Flash Memory

Jin-Soo Kim (jinsookim@skku.edu)
Computer Systems Laboratory
Sungkyunkwan University
http://csl.skku.edu
Memory Types

**EPROM**
- Non-volatile
- High-density
- Ultraviolet light for erasure

**EEPROM**
- Non-volatile
- Lower reliability
- Higher cost
- Lowest density
- Electrically byte-erasable

**FLASH**
- High-density
- Low-cost
- High-speed
- Low-power
- High reliability

**DRAM**
- High-density
- Low-cost
- High-speed
- High-power

**ROM**
- High-density
- Reliable
- Low-cost
- Suitable for high production with stable code

Source: Intel Corporation.
Flash Memory Characteristics

- **Erase-before-write**
  - Read
  - Write or Program – change state from 1 to 0
  - Erase – change state from 0 to 1

- **Bulk erase**
  - Program unit:
    - NOR: byte or word
    - NAND: sector or page
  - Erase unit: block

![Flash Memory Diagram](image-url)
NOR Flash

- **NOR flash**
  - Random, direct access interface
  - Fast random reads
  - Slow erase and write
  - Mainly for code storage
  - Intel, Spansion, STMicro, ...
### NAND Flash

- **NAND flash**
  - I/O mapped access
  - Smaller cell size
  - Lower cost
  - Smaller size erase blocks
  - Better performance for erase and write
  - Mainly for data storage

- Samsung, Toshiba, Hynix, ...
NOR vs. NAND Flash (1)

Source: Toshiba

(*) Dependant on how memory is used. NOR is typically slow on writes and consumes more power than NAND. NOR is typically fast on reads, which consume less power.
NOR vs. NAND Flash (2)

Mass Storage-NAND

- Memory Cards (mobile computers)
- Solid-State Disk (rugged & reliable storage)
- Digital Camera (still & moving pictures)
- Voice/Audio Recorder (near CD quality)

Code Memory-NOR

- BIOS/Networking (PC/router/hub)
- Telecommunications (switcher)
- Cellular Phone (code & data)
- POS / PDA / PCA (code & data)

- Low Cost and High Density
- Good P/E Cycling Endurance
- Fast Random Access
- XIP

Source: Samsung Electronics
§ Hwang’s law

• The density of the top-of-the-line flash memory chips will double every 12 months
NAND Technology (2)

- Density growth

Source: Samsung Electronics
NAND Flash Architecture

- **2Gb NAND flash device organization**

Source: Micron Technology, Inc.
NAND Flash Types (1)

- **SLC NAND flash**
  - Small block (≤ 1Gb)
  - Large block (≥ 1Gb)

- **MLC NAND flash**

Source: Micron Technology, Inc.
## NAND Flash Types (2)

<table>
<thead>
<tr>
<th></th>
<th>SLC NAND(^1) (small block)</th>
<th>SLC NAND(^2) (large block)</th>
<th>MLC NAND(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Page size (Bytes)</td>
<td>512+16</td>
<td>2,048+64</td>
<td>4,096+128</td>
</tr>
<tr>
<td>Pages / Block</td>
<td>32</td>
<td>64</td>
<td>128</td>
</tr>
<tr>
<td>Block size</td>
<td>16KB</td>
<td>128KB</td>
<td>512KB</td>
</tr>
<tr>
<td>(t_R) (read)</td>
<td>15 (\mu)s (max)</td>
<td>20 (\mu)s (max)</td>
<td>50 (\mu)s (max)</td>
</tr>
<tr>
<td>(t_{\text{PROG}}) (program)</td>
<td>200 (\mu)s (typ)</td>
<td>200 (\mu)s (typ)</td>
<td>600 (\mu)s (typ)</td>
</tr>
<tr>
<td></td>
<td>500 (\mu)s (max)</td>
<td>700 (\mu)s (max)</td>
<td>1,200 (\mu)s (max)</td>
</tr>
<tr>
<td>(t_{\text{BERS}}) (erase)</td>
<td>2 ms (typ)</td>
<td>1.5 ms (typ)</td>
<td>3 ms (typ)</td>
</tr>
<tr>
<td></td>
<td>3 ms (max)</td>
<td>2 ms (max)</td>
<td></td>
</tr>
<tr>
<td>NOP</td>
<td>1 (main), 2 (spare)</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Endurance Cycles</td>
<td>100K</td>
<td>100K</td>
<td>10K</td>
</tr>
<tr>
<td>ECC (per 512Bytes)</td>
<td>1 bit ECC, 2 bits EDC</td>
<td>1 bit ECC, 2 bits EDC</td>
<td>4 bits ECC, 5 bits EDC</td>
</tr>
</tbody>
</table>

