Nanophotonics with the Scanning Electron Microscope

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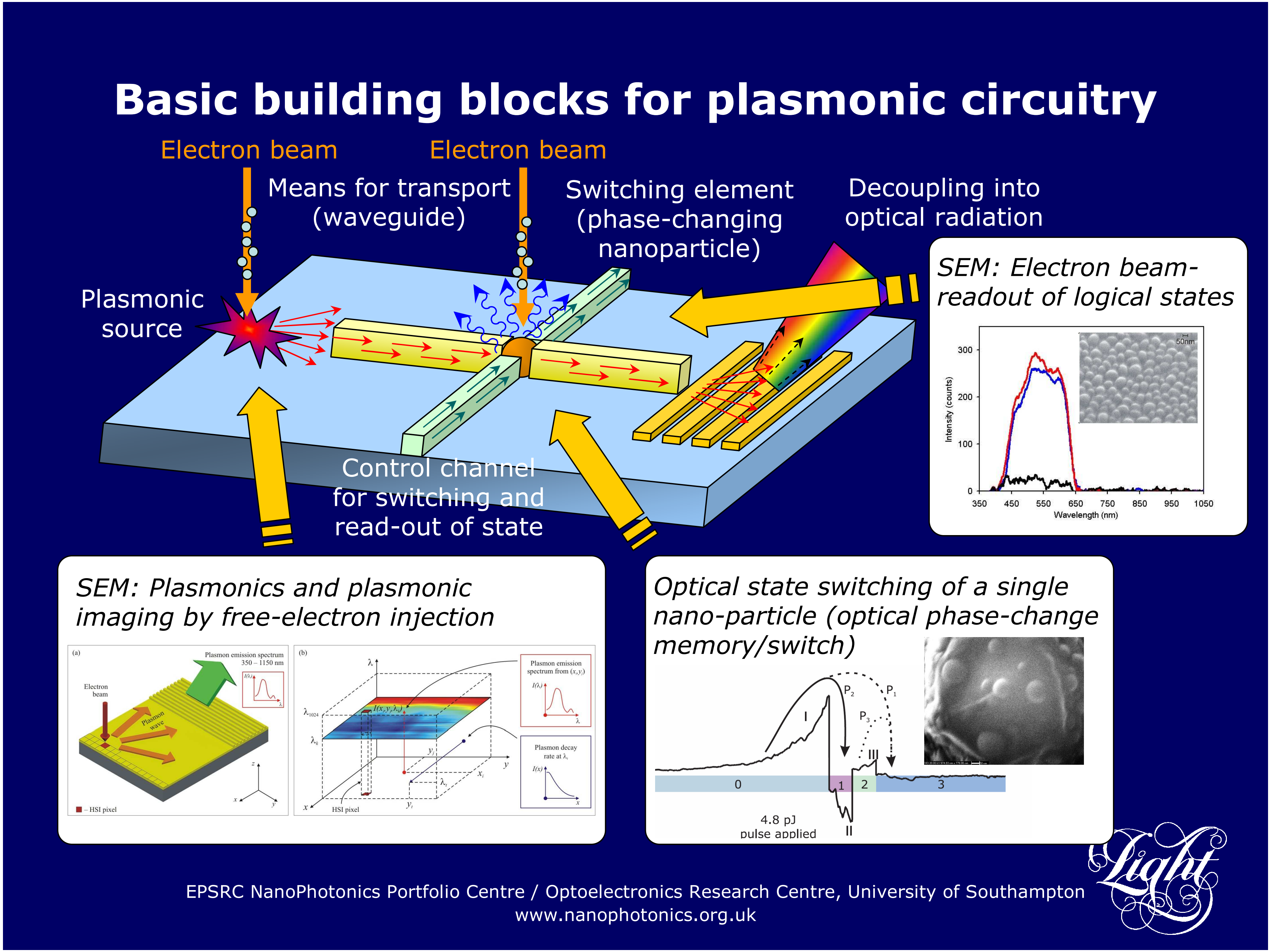
Outline

- Phase change memory functionality
- Growth of nanoparticles for phase-change memory functionality
- Optical read-out of phase-change memory
- Single nanoparticle phase-change memory
- Electron beam readout of phase-change memory states
- Conclusions


Basic building blocks for plasmonic circuitry
Electron beam
Electron beam
Means for transport (waveguide)
Switching element (phase-changing nanoparticle)
Decoupling into optical radiation
Plasmonic source
Control channel for switching and read-out of state
SEM: Electron beam-readout of logical states
300
200
100
0
Intensity (counts)
350
450
550
650
750
850
950
1050
Wavelength (nm)
50nm
SEM: Plasmonics and plasmonic imaging by free-electron injection
(a)
Plasmon emission spectrum 350 – 1150 nm
Electron beam
Plasmon wave
– HSI pixel
(b)
Plasmon emission spectrum from (x, y)
Plasmon decay rate at λ
HSI pixel
Optical state switching of a single nano-particle (optical phase-change memory/switch)
I
II
III
0
1
2
3
4.8 pJ pulse applied
EPSRC NanoPhotonics Portfolio Centre / Optoelectronics Research Centre, University of Southampton
www.nanophotonics.org.uk
Light

In general: Why phase-change memories?

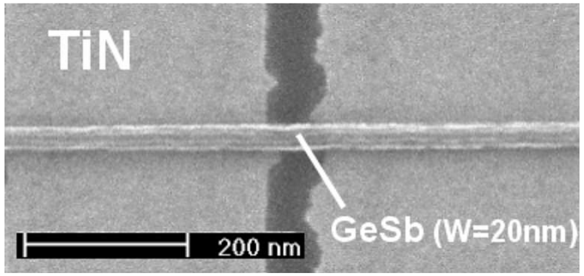
- *Flash memory expected to encounter significant scaling limitations in the near future* - IBM Research (December 2006)
- Writing data into a flash memory is 1000 times slower than DRAM or SRAM
- Extremely difficult to keep current cell design of flash non-volatile as Moore's Law shrinks its minimum feature sizes below 45 nm

