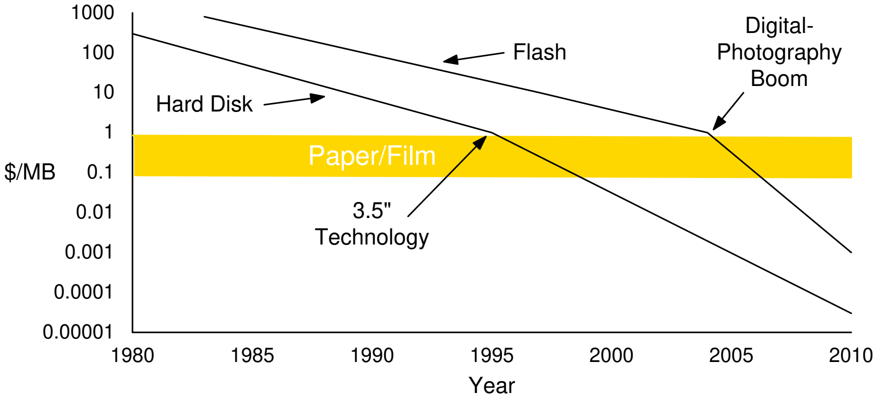
CS 137: File Systems

Persistent Solid-State Storage

Technology Change is Here

- Disks are cheaper than any solid-state memory
- Likely to be true for many years
- But SSDs are now *cheap enough* for some purposes



ROM

- *ROM* (Read-Only Memory) chips were programmed in the factory
  - Array of transistors
  - Trivial to leave out a wire to make one “defective”
  - Result was array of ones and zeros
- Most of chip predesigned; only one mask layer changed
- Still fairly expensive for that mask
- Ultra-low cost in large volumes

PROM

- PROM (Programmable ROM) is field-programmable
  - Array of fuses (literally!)
  - Blow a fuse to generate a zero
  - Special high-voltage circuitry to select fuse
- Much more expensive per chip than ROM
- But low startup cost made cheaper in low volumes
- One-time use meant lots of chips thrown away

EPROM

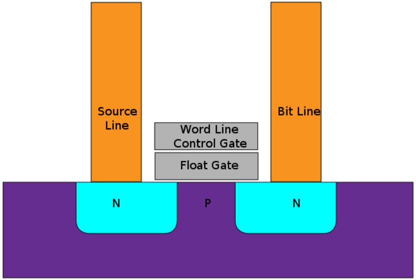
- EPROM (Erasable PROM) used floating-gate technology
  - Direct predecessor to flash
  - Electrons in floating gate (see later slide) store data
  - UV light used to drive out electrons and erase
- 15 minutes to erase
- Expensive, but reusability reduced effective cost

All images from Wikipedia

EEPROM

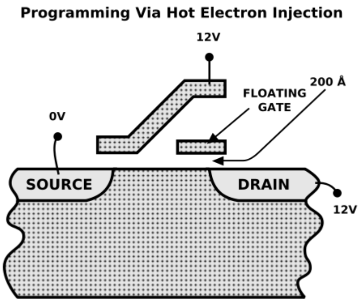
- EEPROM (Electrically Erasable PROM) used thinner oxide layer
- Introduced ca. 1983
- High voltage could erase without UV
- Basically flash memory where entire chip erased at once

The Flash Cell



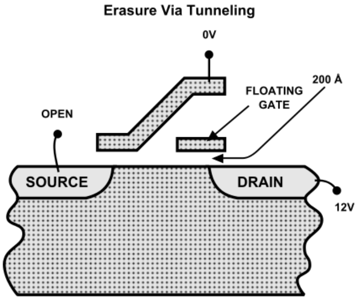
- Source line provides voltage, bit line senses
- Current flows between “N” regions, through “P”
- Voltage on control gate restricts current flow in “P”
- Charge on floating gate “screens” control gate
  - Allows sensing whether charge is present

Programming NOR Flash



- Default state is 1 (current can flow)
- Apply high voltage to control gate
- Run current through channel
- “Hot” electrons jump through insulation to floating gate

Erasing NOR Flash



- Apply reverse voltage to control gate
- Disconnect source
- Electrons will now tunnel off floating gate into drain

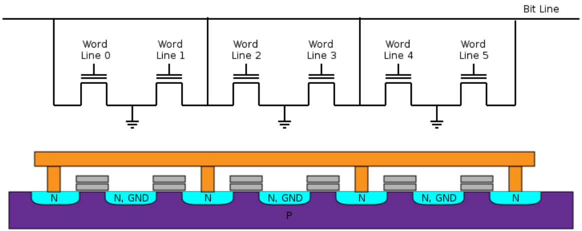
Wear-Out

- Some electrons get stuck in oxide during programming
- Add to electric field from floating gate (even if no charge present)
- Eventually becomes impossible to erase effectively

