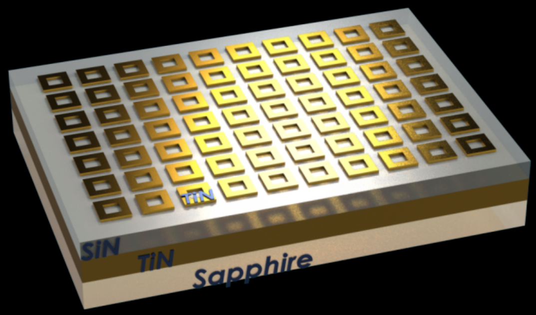


REFRACTORY PLASMONICS

Vladimir M. Shalaev
School of Electrical & Computer Engineering
Birck Nanotechnology Center
PURDUE UNIVERSITY

Major collaborator: Alexandra Boltasseva

The International Year of Light

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

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

Photonics and Material Science


Isamu Akasaki


Hiroshi Amano


Shuji Nakamura

Nobel prizes in physics 2014

Blue LED

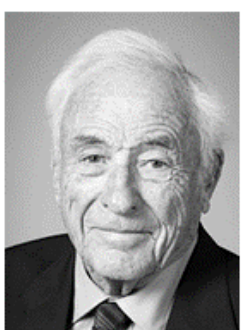

Andre Geim


Konstantin Novoselov

Nobel prizes in physics 2010

Graphene


Charles Kuen Kao


Willard S. Boyle

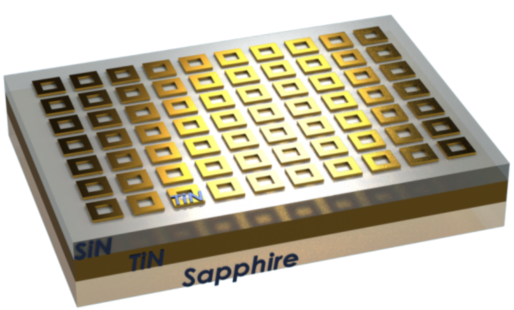

George E. Smith

Nobel prizes in physics 2009

Low-loss optical fiber

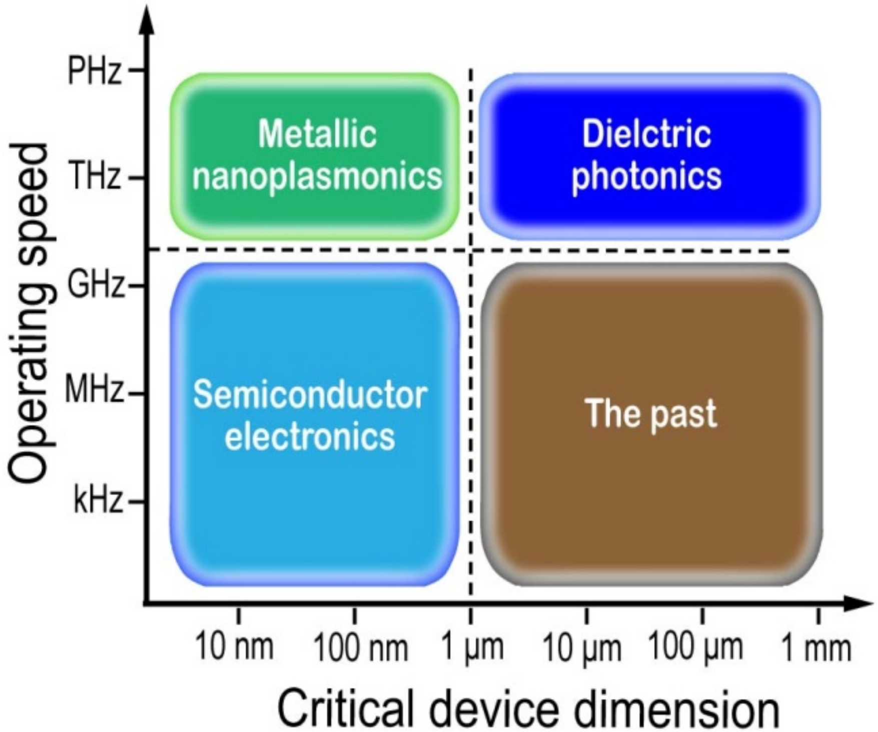
OUTLINE

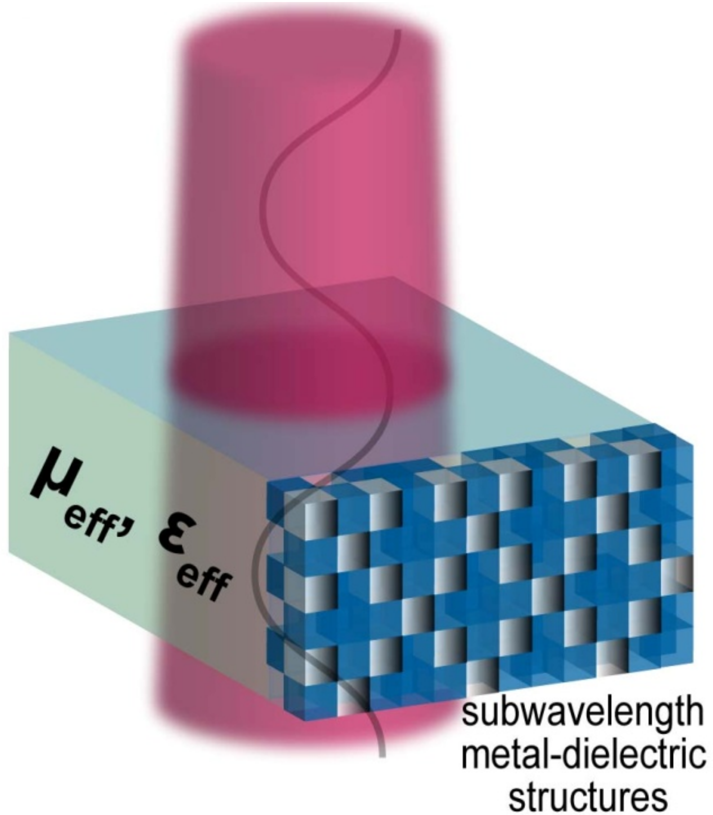
- **Introduction: Plasmonics & Metamaterials**
- Material Requirements & Alternative Materials
- Transition Metal Nitrides
- Applications with Plasmonic Metal Nitrides
  - High Temperature
    - Thermophotovoltaics
    - Heat Assisted Magnetic Recording
    - Coherent thermal sources
  - Plasmonic photothermal therapy
  - Quantum Photonics Application



WHY PLASMONIC TECHNOLOGY?

PURDUE UNIVERSITY



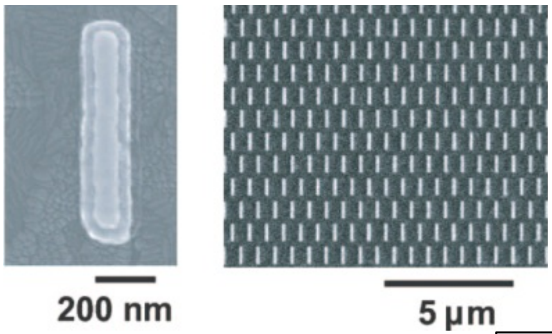


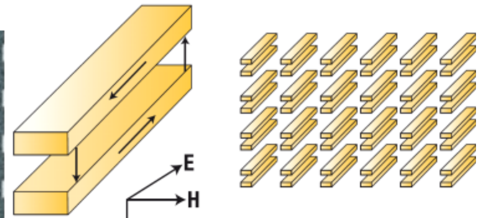
- Improved synergy between electronic and photonic devices
- Solution to the size-compatibility problem
  - Plasmonics naturally interfaces with *similar size electronic components*
  - Plasmonics naturally interfaces with *similar operating speed photonic networks*
- METAMATERIALS

Brongersma and Shalaev, *Science* **328** (2010). G.V. Naik, V.M. Shalaev and A. Boltasseva, *Adv. Materials (2013)*

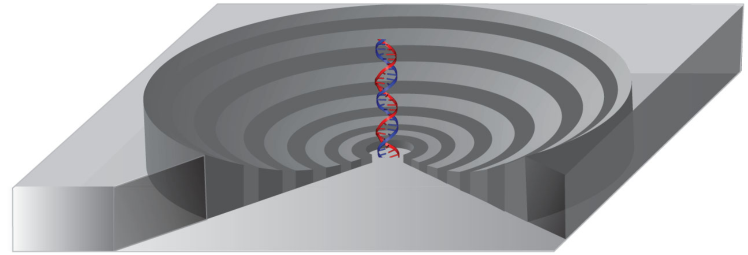
PLASMONICS/METAMATERIALS

PURDUE UNIVERSITY



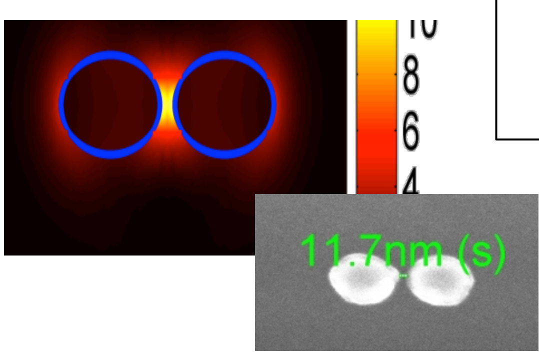


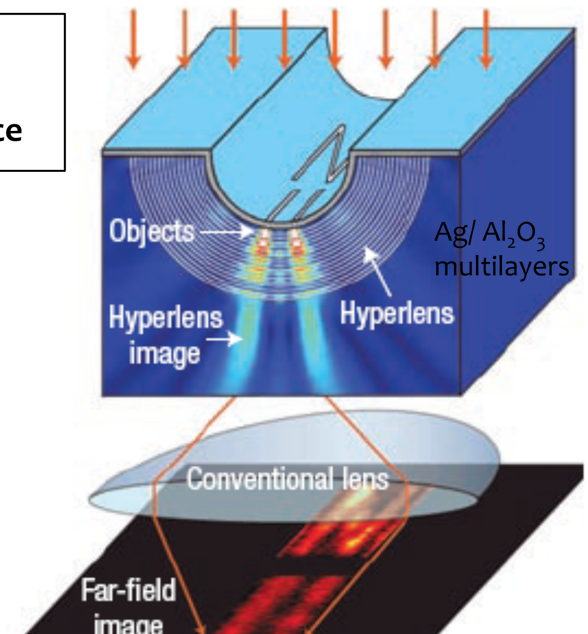
Shalaev



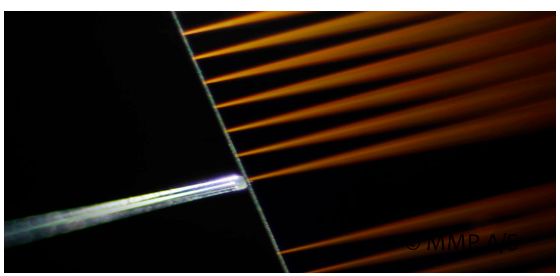
Narimanov, Engheta

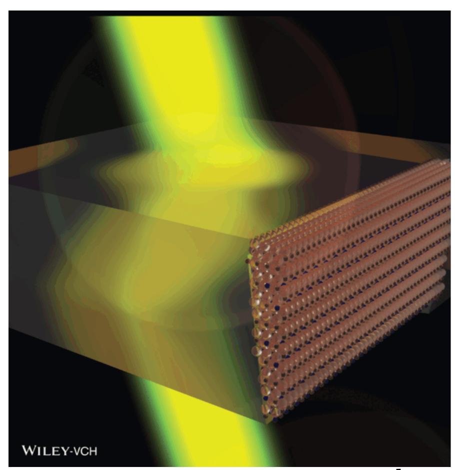
Plasmonics and metamaterials offer an unprecedented ability to control light
Numerous examples of extraordinary science





Z. Liu et. al, Science (2007)



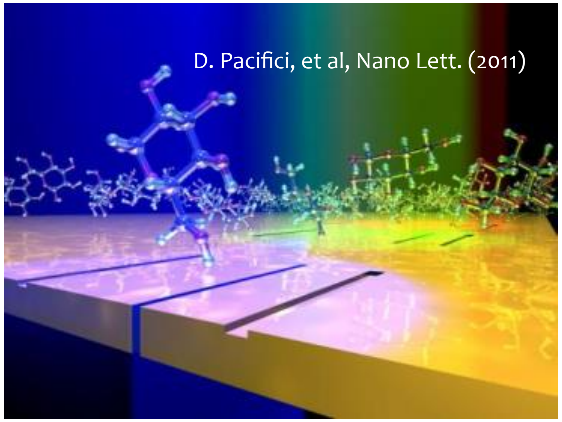


Purdue

Groups of N. Engheta, N. Zheludev, D. Smith, H. Giessen, X. Zhang, V. Shalaev, S. Bozhevolnyi

POTENTIAL TECHNOLOGY IMPACT

- Interconnects/Hybrid photonic circuits
- On-chip optics and optoelectronics
- Data recording/storage
- Sub-λ photodetectors
- Sensors
- Solar cells
- Novel energy conversion schemes
- Imaging
- Medical applications
- Quantum information technology


D. Pacifici, et al, Nano Lett. (2011)

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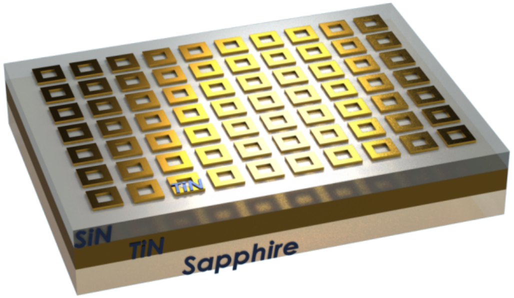
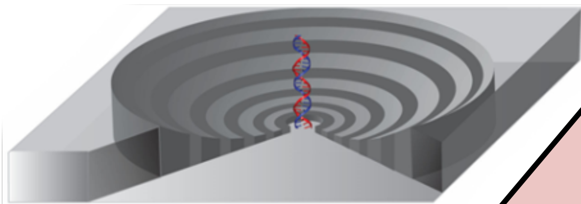
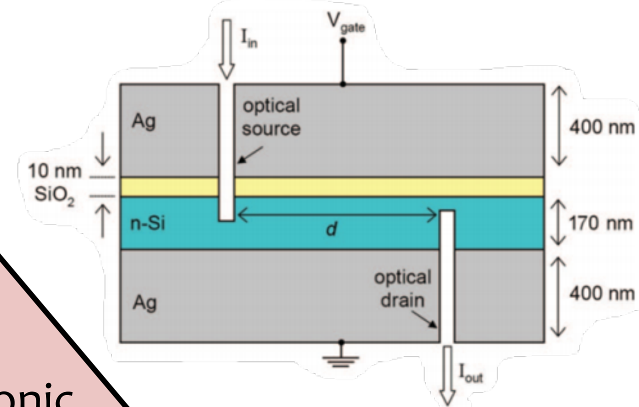


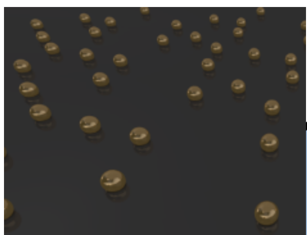
CHALLENGES

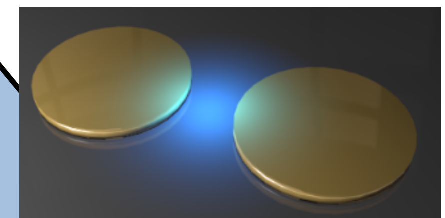




Devices:

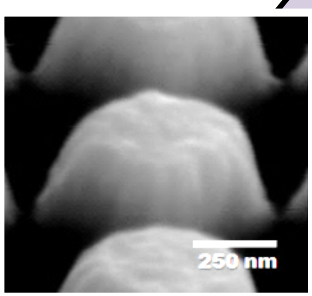
Nanoantennas, Plasmonic waveguides, Metamaterials





Design:

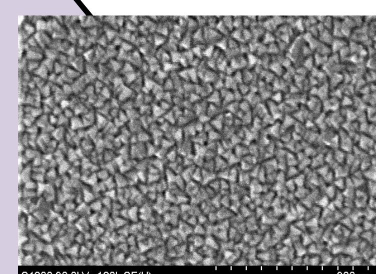
Nanoscale building blocks, nanometer-thin films, nanoparticles



Constituent Materials:

Metals (lossy, not tunable, challenging fabrication and integration)

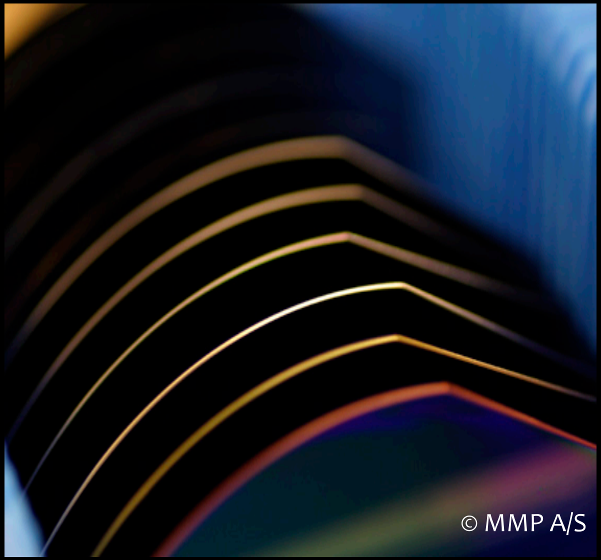
NEW PLASMONIC MATERIALS



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



© MMP A/S

MATERIAL REQUIREMENTS

PURDUE UNIVERSITY

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

J. B. Khurgin and A. Boltasseva, MRS Bulletin (2012)

- **Adjustable / Tunable** optical properties

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

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

Engheta, Narimanov, Alu groups

- **Switchable** devices

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

- **SC-compatible** components

New CMOS-Compatible Plasmonic Materials

SEMICONDUCTORS TO METALS or METALS TO LESS-METALS:

Doped semiconductors + Intermetallics (nitrides, borides, silicides, …)