Hard disk technology,
500 GB (2006, Hitachi),
0.1 Tb/in^2
Bit cell: ~80 nm

Flash technology,
32 GB (2006, Samsung)
40 nm process

HD DVD
15GB/layer (2006), 0.009 Tb/in^2
Bit cell: ~280 nm

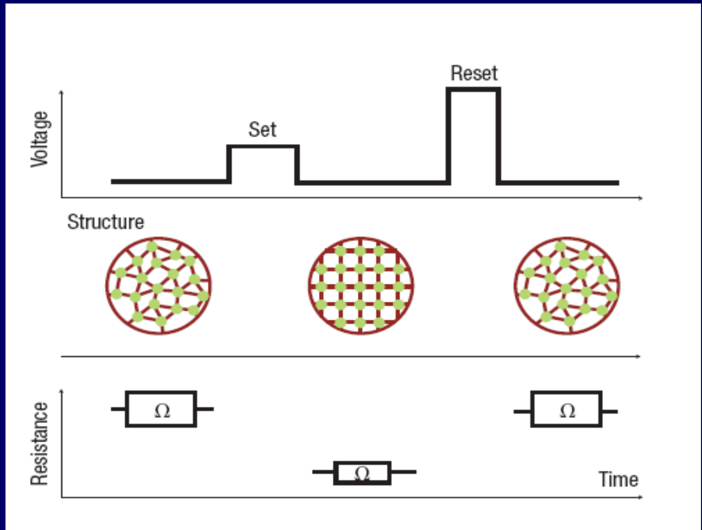
Blu-ray Disc
25GB/layer (2006)
0.015 Tb/in^2
Bit cell: ~220 nm



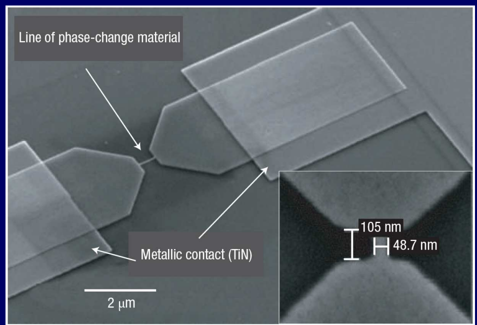
Phase-change memory element
(December 2006, IBM Research)
Bit cell: ~20 nm

Phase-change memory functionality

Electronic

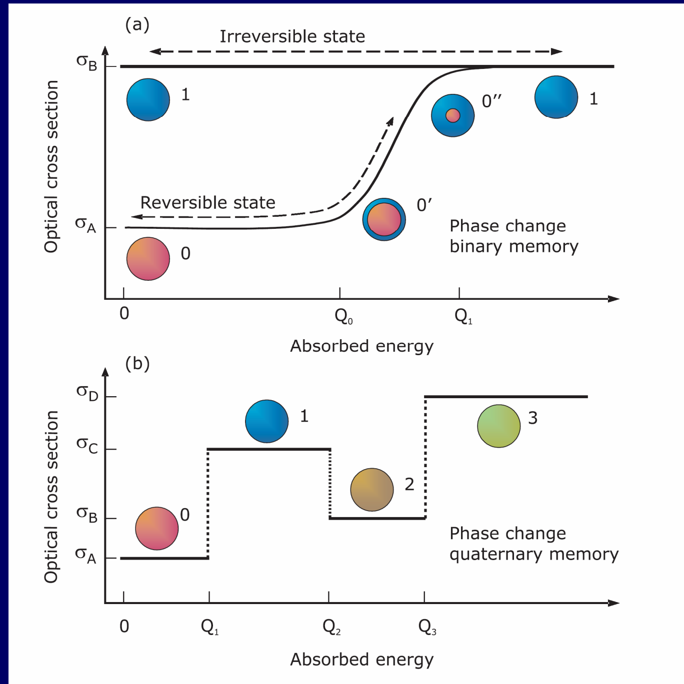


- Transition between crystalline and amorphous phases
- Changing resistivity of medium



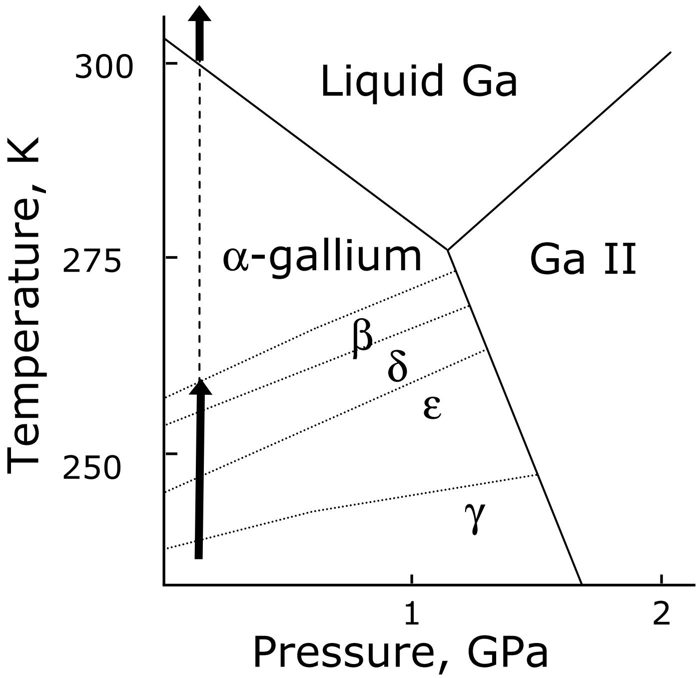
Lankhorst *et al.*, Nature Matrials **4**, 347 (2005)

Optical



- Nanoparticles of phase-change media
- Crystalline-amorphous or crystalline-crystalline transition
- Changing optical cross-section
- Switching energy as low as 400 fJ

