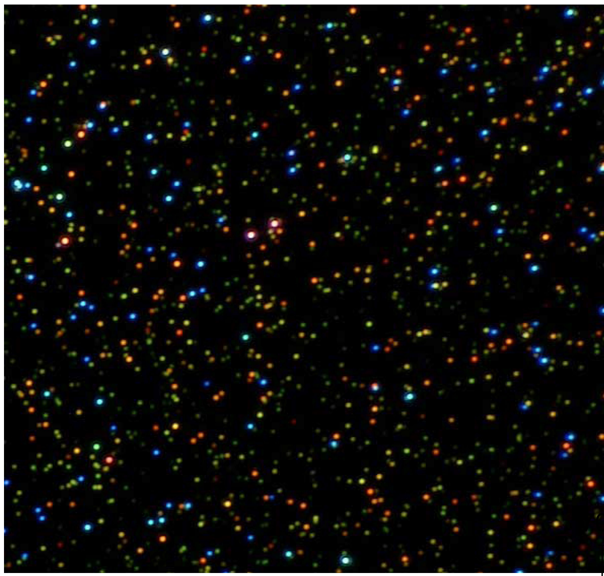
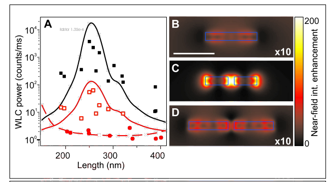
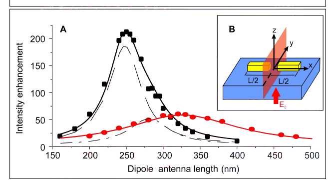
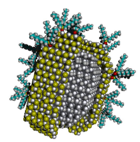
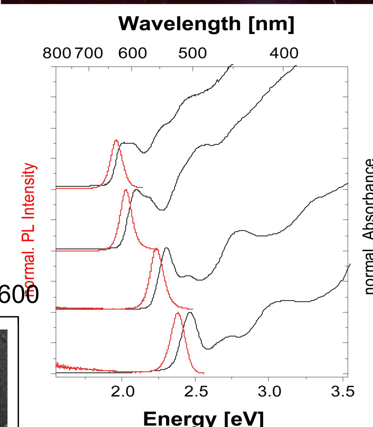
Nanoscale Systems for Opto-Electronics

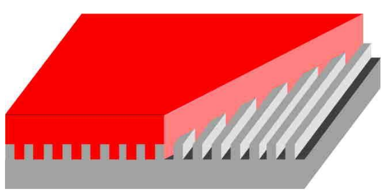


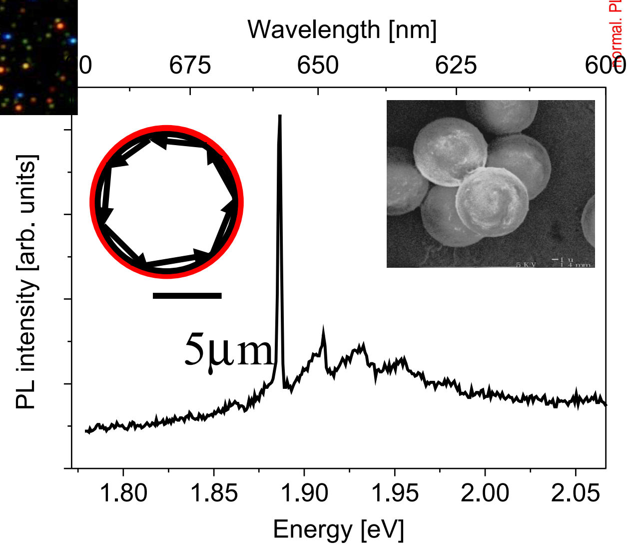












Nanoscale Systems for Opto-Electronics
Lecture 1

Dozent: Dr. rer. nat. habil. Hans-J. Eisler

Lichttechnisches Institut, Geb. 30.34, Raum 224

- Tel: 0721-608-2541
- E-Mail: hans.eisler@lti.uni-karlsruhe.de
- URL: www.lti.uni-karlsruhe.de

Exam: upon request by the end of the lecture series

Organizational

Januar	Februar	März	April	Mai	Juni	Juli	August	September	Oktober	November	Dezember
01 Di Neujahr	01 Fr	01 Sa	01 Di	01 Do Maifeiertag	01 So	01 Di	01 Fr	01 Mo 36	01 Mi	01 Sa Allerheiligen	01 Mo 49
02 Mi	02 Sa	02 So	02 Mi	02 Fr	02 Mo 23 **7**	02 Mi	02 Sa	02 Di	02 Do	02 So	02 Di
03 Do	03 So	03 Mo 10	03 Do	03 Sa	03 Di	03 Do	03 So	03 Mi	03 Fr Dt. Einheit	03 Mo 45	03 Mi
04 Fr	04 Mo 6	04 Di	04 Fr	04 So	04 Mi	04 Fr	04 Mo 32	04 Do	04 Sa	04 Di	04 Do
05 Sa	05 Di	05 Mi	05 Sa	05 Mo 19 **4**	05 Do	05 Sa	05 Di	05 Fr	05 So	05 Mi	05 Fr
06 So Heilige Drei Könige	06 Mi	06 Do	06 So	06 Di	06 Fr	06 So	06 Mi	06 Sa	06 Mo 41	06 Do	06 Sa
07 Mo 2	07 Do	07 Fr	07 Mo 15	07 Mi	07 Sa	07 Mo 28 **12**	07 Do	07 So	07 Di	07 Fr	07 So
08 Di	08 Fr	08 Sa	08 Di	08 Do	08 So	08 Di	08 Fr Friedenstag	08 Mo 37	08 Mi	08 Sa	08 Mo 50
09 Mi	09 Sa	09 So	09 Mi	09 Fr	09 Mo 24 **8**	09 Mi	09 Sa	09 Di	09 Do	09 So	09 Di
10 Do	10 So	10 Mo 11	10 Do	10 Sa	10 Di	10 Do	10 So	10 Mi	10 Fr	10 Mo 46	10 Mi
11 Fr	11 Mo 7	11 Di	11 Fr	11 So Pfingstsonntag	11 Mi	11 Fr	11 Mo 33	11 Do	11 Sa	11 Di	11 Do
12 Sa	12 Di	12 Mi	12 Sa	12 Mo 20 tmontag	12 Do	12 Sa	12 Di	12 Fr	12 So	12 Mi	12 Fr
13 So	13 Mi	13 Do	13 So	13 Di	13 Fr	13 So	13 Mi	13 Sa	13 Mo 42	13 Do	13 Sa
14 Mo 3	14 Do	14 Fr	14 Mo 16 **1**	14 Mi	14 Sa	14 Mo 29 **13**	14 Do	14 So	14 Di	14 Fr	14 So
15 Di	15 Fr	15 Sa	15 Di	15 Do	15 So	15 Di	15 Fr Maria Himmelfahrt	15 Mo 38	15 Mi	15 Sa	15 Mo 51
16 Mi	16 Sa	16 So	16 Mi	16 Fr	16 Mo 25 **9**	16 Mi	16 Sa	16 Di	16 Do	16 So	16 Di
17 Do	17 So	17 Mo 12	17 Do	17 Sa	17 Di	17 Do	17 So	17 Mi	17 Fr	17 Mo 47	17 Mi
18 Fr	18 Mo 8	18 Di	18 Fr	18 So	18 Mi	18 Fr	18 Mo 34	18 Do	18 Sa	18 Di	18 Do
19 Sa	19 Di	19 Mi	19 Sa	19 Mo 21 **5**	19 Do	19 Sa	19 Di	19 Fr	19 So	19 Mi Buß- und Bettag	19 Fr
20 So	20 Mi	20 Do	20 So	20 Di	20 Fr	20 So	20 Mi	20 Sa	20 Mo 43	20 Do	20 Sa
21 Mo 4	21 Do	21 Fr Karfreitag, Frühlingsanfang	21 Mo 17 **2**	21 Mi	21 Sa Sommeranfang	21 Mo 30	21 Do	21 So	21 Di	21 Fr	21 So
22 Di	22 Fr	22 Sa	22 Di	22 Do Fronleichnam	22 So	22 Di	22 Fr	22 Mo 39	22 Mi	22 Sa	22 Mo 52 ranfang
23 Mi	23 Sa	23 So Ostersonntag	23 Mi	23 Fr	23 Mo 26 **10**	23 Mi	23 Sa	23 Di Herbstanfang	23 Do	23 So	23 Di
24 Do	24 So	24 Mo 13 montag	24 Do	24 Sa	24 Di	24 Do	24 So	24 Mi	24 Fr	24 Mo 48	24 Mi
25 Fr	25 Mo 9	25 Di	25 Fr	25 So	25 Mi	25 Fr	25 Mo 35	25 Do	25 Sa	25 Di	25 Do 1. Weihnachtstag
26 Sa	26 Di	26 Mi	26 Sa	26 Mo 22 **6**	26 Do	26 Sa	26 Di	26 Fr	26 So	26 Mi	26 Fr 2. Weihnachtstag
27 So	27 Mi	27 Do	27 So	27 Di	27 Fr	27 So	27 Mi	27 Sa	27 Mo 44	27 Do	27 Sa
28 Mo 5	28 Do	28 Fr	28 Mo 18 **3**	28 Mi	28 Sa	28 Mo 31	28 Do	28 So	28 Di	28 Fr	28 So
29 Di	29 Fr	29 Sa	29 Di	29 Do	29 So	29 Di	29 Fr	29 Mo 40	29 Mi	29 Sa	29 Mo 1
30 Mi		30 So	30 Mi	30 Fr	30 Mo 27 **11**	30 Mi	30 Sa	30 Di	30 Do	30 So	30 Di
31 Do		31 Mo		31 Sa		31 Do	31 So		31 Fr Reformationstag		31 Mi

Readings

- ***Principles of Nano-Optics***, L. Novotny and B. Hecht, Cambridge University Press, 2006
- ***Absorption and Scattering of Light by Small Particles***, C. F. Bohren and D. R. Huffman, John Wiley& Sons, INC. 1998
- ***Principles of Optics***, Born and Wolf, Cambridge University Press
- ***Surface plasmon***, H. Raether, Springer Tracts in Modern Physics, Vol. 111, 1988
- ***Near-Filed Optics and Surface Plasmon Polaritons***, S. Kawata, Springer Topics in Applied Physics, 2001
- ***Optical Properties of Metal Clusters***, U. Kreibig, M. Vollmer, Springer, 1995
- ***Antenna Theory***, C. A. Balanis, second edition, John Wiley & sons, 1997
- ***Resonance Energy Transfer – Theory and Data***, B. Wieb van der Meer, George Coker, S.-Y. Simon Chen, VCH Publisher, Inc. 1994
- **Surface-Enhanced Raman Scattering - Physics and Application**, K. Kneipp, H. Kneipp, M. Moskovits, Springer-Verlag Berlin, Heidelberg 2006
- Recent papers: ***Nature, Science Magazine, Phys. Rev. Lett. ...***as indicated during lecture series

Nanoscale Systems for Opto-Electronics
Lecture 1

Interaction of Light with Nanoscale Systems

- general introdcution and motivation
- nano-metals (Au, Ag, Cu, Al ...)
  - introduction to optical properties
  - mie scattering
  - mie scattering in the near-field
  - mie scattering with nano rods
  - resonant optical antennas

- artificial quantum structures (semiconductor quantum dots, ...)
- quantum dot lasers

