On-Chip Quantum Nanophotonics: Challenges and Perspectives

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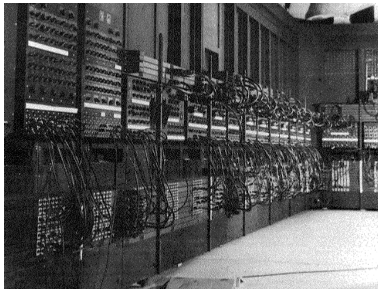
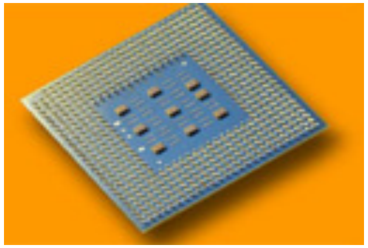
WHY QUANTUM PHOTONICS?

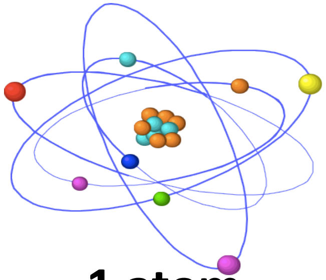
NEXT TECHNOLOGY REVOLUTION is going to be QUANTUM



ENIAC (1947)

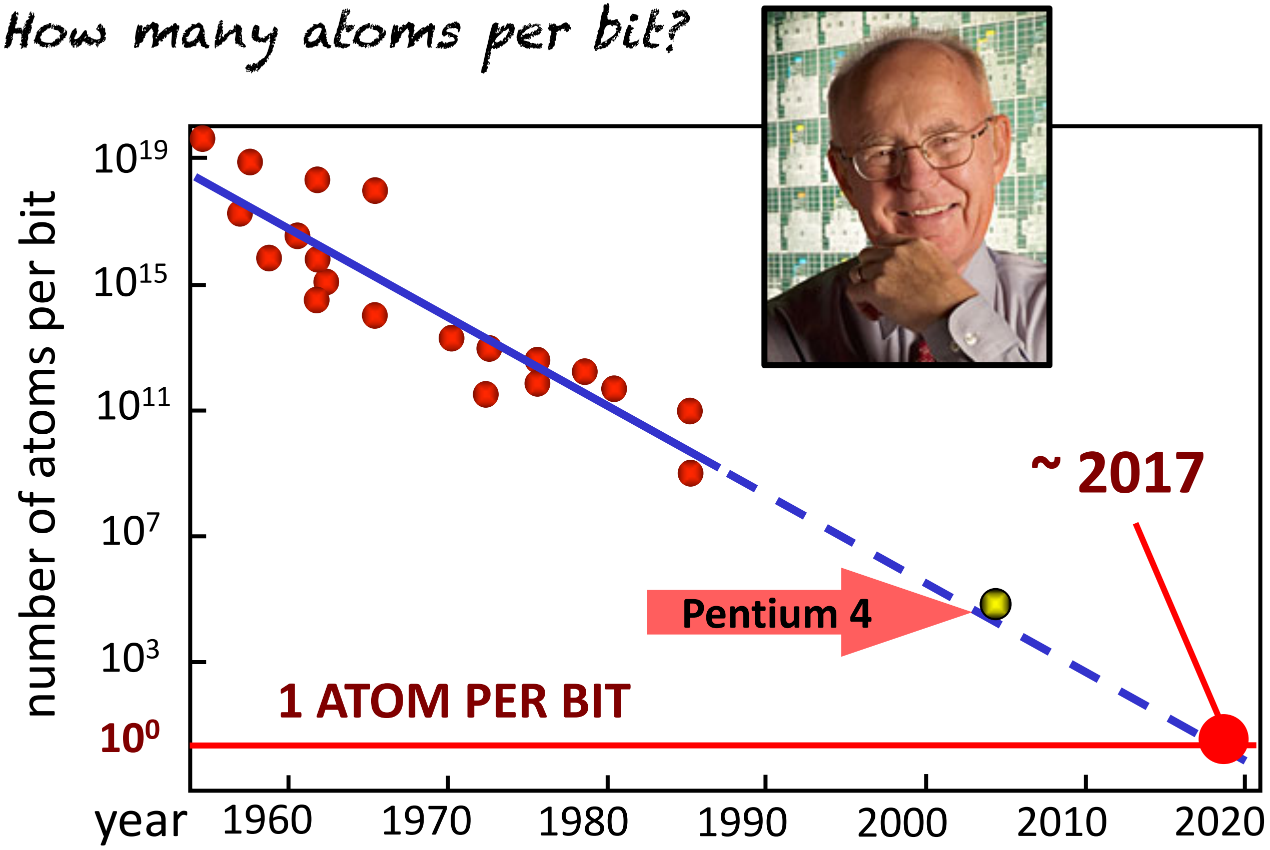


Pentium 4 (2002)



1 atom

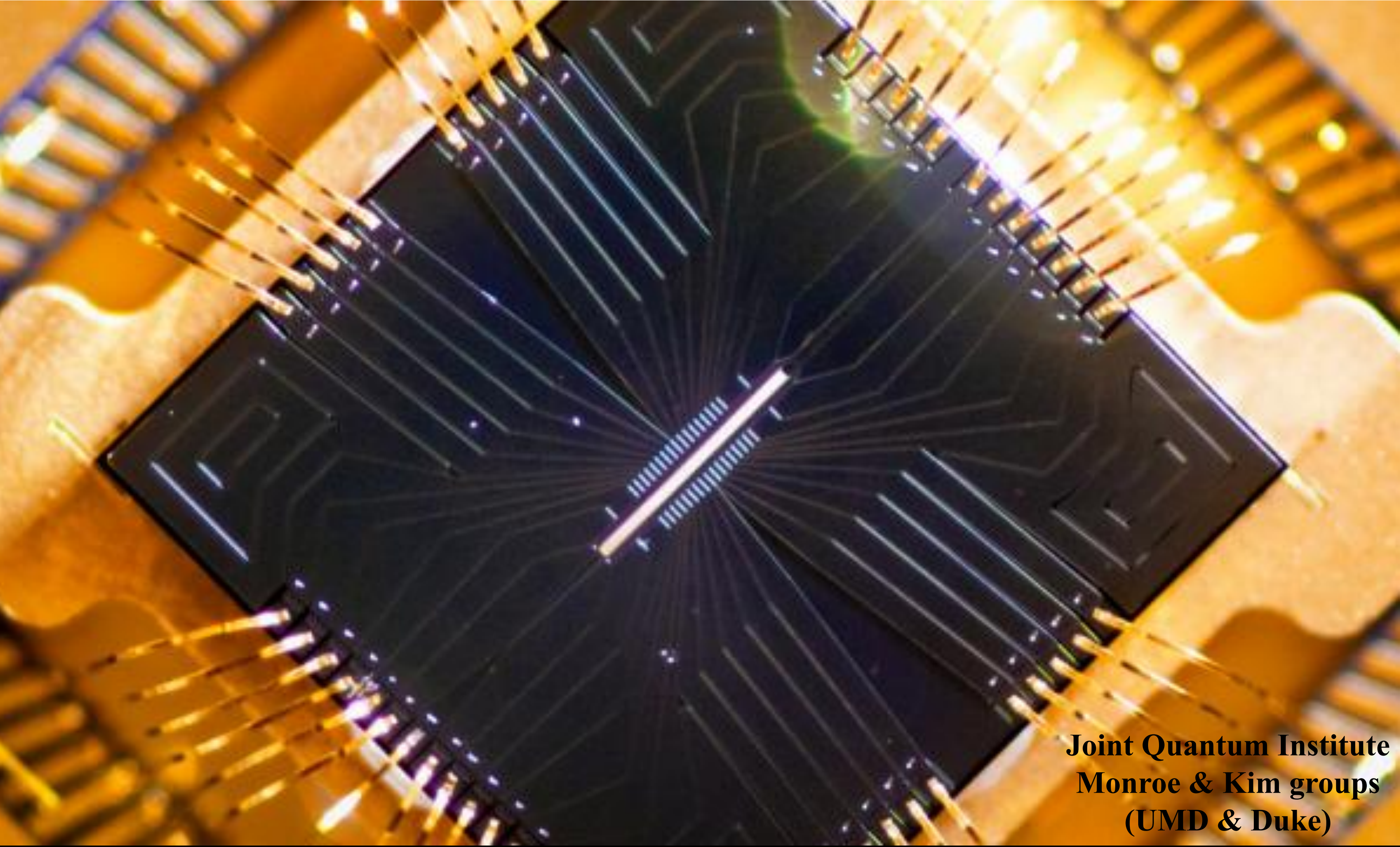
How many atoms per bit?



FASTER + SMALLER ->
Quantum PHOTONICS

R. W. Keyes, IBM J. R&D 32, 26 (1988)

Modern quantum information processing

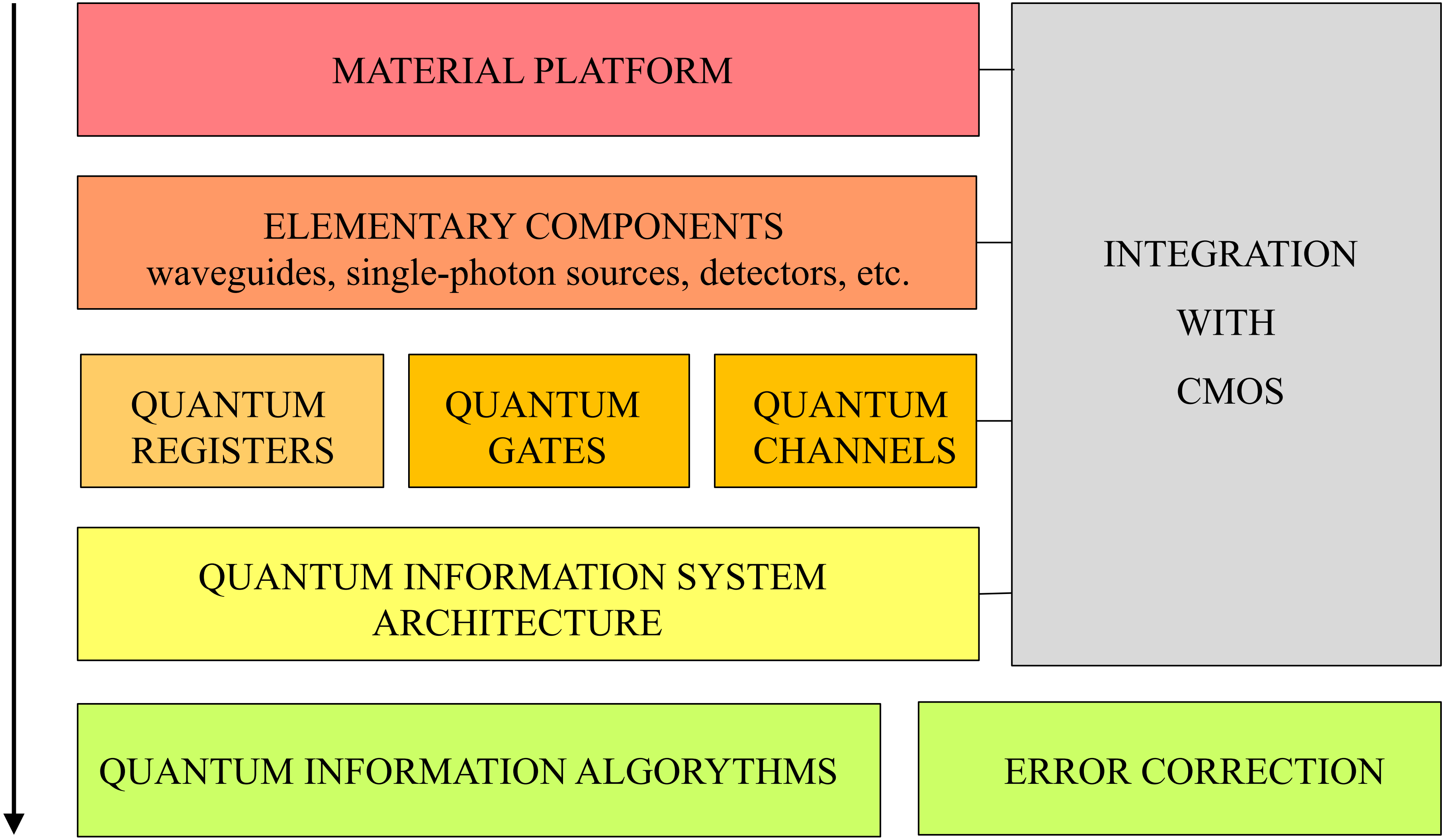


Joint Quantum Institute
Monroe & Kim groups
(UMD & Duke)

Infrastructure for quantum information processing

Memory/Qubit/Gate	**Information channel**	**RT**	**On-chip**
Photon	Dielectric WG	Yes	Yes
Superconductor	Transmission line	No	Yes
Single ion	Free-space optics	No	No
Single atom	Free-space optics	No	No
Quantum dot	Dielectric WG	No	Yes
Topological qubits	Electric wire	No	Yes
Color center	Nanophotonic WG	Yes	Yes

Roadmap for an integrated quantum information system



MATERIAL PLATFORM

ELEMENTARY COMPONENTS
waveguides, single-photon sources, detectors, etc.