The crystalline phases of gallium



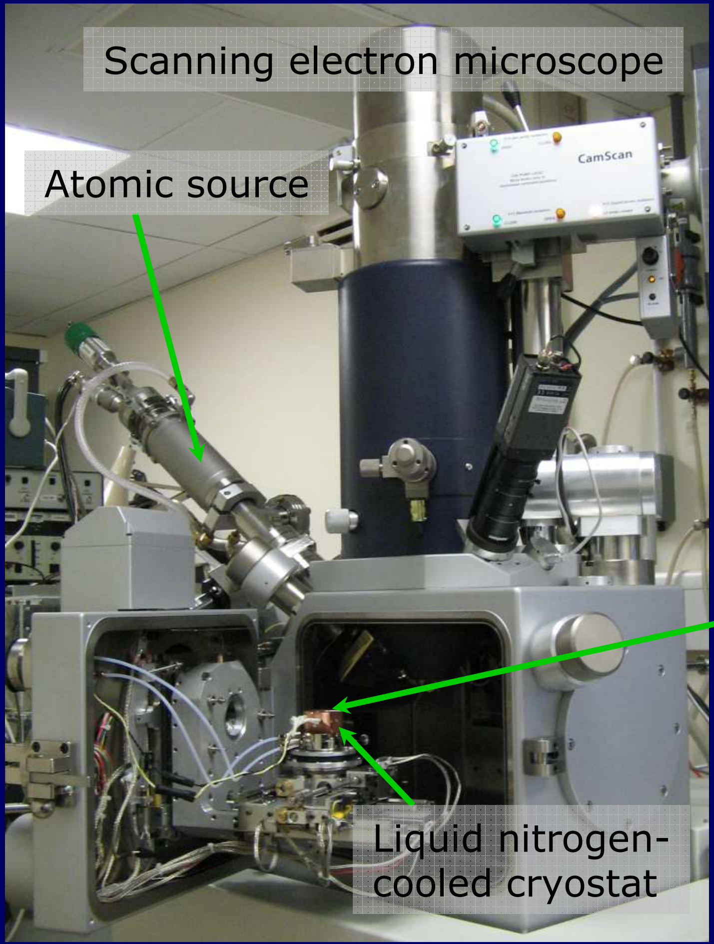
Crystalline parameters at absolute vacuum

Phase	Structure	T_m	Lattice parameters
α (stable)	Orthorhombic	29.78°C / 302.92K	a = 4.5186 b = 7.6570 c = 4.5258 (at $T = T_m$)
β (metastable)	Monoclinic	-16.3°C / 256.85 K	a = 2.7713 b = 8.0606 c = 3.3314 β = 91.574°
δ (metastable)	Rhombic	-19.4°C / 253.8 K	a = 7.729 α = 72.02°
ε (metastable)	unknown	-28.6°C / 244.6 K	unknown
γ (metastable)	Orthorhombic	-35.6°C / 237.6 K	a = 10.593 b = 13.523 c = 5.203 (at $T=T_m$)

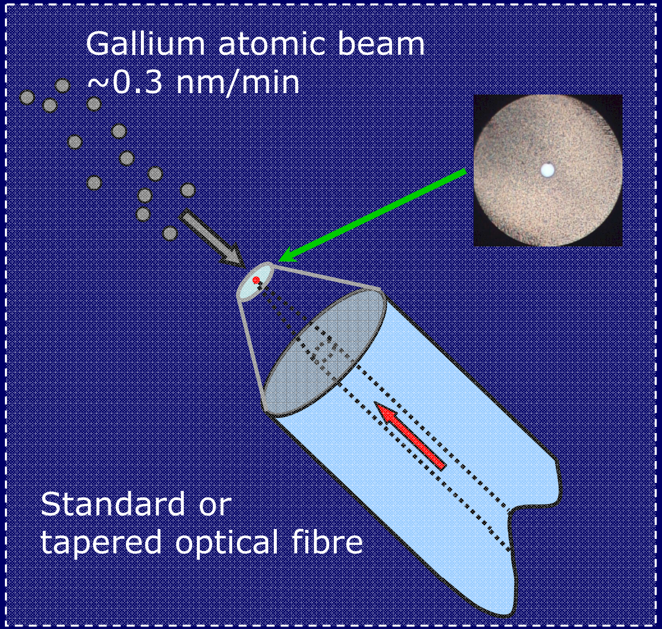
Different phases possess different optical properties

[A. Defrain, J. Chimie Phys. **74**, 851 (1977)]

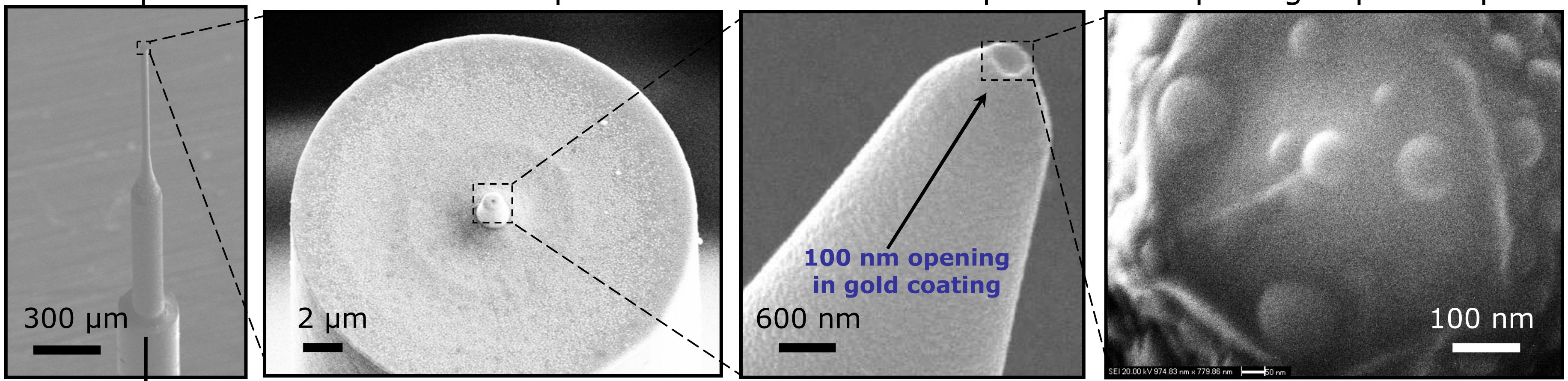
Growth of nanoparticles for phase-change memory functionality