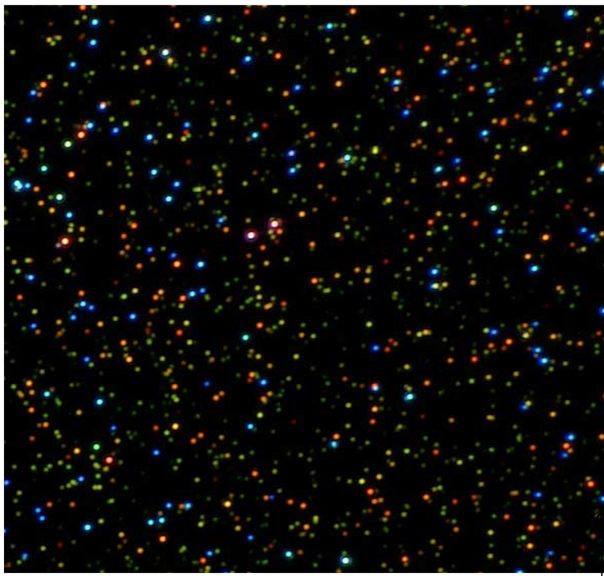
Optical Interactions between Nanoscale Systems

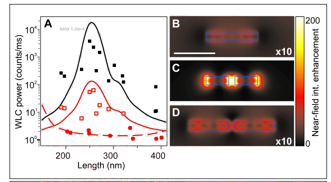
- Förster energy transfer (dipole-dipole interaction)
- super-emitter concept
- SERS (surface enhanced Raman spectroscopy: bio-sensors)

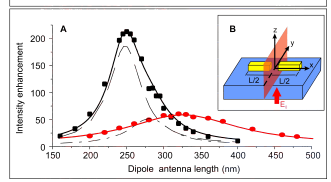
Beating the diffraction limit with Nanoscale Systems

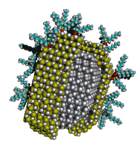
- surface plasmon polariton (SPP) - light confinement at nanoscale
- plasmonic chips
- plasmonic nanolithography

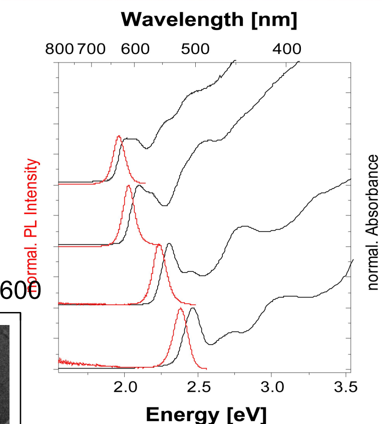
Overview in Images

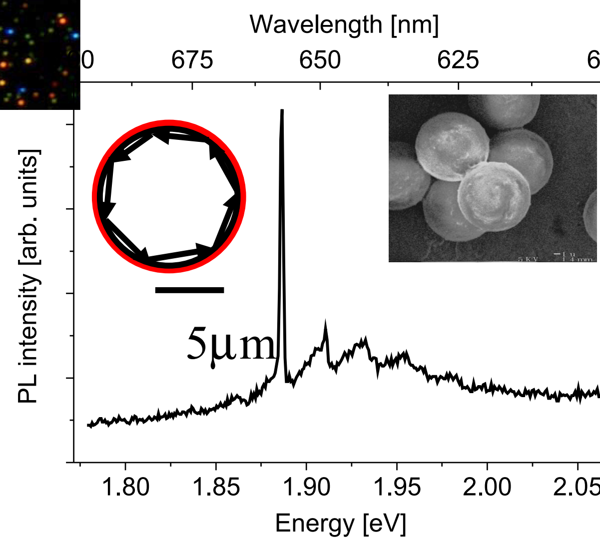


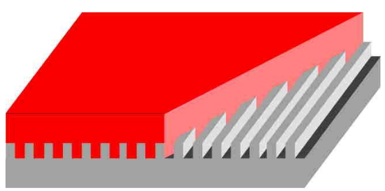




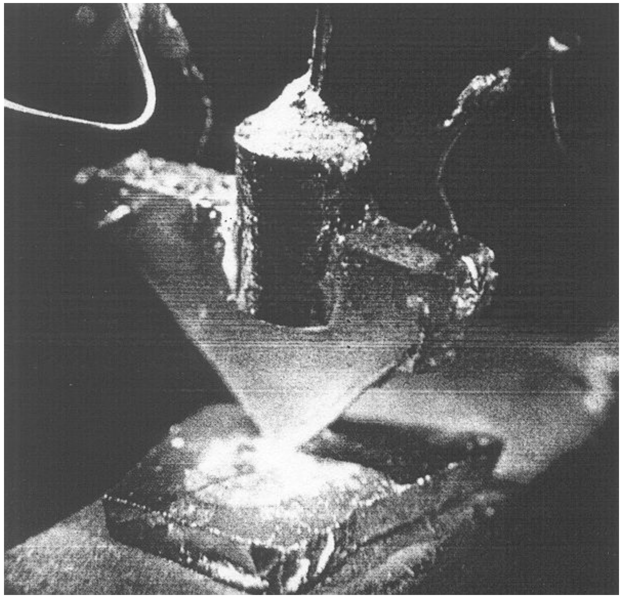


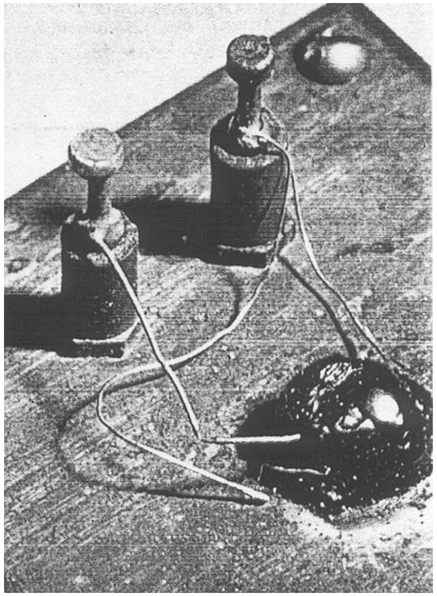




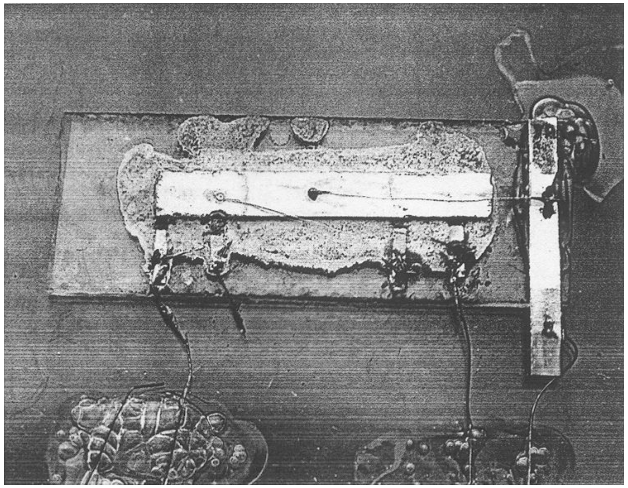


Motivation: Electronic Technology



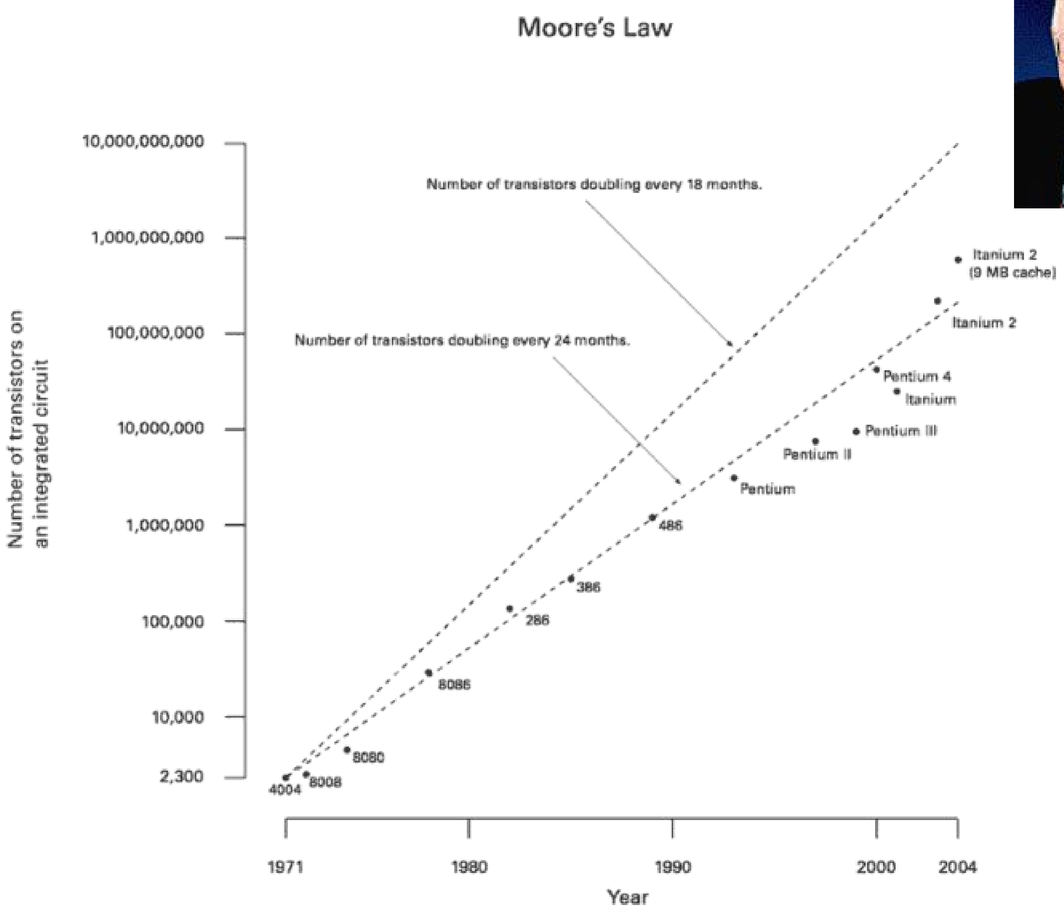


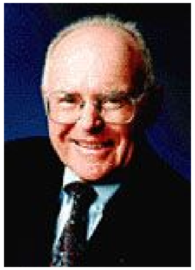
First transistor
Bardeen, Brattain
& Schockley (1949)



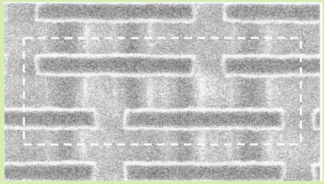
First Integrated Circuit
Noyce & Kilby (1958)