QUANTUM REGISTERS

QUANTUM GATES

QUANTUM CHANNELS

QUANTUM INFORMATION SYSTEM ARCHITECTURE

INTEGRATION WITH CMOS

QUANTUM INFORMATION ALGORYTHMS

ERROR CORRECTION

Outline

- Current material platforms for quantum photonics
- Hybrid material platforms for quantum nanophotonics:

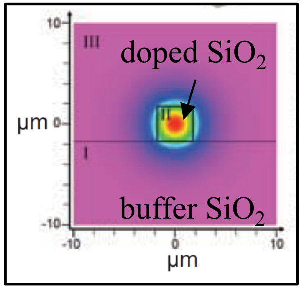
  color centers with ‘on demand’ properties combined with
  - Transition metal nitrides
  - Transparent conducting oxides
- Perspective quantum nanophotonic devices
  - Plasmonics/MM-enhanced single photon sources
  - Plasmonics/MM-enhanced quantum registers
- Integrated quantum information system
  - Outlook for large scale integration

Currently pursued material platforms with a potential for on-chip quantum photonics

Si/SiO_2

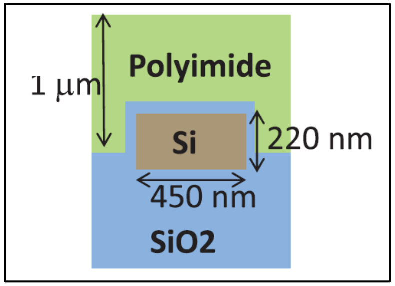
Material system

SiO_2 on Si



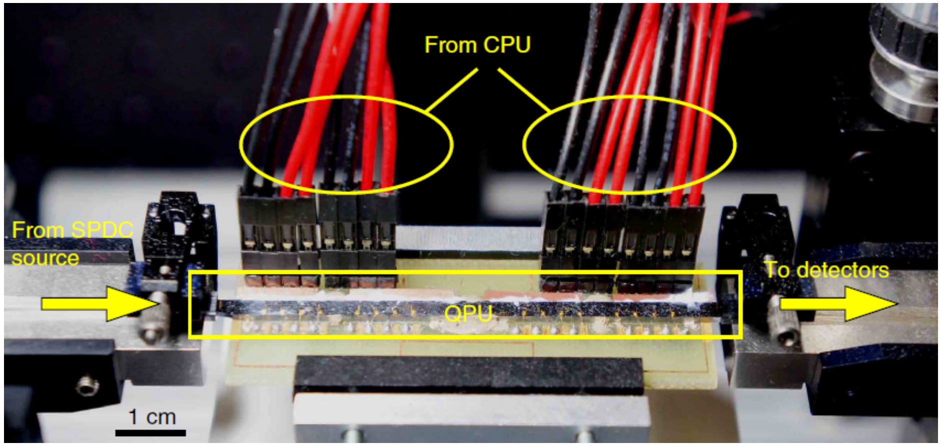
Politi et al., *Science* (2008)
(O'Brien, Bristol)

SOI



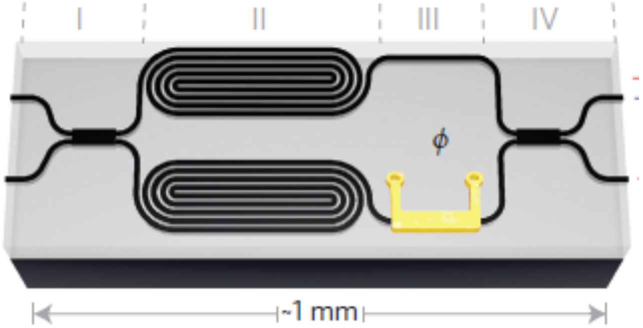
Bonneau et al., *NJP* (2012)
(O'Brien, Bristol)

Photonic quantum processor



Peruzzo et al., *Nat. Comm.* (2014)
(O'Brien, Bristol)

Quantum interference of single-photon sources



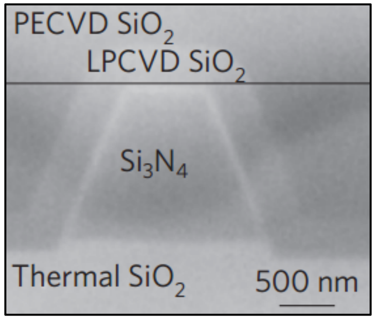
Silverstone et al., *Nat. Photon.* (2013)
(O'Brien, Bristol)

Advantages of the material system

- Tight photon confinement
- Strong $\chi^{(3)}$
- Easy fabrication and integration with CMOS

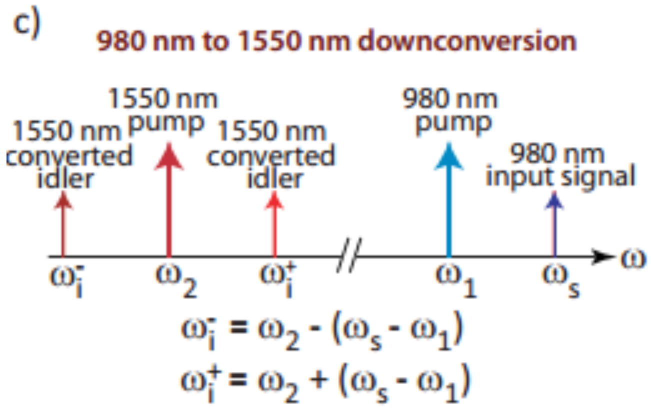
SiN_x/SiO_2

Material system



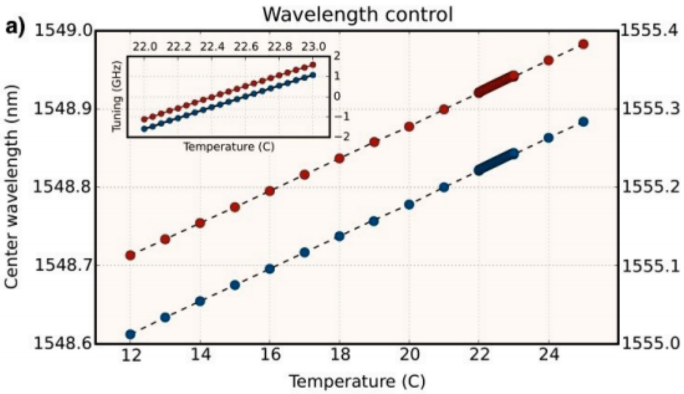
Levy et al., *Nat. Photon.* (2009)

Low noise quantum frequency conversion



Agha et al., *Opt. Exp.* (2013)
(Srinivasan, NIST MD)

Source of tunable narrowband (30MHz) entangled photons



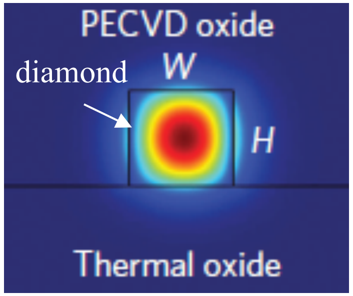
Ramelow et al., *Arxiv.* (2015) (Gaeta, Columbia)

Advantages of the material system

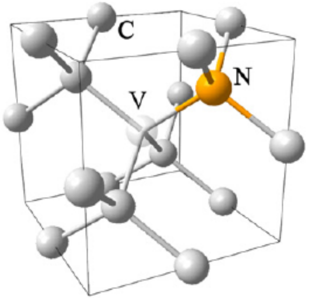
- Strong $\chi^{(3)}$
- High operation bandwidth
- Low thermal expansion

Diamond/SiO$_2$

Material system

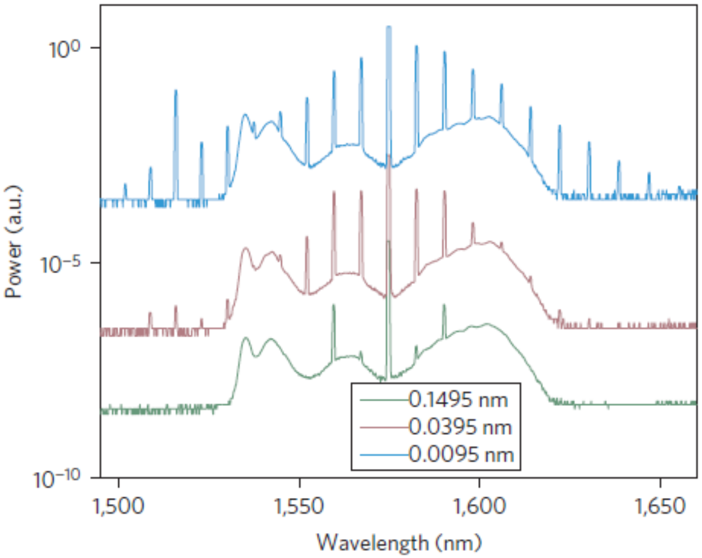


Hausmann et al.,
Nat. Photon. (2014)
(Loncar, Harvard)



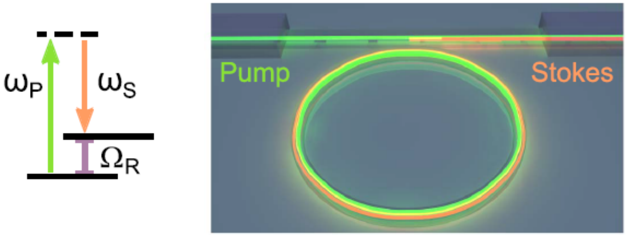
Aharonovich et al.,
Rep. Prog. Phys. (2011)
(Prawer, Melbourne)

Frequency comb generation



Hausmann et al., *Nat. Photon.* (2015) (Loncar, Harvard)

On-chip Raman laser

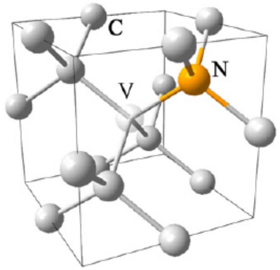


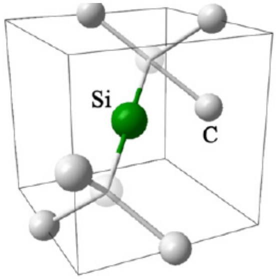
Latawiec et al., *Optica,* (2015) (Loncar, Harvard)

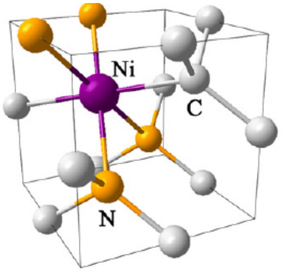
Advantages of the material system

- High transparency in telecom and visible
- Tight photon confinement
- Available color centers

Diamond color centers

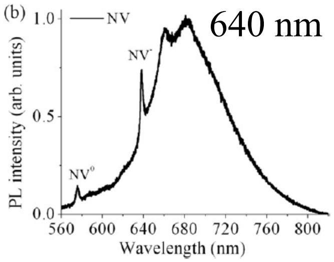




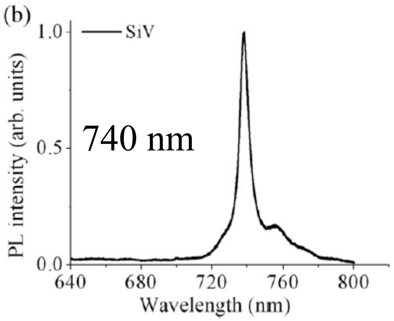


Cr?

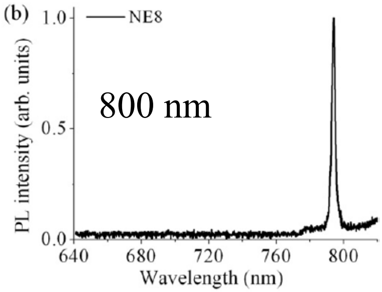
GeV?



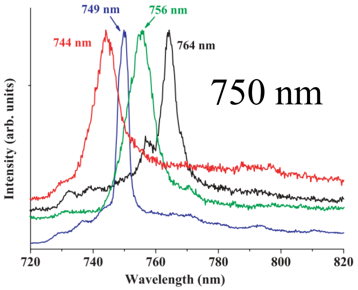
640 nm



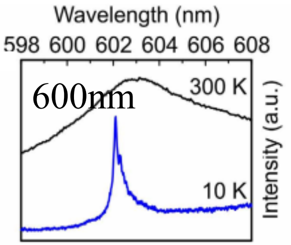
740 nm



800 nm



750 nm



600nm

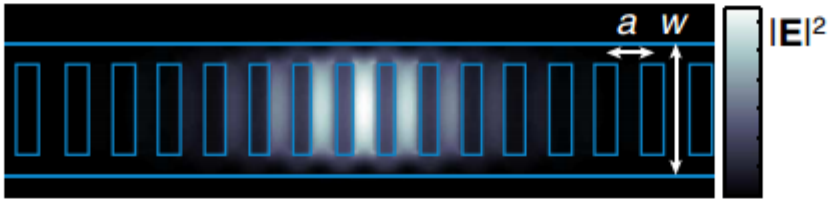
Aharonovich et al,
Rep. Prog. Phys. (2011)
(Prawer, Melbourne)

Aharonovich et al,
PRB. (2010)
(Prawer, Melbourne)

Iwasaki et al,
Sci. Rep. (2015)
(Hatano, Tokyo)

Reproducible

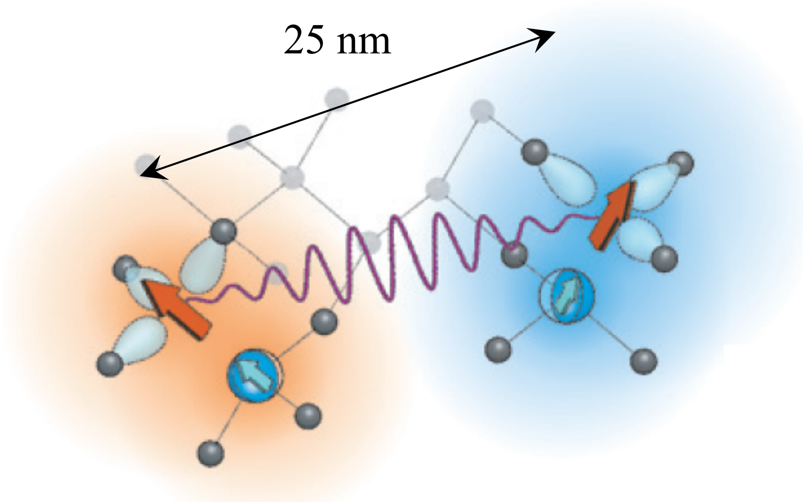
Integration into diamond photonic crystals

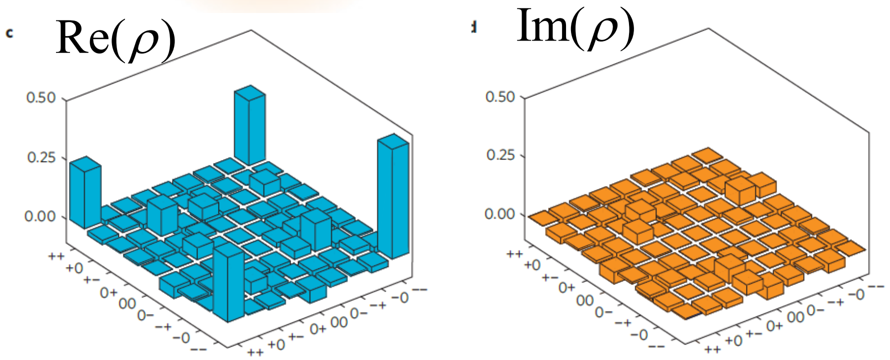


Li et al, *Nat. Comm.* (2014) (Englund, MIT)

Color centers for deterministic QIP

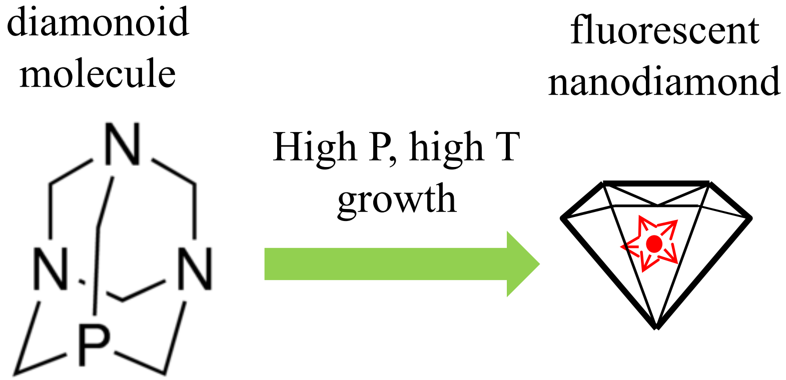
RT entanglement of proximal NVs





Dolde et al. Nat. Phys. (2013)
(Wrachtrup, Stuttgart)