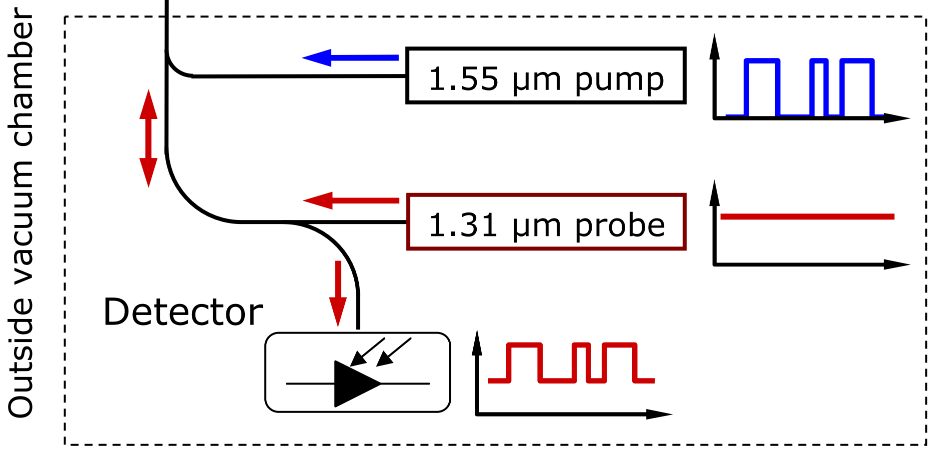


- Sputtering of gallium nanoparticles onto the end face of an optical fiber
- Light-assisted growth performed in situ of a scanning electron microscope



Growth of a single nanoparticle

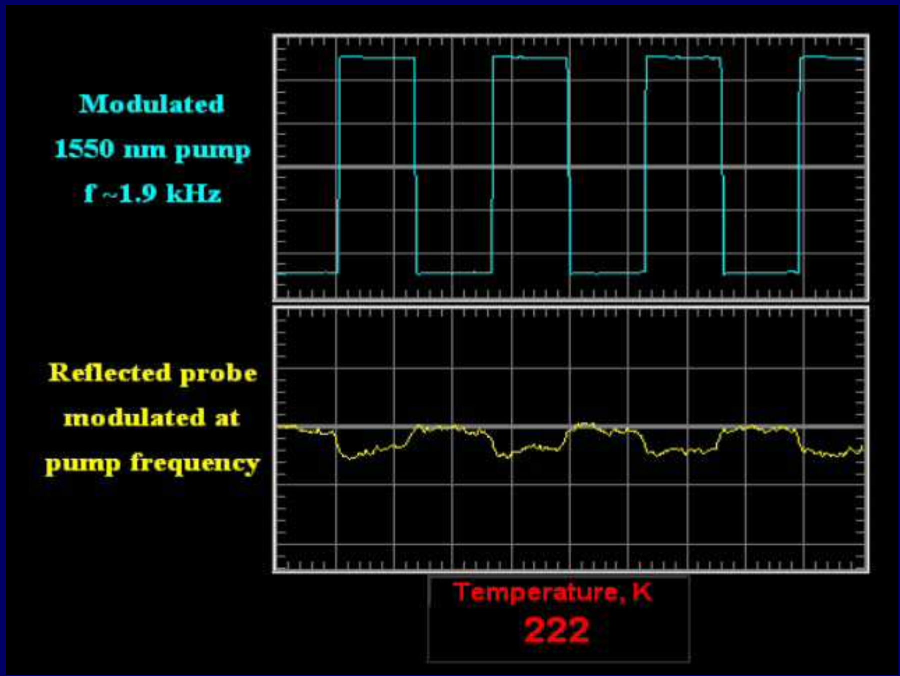




- 80 nm gallium nanoparticle grown at the 30 nm aperture of a scanning-nearfield optical microscopy (SNOM) probe
- Pump-probe setup for reading optical cross-section (reflectivity)

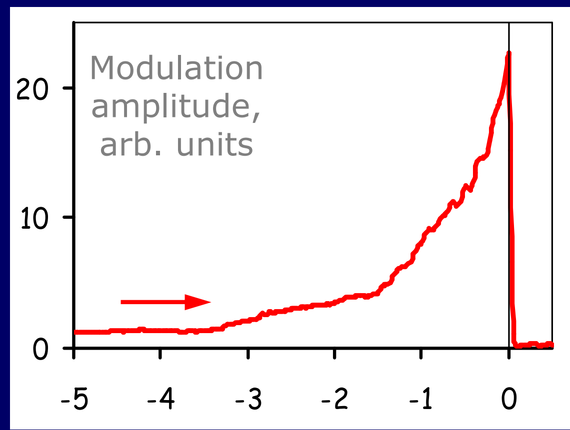
Pump-probe detection of optical cross-section