21 JANUARY 2011 VOL 331 SCIENCE

MATERIALS SCIENCE

Low-Loss Plasmonic Metamaterials

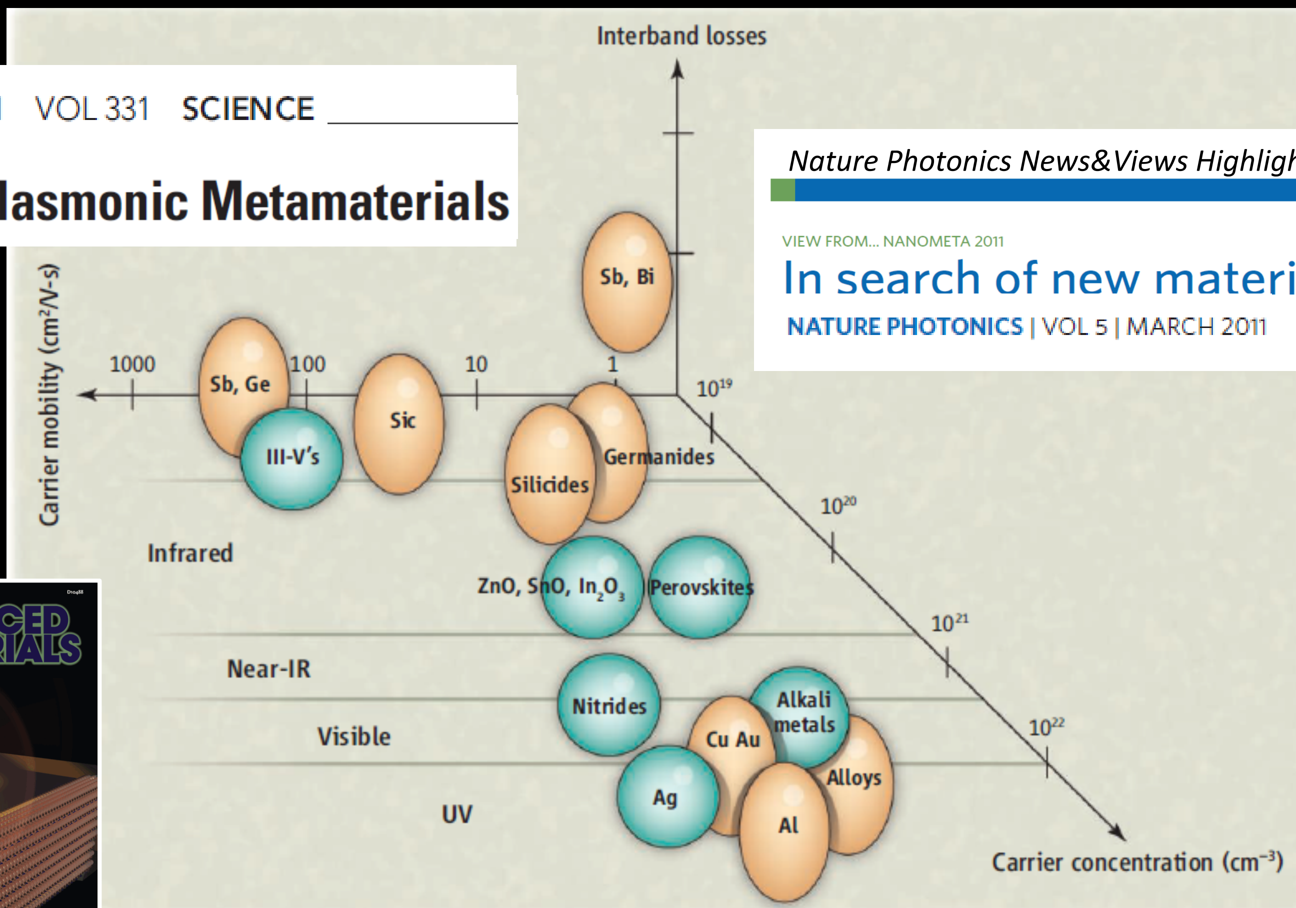
Nature Photonics News&Views Highlight

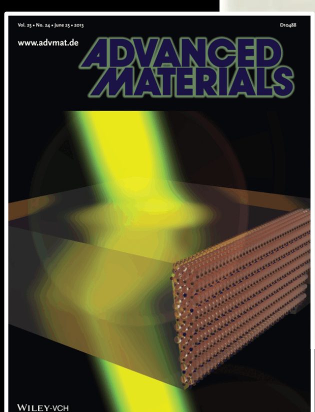
news & views

VIEW FROM... NANOMETA 2011

In search of new materials

NATURE PHOTONICS | VOL 5 | MARCH 2011

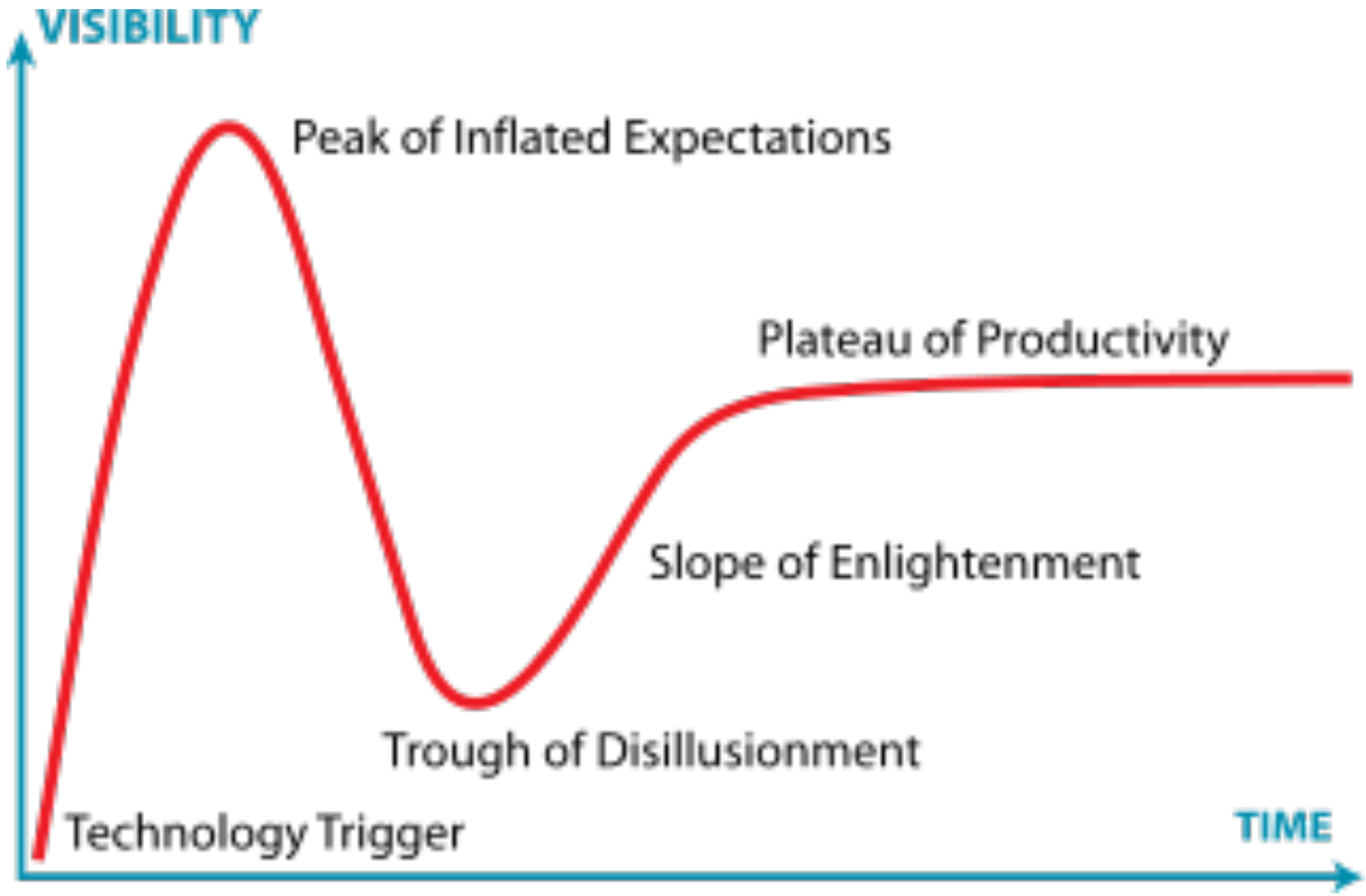




A. Boltasseva and H.A Atwater, Science **331**, 290 (2011)

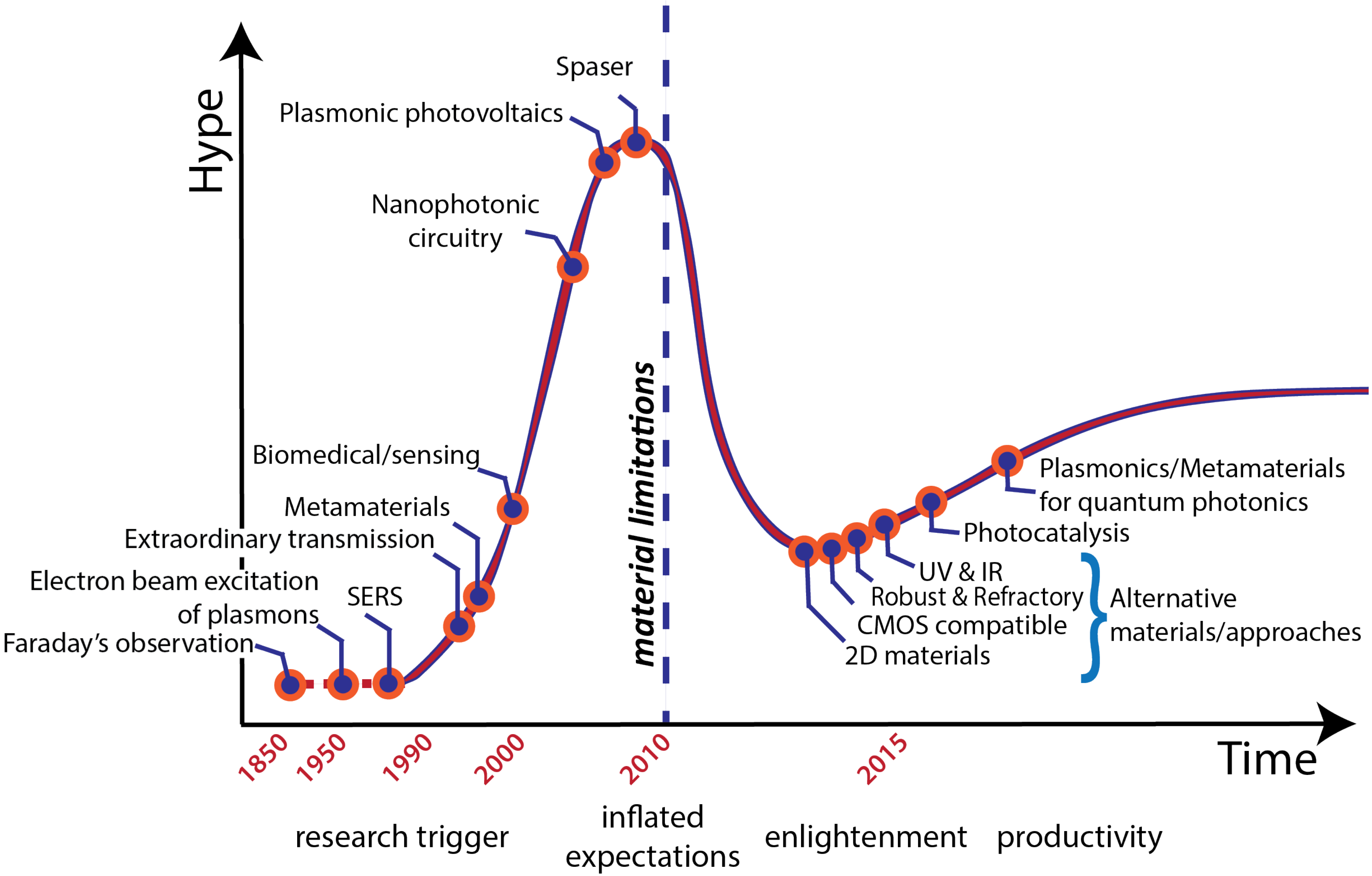
G. Naik, V. Shalaev, A. Boltasseva, Advanced Materials 25 (24), 3264 (2013)

Hype (Gartner) Cycle



http://www.gartner.com/technology

Hype Cycle for Plasmonics



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

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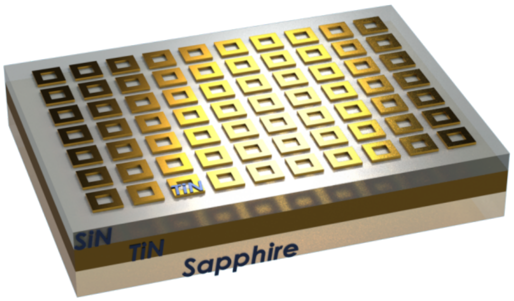
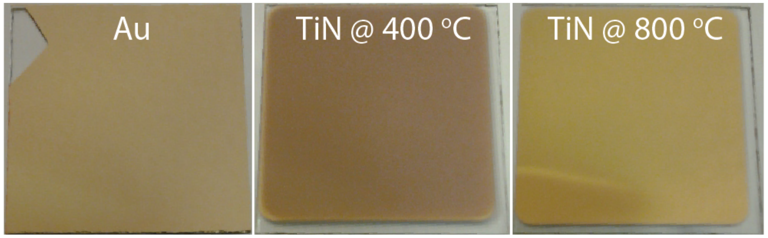
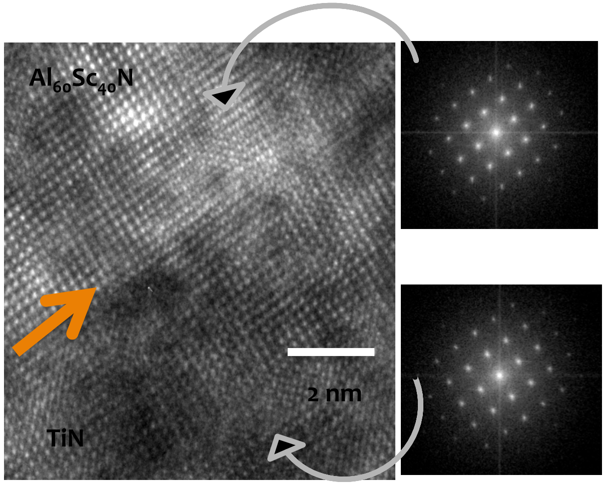


Titanium Nitride

- Hard & tough: high speed drill-bits
- Well-established processing
- Thermally and chemically stable
- High melting point (> 2700°C)
- Epitaxial growth
- CMOS-compatible
- Bio-compatible

Golden Luster



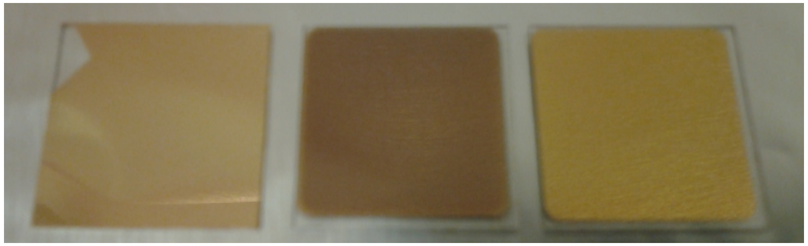


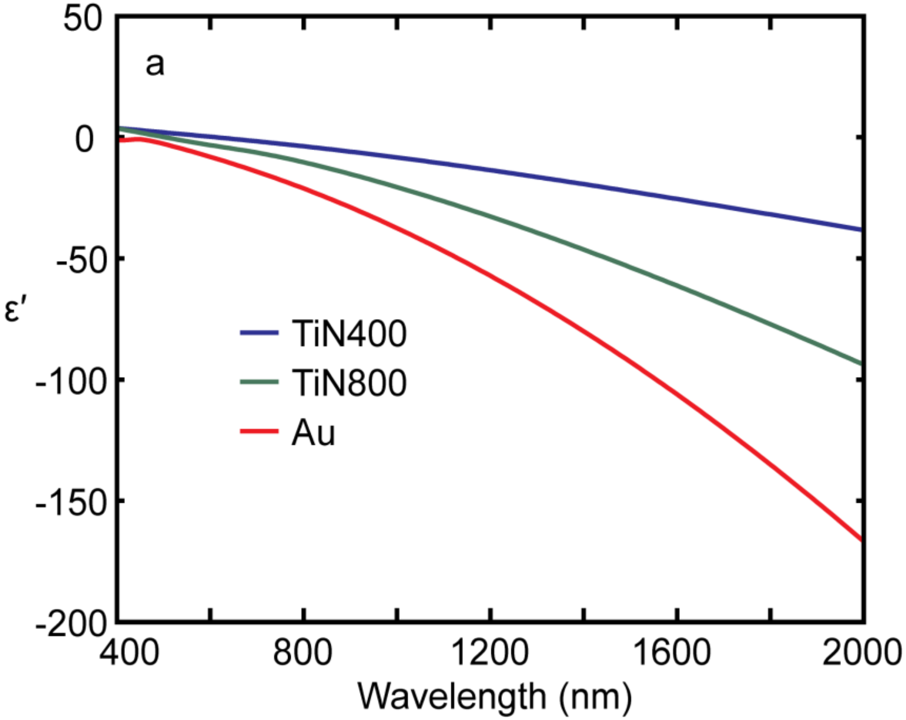
G.V. Naik *et al.*, Optical Materials Express 2 p. 478 (2012)
G. Naik, et al , Advanced Materials (2013)
G. Naik et al., PNAS (2014)

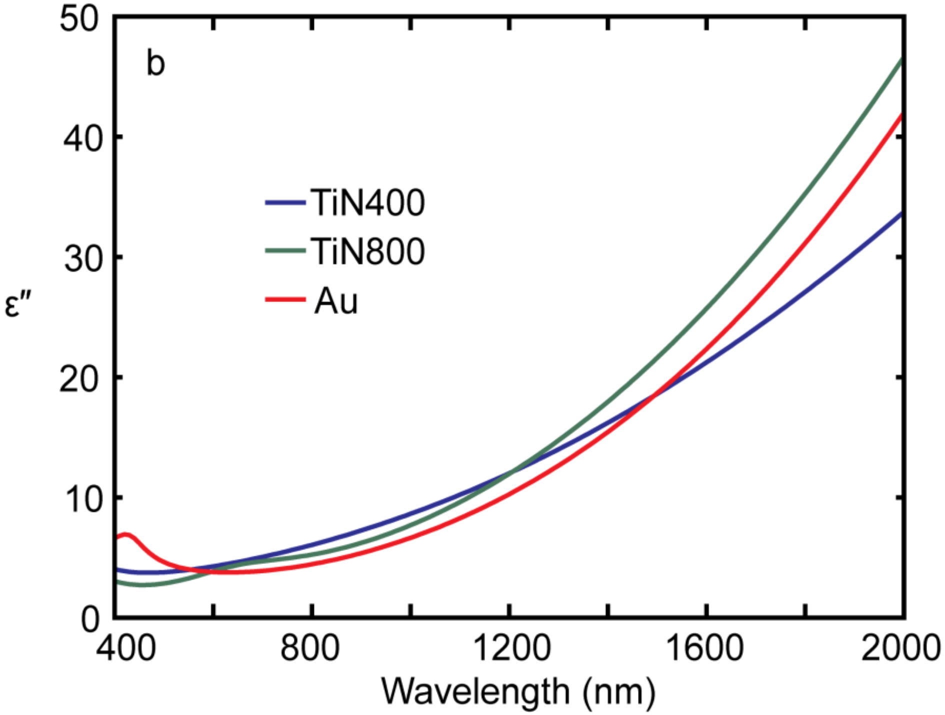
U. Guler et al., Materials Today 18 (4), 227-237 (2015)

Optical Properties of TiN

Plasmonic and tailorable!







