Reliability Issues in Flash Memory Storage Devices

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Outline

- Flash Memory Basics
- Our 10-year Research and Technology Transfer
- Lessons Learned
- Conclusions
Conventional MOS Transistor

- **Gate (G)**
- **p-substrate**
- **n+ source (S)**
- **n+ drain (D)**

Schematic symbol:
Conventional MOS Transistor: A Constant-Threshold Transistor

\[ V_{gs} > V_{th} \]
Flash Memory

- Control gate
- Floating gate
- Thin tunneling oxide

- erasure
- programming

- $n^+$ source
- $p$-substrate
- $n^+$ drain

Schematic symbol:

- G
- S
- D

Flash memory and Advanced Storage Technology group.

SEOUL NATIONAL UNIVERSITY
Flash Memory

- Erased Cell
  - Control gate
  - p-substrate
  - n+ source
  - n+ drain

- Programmed Cell
  - Control gate
  - p-substrate
  - n+ source
  - n+ drain
Flash Memory: A “Programmable-Threshold” Transistor

Erased state

“1” state

“0” state

Programmed state

\( V_{th-0} \) \hspace{2cm} \( V_{th-1} \)

\( V_{gs} \)

\( I_d \)
More Bits Per Transistor

Each read / (in-place) write takes 5~35 ms

- Read physical page
  - (chip #, block #, page #)
  - 20 ~ 80 us
- Write physical page
  - (chip #, block #, page #)
  - 200~800 us
- Erase block
  - (chip#, block #)
  - 2~3 ms
NAND Flash Memory Characteristics

The Good
- Low latency
- Low power consumption
- High shock/vibration resistant
- Small form factor
- Massive parallelism

FROM THE DARK NIGHT
# NAND Flash Memory Market Trends

<table>
<thead>
<tr>
<th>Year</th>
<th>DRAM</th>
<th>NAND Flash</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>$0.97</td>
<td>$1.35</td>
</tr>
<tr>
<td>2001</td>
<td>0.22</td>
<td>0.43</td>
</tr>
<tr>
<td>2002</td>
<td>0.22</td>
<td>0.25</td>
</tr>
<tr>
<td>2003</td>
<td>0.17</td>
<td>0.21</td>
</tr>
<tr>
<td>2004</td>
<td>0.17</td>
<td>0.10</td>
</tr>
<tr>
<td>2005</td>
<td>0.11</td>
<td>0.05</td>
</tr>
<tr>
<td>2006</td>
<td>0.096</td>
<td>0.021</td>
</tr>
<tr>
<td>2007</td>
<td>0.057</td>
<td>0.012</td>
</tr>
<tr>
<td>2008</td>
<td>~0.025</td>
<td>&lt;0.005</td>
</tr>
</tbody>
</table>

**CAGR**

-32.1% / yr  
-50.0% / yr

Source: Lane Mason (Denali Software), “NAND FlashPoint Platform”
# NAND Flash Memory Market Trends

<table>
<thead>
<tr>
<th>Years</th>
<th>Millions GB</th>
<th>DRAM</th>
<th>NAND Flash</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>30</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>50</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>71</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>98</td>
<td>14.6</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>158</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>240</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>340</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>645</td>
<td>1600</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>1000</td>
<td>4000</td>
<td></td>
</tr>
</tbody>
</table>

**CAGR**  

+60.0% / yr  
+150% / yr

*Source: Lane Mason (Denali Software), “NAND FlashPoint Platform”*
Outline

- Flash Memory Basics
- Our 10-year Research and Technology Transfer
- Lessons Learned
- Conclusions
Our 10-year Research on Flash Memory

2000년
SSFTL (For Commercial CF cards) (2000. 05 ~ 2002.01)

2002년
SSFTL - Seoul
SSFTL - Hong Kong
SSFTL - Vancouver

2004년
USB 2.0-based SSD (Flash-only) (2004. 06)

2005년
Hybrid HDD

Chameleon SSD (Flash/FRAM Hybrid) (2005.12)

2006년
Hydra SSD (Flash-only) (2006.02)