Motivation: Electronic Technology





SANTA CLARA, Calif., Jan. 25, 2006

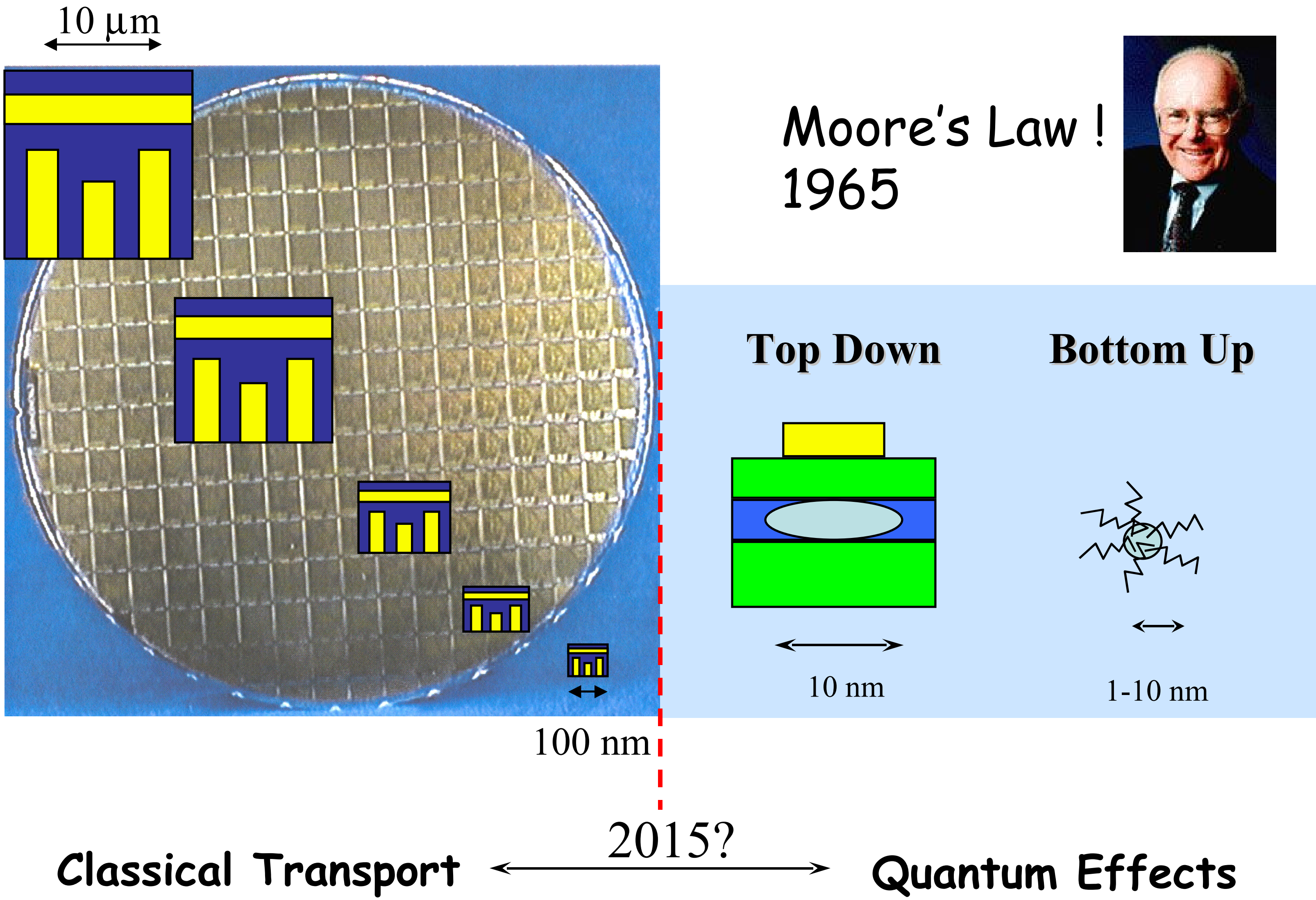


Intel® 45 nm, six transistor SRAM cell

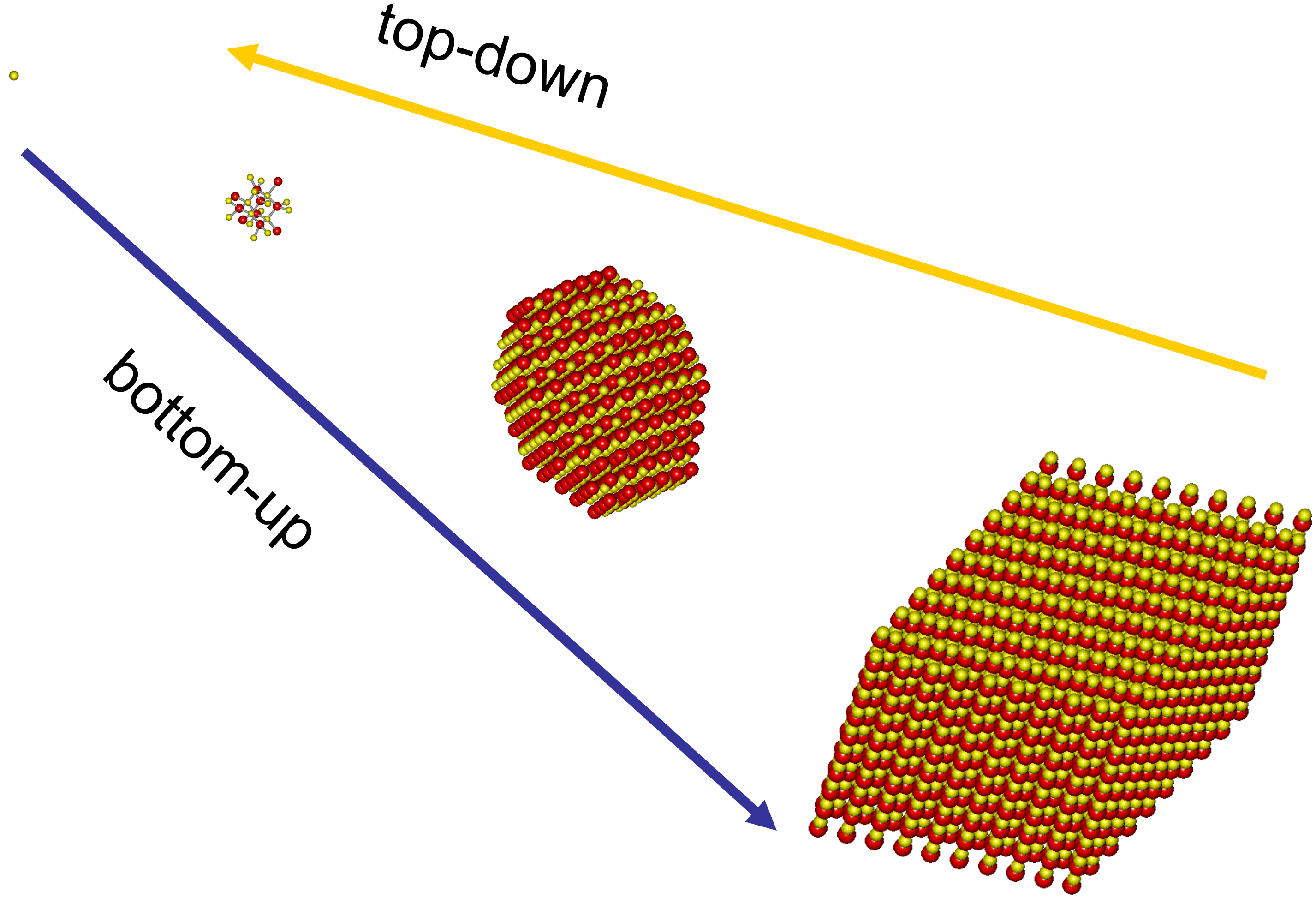
Intel® engineer holding 300 mm wafer with 45 nm shuttle test chips