\(^1\) Samsung K9F1208X0C (512Mb) \(^2\) Samsung K9K8G08U0A (8Gb) \(^3\) Micron Technology Inc.
NAND Applications (1)

- USB Flash Drives (UFDs)
NAND Applications (2)

- Flash Cards
  - CompactFlash, MMC, SD/miniSD, Memory Stick, xD, ...

![Image of various flash cards and a diagram showing the components of a flash card including Host I/F, ROM, SRAM, CPU, NAND I/F, and NAND storage.](image-url)
NAND Applications (3)

- Mobile handset

- [Diagram showing the evolution of mobile-handset technologies from 2003 to 2007, with key milestones such as UMTS Phone, 3D Game Phone, Slim Phone, DMB Phone, and Wibro Phone, and the integration of Fusion Ubiquitous Mobile Handset with DVB-H(EU) and WiBro(KR).]

- [Bar chart illustrating the growth in NOR Flash, NAND Flash, and Mobile DRAM capacities from 2004 to 2008, with CAGR rates of 7%, 88%, and 56% respectively.]

(3G Phone, Source: Samsung)
NAND Applications (4)

- **Flash-embedded CE Devices**
  - MP3 players
  - PMPs
  - PDAs
  - Digital TVs
  - Set-top boxes
  - Car navigation & entertainment systems
  - ...
NAND Applications (5)

- Hybrid HDDs
  - Reduce power consumption
  - Faster boot and resume
  - Higher reliability

- Support in Microsoft Windows Vista
NAND Applications (6)

- **Intel Turbo Memory (a.k.a. Robson)**
  - Non-volatile HDD cache
  - Mini PC-express memory card

- Supported by
  - Microsoft’s ReadyBoost
  - Microsoft’s ReadyDrive
NAND Applications (7)

- Flash SSDs (Solid-State Disks)
  - High performance
    - Sequential read: > 200 MB/s
    - Sequential write: > 150 MB/s
  - Reliable and robust: no mechanical parts
  - Small, light-weight, low power consumption
  - Netbooks, notebooks, desktop & servers, ...
SSDs (1)

- HDDs vs. SSDs

2.5” HDD   Flash SSD
(101x70x9.3mm)

1.8” HDD    Flash SSD
(78.5x54x4.15mm)
SSDs (2)

<table>
<thead>
<tr>
<th></th>
<th>SSD</th>
<th>HDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Performance</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Reliability</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Endurance</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Power</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Size</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Weight</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Shock</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Temperature</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Cost per bit</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
SSDs (3)

- 2-channel, 4-way, 32GB
- 96KB SRAM (code 32KB, data 32KB, buffer 32KB)
- 8KB superpage automatic interleaving

Source: Samsung Electronics
<table>
<thead>
<tr>
<th>Feature</th>
<th>SSD (Samsung)</th>
<th>HDD (Seagate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>MMDOE56G5MXP (PM800)</td>
<td>ST9500420AS (Momentus 7200.4)</td>
</tr>
<tr>
<td>Capacity</td>
<td>256GB (16Gb MLC x 128, 8 channels)</td>
<td>500GB (2 Discs, 4 Heads, 7200RPM)</td>
</tr>
<tr>
<td>Form factor</td>
<td>2.5” Weight: 84g</td>
<td>2.5” Weight: 110g</td>
</tr>
<tr>
<td>Host interface</td>
<td>Serial ATA-2 (3.0 Gbps)</td>
<td>Serial ATA-2 (3.0 Gbps)</td>
</tr>
<tr>
<td></td>
<td>Host transfer rate: 300MB</td>
<td>Host transfer rate: 300MB</td>
</tr>
<tr>
<td>Power consumption</td>
<td>Active: 0.26W</td>
<td>Active: 2.1W (Read), 2.2W (Write)</td>
</tr>
<tr>
<td></td>
<td>Idle/Standby/Sleep: 0.15W</td>
<td>Idle: 0.69W, Standby/Sleep: 0.2W</td>
</tr>
<tr>
<td>Performance</td>
<td>Sequential read: Up to 220 MB/s</td>
<td>Power-on to ready: 4.5 sec Average latency: 4.17 msec</td>
</tr>
<tr>
<td></td>
<td>Sequential write: Up to 185 MB/s</td>
<td></td>
</tr>
<tr>
<td>Measured performance¹</td>
<td>Sequential read: 176.73 MB/s</td>
<td>Sequential read: 86.07 MB/s</td>
</tr>
<tr>
<td></td>
<td>Sequential write: 159.98 MB/s</td>
<td>Sequential write: 84.64 MB/s</td>
</tr>
<tr>
<td></td>
<td>Random read: 10.56 MB/s</td>
<td>Random read: 0.61 MB/s</td>
</tr>
<tr>
<td></td>
<td>Random write: 2.93 MB/s</td>
<td>Random write: 1.28 MB/s</td>
</tr>
<tr>
<td>Price²</td>
<td>795,000 won</td>
<td>183,840 won</td>
</tr>
</tbody>
</table>