Color centers on demand

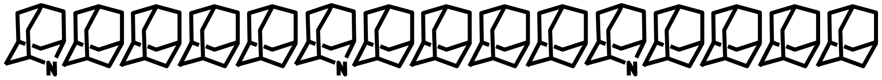


diamonoid molecule

High P, high T growth

fluorescent nanodiamond

Make polymer



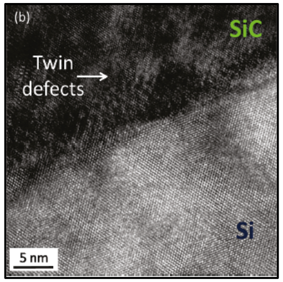
Use as diamond seed to get
near-deterministic array of NVs

Hemmer group, TAMU

SiC/Si

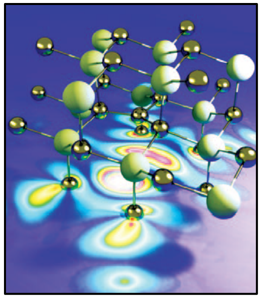
Material system

SiC on Si



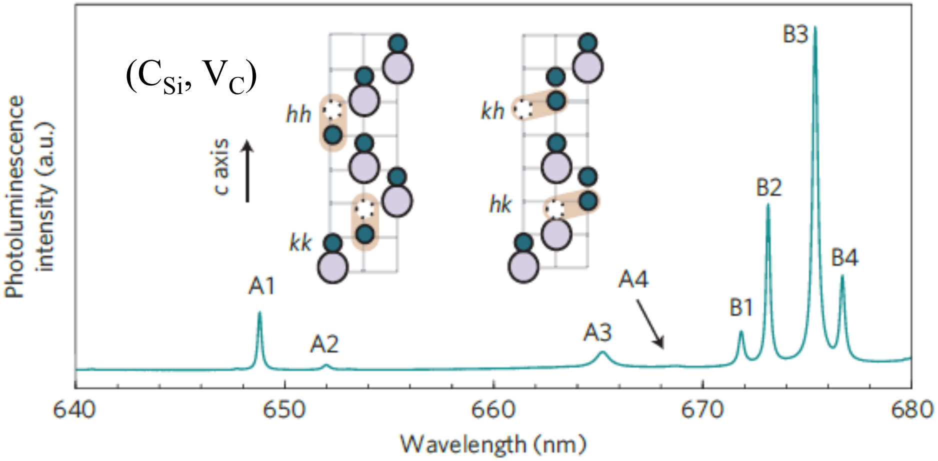
Lien et al.,
Cryst. Gr. & Des. (2010)
(Maboudian, Berkeley)

Color defects



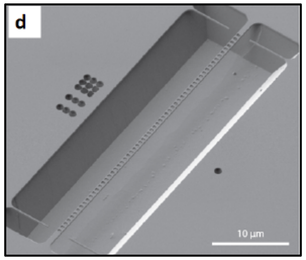
Boretti et al.,
Nat. Photon. (2014)
(Melbourne)

Single-photon defects

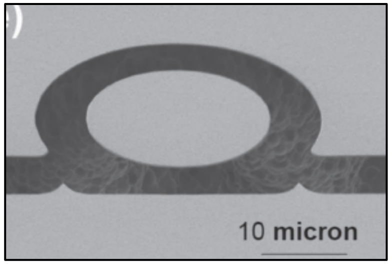


Casteletto et al., *Nat. Mater.* (2013)
(Melbourne)

Monolithic photonic fabrication



Lee et al., *APL* (2015)
(Lin, Rochester)



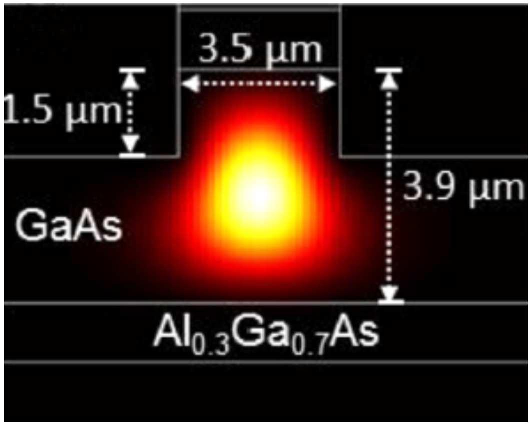
Lu et al., *Opt. Lett.* (2013)
(Lin, Rochester)

Advantages of the material system

- Bright color centers (SPS with rate 2Mcps)
- Low optical losses
- High refractive index
- Can be *p* and *n* doped

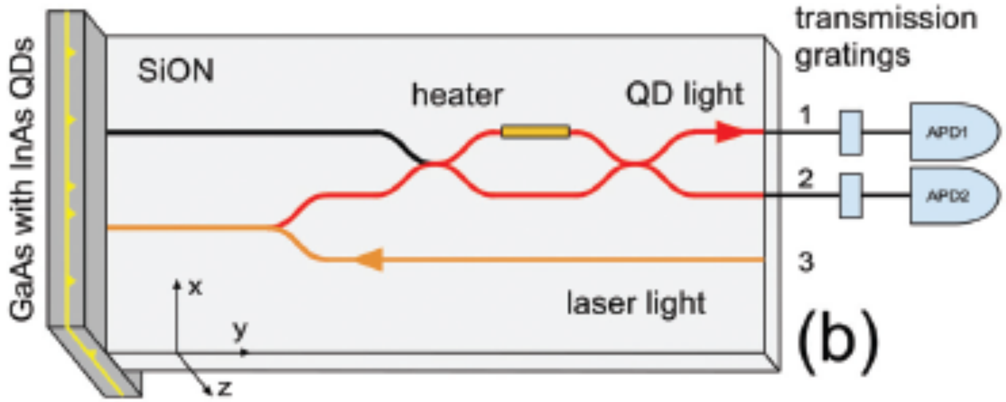
Other material systems

GaAs



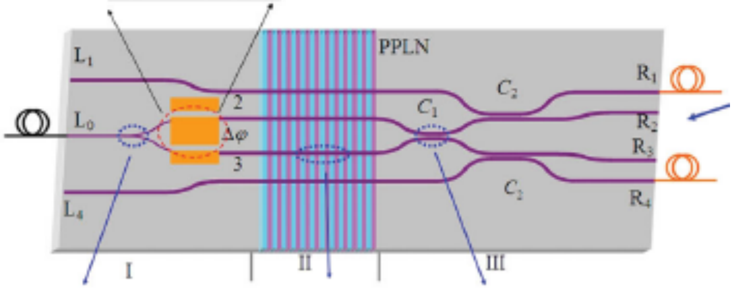
Wang et al., *Opt. Comm.* (2014)
(Thompson, Bristol)

GaAs/SiON/SiO$_2$



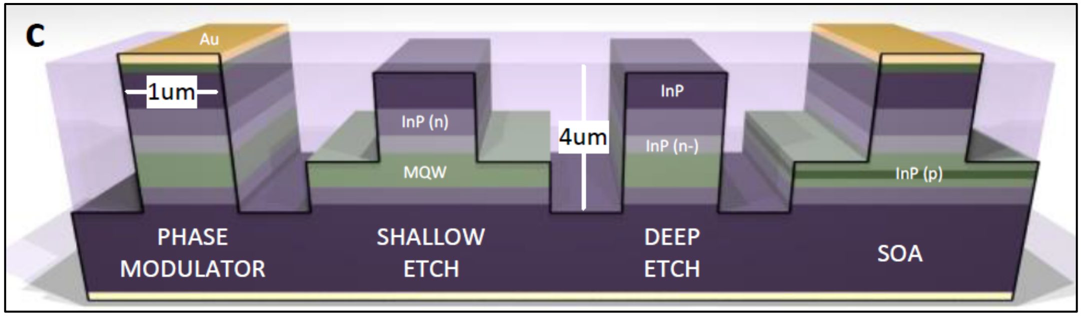
Murray et al., *APL* (2015)
(Shields, Cambridge)

LN/PPLN



Jin et al., *PRL* (2014) (Zhu, Nanjing)

InP



Sibson et al., *Arxiv* (2015)
(Thompson, Bristol)

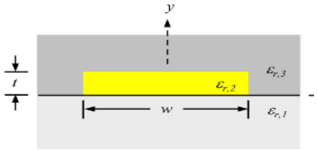
Hybrid material platform for quantum nanophotonics

Alternative Plasmonic Materials
for
Controlling/Enhancing Quantum Properties

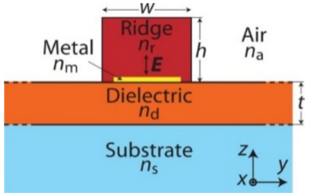
Advantages of Plasmonics

Can Plasmonics be Useful for Quantum Photonics?

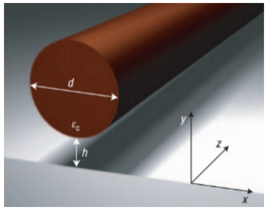
- Active devices compact length
  - Low energy consumption (fJ/bit)
- Coupling to other plasmonic devices
  - Innate compatibility of evanescent mode profiles
- Metal serves dual purpose
  - Reduces overall chip complexity
- Enormous sensitivity to surface
  - Single molecule sensors
- Reduced fabrication complexity
  - Patterning ultra-thin layers
- Polarization purity
  - Feedback systems
- *Would like to utilize CMOS-c materials*



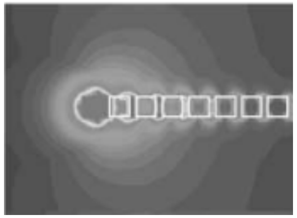
P. Berini et al., Adv. Opt. Photon., 2009.



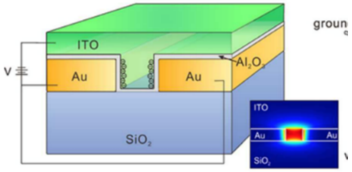
V. Volkov, et al, Opt. Lett., 2011. (Bozhevolnyi Group)



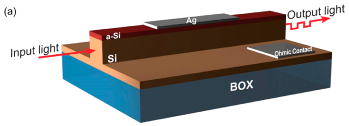
R. Oulton, et al, Nat. Photon., 2008. (Zhang Group)



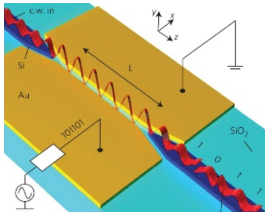
S. Maier et al., Nat. Mater. 2, 2003.



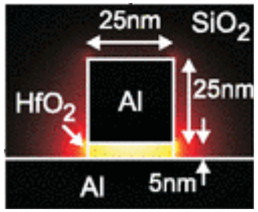
H. Lee et al, Nano Lett. 14(11), 2014 (Atwater Group)



A. Emboras et al., Nano. Lett. 13, 2013. (Levy Group)



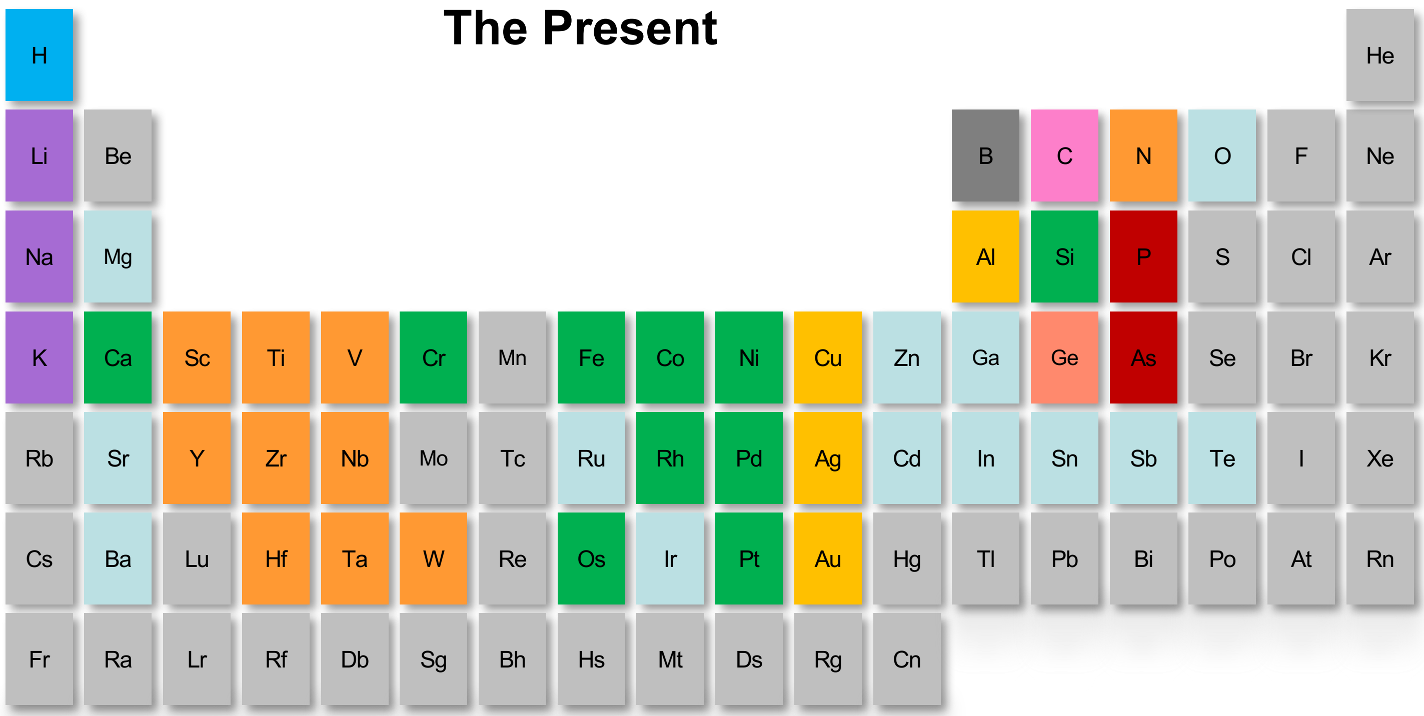
A. Melikyan et al, Nat. Photon. 8, 2014 (Leuthold Group)



A. V. Krasavin & A. V. Zayats, Phys. Rev. Lett. 109, 2012.

Alternative Plasmonic Materials

The Present



H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn						

TiN, TiAlN, Zr_xN_y, HfN, ScN, TaN, YN, VN, NbN, Cu_3N, WN

SnO_2, In:SnO_2, ZnO, Ga:ZnO, Al:ZnO, InGa:ZnO, CdO, $CdSb_2O_6$, In_2O_3, $GaInO_6$, $MgIn_2O_4$, TiO_2, $SrTiO_3$, $SrSnO_3$, Cd_3TeO_6, $BaSnO_3$, $SrGeO_3$, IrO_2, VO_2, RuO_2

$CoSi_2$, $CrSi_2$, $FeSi_2$, $HfSi_2$, $IrSi_2$, $NbSi_2$, Ni_xSi_x, Os_2Si_3, Pt_2Si, Pd_2Si, $ReSi_2$, $RhSi_2$, Ru_2Si3, $TaSi_2$, $TiSi_2$, V_xSi_y, WSi_2, $ZrSi_2$, Ca_2Si, Mg_2Si