Motivation: Electronic Technology

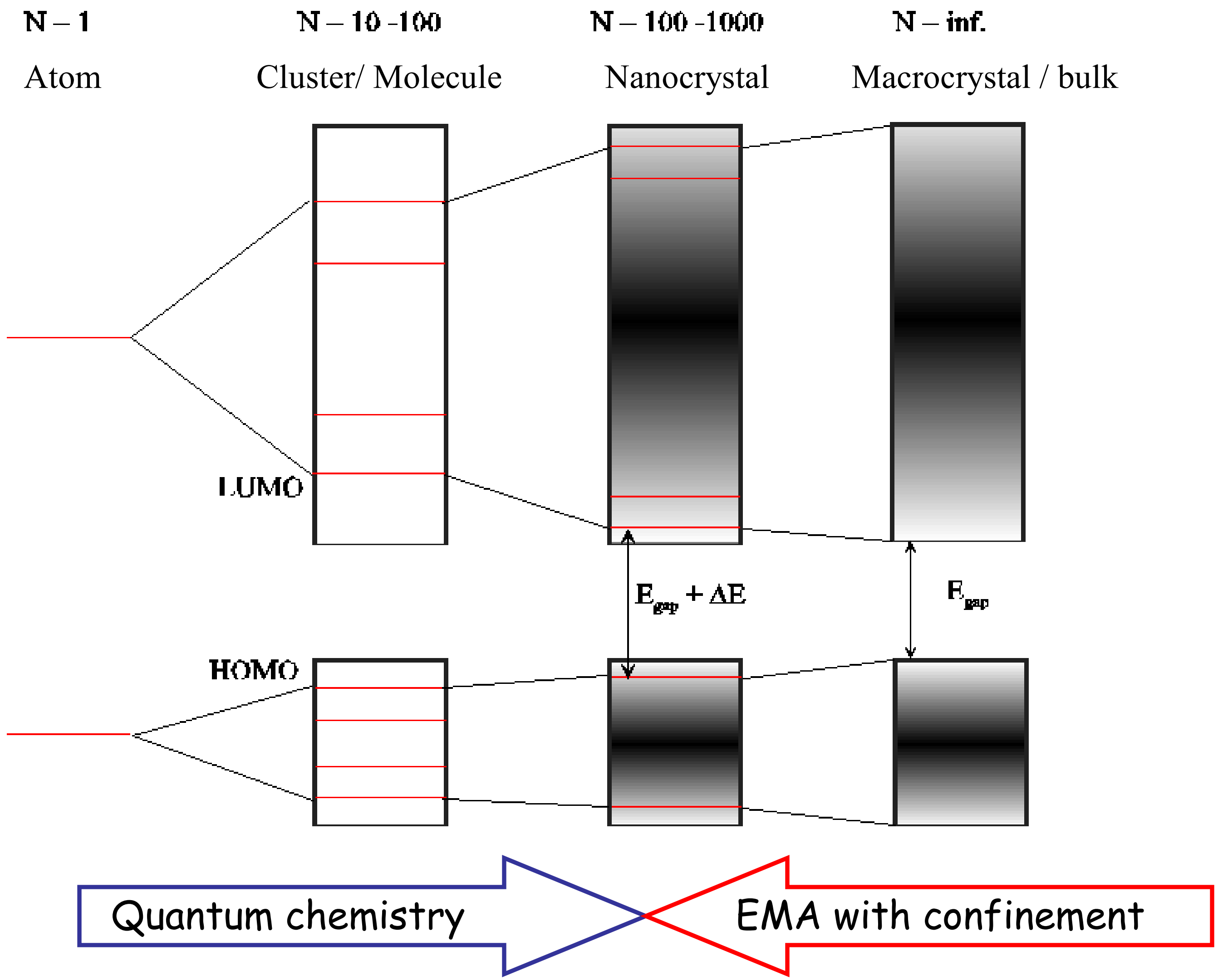
Moore's Law !
1965



Motivation: Fundamental Science

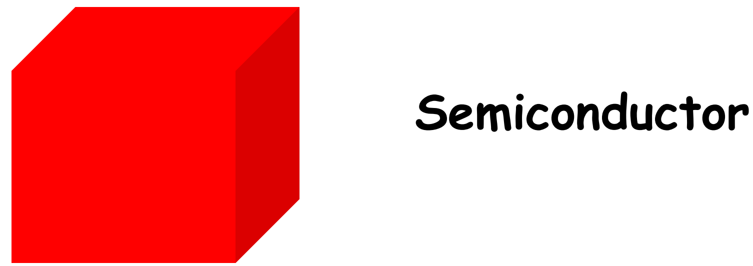


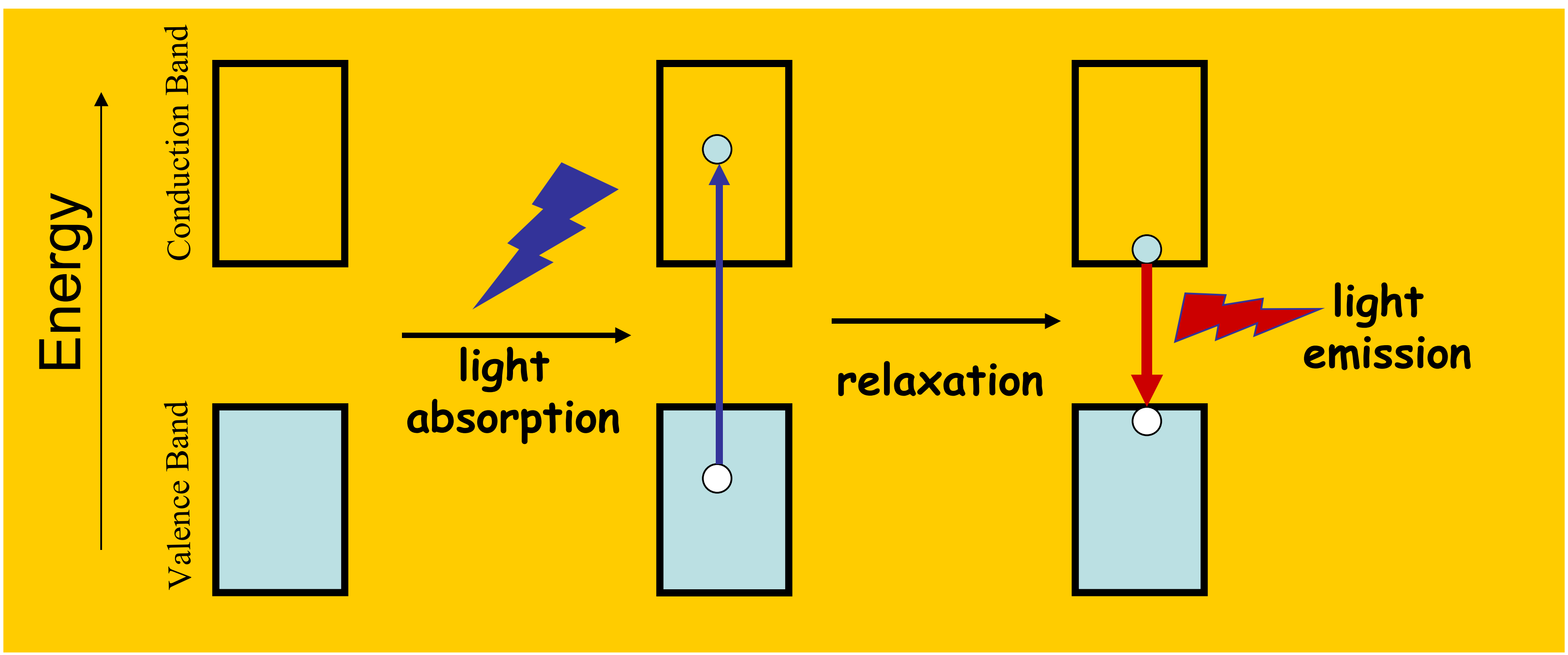
From Small to Big



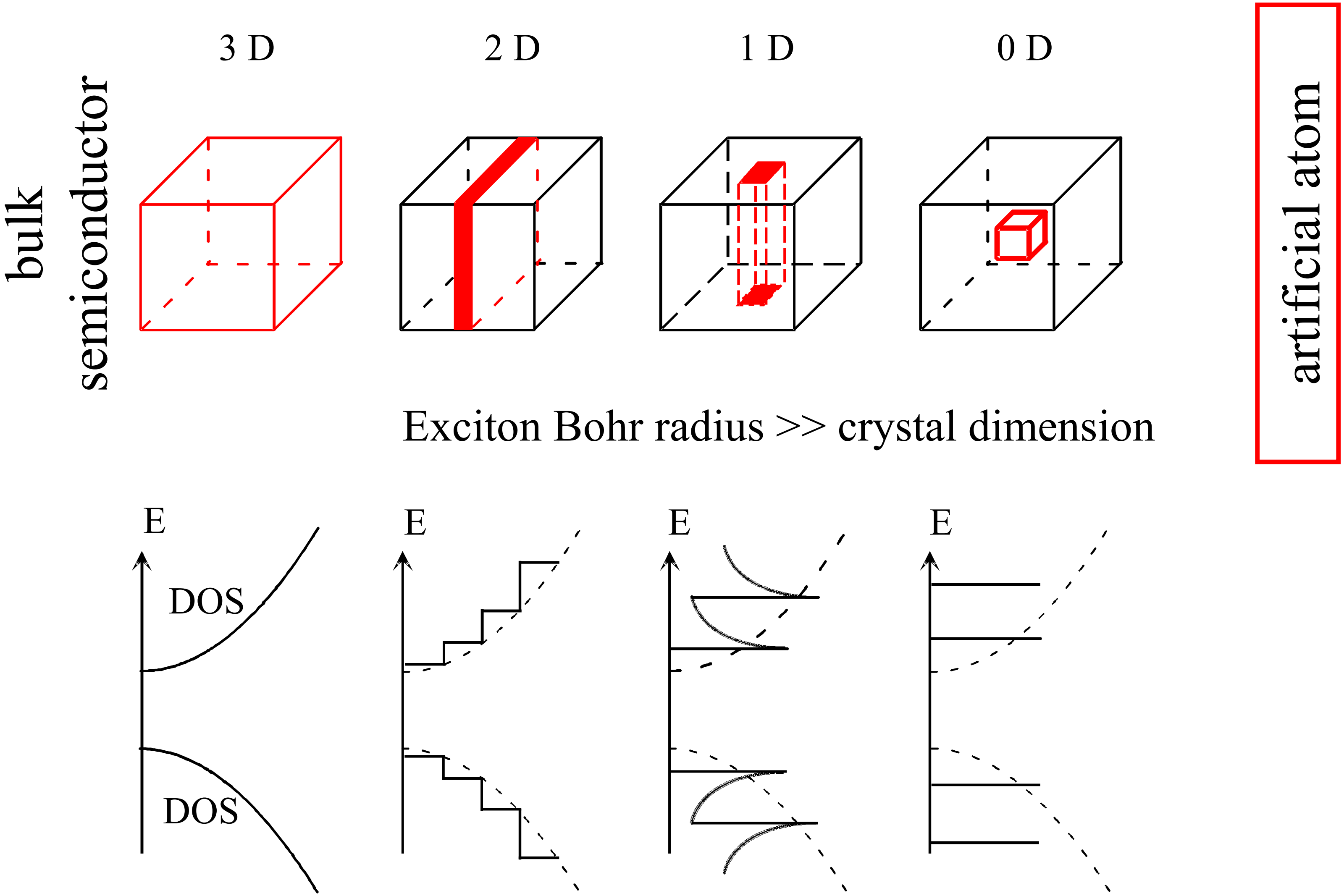
Semiconductor Clusters, Nanocrystals, and Quantum Dots
A. P. Alivisatos *Science* 1996 February 16; 271: 933-937.

Bulk Semiconductor



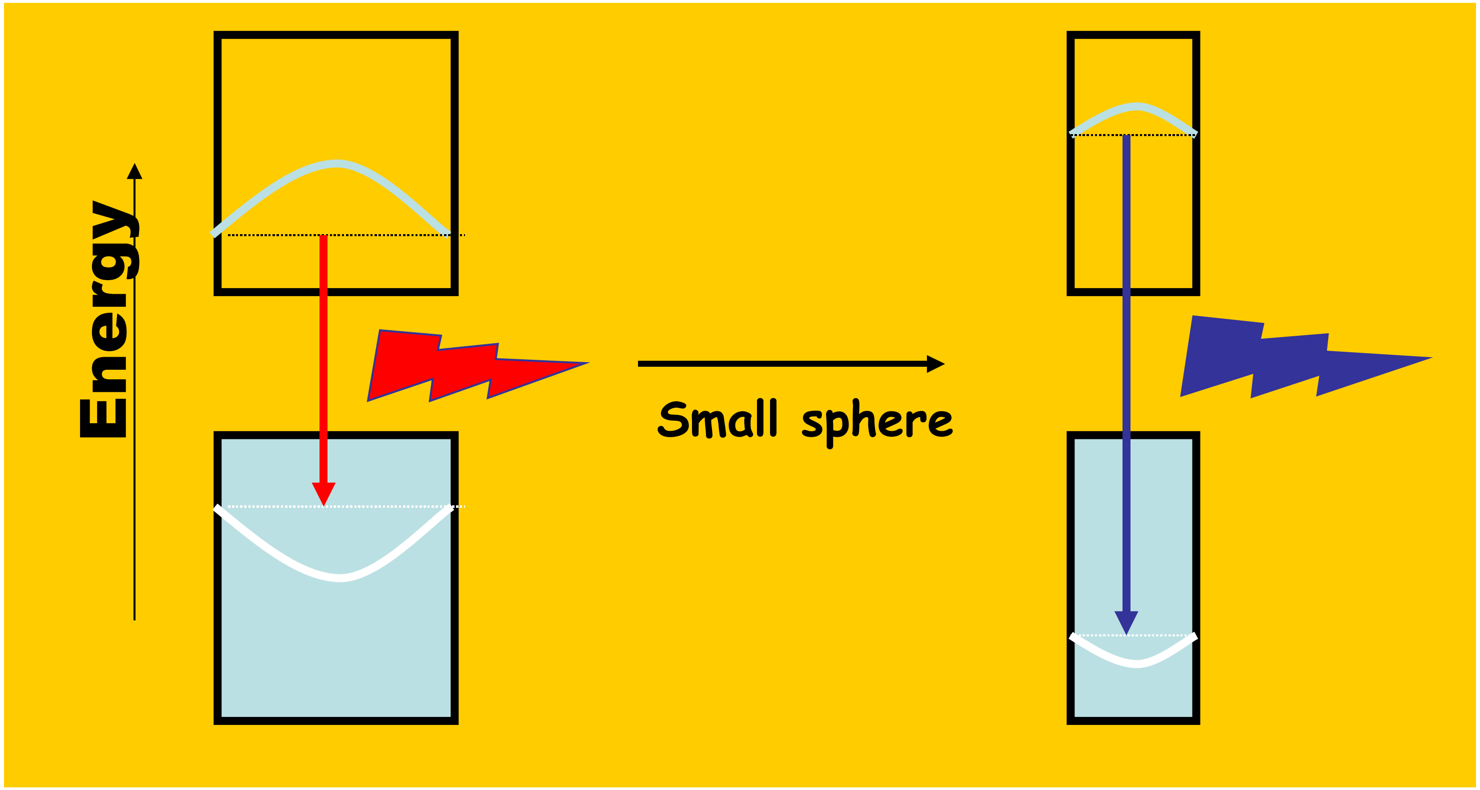


Electronic DOS does matter !