² Source: [http://www.danawa.com](http://www.danawa.com) (As of Nov. 24, 2009)
NAND Constraints (1)

- **Bit errors**
  - Error correction codes (ECC) in spare area
  - Hardware vs. Software

<table>
<thead>
<tr>
<th>Error Correction Level</th>
<th>Bits Required in the NAND Flash Spare Area</th>
<th>Hamming</th>
<th>Reed-Solomon</th>
<th>BCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>13</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>N/A</td>
<td>36</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>N/A</td>
<td>54</td>
<td>39</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>N/A</td>
<td>72</td>
<td>52</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>N/A</td>
<td>90</td>
<td>65</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>N/A</td>
<td>108</td>
<td>78</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>N/A</td>
<td>126</td>
<td>91</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>N/A</td>
<td>144</td>
<td>104</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>N/A</td>
<td>162</td>
<td>117</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>N/A</td>
<td>180</td>
<td>130</td>
</tr>
</tbody>
</table>

Source: Micron Technology, Inc.
NAND Constraints (2)

- **Bad blocks**
  - Factory-marked bad blocks
  - Run-time bad blocks
  - Bad block table
  - Bad block remapping

- **Limited program/erase cycles**
  - < 100K for SLCs
  - < 10K for MLCs
  - Wear-leveling
NAND Constraints (3)

- **NOP**
  - Partial-page programming
  - 1 / sector for most SLCs (4 for 2KB page)
  - 1 / page for most MLCs

- **Sequential page programming**
  - For large block SLCs and MLCs
  - From page 0 to page 63 for SLCs
  - From page 0 to page 127 for MLCs
NAND Constraints (4)

- Pair-page programming in MLCs
  - Performance difference
  - Interference

![Diagram showing pair-page programming in MLCs]

<table>
<thead>
<tr>
<th>Page 0</th>
<th>Page 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSB Page</td>
<td>LSB Page</td>
</tr>
</tbody>
</table>

**I/O-split MLCs**

<table>
<thead>
<tr>
<th>IO7</th>
<th>IO6</th>
<th>IO5</th>
<th>IO4</th>
<th>IO3</th>
<th>IO2</th>
<th>IO1</th>
<th>IO0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Page-split MLCs**

<table>
<thead>
<tr>
<th>IO7</th>
<th>IO6</th>
<th>IO5</th>
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<th>IO2</th>
<th>IO1</th>
<th>IO0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
Beauty and the Beast

- NAND flash memory is beauty.
  - Small, light-weight, robust, low-cost, low-power non-volatile device

- NAND flash memory is the beast.
  - Much slower program/erase operations
  - No in-place-update
  - Erase unit > write unit
  - Limited lifetime (10K~100K program/erase cycles)
  - Bad blocks, bit errors, ...

- Software support for NAND flash memory is very important for performance & reliability.
FTL (1)

- Flash cards internals
**FTL (2)**

- **Flash Translation Layer (FTL)**
  - A software layer to make NAND flash fully emulate traditional block devices (e.g., disks).

- **Why FTL?**
  - No in-place-update
  - Bulk erase
FTL (3)

- For Performance
  - Sector mapping (or address translation)
  - Garbage collection

- For Reliability
  - Power-off recovery
  - Wear-leveling
  - Bad block management
  - Error correction code (ECC)