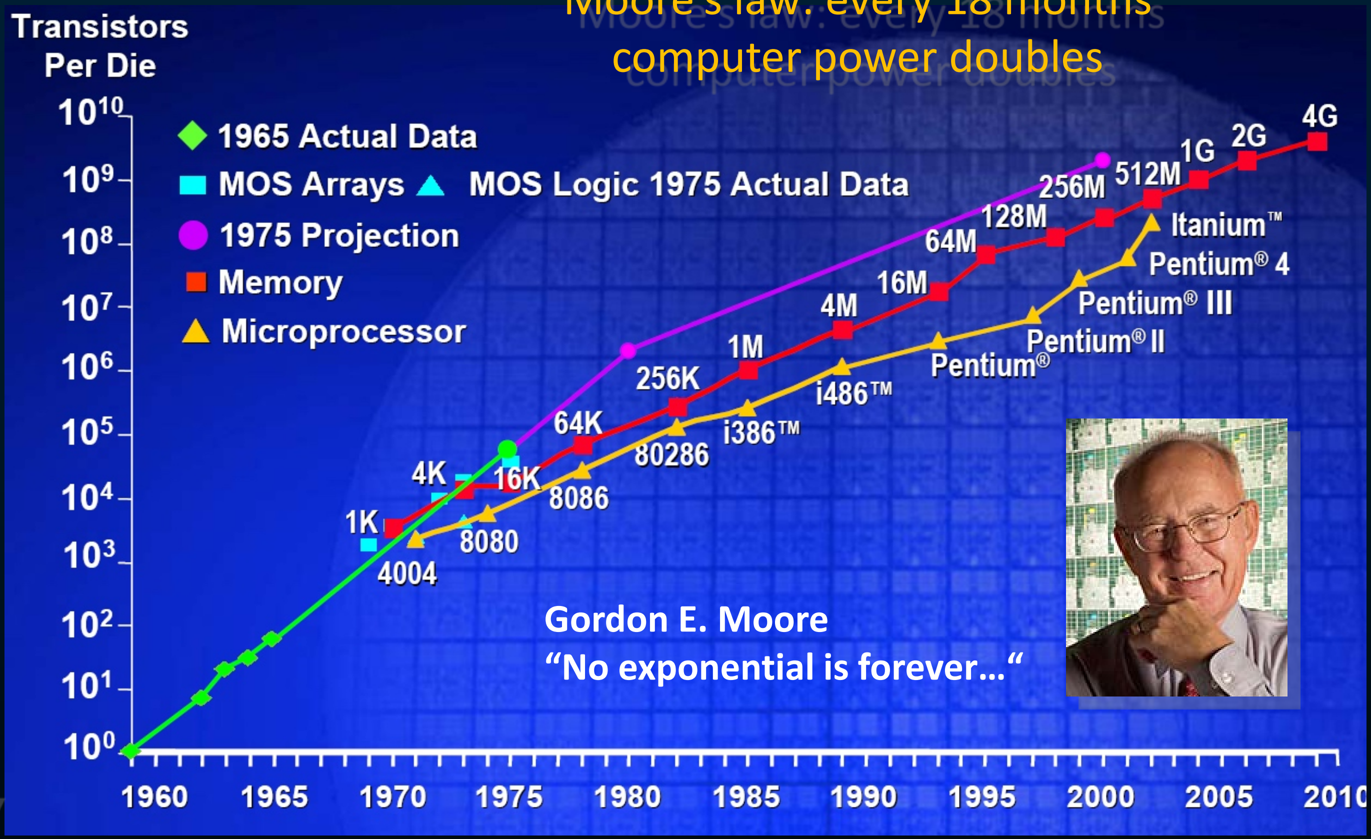
PURDUE UNIVERSITY

PROGRESS IN TECHNOLOGY


ENIAC (1947)


Pentium 4 (2002)

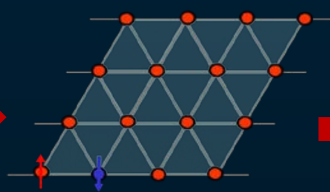
Moore's law: every 18 months computer power doubles



