NAND Flash-based Storage

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Today’s Topics

- NAND flash memory
- Flash Translation Layer (FTL)
- OS implications
Flash Memory Characteristics

Flash memory
- Non-volatile, Updateable, High-density
- Low cost, Low power consumption, High reliability

Erase-before-write
- Read
- Write or Program: 1 → 0
- Erase: 0 → 1

Read faster than write/erase

Bulk erase
- Erase unit: block
- Program unit: byte or word (NOR), page (NAND)
NOR Flash

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

![Diagram of NOR Flash memory structure](image-url)
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, ...
NAND Flash Architecture

- 2Gb NAND flash device organization

Serial input (x8 or x16): 30ns (MAX CLK)

NAND Flash Memory Array

- NAND Flash Page 2,112 bytes
- 64 pages per block

NAND Flash Block

- Data area: 2,048 bytes
- Spare area (ECC, etc.): 64 bytes

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

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

- **MLC NAND Flash**

- **TLC 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) 500 (\mu s) (max)</td>
<td>200 (\mu s) (typ) 700 (\mu s) (max)</td>
<td>600 (\mu s) (typ) 1,200 (\mu s) (max)</td>
</tr>
<tr>
<td>(t_{\text{BERS}}) (erase)</td>
<td>2 ms (typ) 3 ms (max)</td>
<td>1.5 ms (typ) 2 ms (max)</td>
<td>3 ms (typ)</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

- Universal Flash Drives (UFDs)
- Flash cards
  - CompactFlash, MMC, SD, Memory stick, ...
- Embedded devices
  - Cell phones, MP3 players, PMPs, PDAs, Digital TVs, Set-top boxes, Car navigators, ...
- Hybrid HDDs
- Intel Turbo Memory
- SSDs (Solid-State Disks)
SSDs vs. HDDs (1)

Source: [http://www.anandtech.com](http://www.anandtech.com)
### SSDs vs. HDDs (2)

<table>
<thead>
<tr>
<th>Feature</th>
<th>SSD (Samsung)</th>
<th>HDD (Seagate)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model</strong></td>
<td>Samsung SSD 840 EVO</td>
<td>ST3000DM001 (Barracuda 7200.14)</td>
</tr>
<tr>
<td><strong>Capacity</strong></td>
<td>1TB (19nm 128Gb TLC x 64, 3 cores)</td>
<td>3TB (3 Discs, 6 Heads, 7200RPM)</td>
</tr>
<tr>
<td><strong>Form factor</strong></td>
<td>2.5” Weight: 53g</td>
<td>3.5” Weight: 626g</td>
</tr>
<tr>
<td><strong>Host interface</strong></td>
<td>Serial ATA-3 (6.0 Gbps) Host transfer rate: 600MB</td>
<td>Serial ATA-3 (6.0 Gbps) Host transfer rate: 600MB</td>
</tr>
<tr>
<td><strong>Power consumption</strong></td>
<td>Active: 0.1W Idle/Standby/Sleep: 0.045W</td>
<td>Active: 8.0W Idle: 5.8W, Standby/Sleep: 0.75W</td>
</tr>
<tr>
<td><strong>Performance</strong></td>
<td>Sequential read: Up to 540 MB/s</td>
<td>Power-on to ready: 15 sec (typ)</td>
</tr>
<tr>
<td></td>
<td>Sequential write: Up to 520 MB/s</td>
<td>Average latency: 4.16 msec</td>
</tr>
<tr>
<td>Measured performance¹</td>
<td>Sequential read: 428.7 MB/s</td>
<td>Sequential read: 145.7 MB/s</td>
</tr>
<tr>
<td></td>
<td>Sequential write: 374.0 MB/s</td>
<td>Sequential write: 138.8 MB/s</td>
</tr>
<tr>
<td></td>
<td>Random read: 96.0 MB/s</td>
<td>Random read: ? MB/s</td>
</tr>
<tr>
<td></td>
<td>Random write: 366.3 MB/s</td>
<td>Random write: 1.09 MB/s</td>
</tr>
<tr>
<td><strong>Price²</strong></td>
<td>762,900 won (763 won/GB)</td>
<td>121,000 won (43 won/GB)</td>
</tr>
</tbody>
</table>

¹ Source: [http://www.anandtech.com](http://www.anandtech.com)
² Source: [http://www.danawa.com](http://www.danawa.com) (As of Nov. 24, 2013)
NAND Constraints (1)

- **No in-place update**
  - Require sector remapping (or address translation)

- **Bit errors**
  - Require the use of error correction codes (ECC)

- **Bad blocks**
  - Factory-marked & run-time bad blocks
  - Require bad block remapping

- **Limited program/erase cycles**
  - < 100K for SLCs
  - < 5K for MLCs
  - Require wear-leveling
NAND Constraints (2)

- Limited NOP (Number of Programming)
  - 1 / sector for most SLCs (4 for 2KB page)
  - 1 / page for most MLCs

- Sequential page programming
  - For large block SLCs and MLCs

- Pair-page programming in MLCs
  - Two pages inside a block are linked together
  - Performance difference
  - Interference
**FTL (1)**

**What is FTL?**

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

![Diagram](source: Zeen Info. Tech.)
FTL (2)