U. Guler et al., Nano Letters 13, 6078 (2013)
U. Guler, V. Shalaev, A. Boltasseva, Materials Today 18 (4), 227-237 (2015)

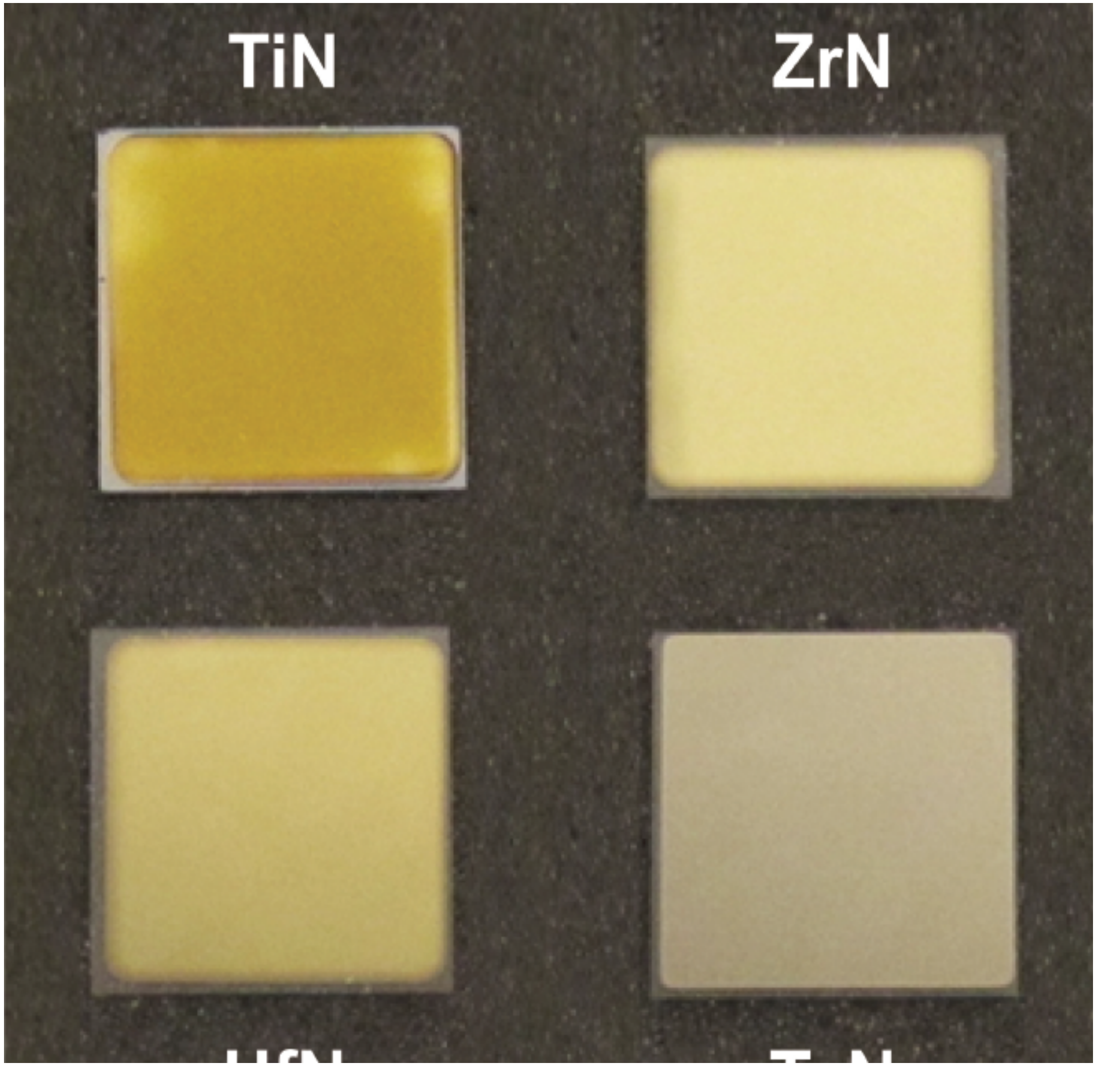
TRANSITION METAL NITRIDES

Transition metal nitrides

Mimic Au optical properties

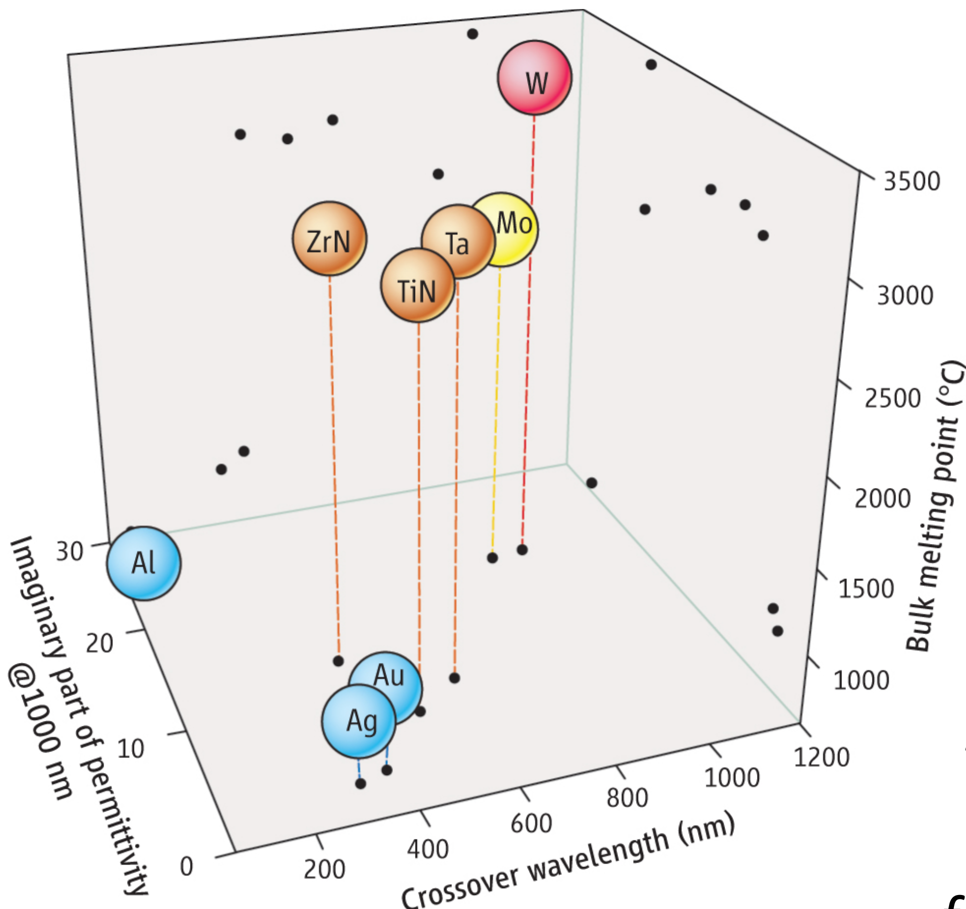
High melting point! REFRACTORY

Hard materials



G. Naik, V. Shalaev, A. Boltasseva, Advanced Materials 25 (24), 3264 (2013)
U. Guler, V. Shalaev, A. Boltasseva, Materials Today 18 (4), 227-237 (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)

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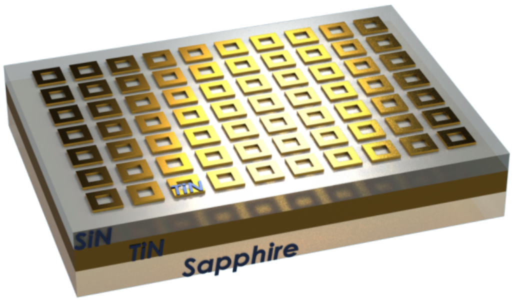
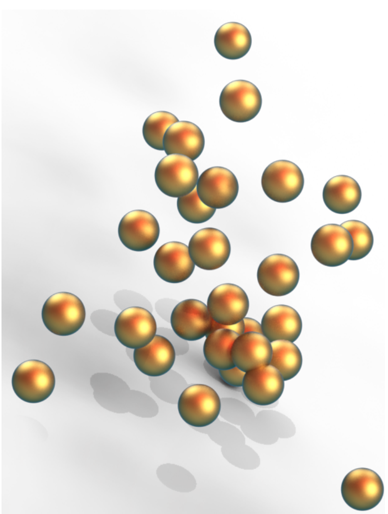
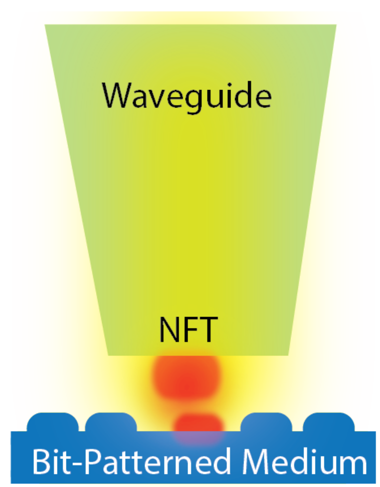
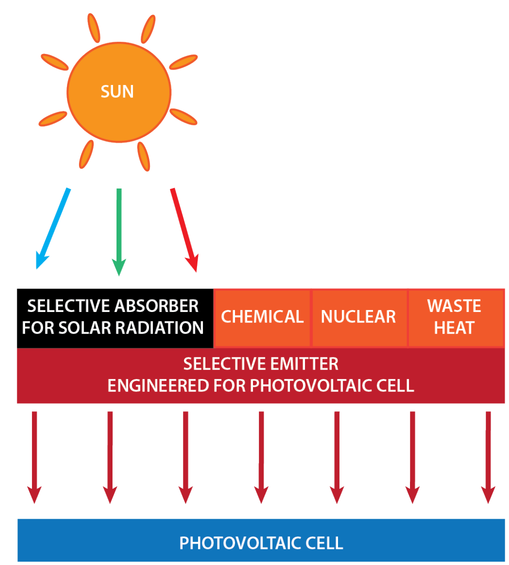


Potential

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





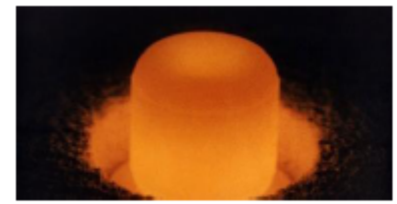


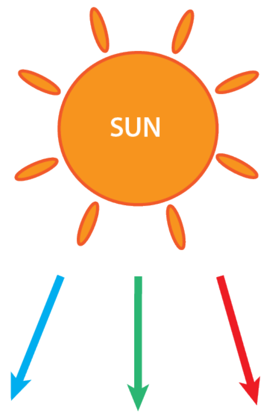
U. Guler, V. Shalaev, A. Boltasseva, Materials Today 18 (4), 227-237 (2015)

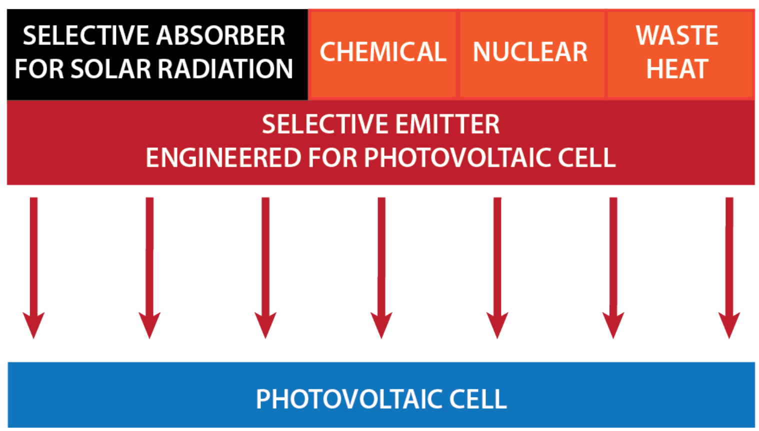
Thermophotovoltaics

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.







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.

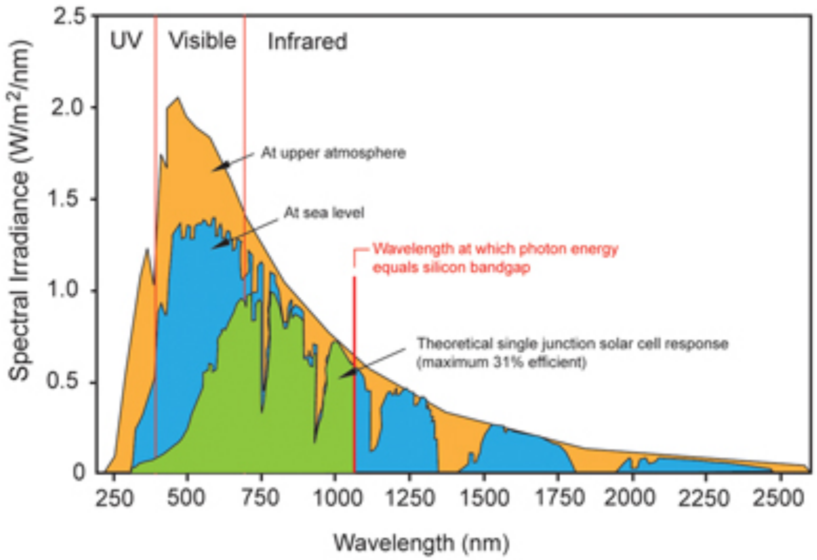
Solar Energy Concentration
S/TPV is perfect for solar energy concentration plants as it is designed for high-temperature operation. Arrangement of cells in small (10-20x) clusters will increase cost effectiveness.

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

Solar Thermophotovoltaics

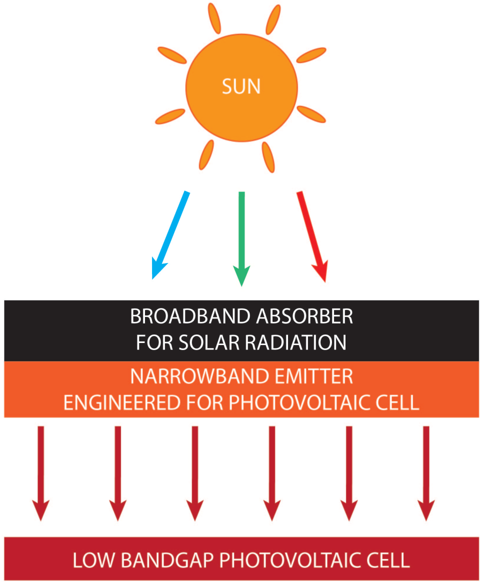
Lower energy photons are not absorbed

- Higher energy photons are not efficiently converted
  - Excess energy is lost as heat
  - Heated semiconductor efficiency drops
  - Long term high temperature operation shortens lifetime

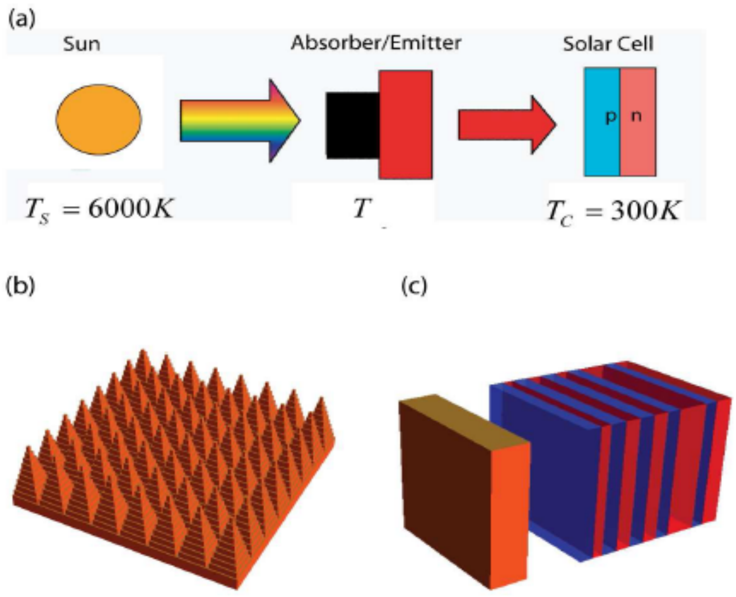


Solar/Thermophotovoltaics:

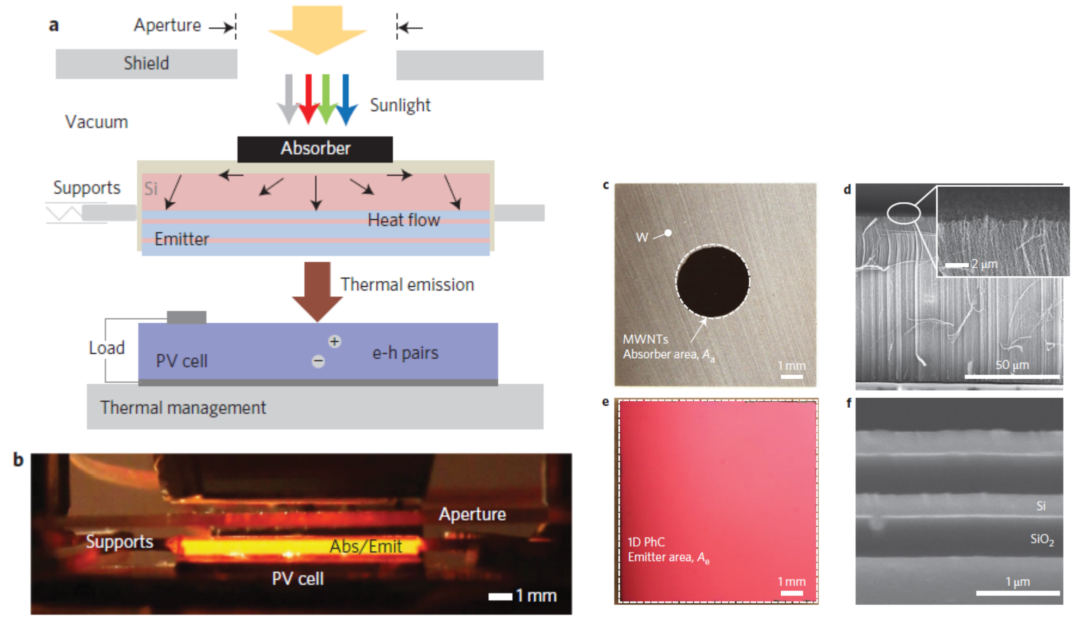
- Provide broad absorption at sun emission peak
- Emit all the collected energy at wavelengths optimized for maximum absorption
- Protect semiconductor against environmental factors
  - UV degradation
  - Humidity



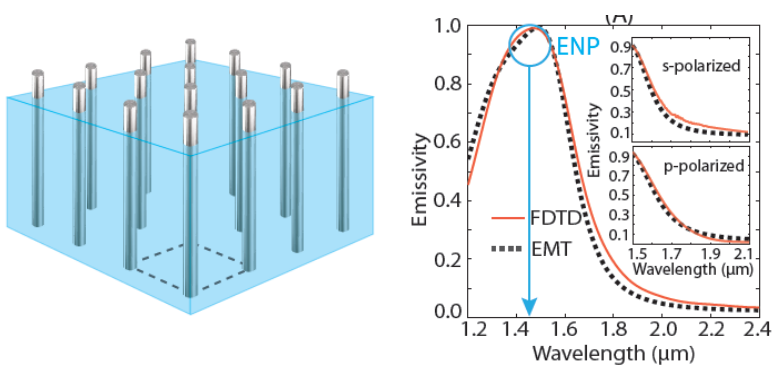
S/TPV Absorbers & Emitters



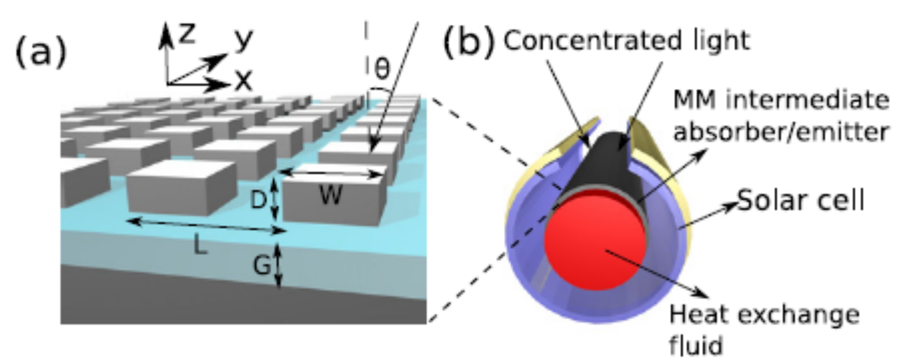
E. Rephaeli and S. Fan, Opt. Exp. 17, 15145 (2009).