FASTER = SMALLER

TOWARD QUANTUM COMPUTING

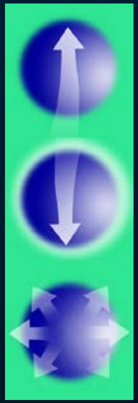
Classical Hard-disk



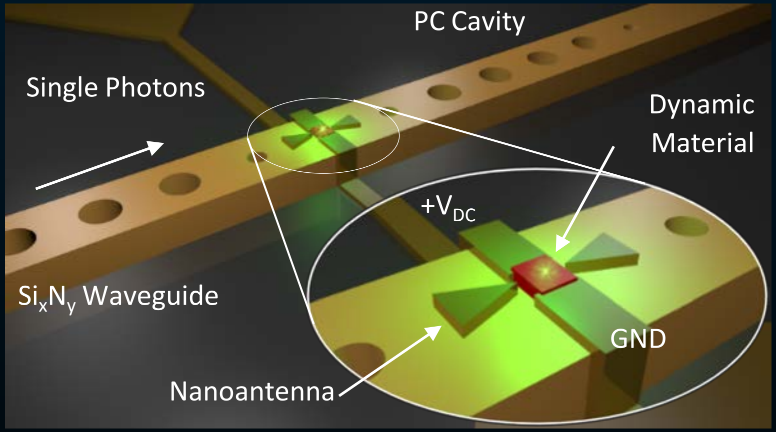
- **atoms as "small magnets"**
- **store numbers „0" or „1"**

CAN BE QUANTUM OBJECTS!

http://www.nist.gov/public_affairs/releases/quantum_repairkit.cfm



SUPERPOSITION / ENTANGLEMENT
is a key resource for quantum IT
Bits to qubits -> quantum speed up
(to process many inputs in parallel)



- Utilize the advantages of photonics, electronics, and plasmonics to achieve high performance
- Explore new materials and new structures

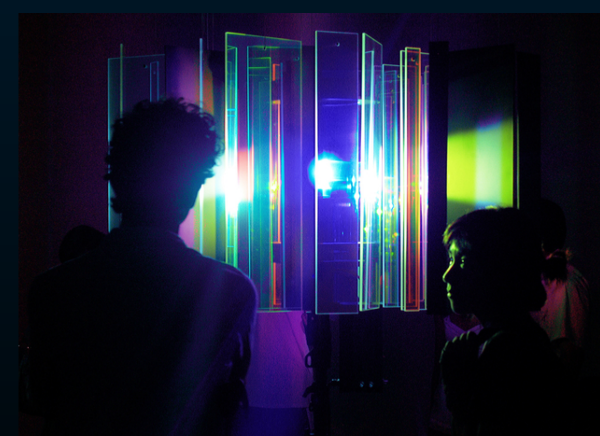
Shalaev, Boltasseva groups

FUTURE PHOTONIC TECHNOLOGIES

Medical/bio/Chemical Sensors/Contacts

Harsh Environment Sensors

Food/Water Safety



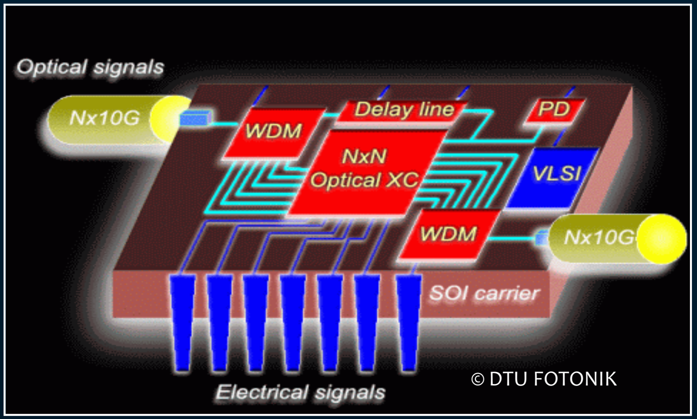
Photonics for Arts and Fashion

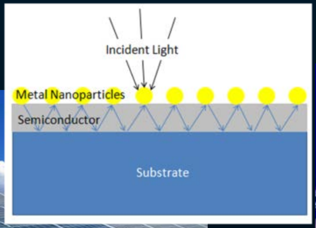
Images from Dreamstime.com/Phys.org/Hight3ch.com

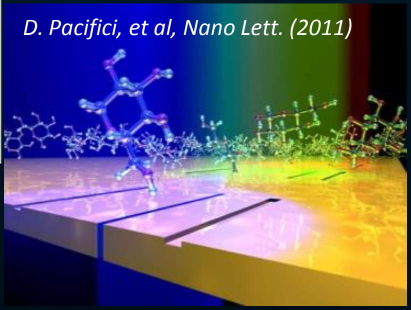
TEAM AND SUPPORT

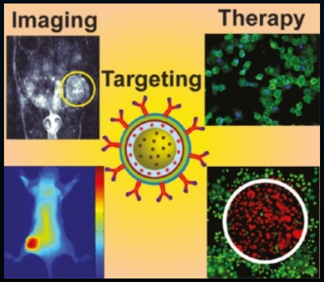
POTENTIAL TECHNOLOGY IMPACT

- 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