CW 1310 nm probe

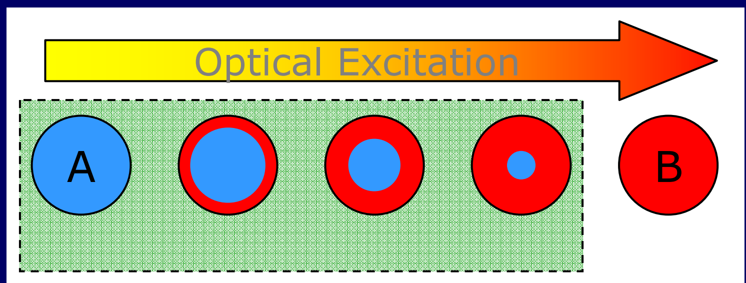


1550 nm pump
~30 nW

Reflected probe

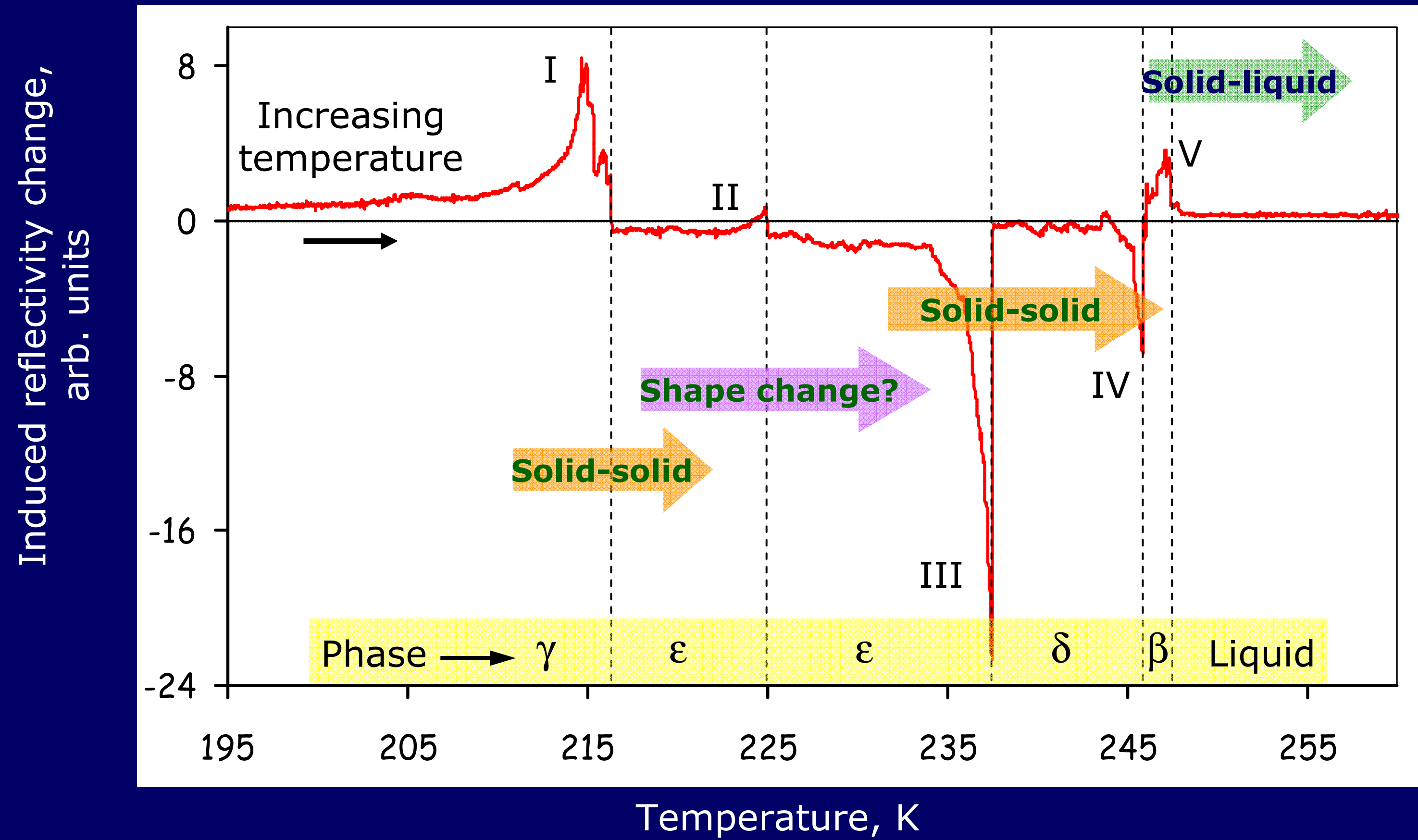


$T - T_{peak}$, K



Reversible phase transitions

Light-induced phase transitions in a single nanoparticle

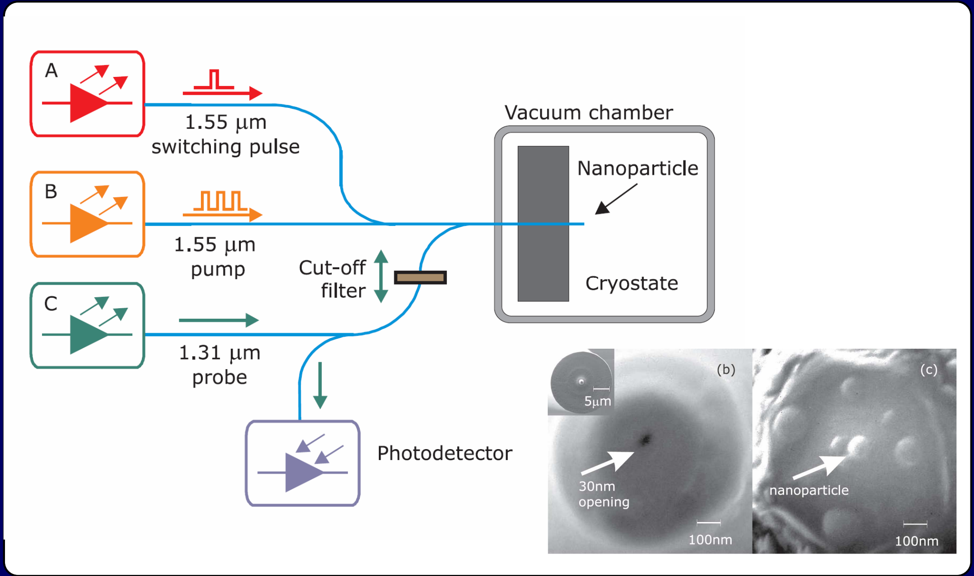


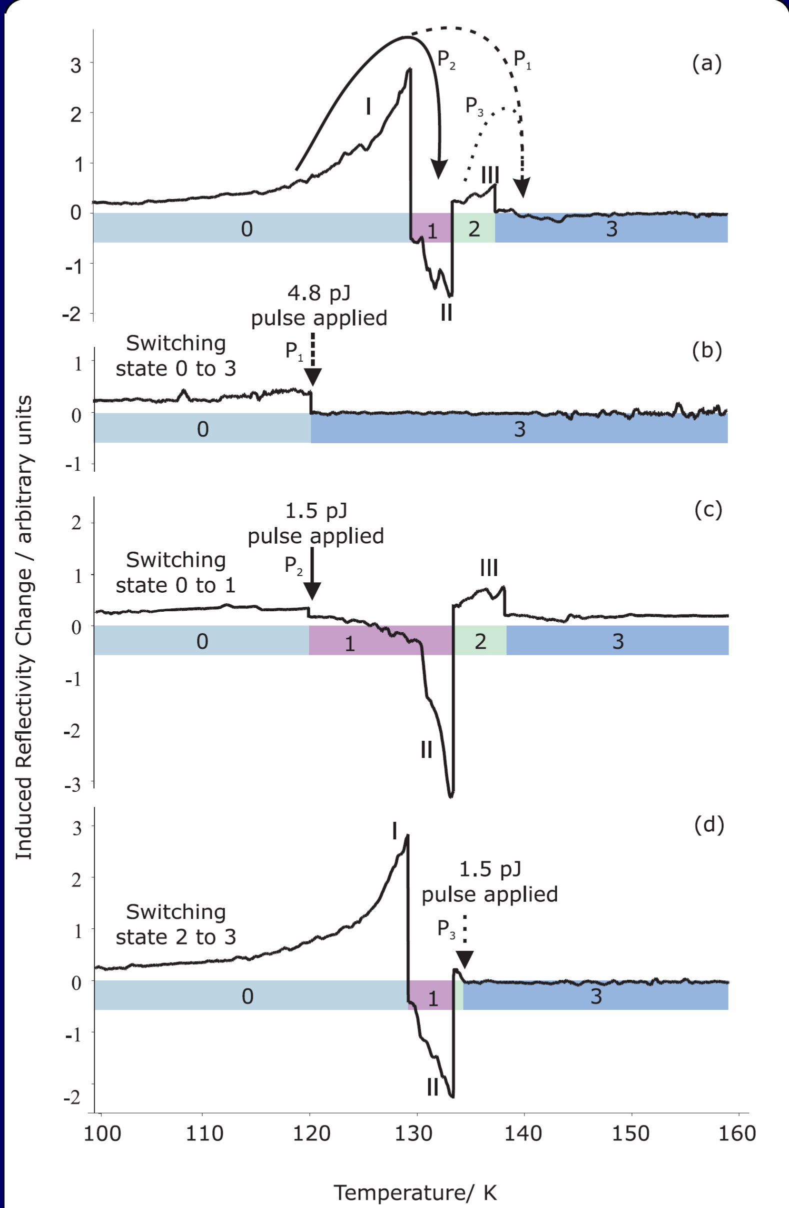
[Soares *et al*., Nano Lett. **5**, 2104 (2005)]

- Control power at aperture ~30 nW
- Detection of nanoparticle's optical sensitivity to supplied thermal energy