Ru_2Ge_3, Os_2Ge_3, $BaGe_3$, $SrGe_2$, Ca_2Ge, Mg_2Ge, $CrGe_2$

GaAs, AlGaAs, InGaAs, InP, AlInAs

Graphene

YH_2

Li, Na, K

MgB_2

Al, Cu, Ag, Au

See the works of M. Wegener, M. Blaber, M. Noginov, R. Soref, H. Giessen, O. Muskens, T. Sands, N. Zheludev, M. Polini

N. Kinsey et al, JOSA B **32**(1), 2015

Material Requirements

- 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

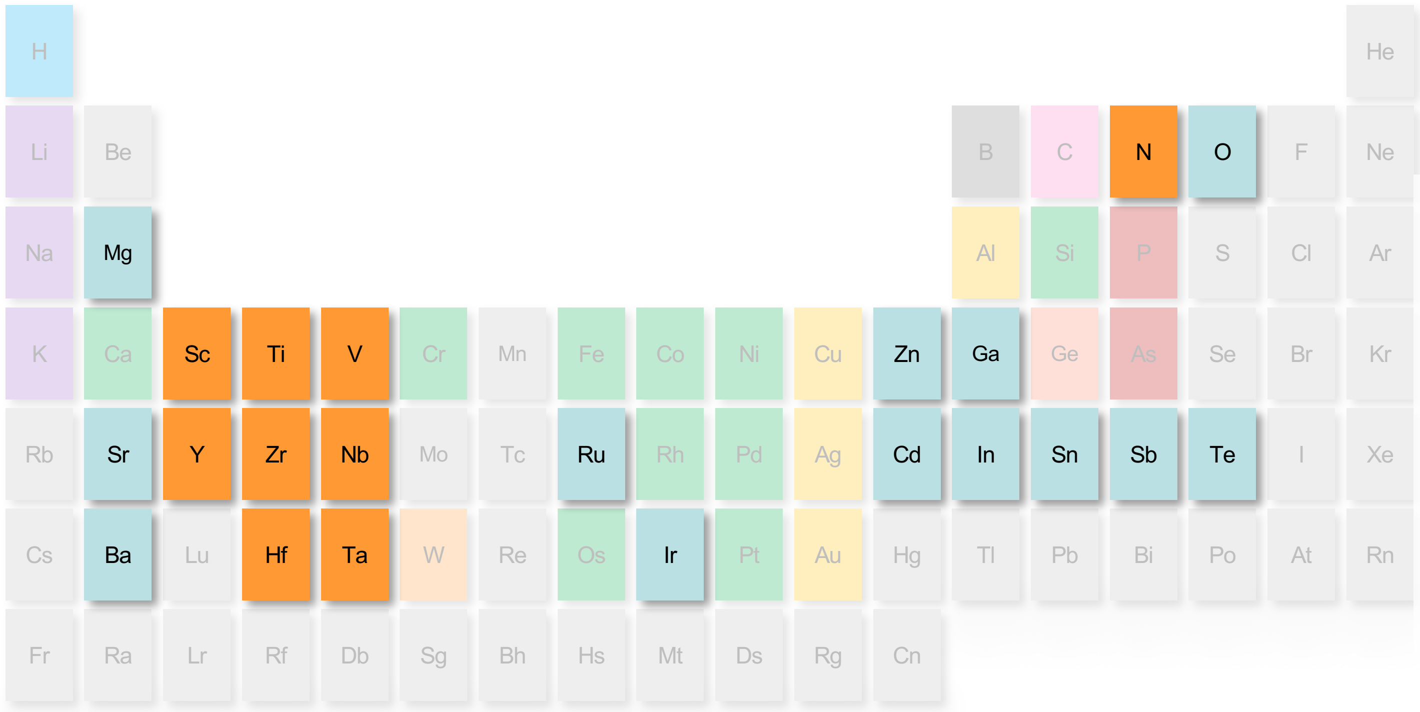
M. Ren *et al.*, *Adv. Mater.* 23 (2011) 5540; J.Y. Ou *et al.*, *Nano Lett.* 11 (2011) 2142 – Zheludev group
E. Feigenbaium *et* al., *Nano Lett.* 10 (2010) 2111 – Atwater group
Also work by M. Brongersma

- CMOS-compatible components

"Less-Metallic" Materials

- Metals: Too large carrier concentration *Metals are too metallic…*
  - Large plasma frequency (ω_P)
    - $\omega_p \propto \sqrt{N}$
    - N ~ 10^{22} cm^{-3} in metals
    - Large loss ($\varepsilon'' \alpha \omega_P^2$) + large magnitude of ε'
- Semiconductors → Quasi-Metals
  - Semiconductors: Doping can control carrier concentration
    - Conventional semiconductors: too low carrier concentration (dielectrics)
    - Doping density of $10^{21}cm^{-3}$ could produce $\varepsilon' < 0$ in NIR
- Metals → Dilute Metals
  - Lower carrier concentration in metals
    - Abstract electrons by non-metal inclusions
    - Non-stoichiometric: controllable properties

Alternative Materials



🟧 TiN, TiAlN, Zr_xN_y, HfN, ScN, TaN, YN, VN, NbN, Cu_3N, WN

🟦 SnO_2, In:SnO_2, ZnO, Ga:ZnO, Al:ZnO, InGa:ZnO, CdO, $CdSb_2O_6$, In_2O_3, $GaInO_6$, $MgIn_2O_4$, TiO_2, $SrTiO_3$, $SrSnO_3$, Cd_3TeO_6, $BaSnO_3$, $SrGeO_3$, IrO_2, VO_2, RuO_2

🟩 $CoSi_2$, $CrSi_2$, $FeSi_2$, $HfSi_2$, $IrSi_2$, $NbSi_2$, Ni_xSi_x, Os_2Si_3, Pt_2Si, Pd_2Si, $ReSi_2$, $RhSi_2$, Ru_2Si3, $TaSi_2$, $TiSi_2$, V_xSi_y, WSi_2, $ZrSi_2$, Ca_2Si, Mg_2Si

🟧 Ru_2Ge_3, Os_2Ge_3, $BaGe_3$, $SrGe_2$, Ca_2Ge, Mg_2Ge, $CrGe_2$

🟥 GaAs, AlGaAs, InGaAs, InP, AlInAs

🟪 Graphene

🟦 YH_2

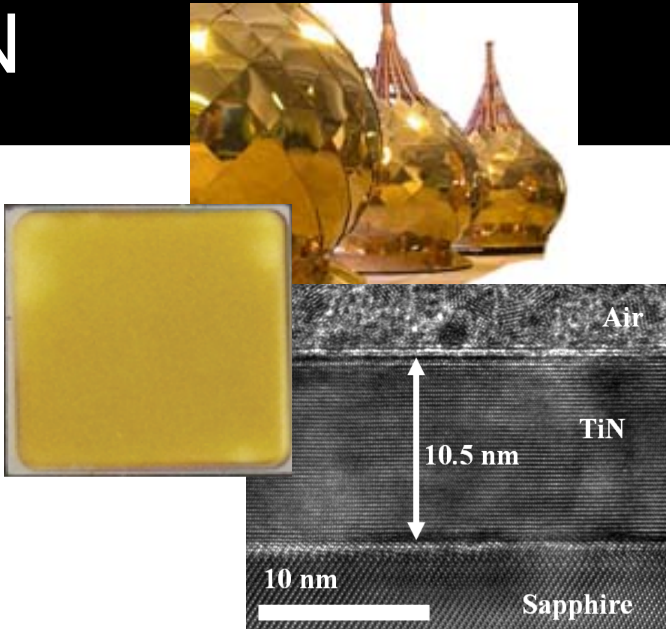
🟪 Li, Na, K

⬜ MgB_2

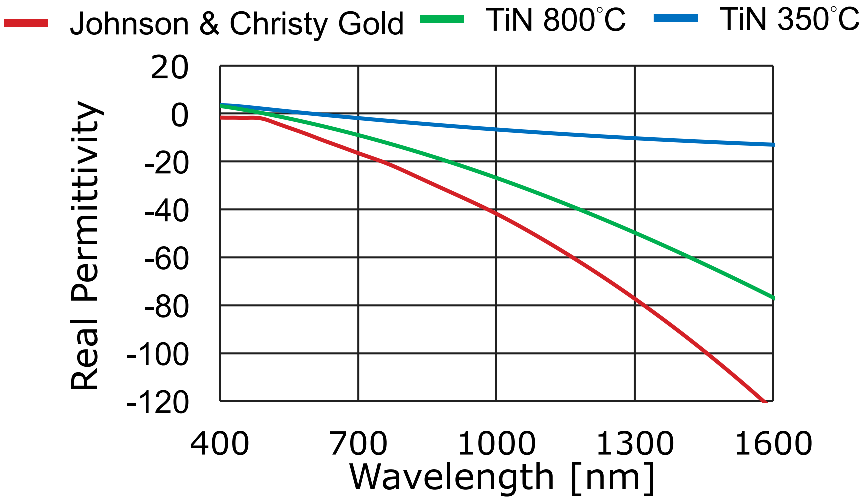
🟨 Al, Cu, Ag, Au

N. Kinsey et al, JOSA B **32**(1), 2015

Advantages of TiN

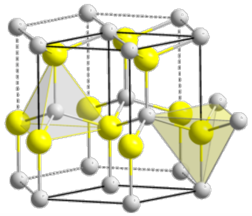


- Metallic/Plasmonic in visible
  - Golden Luster
- Grows epitaxial on silicon, c-sapphire, and MgO
  - Ultra-thin films down to 2 nm
- Nonstoichiometric = tunable properties
- Refractory (melting point 2900°C)
- Mechanically tough
- Chemically stable
- Copper/aluminum require a TiN diffusion barrier
- Biocompatible
- CMOS-compatible

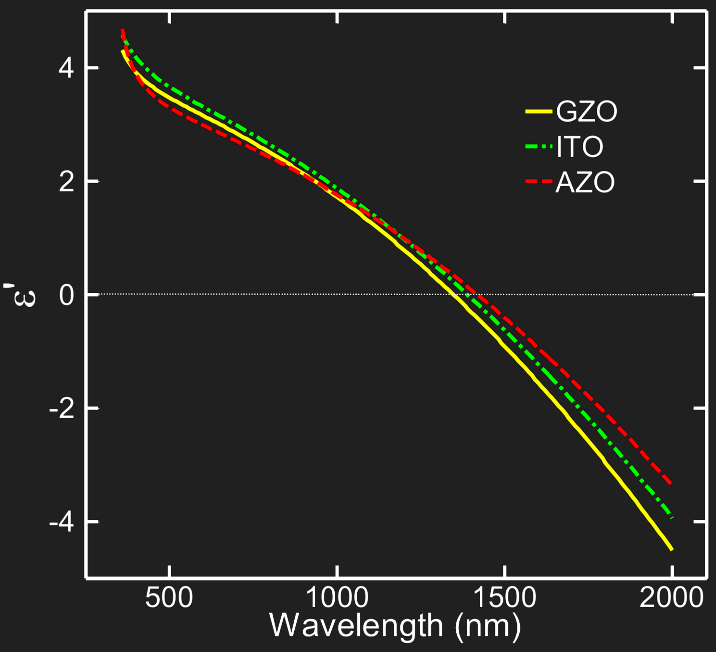


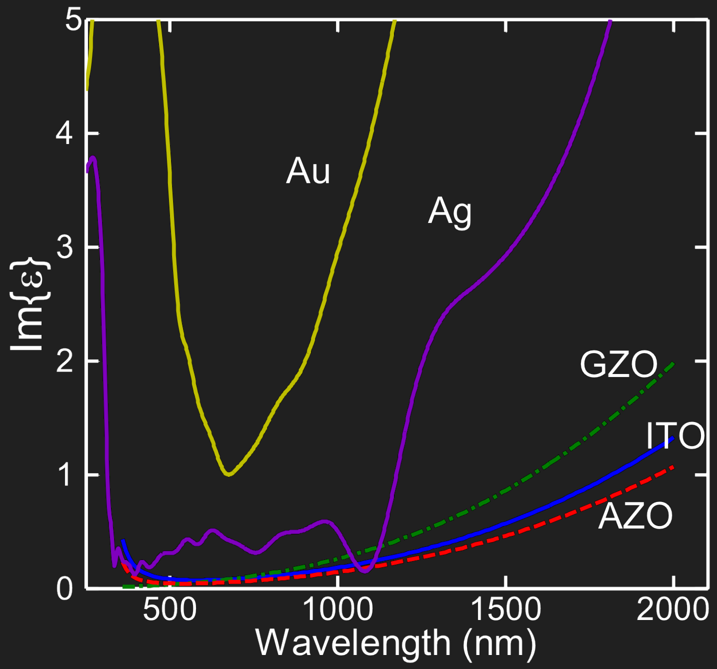
G.V. Naik et al, Adv. Mater. 25, 2013

Transparent Conducting Oxides



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





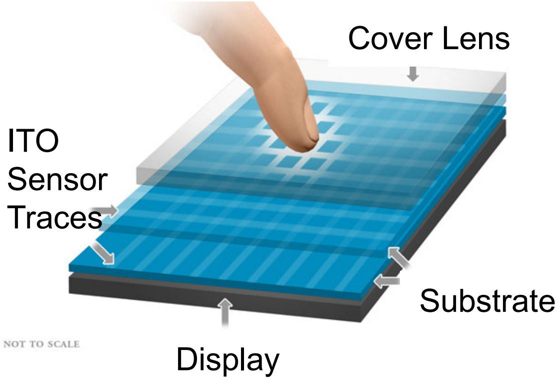
Also see works of:
O. L. Muskens
H. A. Atwater
M. A. Noginov
C. B. Murray
D. J. Milliron
V. J. Sorger
R. P. H. Chang
M. Wegener
S. Franzen
T. W. Odom
N.I. Zheludev
V. A. Podolskiy

AZO: Lowest Drude damping, Longest cross-over wavelength ($5x10^{20}$ 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)

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 at telecommunication wavelengths



ITO-based touch screens

IGZO-based highly resolved flexible screen

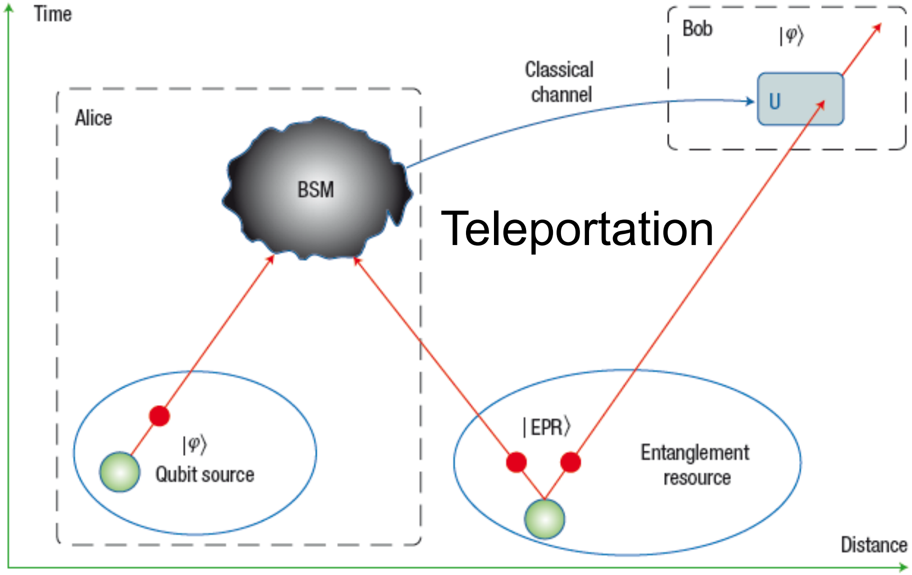
G.V. Naik et al, Opt. Mater. Express **1**(6), 2011