A. Lenert et al., Nat. Nano. 10.1038/nnano.2013.286 (2014).

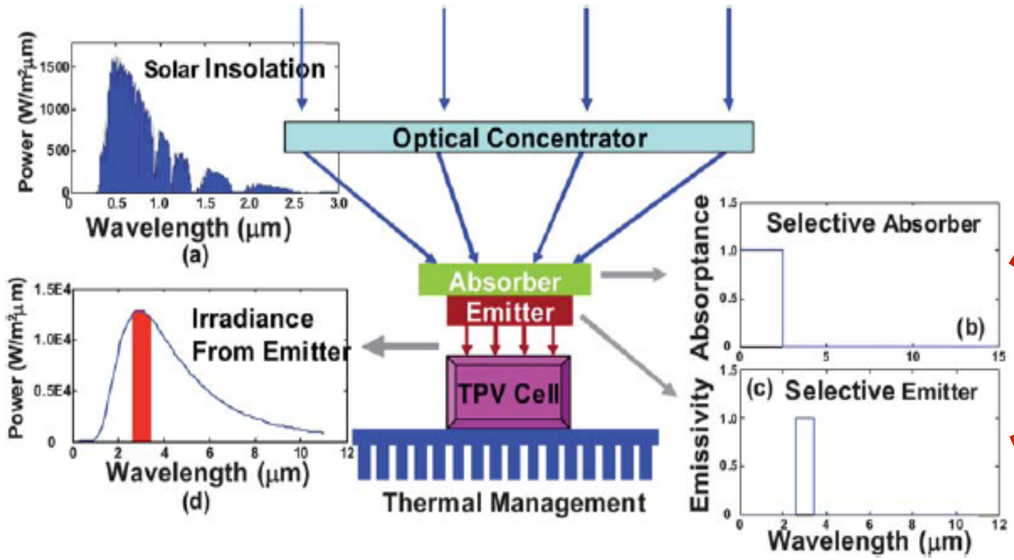


S. Molesky, C. Dewalt and Z. Jacob, Opt. Exp. 21, A96 (2013).



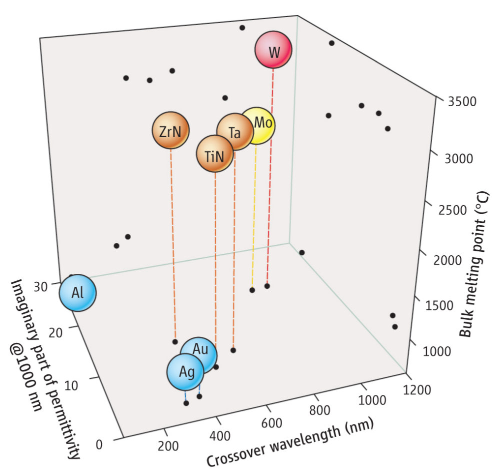
C. Wu et al., J. Opt. 14, 024005 (2012).

Solar Thermophotovoltaics

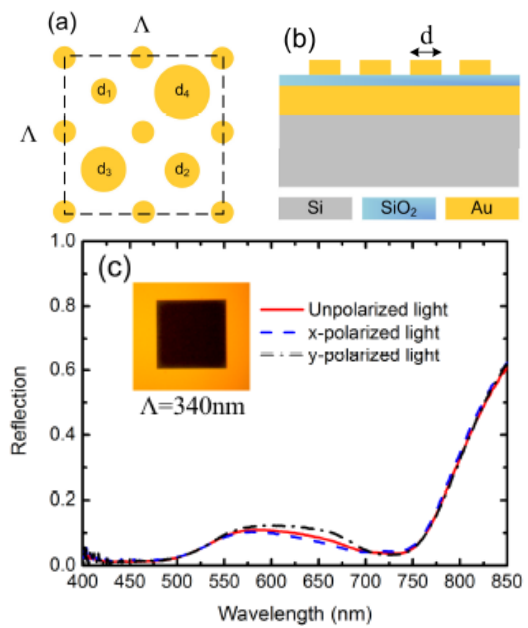


Baxter et al, Energy Environ. Sci. **2**, 559 (2009)

Metamaterials!

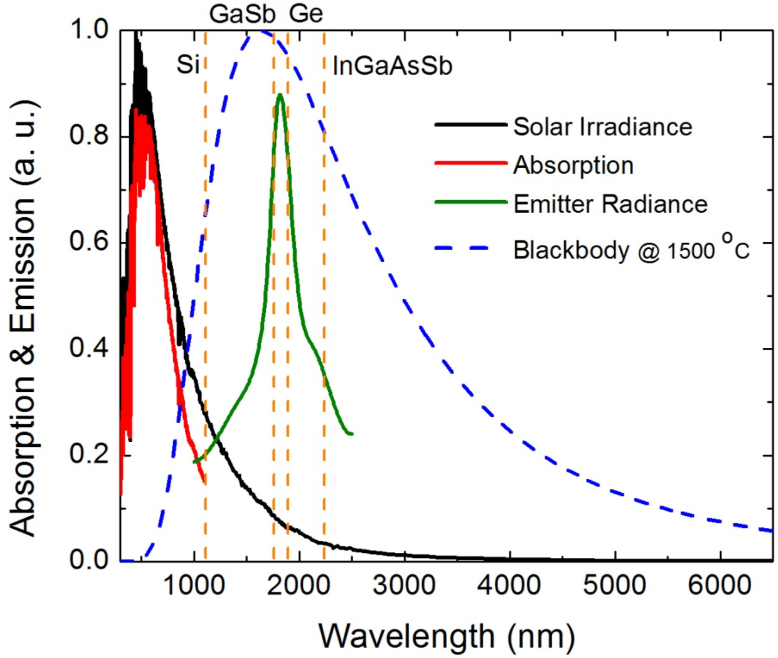


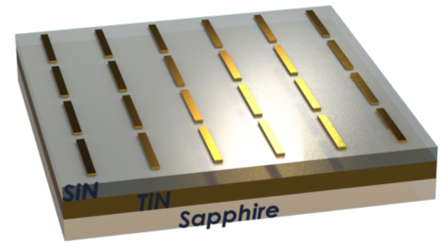
U. Guler et al, Science 344, 263 (2014)

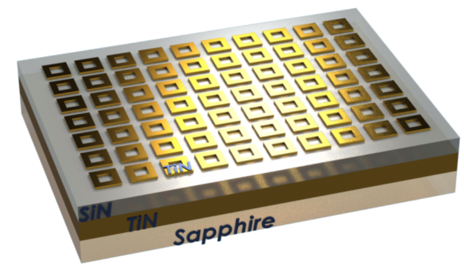


M. G. Nielsen et al, Opt. Express **20**, 13311

Example: TiN Absorber for S/TPV

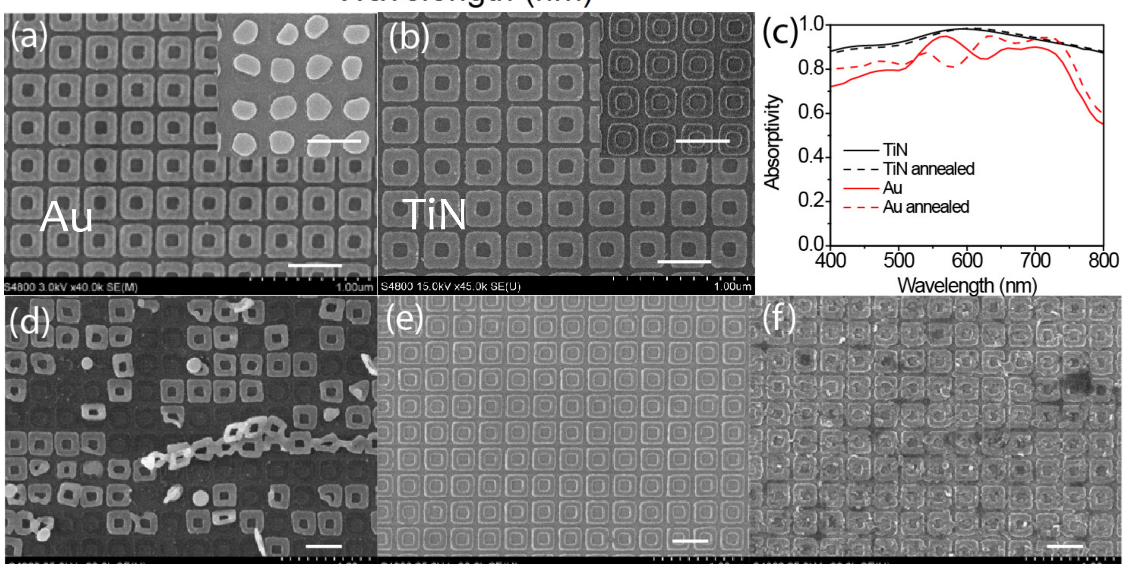


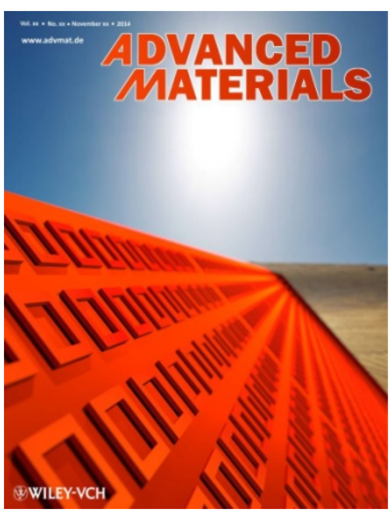




Furnace, 800 °C

Pulsed Laser 550 nm

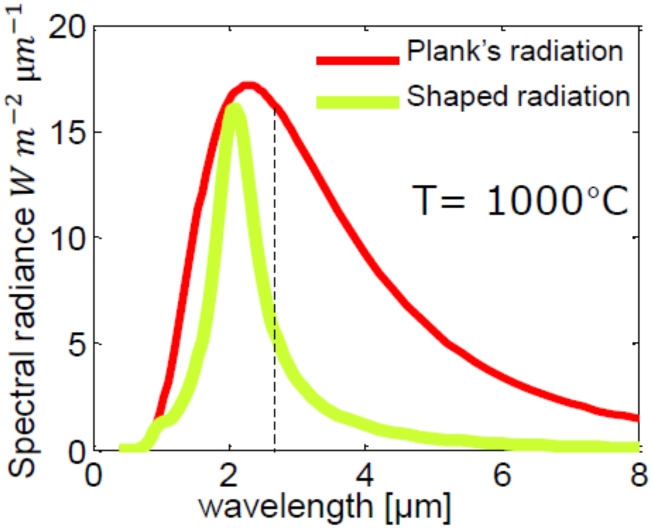


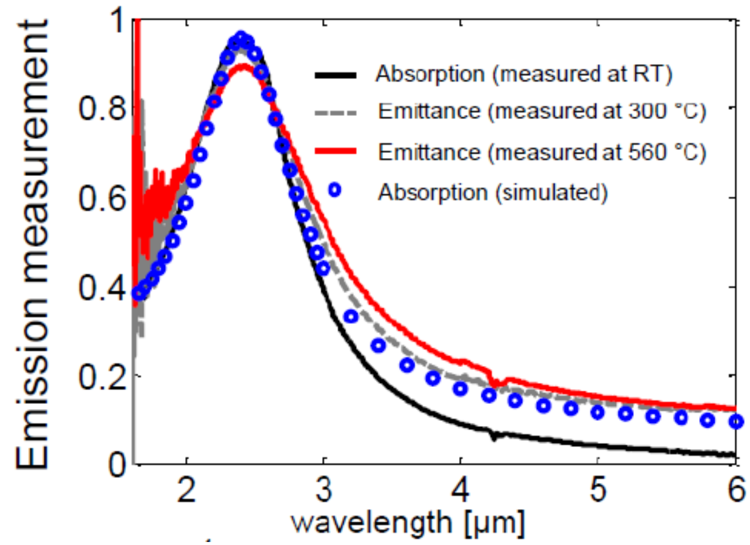


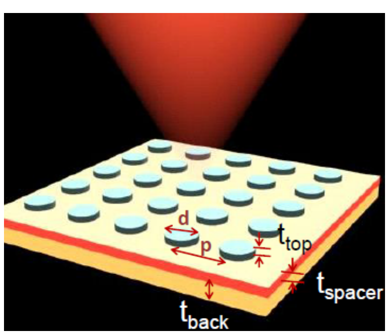
W. Li et al., Advanced Materials 26 (47) 7959-7965 (2014).

Example: TiN Emitter for S/TPV

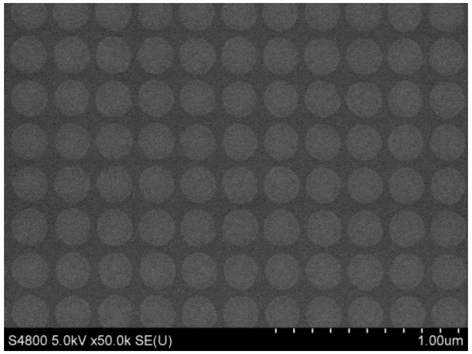
Emitter in the TPV cell: reshape the broadband spectrum of input thermal energy into emission above the bandgap of photovoltaic cells.