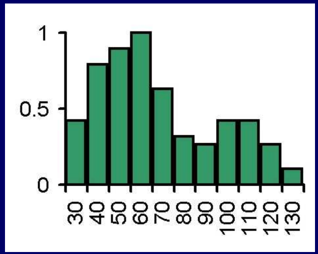
Memory functionality of a single nanoparticle

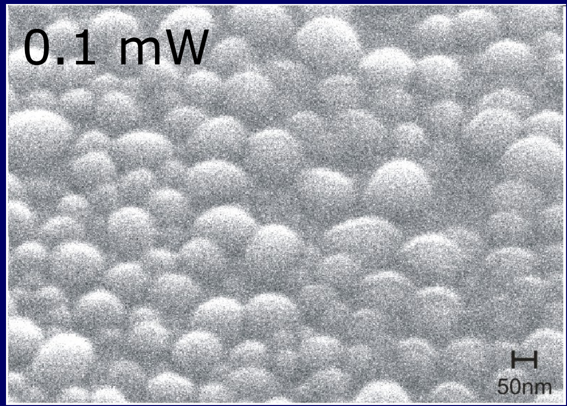
- Switching of state achieved by single optical pulses of 1.5 and 4.8 pJ (in fiber)
- Switching energies of 150 and 480 fJ
- Optical pump-probe readout of cross-section of nanoparticle
- Four-level (quaternary-logic) memory

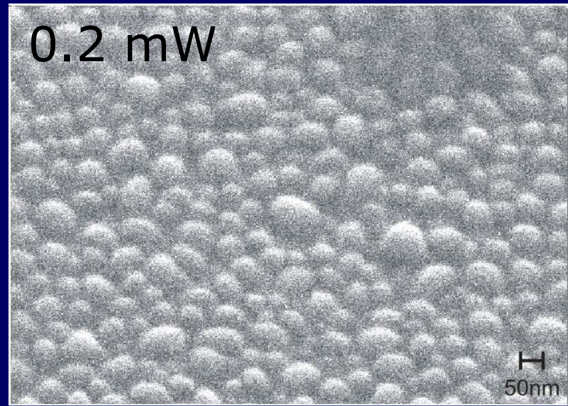


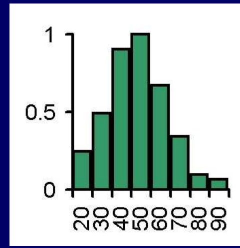


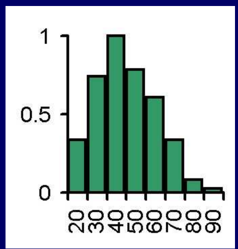
Optimisation of light-assisted nanoparticle growth

