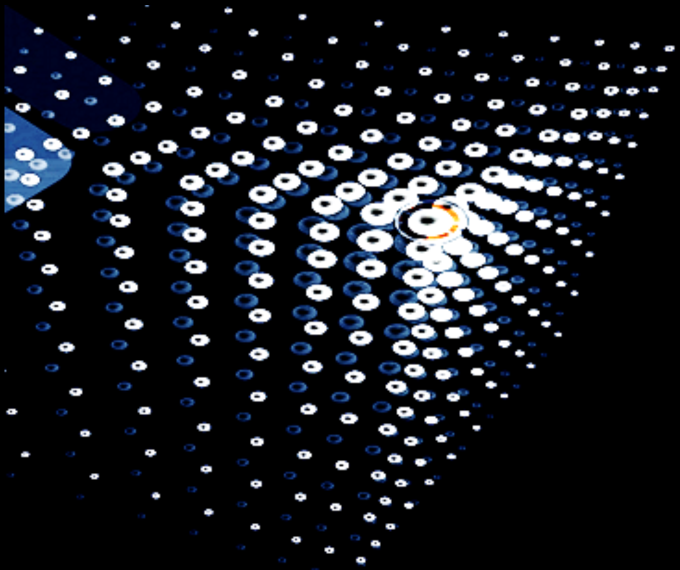
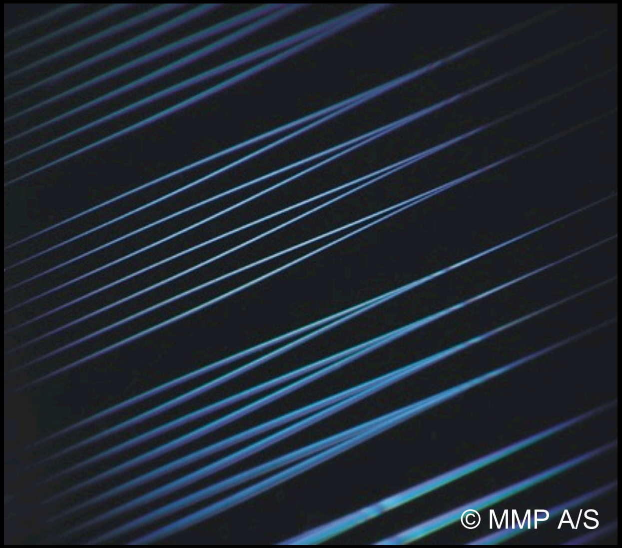


Enabling Nanophotonics with Plasmonics and Metamaterials

Vladimir M. Shalaev

OUTLINE

- Why NANOPHOTONICS?
- Si nanophotonics
- Why metamaterials/ plasmonics?
- Future of nanophotonics with metamaterials
- All begins with materials /nanofabrication
- Towards quantum computing



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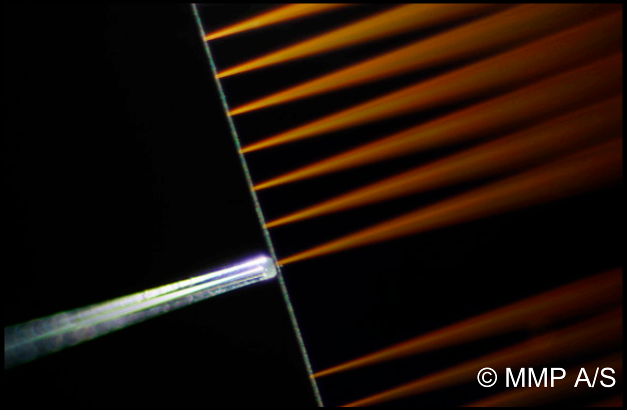

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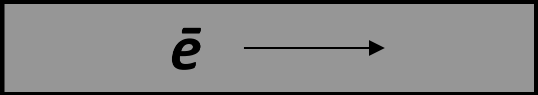
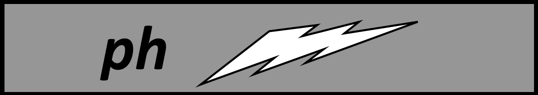
Thanks go to A. Boltasseva, M. Brongersma, S. Bozhevolniyi , M. Lukin and Y. Vlasov for slide materials

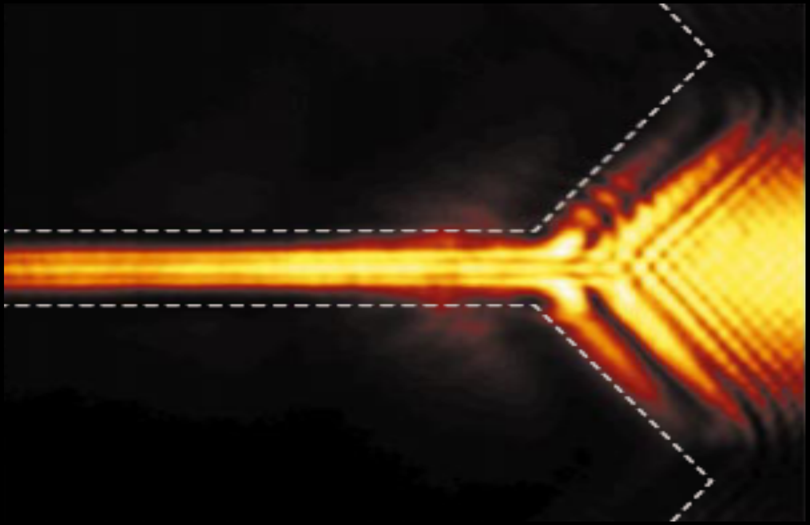
NANOPHOTONICS

Nanophotonics ≠ Nano-optics

Electronics	Nanophotonics
Electrons	Photons
Wires	Waveguides
	
f ~ 10^{10} Hz	f ~ 10^{15} Hz

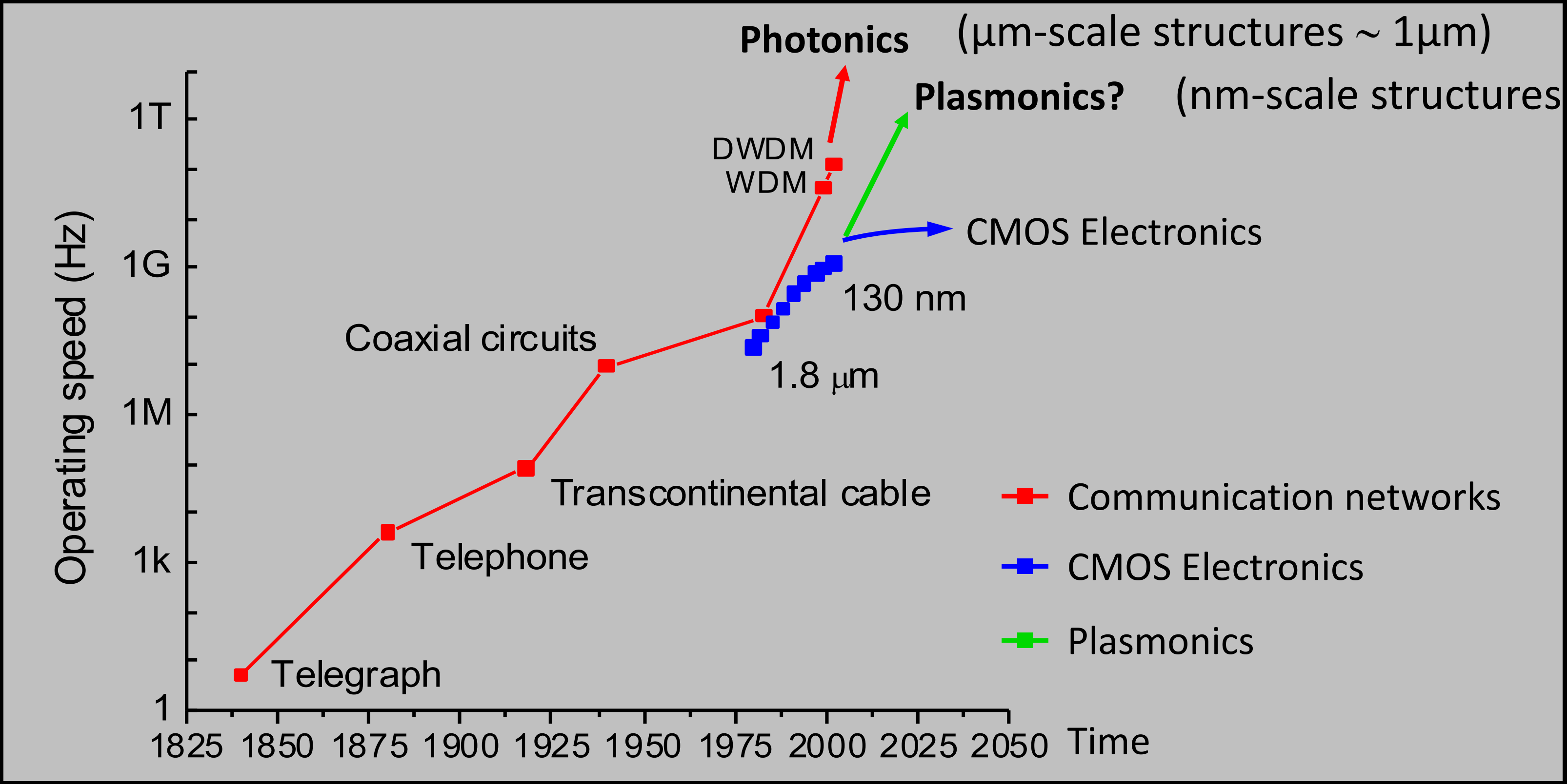
NANOPHOTONICS

- Photonics vs. Electronics
- Fiber Optics: Transmitting Information
- Integrated Optics: Processing Information
- New Paradigms:
    - Plasmonics
    - Metamaterials



NEXT STEPS?

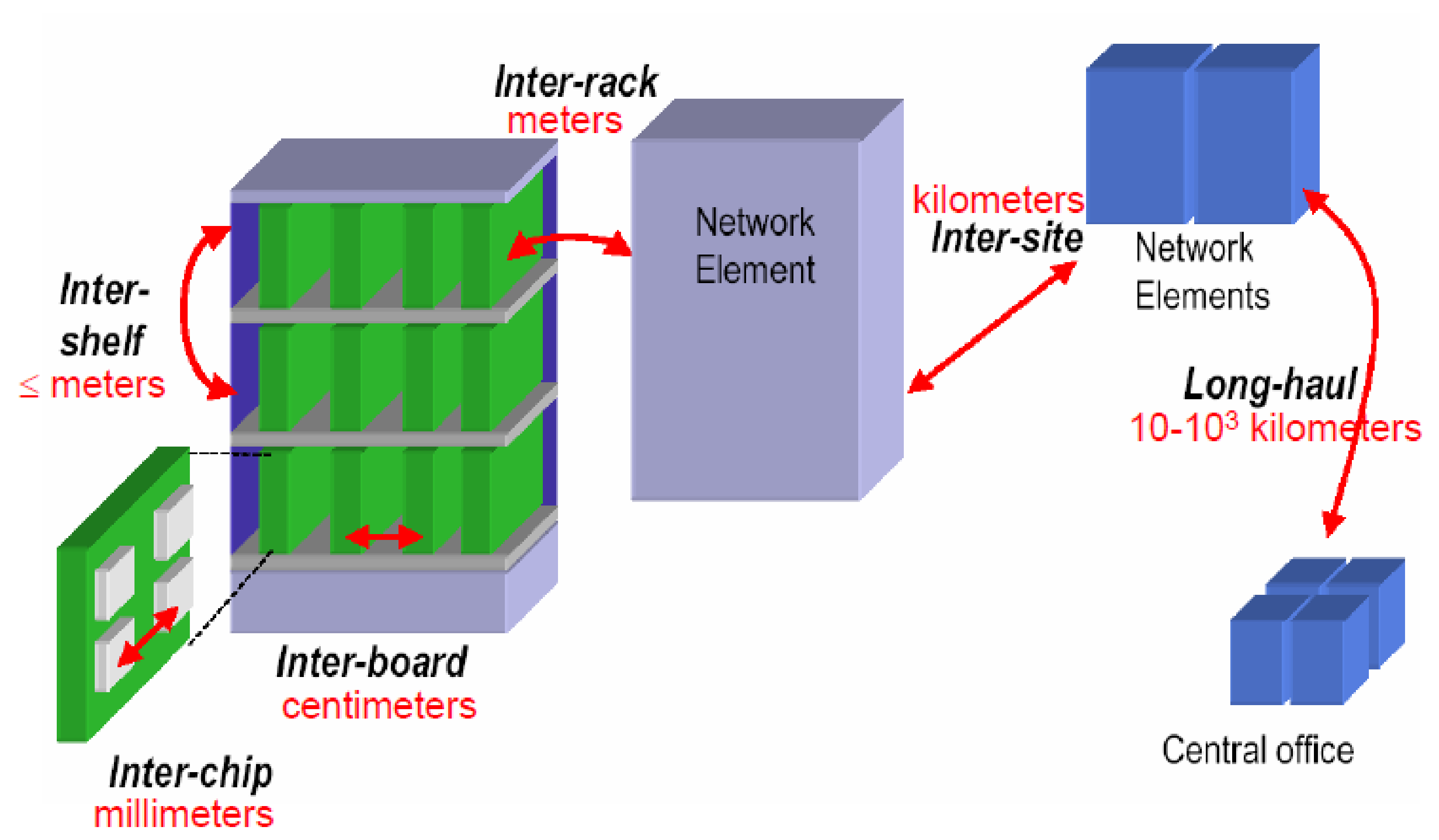
The operating speed of data transporting and processing systems



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

Electronic components are running out of steam due to issues with RC-delay times

SYSTEM INTERCONNECT HIERARCHY



Slide credit to Vlasov

Si NANOPHOTONICS

1989

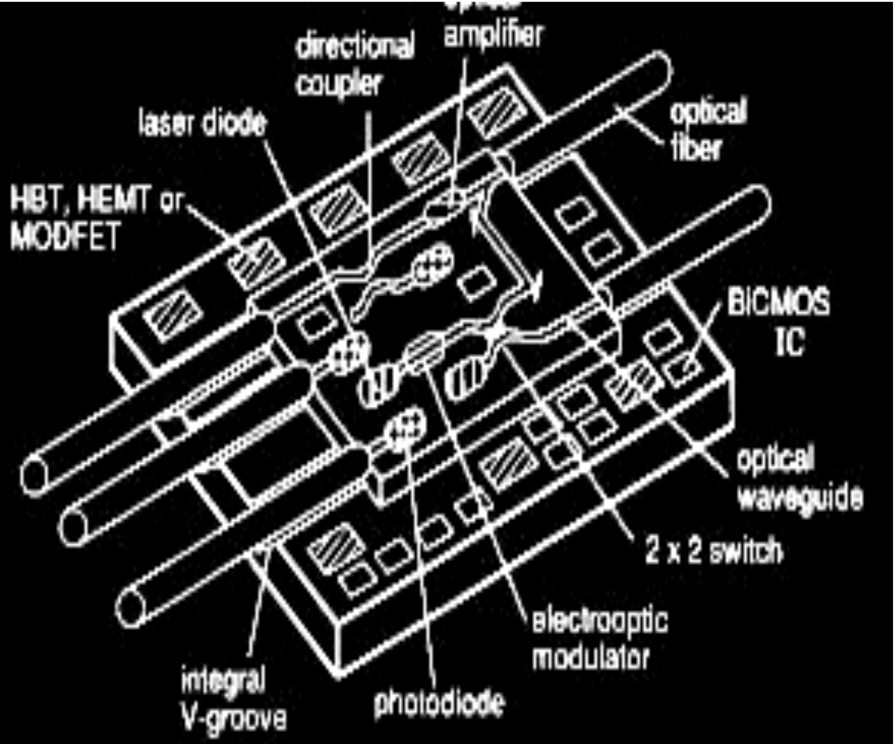


Fig. 3. Silicon-based OEIC "superchip," similar to the one proposed by Abstreiter [2].

R. Soref et al

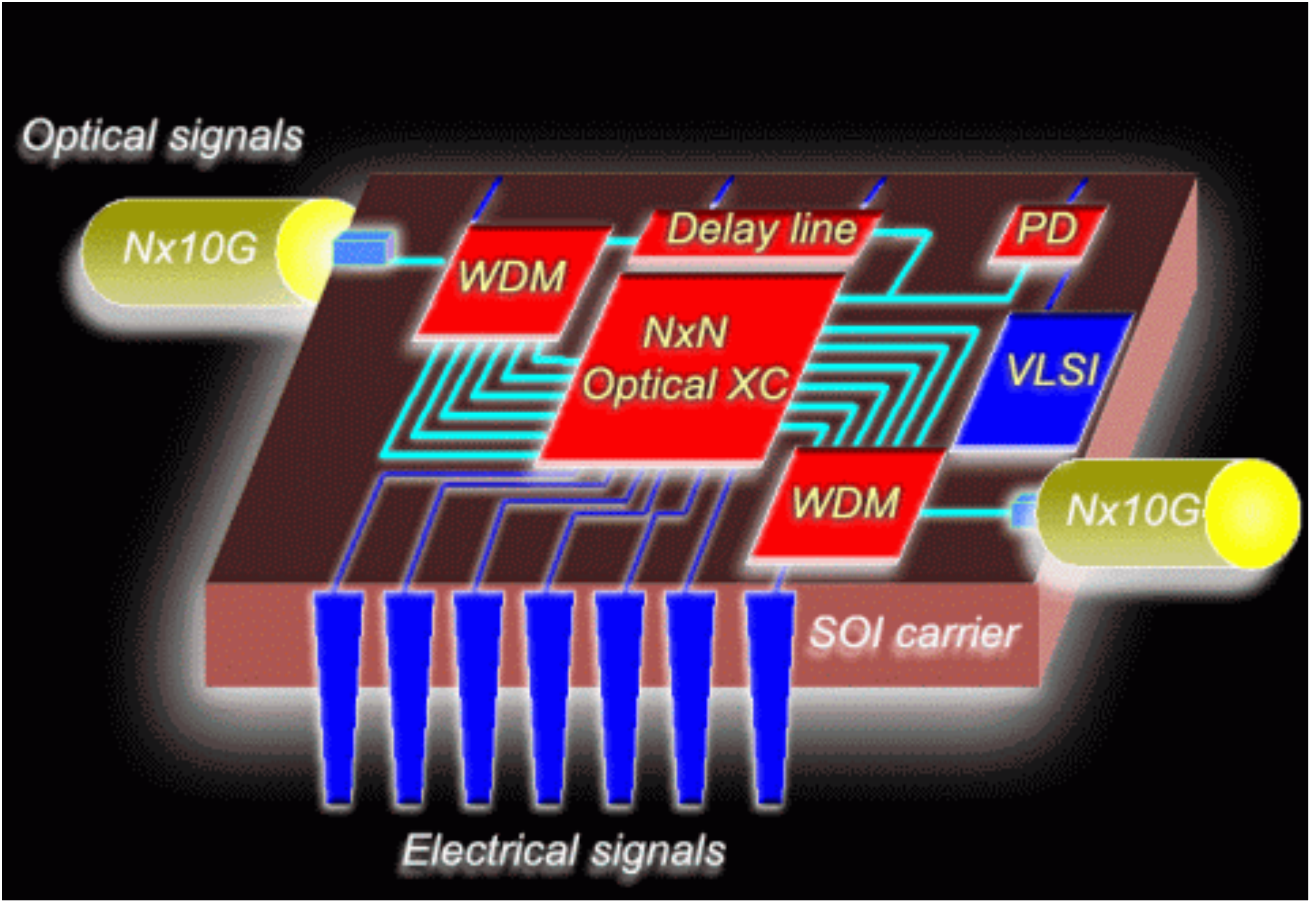
Concept:

Deep scaling of optics (materials with high refractive index – *but still diffraction limited*!)