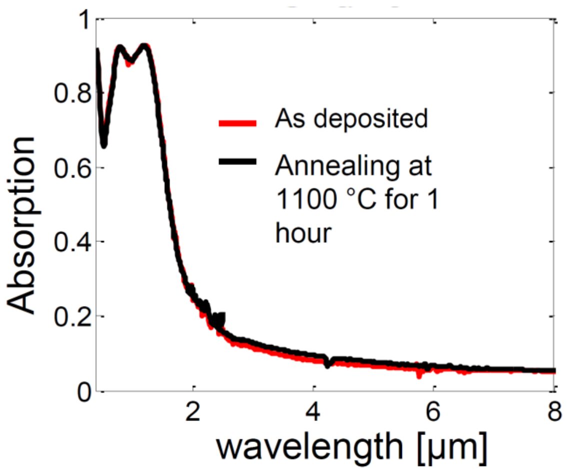






SEM image after annealing at 1100°C for 1h in the atmosphere





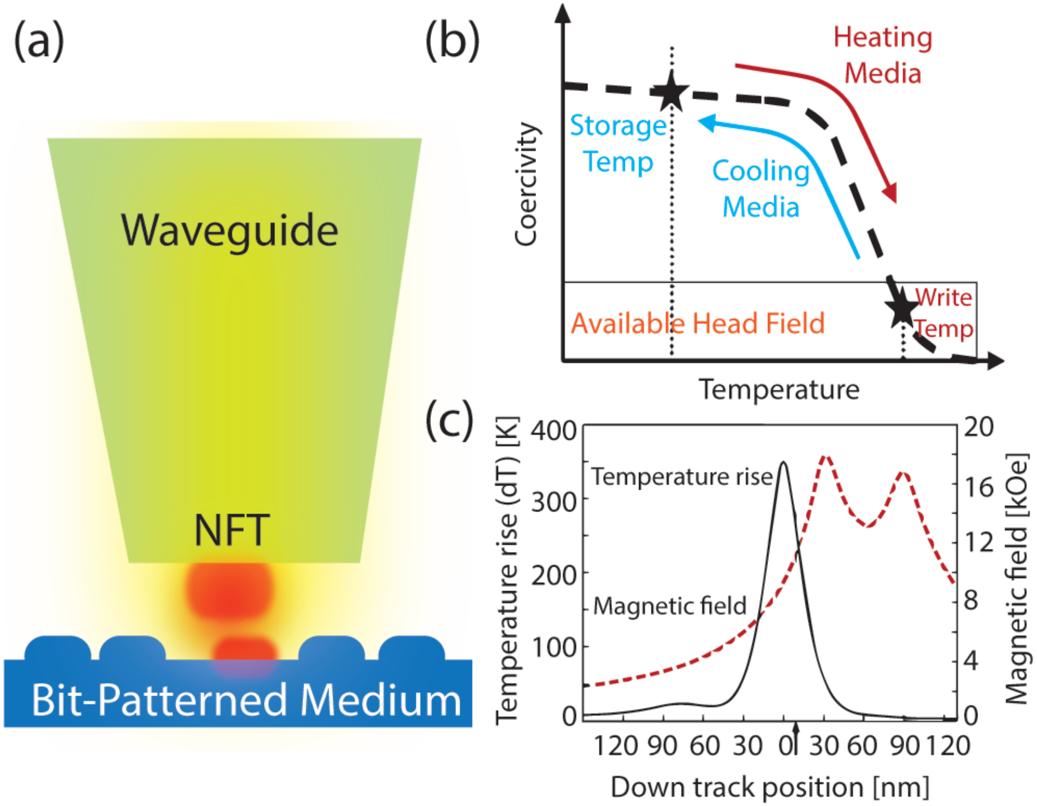
Heat Assisted Magnetic Recording

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***



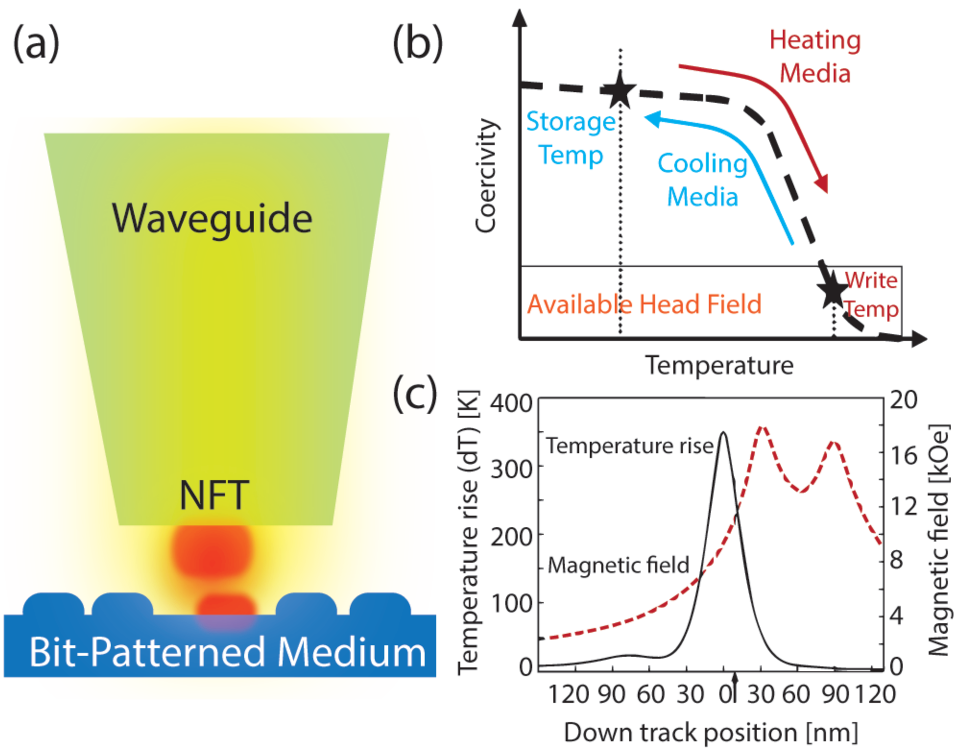
HAMR promises 10 – 16X greater HDD storage densities!

Temperatures up to 500 °C

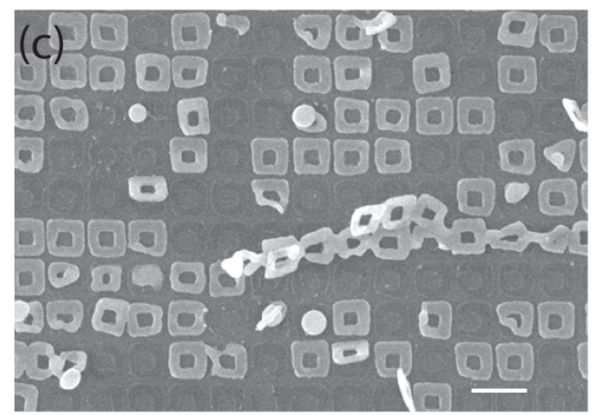
The Problem

Noble metals are good plasmonic materials,

but not mechanically robust for HAMR operation.



OEMs can't devise robust heat source.

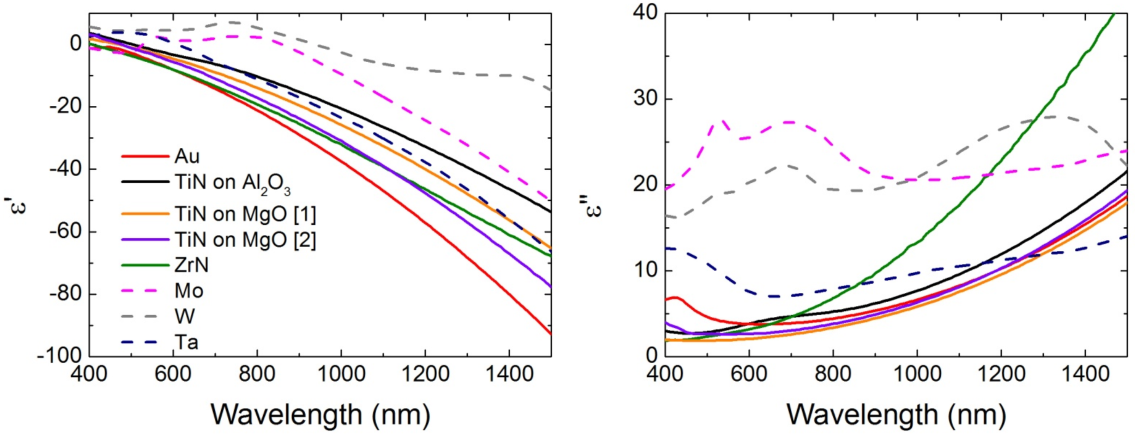


HAMR operation principles

Gold nanostructures after laser illumination.

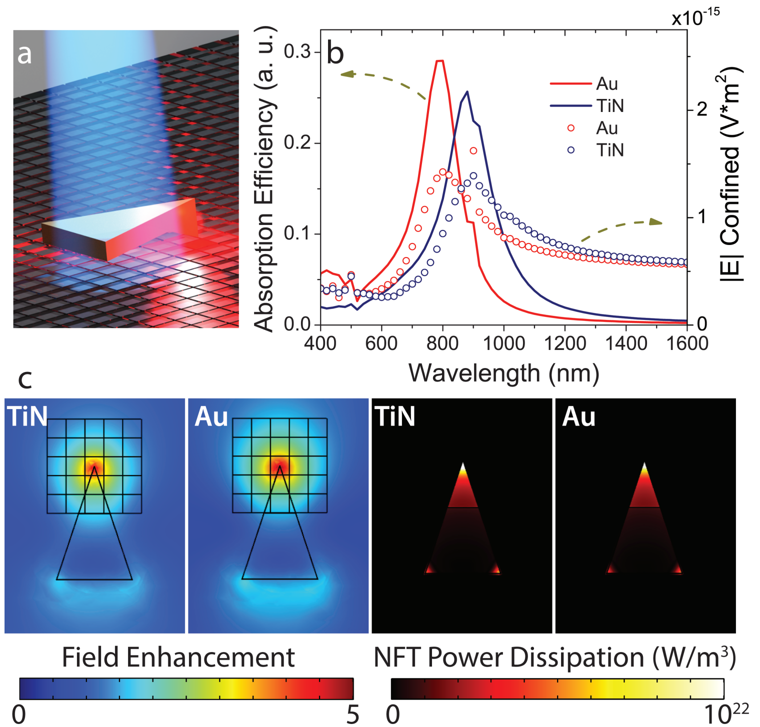
U. Guler, V. Shalaev, A. Boltasseva, Materials Today 18 (4), 227-237 (2015)

TiN for HAMR



Optical Figure of Merit for TiN is close to Au

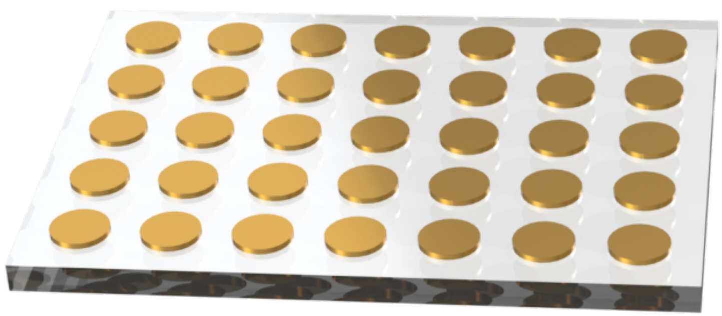
Material	Permittivity (real)	Permittivity (imaginary)	FOM (|ε'|/ε'')
Au	-23.39	4.67	5.01
TiN (Al_2O_3)	-11.73	5.47	2.14
TiN (MgO) [1]	-15.57	3.68	4.23
TiN (MgO) [2]	-19.08	4.11	4.64
ZrN	-21.15	7.64	2.77
Mo	1.43	23.16	NA
W	4.21	19.41	NA
Ta	-12.89	8.15	1.58



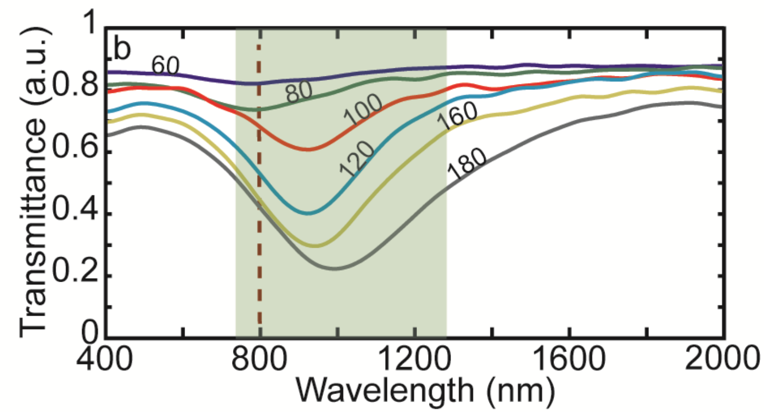
U. Guler et al., Faraday Discussions 178, 71-86 (2015)

LSPR - Transmittance

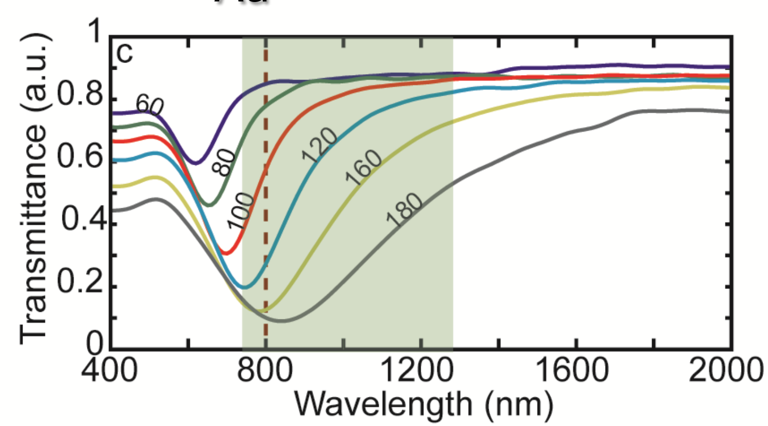
Broad resonance with higher absorption in biological window: Therapeutical applications

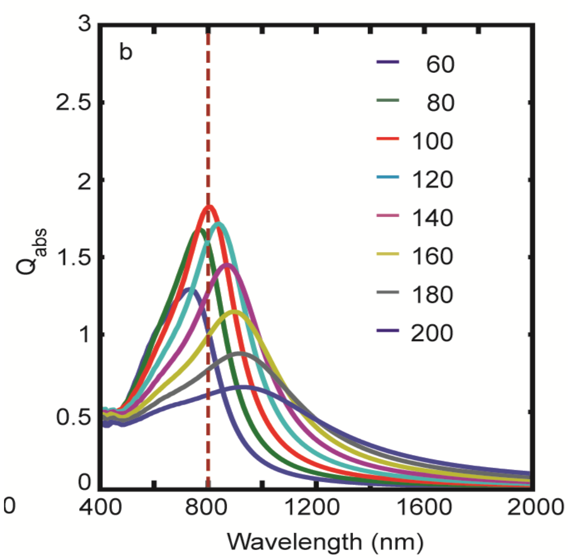


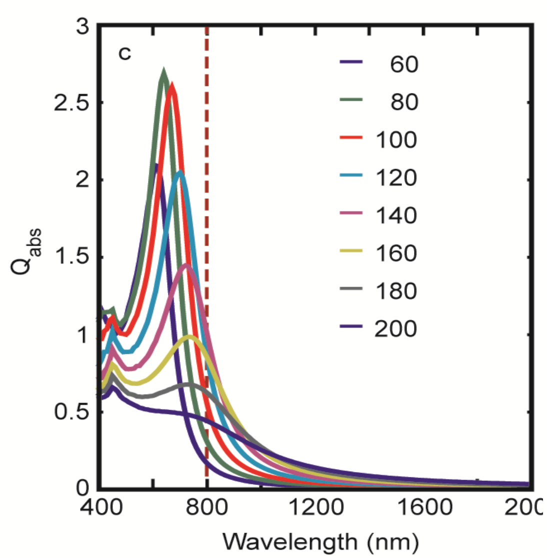
TiN grown @ 800 °C



Au



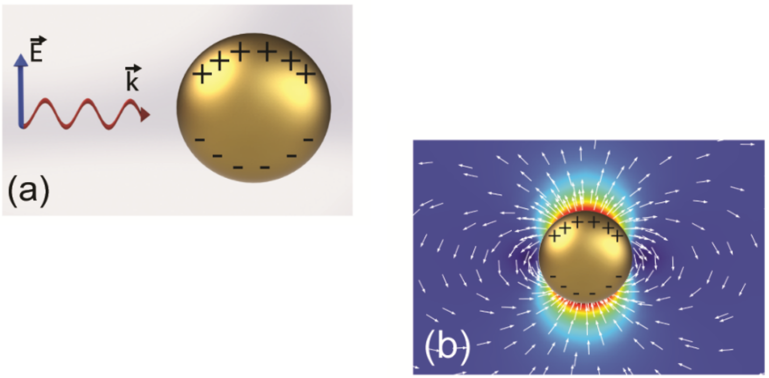




U. Guler et al., Nano Letters 13 (12), 6078-6083 (2013)

U. Guler et al., Appl. Phys. B 107 (2), 285-291 (2012)

Local heating

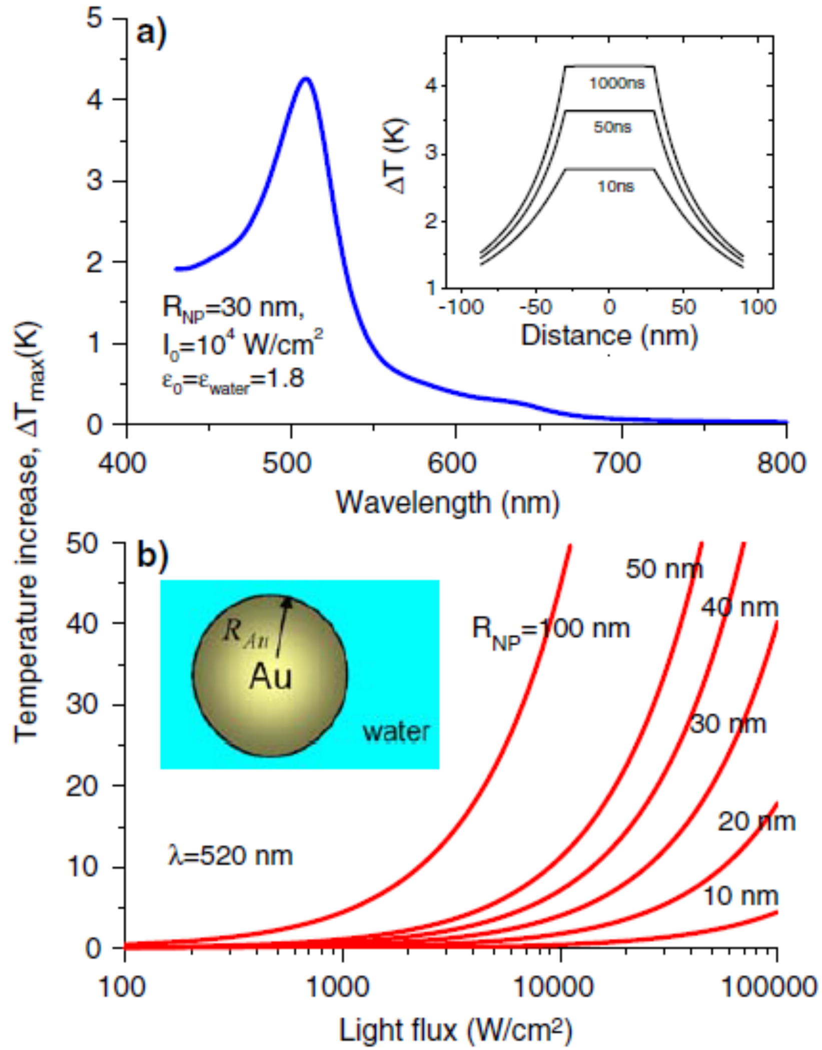


$$\Delta T(\mathbf{r}) = \frac{V_{\rm NP} Q}{4\pi k_0} \frac{1}{r} (r > R_{\rm NP})$$

$$Q = -\mathrm{Re}\left[i\omega \frac{\varepsilon(\mathbf{r}) - 1}{8\pi} \mathbf{E}_0^2 \left| \frac{3\varepsilon_0}{2\varepsilon_0 + \varepsilon_m} \right|^2 \right]$$

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

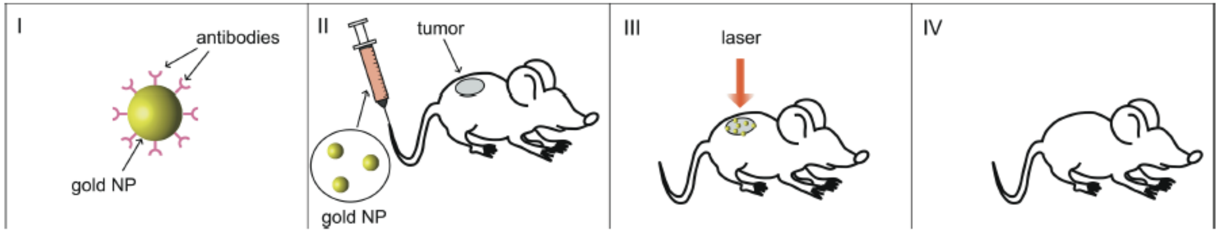
TiN?