Hydra FPGA version Technology Transfer
Hydra ASIC version Technology Transfer

2011년
Hydra SSD Platform

NV-RAM Modules

- Hynix MLC NAND
- Samsung SLC NAND
- Samsung MLC NAND
- RAMTRON FRAM (serial)
- RAMTRON FRAM (parallel)
- FREESCALE MRAM (parallel)
Performance Results

- PC Mark 05 Results

<table>
<thead>
<tr>
<th>Drive Type</th>
<th>PC Mark 05 HDD Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seagate 2.5 in HDD</td>
<td>3431</td>
</tr>
<tr>
<td>Seagate 3.5 in HDD</td>
<td>5169</td>
</tr>
<tr>
<td>Adtron 3.5 in SSD</td>
<td>2255</td>
</tr>
<tr>
<td>M-Systems 2.5 in SSD</td>
<td>4494</td>
</tr>
<tr>
<td>Samsung 2.5 in SSD</td>
<td>6080</td>
</tr>
<tr>
<td>Hydra SSD</td>
<td>11045</td>
</tr>
</tbody>
</table>


Technology Transfer

Oct. 30, 2007, NotebookReview.com

“… In fact, it may well be the single fastest storage medium available to the customer today.…”
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NAND Flash Memory Characteristics

The Good
- Low latency
- Low power consumption
- Small form factor
- Massive parallelism

The Bad
- Power failures
- Bad blocks (Program/Erase Errors)
- Program disturbance
- Read disturbance

FROM THE DARK NIGHT
On A Fine Spring Day in 2007

Dear professor Min,

I want to ask some help for the recovery of the data on a Samsung CompactFlash card.

The defunct card is a 256MB CompactFlash module with a S3F49FAX controller and four 64x8-Mbit K9F1208U0M modules. I was able to remove the irresponsible S3F49FAX controller and read out the flash ICs directly (using a Virtex-II pro board and self-written VHDL code).
Tragic Remains
Around That Time…

http://en.wikipedia.org/wiki/Edison_Chen_photo_scandal
A Few of Recovered Photos
Dear professor Sang Lyul Min,
Dear Mr JiHyuck Yun,

You have helped me with the part of the recovery process of my pictures that was unattainable for me but achievable for you. Analogous to this I thought it would be appropriate to thank you with something that is regular for me but probably exclusive for you: authentic Belgian chocolates! They are from my favorite local artisan chocolatier. I hope both boxes survived the mail and that you may enjoy them!

Kind regards,

Michiel
Reliability Analysis of NAND Flash Memory-based Storage Device (Ideal)

Users

Power failure
Flash operation failure

cumulative failure ratio

cumulative failure ratio

system failure

system failure

1day 1month 1year 10years ...

cumulative distribution

cumulative failure ratio

time

cumulative distribution

time
Reliability Analysis of NAND Flash Memory-based Storage Device (Practical)

Emulated users

- Power failure
- Flash operation failure

Cumulative failure ratio

Physical time
Virtual time

Cumulative distribution
Failure Analysis

Reliability assessment

Fail state diagnostics

Debugging

Regression test
Post-mortem Analysis of Customer Returns

Causal relationship between bugs and symptoms

Failure instances in real world

Post-mortem analysis
Two Key Findings

- “Many” customer returns (cellular phones) are due to bugs in flash memory management software
- “Most” bugs in flash memory management software are due to inadequate/incorrect handling of nested power failures and flash memory errors
NAND Flash Memory Characteristics

The Good
- Low latency
- Low power consumption
- High Reliability
- Small form factor
- Massive parallelism

The Bad
- Power failures
- Bad blocks
  (Program/Erase Errors)
- Program disturbance
- Read disturbance

The Ugly
- Limited Endurance
- Retention errors
The State of Affairs – Flash Memory

Scanning tunneling microscope image of a silicon surface showing 10 nm is ~20 atoms across

A “Deadly” Combination

Outline

- Flash Memory Basics
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- Conclusions
Conclusions (Call for Actions)

- “Provably-Correct” Flash Memory Software
  - Bad Block Management Scheme
  - Crash Recovery Scheme
  - etc
- “Open” Reliability Evaluation Platform
  - High-fidelity Flash Memory Modeling
  - Configurable Fault Injection
- Prepare for the future “when everything fails”