CMOS compatible

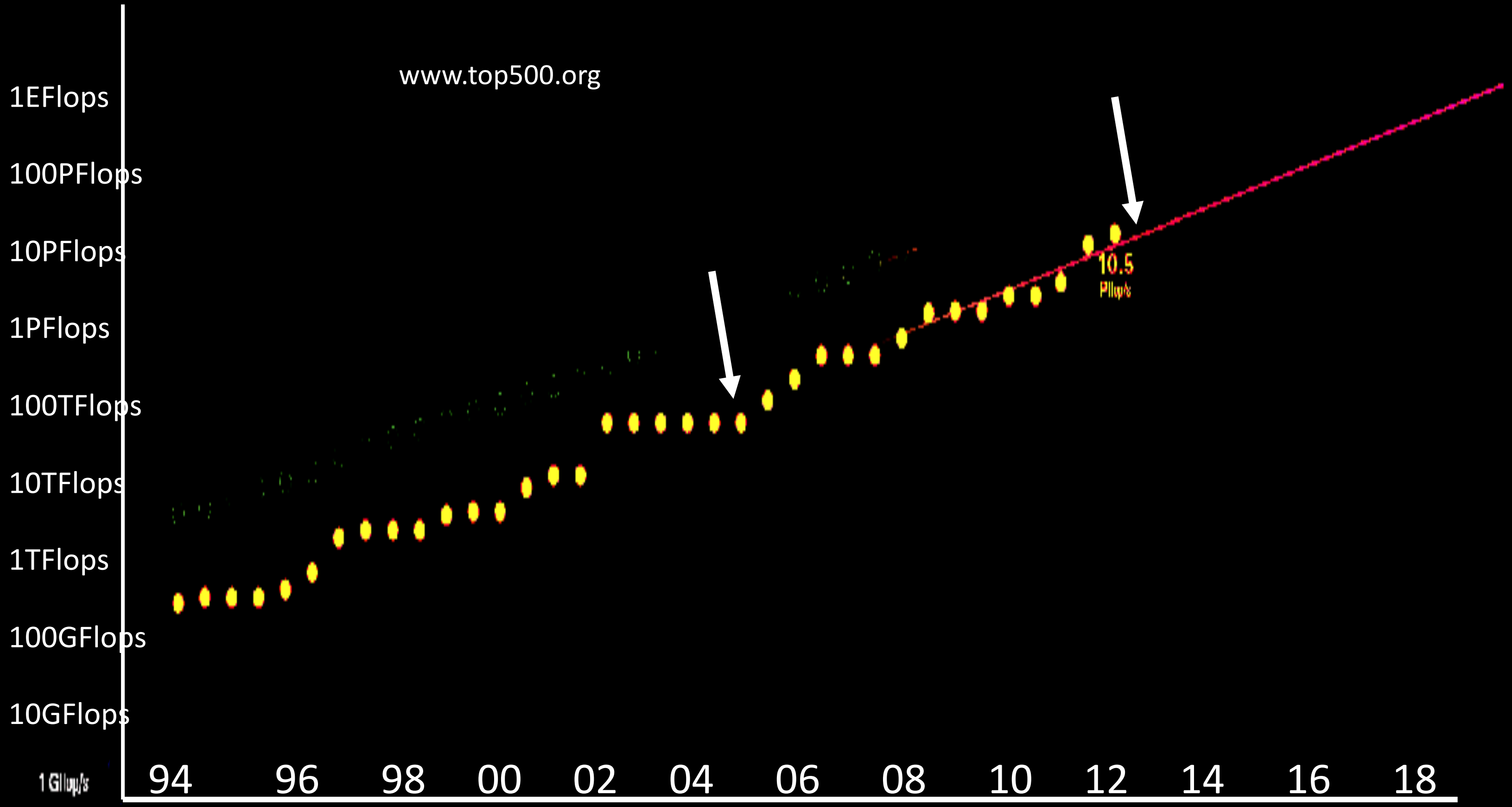
- **Materials**
- **Processing**

Silicon Integrated Nanophotonics



Slide credit to Vlasov

Top 500 most powerful supercomputers



Slide credit to Vlasov

IBM HPC systems

MareNostrum
2006

10,240 PowerPC970 processors, 90 TFlops

IBM P775 system
2011

256 P7 processors, 90 TFlops

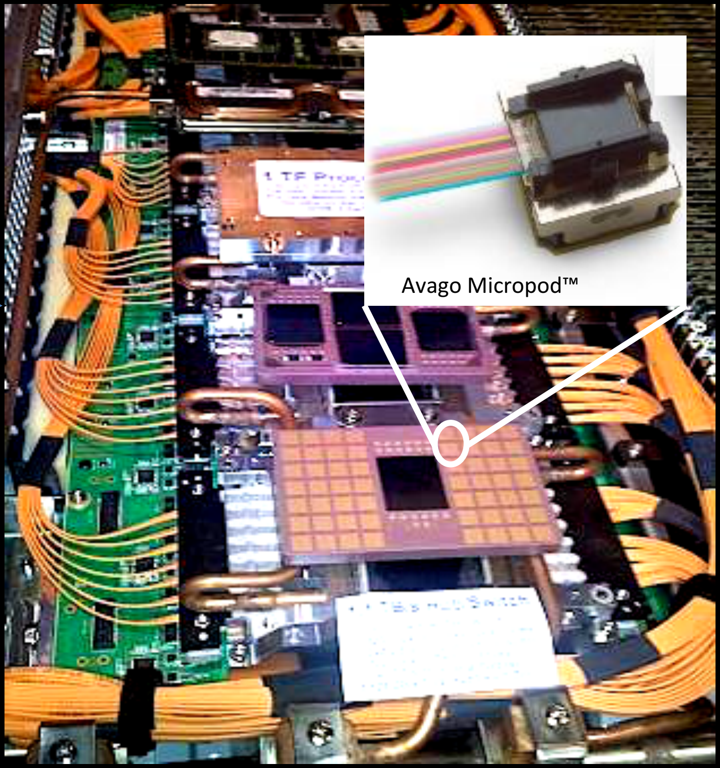
Slide credit to Vlasov

FROM 5K TO 1M FIBER LINKS

2006

MareNostrum
~5K fiber cables

2011



P775 system
~500K fiber cables

Slide credit to Vlasov

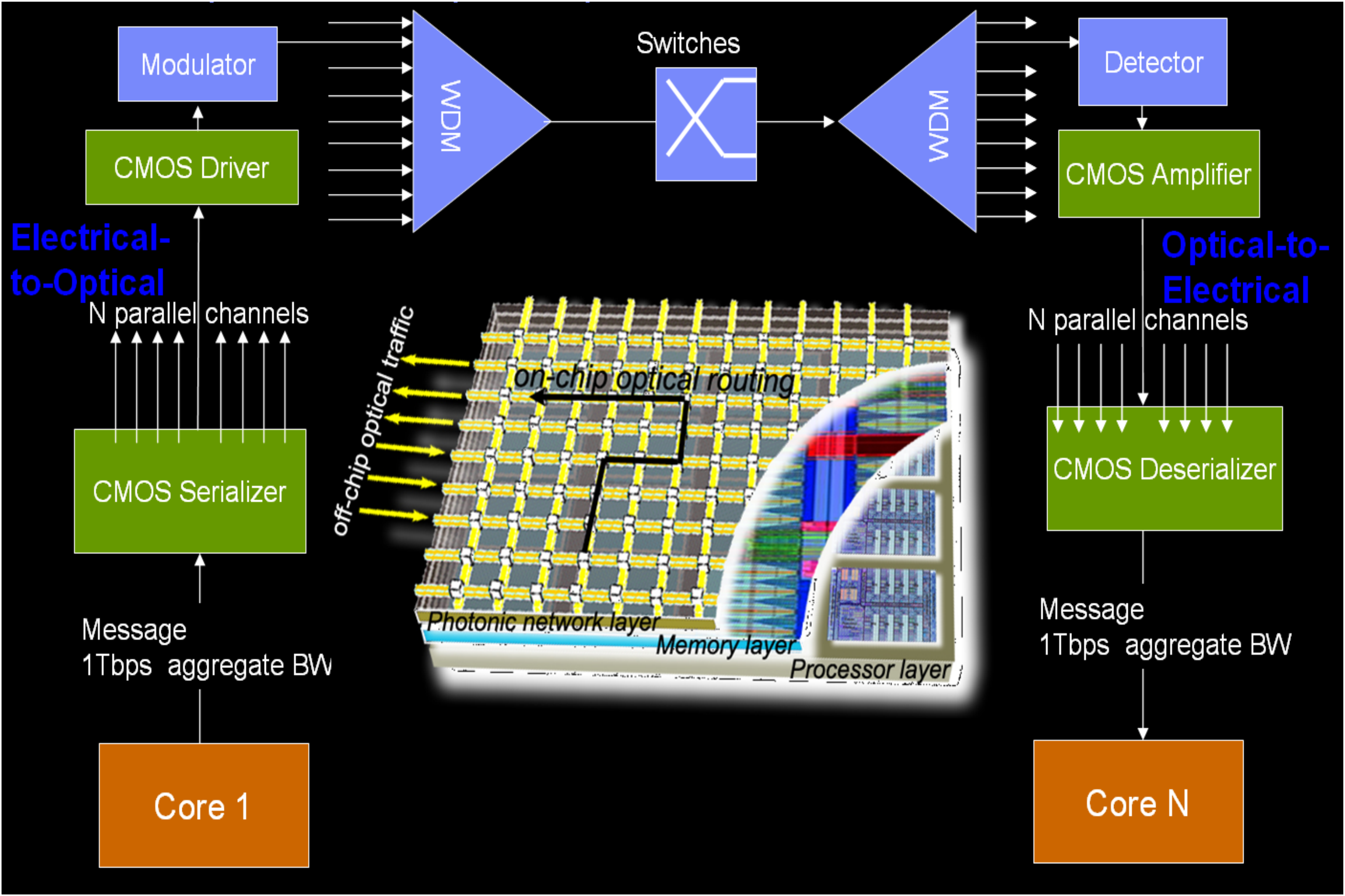
COST AND POWER PER BIT

Year	Peak Performance	number of optical channels	Optics Power Consumption	Optics Cost
2008	1PF	48,000 (@ 5Gb/s)	50mW/Gb/s (50pJ/bit)	$10,000 per Tb/s
2012	10PF	2×10^6 (@ 10Gb/s)	25mW/Gb/s	$1,100 per Tb/s
2016	100PF	4×10^7 (@ 14-25 Gb/s)	5mW/Gb/s	$170 per Tb/s
2020	1000PF (1EF)	8×10^8 (@ 25 Gb/s)	1mW/Gb/s	$25 per Tb/s

Acknowledgment: A. Benner, J.Kash

Slide credit to Vlasov

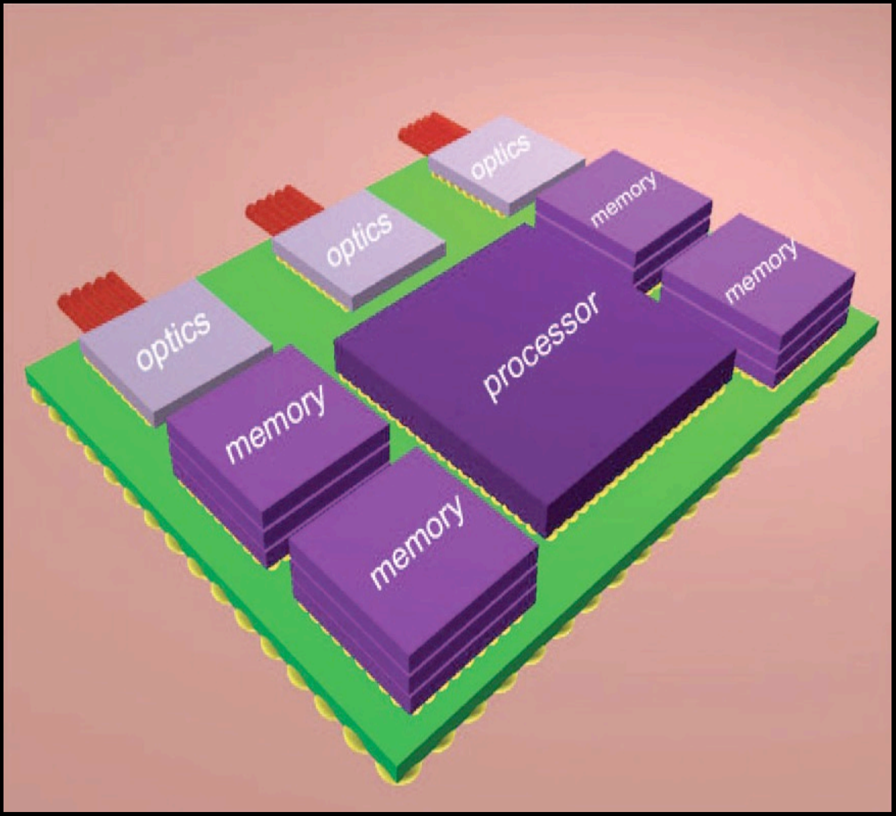
OFF-CHIP NP INTERCONNECTS



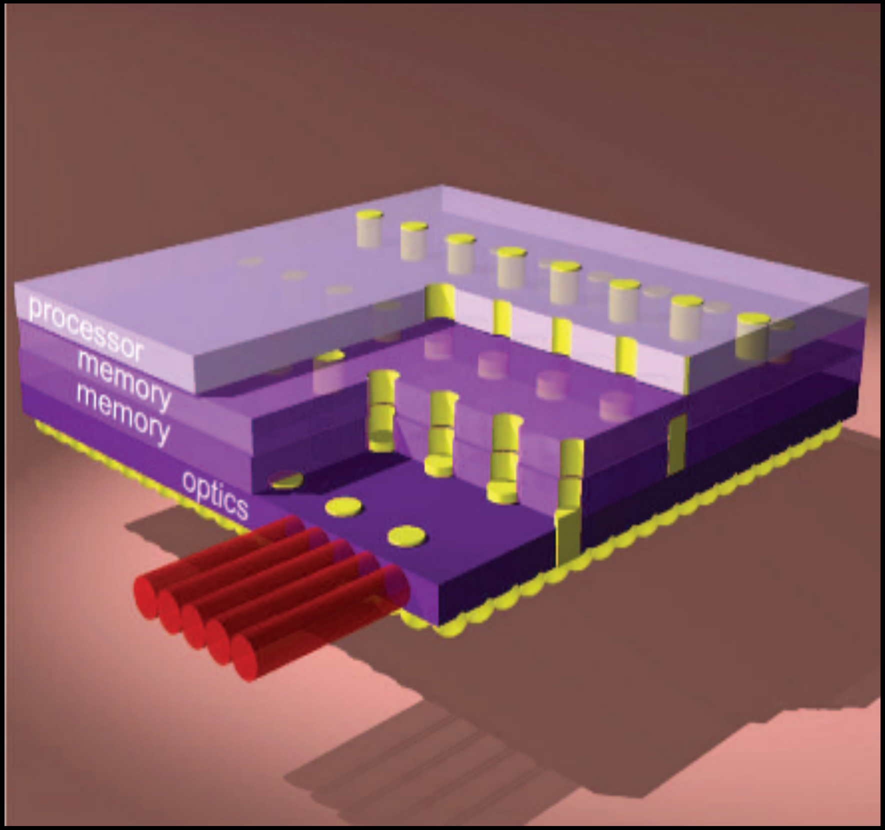
Goal: Integrate Ultra-dense Nanophotonics Circuits with CMOS chip

MAP OF THE ROAD

Circa 2015

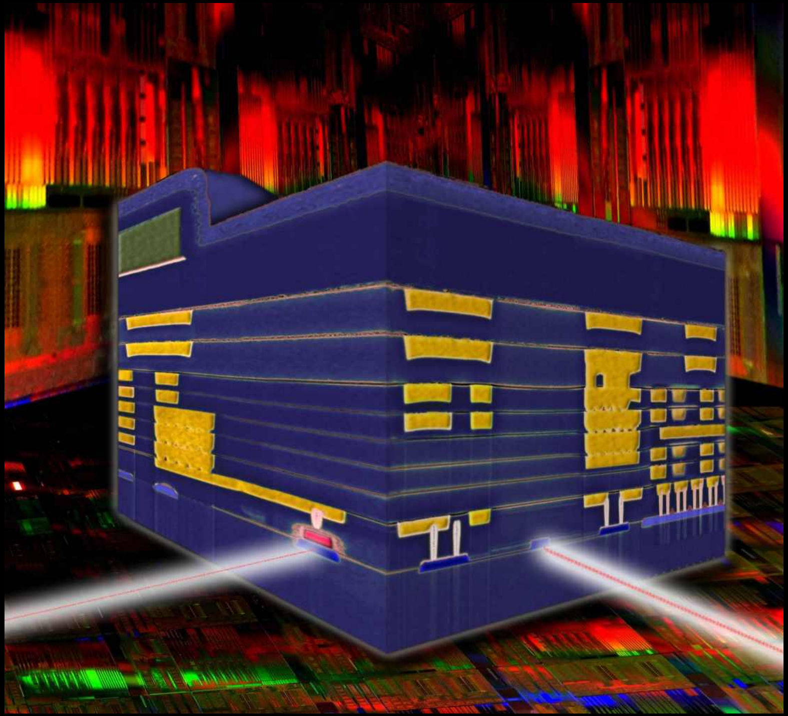


Circa 2020

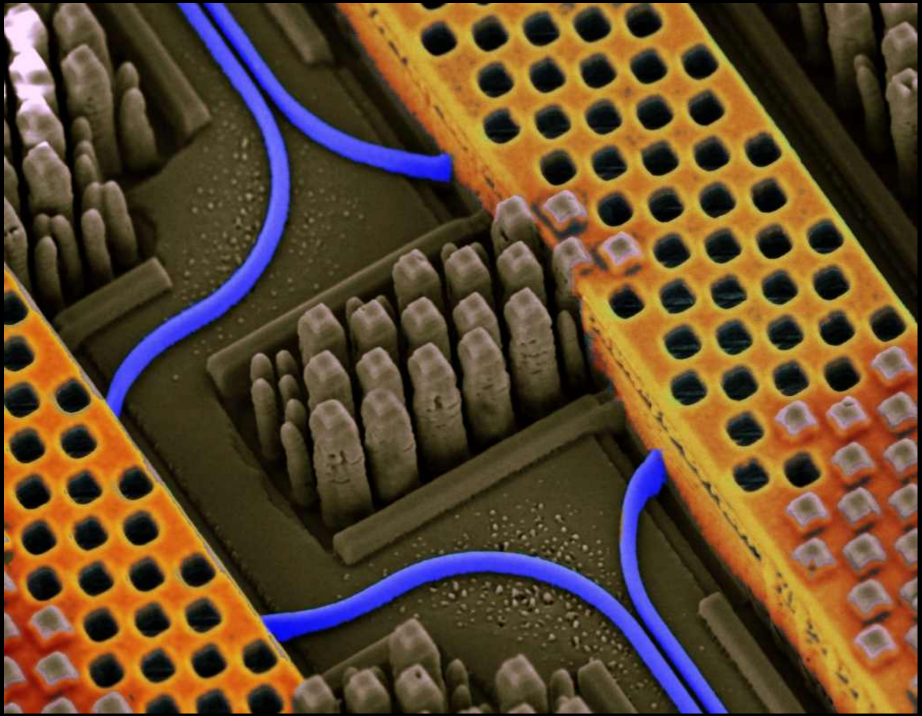


“Technologies for Exascale systems”, P. Coteus, J.Knickerbocker, C. Lam, and Y. Vlasov
IBM Journ. R&D, 55, No.5, 2011

IBM Silicon Integrated NP Technology



IBM 90nm Silicon Integrated Nanophotonics:
Integrated photodetector (red feature)
Modulator (blue feature)
Silicon transistors (red sparks)

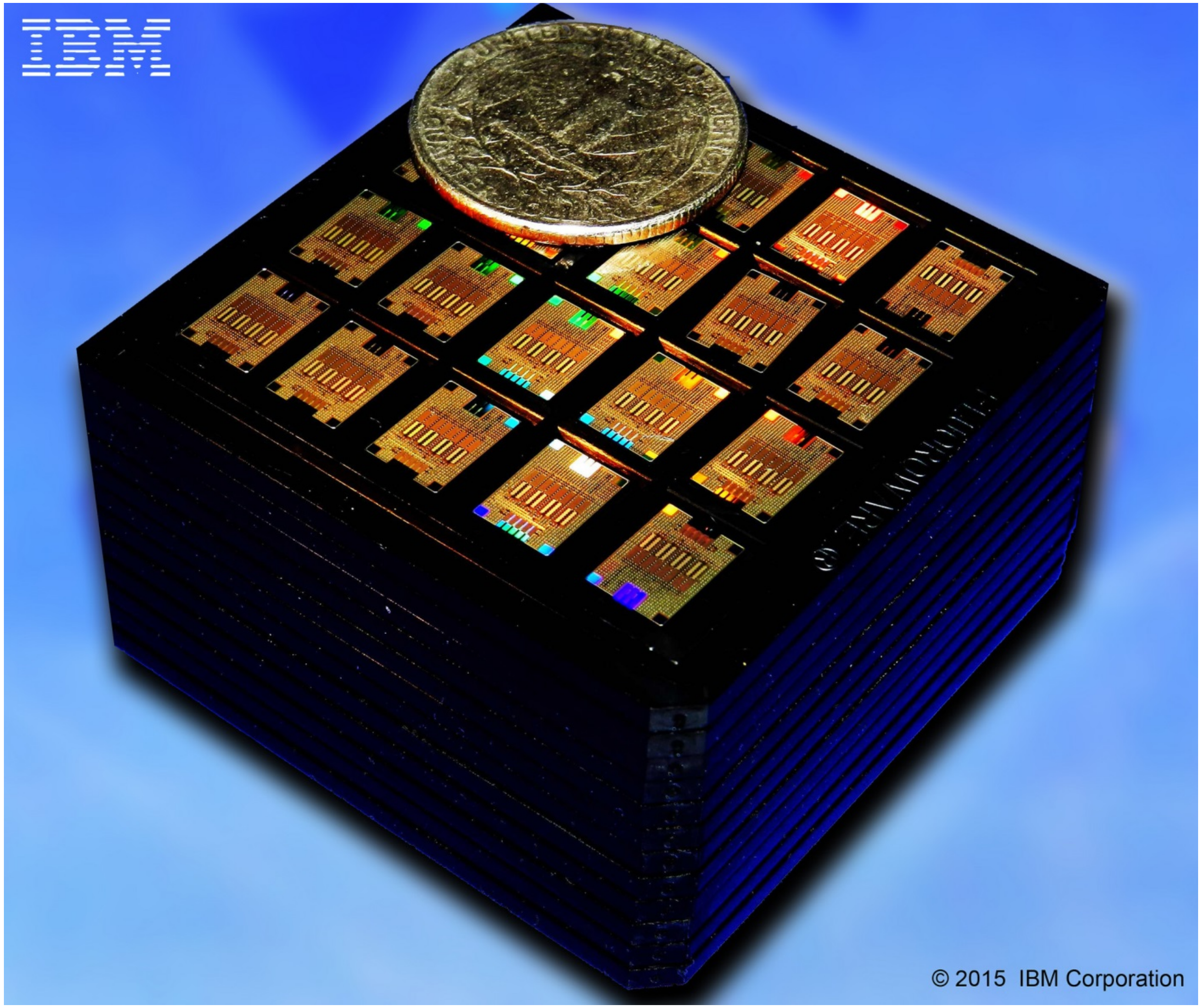


IBM chip:
BLUE optical waveguides and
YELLOW copper wires

"After More Than a Decade of Research, Silicon Nanophotonics is Ready for Development of Commercial Applications."

IBM Press release, December 10, 2012

Cloud and Big Data Applications



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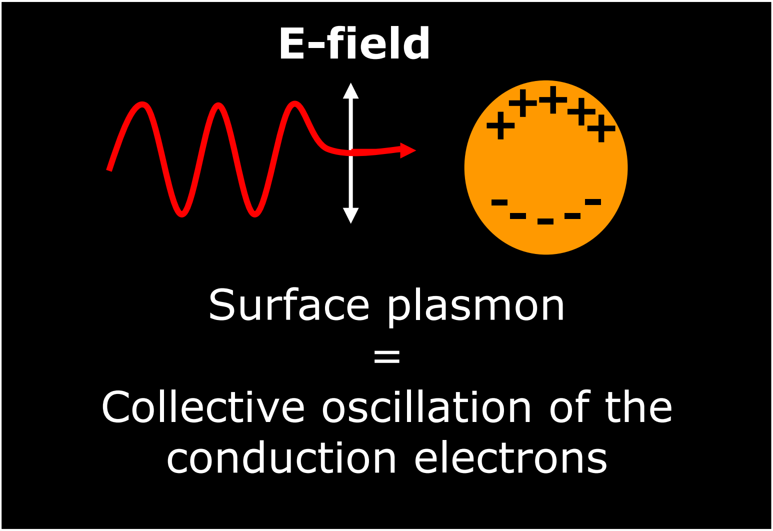
Release: 12 May 2015, Yorktown Heights, N.Y.

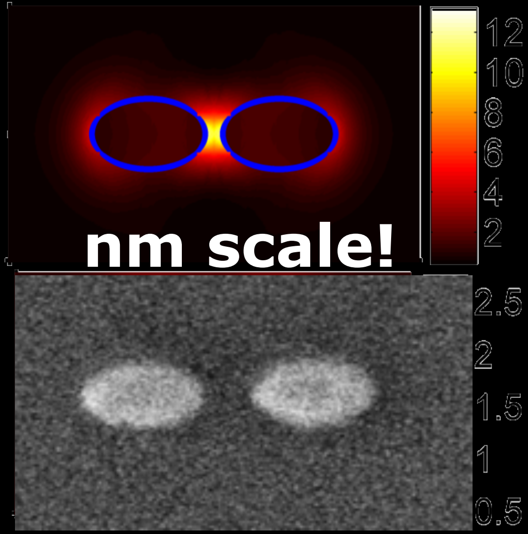
WHY ELECTRICAL METAMATERIALS/PLASMONICS?

Plasmonic (Metal) Antennae as Electrical Metamaterials: Focusing Light to Nanoscale

