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**

- **Plasmonic source**
- **Means for transport (waveguide)**
- **Switching element (phase-changing nanoparticle)**
- **Decoupling into optical radiation**

**Control channel for switching and read-out of state**

**SEM: Plasmonics and plasmonic imaging by free-electron injection**

**Optical state switching of a single nano-particle (optical phase-change memory/switch)**
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/in²
Bit cell: ~80 nm

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

**HD DVD**, 15GB/layer (2006), 0.009 Tb/in²
Bit cell: ~280 nm

**Blu-ray Disc**, 25GB/layer (2006) 0.015 Tb/in²
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

**Optical**

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

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The crystalline phases of gallium

Different phases possess different optical properties

[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

Modulated
1550 nm pump
f ~ 1.9 kHz

Optical Excitation

Reversible phase transitions

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www.nanophotonics.org.uk
Light-induced phase transitions in a single nanoparticle

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

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

<table>
<thead>
<tr>
<th>Average power</th>
<th>0.1 mW</th>
<th>0.2 mW</th>
<th>0.4 mW</th>
<th>0.8 mW</th>
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</thead>
<tbody>
<tr>
<td>Median size</td>
<td>70 nm</td>
<td>50 nm</td>
<td>45 nm</td>
<td>60 nm</td>
</tr>
</tbody>
</table>

Ga atoms

silica
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
Non-volatile data storage – a brief overview

**Optical binary phase-change media**
- 25GB/layer (2006) 0.015 Tbit/in²
  - Bit cell: ~220 nm
- 4.7 GB/layer (1996)
  - Bit cell: ~510 nm
- CD 650 MB (1983)
  - Bit cell: ~1.4 µm
- 15GB/layer (2006), 0.009 Tbit/in²
  - Bit cell: ~280 nm

**Electronic binary phase-change media**
- Examples:
  - Doped SbTe (1)
  - Ge₂Sb₂Te₅ (2)

**Electronic magnetick hard disk technology**
- 0.34 Tbit/in² (Sep 2006, Hitachi Research)
  - Bit cell: ~45 nm

**Magnetic hard disk technology**
- 5 MB (1957, IBM Ramac)
  - Bit cell: ~600 µm
- 50 24” discs, 1.7 Kb/in²

**Electronic storage, USB memories**
- Flash, 128 KB (1988, Toshiba)
  - Flash, 32 GB (2006, Samsung)
  - 40 nm process

**Audio, Mobile storage, USB memories**
- Cameras, iPods, ...

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

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