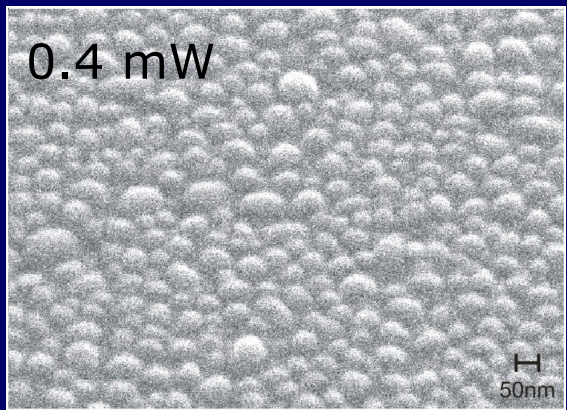


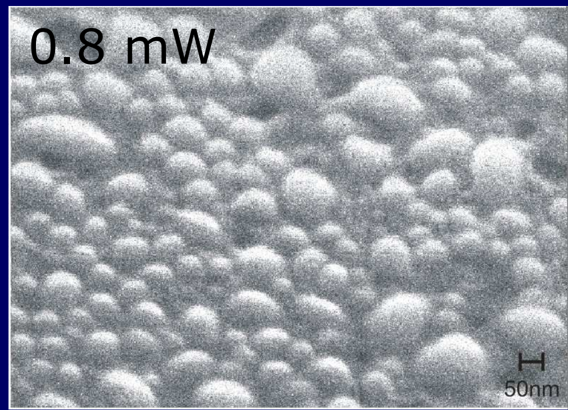


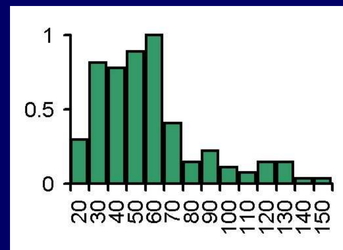


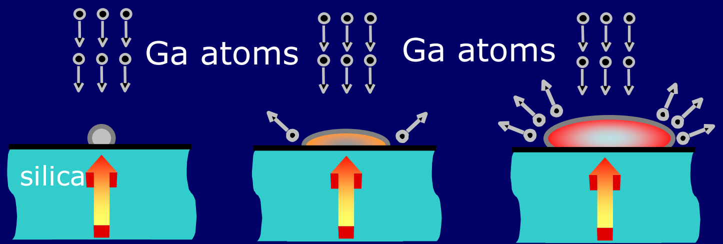






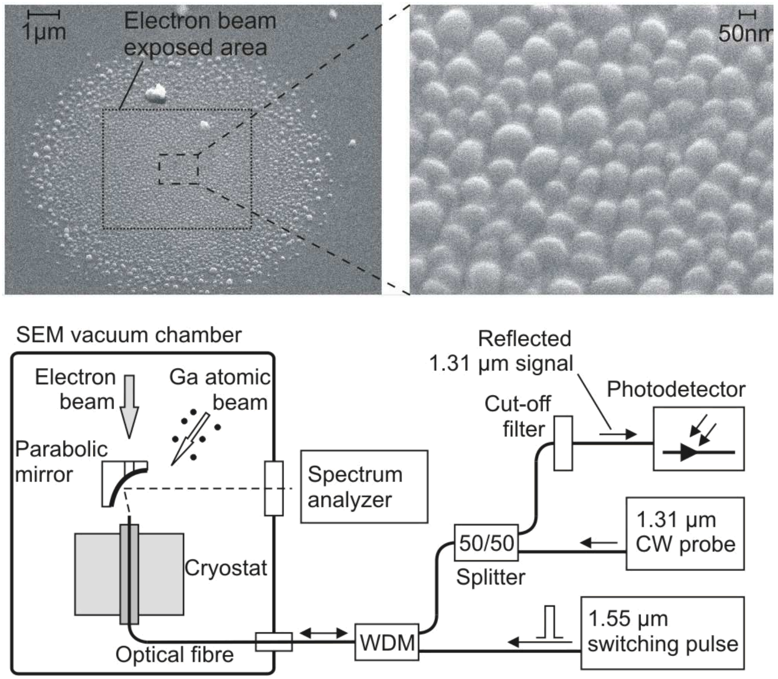


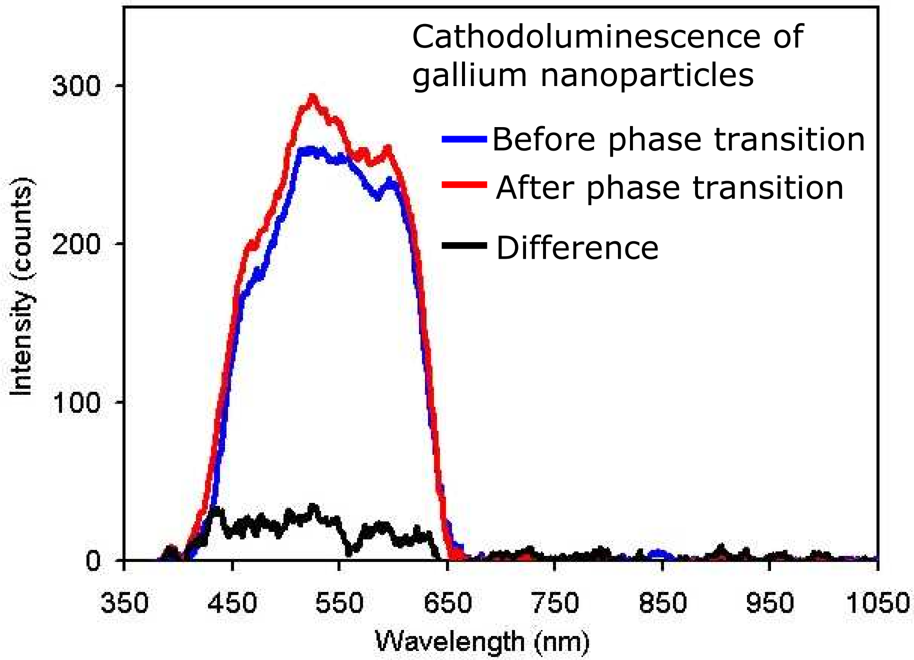




Average power	0.1 mW	0.2 mW	0.4 mW	0.8 mW
Median size	70 nm	50 nm	45 nm	60 nm

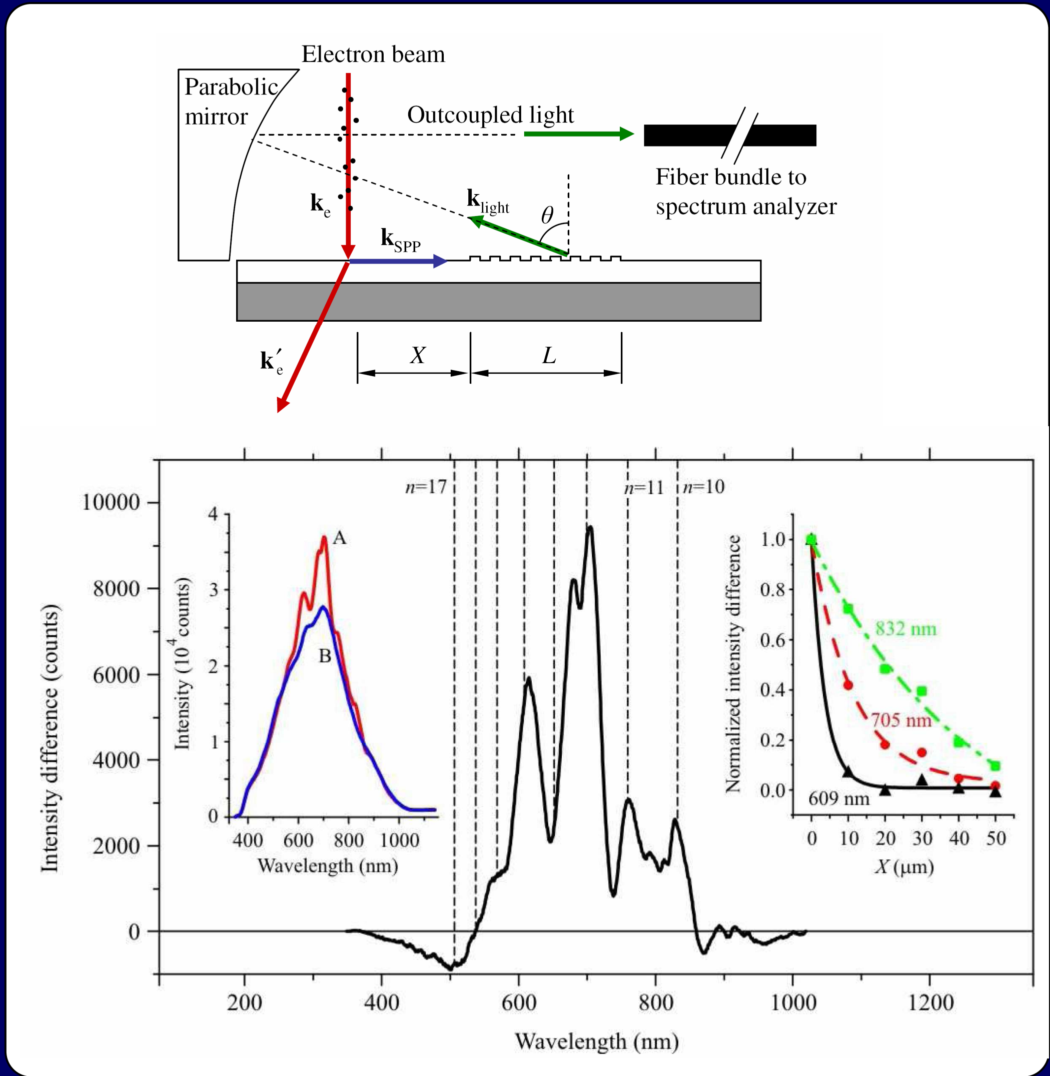
Electron beam-readout of phase

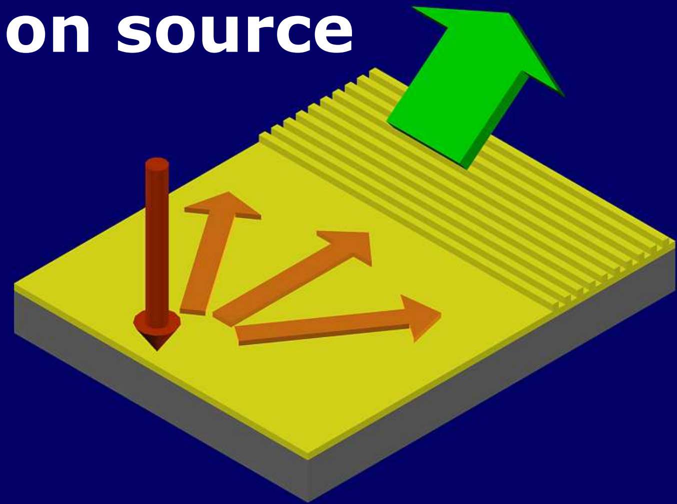




- Cathodoluminescence readout of phase of nanoparticles
- Difference of 10% in emission detected at 520 nm
- Technique not limited by optical diffraction
- Low energy deposition leaves memory state intact

Future outlook: The scanning electron microscope as a plasmon source





- The SEM as a tool for analysis of plasmonic structures
- The injected electron beam as a highly confined source of plasmons

  [Bashevoy *et al.*, Nano Letters **6**, 1113-1115 (2006)]

Recent developments on plasmonic imaging is reported tomorrow, talk THU2o.1

Conclusions

- The scanning electron microscope as an optical workbench for nanophotonics
- First demonstration of a quaternary optical phase-change memory element in a single gallium nanoparticle
- Optimization of light-assisted growth of nanoparticles, to reach below 45 nm size
- Cathodoluminescence readout of optically written state
