Materials, devices and applications of Si-based optoelectronics

S. Coffa

Si Optoelectronics, bioelectronics and nano-organics
Corporate R&D, STMicroelectronics, Catania
Outline

◆ Aims

➢ Scientific challenges, targets and market perspectives of Si-based optoelectronics

◆ Applications

➢ Fabrication, performances and applications of Si-based optical devices
➢ Integrated Si-based optoelectronics as enabling technology in multifunctional devices

• Biosensors
• Novel optical memories and molecular switches

◆ Conclusions
Scientific challenges, targets and market perspectives of Si-based optoelectronics
Science and Technology for Fun and Profit

“TECHNOLOGICAL INNOVATION AND SCIENTIFIC DISCOVERY generated much of the Nation’s economic growth over the past 50 years, creating millions of jobs, and improving the quality of life. For example, about two-thirds of the 80% gain in economic productivity since 1995 can be attributed to information technology.”

*The Budget of the United States Government for Fiscal Year 2003*
# OPTICAL SMC vs TOTAL SMC DEVICES

## WW REVENUE and FORECAST 99-05

<table>
<thead>
<tr>
<th>($M)</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>CAGR (%) 2000-2005</th>
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<td><strong>Total Semiconductors</strong></td>
<td>170,678</td>
<td>225,475</td>
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<td>147,529</td>
<td>191,929</td>
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<td>202,097</td>
<td>252,343</td>
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<td>Nonvolatile Memory</td>
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<td>17,365</td>
<td>15,151</td>
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<td>Other Memory</td>
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<td>899</td>
<td>800</td>
<td>841</td>
<td>951</td>
<td>1,000</td>
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<td>68,372</td>
<td>54,820</td>
<td>59,830</td>
<td>70,900</td>
<td>90,900</td>
<td>100,400</td>
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<td>Microprocessors</td>
<td>28,531</td>
<td>31,502</td>
<td>25,100</td>
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<td>31,000</td>
<td>37,000</td>
<td>40,000</td>
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<td>Microcontrollers</td>
<td>11,747</td>
<td>15,304</td>
<td>13,600</td>
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<td>18,000</td>
<td>23,000</td>
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<td>Microperipherals</td>
<td>12,570</td>
<td>15,271</td>
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<td>Digital Signal Processors</td>
<td>4,690</td>
<td>6,285</td>
<td>4,720</td>
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<td>7,300</td>
<td>9,600</td>
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<td><strong>Digital Logic</strong></td>
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<td>38,508</td>
<td>30,485</td>
<td>34,017</td>
<td>39,366</td>
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<td>ASICS</td>
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<td>24,487</td>
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<td>Custom ICs</td>
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<td>1,258</td>
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<td>633</td>
<td>402</td>
<td>235</td>
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<td>Standard Logic</td>
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<td>3,145</td>
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<td>2,225</td>
<td>2,155</td>
<td>2,041</td>
<td>1,909</td>
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<td><strong>Total Other Logic</strong></td>
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<td>8,946</td>
<td>10,302</td>
<td>12,322</td>
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<td><strong>Discrete</strong></td>
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<td>22,999</td>
<td>4.4</td>
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<td>7,235</td>
<td>10,690</td>
<td>9,100</td>
<td>10,550</td>
<td>13,230</td>
<td>16,790</td>
<td>16,880</td>
<td>9.6</td>
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Source: Gartner Dataquest (September 2001)

OPTICAL SEMICONDUCTOR PF & Supplier 2000

Structure Sem. OptoElec PF

Source: WSTS

- Optoelectronics: Total $9.8B
  - Laser: 35%
  - Image sensors: 15%
  - Others & infrared: 11%
  - Other devices: 26%
  - Couplers: 13%

Opto is a fast-growing market driven by communication and consumer!

TOP Five SUPPLIERS Ranking

Source: Gartner Dataquest Sept 01

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<th>Rank</th>
<th>Company</th>
<th>Revenue</th>
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<td>Agilent Technologies</td>
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<td>2</td>
<td>Lucent Technologies</td>
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<td>3</td>
<td>Sharp</td>
<td>1,238</td>
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<td>4</td>
<td>Sony</td>
<td>1,095</td>
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<tr>
<td>5</td>
<td>Toshiba</td>
<td>741</td>
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Top Five Total - 5,919
Top Five Share of Market (%) - 55.4

Total Opt.Smc. 2000 $10.69B
NEW OPPORTUNITIES FOR OPTOELECTRONIC

Electronic Market growth by Segment

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<th>Segment</th>
<th>CAGR 2000-2006 in %</th>
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<td>Communication</td>
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<td>Automotive</td>
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<td>PC</td>
<td>7.5%</td>
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<tr>
<td>Consumer</td>
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<td>Industrial &amp;</td>
<td>5%</td>
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<tr>
<td>Military</td>
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<tr>
<td>Total</td>
<td>8%</td>
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TOT 2000 $ 975B

Communication Segment will be the best future “opportunity” in electronic market.