Coupling Light to Nanoscale via Surface Plasmons



Surface plasmon
=
Collective oscillation of the
conduction electrons

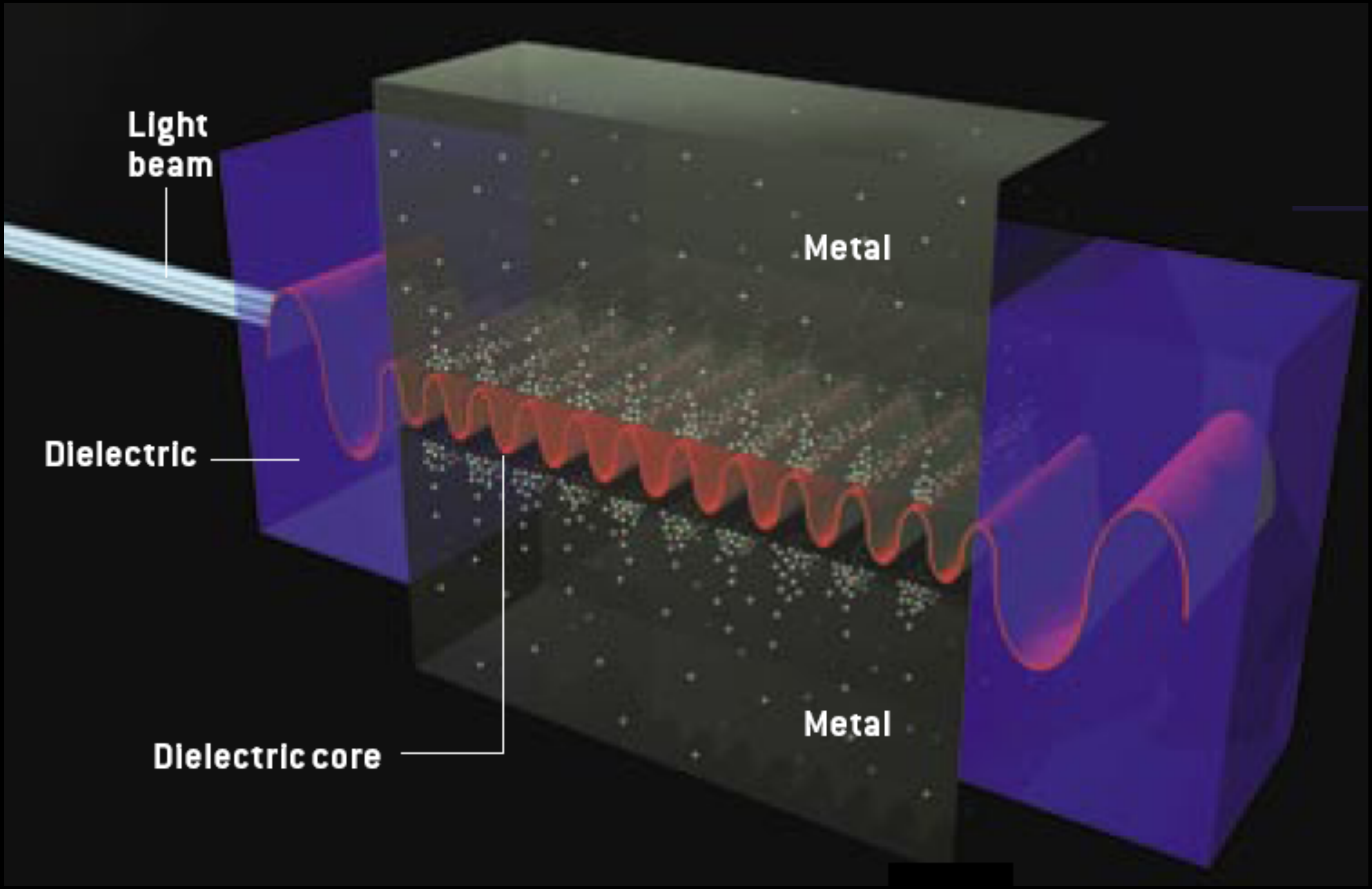


Z. Liu et al, Metamaterials (2008)

Localized SURFACE PLASMON resonance = Optical **NANO-ANTENNA**

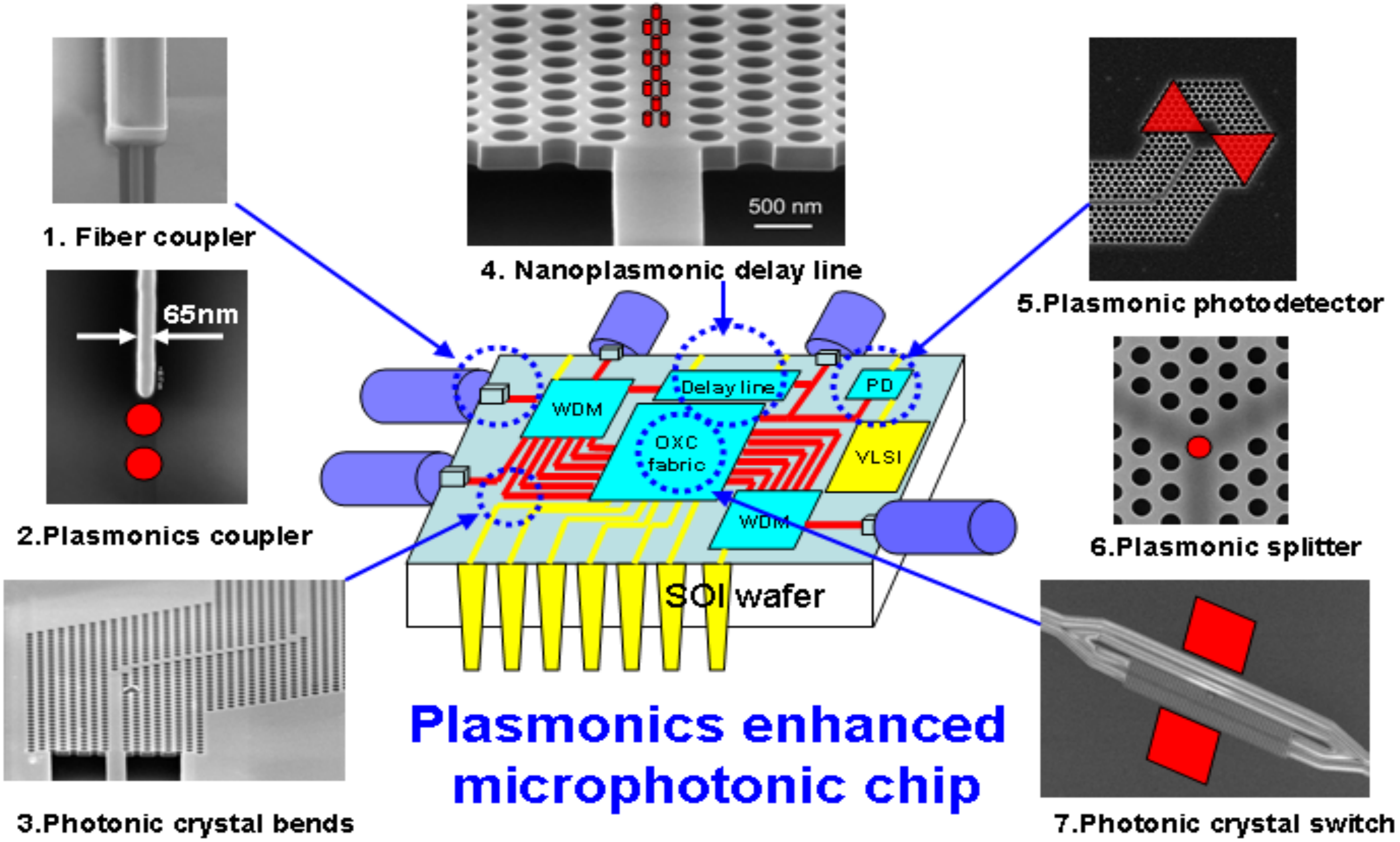
PLASMONIC WAVEGUIDES

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



H. Atwater, Scientific American, April 2007

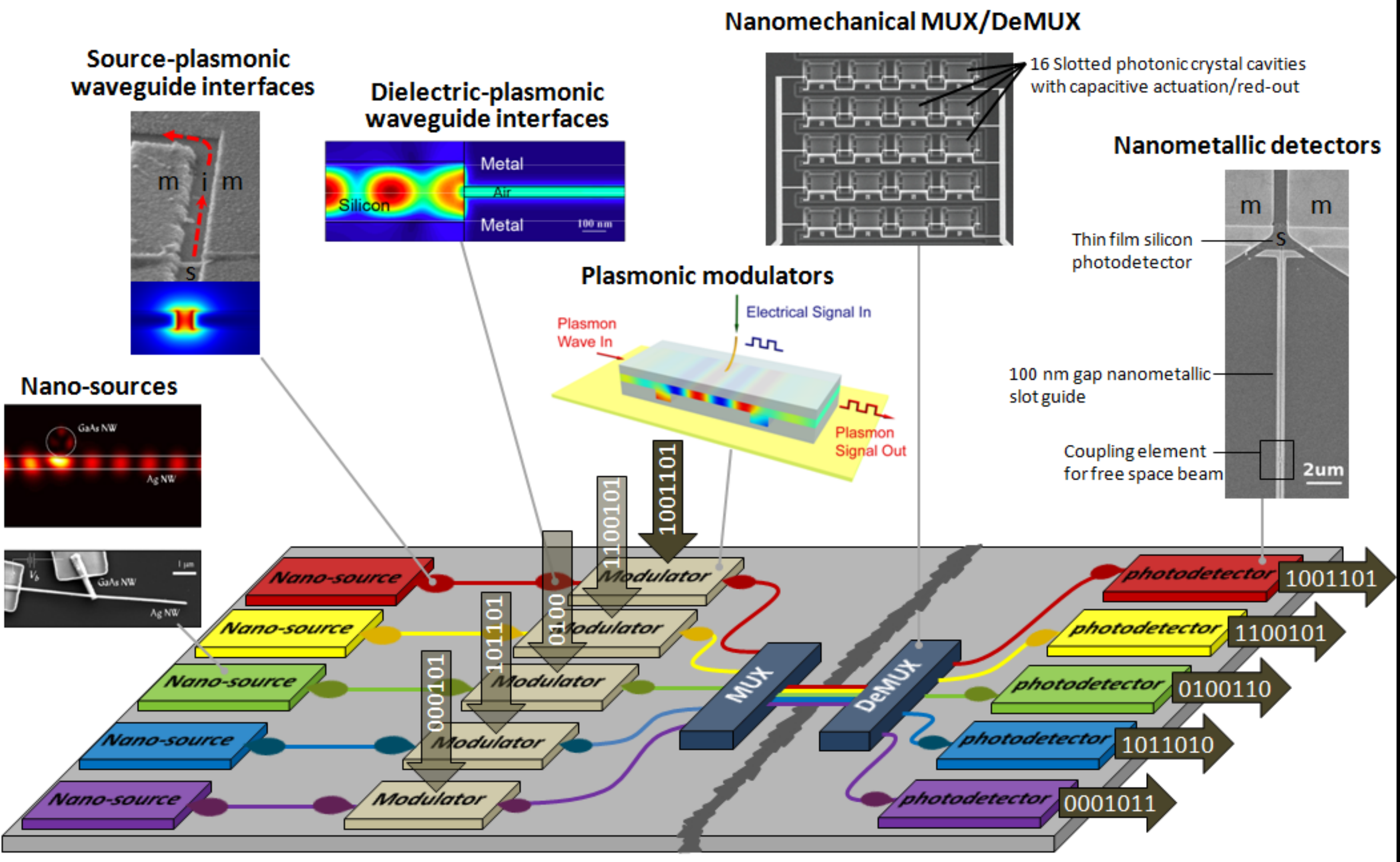
MERGING PLASMONICS WITH Si TECHNOLOGY



Integration of plasmonic elements onto Si-based microphotonic chips
SEM images are of actual photonic devices

Courtesy of Y. Vlasov (IBM)

HYBRID CIRCUITS

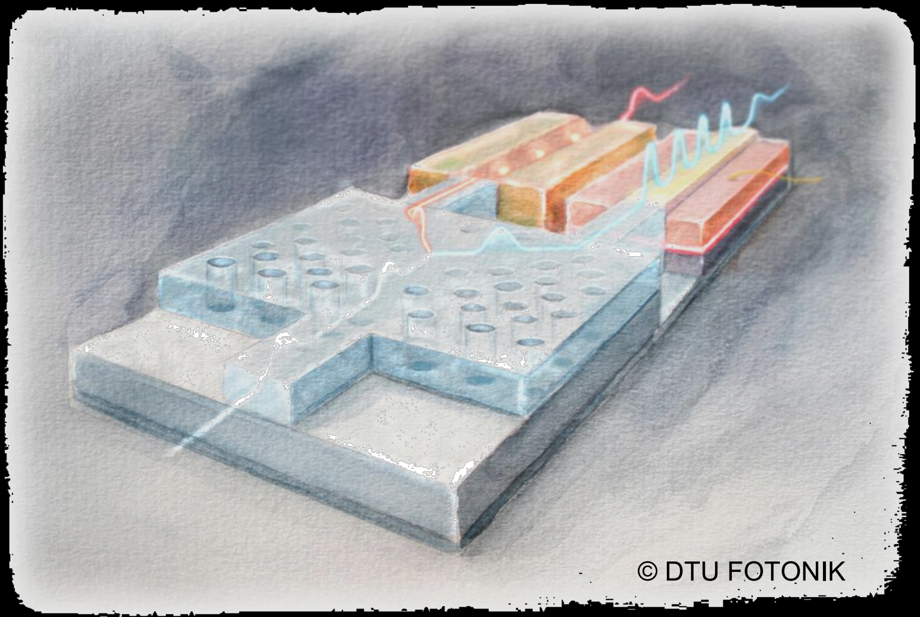


Unleashing the full potential of **HYBRID** nanophotonic components for on-chip optical communication by leveraging the ability of METALS to perform simultaneous electronic and optical functions

Courtesy of M. Brongersma

PLASMONICS/METAMATERIALS

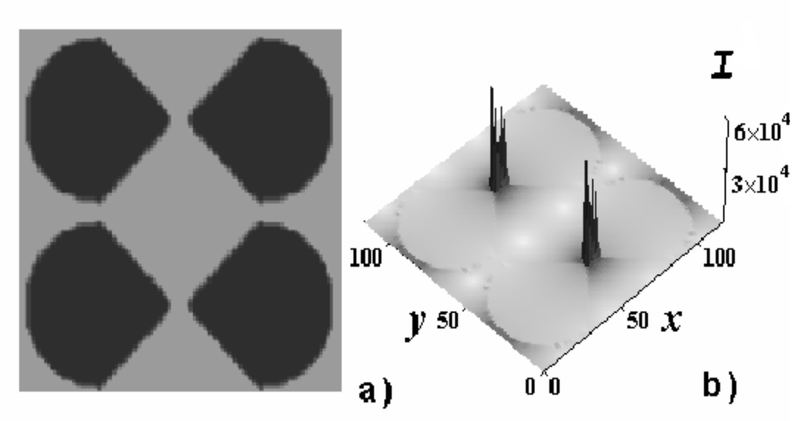
- Interconnects
  - Optical processing of data
  - Subwavelength confinement
  - Electrodes are in place
  - Coupling to other on-chip devices
  - Combination of guiding, detection, modulation, sensing
  - Usage of field enhancement for nonlinear optics
  - Integration with optoelectronics, lab-on-a-chip, solar cells
- Nano-imaging & spectroscopy
- Data recording and storage
- Sensing, SERS
- Sub-λ photodetectors
- Medical applications

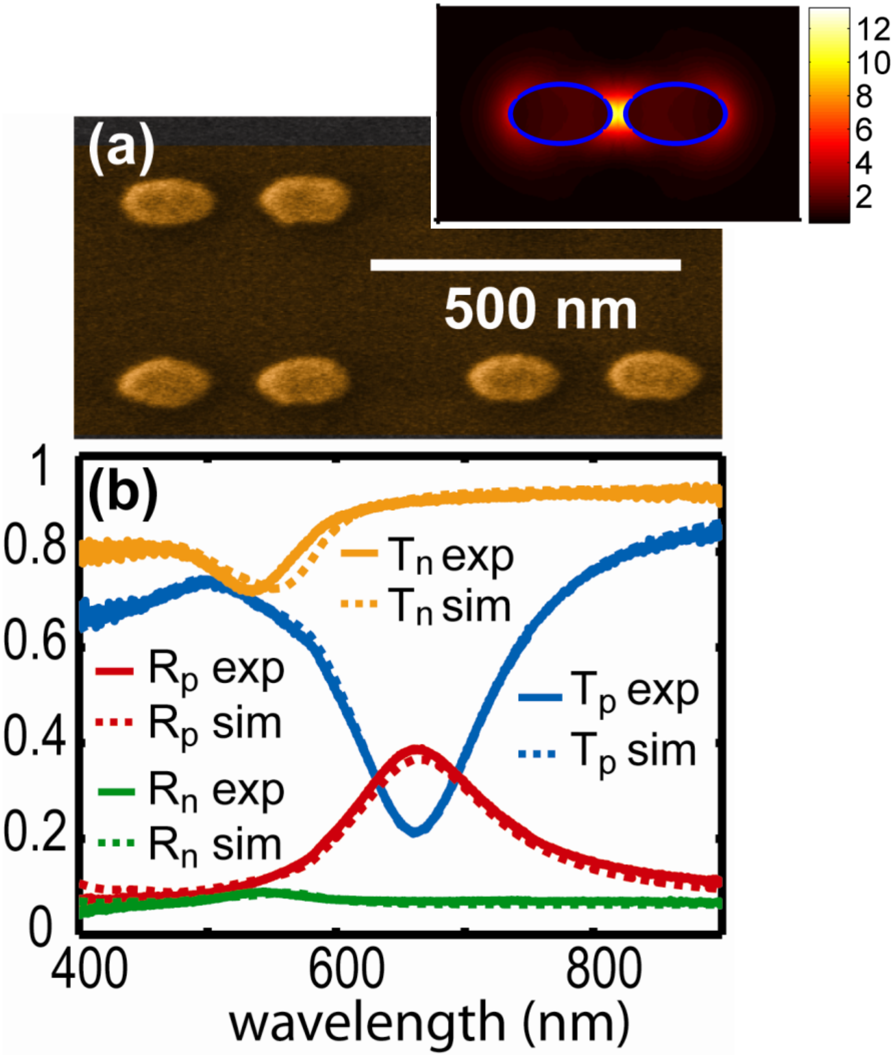

© DTU FOTONIK

OPTICAL NANOANTENNAE

OE (2009); NJP (2008); Metamaterials (2008); APL (2008)

[Bow-tie antennas]



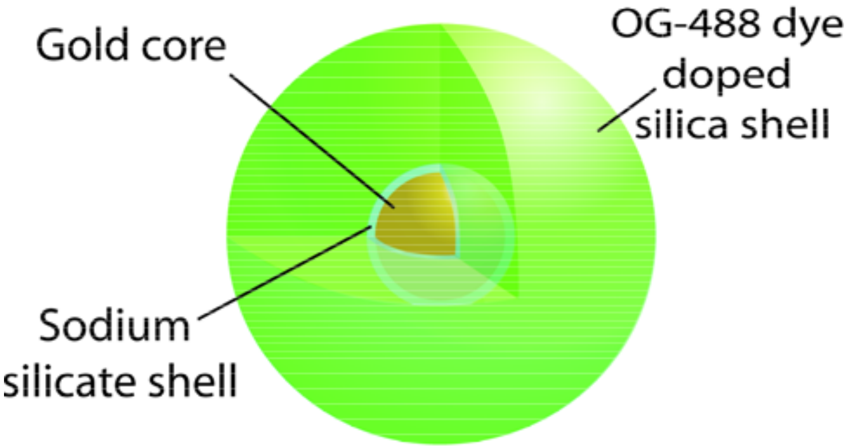


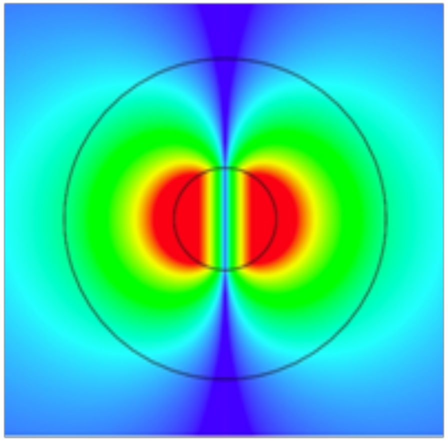
from LC-contour to nanophotonic circuits (Engheta – ‘metatronics’)

<u>Other Applications:</u>
Sensors

NANOLASER

Related prior theory:
Stockman (SPASER)





Noginov, Shalaev, Wiesner groups, Nature (2009)

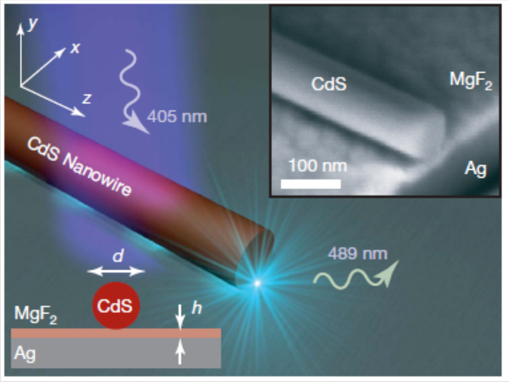
Optical MOSFET
(Stockman)

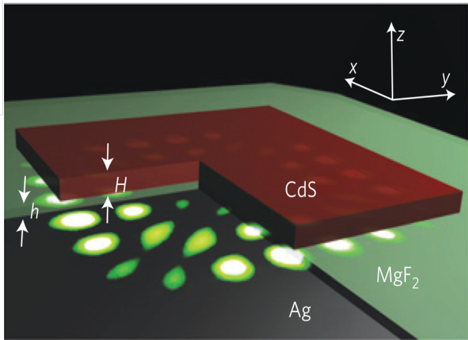
Zhang group: Plasmon Laser (Nature,2009)
Room-T Plasmon Laser (Nat. Mat, 2010)

"Spasing Laser" – Zheludev, Stockman

M. T. Hill, et al; C. Z. Ning, et al (electr. pump)

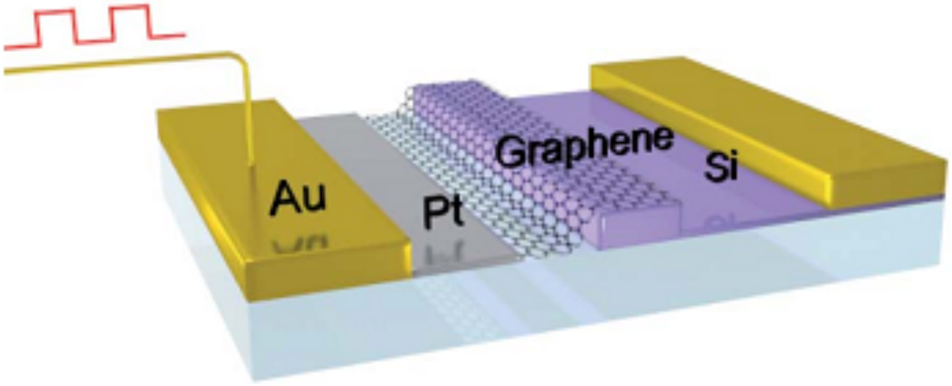
Spotlight on Plasmon Lasers (Perspective, Science, 2011)- X. Zhang, et al

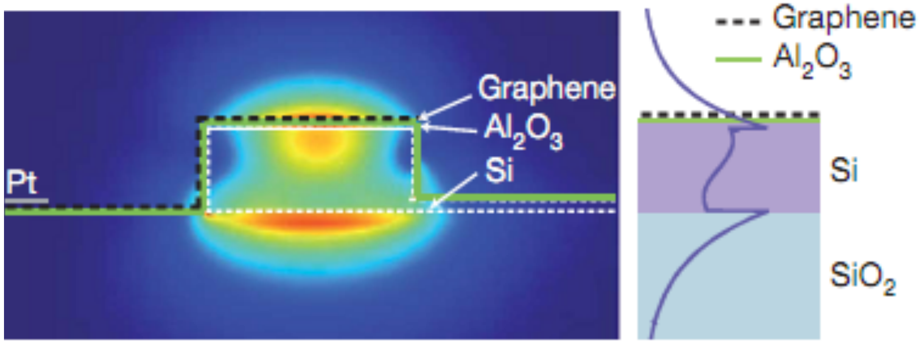


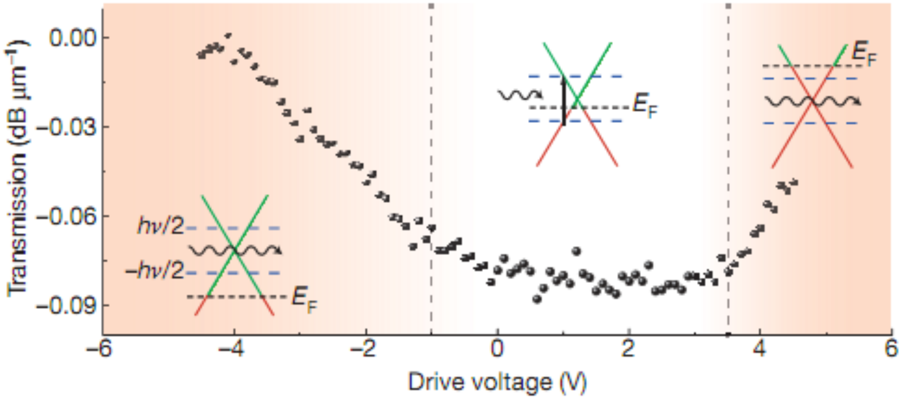


GRAPHENE-BASED OPTICAL MODULATOR

Guided light is electrically modulated in a broad spectral range of 1.35-1.6 m by controlling the interband transitions in graphene.



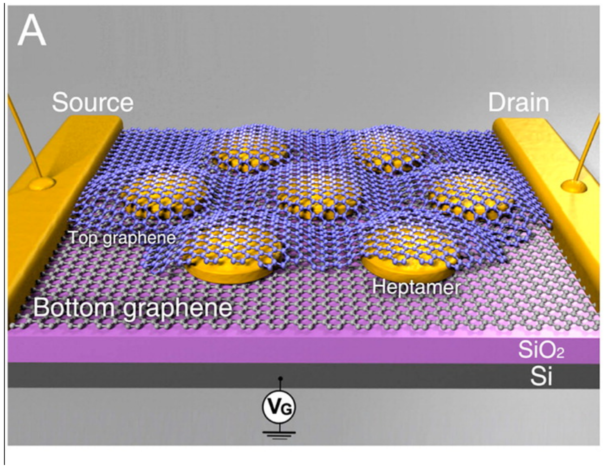


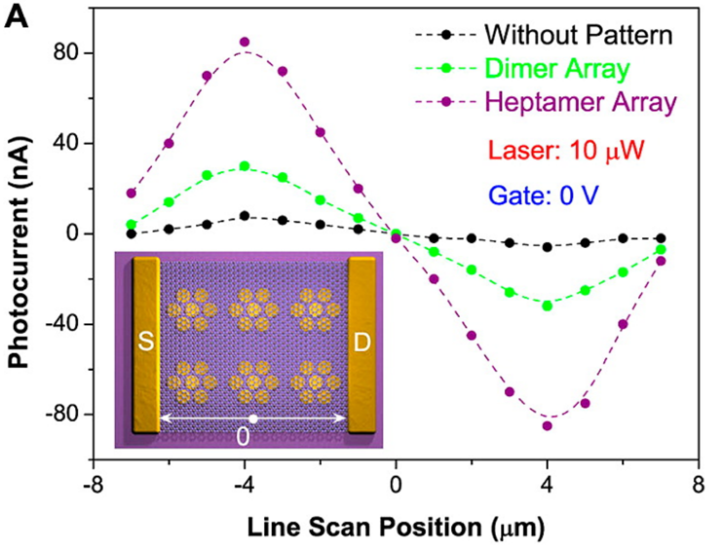


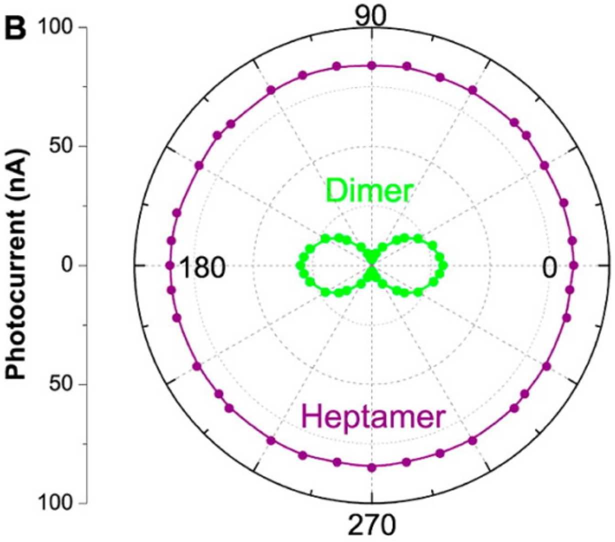
M. Liu, et al, Nature (2011) (Zhang Group)

GRAPHENE ANTENNA PHOTODETECTOR

- Hot electrons in metallic nanoantennas and direct excited electrons due to high local field are collected by graphene resulting in a photocurrent
- 20% Internal Quantum Efficiency in visible and near-IR



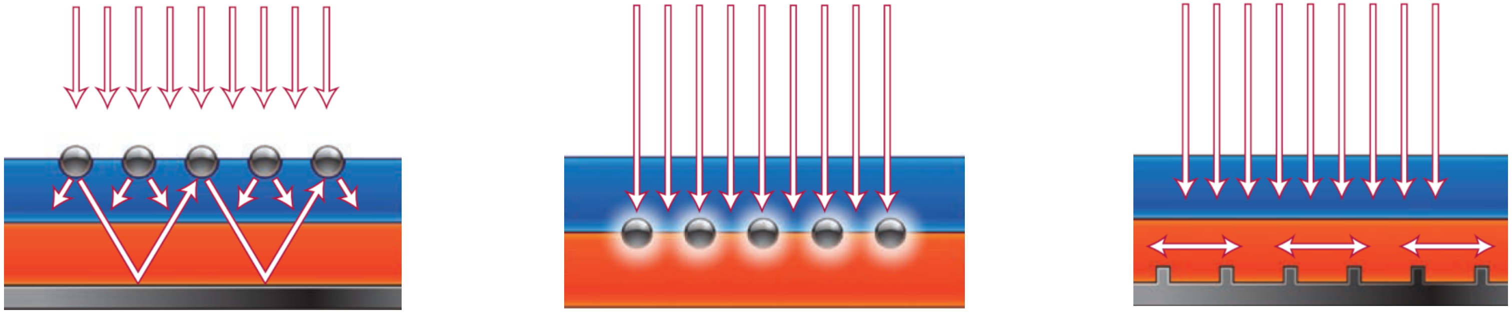




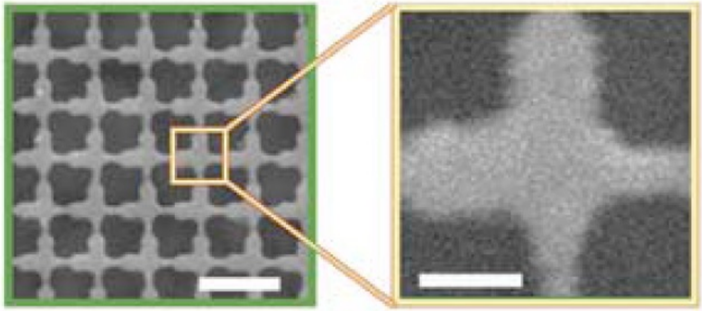
Z. Fang, et al, Nano Letters (2012) (Halas group)

