Quick Review over the Last Lecture

Shingled write recording : *

Bit patterned media (BPM) : **

Discrete tracks : ***

* S. Matsuo, H. Uwazumi and N. Hara, Fujidenki Gihou 85, 316 (2012);
** http://news.cnet.com/2300-1008_3-6108692.html;
*** http://www.tdk.co.jp/
**07 Optical Storages**

- Read-only
- Writable
- High density
- Physical phenomena
- Phase change

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**Optical Storage**

Read-only :

Writable (once only) :

Writable (multiple) :

High density :

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Properties of Optical Storage

Advantages of optical storage:

- Removable
- Large capacity
- High density
- Random access
- Fidelity

- Not as high as HDD
- Not as fast as HDD
- Not as good as HDD

Physical Phenomena Used

Various phenomena are used for optical storage:

- Recording bit formation – CD-ROM, DVD-ROM
- Chemical reaction of organic dye – CD-R, DVD-R
- Amorphous phase change – CD-RW, DVD-RAM, DVD-RW, DVD+RW
- Ferromagnetic-paramagnetic phase change – MO, MD
- Photorefractive effect – Holographic memory
Principles of CD

CD operation:

Numerical Aperture for Optical Storage

Numerical aperture (NA): *

The NA is expressed by 

where $n$ : the refraction index (in air).

The larger the NA, the greater the $\theta$ value (> ) and the smaller the laser spot size.

* http://www.youtube.com/watch?v=MPQElGo4AIH

* https://azkurs.org/whats-the-blu-ray-disc-why-was-the-blu-ray-disc-created.html
NA and the corresponding laser wavelength:

By increasing NA, laser spots can become smaller for higher storage density. The corresponding laser wavelength also becomes shorter.

* https://azkurs.org/whats-the-bluray-disc-why-was-the-bluray-disc-created.html

NA and the corresponding laser spot size:

* https://azkurs.org/whats-the-bluray-disc-why-was-the-bluray-disc-created.html
Increase in Storage Density

Comparison between DVD and BD :

* [azkurs.org/whats-the-blu-ray-disc-why-was-the-blu-ray-disc-created.html](http://azkurs.org/whats-the-blu-ray-disc-why-was-the-blu-ray-disc-created.html)

Bit Size Comparison

Data bits used for optical storage :

* [www.wikipedia.org](http://www.wikipedia.org);
** [azkurs.org/whats-the-blu-ray-disc-why-was-the-blu-ray-disc-created.html](http://azkurs.org/whats-the-blu-ray-disc-why-was-the-blu-ray-disc-created.html)
Nyquist-Shannon Sampling Theorem

Data sampling:

For accurate data reconstruction, sampling up to the Nyquist frequency as the required value is needed due to folding noise.

Optical Storage Capacity

<table>
<thead>
<tr>
<th>LaserVision</th>
<th>LaserDisc/CD-Video</th>
<th>Video-CD</th>
<th>DVD-Video</th>
<th>Blu-ray Disc</th>
<th>Ultra HD Blu-ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser wavelength</td>
<td>780 nm (infra-red)</td>
<td>780 nm</td>
<td>780 nm</td>
<td>650 nm (red)</td>
<td>405 nm (blue)</td>
</tr>
<tr>
<td>Sides</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1 or 2</td>
<td>1</td>
</tr>
<tr>
<td>Layers</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1-2</td>
<td>1-2</td>
</tr>
<tr>
<td>Substrate thickness</td>
<td>1.25mm</td>
<td>1.25mm</td>
<td>1.1mm</td>
<td>0.6nm</td>
<td>0.1mm</td>
</tr>
<tr>
<td>Numerical Aperture</td>
<td>0.50</td>
<td>0.60</td>
<td>0.85</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>Track pitch</td>
<td>1.5 Åm</td>
<td>740 nm</td>
<td>320 nm</td>
<td>225 nm</td>
<td></td>
</tr>
<tr>
<td>Data bit length</td>
<td>800 nm</td>
<td>400 nm</td>
<td>150 nm</td>
<td>80 nm</td>
<td></td>
</tr>
<tr>
<td>Capacity</td>
<td>700 MB</td>
<td>4.7 GB or 8.5 GB</td>
<td>25 GB or 50 GB</td>
<td>33 GB, 66 GB or 100 GB</td>
<td></td>
</tr>
</tbody>
</table>

* http://yoeri.geutskens.com/blog/ultrahdbluray-history.html

** http://www.wikipedia.org/
Amorphous Phase Change

Additional writing process:

Rapid quenching of chalcogenide glass in an amorphous phase.
Laser heating promotes crystallisation → reflection.

Rewriting process:

Initial crystallised phase by slow quenching below $T < 400^\circ C$.
Written phase by rapid quenching above $T > 600^\circ C$.
DVD-RAM – GeSbTe (> 100,000 times writing cycles).
DVD-RW – AgInTe (> 1,000 times writing process).
Slow data transfer speed (11 ~ 47 Mbps).