“fiber-optic system and optical interconnect technologies” as one of the strategic area for future significant investment....


Driving force: Internet and Portability

A great future for Integrated Optoelectronic devices

Integrated Optoelectronics Component Growth:
<1% in 00 to 37% in 2009

Source: ElectronicCast Corp, May 01

DEVELOPMENT OF INTEGRATED PHOTONIC DEVICES

Active Components + Passive Components + electronics

on the Same Chip

using PLANAR TECHNOLOGY

Manufactured with Si Electronic IC technologies

Si-based materials and processes for optical devices
Fabrication, performances and applications of Si-based optical devices

See also:  D21.3 Quantum dot materials and devices for light emission in Si by M.E. Castagna et al.
          DP.28 Integrated Si-based Opto-couplers: a novel approach to galvanic insulation by A. Alessandria et. al
Si-based light emitting devices (LEDs)

Gate dielectric:

- Thermally grown SiO₂ layer (620 A)
- PECVD Silicon Rich Oxide (SRO, 1000 A)

Er introduced by ion implantation
Post implantation anneal: 800-1100°C
World record efficiency for Si-based LEDs

- We have fabricated the world-record Si-based LED using Si processing
- The efficiency (10%) is similar to that of state-of-the-art LED using III-V semiconductors
Charge transport in an Er doped SiO$_2$ film: Fowler-Nordheim

\[ J = AE^2 e^{-\frac{B}{E}} \]

\[ Q_{BD}=13.2 \text{ C/cm}^2 \text{ (undoped SiO}_2\text{)} \]

\[ Q_{BD}=30 \text{ C/cm}^2 \text{ (Er-doped SiO}_2\text{)} \]

\( J = 0.04 \text{ A/cm}^2 \)
Devices emitting at different wavelengths

Ion implantation: Pr, Ce, Tb e Yb:
- fluence: $1 \cdot 10^{15}$ cm$^{-2}$
- implantation energy: 50 keV

TERBIUM

CERIUM
Rare earth doped SRO films

Si nanostructures

SiO₂

Si

Er

EC

Eₐ

Ev

Si nanostructure

Er ion

Annealing: 1050 °C 30 min, N₂

SRO films deposited by PECVD
Rare earth ion incorporation by ion implantation
Electro-luminescence from Er-doped SRO films

\[ EL = EL_{\text{max}} \frac{\sigma \tau J}{\sigma \tau J + 1} \]

\[ \sigma(1.61) = 8 \cdot 10^{-16} \text{ cm}^2 \]

\[ \sigma(1.70) = 6 \cdot 10^{-17} \text{ cm}^2 \]

\[ Q_{\text{BD}} = 1000 \text{ C/cm}^2 \]
Infrared detectors using Si/SiGe multilayers

680 °C

750 °C
1.54 μm absorption from Ge films on Si

R = 40 mA/W at 1.5 μm
Light transmission in integrated waveguides

a) SiON waveguides

b) polymer waveguides

Light transmitted through 2 cm long waveguides
Applications of Si-based optoelectronics

Power devices with integrated galvanic insulation

**Optocouplers**
(Functional isolation)

- Digital logic interfaces
- Level shifting
- Data Transmission
- Telecommunications

**Power optoisolation**
(Safety isolation)

- Motor control
- Power supplies
- Solid state relays
- Power meters
Galvanic insulation using Si-based optoelectronics

- Low cost SOI
- Er-doped Si LEDs
- Schottky detectors
- SiON waveguides
**Optical transmission demonstrator**

- **Critical process step**
  - Erbium implantation for emitting diodes
  - SiON etching for waveguides
  - Silicide formation for photodetectors diodes

- **Devices**
  - Erbium-doped LEDs
  - Schottky photodetectors
  - SiON waveguides

- **Process rules**
- **Layout rules**

- **Electrical testing**
  - LED quantum efficiency
  - Photodetectors responsivity
  - Waveguides losses
  - System efficiency
  - Channels decoupling

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*S. Coffa, Si Optoelectronics, Bioelectronics and Nano-Organics, Corporate R&D, ESSDERC 2002, Florence, September 22th, 2002*
Low cost SOI for galvanic isolation