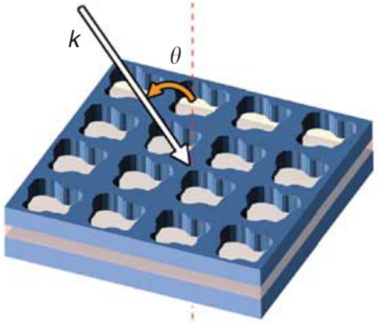
PLASMONICS FOR PHOTOVOLTAICS

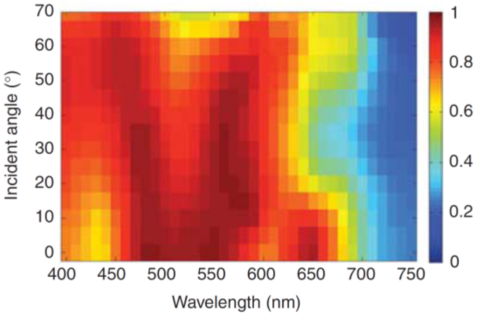
Ideas: Plasmonics can be used to improve absorption in photovoltaic devices, permitting a considerable reduction in the physical thickness of solar photovoltaic absorber layers



Demonstration of an ultrathin (260 nm) plasmonic super absorber consisting of a metal(Ag)–insulator(SiO2)–metal(Ag) stack with a nanostructured top silver film composed of crossed trapezoidal arrays





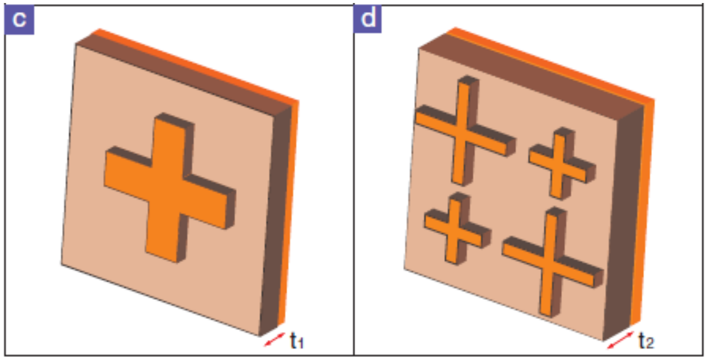


Atwater & Polman. Nature Mater., (2010)

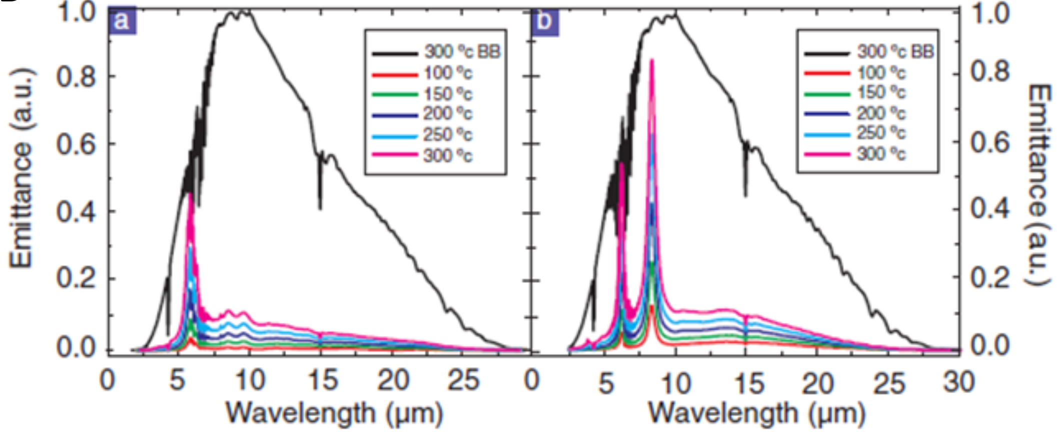
K. Aydin et.al. Nature Comm. (2012) (Atwater group)

CONTROL OF THERMAL RADIATION

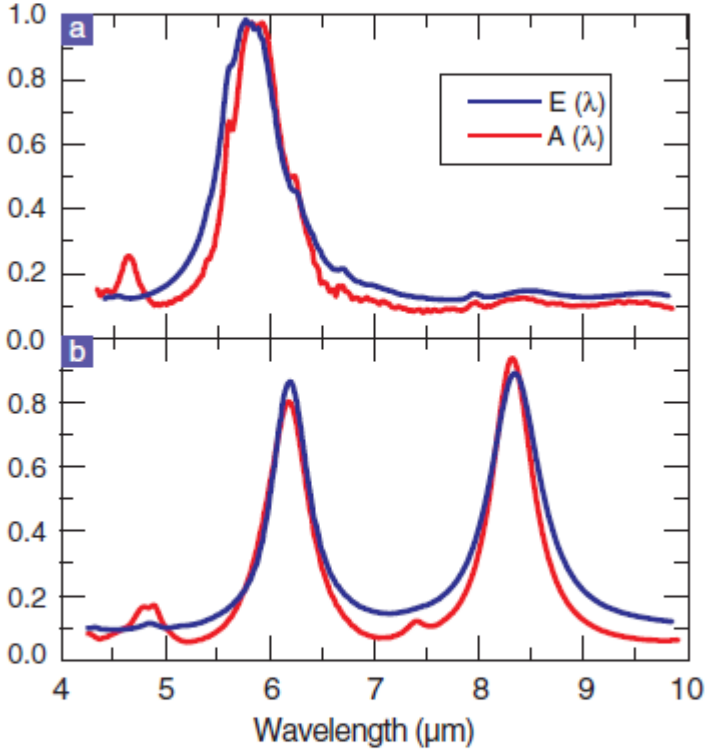
A



B



C

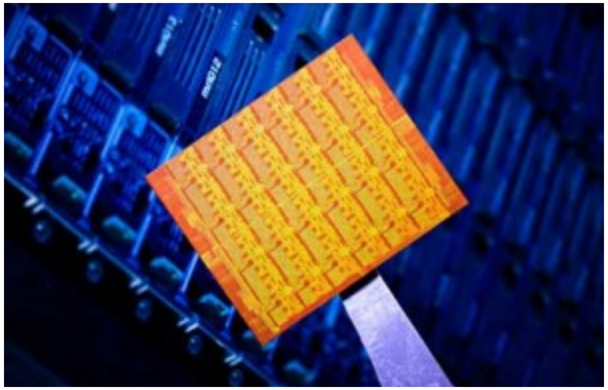


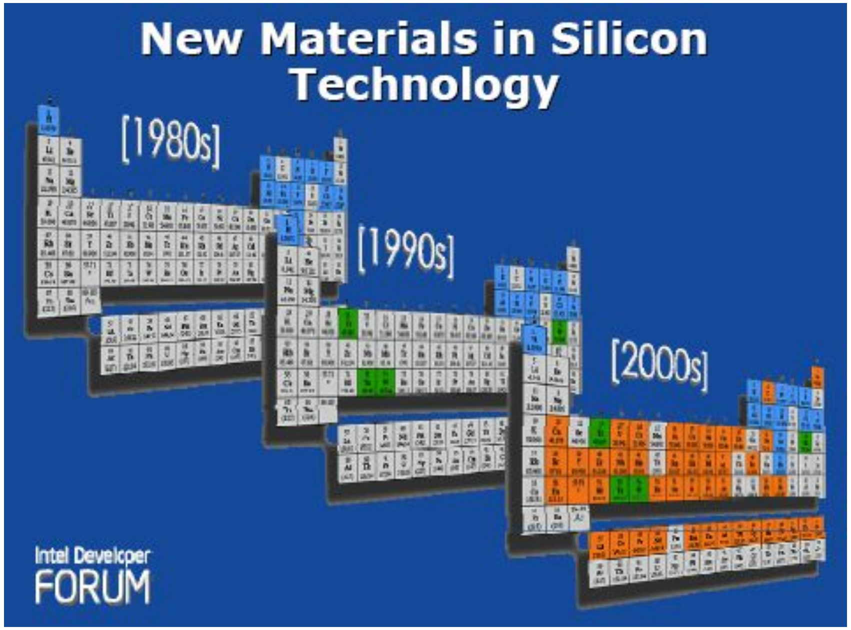
Features: experimentally realize a narrow band MIR thermal emitter

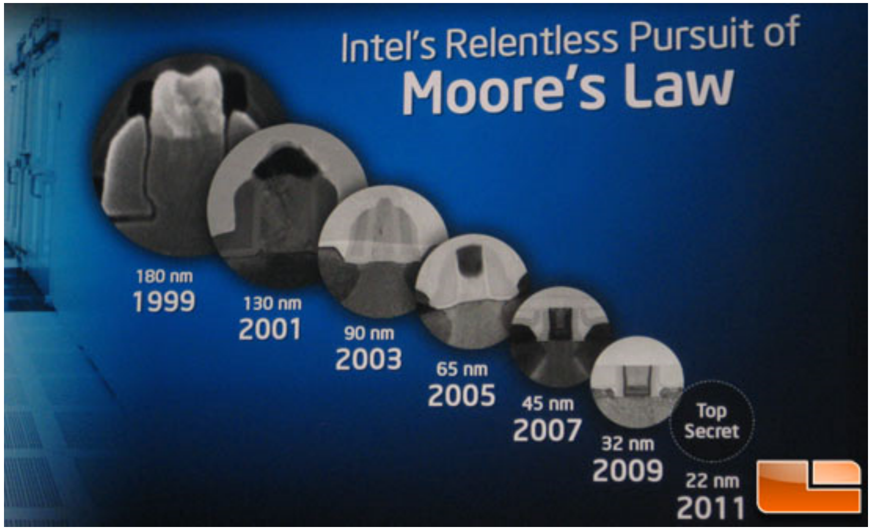
X. Liu, et al. Phys. Rev. Lett. (2011)

AGE OF SILICON TO SILICON ++

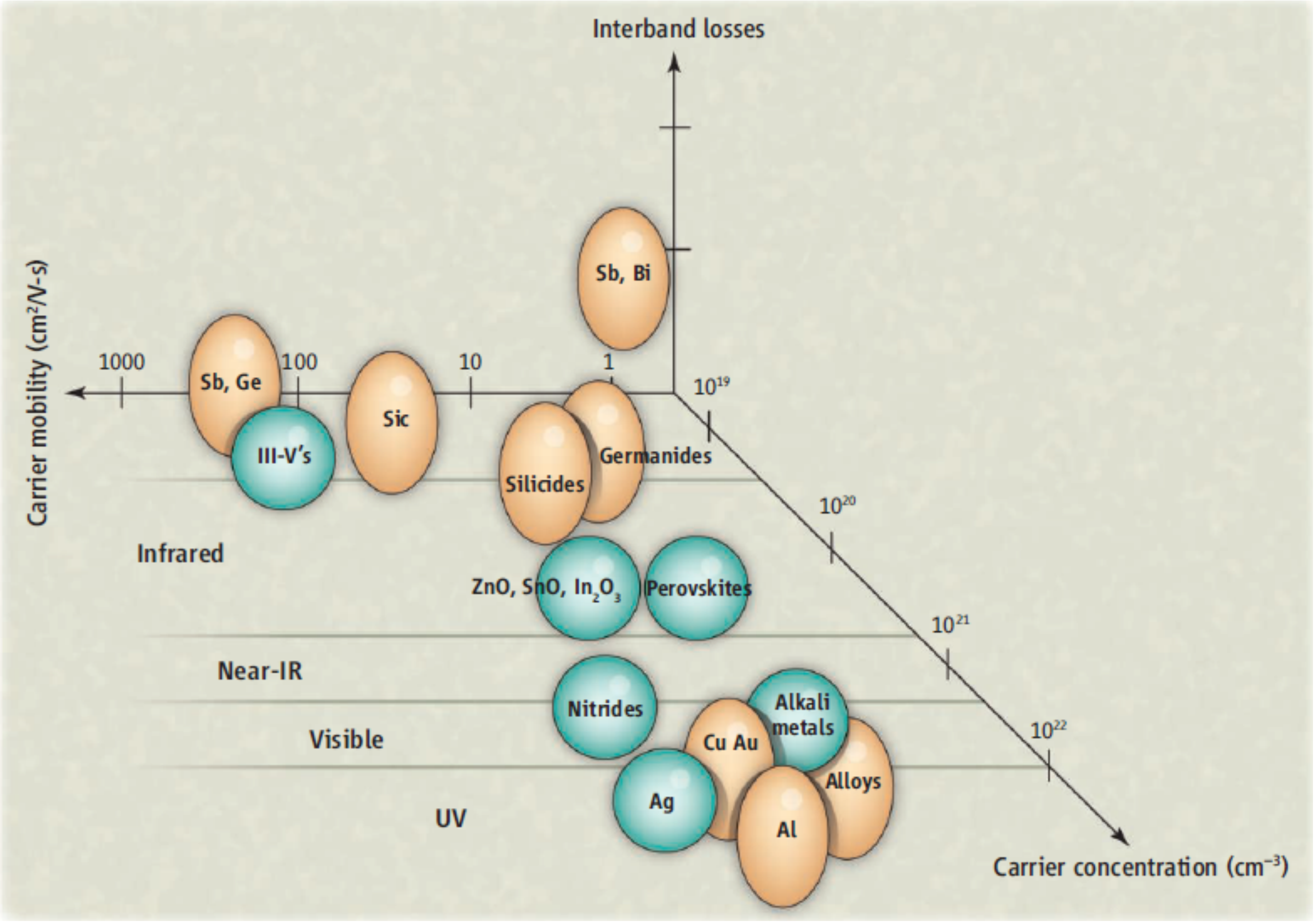
NEED FOR NEW PLASMONIC MATERIALS







NEW CMOS-COMPATIBLE PLASMONIC MATERIALS



PURDUE
UNIVERSITY

New Platforms & Metasurface Designs for Nano- & Quantum Photonics

Vladimir M. Shalaev

Birck Nanotechnology Center, Purdue University

Major collaborator: Alexandra Boltasseva

Photonics and Material Science


Isamu Akasaki


Hiroshi Amano


Shuji Nakamura

Nobel prizes in physics 2014

Blue LED

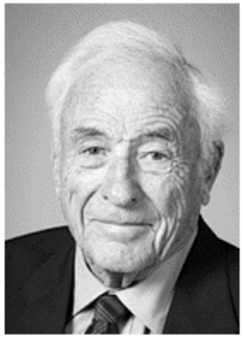

Andre Geim


Konstantin Novoselov

Nobel prizes in physics 2010

Graphene


Charles Kuen Kao


Willard S. Boyle

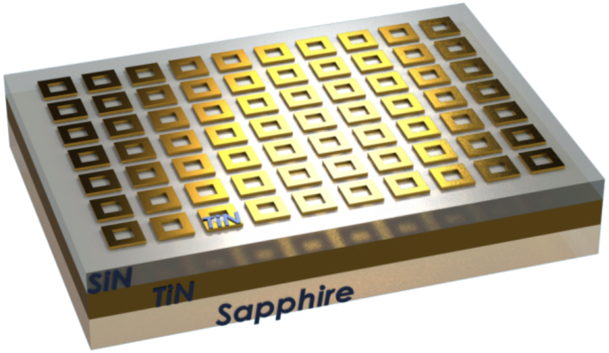

George E. Smith

Nobel prizes in physics 2009

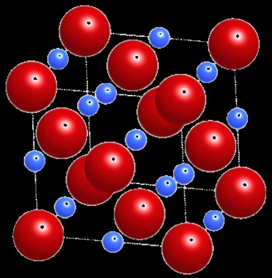
Low-loss optical fiber

OUTLINE

- **New Material Platforms for Plasmonics**
- Transition Metal Nitrides as Plasmonic Ceramics & Transparent Conducting Oxides
- Applications:
  - Thermophotovoltaics
  - Heat Assisted Magnetic Recording
  - Plasmonic photothermal therapy
  - NLO & Nanophotonic circuitry



- **New Materials for Quantum Photonics**
  - Single-photon sources and quantum registers
- **Metasurface Designs for Nano- & Quantum Photonics**



New Material Platforms

in collaboration with Boltasseva group, Purdue

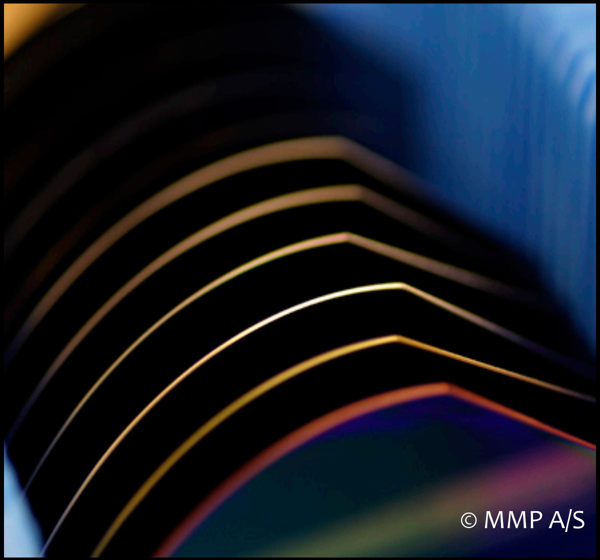
Recent Reviews:
G. Naik, VMS, A. Boltasseva, Advanced Materials (2013)
U. Guler, VMS, A. Boltasseva, Materials Today (2014)

:
J. Ndukaife, A. Boltasseva, VMS, Science (2016)
U. Guler, A. Boltasseva, VMS, Science (2014)
A. Boltasseva, VMS , Science (2015)

MATERIALS

- GOLD and SILVER used so far…
  - High cost
  - Not adjustable optical properties
  - Not CMOS-compatible
  - Cn’t sustain high T
  - Not mechanically robust

- Refractory (high-T) plasmonic materials
- Adjustable / Tunable
- SC-compatible
- Low cost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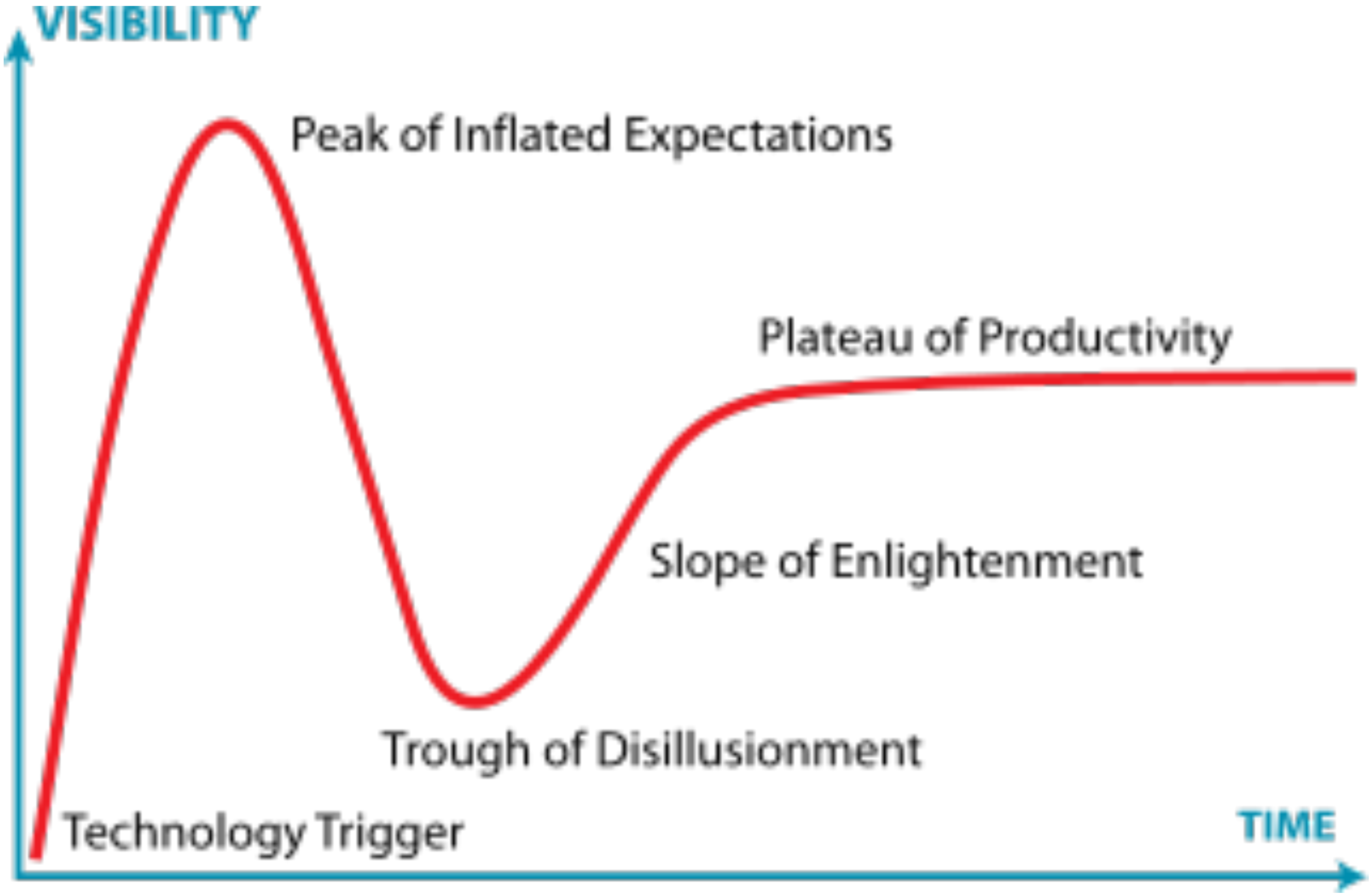
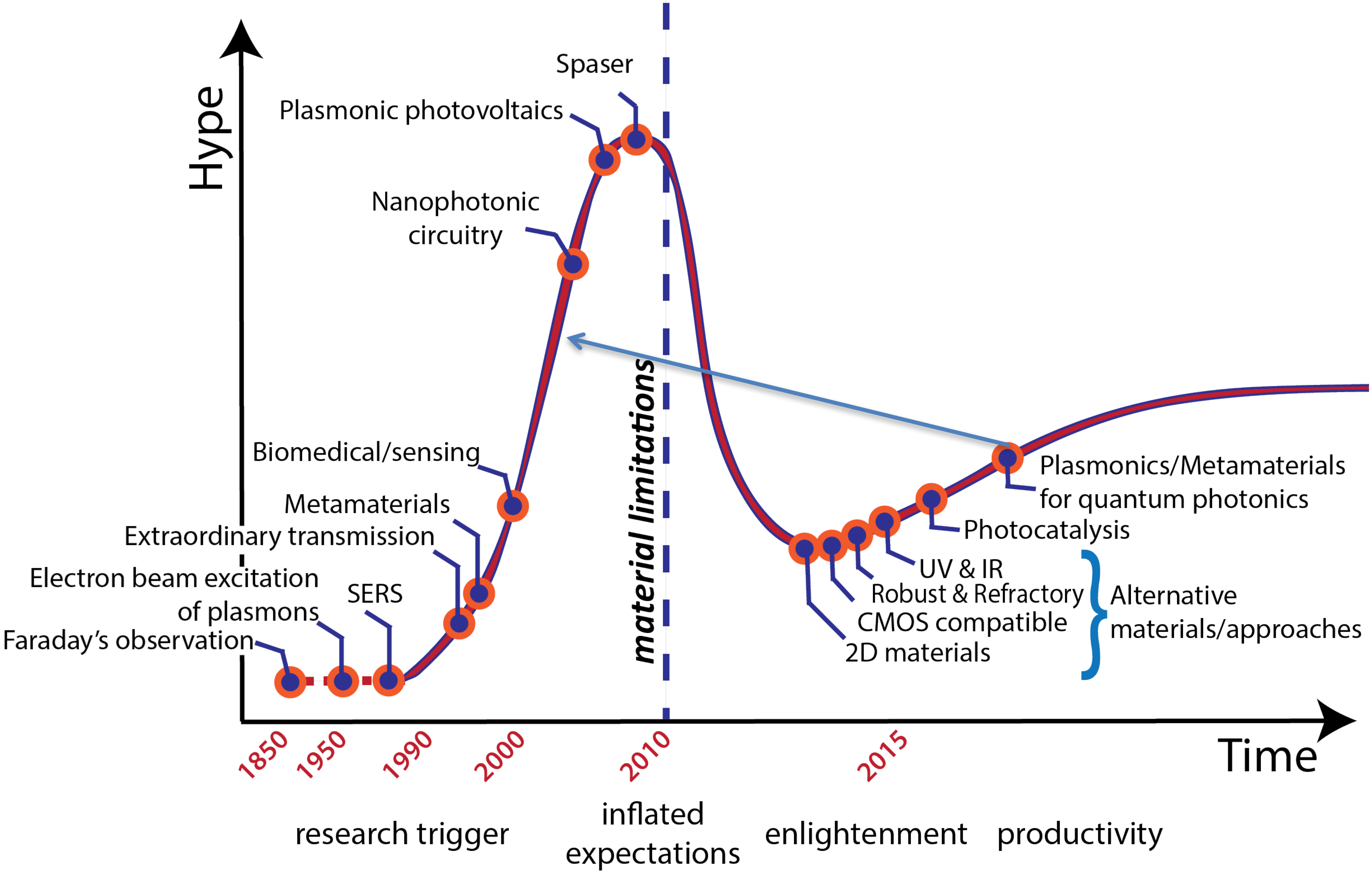
Hype (Gartner) Cycle