Phase Change Processes

Initialisation and writing processes:

Initial crystallised phase
Written amorphous phase

Magneto-Optical Storage

Writing process:
* Laser-induced heating to promote magnetic phase change above the Curie temperature.

Reading process:
Detection of the polarisation rotation through the Faraday effect. TbFeCo (> 10,000,000 times writing cycles).


Magneto-Optical Disc

In 1971, Honeywell proposed magneto-optical recording:

Faraday Effect

Rotation of a linearly polarised direction by a magnetic moment:

\[
\beta = \frac{\mathbf{E} \times \mathbf{B}}{2 \mathbf{E} \mathbf{B}}
\]

Comparison among Optical Storage

<table>
<thead>
<tr>
<th>Name</th>
<th>Capacity</th>
<th>Experimental Note</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaserDisc (LD)</td>
<td>0.3 GB</td>
<td></td>
<td>1971–2001</td>
</tr>
<tr>
<td>Write Once Read Many Disk (WORM)</td>
<td>0.2–6.0 GB</td>
<td></td>
<td>1979–1984</td>
</tr>
<tr>
<td>Compact Disc (CD)</td>
<td>0.7–0.9 GB</td>
<td></td>
<td>1982–today</td>
</tr>
<tr>
<td>Electron Trap Optical Memory (ETOM)</td>
<td>6.0–12.0 GB</td>
<td></td>
<td>1987–1996</td>
</tr>
<tr>
<td>MiniDisc (MD)</td>
<td>0.14 GB</td>
<td></td>
<td>1989–today</td>
</tr>
<tr>
<td>Magnetic Optical Disc (MOD)</td>
<td>0.1–16.7 GB</td>
<td></td>
<td>1990–present</td>
</tr>
<tr>
<td>Digital Versatile Disc (DVD)</td>
<td>4.7–17 GB</td>
<td></td>
<td>1995–present</td>
</tr>
<tr>
<td>LIMDOW (Laser Intensity Modulation Direct OverWrite)</td>
<td>2.6 GB</td>
<td>10 GB</td>
<td>1996–present</td>
</tr>
<tr>
<td>CD-ROM</td>
<td>1.2 GB</td>
<td></td>
<td>1997–present</td>
</tr>
<tr>
<td>Versatile Multilayer Disc (VMD)</td>
<td>5–20 GB</td>
<td>100 GB from 1999–2010</td>
<td></td>
</tr>
<tr>
<td>Nero CD-ROM</td>
<td>1 PB</td>
<td>100 GB</td>
<td>1999–7</td>
</tr>
<tr>
<td>Ultra Dense Optical (UDO)</td>
<td>30–60 GB</td>
<td></td>
<td>2000–present</td>
</tr>
<tr>
<td>FVD (FVD)</td>
<td>5.4–15 GB</td>
<td></td>
<td>2001–present</td>
</tr>
<tr>
<td>Enhanced Versatile Disc (EVD)</td>
<td>DVD</td>
<td></td>
<td>2002–2004</td>
</tr>
<tr>
<td>UD DVD</td>
<td>15–51 GB</td>
<td>1 TB</td>
<td>2002–2008</td>
</tr>
<tr>
<td>BlueRay Disc (BD)</td>
<td>25 GB</td>
<td>50 GB</td>
<td>2002–present</td>
</tr>
<tr>
<td>Professional Disc for Data (PDD)</td>
<td>23 GB</td>
<td></td>
<td>2003–2006</td>
</tr>
<tr>
<td>Professional Disc</td>
<td>23–128 GB</td>
<td></td>
<td>2003–present</td>
</tr>
<tr>
<td>Multilayer Optical Data Storage (MODS-Disc)</td>
<td>250 GB–1 TB</td>
<td></td>
<td>2004–present</td>
</tr>
<tr>
<td>Universal Media Disc (UMD)</td>
<td>0.9–1.6 GB</td>
<td></td>
<td>2004–2014</td>
</tr>
<tr>
<td>Holographic Versatile Disc (HVD)</td>
<td>6.0 TB</td>
<td></td>
<td>2004–present</td>
</tr>
<tr>
<td>Protein-coated Disc (PCD)</td>
<td></td>
<td></td>
<td>2005–present</td>
</tr>
<tr>
<td>M-DISC</td>
<td>4.7 GB (Blu-ray format)</td>
<td></td>
<td>2009–today</td>
</tr>
<tr>
<td>Archival Disc</td>
<td>0.3–1 TB</td>
<td></td>
<td>2014–present</td>
</tr>
<tr>
<td>Ultra HD Blu-ray</td>
<td>50 GB</td>
<td>66 GB</td>
<td>2015–present</td>
</tr>
</tbody>
</table>

Holographic Storage

Holographic storage has been proposed:


Three-Dimensional Optical Storage

3D optical storage:

Cold Storages

Definition of cold storages:

![Cold vs Hot Storages](https://www.backblaze.com/blog/whats-the-diff-hot-and-cold-data-storage/)

**Comparison of Cold Storages**

Optical storages are advantageous for long time storage:

* [Comparison Table](https://techtarget.itmedia.co.jp/tt/news/1802/12/news02.html#aa8260Kaigai)