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

A. O. Govorov et al., Nanoscale Res. Lett. 1, 84 (2006)

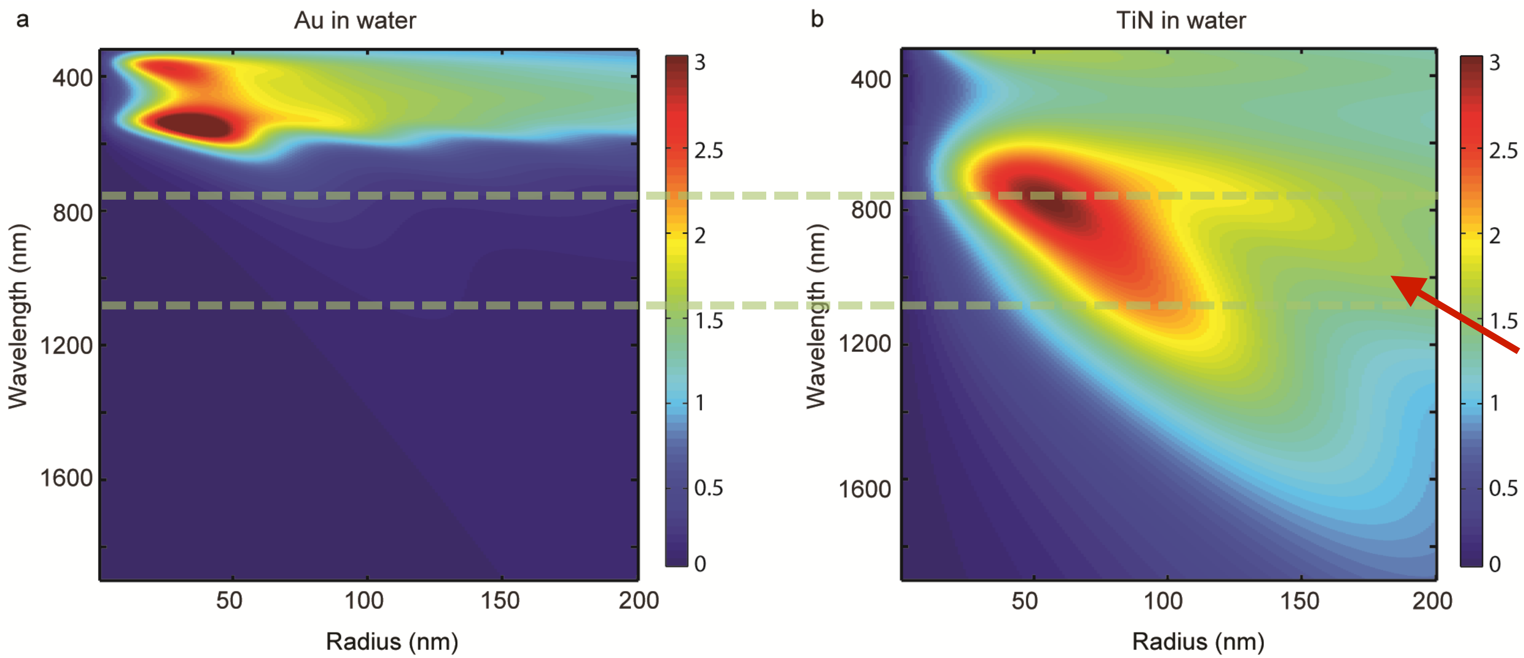
Thermal Therapy - TiN



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

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

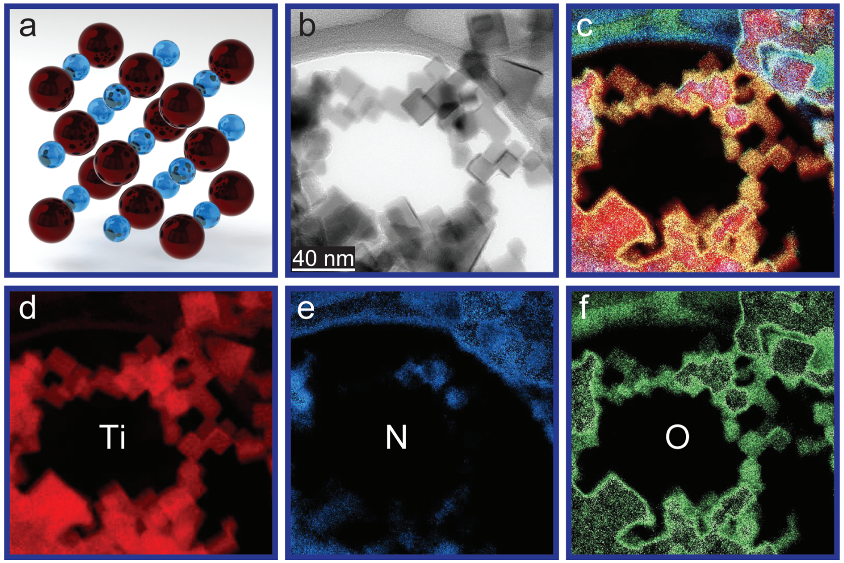
L. R. Hirsch et al., PNAS **100**, 13549 (2003).
N. Halas, MRS Bulletin **30**, 362 (2005).
B. E. Brinson et al., Langmuir **24**, 14166 (2008).

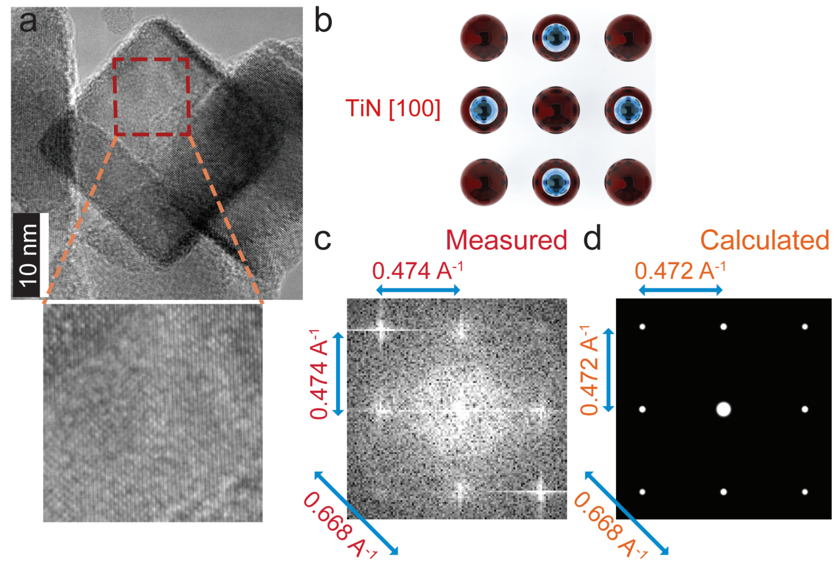


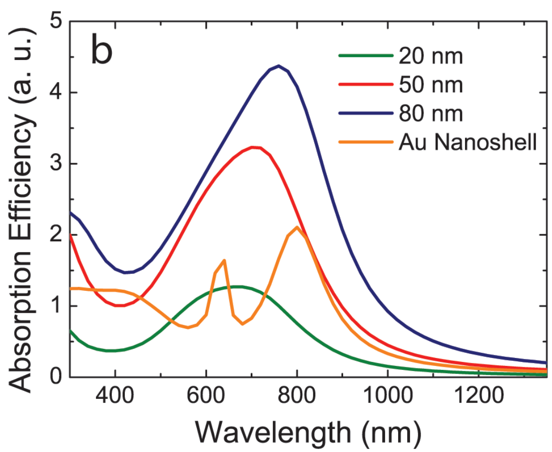
Transparency window

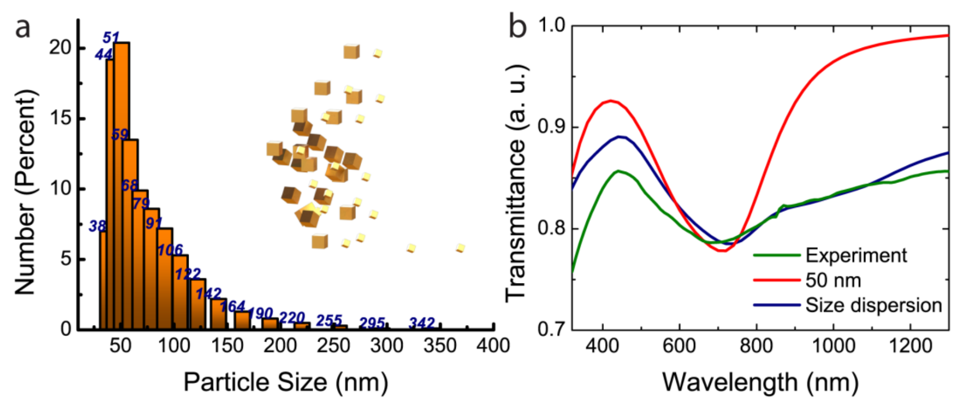
U. Guler et al., Nano Letters 13, 6078 (2013)

Plasmonic TiN in Colloids & photothermal therapy

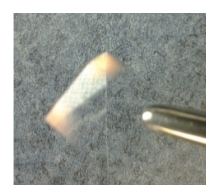








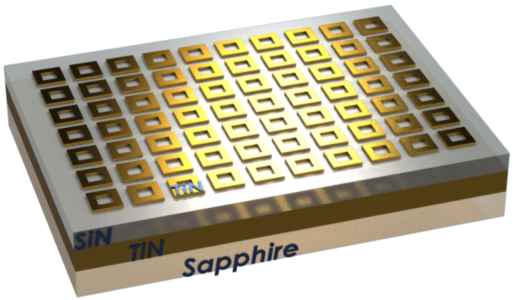
U. Guler et al., Nanophotonics, accepted.



Golden luster of dispersed TiN powder

OUTLINE

- Introduction: Plasmonics & Metamaterials
- Material Requirements & Alternative Materials
- Transition Metal Nitrides
- Applications with Plasmonic Metal Nitrides
  - High Temperature
    - Thermophotovoltaics
    - Heat Assisted Magnetic Recording
    - Coherent thermal sources
  - Plasmonic photothermal therapy
  - **Quantum Photonics Application**



Single NV Centers Coupled to TiN HMM

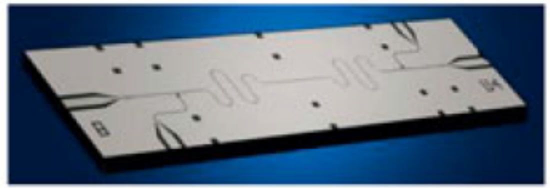
"Nature isn't classical dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem because it doesn't look so easy."

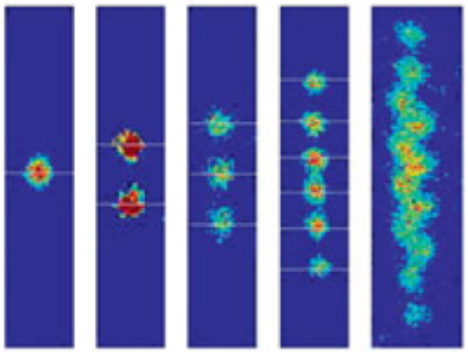
R.P. Feyman, Int. J. Theor. Phys. 21, 467

Materials → Quantum sensors, simulators & computers

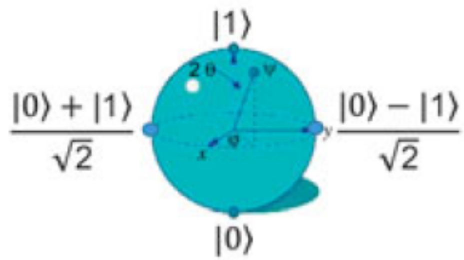
Information is physical

Superconducting resonators/Josephson junctions

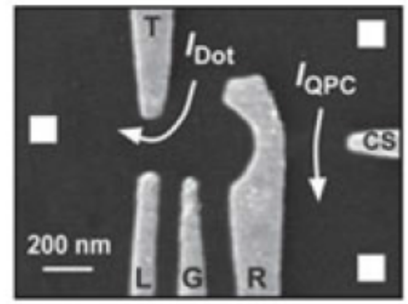


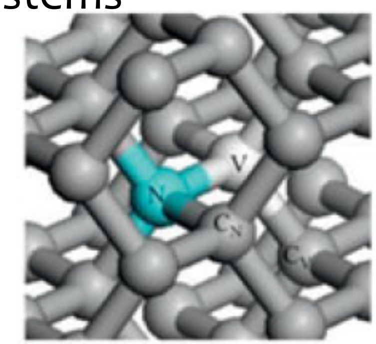


Trapped ion/atom systems

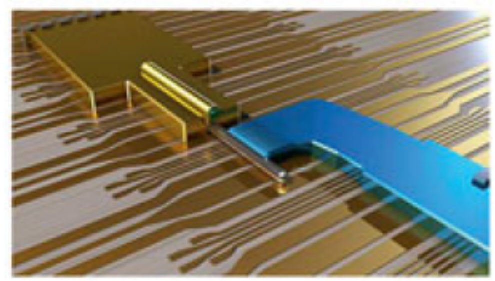


Gate-defined semiconductor structures





Atomic centers in solids

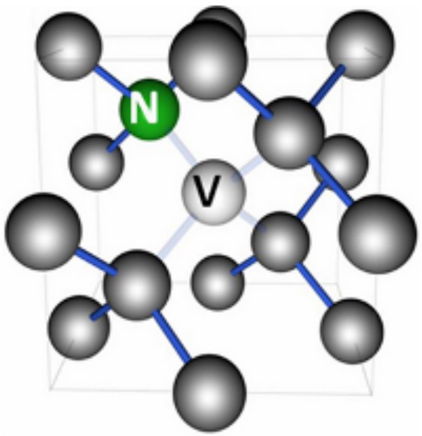


Majorana fermions in nanowire hybrid materials

Eckstein & Levy, MRS Bulletin (2013)

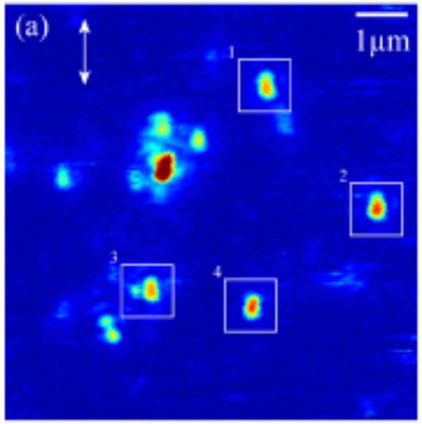
Diamond NV center

Solid-state defect:
artificial atom
"with handles"



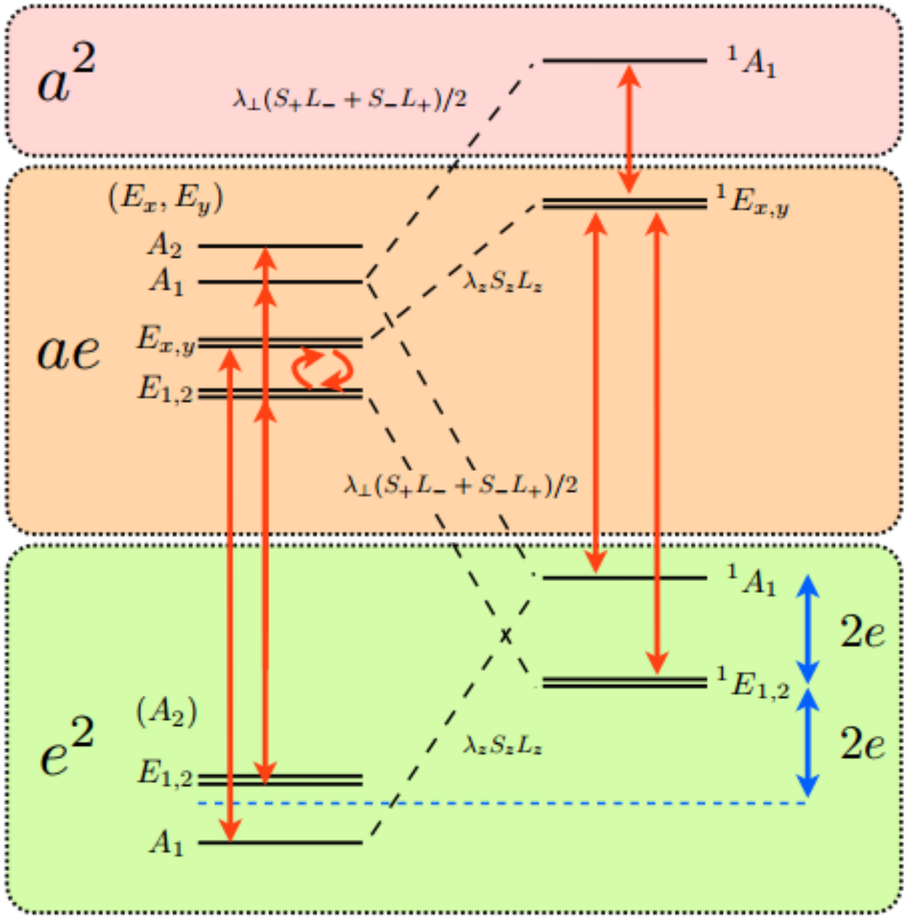
Jelezko et al., *Phys. Stat. Sol.* (2006)

Single-photon fluorescence at room temperature



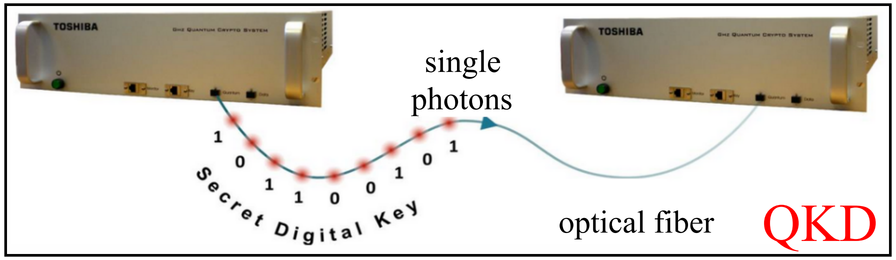
Dolan et al., *Opt. Express.* (2014)

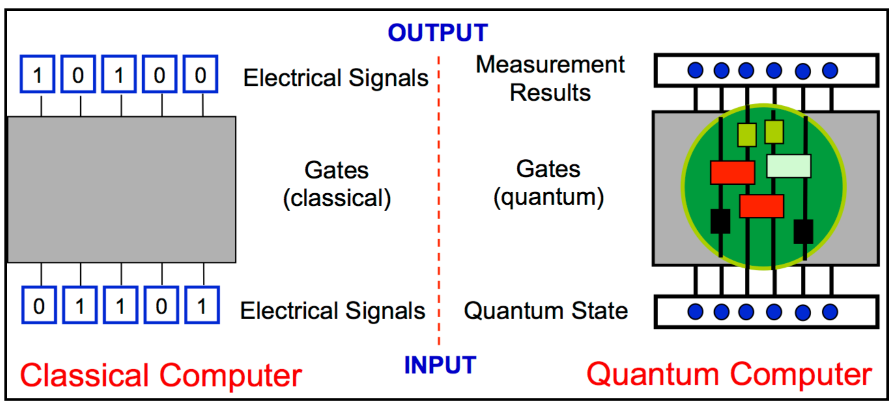
Many degrees of freedom = many applications