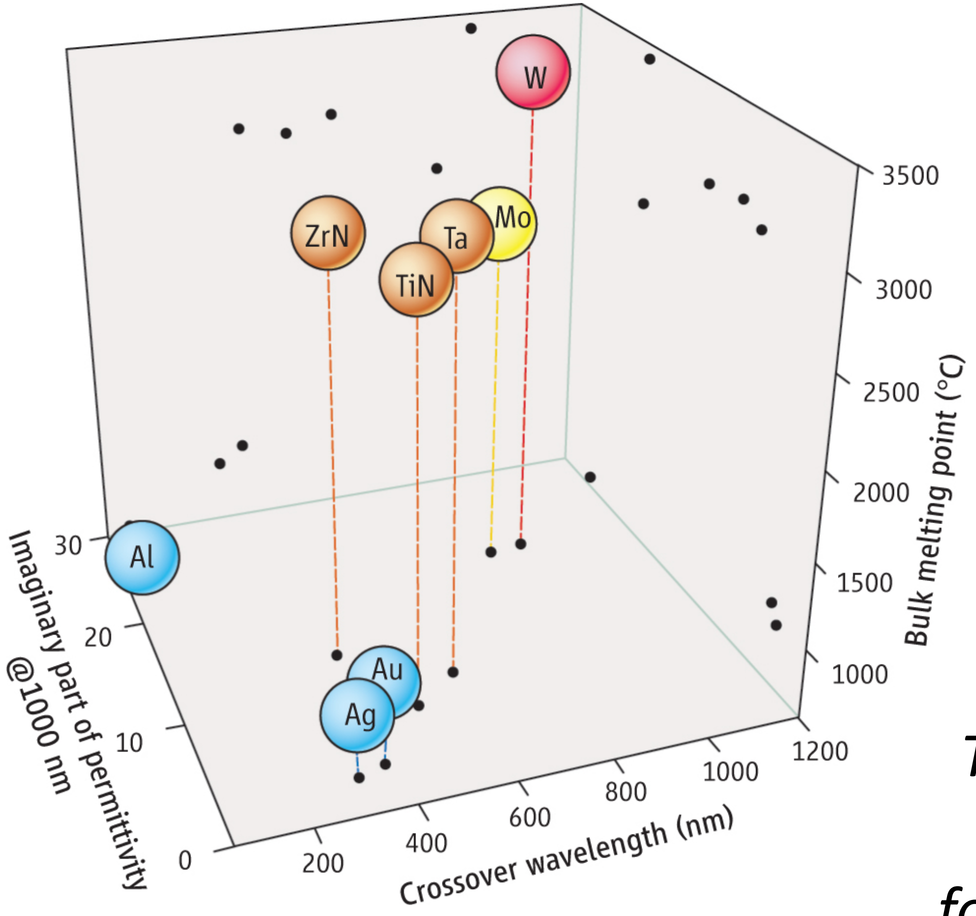
http://www.gartner.com/technology

Hype Cycle for Plasmonics



U. Guler et al., Faraday Discussions 178, 71-86 (2015)

Refractory Plasmonics



- Plasmonic metals
  - Low melting points
  - Soft
- Refractory metals
  - Lossy, non-plasmonic

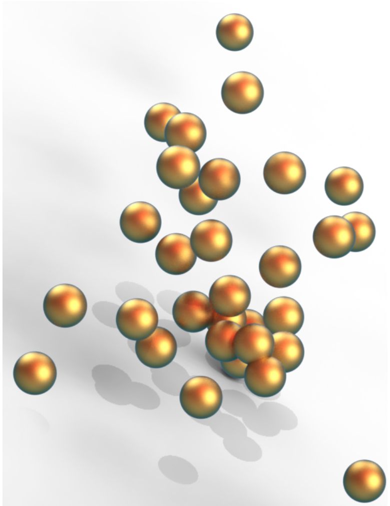
- **Transition metal nitrides**
  - **Mimic Au optical properties**
  - **High melting point**
  - **Hard materials**

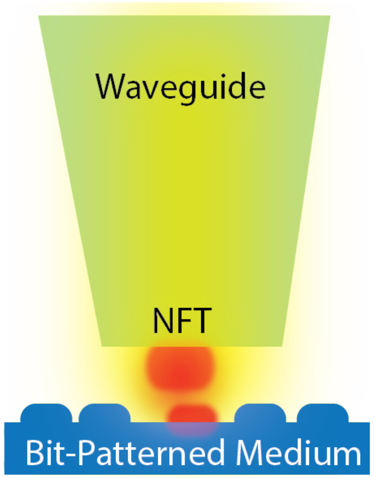
Transition Metal Nitrides can be the solution for high temperature applications

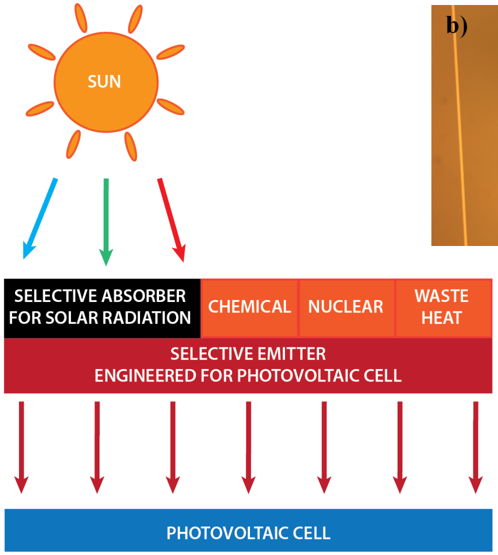
U. Guler, A. Boltasseva, V. M. Shalaev, Science 344, 263 (2014)

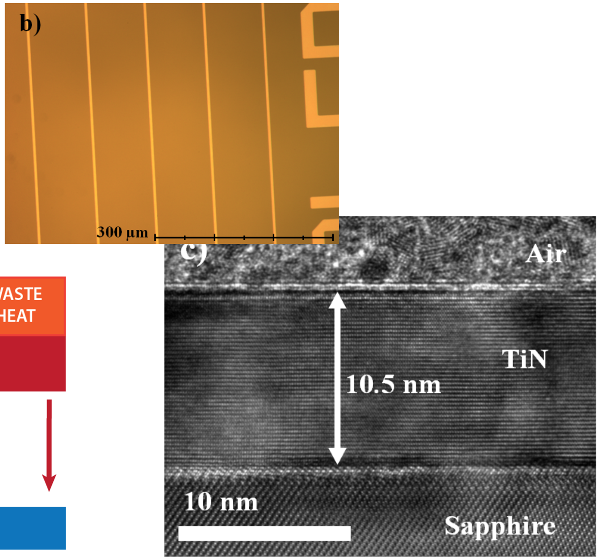
Technology Potential

- Plasmonic ceramics for
  - Solar/Thermophotovoltaics (S/TPV)
  - Heat-assisted magnetic recording (HAMR)
  - Photothermal therapy
  - Nanophotonic circuitry and NLO









U. Guler et al., Mater. Today (2014)
W. Li et al., Advanced Materials (2014)
N. Kinsey eta al., JOSA B (2015)

Nano-Meta Technologies Inc. (NMTI)

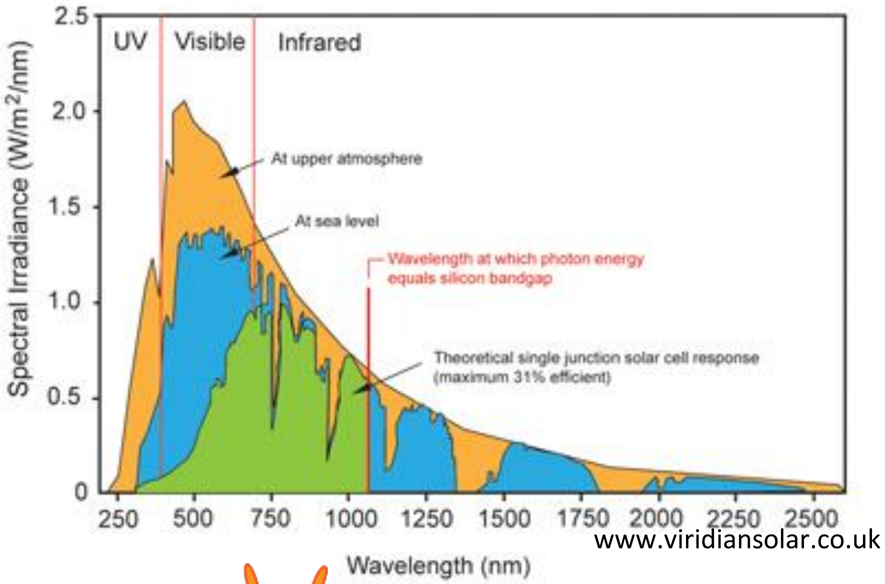
SOLAR/THERMOPHOTOVOLTAICS (S/TPV)

Single Junction PV
Fundamental Limits

Spectrum Losses

- Lower energy photons are completely lost 19%
- Higher energy photons are partly lost 33%

Shockley–Queisser limit 33.7%

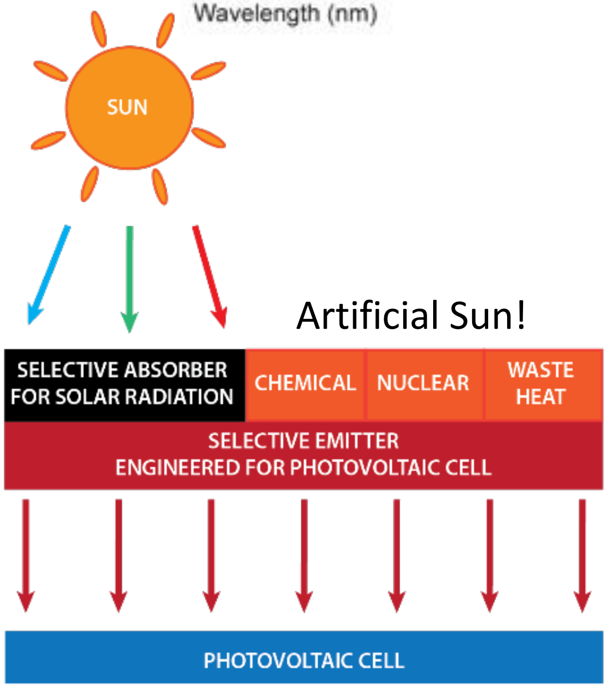


www.viridiansolar.co.uk

Solar/Thermophotovoltaics:

- Broad absorption of sunlight
- Selective "in-band" emission
- Suitable for hybrid operation
  "Human-made sun"

85% theoretical limit!



Artificial Sun!

SELECTIVE ABSORBER FOR SOLAR RADIATION

CHEMICAL

NUCLEAR

WASTE HEAT

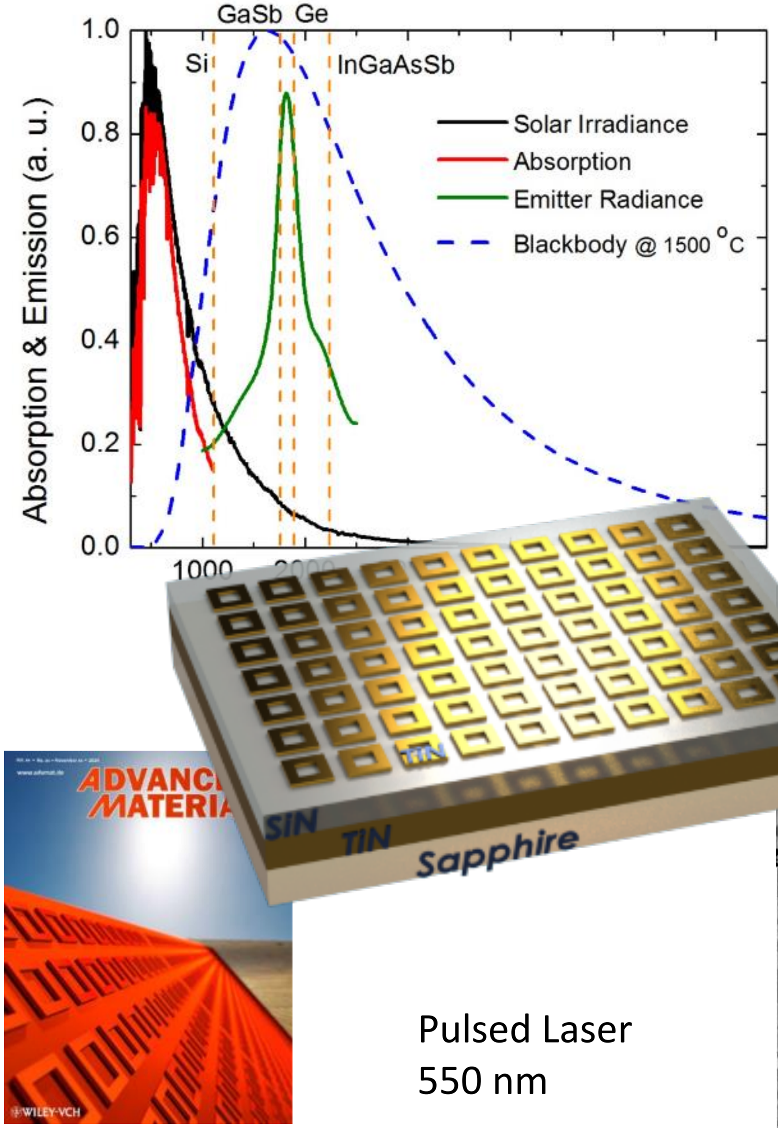
SELECTIVE EMITTER ENGINEERED FOR PHOTOVOLTAIC CELL

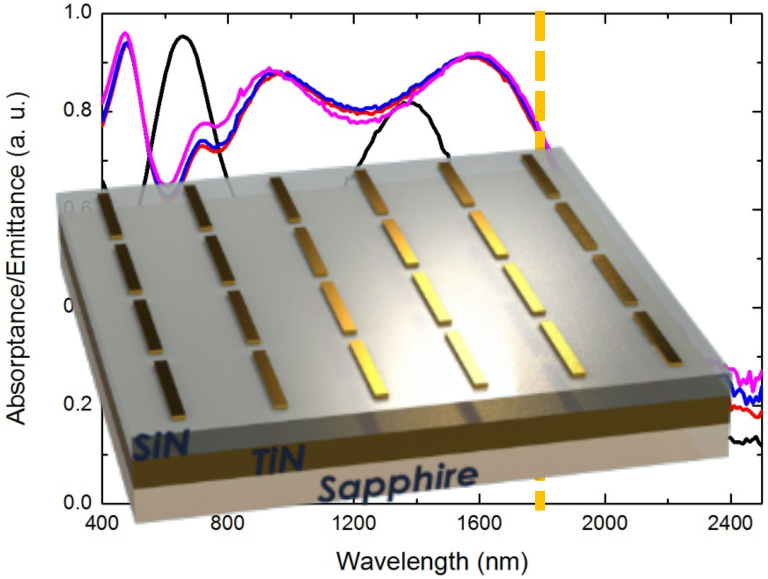
PHOTOVOLTAIC CELL

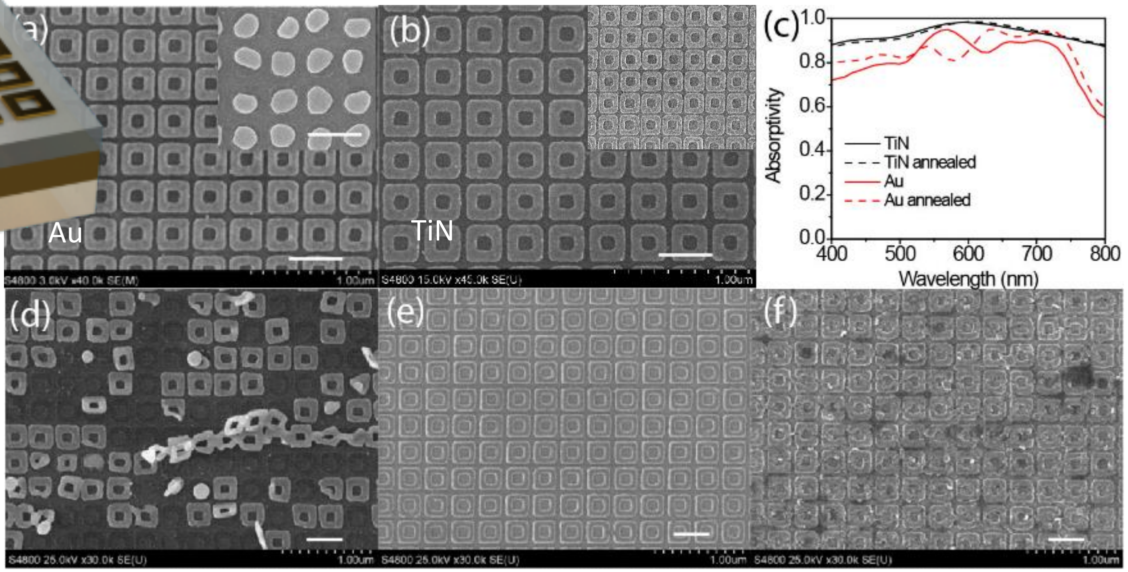
High operation temperatures: Material Limitations.

TiN for S/TPV

Nano-Meta Technologies Inc. (NMTI)







Pulsed Laser
550 nm

W. Li et al., Adv. Mater. 26, 7959-7965 (2014)

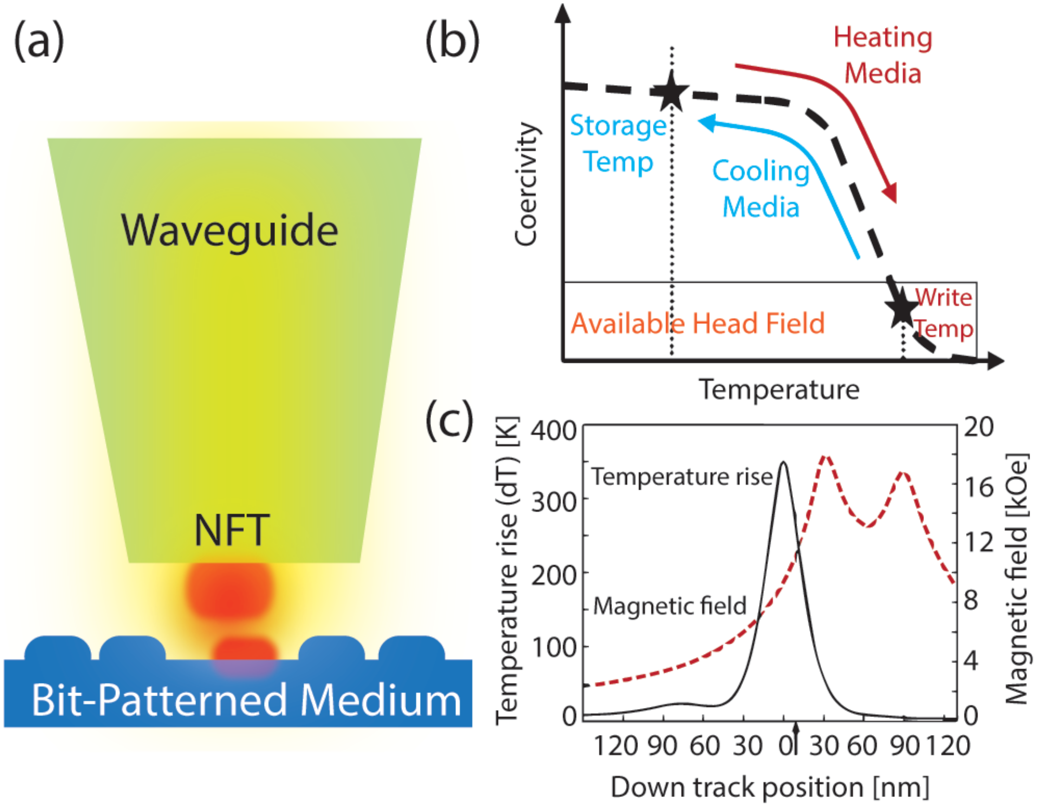
Heat Assisted Magnetic Recording

Denser storage required - ***smaller bit sizes***

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

Higher coercivity material requires higher writing temperatures
- ***light induced heating***

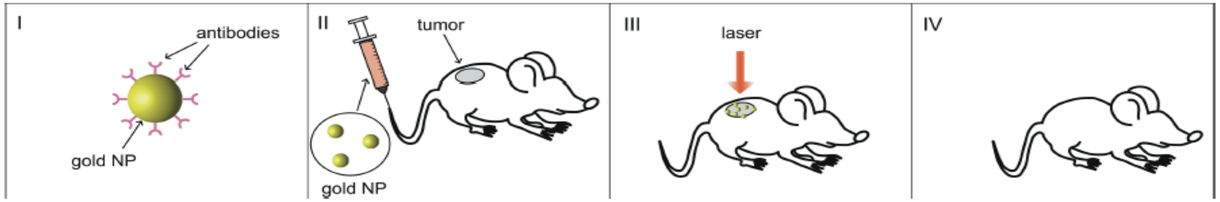
Sub-diffraction focusing required - ***antenna for visible light***



HAMR promises 10 – 16X greater HDD storage densities!

Temperatures up to 500 °C

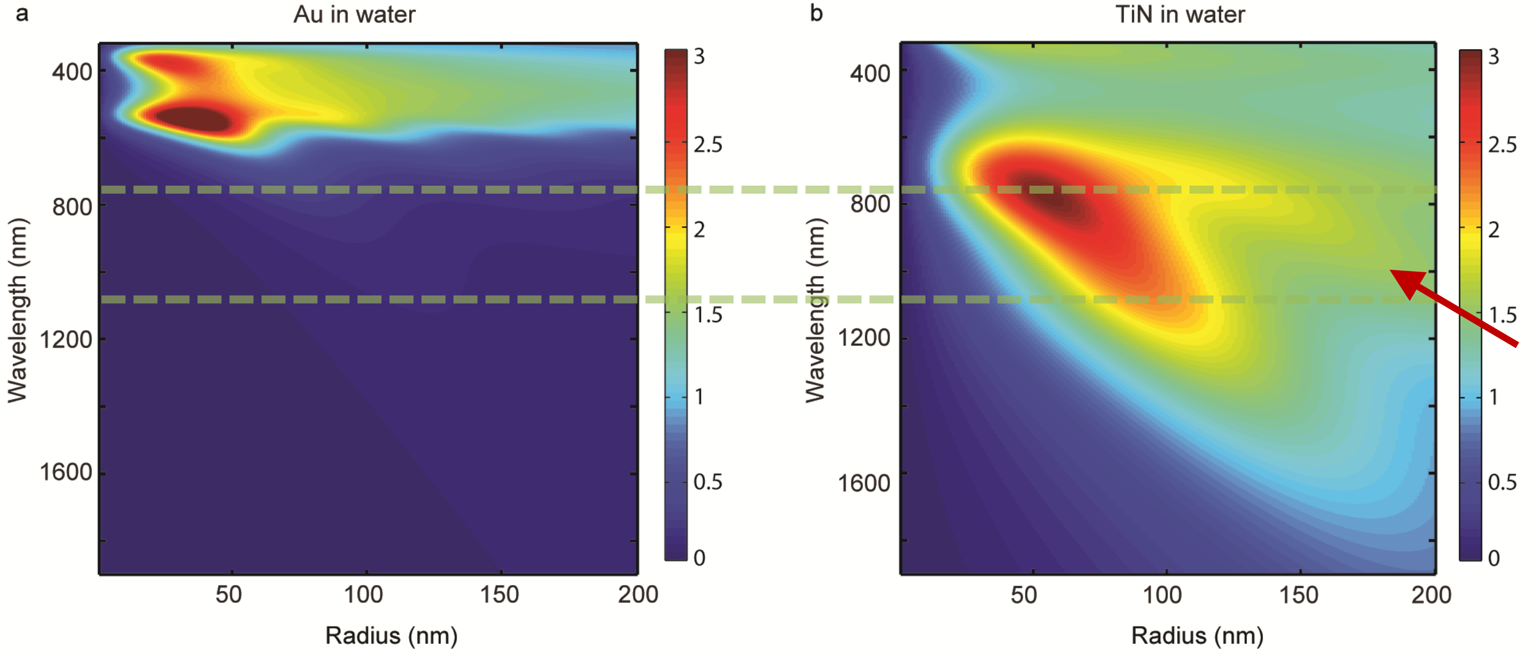
Thermal Therapy - TiN



G. Baffou et al., LPR **7**, 2 (2013).
J. M. Stern et al., J. Urol. **179**, 748 (2008).

$$Q = \sigma_{\mathrm{abs}} I = \sigma_{\mathrm{abs}} \frac{nc\varepsilon_0}{2} |\mathbf{E}_0|^2$$

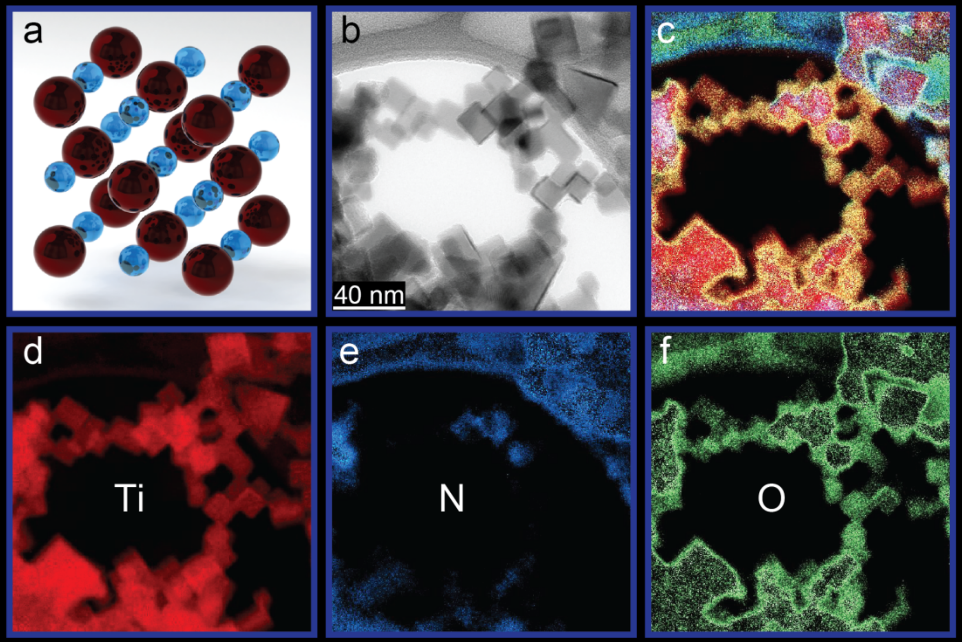
L. R. Hirsch et al., PNAS **100**, 13549 (2003).
N. Halas, MRS Bulletin **30**, 362 (2005).
B. E. Brinson et al., Langmuir **24**, 14166 (2008).