- The scanning electron microscope as a highly localised plasmonic source

References

[1] M.V. Bashevoy *et al.*, Nano Lett. **6**, 1113 (2006).

[2] B.F. Soares *et al.*, Optics Express **14**, 10652 (2006).

[3] B.F. Soares *et al.*, Nano Lett. **5**, 2104 (2005).

[4] S. Pochon *et al.*, Phys. Rev. Lett. **92**, 145702 (2004).

Non-volatile data storage – a brief overview

Optical binary phase-change media

CD 650 MB (1983)
Bit cell: ~1.4 μm

4.7 GB/layer (1996)
Bit cell: ~510 nm

25GB/layer (2006)
0.015 Tb/in^2
Bit cell: ~220 nm

15GB/layer (2006), 0.009 Tb/in^2
Bit cell: ~280 nm

Audio, Mobile storage, USB memories

Electronic

Flash, 128 KB
(1988, Toshiba)

Flash, 32 GB (2006, Samsung)
40 nm process

Cameras, iPods, ...

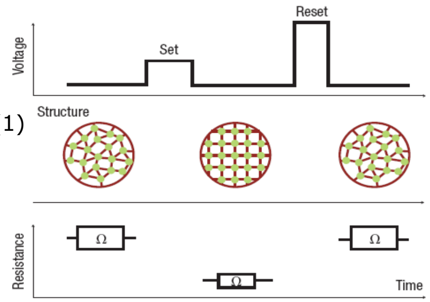
Magnetic hard disk technology

5 MB (1957, IBM Ramac)
50 24” discs, 1.7 Kb/in^2
Bit cell: ~600 μm

500 GB (2006, Hitachi),
0.1 Tb/in^2
Bit cell: ~80 nm

Electronic binary phase-change media

Examples:
- Doped SbTe [1]
- $Ge_2Sb_2Te_5$ [2]



[1]Lankhorst, Nature Mat. 4, 347 (2005)
[2]Welnic, Nature Mat. 5, 56 (2006)

Isolated nanoparticles for optical phase change memory functionality and *optical or plasmonic switches*
Bit cell: ~45 nm

Perpendicular recording

0.34 Tb/in^2 (Sep 2006, Hitachi Research)
Bit cell: ~45 nm