- Flash cards internals
FTL (3)

- SSD internals

Source: Indilinx
FTL (4)

Flash Cards, SSDs

Applications

Operating System

File Systems

Block Device Driver

Flash Translation Layer

NAND Controller

NAND Flash Memory

Embedded Flash Storage

Applications

Operating System

File Systems

Block Device Driver

Flash Translation Layer

NAND Controller

NAND Flash Memory
FTL (5)

- For performance
  - Address translation
  - Garbage collection
  - Hot/cold data identification/separation
  - Interleaving over multiple channels & flash chips
  - Request scheduling
  - Buffer management
  - ...
FTL (6)

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

- **Other features**
  - Encryption
  - Compression
  - Deduplication
  - ...
Sector Mapping (1)

- Naïve block mapping
  - Each table entry maps one block
  - Small RAM usage
  - Inefficient handling of small writes

\[ W = \{4, 5, 6, 7, 1\} \]
Log block scheme [IEEE TOCE 2002]

- A small number of log blocks
- 1+ log block(s) per data block
- Page mapping for log blocks
- Full/partial/switch merge
- Switch merge for sequential updates
- Low log block utilization

$L = \langle 1, 2, 8, 1, 2, 12, 13, 9 \rangle$
Sector Mapping (3)

- **FAST** [ACM TECS 2007]
  - Log blocks shared by all data blocks
  - Sequential/random log blocks
  - Improved log block utilization
  - Increased merge time

\[ W = \langle 1, 2, 8, 1, 2, 12, 13, 9 \rangle \]
Sector Mapping (4)

- **Superblock FTL** [ACM EMSOFT 2006]
  - Superblock = logically adjacent N blocks
  - A superblock shares log blocks
  - Up to M log blocks per superblock
  - Page mapping within a superblock
  - Hot/cold pages separation

- The amount of mapping information increased

\[ W = \langle 1, 2, 8, 1, 2, 12, 13, 9 \rangle \]
Sector Mapping (5)

- General page mapping
  - Most flexible
  - Efficient handling of small writes
  - Large memory footprint
    - One mapping entry per page: 32MB for 32GB MLC (4KB page)
    - Bitmap for page validity
    - Per-block invalid page counter
  - Sensitive to the amount of reserved blocks
  - Performance affected as the system ages

\[ W = \langle 1, 2, 8, 1, 2, 12, 13, 9 \rangle \]
Flash Storage

- Server Flash
- Flash Appliance
- Flash Array

Source: Pure Storage, Inc.
OS Implications (1)

- NAND flash has different characteristics compared to disks
  - No seek time
  - Asymmetric read/write access times
  - No in-place-update
  - Good sequential read/sequential write/random read performance, but bad random write performance
  - Wear-leveling
  - ...

- Traditional operating systems have been optimized for disks. What should be changed?
OS Implications (2)

- SSD support in Microsoft Windows 7
  - Turn off “defragmentation” for SSDs
  - New “TRIM” command
    - Remove-on-delete
  - Align file system partition with SSD layout
  - Larger block size proposal (4KB)
Beauty and the Beast

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

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

- Software support for NAND flash memory is very important for performance & reliability.
Beyond Flash

- Resistance-based memory technologies

Table 1. Characteristics of major existing and emerging memory devices.

<table>
<thead>
<tr>
<th></th>
<th>DRAM</th>
<th>NAND</th>
<th>MRAM</th>
<th>PRAM</th>
<th>ReRAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell size</td>
<td>~8F²</td>
<td>~5F² (SLC)</td>
<td>~8F²</td>
<td>~4F²</td>
<td>~8F² (transistor)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt;1 F² (stack)</td>
</tr>
<tr>
<td>Density</td>
<td>xGigabit</td>
<td>xxGigabit</td>
<td>xxMegabit</td>
<td>xGigabit</td>
<td>--</td>
</tr>
<tr>
<td>Latency</td>
<td>~50 ns</td>
<td>20 to ~200μs</td>
<td>~50 ns</td>
<td>~200 ns</td>
<td>~50 ns to ~1 μs</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>~1 GBps</td>
<td>~100 MBps</td>
<td>~1 GBps</td>
<td>~100 MB/s</td>
<td>~100 MBps</td>
</tr>
<tr>
<td>Volatility</td>
<td>Volatile</td>
<td>Nonvolatile</td>
<td>Nonvolatile</td>
<td>Nonvolatile</td>
<td>Nonvolatile</td>
</tr>
<tr>
<td>Endurance</td>
<td>&gt;10¹⁵</td>
<td>&gt;10⁵</td>
<td>&gt;10¹⁵</td>
<td>&gt;10⁶ to 10⁻¹²</td>
<td>&gt;10⁵</td>
</tr>
<tr>
<td>Retention</td>
<td>&gt;64 ms</td>
<td>&gt;10 years</td>
<td>&gt;10 years</td>
<td>&gt;10 years</td>
<td>&gt;10 years</td>
</tr>
<tr>
<td>Application</td>
<td>Working memory</td>
<td>Data storage memory</td>
<td>Working nonvolatile RAM</td>
<td>Code memory and buffer memory</td>
<td>Data storage memory</td>
</tr>
</tbody>
</table>