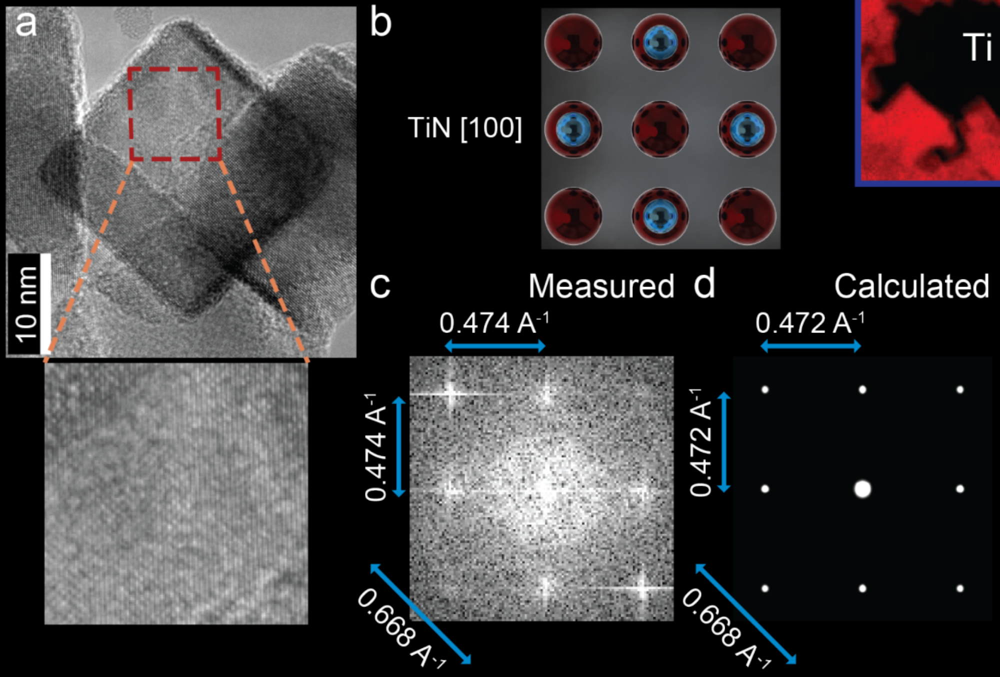


Transparency window

U. Guler et al., Nano Letters 13, 6078 (2013)

Plasmonic TiN in Colloids



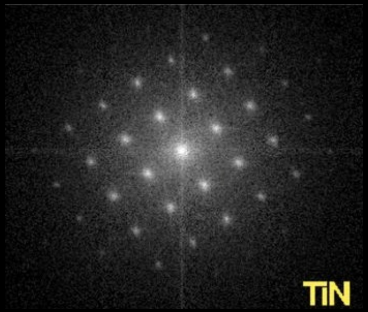


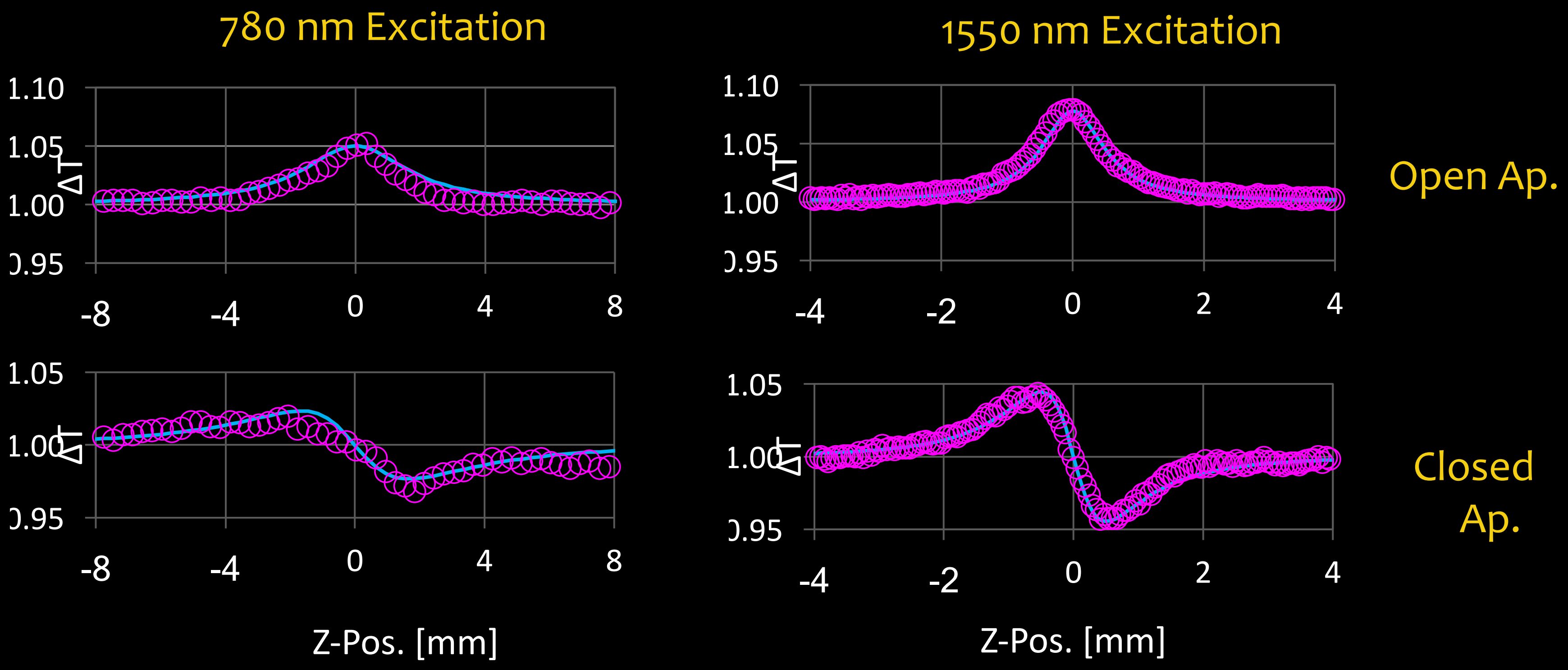
Golden luster of dispersed TiN powder

U. Guler et al, Materials Today (2014)
U. Guler et al, Nanophotonics (2015)

Effective Third-Order Nonlinearities TiN

- TiN has a cubic lattice
  - No bulk $\chi^{(2)}$
- Investigate $\chi^{(3)}$ response using the Z-scan method





In collaboration with NSU and CREOL

G.V. Naik et al, Proc. Nat. Acad. Sci. US **111**(21) 7546-7551m 2014

N. Kinsey et al, arXiv 1507.06674, 2015

Effective Third-Order Nonlinearities TiN

- Although direct comparison is difficult between available metal films
  - Varying methods of testing, wavelength, pulse width, etc.

- TiN exhibits nonlinearities of similar strength to gold & silver
  - Added bonus of increased damage threshold (up to 1 order of magnitude) [2]

- TiN exhibits saturable absorption up to 780 nm
  - Gold exhibits 2-photon absorption

Material	λ [nm]	Pulse-Width	α_o [cm^{-1}]	Re$\{\tilde{\chi}_{\mathrm{eff}}^{(3)}\}$ [esu]	Im$\{\tilde{\chi}_{\mathrm{eff}}^{(3)}\}$ [esu]
52 nm TiN film on Fused Silica	1550	95 fs	3.5×10^{5}	-4.2×10^{-9}	-1.2×10^{-8}
	780	220 fs	3.5×10^{5}	-3.8×10^{-10}	-1.3×10^{-9}
52 nm Au film [1]	532	35 ps	3.3×10^{5}	7.0×10^{-10}*	4.0×10^{-9} *

*Utilized simplified expressions for susceptibility

**Results were recalculated from provided data using complex susceptibility relation

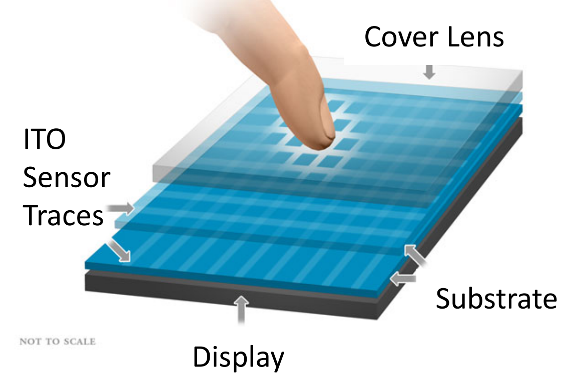
N. Kinsey et al, arXiv 1507.06674, 2015

1 E. Xenogiannopoulou & P. Aloukos, Opt. Commun. **275**, 217-222 2007

2 B. Gakovic et al, J. Opt. A – Pure Appl. Op. **9**, S76-S80, 2007

TCOs as Dynamic Materials

- TCOs with extremely high dopant solubility
  - 10^{21} cm^{-3}
- Numerous advantages for plasmonic applications
- Mature fabrication processes
  - Sputtering, PLD, ALD, CVD, etc.
- Non-stoichiometric material
  - Plasma frequency highly tunable from VIS to NIR (ex. ITO 600 - 1600 nm)
- AZO and GZO can have significantly lower permittivity (both |ε'| and ε") at telecommunication wavelengths

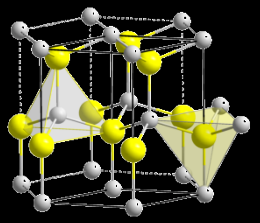


ITO-based touch screens

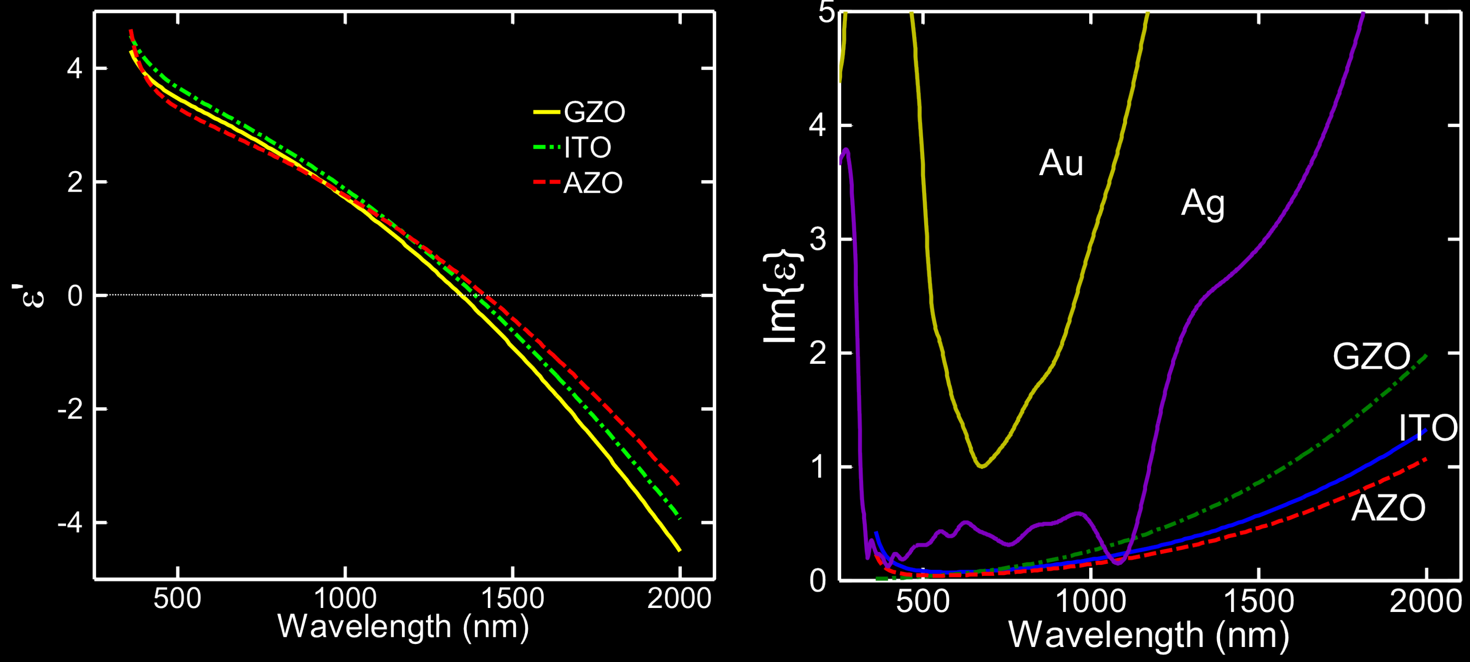
IGZO-based highly resolved flexible screen

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

Transparent Conducting Oxides



- Doped Zinc Oxide: Wide band-gap (3.37 eV @ 300K)
- Al or Ga (up to 10^{21} cm^{-3})



Also see works of:
O. L. Muskens
H. A. Atwater
M. A. Noginov
N. Zheludev
C. B. Murray
D. J. Milliron
V. J. Sorger
R. P. H. Chang
M. Wegener
S. Franzen
T. W. Odom
H. Giessen
V. A. Podolskiy

AZO: Lowest Drude damping, Longest cross-over wavelength ($5\text{x}10^{20}$ cm^{-3})
GZO: Cross-over wavelength as low as 1.2 μm
Theoretical studies: with Norfolk and Navy Research Lab

G.V. Naik, et al, Optical Mater. Exp. 1 (2011)
J. Kim, et al, PRX (2013)

TiN Interconnects & AZO all-optical modulator

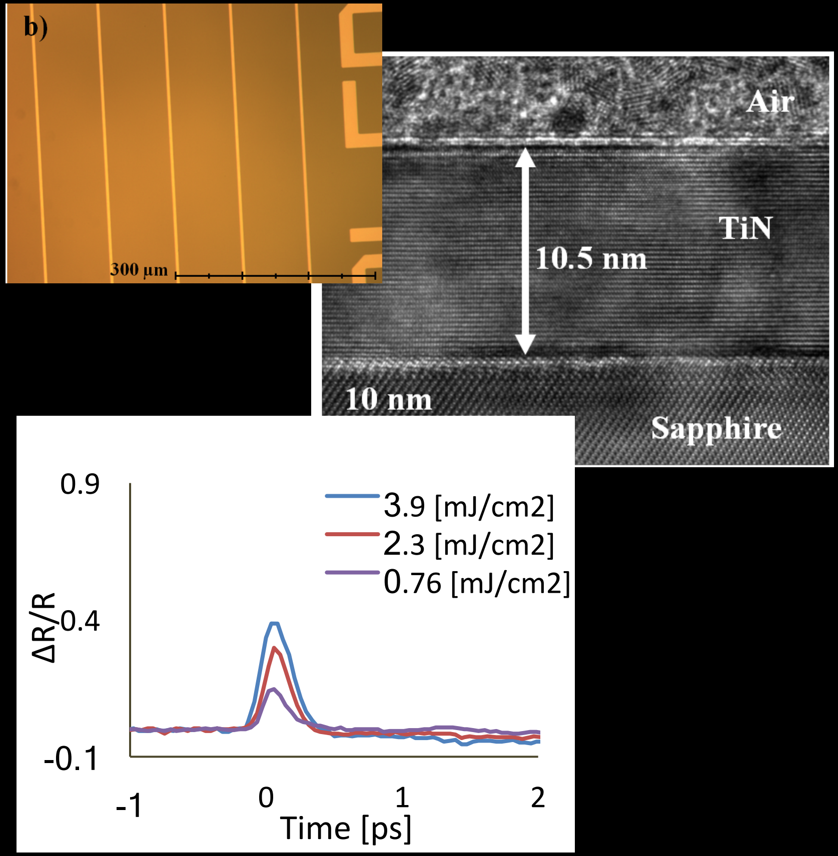
N. Kinsey, et al, Optica (2015)
- cover article

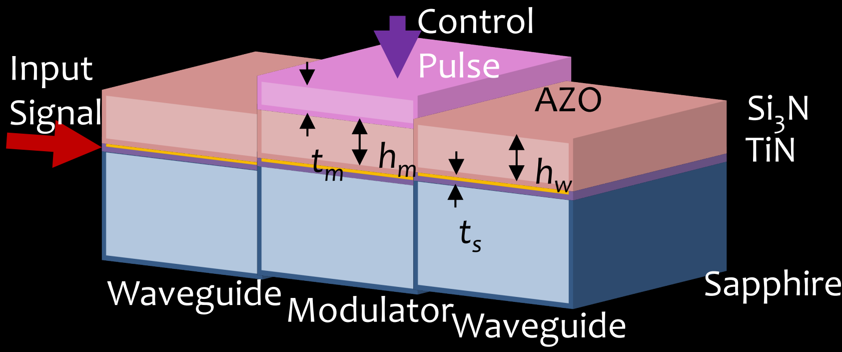
TiN Platform for Integrated Circuits

Experimentally tested low-loss TiN interconnects

- 5.5 mm propagation length

- All-optical Modulator
  - Tuning AZO: 40% (30%) change in R (T) [ΔN = 0.7 x 10^{20} cm^{-3}]
  - 90 fs response time
  - Modulation depth 0.4 dB/µm
  - 0.06dB insertion loss





N. Kinsey, et al, *Optics Express*, **22**(10), 2014.
N. Kinsey, et al., JOSA B (2015), Optica (2015)

See also work by the Atwater, Zheludev, Muskens, Giessen groups and others

Giant Optical Kerr Effect in ENZ-AZO

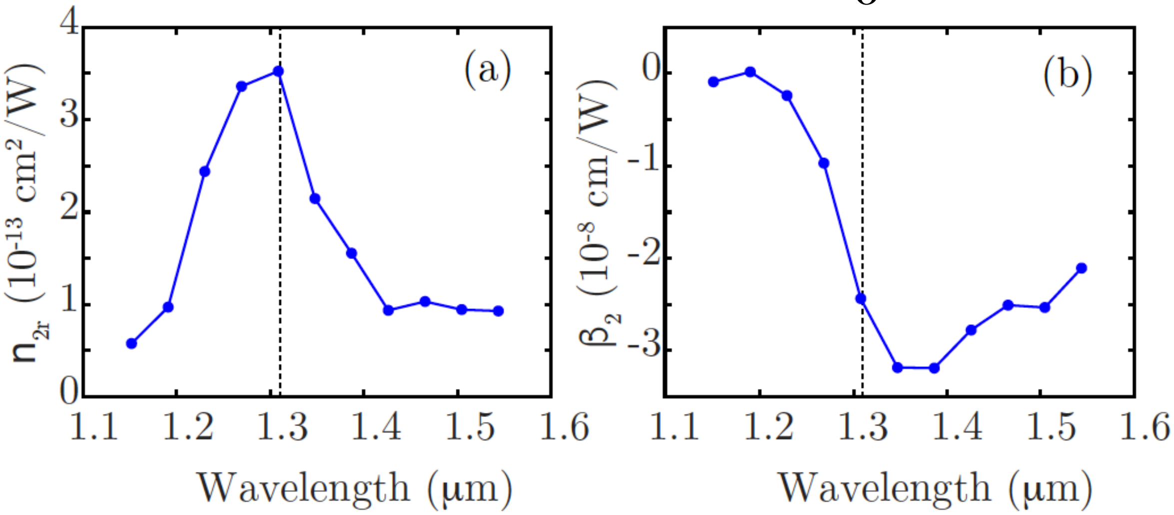
PURDUE UNIVERSITY

Enhanced nonlinear refractive index in epsilon-near-zero materials

L. Caspani[1], R. P. M. Kaipurath[1], M. Clerici[2], M. Ferrera [1], T. Roger[1], A. Di Falco[3], J. Kim[4], N. Kinsey[4], V. Shalaev[4], A. Boltasseva[4], D. Faccio[1]*

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

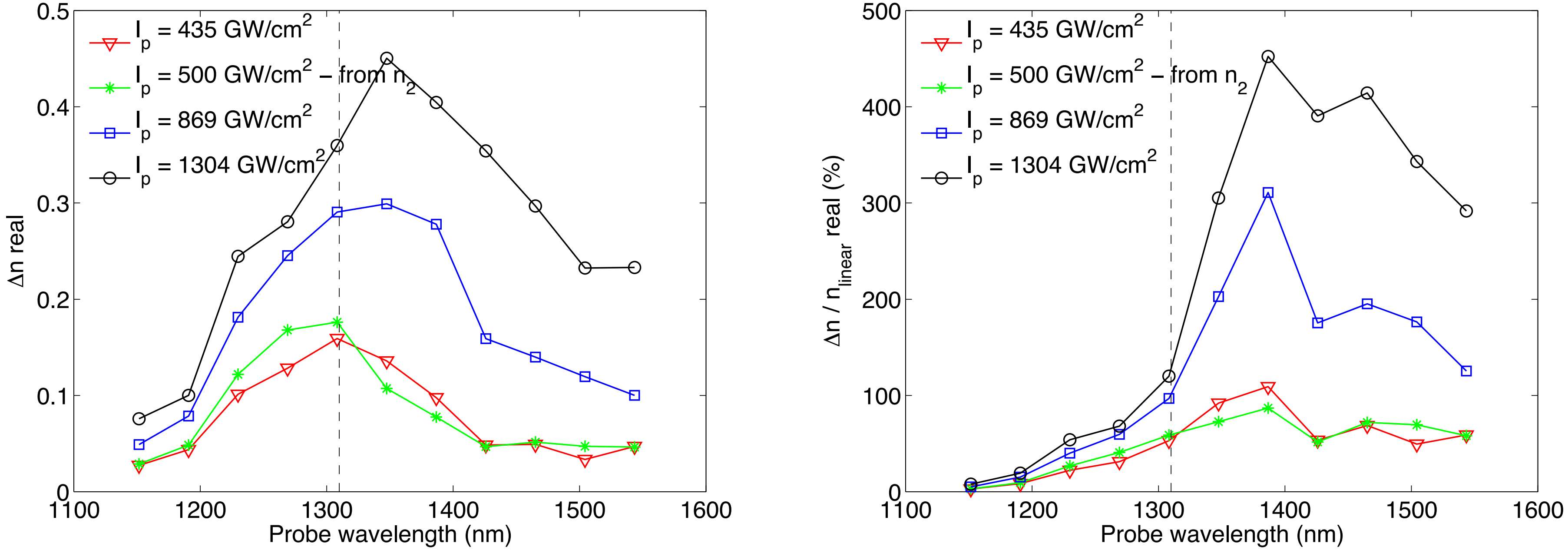
$$n_2 = n_{2r} + i\beta_2 \sim \frac{\chi^{(3)}}{n_0}$$



1 micron thick AZO, pumped at 800 nm

Giant Optical Kerr Effect in ENZ-AZO

Light-induced refractive index changes of the order of unity



Outlook

NEW MATERIAL PLATFORMS FOR PLASMONICS & NANOPHOTONICS

- Refractory (Ceramic) Plasmonic Materials Enable Nanophotonics, Biomed, Energy Conversion (S/TPV) and Data Storage Applications
- TCOs as switchable/tunable/tailorable plasmonic materials

NEW MATERIALS FOR QUANTUM PHOTONICS

- Quantum photonics on chip with new materials
- Single-Photon Sources and Quantum Registers

METASURFACE DESIGNS

- Ultrathin, flat optics with metasurfaces:
  - Lenses, holograms, optical plates, cavities, spectrometers,… ..
- Nonlinear, active, hyperbolic, and time-varying metasurfaces
  - Chip-based active and quantum nanophotonics

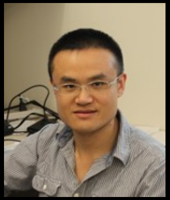
TEAM AND SUPPORT

Shalaev Group

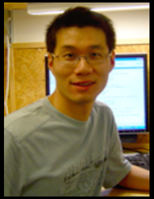
Dr. Marcello Ferrera

Dr. Simeon Bogdanov

Dr. Urcan Guler



Dr. Xiangeng Meng



Jieran Feng

Rohith Chandrasekar

Amr Shaltout

Mikhail Shalaginov

Di Wang

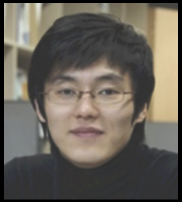
Jingjing Liu

Harsha Eragmareddy

Clayton DeVault

Dewan Woods

Boltasseva Group



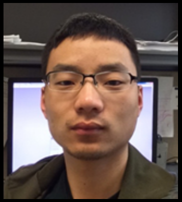
Jongbum Kim

Nate Kinsey

Justus Ndukaife

Aveek Dutta

Krishakali Choudhuri



Zhouxian Wang

Sajid Choudhury

Collaborations

- Prof. A. Kildishev (Purdue)
- Prof. A. Alu (UTexas Austin)
- Prof. N. Engheta (UPenn)
- Prof. M. Ferrera (Heriot-Watt)

Former members

- Dr. G. Naik (Stanford)
- Dr. N. Emani (DSI Singapore)