Porous Si formation

\[ (+) \text{ Si} + 2\text{H}_2\text{O} + 4\text{h}^+ = \text{SiO}_2 + 4\text{H}^+ \]
\[ \text{SiO}_2 + 6\text{HF} = \text{SiF}_6^{2-} + 2\text{H}_2\text{O} + 2\text{H}^+ \]

\[ (-) \quad \text{H}^+ + \text{e}^- = \frac{1}{2} \text{H}_2 \]

SEM top view of P-Si structure

Selective formation of buried porous Si films for low cost SOI
Electrical and structural characterisation of oxidised porous Si layers

Poli n+

Oxidised porous Si

p-type Si

![Breakdown Voltage](image)

Y208080 wafer 03

Current [A]

Voltage [V]

-6.0E-05 -4.0E-05 -2.0E-05 0.0E+00 2.0E-05 4.0E-05 6.0E-05

-800 -600 -400 -200 0 200 400 600 800

2.55 micron

0.5 μm

bulk
Schottky photodetectors: structural and electrical characterisations

X-TEM

190 Å

X-SEM

Field oxide
N+ contact
N- well
P+ guard ring

A revolutionary application Si-based optoelectronics

On-chip optical interconnects

- Remove RC bottleneck and simplify design in future Si CMOS ICs
- Optical clock transmission guaranteed by fully integrated optical devices such as Si-based optical amplifiers and lasers
- Development of low cost components for DWDM optical transmission
Design and fabrication of photonic bandgap materials

Photonic bandstructure

cubic array of cylindrical pillars

Si base material (n=3.5):

optimum gap at 1.53 μm
diameter: 225 nm
spacing: 550 nm

Joannopoulos et al.
Structures for photonic bandgap materials (1/2)

The silicon “Temple” Valley

Using these structure full control of light flux can be achieved and ultra-compact optical devices can be fabricated.
Structures for photonic bandgap materials (2/2)

Use of advanced optical lithography instead of e-beam lithography

A light splitter using 0.18 um holes in Si
Optical gain materials for lasers and optical amplifiers

Prototypes available by Q2 2003
Dielectric Mirrors and Resonant Cavities

\[ R(\lambda_0) = \left( \frac{n_H^{J+1} - n_L^{J-1} n_s}{n_H^{J+1} + n_L^{J-1} n_s} \right)^2 \]

\( Q_{\text{SiO}_2/\text{SiN}} = 20 \)

\( Q_{\text{SiO}_2/\text{Si}} = 120 \)
Integrated Si-based optoelectronics as enabling technology in multifunctional devices

I. Biosensors
Silicon technologies versus biotechnologies

When biology meets silicon technology……

……an entirely new world is disclosed

- Using Si Technologies for exploring and understanding complex biological systems (biosensors, DNA chip, protein chip, etc.)

- Biomimic: learning from nature and mimic behavior in Si chips

- Hybrid approaches: operations in the biological systems, inputs and outputs from/in Si-based devices
The role of optics in biosystems analysis

Various biological samples can be marked by fluorescent chromophores and observed by fluorescence microscope.

Photons are used to exchange informations between biological systems and outside world.

Many optical functions (light sources, light detectors, filters etc.) are used.

Example: analysis of a DNA microarray.
Innovative silicon technologies meet biology

- Optical and mechanical functions bridge the gap between Si technology and biological world
- We are able to integrate these functions with Si electronic functions on the same chip
Gene Expression Profiling

- It is the study of the patterns of gene expression in various environmental circumstances.

- Parallel genetic analysis allow to understand:
  - Candidate genes for each disease (comparing healthy and sick cells)
  - Cellular differentiation (comparing different tissues or the same one in different stage of development)
  - How organisms function in response to exposure to environmental toxicants or other stimuli (elucidating the molecular mechanism that underlie them)
DNA –CHIPS TECHNOLOGIES

DNA-microarray

Oligonucleotide-microarray

Stanford, Nanogen

Affimetrix
Active Biochip: technological steps implementation

**Target:** integration of DNA-microarray & Oligonucleotide-microarray on either Silicon or Si-compatible materials

**Aim:** to allows *real time* analysis for both clinical & diagnostic targets

**Methods:** an innovative trasduction techniques coupled to an electronic integrated system for signals reading & elaboration
DNA grafting on a Si chip

Functional groups Si-(CH$_2$)$_3$NH$_2$ on the surface

Reaction with aldehyde terminated DNA

Covalent bond formation between the carbonyl compounds and the amines by dehydration.
Experimental results: DNA grafting on thin films on Si

- Idroxilation (NaOH)
- Silanisation (APS)
- DNA spotting
- DNA grafting
DNA chips

DNA immobilization in materials compatible with silicon technology

DNA spots on silanised SiO2/Si

2D AFM analysis area not spotted

2D AFM analysis area DNA spotted

Porous Si optical cavities in DNA sensors applications

A reversible peak shift is induced by gas or organic/biological molecules in the pore of the material.