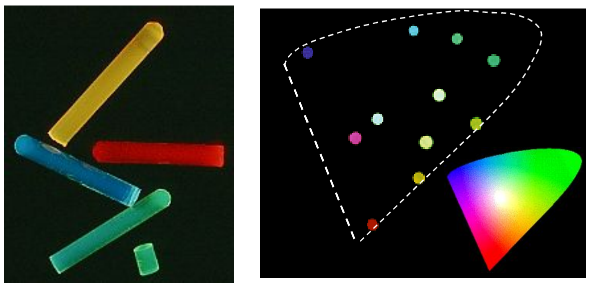


Early motivation for semiconductor nanostructures

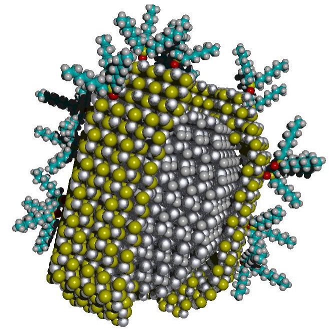
Squeeze the Bohr radius

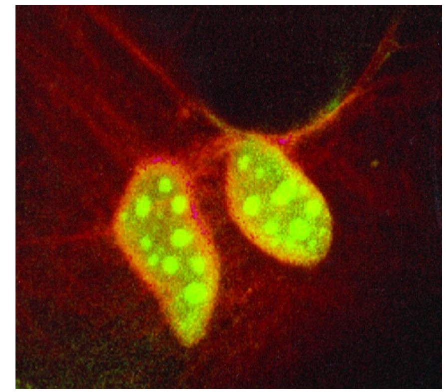


Nanocrystals towards Technology

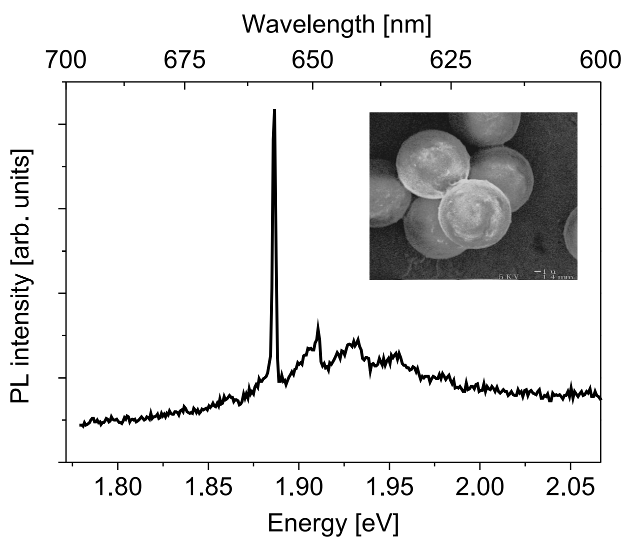


J. Lee *et al*, Adv. Materials, **12**, *1102* (2000)

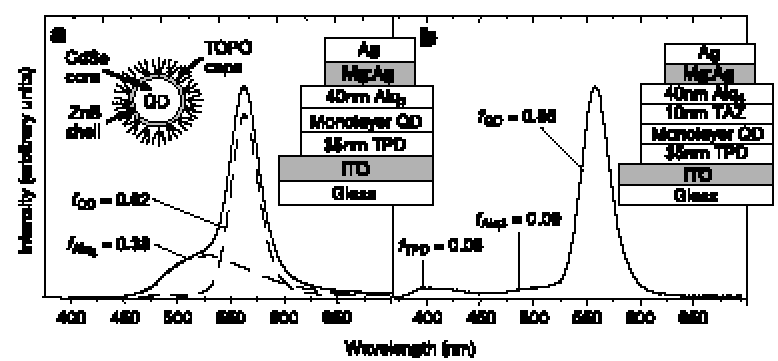




M. Bruchez *et al.* Science **281**, 2013 (1998)



HJ Eisler *et al.* unpublished



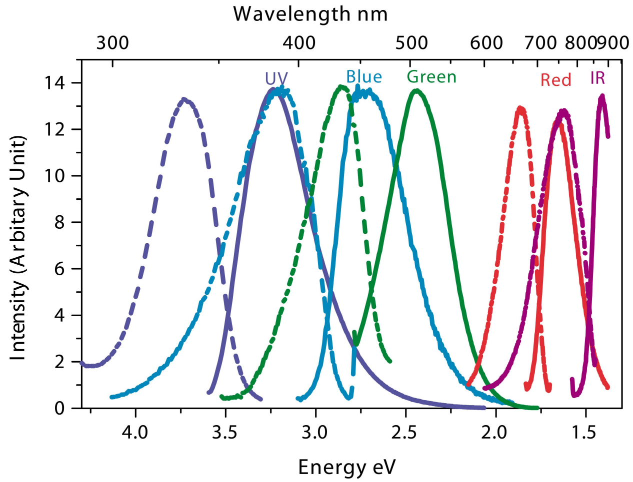
S. Coe, W.-K. Woo *et al.*, NATURE, **Vol. 420**, 800 (2002)

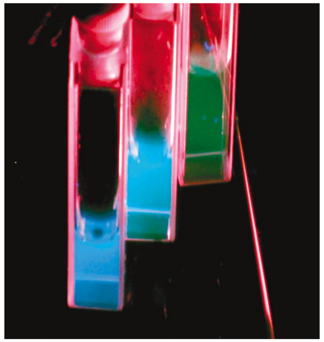
What about metals ?

characteristic length scale, e.g. Au

$$E_{Fermi,Au} = 5.53eV, \rightarrow v_{Fermi,Au} = 1.4 \cdot 10^6 \, m/s$$

$$\lambda_{deBroglie,Au} = \frac{h}{p}; \rightarrow \lambda_{deBroglie,Au} \approx 0.7nm$$





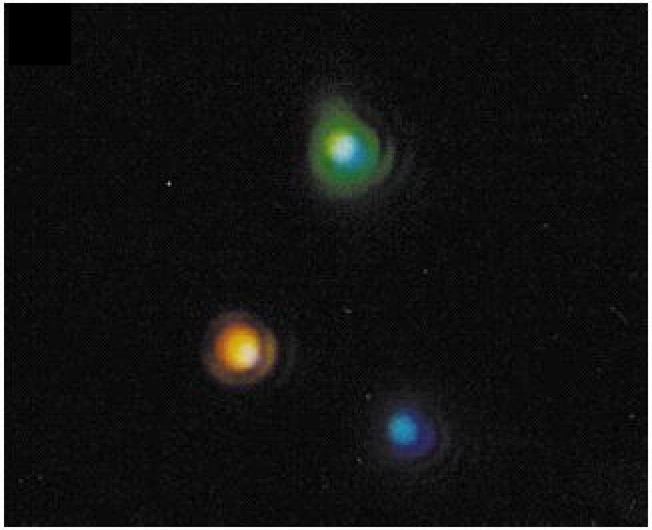
dashed lines : absorption
solid line: emission

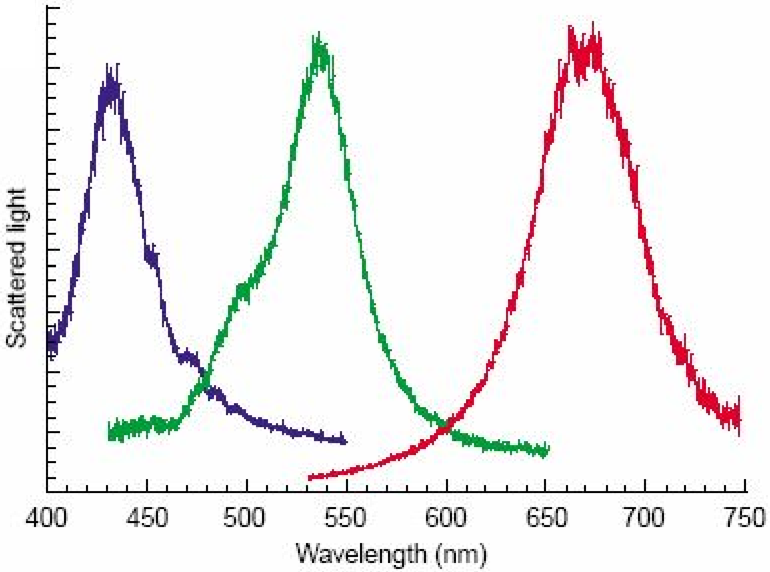
{Au}5 (385 nm)
{Au}8 (455 nm)
{Au}13 (510 nm)
{Au}23 (760 nm)
{Au}31 (866 nm)

Phys.Rev.Lett., Vol.93, pp.077402 (2004)

Nanoscale and some spirit

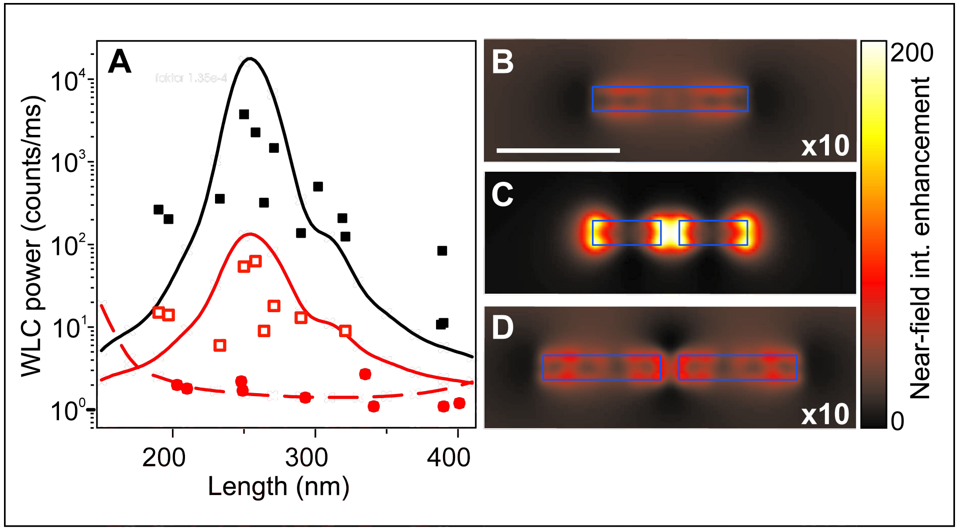
Particle plasmon polaritons

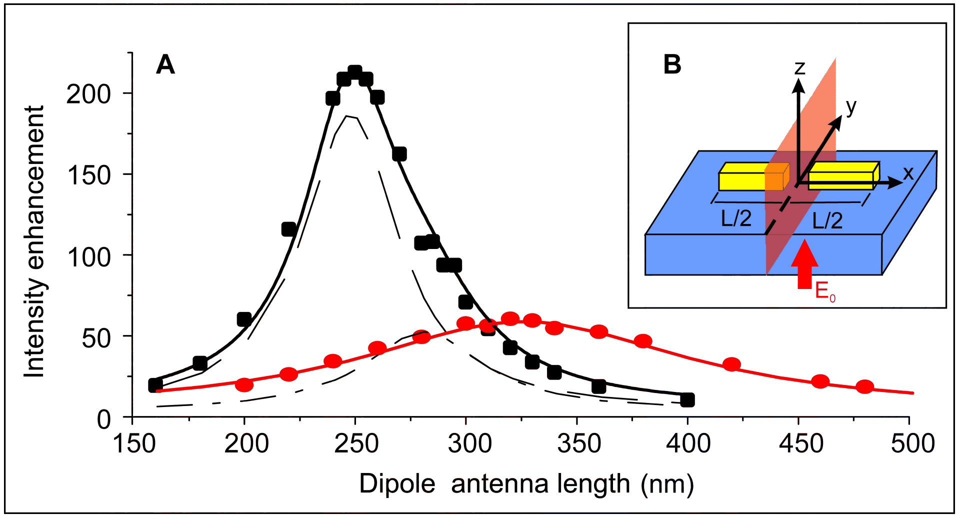




The particle plasmon resonance is sensitive to shape, size, material, and environment

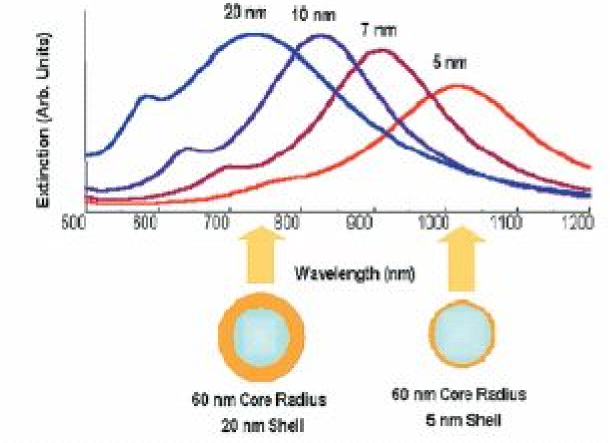
Nanoscale Architecture – Optical Antenna