Plasmonics for Single Photon Sources

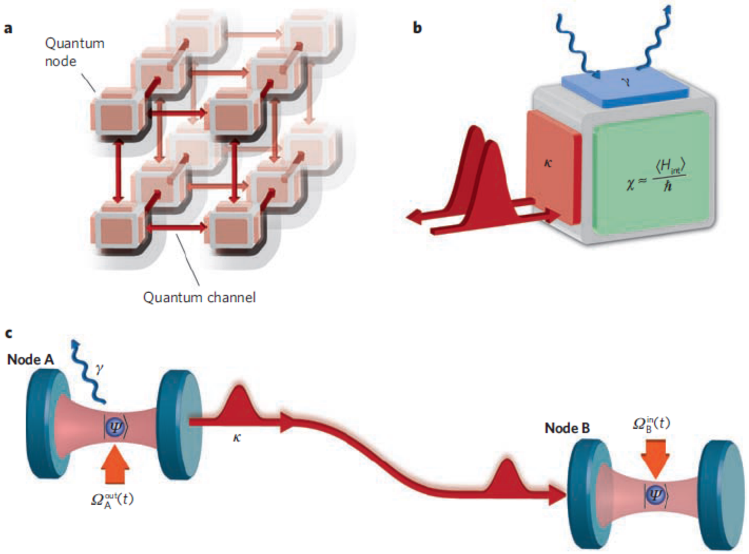
Single-photon source applications

Long-distance quantum key distribution

Transmission of quantum information



Teleportation



Gisin et al., *Nature* Photonics (2000)

Kimble et al., *Nature* (2006)

Single-photon sources

BASIC REQUIREMENTS

- On-demand (emits at time defined by user)
- Emits every time it is triggered (QE = 100%)
- Single-photon ($g^{(2)} = 0$)
- Indistinguishable photons
- Arbitrarily high repetition rate

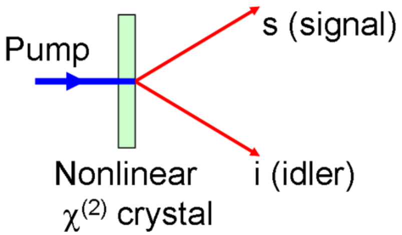
+

ADDITIONAL REQUIREMENTS

- Wavelength = telecom (1.5 or 1.3 μm)
- Operates on-chip
- Operates at room temperature

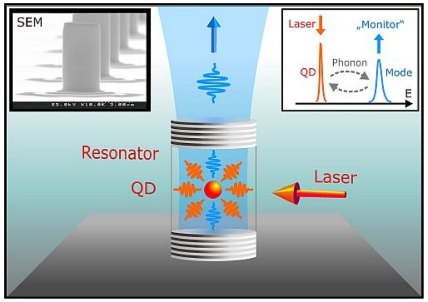
Existing single-photon sources

Nonlinear scattering



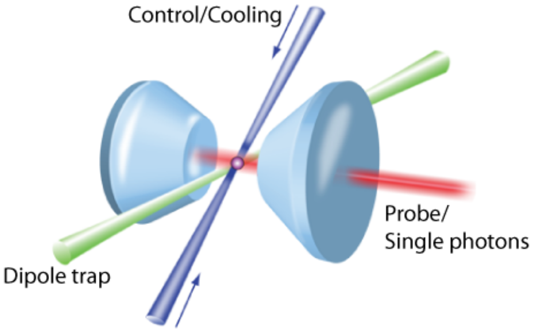
Source: Wikipedia

Quantum dots



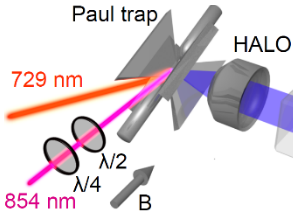
Source: IQST, Germany

Trapped atoms



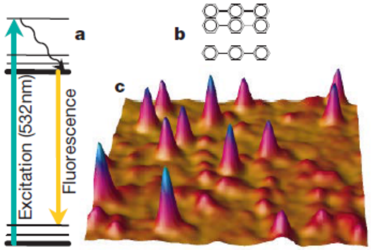
Source: Max Planck, Germany

Trapped ions



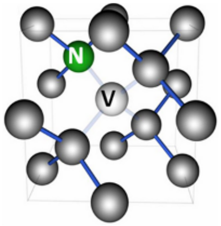
Source: QScale, Europe

Single molecules



Lounis et al., *Nature* (2000)

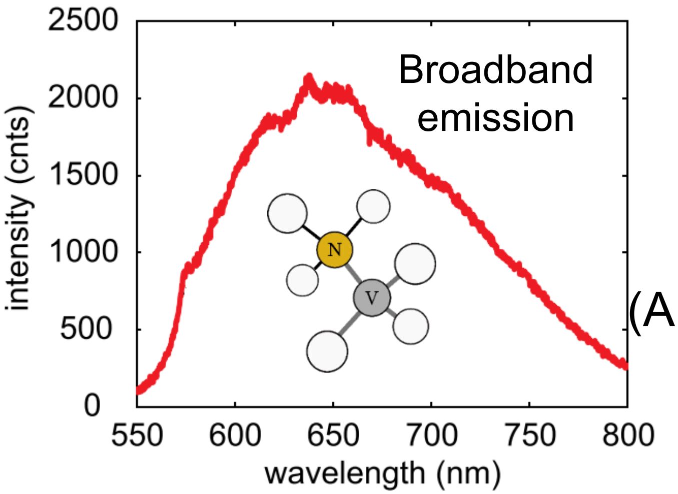
Color centers



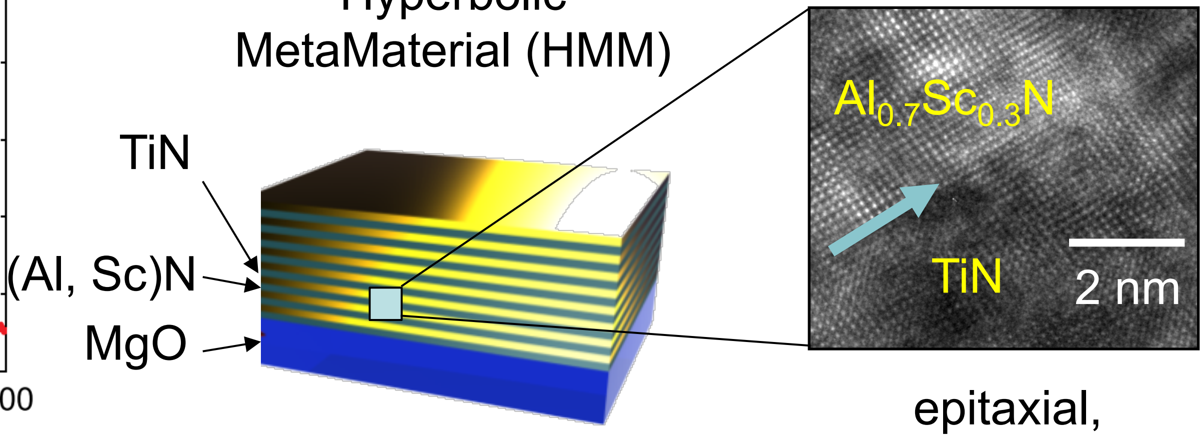
Jelezko et al., *Phys. Stat. Sol.* (2006)

HOLY GRAIL — On-demand single-photon source with ultrafast (1 THz) bit rate, RT operation, indistinguishable photons + conversion to telecom

CMOS-compatible hyperbolic metamaterial

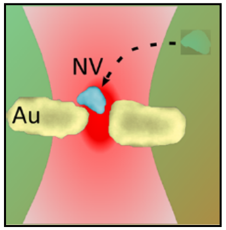


Hyperbolic MetaMaterial (HMM)



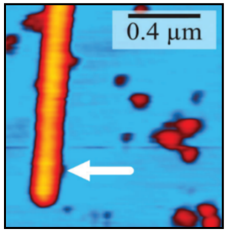
epitaxial, CMOS-compatible

Gap-antenna (gold)



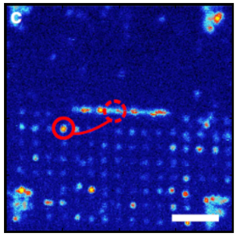
Geiselmann et al., *Nano Lett* (2014)

Nanowire (silver)



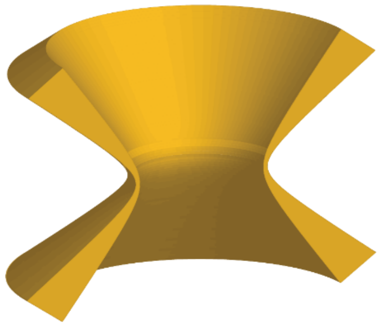
Huck et al., *PRL* (2011)

V-groove (gold)



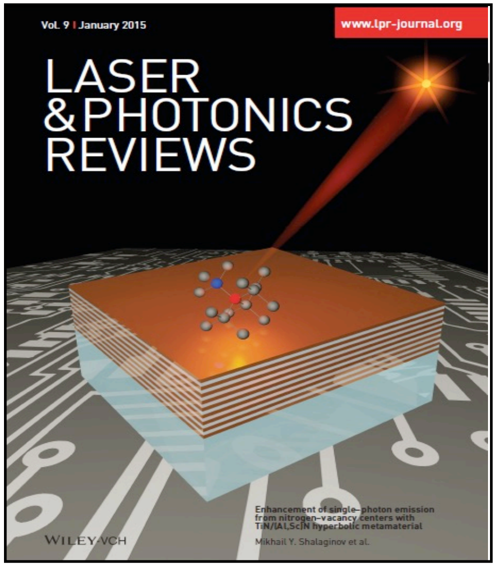
Bermudez-Urena et al., *Nat Comm* (2015)

HMM iso-frequency surface



$$DOS \implies \infty$$

Single NV centers coupled to CMOS-compatible HMM



Vol. 9 | January 2015

www.lpr-journal.org

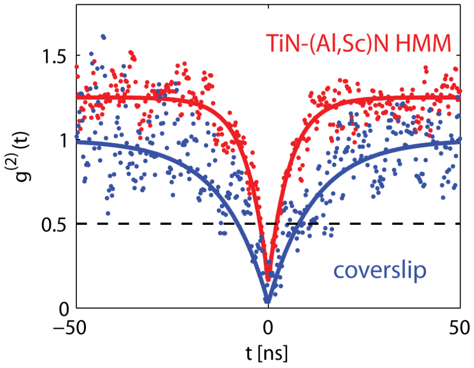
LASER & PHOTONICS REVIEWS

Enhancement of single-photon emission from nitrogen-vacancy centers with TiN/(Al,Sc)N hyperbolic metamaterial

Mikhail Y. Shalaginov et al.