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)
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- Advanced Materials 25 (24), 3264 (2013)
- Nano Letters, 13 (12), 6078-6083 (2013)
- Optics Express 21(22), 2013.
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- ACS Nano 8(9), 9035, 2014
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- Faraday Discussions 178, 71 (2015)
- Materials Today 18(4) 227, (2015)
- Science 347, 1308, 2015
- Laser & Photonics Reviews 9(1), 120 (2015)
- Science (2016)

Nature Photonics News&Views Highlight

news & views

VIEW FROM... NANOMETA 2011

In search of new materials

NATURE PHOTONICS | VOL 5 | MARCH 2011

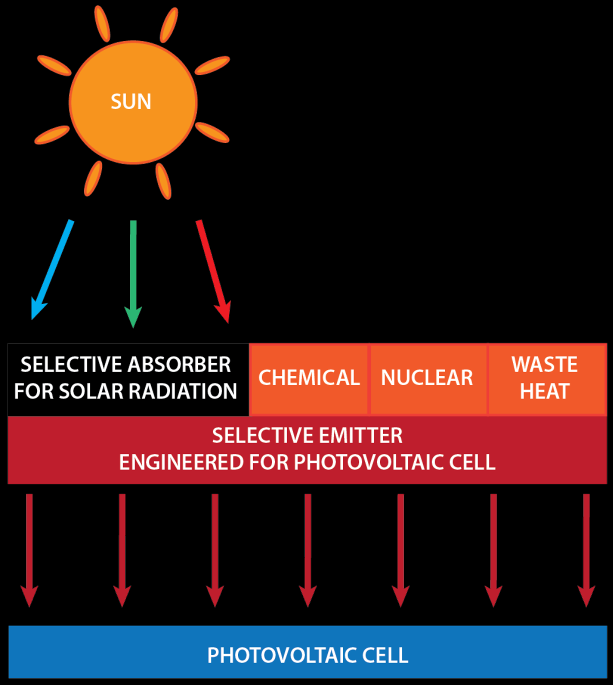
MATERIALS SCIENCE

Low-Loss Plasmonic Metamaterials

21 JANUARY 2011 VOL 331 SCIENCE

S/TPV (SOLAR/THERMOPHOTOVOLTAICS)

- Big promise on efficiencies in theory
- Fewer / lower cost components than multi-junction PV
- Challenges due to material limitations
  - Materials with high temperature durability
  - Materials with good optical properties
- ***Solution:*** Refractory materials with plasmonic properties
  - Hard & thermally stable metamaterials



SUN

SELECTIVE ABSORBER FOR SOLAR RADIATION | CHEMICAL | NUCLEAR | WASTE HEAT

SELECTIVE EMITTER ENGINEERED FOR PHOTOVOLTAIC CELL

PHOTOVOLTAIC CELL

U. Guler, V. Shalaev, A. Boltasseva, Materials Today 18 (4), 227-237 (2015)

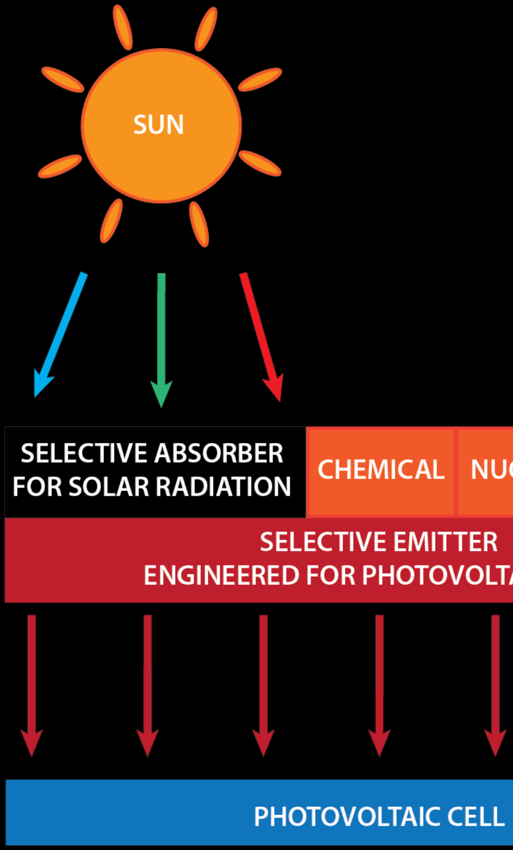
THERMOPHOTOVOLTAICS

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.

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.



SELECTIVE ABSORBER FOR SOLAR RADIATION | CHEMICAL | NUCLEAR | WASTE HEAT

SELECTIVE EMITTER
ENGINEERED FOR PHOTOVOLTAIC CELL

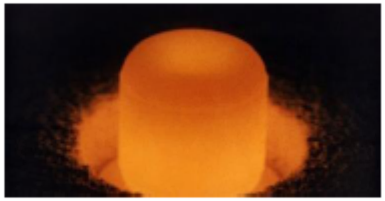
PHOTOVOLTAIC CELL

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.

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.

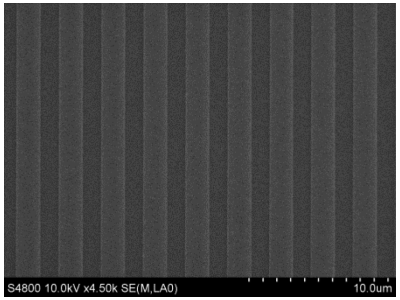


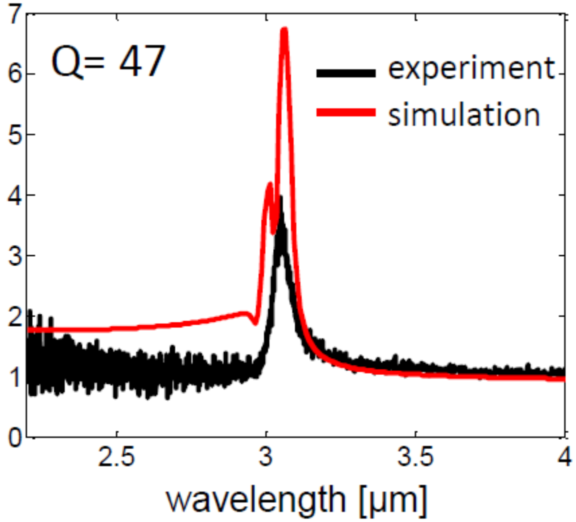
Solar Energy Concentration

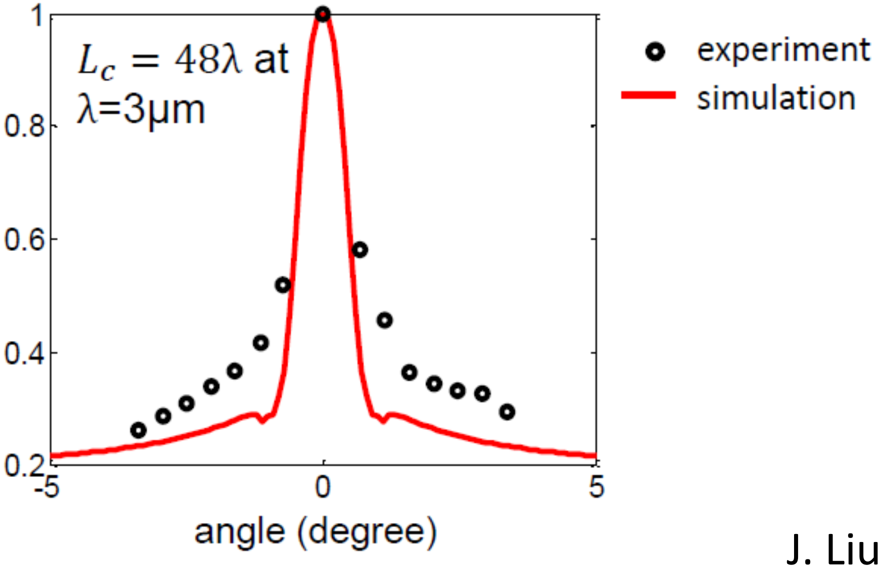
S/TPV is perfect for solar energy concentration plants as it is designed for high-temperature operation. Arrangement of cells in small (10-20x) clusters will increase cost effectiveness.

U. Guler, V. Shalaev, A. Boltasseva, Materials Today 18 (4), 227-237 (2015)

Coherent thermal source







Thermal radiation: uncorrelated spontaneous emission in matter; low coherence.

Coherent thermal sources:

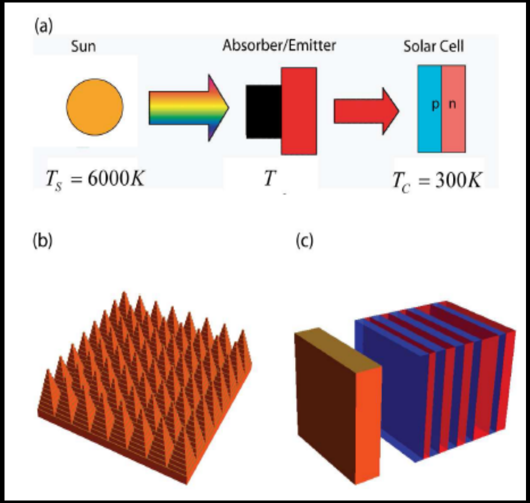
- Spatial coherent: directional radiation by delocalized surface modes
- Temporal coherent: narrow band thermal emission by optical antenna

❖ Gold & Silver: rather high surface energy; thermal heating leads to dewetting and formation of metal islands.

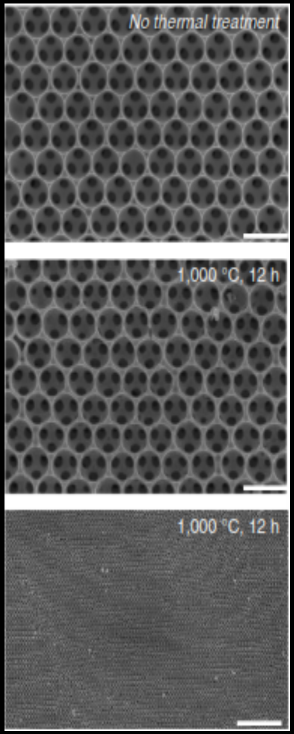
❖ Transition metal nitrides provide stable coherent thermal source.

J. Liu et al, OMEX (2015)

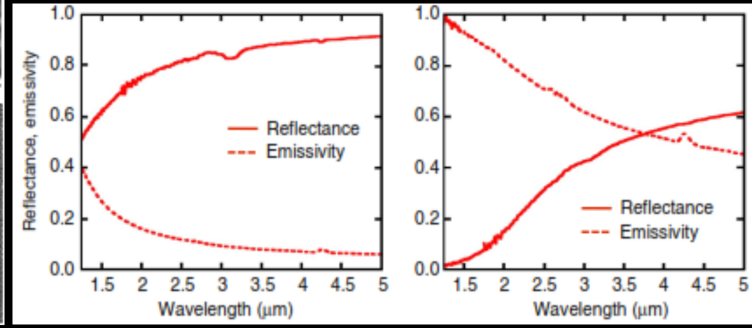
Current S/TPV approaches

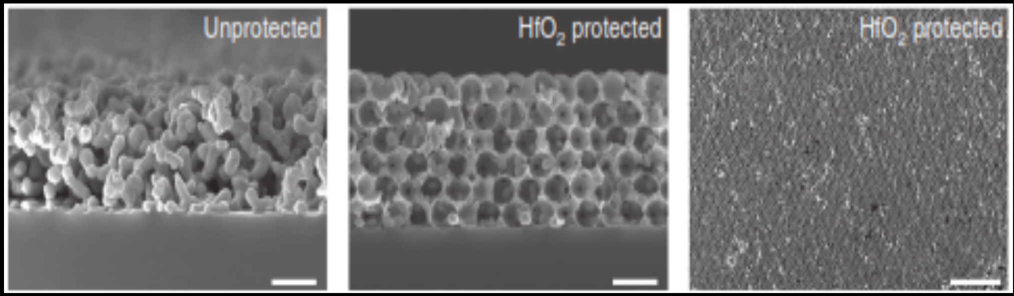


E. Rephaeli and S. Fan, Opt. Exp. 17, 15145 (2009)

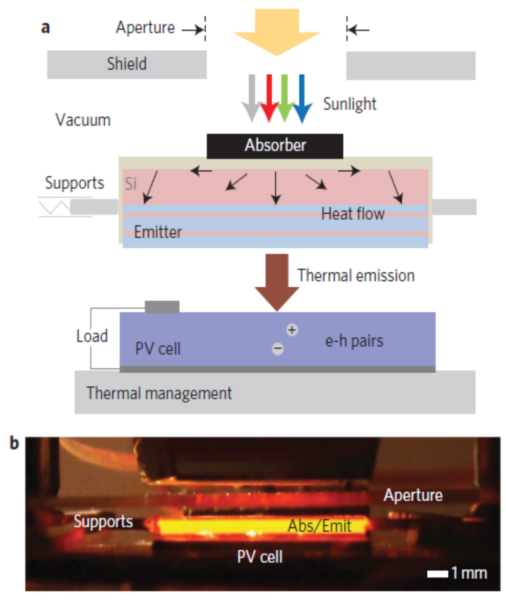


Photonic crystals

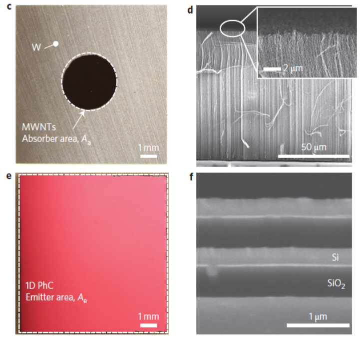




Arpin et al., Nature Comm. 4, 2630 (2013).

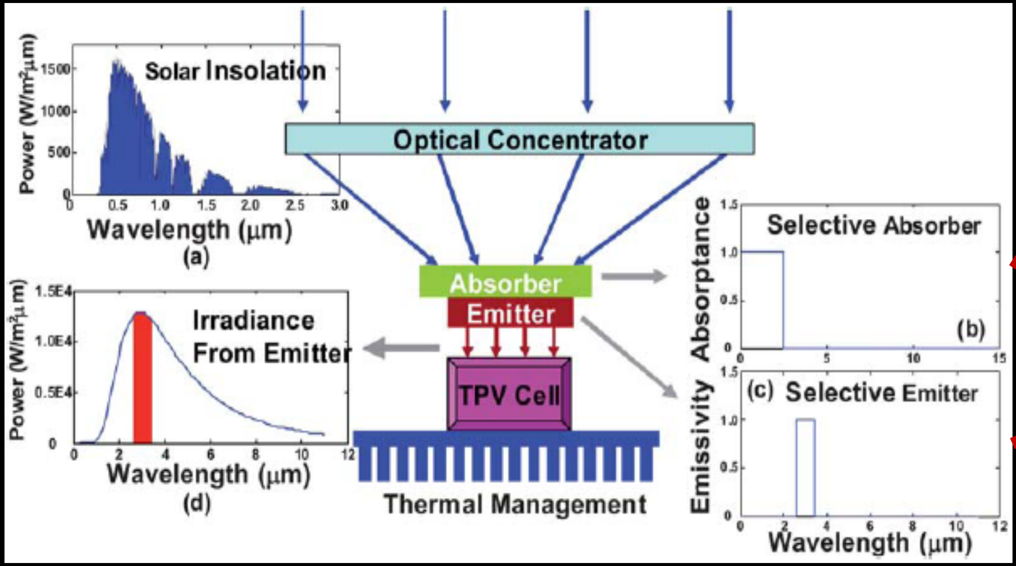


3.2%



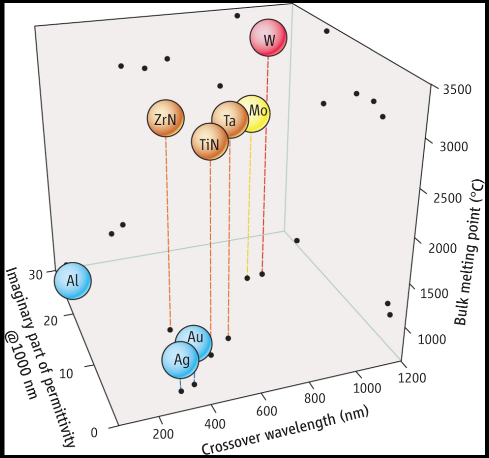
A. Lenert et al., Nat. Nano. 9, 126-130 (2014).

S/TPV with Metamaterials

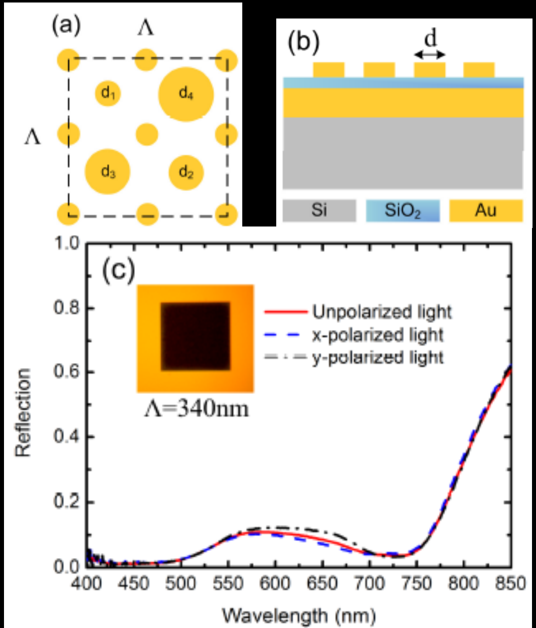


Baxter et al, Energy Environ. Sci. **2**, 559 (2009)

Metamaterials!

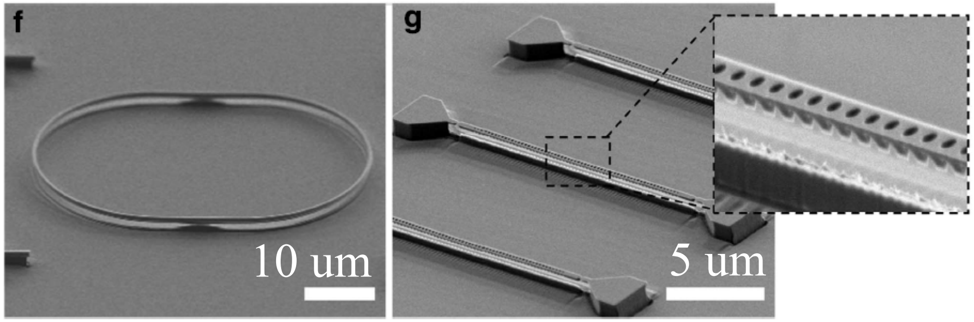


U. Guler et al, Science 344, 263 (2014)



M. G. Nielsen et al, Opt. Express **20**, 13311

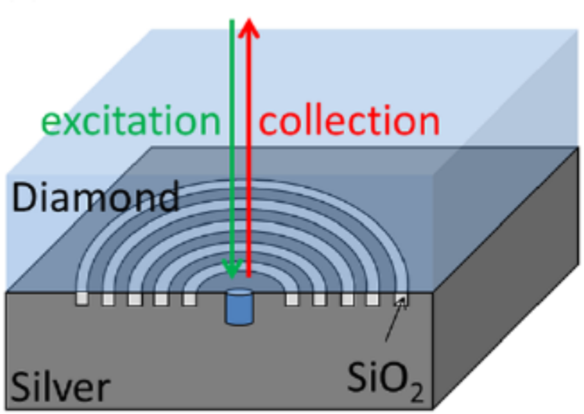
Resonant ways to enhance emission rate



diamond racetrack resonator

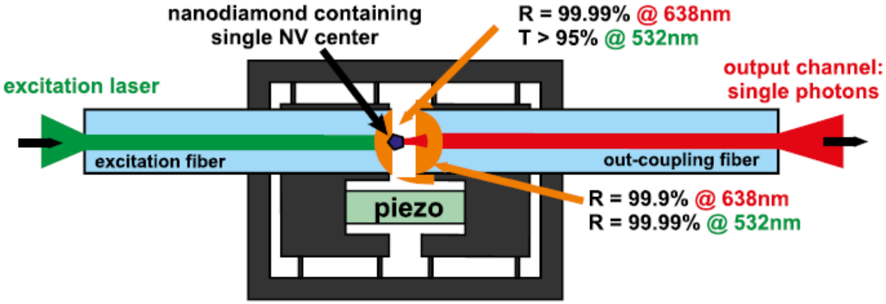
& nanobeam photonic crystal cavity

M. J. Burek et al., Nat. Comm. 2014 (Lukin & Loncar)



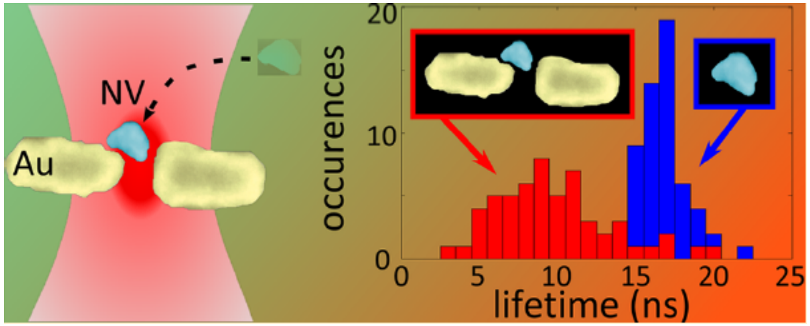
diamond-silver apertures

J. T. Choy et al., APL 2013 (Loncar)



all-fiber cavity

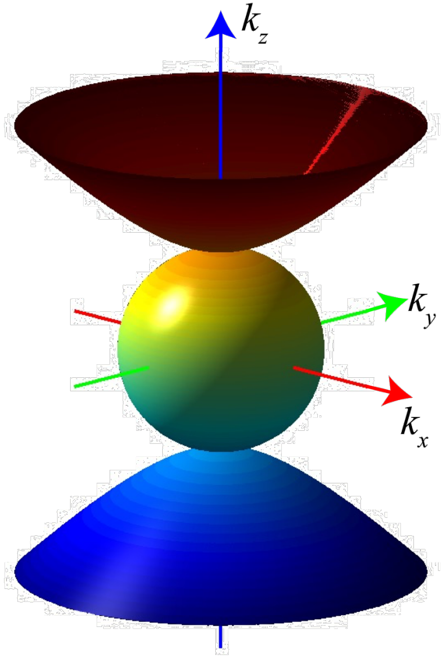
R. Albrecht et al., APL 2014 (Benson)



plasmonic gap-antenna

M. Geiselmann et al., Nano Lett 2014 (Quidant)

Metamaterials with Hyperbolic Dispersion



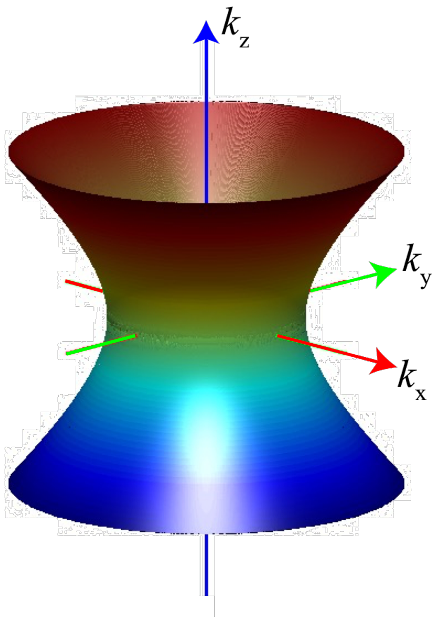
normal dispersion

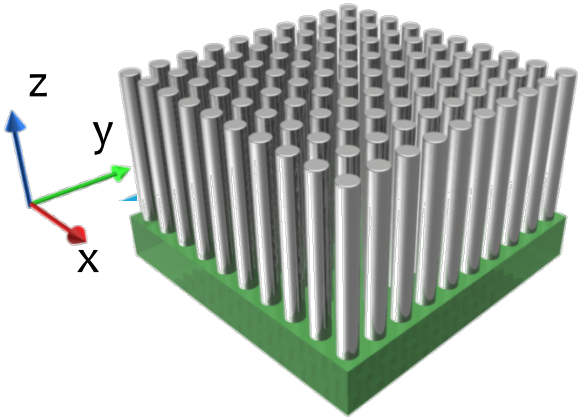
$$\frac{k_x^2+k_y^2+k_z^2}{\varepsilon}=\left(\frac{\omega}{c}\right)^2$$

hyperbolic dispersion

$$\frac{k_x^2+k_y^2}{\varepsilon_P}-\frac{k_z^2}{|\varepsilon_\perp|}=\left(\frac{\omega}{c}\right)^2$$

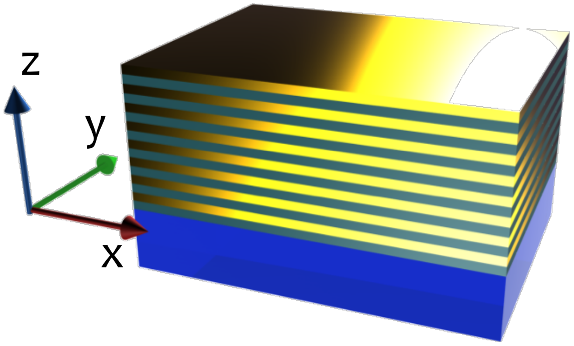
$$-\frac{k_x^2+k_y^2}{|\varepsilon_P|}+\frac{k_z^2}{\varepsilon_\perp}=\left(\frac{\omega}{c}\right)^2$$





transverse positive (type I)