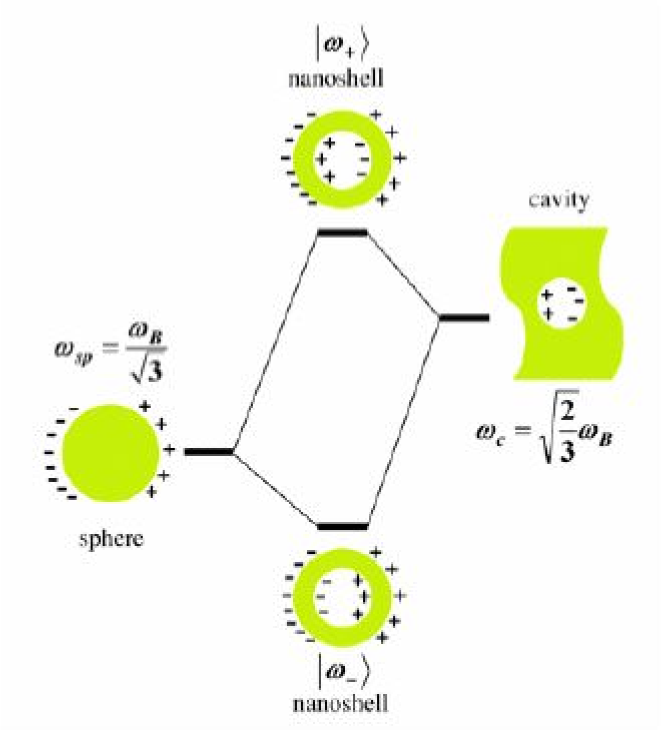




Optical impedance matching, field confinement, *designer* hot spot

Core/shell nanoscale metals

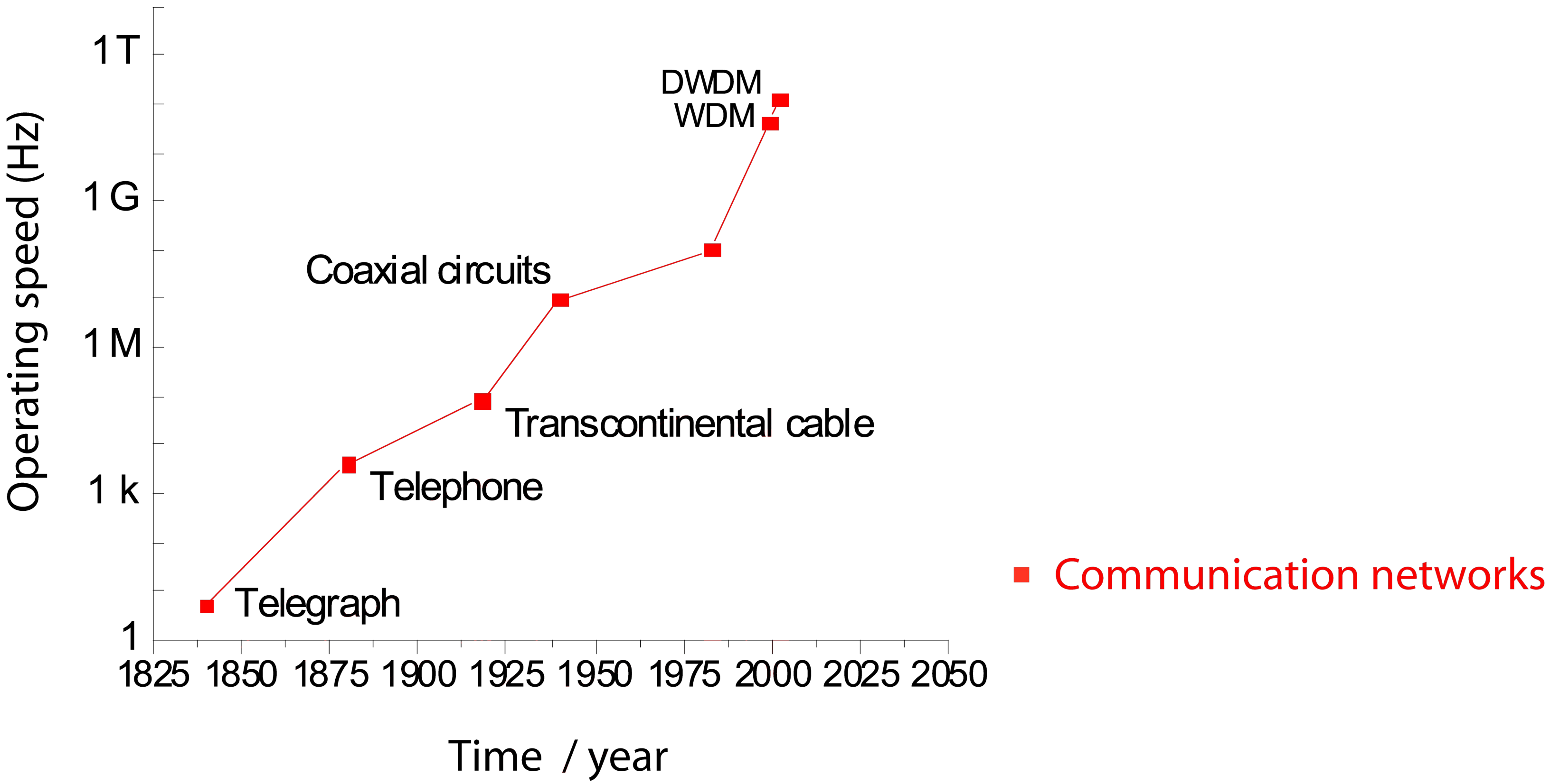




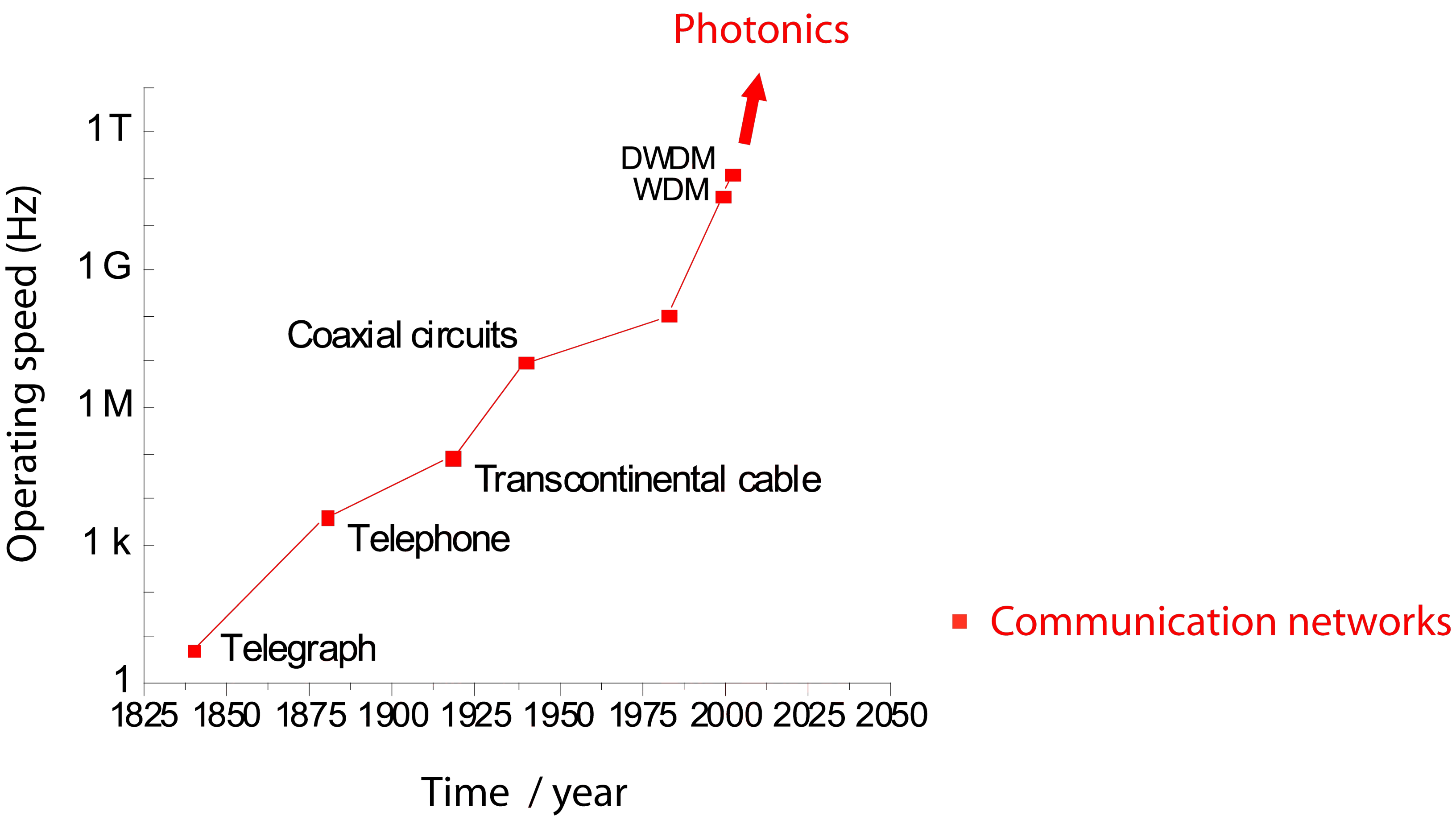
http://www-ece.rice.edu/~halas/pubs.html

Tuning optical response fucntions for e.g. biomedical application

Nanoplasmonics emerging from photonics and electronics



Nanoplasmonics emerging from photonics and electronics



Limitation in photonics

The bit **rate** in optical communications is fundamentally limited **only** by the carrier frequency: $B_{max} < f \sim 100$ Tbit/s (!),

but **light propagation is subjected to diffraction**

Propagation of e.m. wave in free space: $\hbar\omega = c \cdot \hbar k_{photon}$

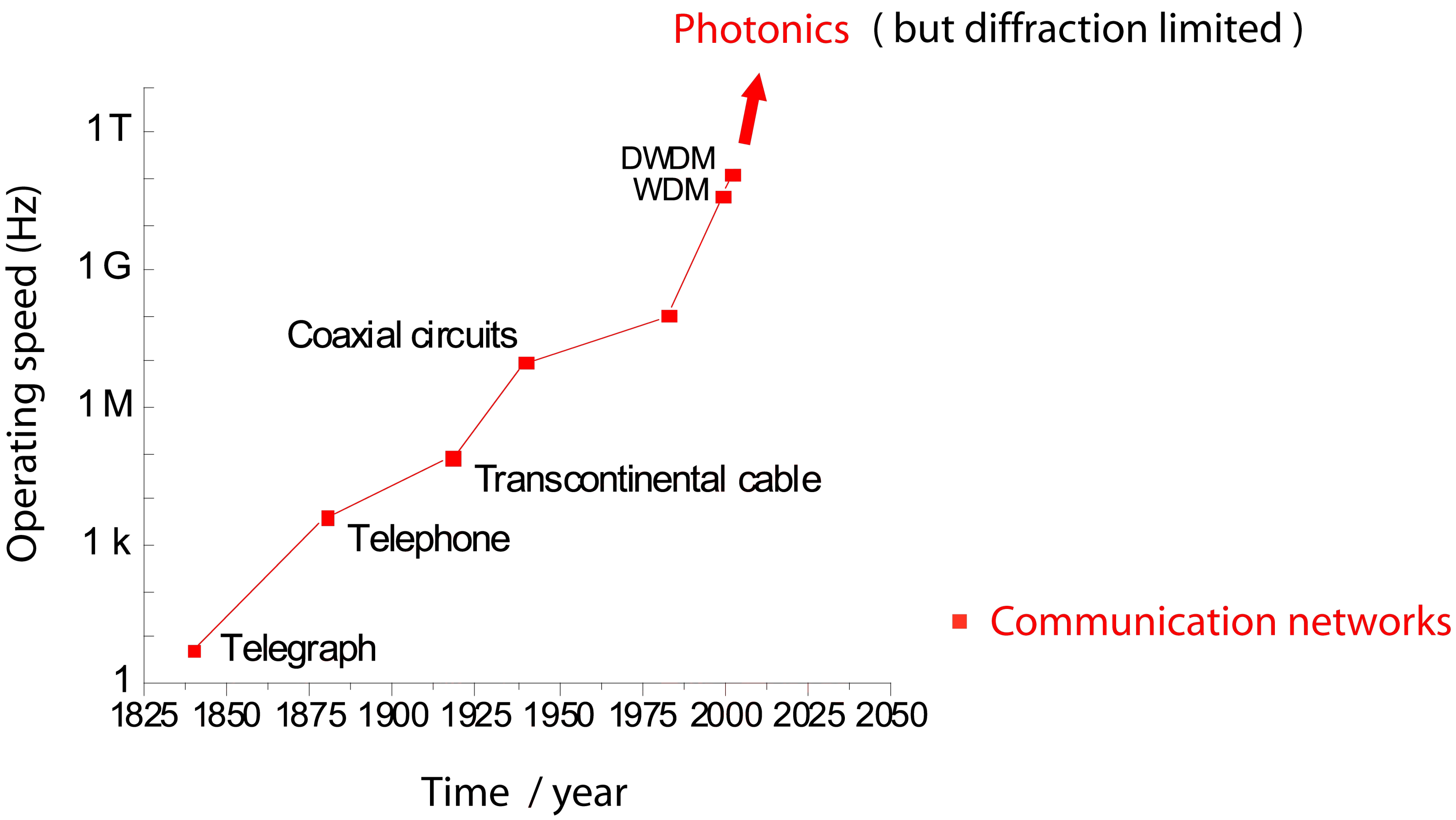
Heisenberg‘s uncertainty relation: $\Delta \hbar k_x \cdot \Delta x \geq \hbar / 2$