Porous Si optical cavity
Experimental demonstration of sensing using porous Si cavities

• A peak shift is measured (green line) when biological or organic material is introduced in the pore of the cavity

• The effect is fully reversible
Patterning and pore wall oxidation of porous Si for DNA sensors

Using proper oxidation steps the pore structures is maintained
Integrated Si-based optoelectronics as enabling technology in multifunctional devices

II. Novel optical memories and molecular switches
MEMORIES TECHNOLOGY OVERVIEW


## THE SEMICONDUCTOR MEMORIES MARKET

### The memory market

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<tr>
<td>DRAM</td>
<td>6,356</td>
<td>6,605</td>
<td>8,523</td>
<td>13,140</td>
<td>23,417</td>
<td>40,833</td>
<td>26,132</td>
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<td>14,014</td>
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<tr>
<td>Mask Programmable ROM</td>
<td>0.997</td>
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<td>1,226</td>
<td>1,624</td>
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<td>1,965</td>
<td>1,342</td>
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<td>0.000</td>
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<td>1.860</td>
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<td>2.498</td>
<td>4.560</td>
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<td><strong>Total non-volatile</strong></td>
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<td>6,552</td>
<td>6,142</td>
<td>5,695</td>
<td>5,083</td>
<td>6,910</td>
<td>13,048</td>
<td>10,165</td>
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<tr>
<td><strong>Total memory</strong></td>
<td>9,710</td>
<td>12,234</td>
<td>14,836</td>
<td>21,267</td>
<td>32,449</td>
<td>53,458</td>
<td>36,019</td>
<td>26,335</td>
<td>22,990</td>
<td>32,286</td>
<td>49,498</td>
<td>26,823</td>
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### as % of total memory

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<td><strong>Volatile:</strong></td>
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</tr>
<tr>
<td>DRAM (%)</td>
<td>65</td>
<td>54</td>
<td>57</td>
<td>62</td>
<td>72</td>
<td>76</td>
<td>70</td>
<td>67</td>
<td>61</td>
<td>64</td>
<td>61</td>
</tr>
<tr>
<td>SRAM (%)</td>
<td>24</td>
<td>20</td>
<td>19</td>
<td>15</td>
<td>12</td>
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<td>13</td>
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<td>13</td>
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<td>13</td>
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<tr>
<td><strong>Non-volatile:</strong></td>
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<td></td>
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</tr>
<tr>
<td>Mask Programmable ROM (%)</td>
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<td>EPROM (%)</td>
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<td>12</td>
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<td>6</td>
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<td>3</td>
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<td>2</td>
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<td>EEPROM (%)</td>
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<td>6</td>
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<td>9</td>
<td>3</td>
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<td>Flash (%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>9</td>
<td>11</td>
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<td><strong>Total non-volatile (%)</strong></td>
<td>10</td>
<td>26</td>
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<td>23</td>
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<td>17</td>
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<td><strong>Total memory (%)</strong></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
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</table>

Source: WestLB Panmure, Jan 2002

THE NEW NOMADIC SCENARIO

Nomadic era

Next generation device
Multi-function

Broad band
High data rate

Need of more data storage capacity

In 2003 data storage will over code storage
Information storage: the search for new solutions

New memory technologies

**FRAM**  
Ferroelectric Random Access Memory, data storage via the electrical polarisation of a ferroelectric film

**Polymer FRAM**  
Polymers with ferroelectric characteristics, which are used as data memories

**MRAM**  
Magnetoresisitive Random Access Memory, based on a physical effect similar to that of hard disk drives, in which a bit (0 or 1) is stored via the alignment of miniaturised magnets

**GMR**  
Giant Magneto Resistor, magnetic field-sensitive resistor

**TMR**  
Tunnel Mageneto Resistor, magnetic field-sensitive resistor in which a tunnel current is read out

**OUM**  
Ovonic Unified Memory, based on the physical storage mechanism of optical data carriers (CDs and DVDs). Depending on the state of the memory cell (0 or 1), the material is present in a structured (crystalline) or unstructured (amorphous) phase.
HDD SMALL FORM FACTOR

(with moving parts) (with no moving parts)

Stacked NAND Flash + controller
DVD/CD TECHNOLOGY: LASER, SUPPORT, STANDARDS
ORGANIC COMPOUNDS-based MATERIALS for Optical Memories

Spirobenzopyrans

Figure 1. Chemical structure of spirobenzopyran. A and B are spirobenzopyran isomers.