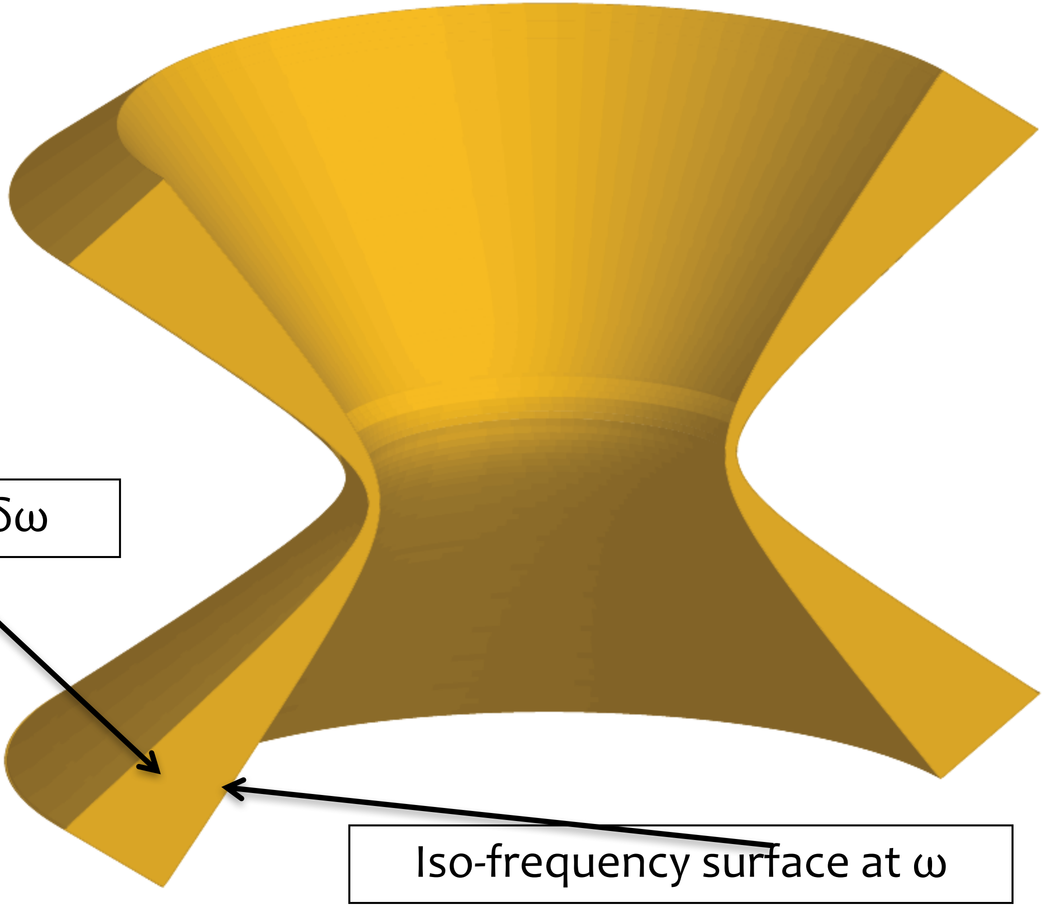
Smith & Schurig PRL (2003)
Jacob, et al, Opt. Express (2006)



transverse negative (type II)

PHOTONIC DENSITY OF STATES (PDOS)

Fermi's Golden Rule: $\Gamma = \frac{2\pi}{\hbar}\rho(\omega_f) \times$ (Dipole matrix element)^2



Iso-frequency surface at ω+δω

Iso-frequency surface at ω

unbounded |k|

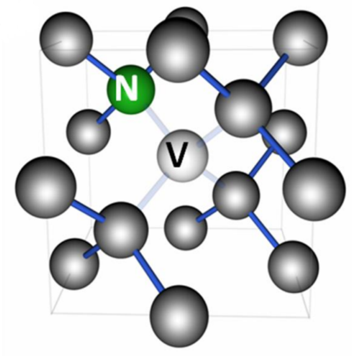
singularity in PDOS

Appl. Phys. B, 100(1) 215, 2010

$$\mathrm{DOS} = \infty, \ \forall\omega \ !$$

HMMs + Emitters

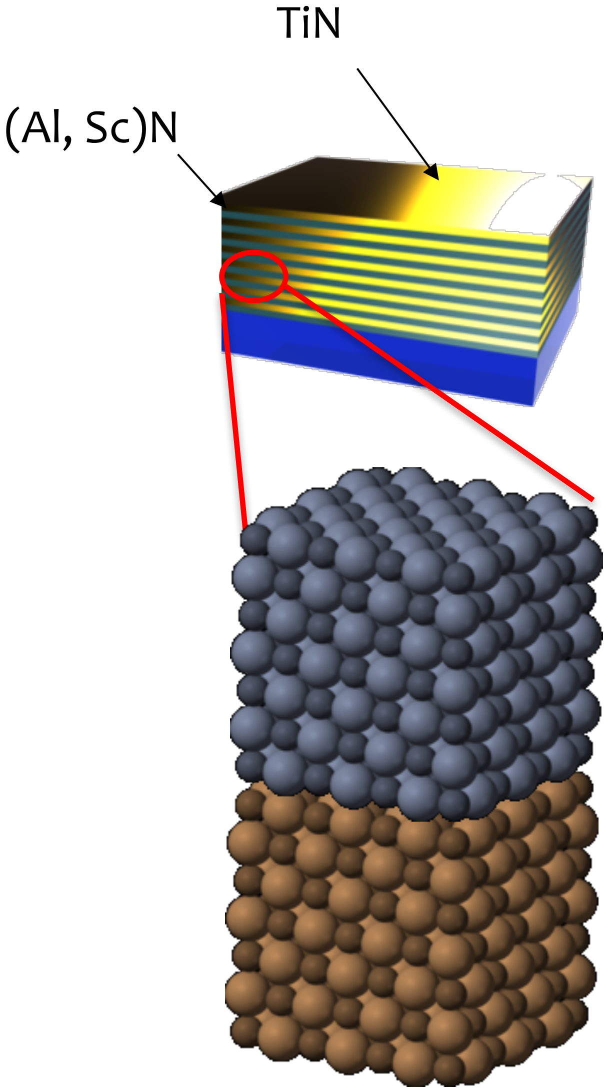
Nitrogen-vacancy centers in diamond

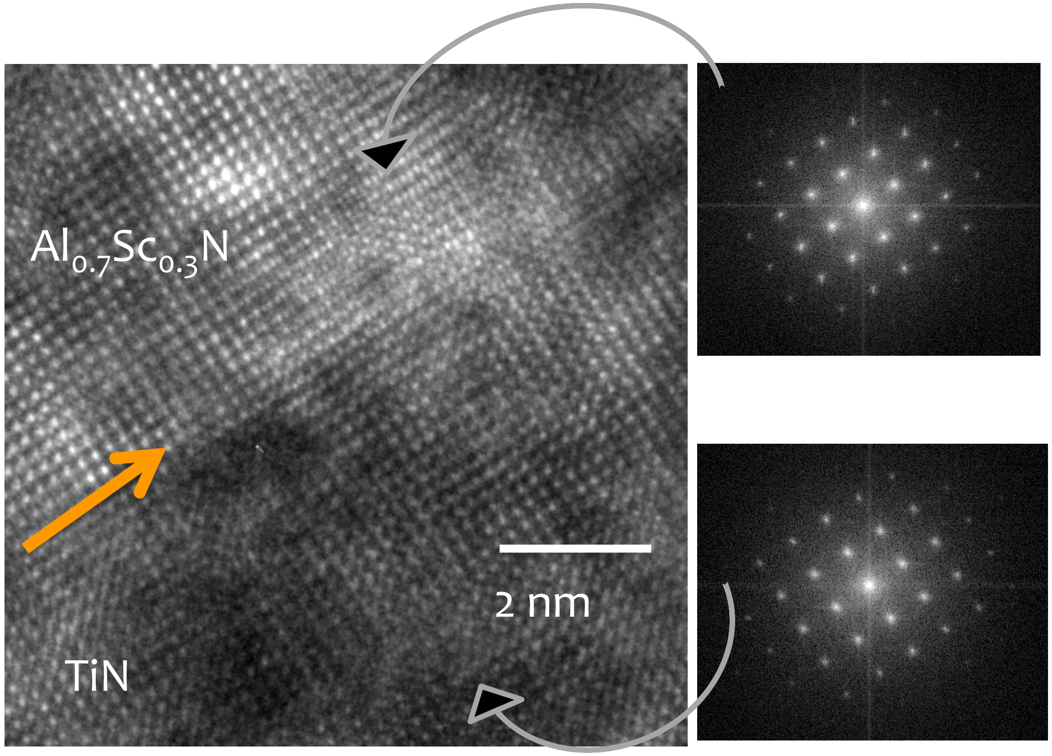


Color centers in diamond

- Photostable source
- Operates at room temperature
- Relatively simple and inexpensive fabrication
- Broadband emission
- Long spin coherence time

HMM based on CMOS-compatible materials

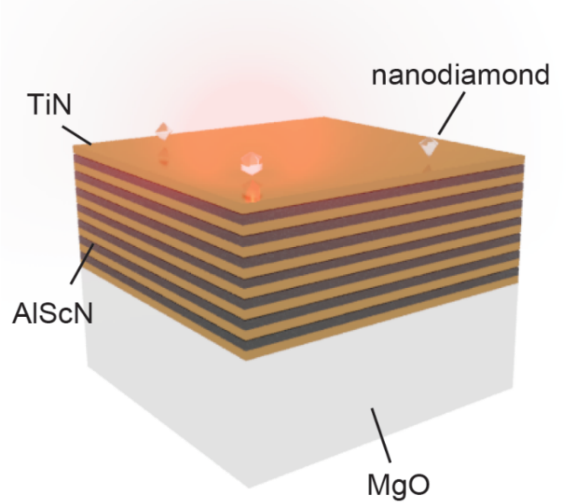


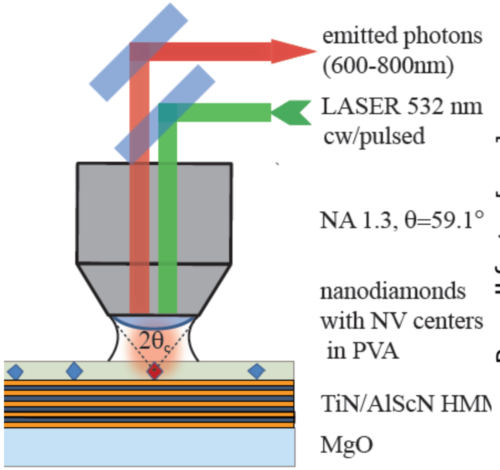


- Extremely high broadband photonic density of states
- 1st epitaxial single crystalline metal/semiconductor superlattice
- CMOS-compatible

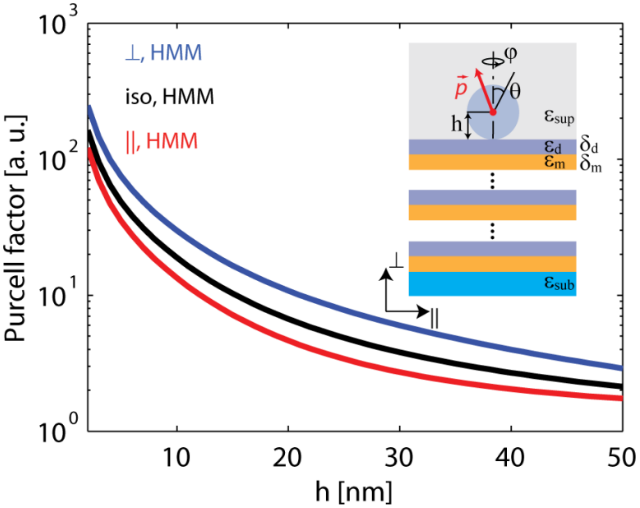
Naik, et al, PNAS (2014)

Single NV centers coupled to TiN HMM

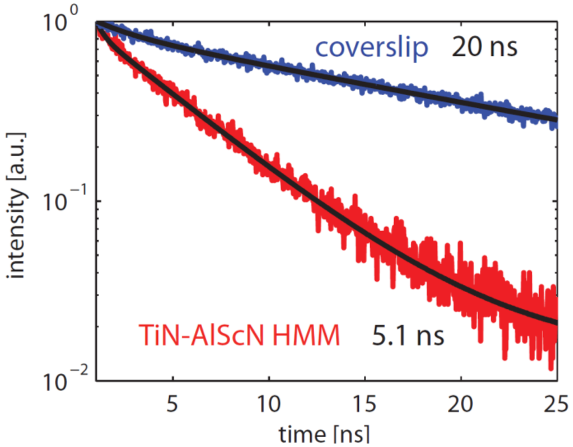




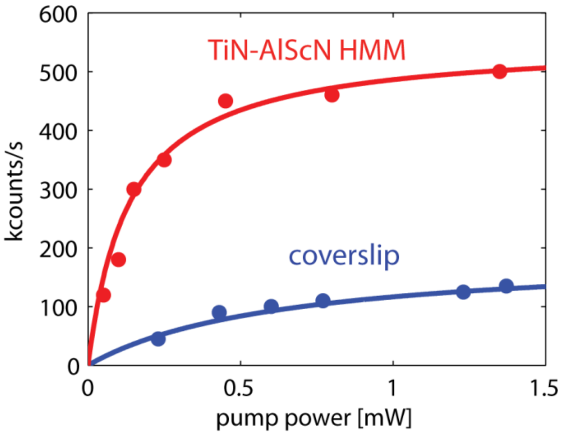
Increased PDOS

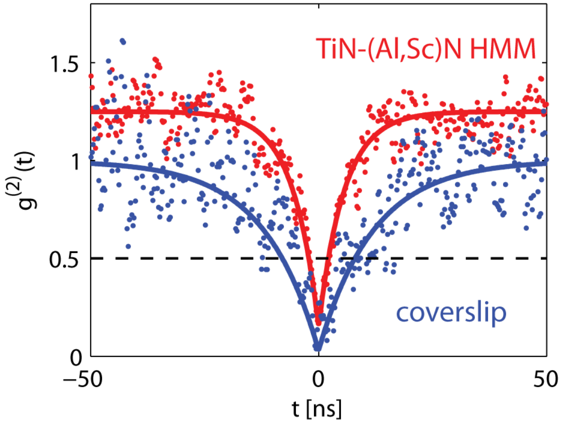


Fluorescence lifetime



Collected emission rate Photon anti-bunching statistics





M. Y. Shalaginov, et al, LPR, 9(1), 120 (2015)

Enabling Quantum Photonics with Metamaterials

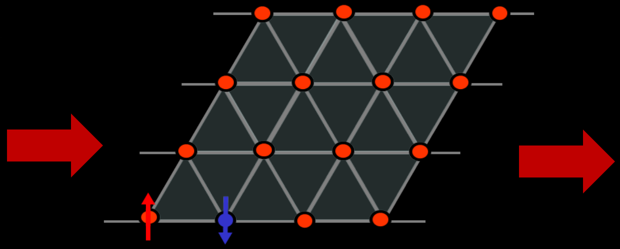
Next technology revolution:

Going Quantum

Lecture 14

TOWARD QUANTUM COMPUTING

Classical Hard-disk



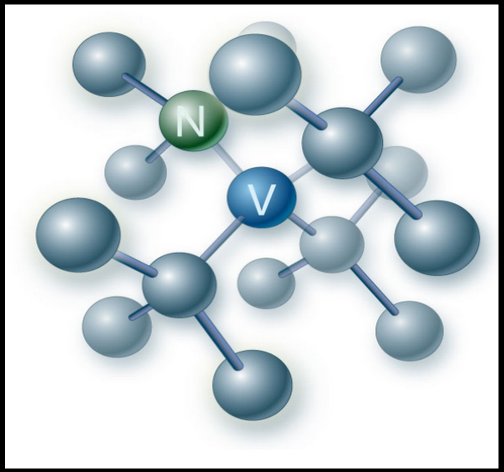
- **atoms as “small magnets”**
- **store numbers „0“ or „1“**

CAN BE QUANTUM OBJECTS!

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

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

DIAMOND NANOPHOTONICS:



nitrogen-vacancy (NV) color center in diamond

NV center as a single-photon source:

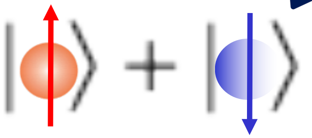
- Photostable
- Operates as single-photon source at room T
- Broadband emission spectrum

NV center as a quantum memory unit:
long electron-spin coherence time
can be optically read out

Maurer, et al, Science 336, 1283 (2012)

Unique feature: quantum superpositions

0 or 1 or 01



One word answer: good

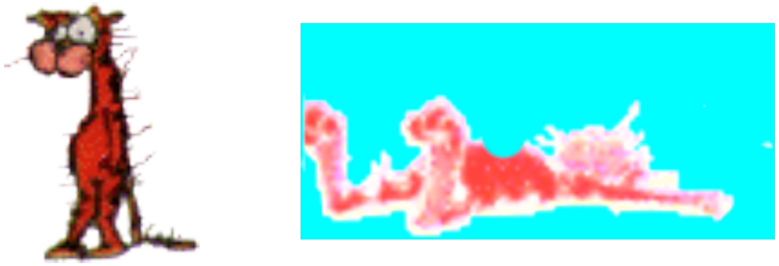
Two word answer: not good

- Superposition is a key resource for quantum technologies

Slide credit to Lukin

Quantum Superpositions

- Classical Cats



live *or* dead

E. Schrödinger

Verschränkung

- Schrödinger Cats

live *and* dead (?)

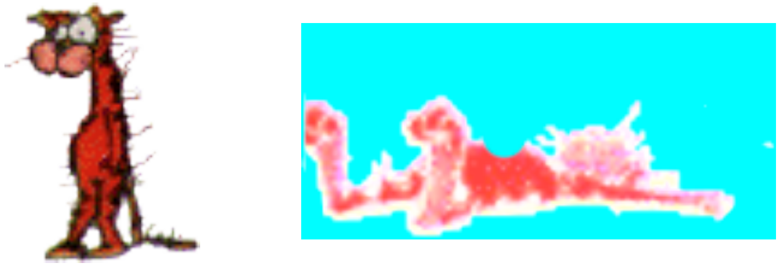
entanglement

Slide credit to Lukin

Quantum Computer = Schrödinger Cats of the Different Kind

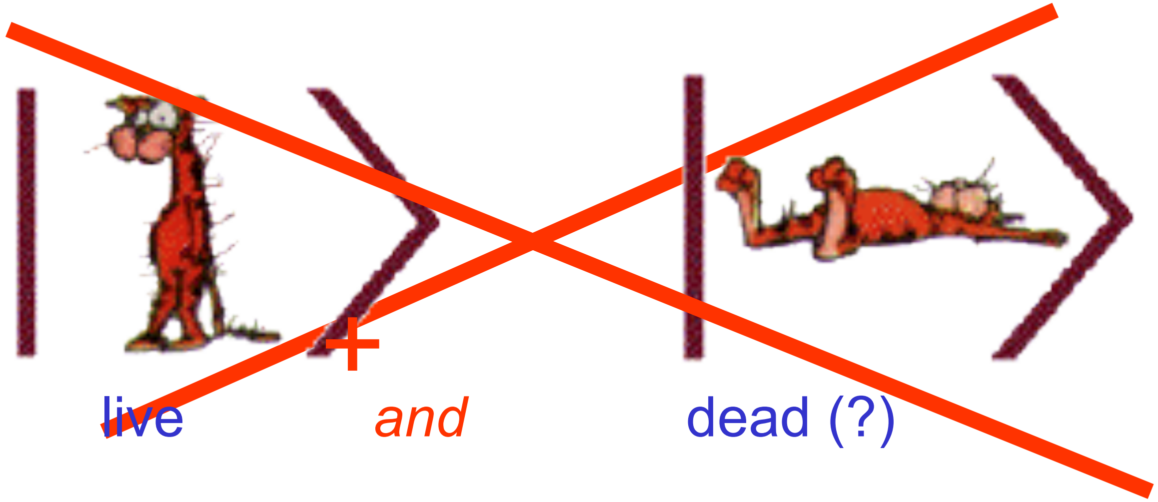
Quantum Superpositions

- Classical Cats

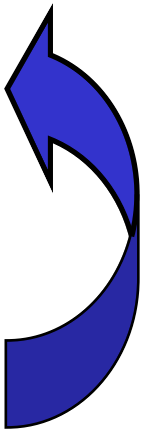


live *or* dead

- Schrödinger Cats



live *and* dead (?)



curiosity (and decoherence) kills the cat (and quantum computers)

Slide credit to Lukin

from bit to qubit

Develop components and prototypes for communication, sensing and computing at the level of standard quantum limits and beyond

New Paradigm: Quantum Sensing **CLOCKS**

Magnetic field sensors

Plasmonics and metamaterials

New Paradigm: Quantum Communication

Quantum cryptography

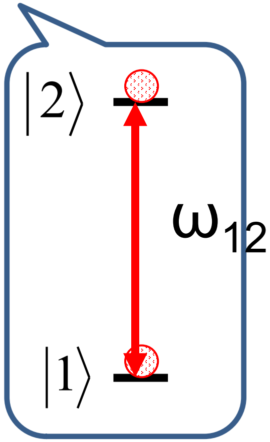
Quantum Random number generator

New Paradigm: Quantum Computing

Quantum repeater for long distance q. network

Quantum simulator (materials, games)

Superpositions and entanglement



Single NV Centers Coupled to TiN HMM

"Nature isn't classical dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem because it doesn't look so easy."

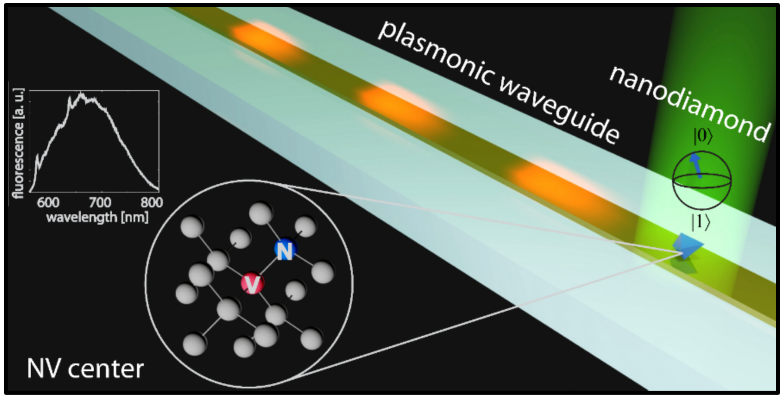
R.P. Feyman, Int. J. Theor. Phys. 21, 467

Materials → Quantum sensors, simulators & computers

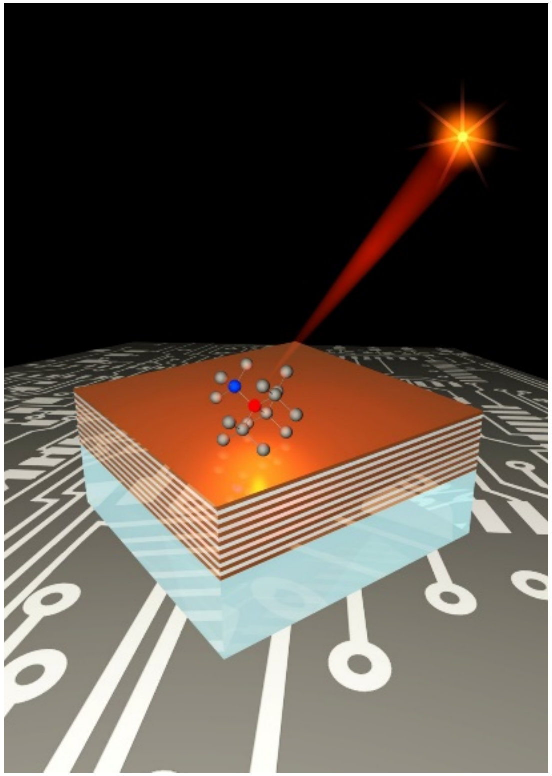
Outline

Going Quantum:

1. Enhancement of single-photon emission from NV centers with hyperbolic metamaterials & metasurfaces
2. Nanoscale sensing of photonic density of states with spins in diamond



Bogdanov, et al, (2015)



Shalaginov, et al, LPR (2015)
Kildishev et al, Science 339 (2013)

Why quantum technologies?

- Information, its acquisition, storage, transmission and processing is fundamentally physics
- Ultimate elements of processors will be of quantal size
- Tremendous “speed-up” may be possible using quantum mechanical systems
- Quantum techniques will have wide applications in science and technology

On another hand:

- Basic science is motivated by the quest to understand the world
- It is a long-term undertaking
- It results in transformative (not incremental) changes in technology
- These changes define the modern society

Quantum technologies: near term

Quantum communication

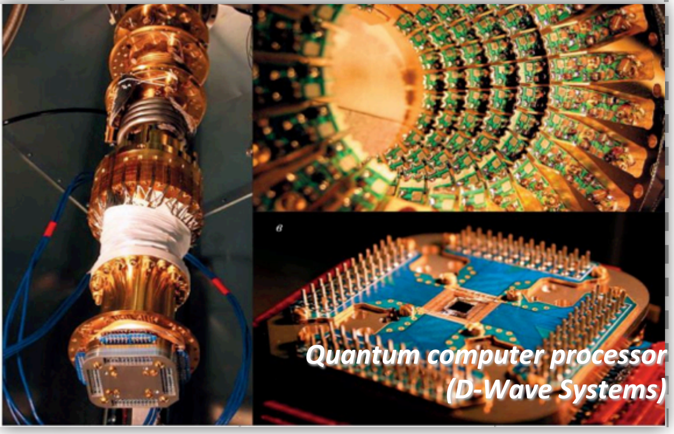
- Secure quantum key distribution
- Quantum random number generators

MagiQ

id Quantique

Quantum Clocks

- Compact stable clocks
- Navigation systems, including satellite based navigation



Quantum computer processor (D-Wave Systems)

Symmetricom

Honeywell

Quantum detectors

- Fast optoelectronics at low light level

Quantum DETECTORS

WWW.SCONTEL.RU
SCONTEL
SUPERCONDUCTING NANOTECHNOLOGY

Quantum technologies could create new markets