with $k_{x,\max} = k = 2\pi / \lambda$

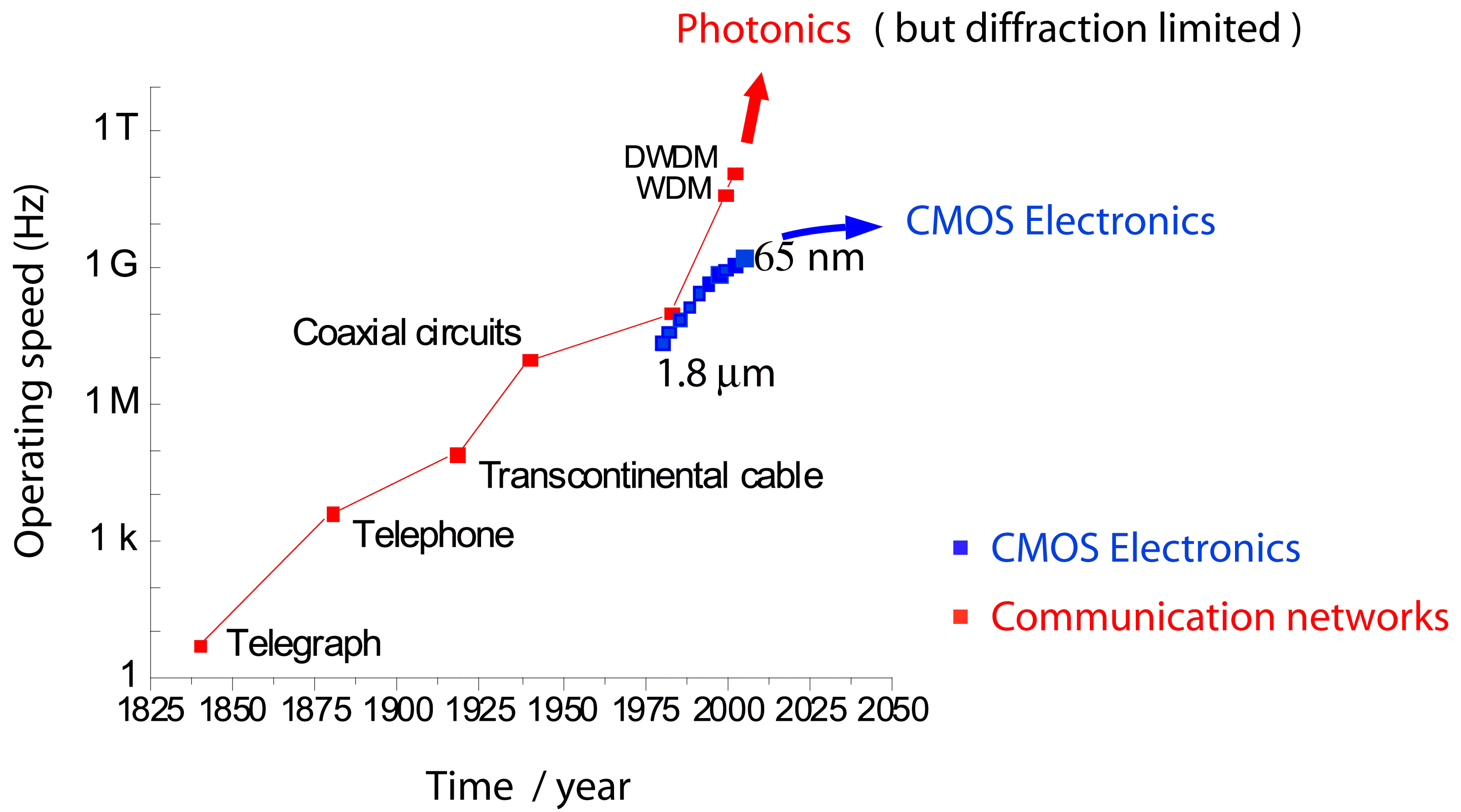
$$\Delta x \geq \frac{\lambda}{4\pi}$$

Photonics is diffraction- *limited in size*!

Nanoplasmonics emerging from photonics and electronics



Nanoplasmonics emerging from photonics and electronics



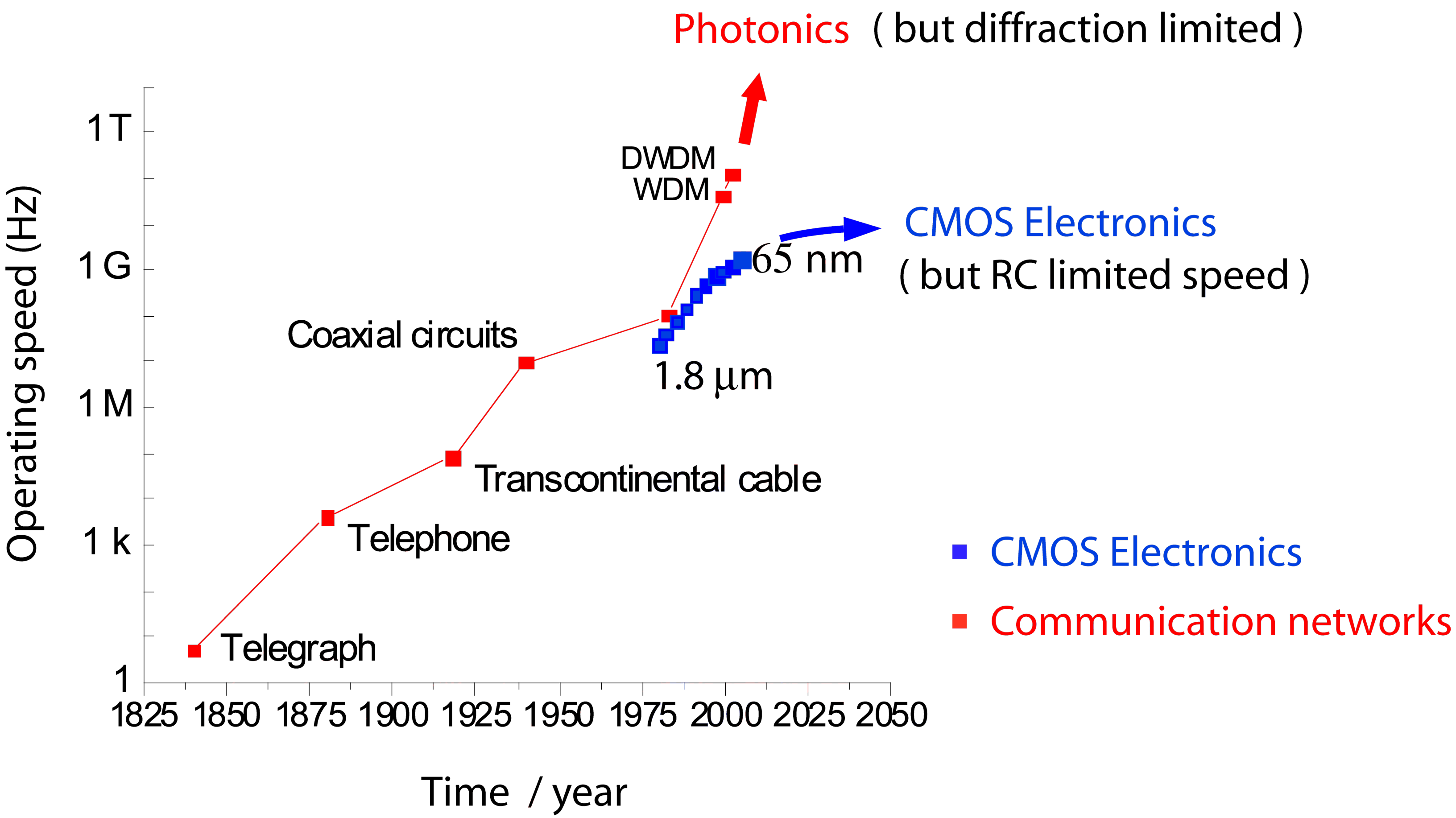
CMOS limitations

As **bit rates** *and* packing **densities** INCREASE,
electrical interconnects become progressively limited by ***RC***-delay:

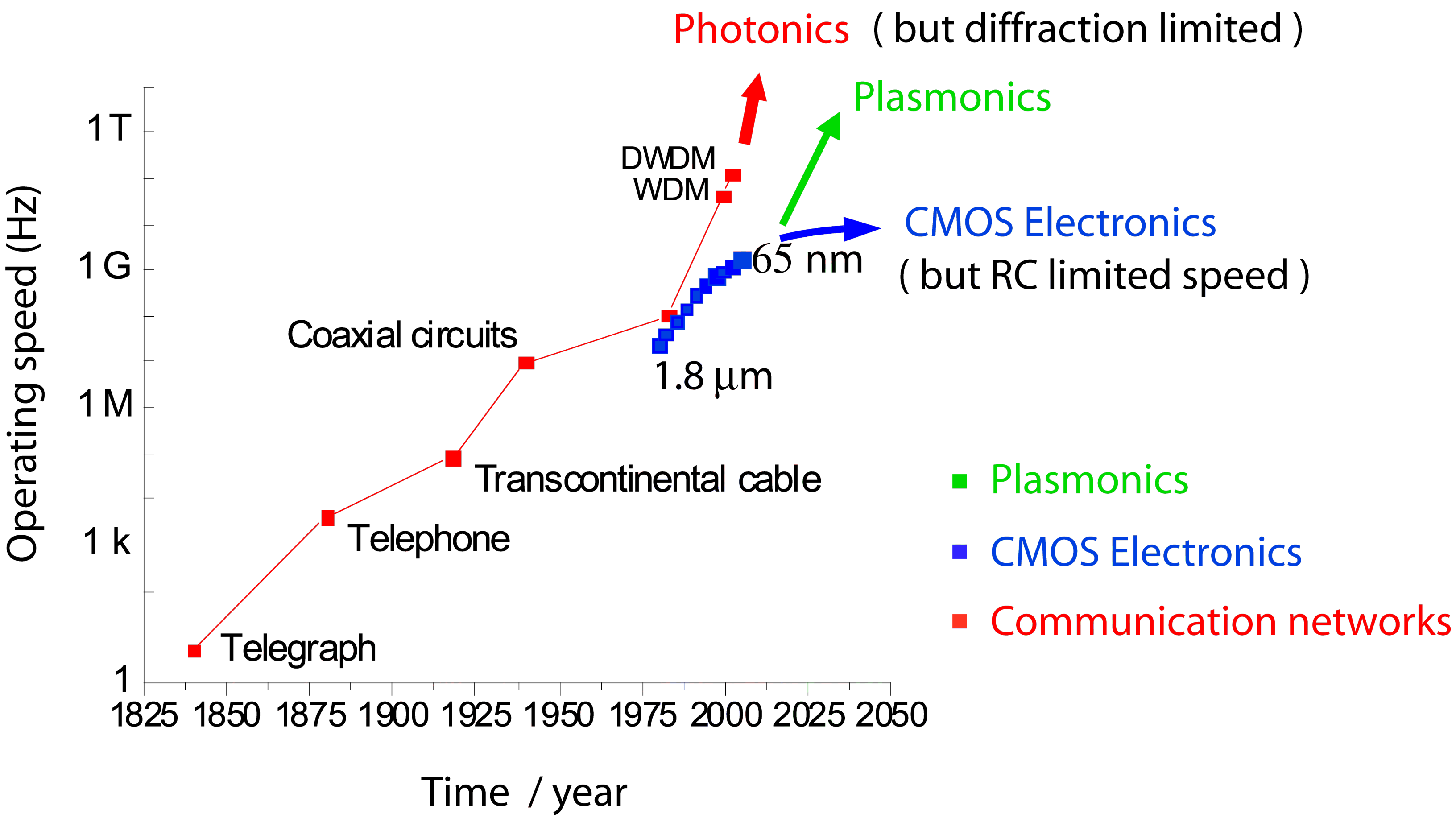
$$R \propto \frac{L}{A} \;\forall\; C \propto L \Rightarrow B_{\max} \propto \frac{1}{RC} \propto \frac{A}{L^2}$$