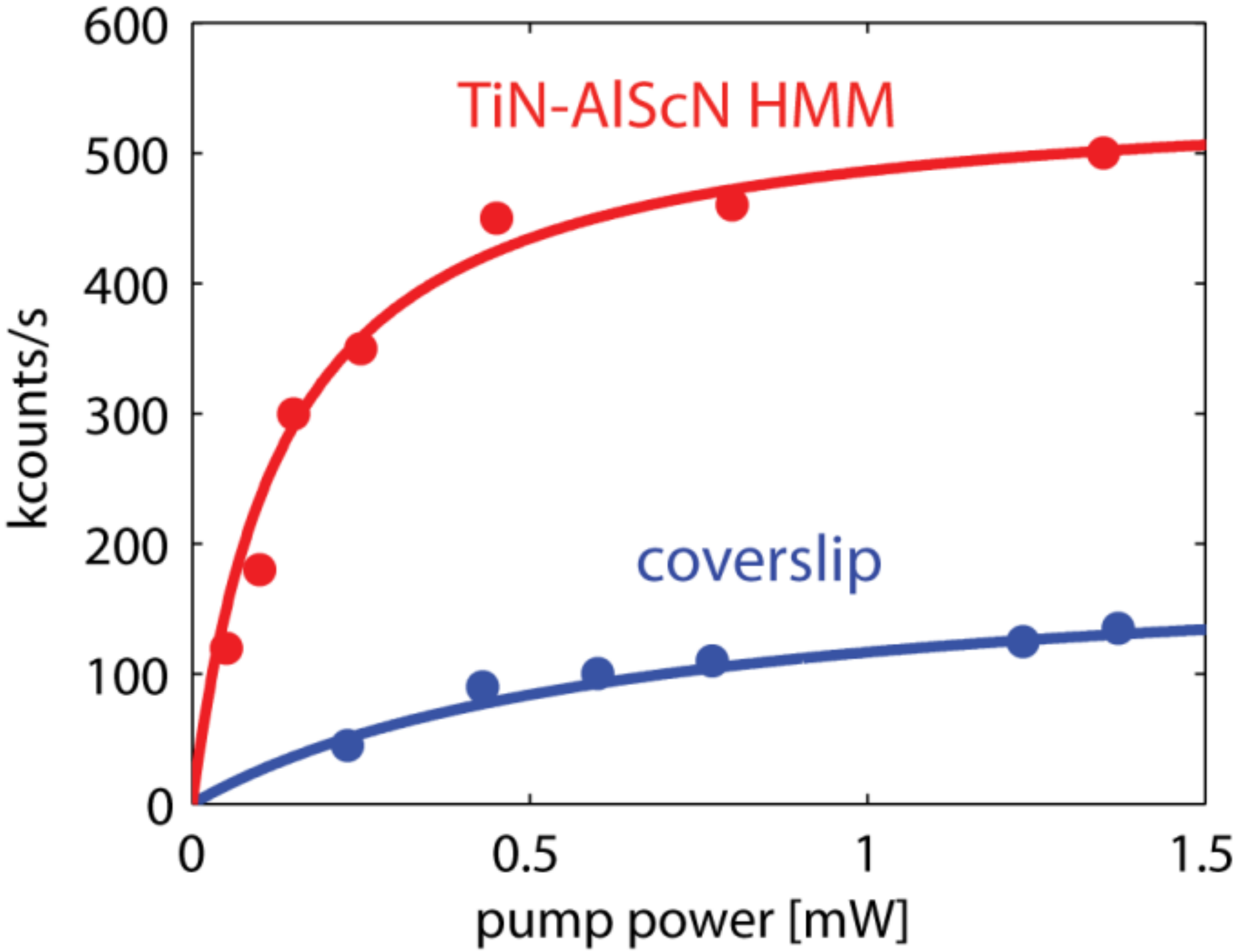
WILEY-VCH

Photon anti-bunching

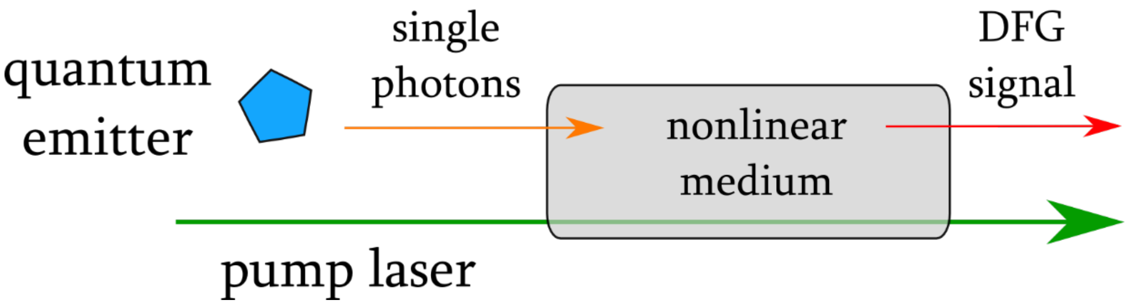


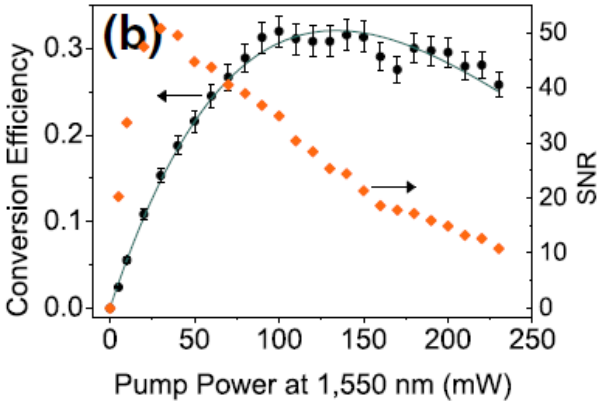
Shalaginov et al, *LPR* (2015)

Collected emission rate



Conversion of SPS to telecom range





Zaske et al., *PRL* (2012)

$$\omega_s = \omega_p + \omega_c$$

$$\omega_c > \omega_p$$

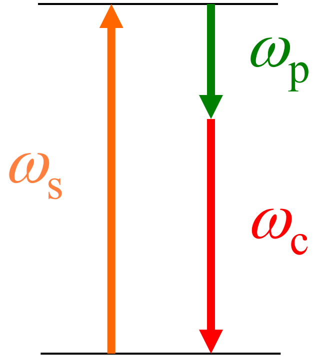
700 nm **Source**

=

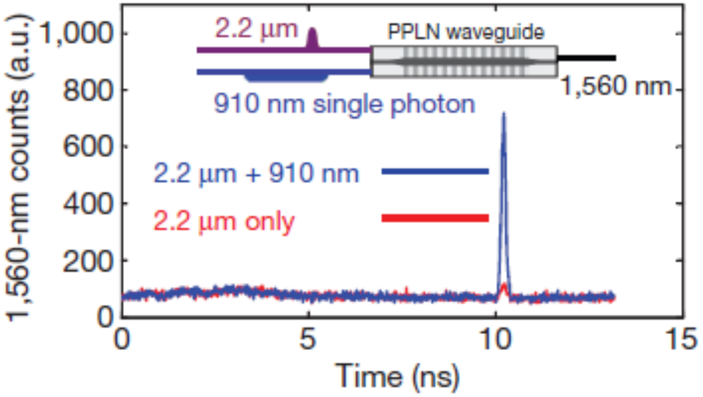
1.5 µm **Pump**

\+

1.3 µm **Converted**



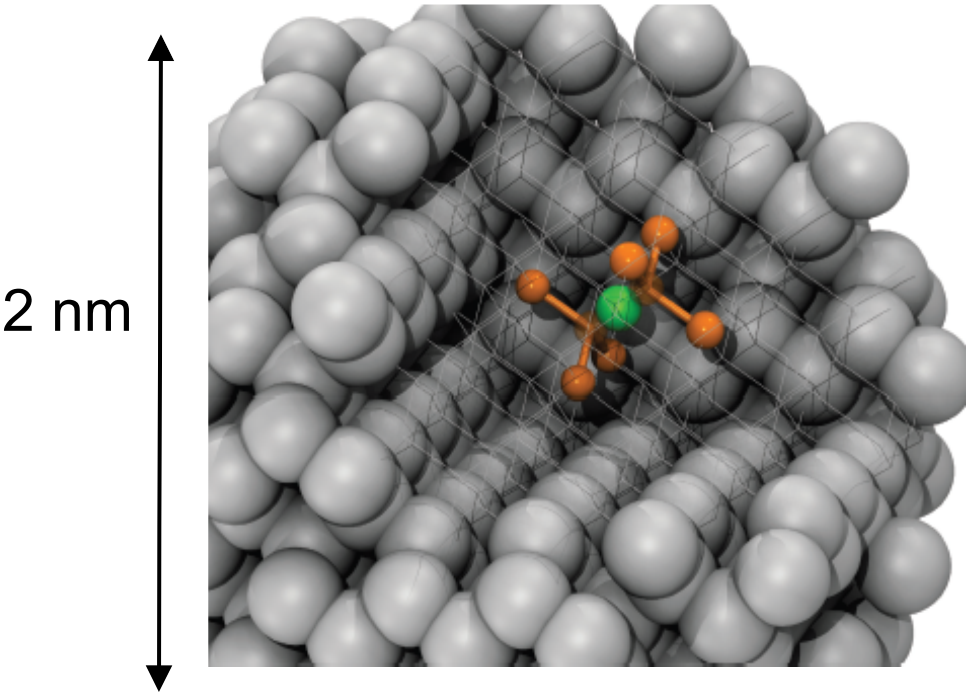
Kumar et al., *OL* (1990)
(Northwestern)



De Greve et al., *Nature* (2012)
(Yamamoto, Stanford)

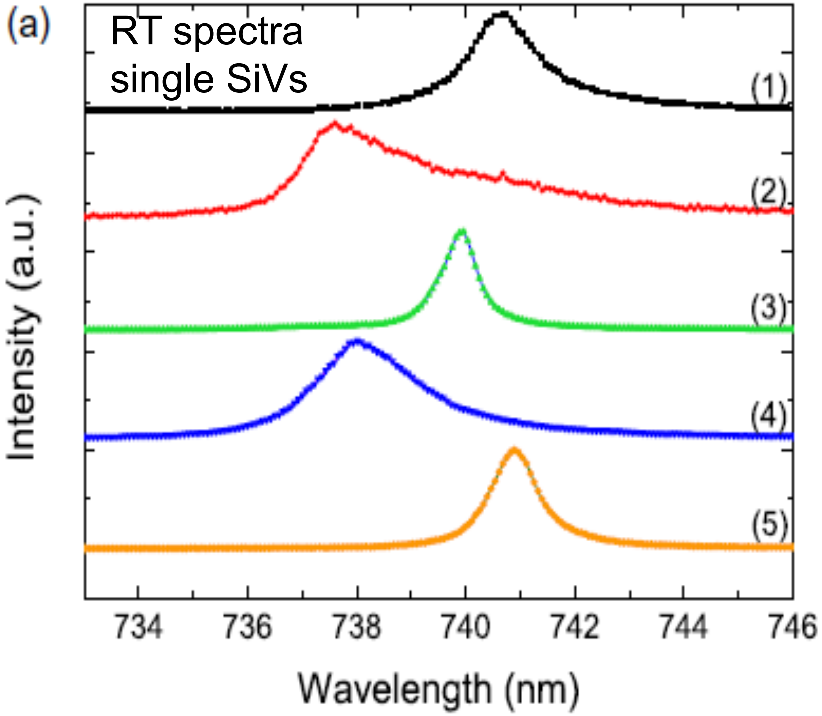
SiVs as single-photon source

Molecular-size nanodiamonds



Vlasov et al. *Nat Nano* (2014)
(Moscow)

Narrow linewidth ~ 1 nm



Neu et al. *NJP* (2011)
(Becher, Saarbrucken)

SiVs are robust to surface effects

Plasmonic cavity for ultrafast emission

Plasmonic cavity

High quality plasmonic materials

+

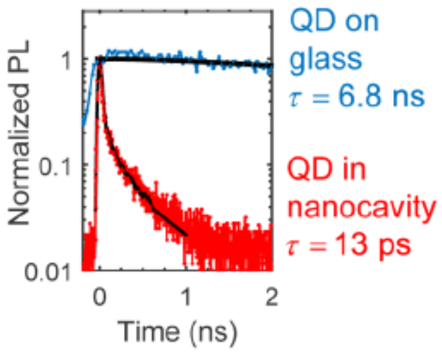
Gap plasmon cavity design

=

Ultrafast emission

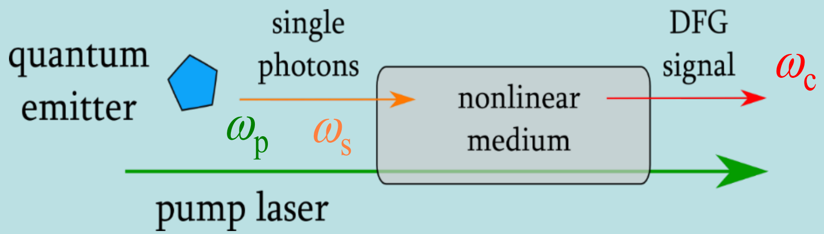
+

High quantum efficiency



Hoang, et al. *NL* (2015):
Quantum dots

Conversion to telecom with $\chi^{(2)}$



On-demand indistinguishable

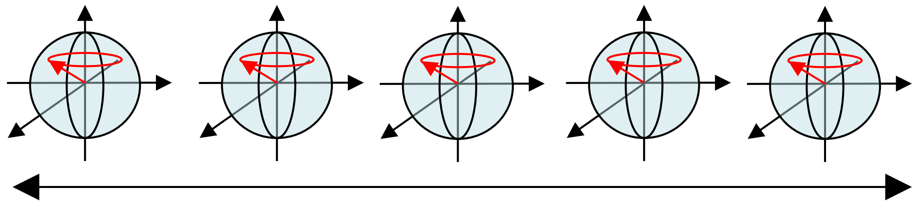
photons

on-chip

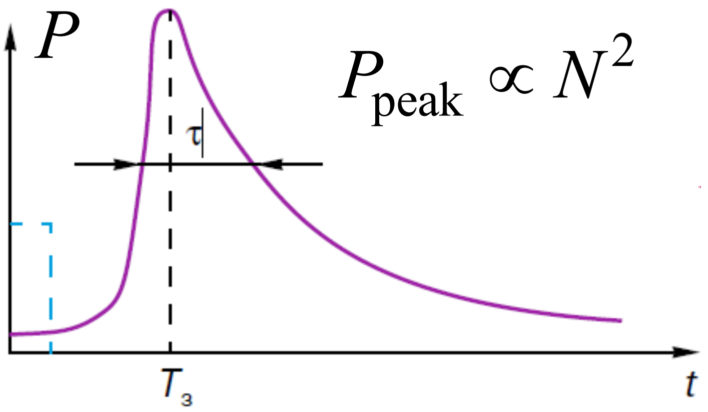
at room temperature?

Quantum dipoles and epsilon near zero materials

Superradiance: coherent spontaneous emission



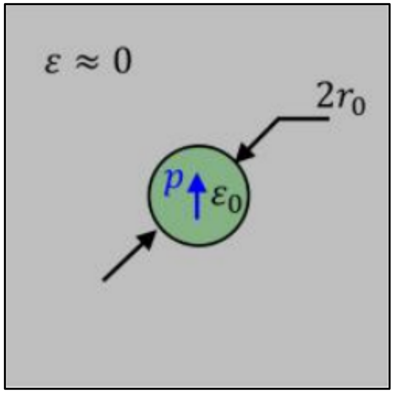
$d = \lambda$

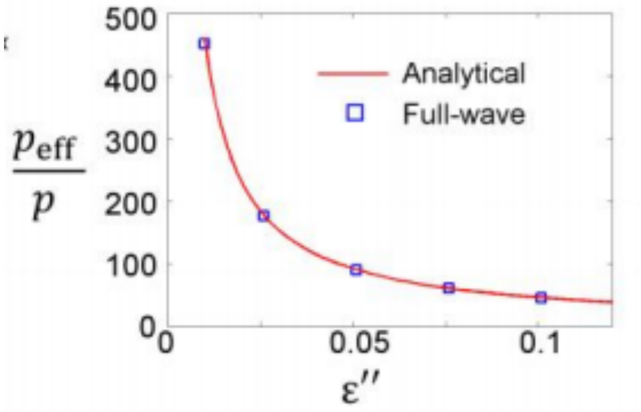


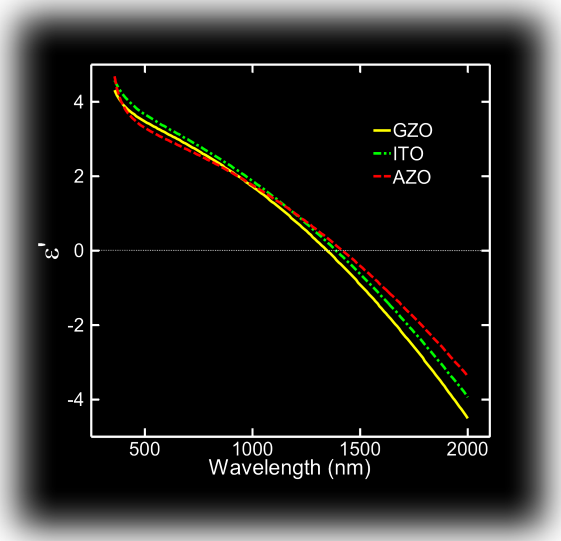
$P_{\text{peak}} \propto N^2$

Emitter inside ENZ

TCOs: natural ENZ crossover @ telecom





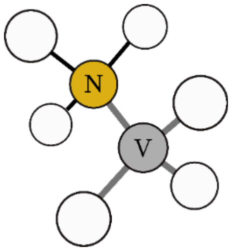


Liberal et al., *Arxiv* (2015)
(Engheta, UPenn)