Bit patterns read by near IR-Microscopy: (a) first layers; (b) second layer. The bit interval is 5 µm and the layers distance is 70 µm. Write by 2 photons.

Figure 2. Absorption spectra of a polystyrene film containing spirobenzopyran both before (A) and after (B) exposure to 442-nm light.

Chem.Rev., 2000, 100, 1777
Biological molecules integrated within a Si chip

Novel optical memory and switches using photochromic biological molecules

Photons allow communication between Si and the protein

- A red photon is used to change the colour
- A blue photon can be used to switch back or to interrogate the status
Bacteriorhodopsin photocycle

Black lines: thermal relaxation
Coloured lines: light induced transitions

10 ms

Red light

1-10 µs

Blue light

1 ps

yellow light

(yellow)

(Purple)
Proteins with a simpler photo-cycle (e.g. Euglena-rhodopsin, GFP)

- Fast switch between the states
- Single photon switch
- High density
- Infinite cycling

Advantages for optical memories

- Superior performances compared to organic photochromic materials
- Use of integrated Si optics
- Protein properties can be changed using biotechnology

PROTEINS-based MATERIALS for Optical Memories

Modified-GFP (E²GFP)

NEST-INFM patent
Experimental determination of Rodhopsin Photo-cycle

Photocycle promoted by a 10 ns laser pulse

(yellow state) M

Bacteriorhodopsin in water

Spectra recorded on 40 μs/div

bR (purple state)
Formation of the M state

Bacterio-rodhopsin in a PAA film

![Graph showing the formation of the M state in bacterio-rodhopsin in a PAA film.](image)
STRUCTURAL PERFORMANCES Active bR films

Optical micrography bR film on glass (casting)

Optical micrography bR film on glass (casting) + 5% glycerol
Combine integrated optics and photochromic molecules to develop innovative devices
Integration of the protein films

Protein film (pf)

\[ n_{\text{SiON}} = n_{\text{pf}} \]  (no reflection, only absorption)

Use of Hydrophilic/hydrophobic surfaces for selective location of the protein film
Integration of the protein film

Top view

Protein film

SiON
Foreseen use of the photochromic films

High resolution memories through a SNOM Approach

3D data and hologram storing using DVD-like approach
## STORAGE TECHNOLOGY PARAMETERS

### Parameters compared

<table>
<thead>
<tr>
<th>Parameters compared</th>
<th>SRAM</th>
<th>DRAM</th>
<th>EEPROM (NAND)</th>
<th>Flash (NOR)</th>
<th>FRAM</th>
<th>MRAM (X-Point)</th>
<th>MRAM (FET)</th>
<th>OUM</th>
<th>Polymer</th>
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<tr>
<td><strong>Speed:</strong></td>
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<td></td>
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<td>30-70</td>
<td>60-150</td>
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<td>90</td>
<td>35-50</td>
<td>&lt;1us</td>
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<td><strong>Lifetime:</strong></td>
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<td>Non-Volatility</td>
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<td>Yes</td>
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<td>Destructive read</td>
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<td>Refresh need</td>
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<td>Operating current in mA</td>
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<td>Standby current in μA</td>
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<td>Write energy in pJ</td>
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<td>1T1C</td>
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<td>Ease in shrinking</td>
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</table>

Source: WestLB Panmure

Conclusions

- State of the art of Si-based optical devices have been fabricated
- Marketable applications of integrated Si-based optoelectronic circuits are foreseen
- Integrated Si-based optoelectronics is a suitable enabling technology for several multifunctional devices
The work described has been carried out within:

**a) ST Innovation Lab**

- Advanced microfabrication processes
- Electro-optic characterisation of materials and devices
- Molecular biology lab.
- DNA Chips prototyping
- Biological films for various applications
- Etc.

**b) ST 6 inches pilot line**

Here, novel dedicated processes for photonic devices have been implemented on existing equipments for Si ICs fabrication
The work described has been carried out by:

Si optoelectronics, bioelectronics and nano-organics group (50 people)  Corporate R&D, STMicroelectronics

Pilot line technologies and New Power Device Structure groups (10 people)  DSG R&D, STMicroelectronics

Established collaborations: CNR-IMM, CNR-IBFSNC, CIB Trieste