Electronics is aspect-ratio *limited in speed!*

Nanoplasmonics emerging from photonics and electronics

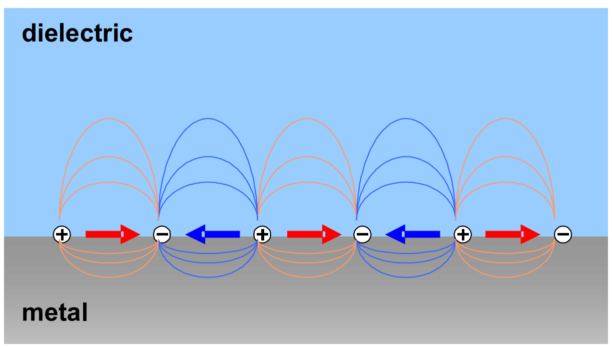


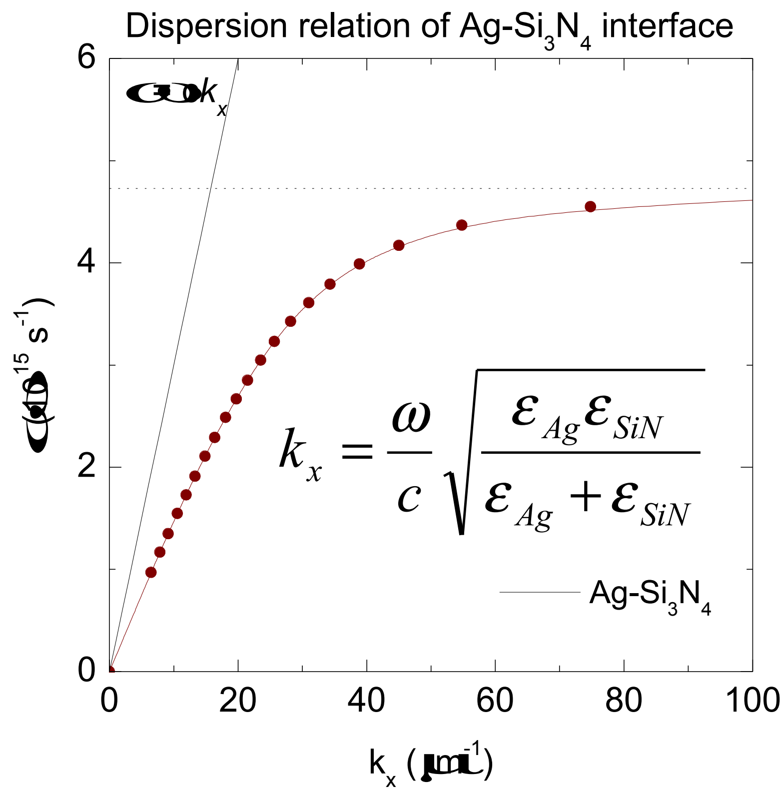
Nanoplasmonics emerging from photonics and electronics



Surface Plasmonics

ω_{SP} when $\varepsilon_m = -\varepsilon_d$

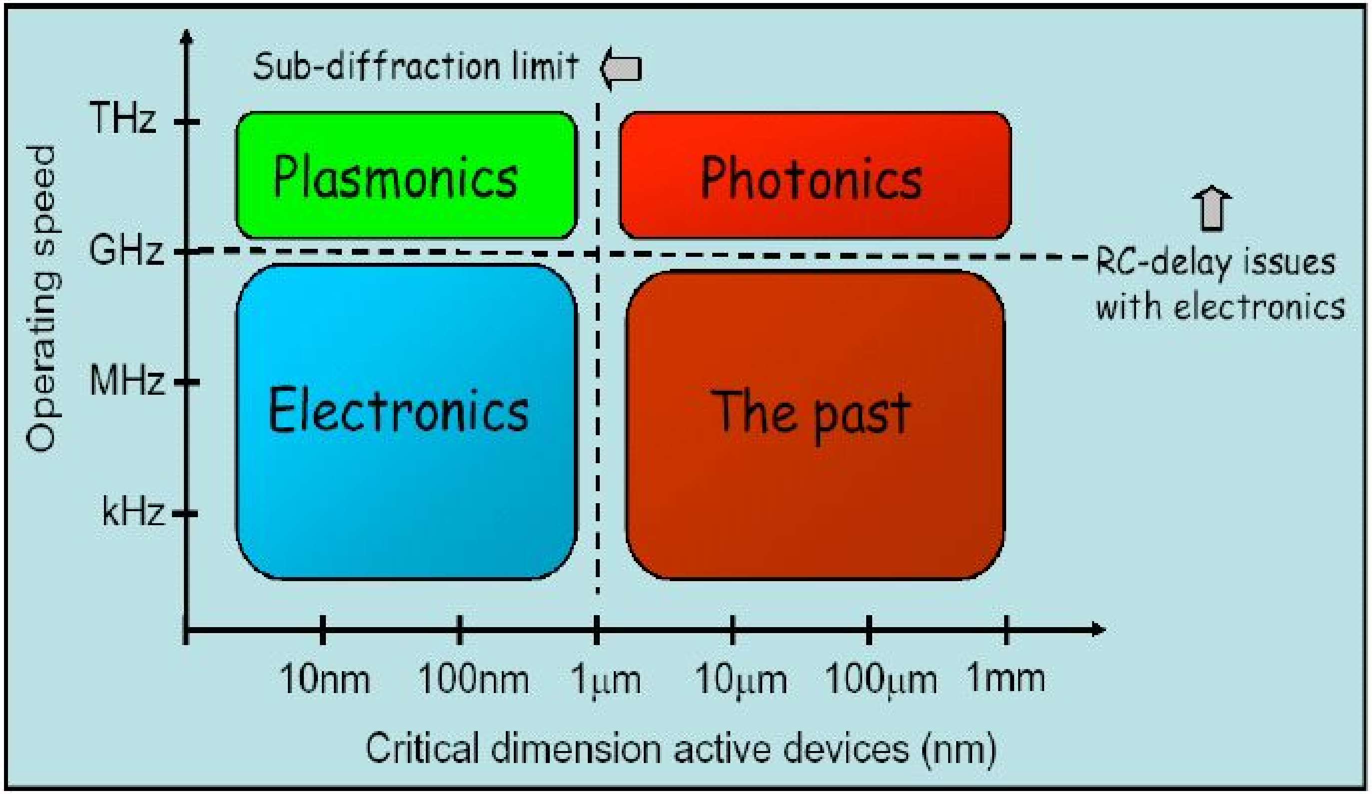




***Surface Plasmons wavelengths* can reach nanoscale dimension at optical frequencies!**

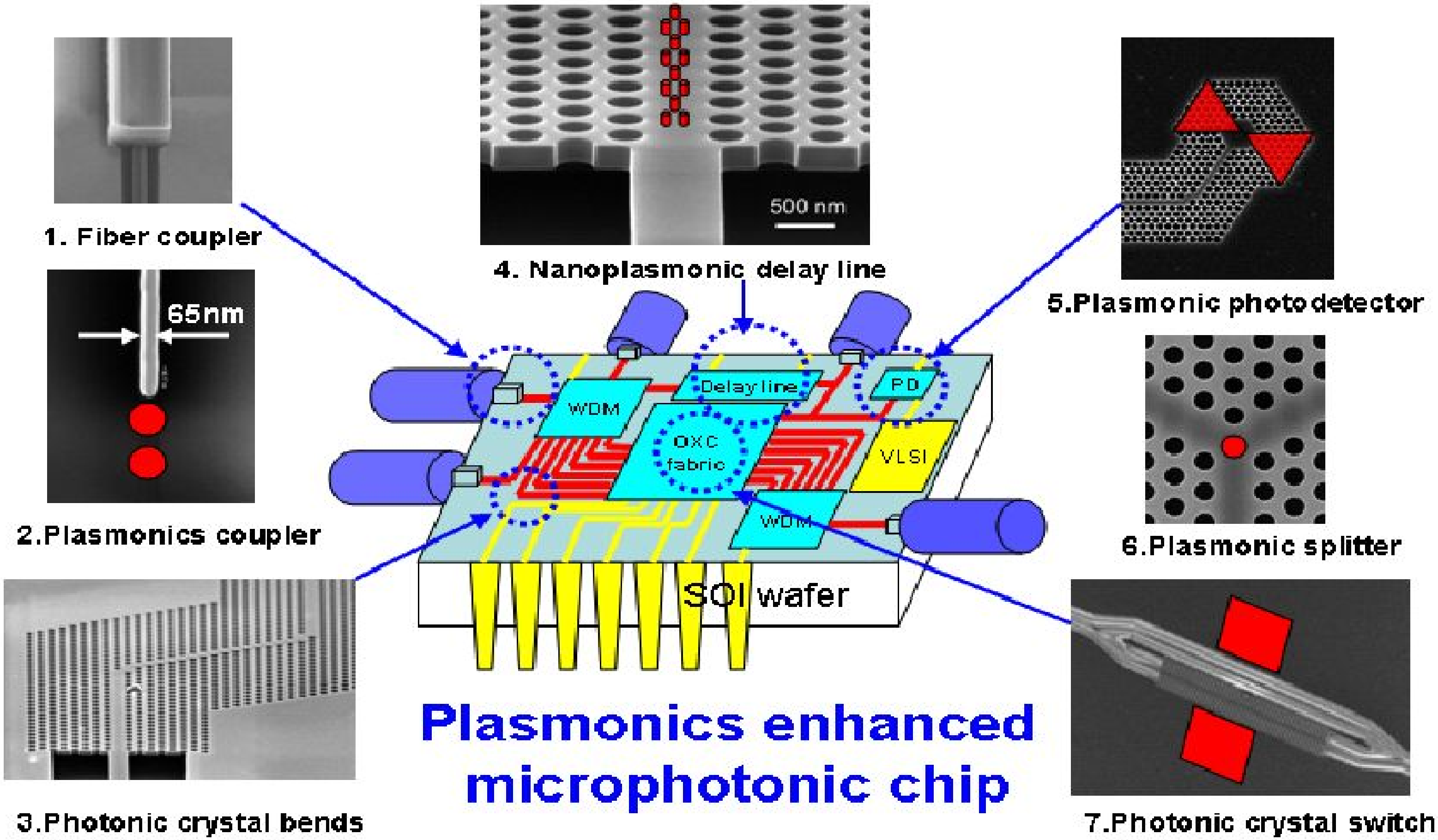
SPPs are "x-ray waves" with optical frequencies

Nanoplasmonics emerging from photonics and electronics



Courtesy of M. Brongersma

Down the Road: Plasmonic Chips



Courtesey: Y. Vlasov, IBM