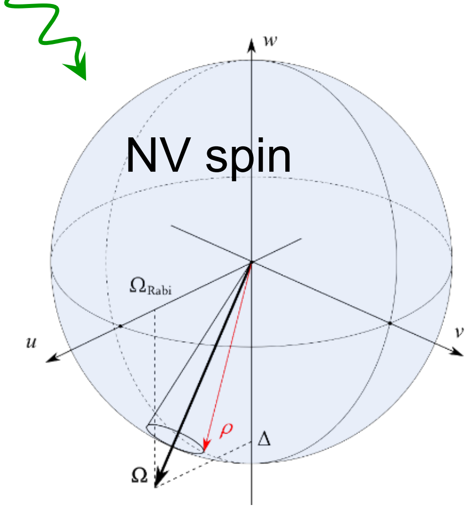
Integrated Quantum Register

Nitrogen-vacancy center in diamond

Nitrogen-vacancy center



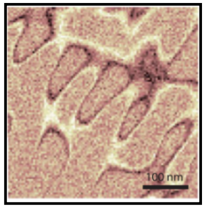
optical initialization



optical readout

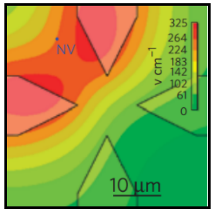
Nanoscale sensing

Magnetic fields



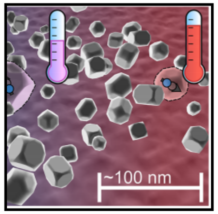
Hong et al. *MRS Bulletin* (2013)

Electric fields



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

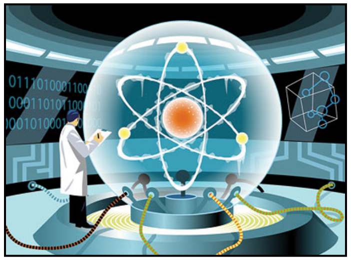
Temperature



Neumann et al. *Nanolett.* (2013)

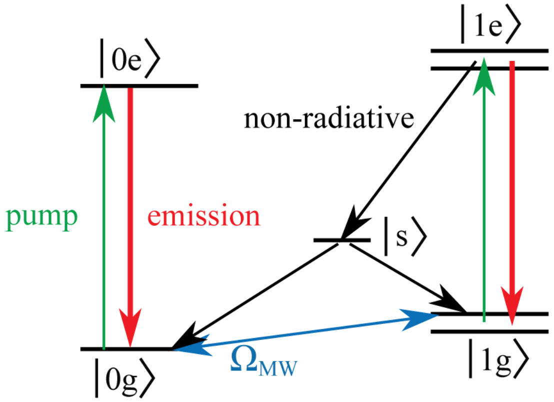
Quantum information

Quantum key distribution

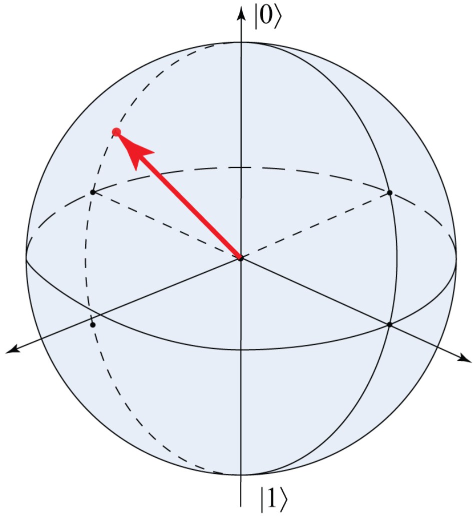


Computation

Nitrogen-vacancy center as a quantum register



NV level diagram

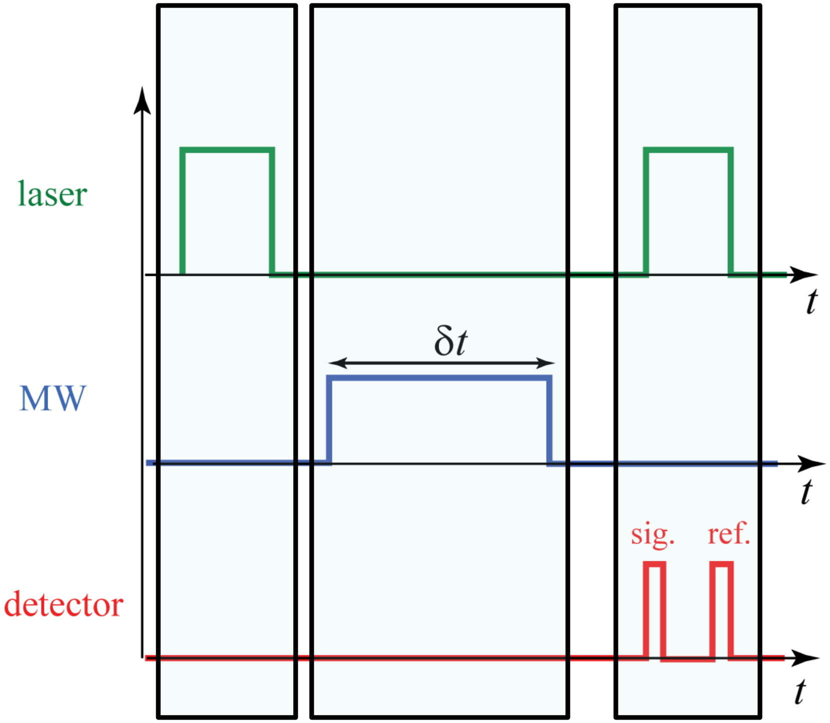


NV electron spin

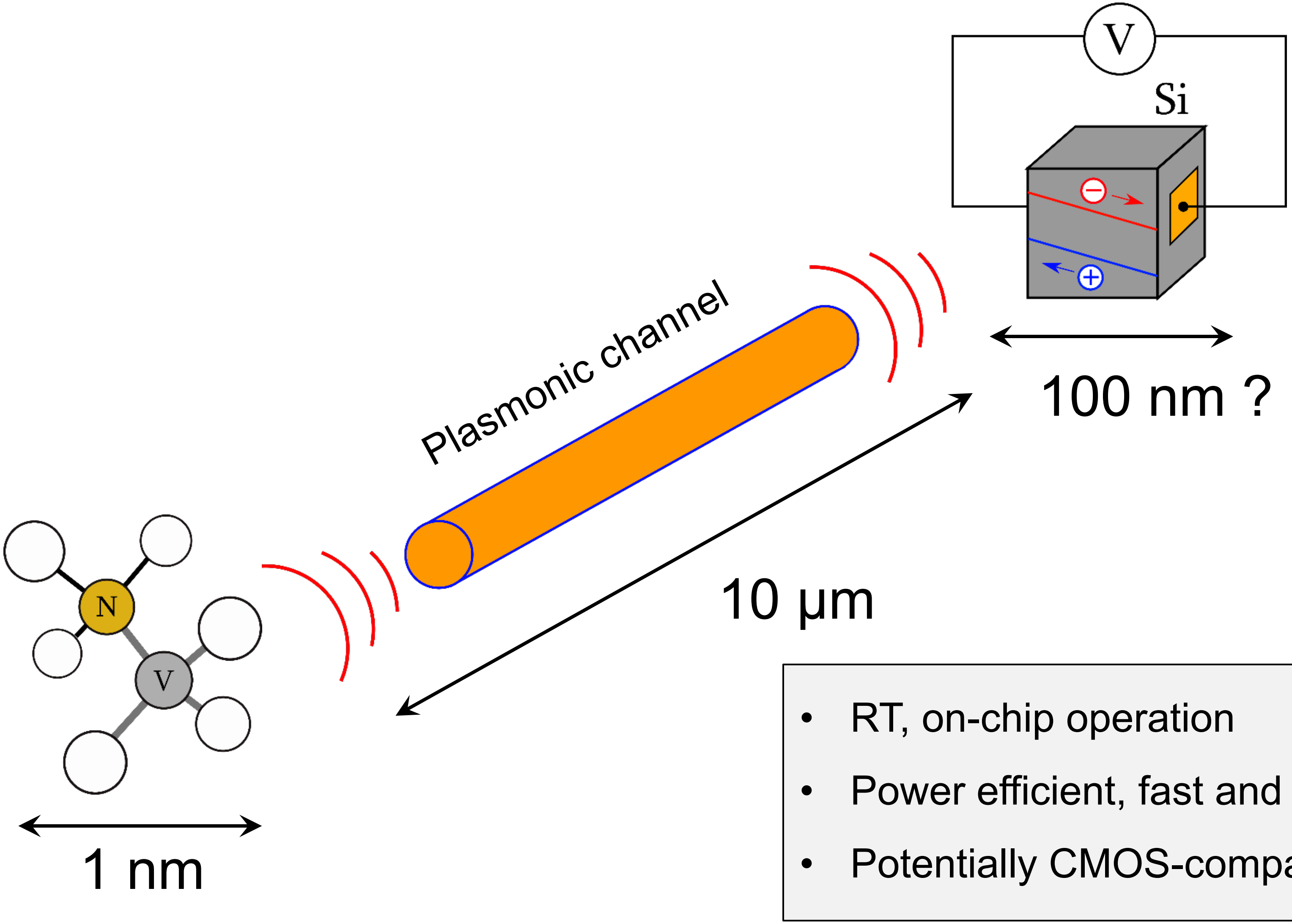
initialization in |0⟩ state

rotation on a Bloch sphere

projection measurement

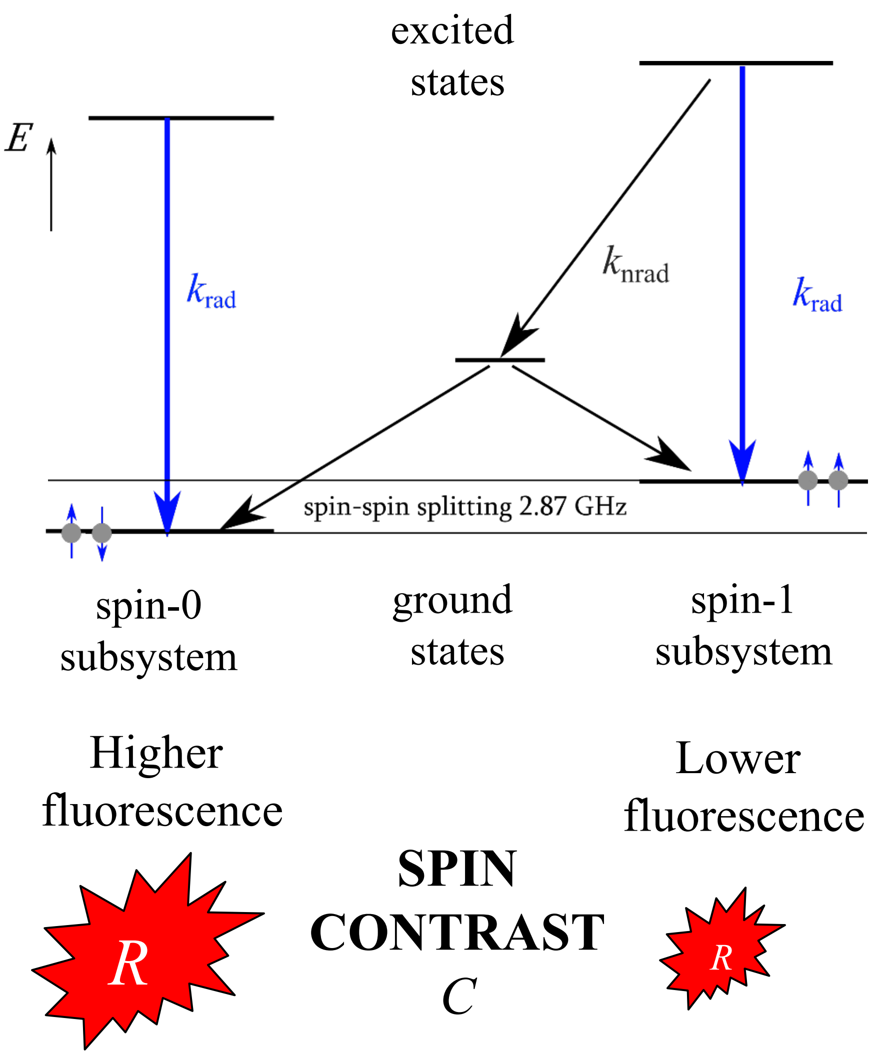


Plasmonic quantum register



- RT, on-chip operation
- Power efficient, fast and compact
- Potentially CMOS-compatible