Maze et al., *New J. of Phys.* (2011)

Quantum information

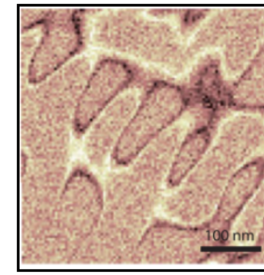




Andrew Daley, University of Strathclyde

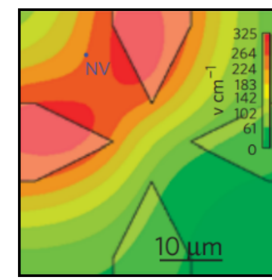
Nanoscale sensing

Magnetic fields



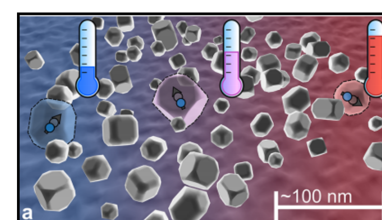
Hong et al. *MRS Bulletin* (2013)

Electric fields



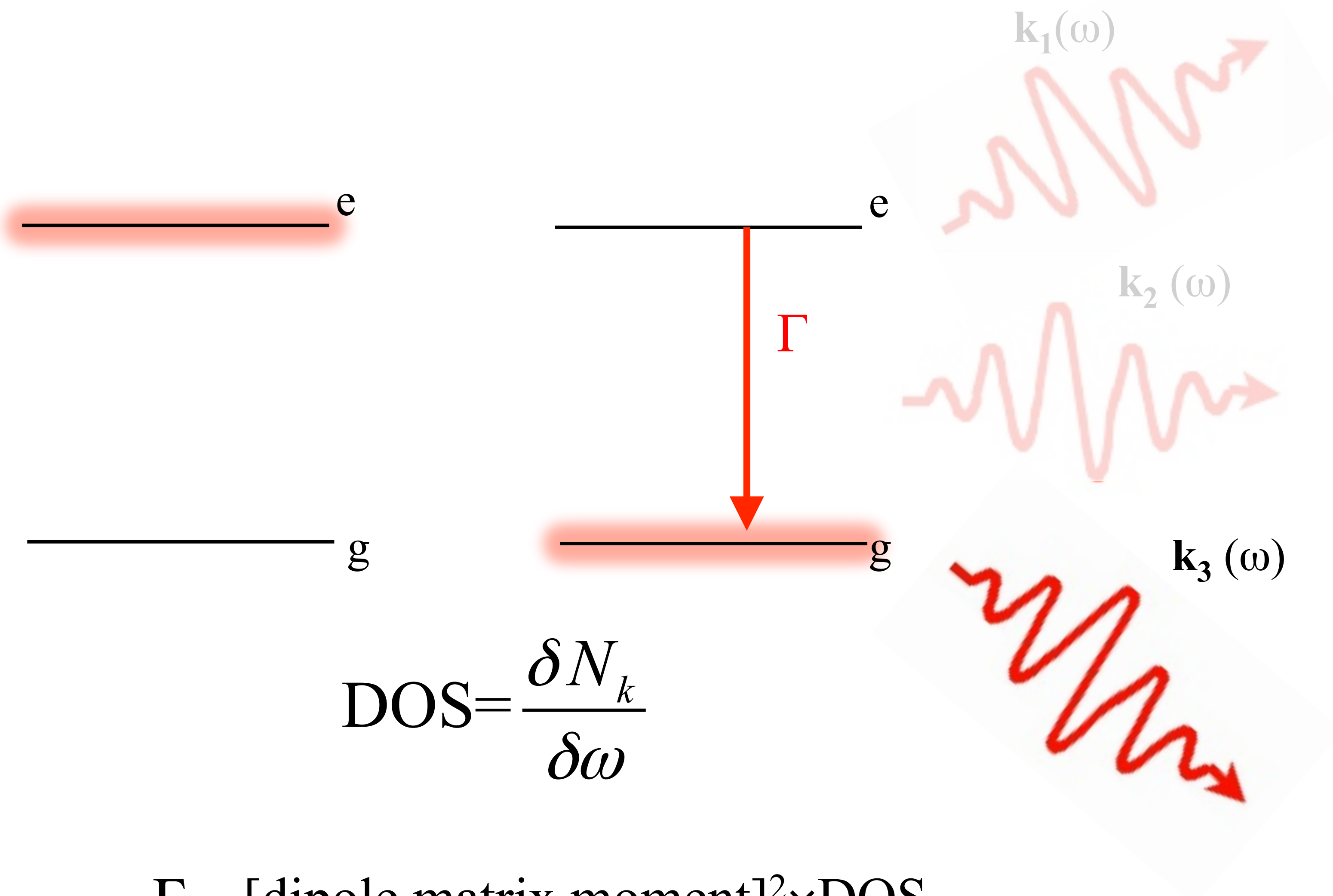
Dolde et al. *Nat. Phys.* (2011)

Temperature



Neumann et al. *Nanolett.* (2013)

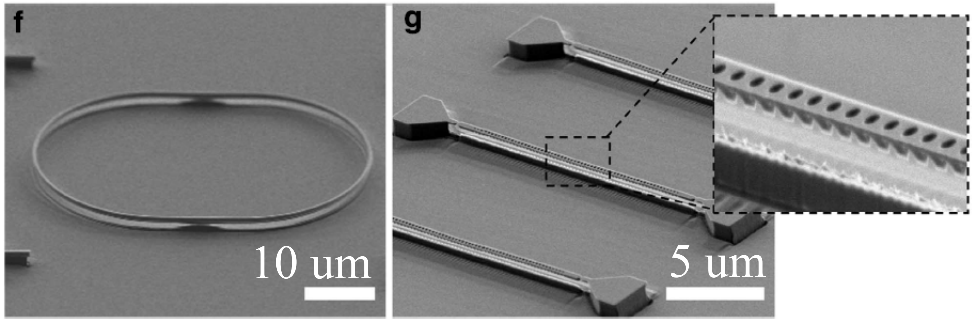
Enhancing the emission rate



$$\mathrm{DOS} = \frac{\delta N_k}{\delta \omega}$$

$\Gamma \sim$ [dipole matrix moment]$^2 \times$DOS

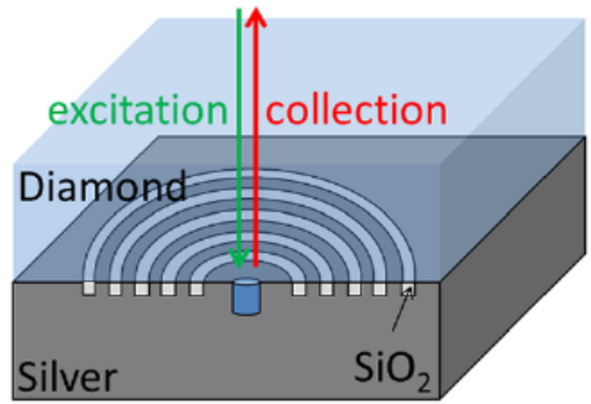
Resonant ways to enhance emission rate



diamond racetrack resonator

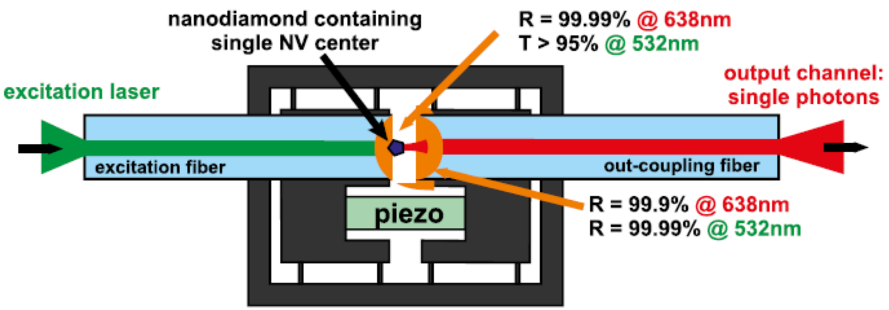
& nanobeam photonic crystal cavity

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



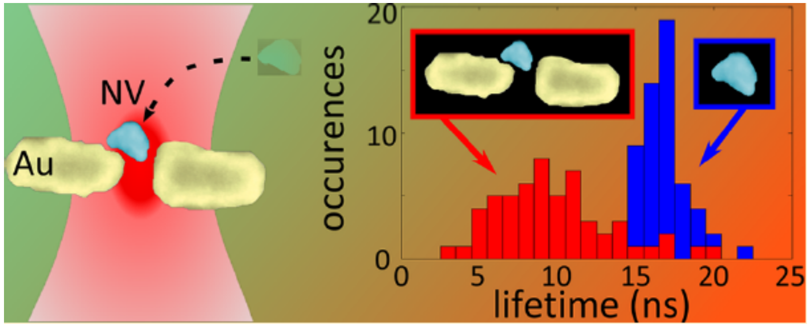
diamond-silver apertures

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



all-fiber cavity

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



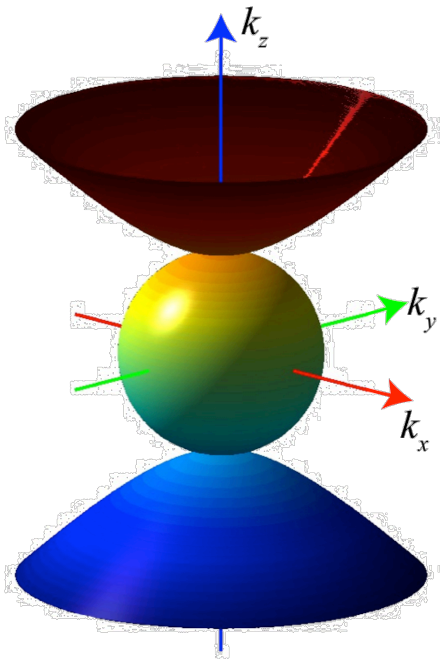
plasmonic gap-antenna

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

Single NV Centers Coupled to TiN HMM

Shalaginov, et al, LPR (2105): Enhancement of single-photon emission from NV centers with TiN/(AlSc)N hyperbolic metamaterial

Metamaterials with Hyperbolic Dispersion



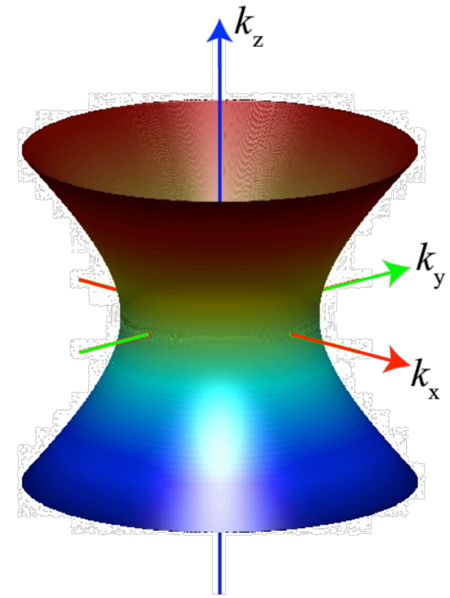
normal dispersion

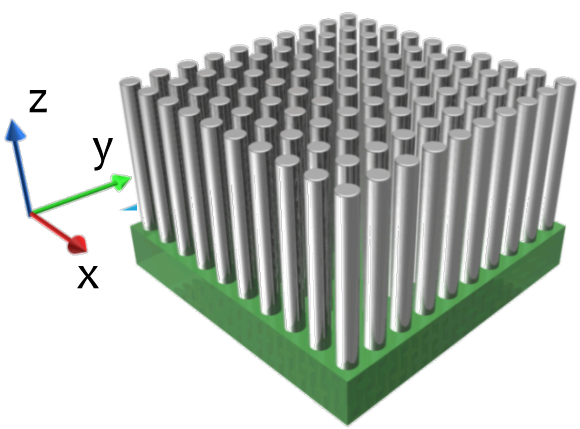
$$\frac{k_x^2 + k_y^2 + k_z^2}{\varepsilon} = \left(\frac{\omega}{c}\right)^2$$

hyperbolic dispersion

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

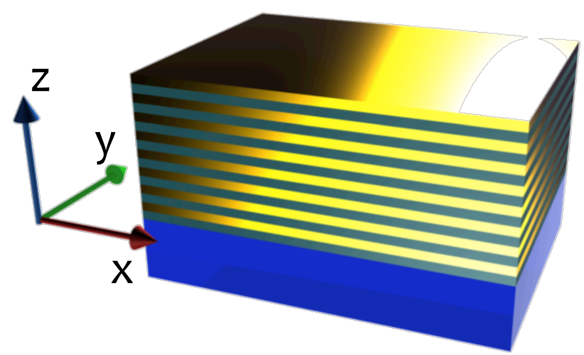
$$-\frac{k_x^2 + k_y^2}{|\varepsilon_{\mathrm{P}}|} + \frac{k_z^2}{\varepsilon_{\perp}} = \left(\frac{\omega}{c}\right)^2$$





transverse positive (type I)

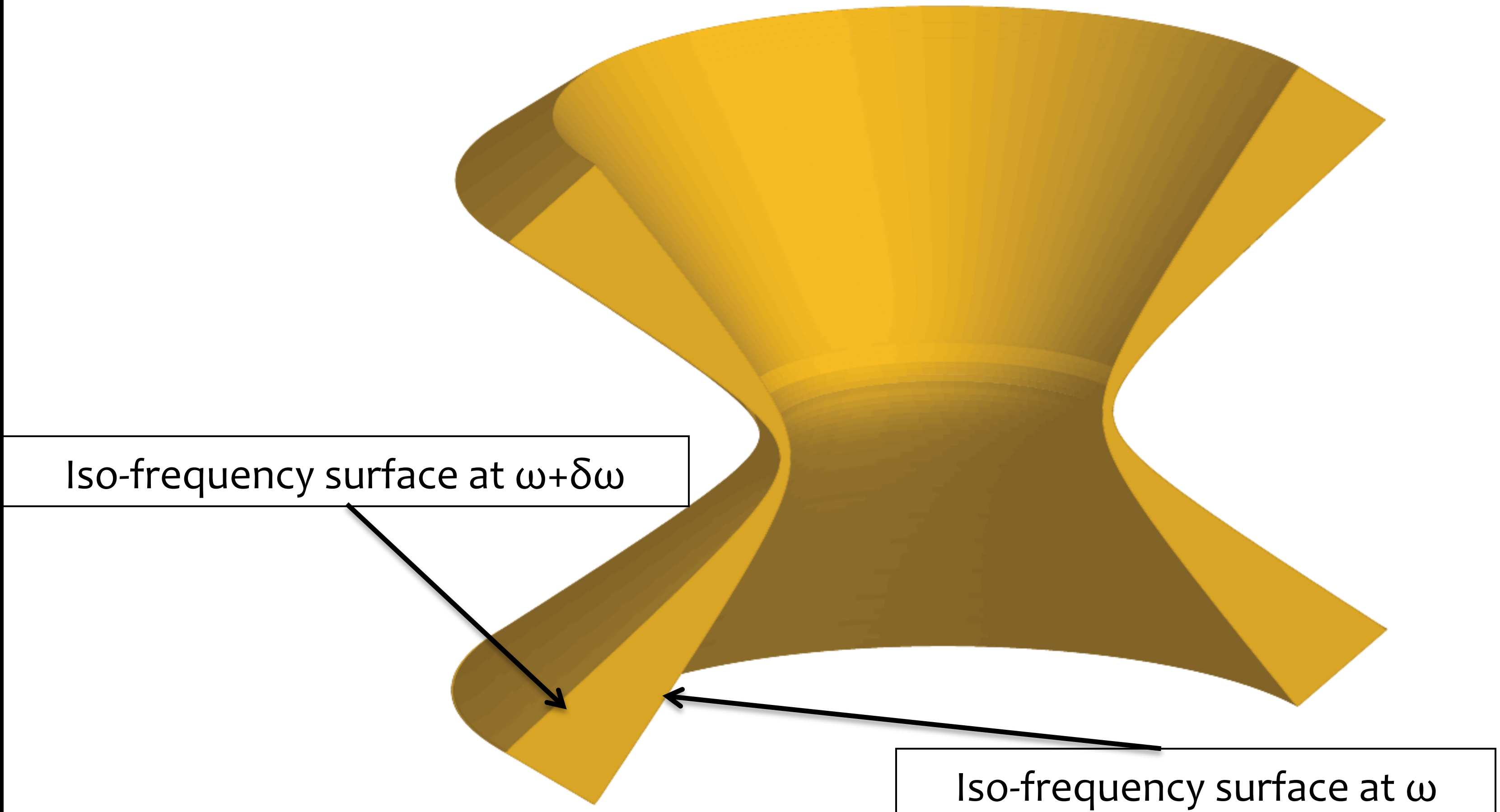
Smith & Schurig PRL (2003)
Jacob, et al, Opt. Express (2006)



transverse negative (type II)

PHOTONIC DENSITY OF STATES (PDOS)