NV center electronic levels



Higher fluorescence

Lower fluorescence

SPIN CONTRAST

C

High LDOS

⇩

High radiative rates

⇩

Less contrast

Low LDOS

⇩

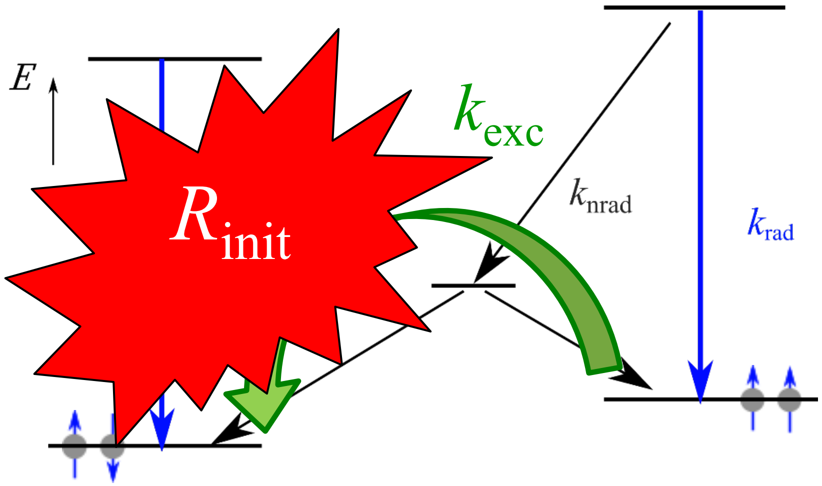
Important non-radiative rate

⇩

More contrast

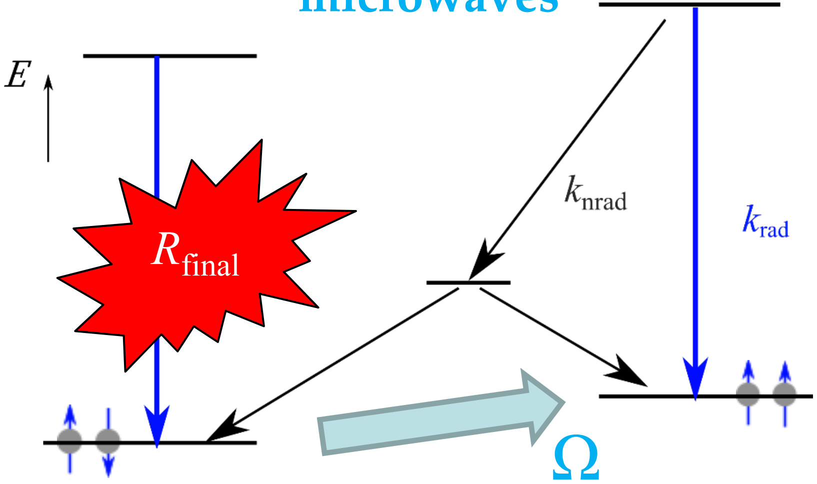
Spin population control and readout

Optical initialization



Spin polarized into the spin-0 subsystem

Coherent spin preparation with microwaves



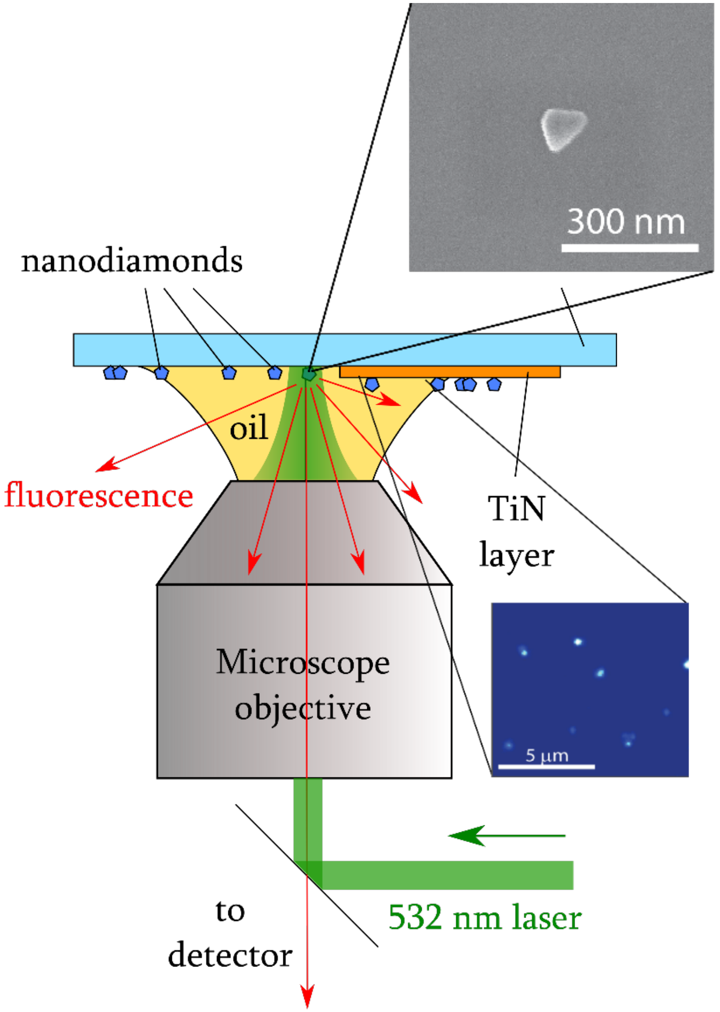
Spin can be coherently transferred to 1

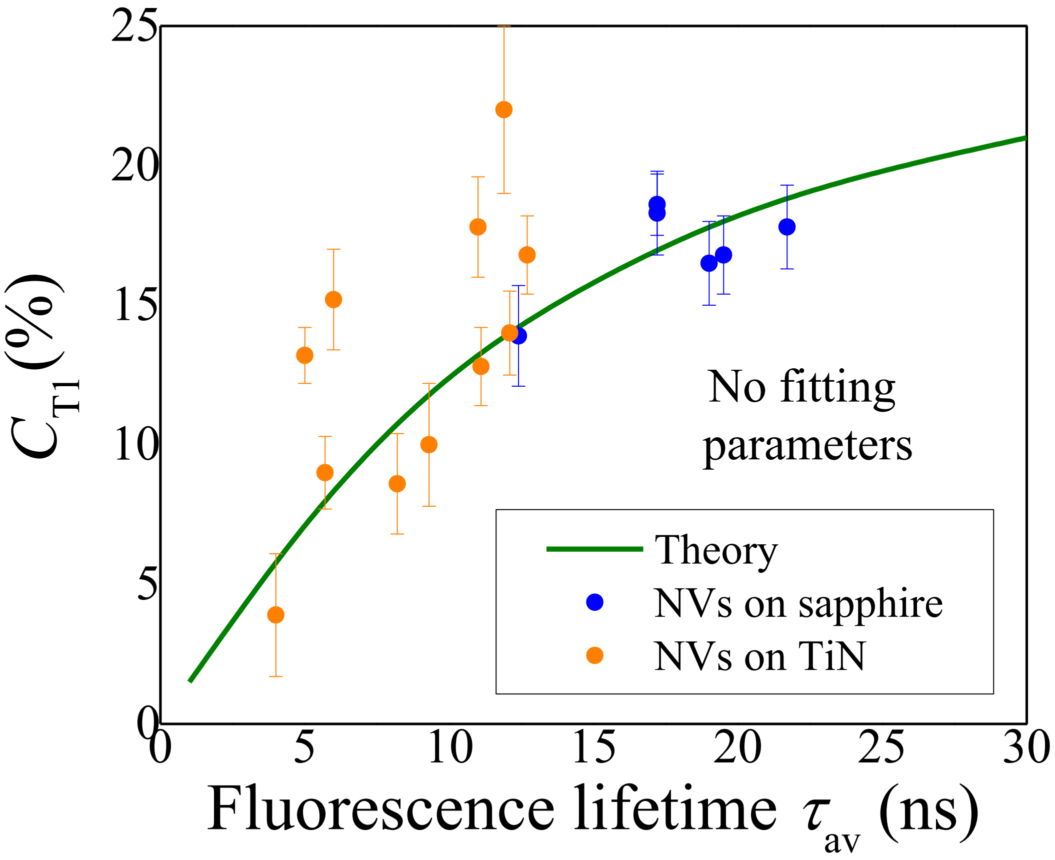
The change in fluorescence quantifies the spin populations

Spin contrast

$$C = \frac{R_{\text{init}} - R_{\text{final}}}{R_{\text{init}}}$$

Spin contrast VS fluorescence lifetime

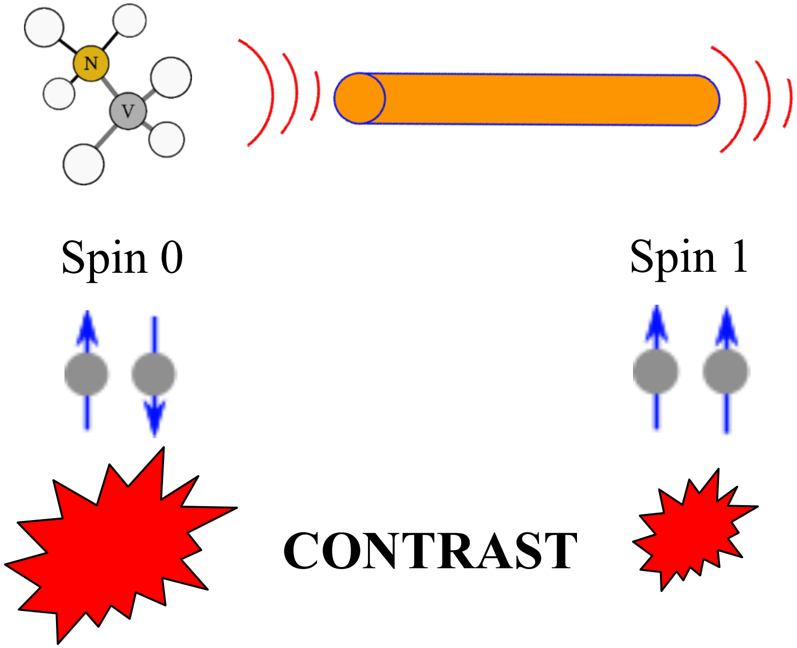


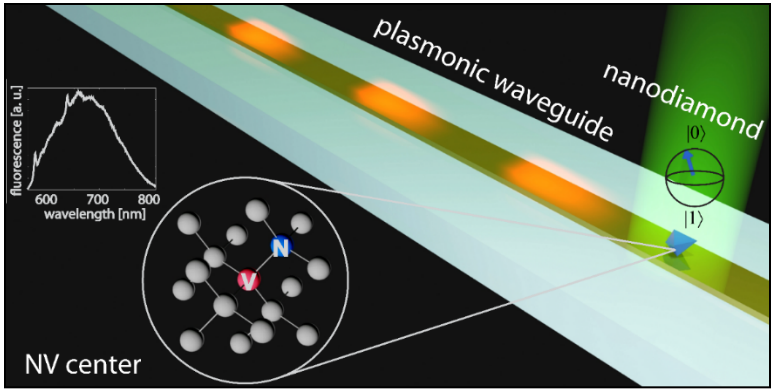


Quantum Register:
Reading/Controling spin with SPs on a chip

NV centers can optically couple to plasmonic modes in CMOS-compatible materials

Optical spin readout is possible in a plasmonic environment with $F_P > 3$





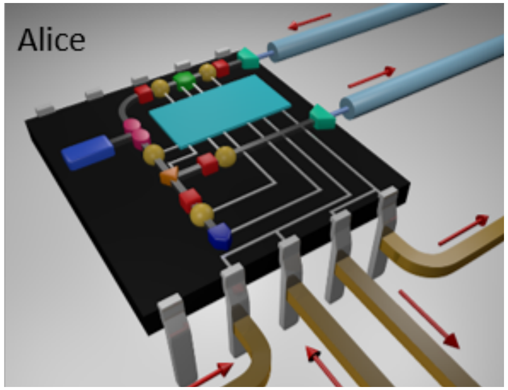
Partially supported by the AFOSR-MURI grant (FA9550-10-1-0264), and NSF-MRSEC grant (DMR-1120923).

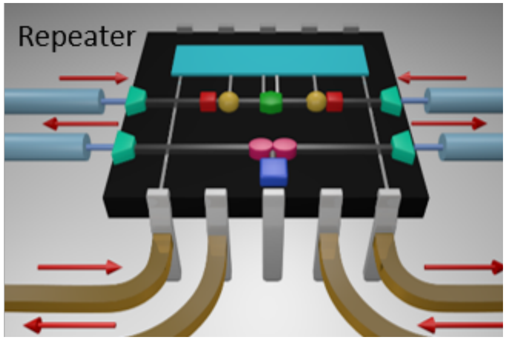
Outlook: Integrated and Scalable Quantum Information Systems

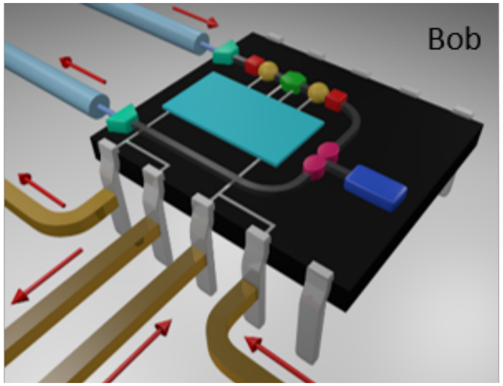
Integrated/Scalable Quantum Information

- Grand Challenge:
  - Build a practical integrated platform for quantum information sharing
  - Provide safer data transfer and storage for numerous applications

- Focus on key parameters for realistic systems
  - Room temperature operation
  - Scalability
  - Efficiency
  - Robustness
  - Cost



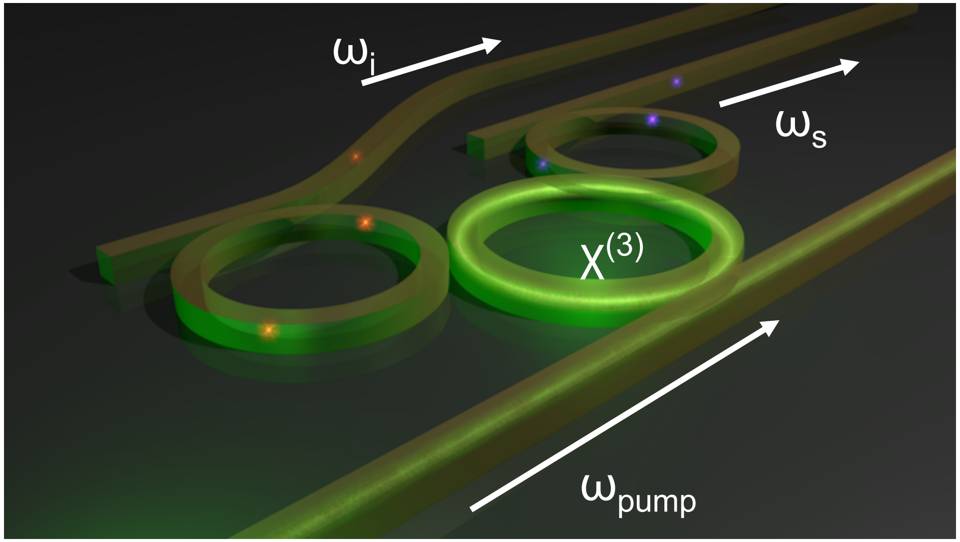




Frequency Conversion
Quantum Memory
Bell State Measurement
Entangled Photon Source
Single Photon Detector
Pump Laser
Quantum Gate
CMOS Electronics
Switch

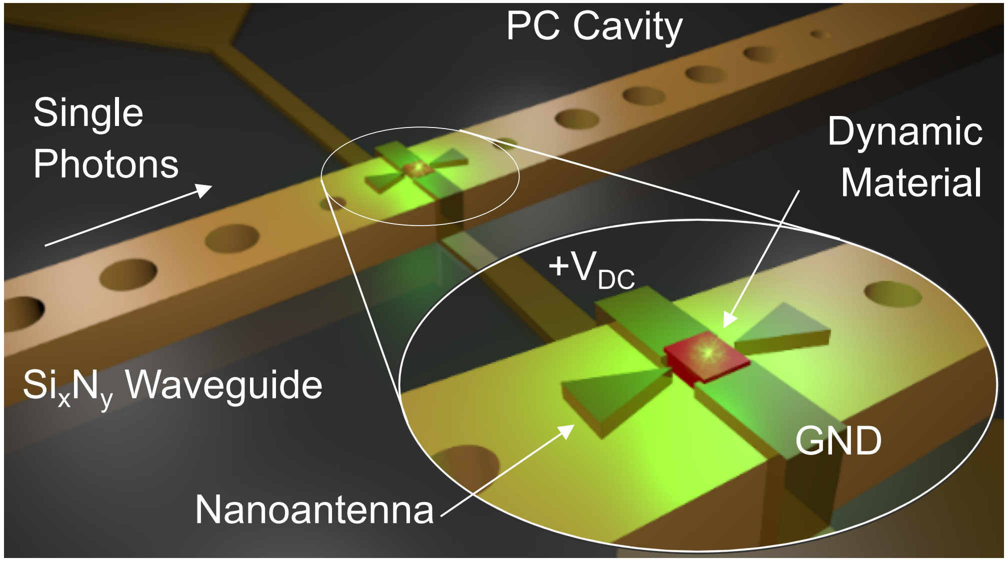
Integrated/Scalable Quantum Information

- Bring together advances from differing areas on a single platform
  - Memory
  - Light-Matter Interfaces
  - Sources (single and entangled photon(s))
  - Detectors
  - Logical Gates
  - Frequency Conversion
- Device interconnection schemes to enable scalability
- Consider challenges from both a device level and a system level



Integrated/Scalable Quantum Information

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



Conclusions

- Current material platforms for quantum photonics
- Alternative plasmonic materials and a new hybrid platform for quantum photonics
- Enhanced single-photon sources using CMOS-compatible metamaterials
- Schemes for on-chip quantum registers
- A quantum information system for room-temperature, scalable, and integrated devices