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



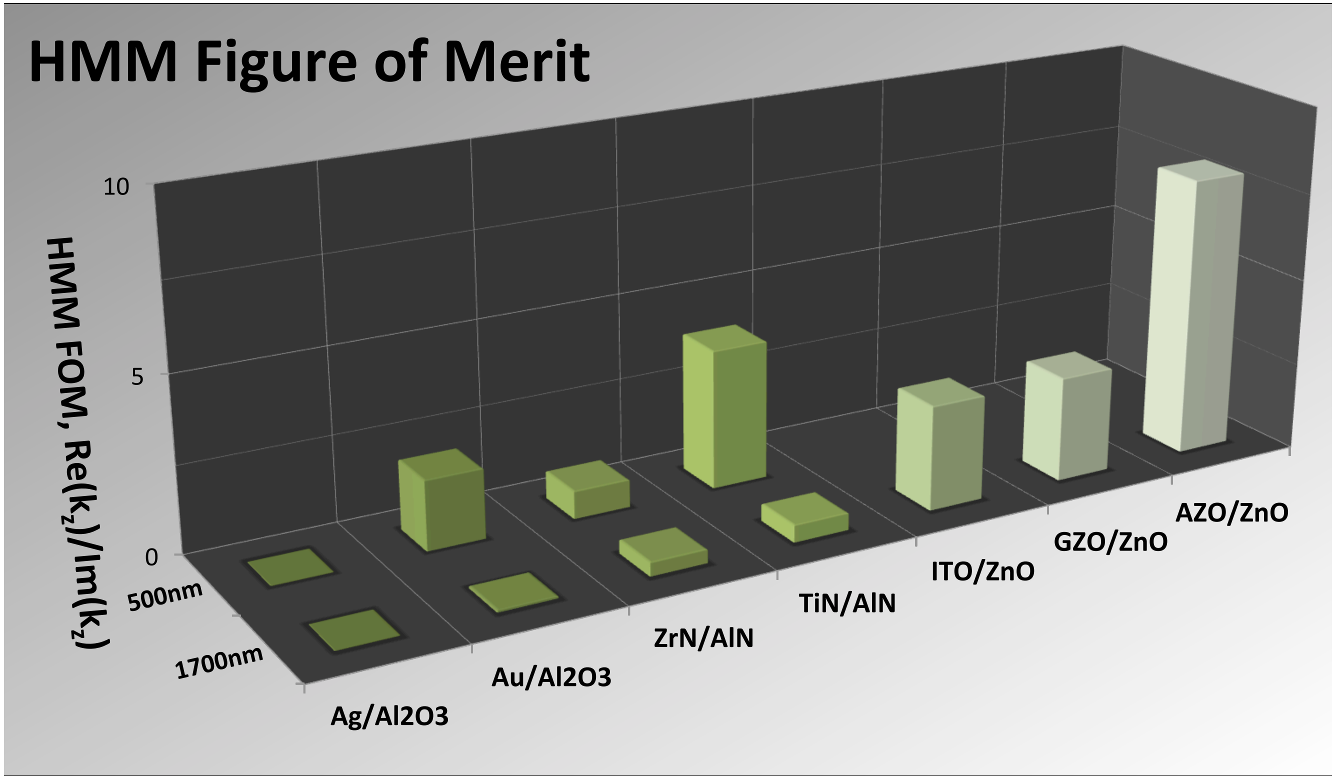
unbounded |k|

singularity in PDOS

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

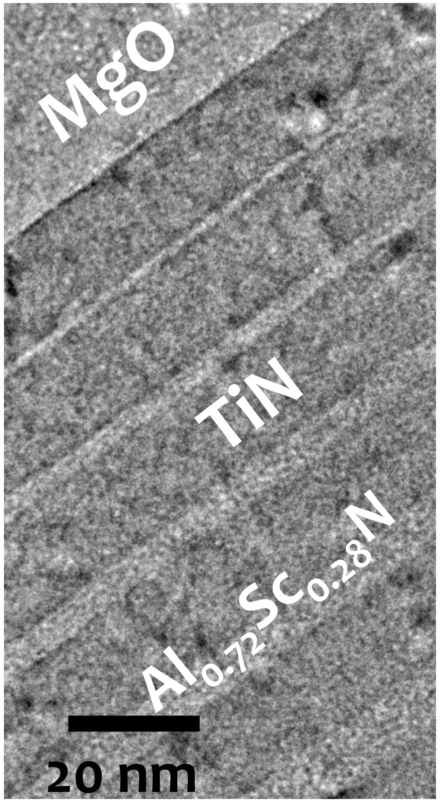
$$\mathrm{DOS} = \infty, \ \forall\omega \ !$$

Comparison: HMMs



$Re(\beta_{\perp})/Im(\beta_{\perp})$

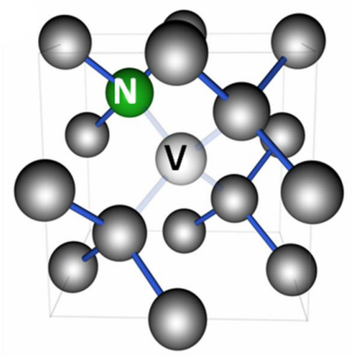
Describes the transmission of a low-loss HMM



- HMMs have extremely large photonic density of states
- Can tailor mechanical, thermal, and electromagnetic properties

HMMs + Emitters

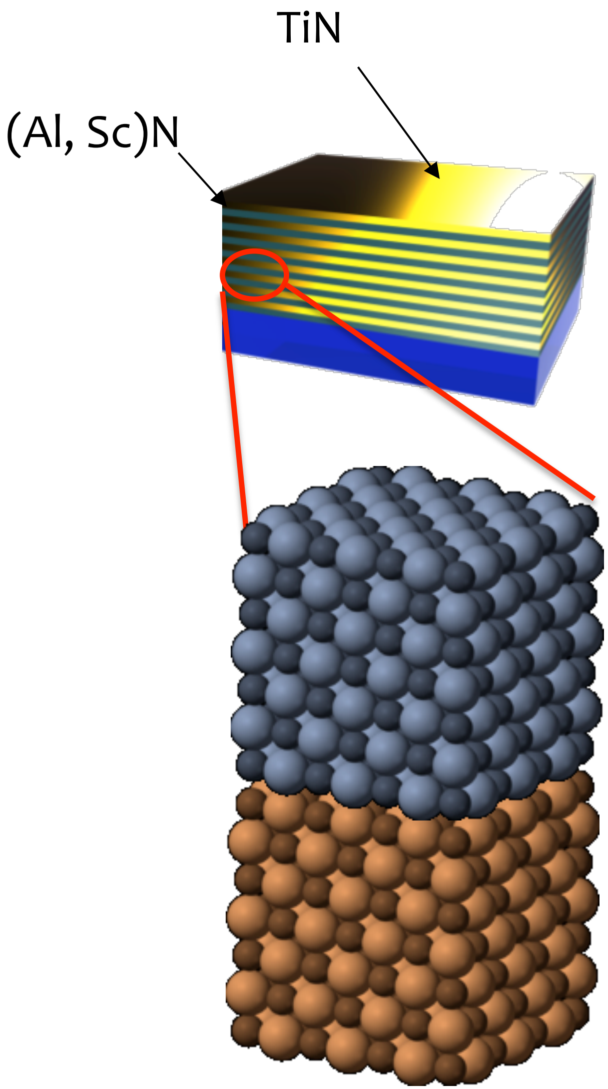
Nitrogen-vacancy centers in diamond

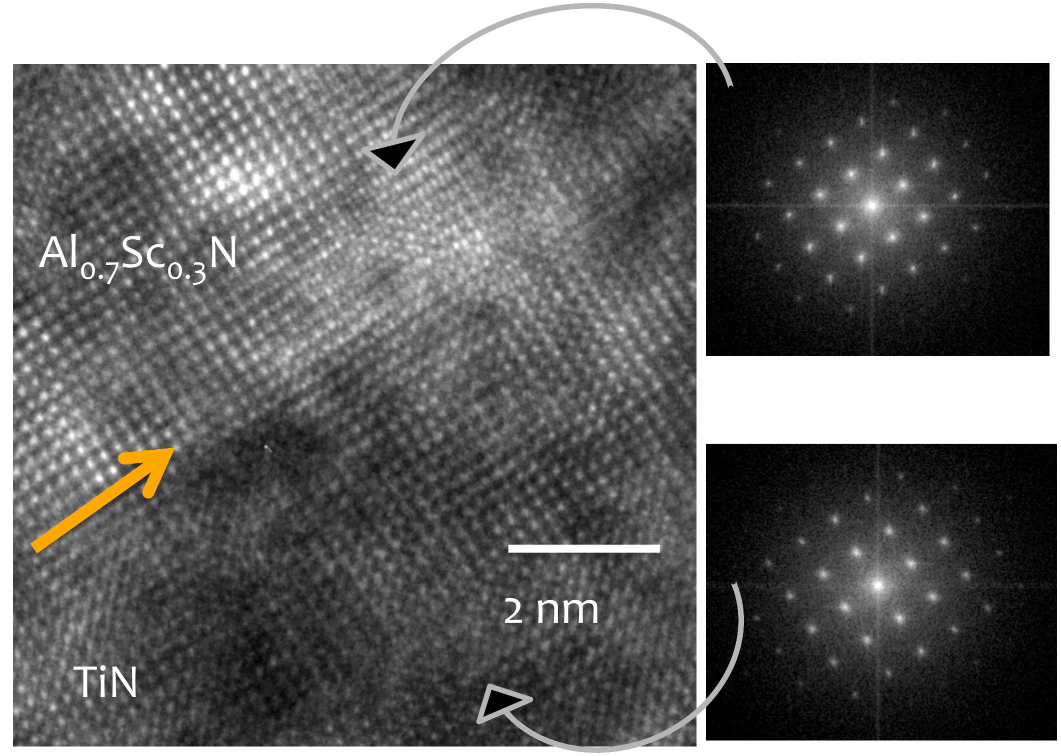


Color centers in diamond

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

HMM based on CMOS-compatible materials





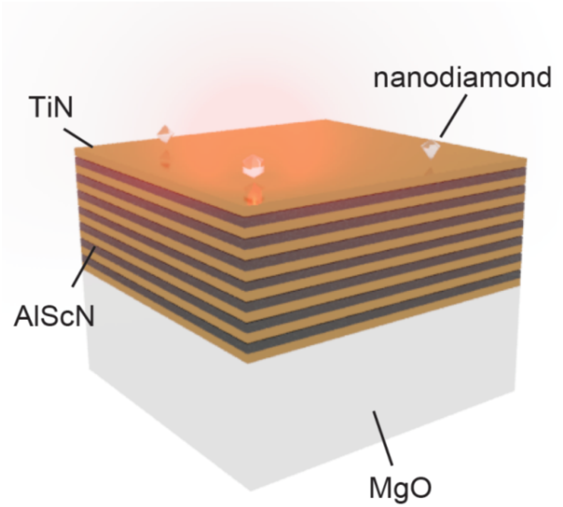
- Extremely high broadband photonic density of states
- 1st epitaxial single crystalline metal/semiconductor superlattice
- CMOS-compatible

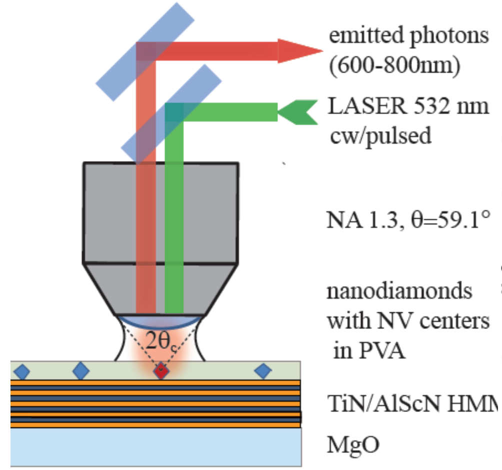
Naik, et al, PNAS (2014)

Single NV centers coupled to TiN HMM

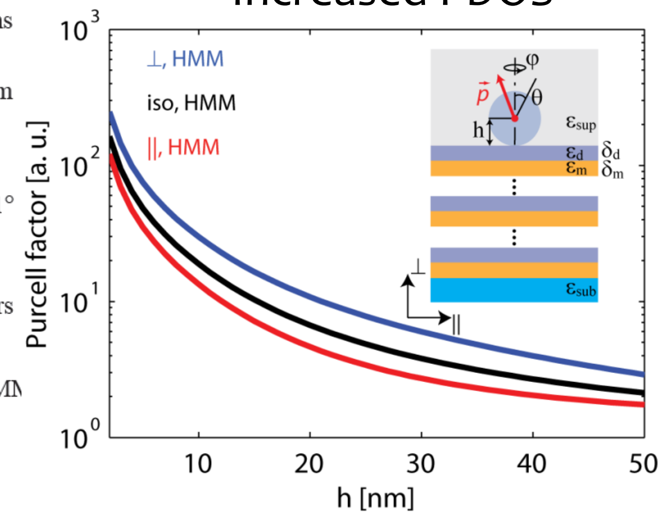
PURDUE UNIVERSITY

C-PHOM Center for Photonic and Multiscale Nanomaterials

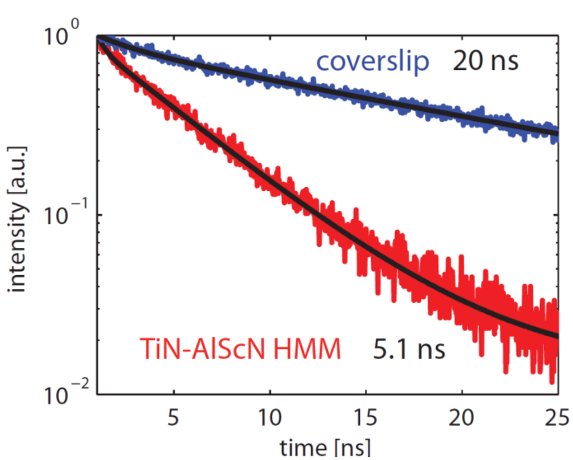




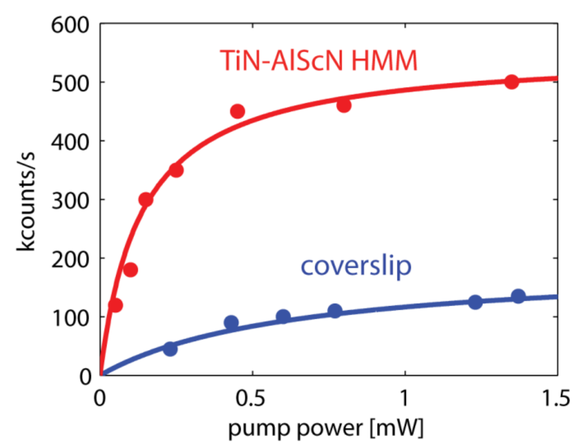
Increased PDOS



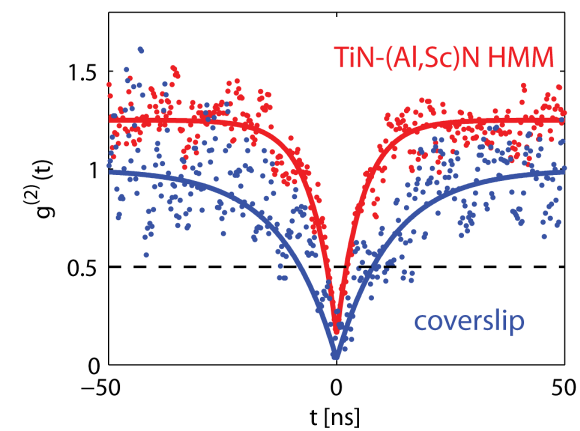
Fluorescence lifetime



Collected emission rate



Photon anti-bunching statistics



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

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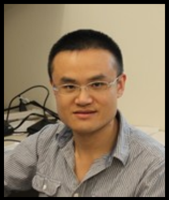
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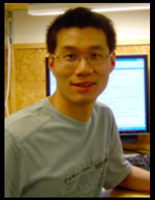
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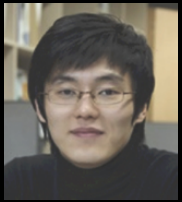
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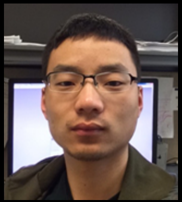
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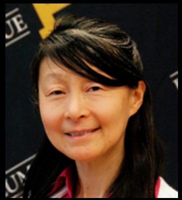
Sajid Choudhury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- Prof. A. Alu (UTexas Austin)
- Prof. M. Ferrera (Heriot-Watt)

Former members

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- Dr. N. Emani (DSI Singapore)

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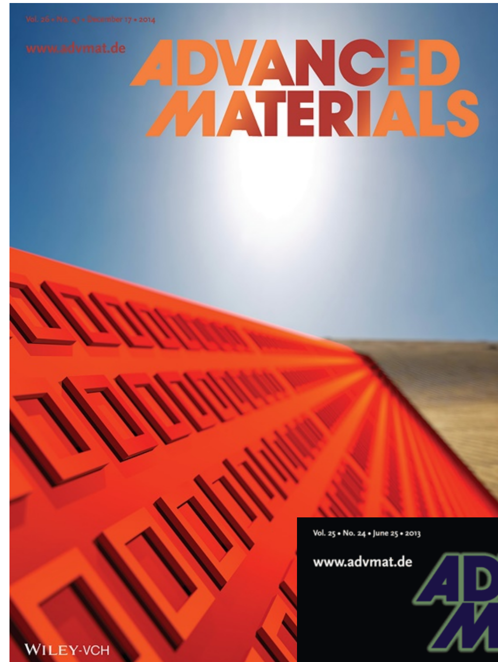

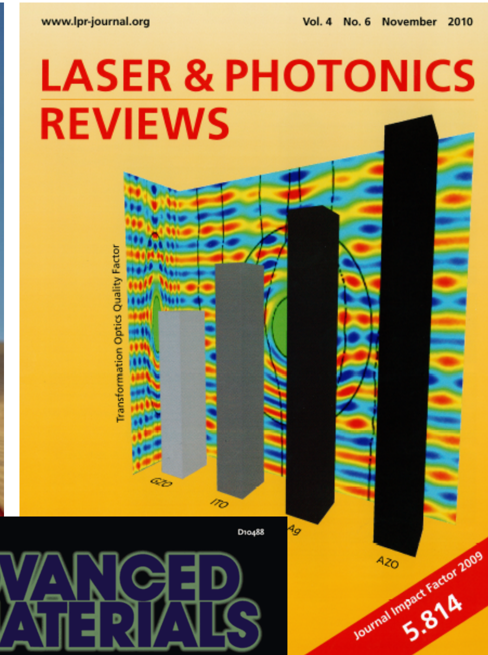

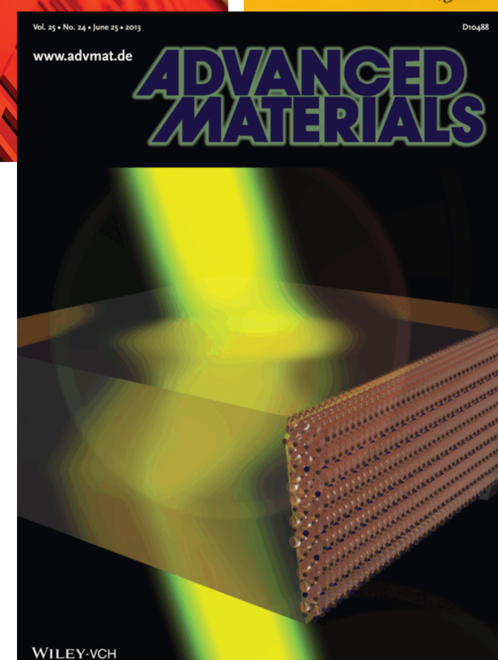

THANK YOU!

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MATERIALS SCIENCE

Low-Loss Plasmonic Metamaterials

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