Multilevel Cells (MLC)

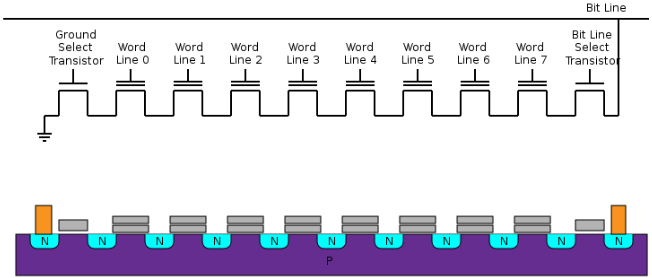
- Classic flash stores charge or not: zero or one
- Possible to store different charge quantities
  - Sense varying current levels
  - Can translate back into multiple bits
  - Current limit is sixteen levels $\equiv$ four bits
- Obvious density improvement as number of levels rises
- Slower to read and write
- Poorer reliability
- Modern chips often combine single-level cells (SLC) for speed with MLC/TLC/QLC for density

NOR Flash



- All bit lines tied together
- Readout voltage placed on exactly one word line
- If “0” stored, nobody conducts
- If “1” stored, bit line is connected to ground
  - Works like NOR of word lines

NAND Flash



- Extra-high voltage placed on all but one word line
  - All will conduct
- Remaining line gets “just barely” voltage
  - If programmed, will conduct
- Lower number of bit & ground lines means better density
- Programming via tunnel injection, erase via tunnel release

Comparison of NOR and NAND

NOR flash:

- Lower density
- Usually wired for true random read access
- Wired to allow writing individual cells
- Erase in blocks of 64-256 KB

NAND flash:

- Cells take about 60% of NOR space
- More space saved by block-read wiring
- Writing (“programming”) is in page-sized chunks of 0.5-4 KB
- Erase in blocks of 16-512 kB
- Extra bits (more individually accessible) to provide ECC and per-page metadata
- OK to have bad blocks

A Sample NAND Chip

Samsung K9F8G08U0M (1G$\times$8)

- Each page is 4K bytes + 128 extra
- One block is 64 pages
- Entire device is 8448 Mbits
- 5-cycle access: CAS1, CAS2, RAS1, RAS2, RAS3
  - Eight address bits per cycle
  - CAS is 13 bits + 3 for future
  - RAS is 18 + 6 for future
  - Spare bits mean can later put bigger device into same circuit design
- On RAS3, loads 4K + 128 into *Page Register*

Chip Commands

Samsung K9F8G08U0M accepts 16-bit commands, such as:

- Reset
- Read
- Block Erase
- Page Program
- Read Status
- Read for Copy Back
- Copy-Back Program

“Two-plane” commands available for overlapped speedup

Random programming prohibited—but can go back and change metadata

Chip Timing

For Samsung K9F8G08U0M:

- Block erase: 2ms (probably not accurate to μs level)
- Program: 700μs
- Read page to buffer: 25μs
- Read bytes: 25ns per byte

Bottom line:

- $25\mu s + 4096 \times .025 = 25 + 102.4 = 127.4\mu s$ to read a page
  = 32.15 MB/s data rate
- $102.4\mu s + 700 = 802.4\mu s$ to write page if already erased
  - Otherwise extra 31.25μs (amortized) to erase
  - Writing is $\approx 6.3 - 6.5\times$ slower than reading

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BUT 2ms latency if nothing currently erased.

Comparison to Disk Timing

For 3-TB Seagate Barracuda XT (3.5-inch):

- Average latency: 4.16 ms (7200 RPM)
- Average seek time: 8.5 ms (read), 9.5 ms (write)

$\Rightarrow$ 12.66 ms to read one random page

- Sustained transfer rate: 149 MB/s = 27.5μs per 4K bytes

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- 99.4$\times$ slower!
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- Sequential writes are $\approx$ 30$\times$ faster

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- Sequential writes are $\approx$ 30$\times$ faster
- **But** can wire flash chips in parallel to increase bandwidth

Issues in Using Flash for Storage

- Pre-erasing blocks
- Wear leveling
- Clustering blocks for group writing
- Efficient updates
- ECC and bad-block mapping

Issues in Simulating a Disk

- Can't tell what pages are live
- Expected to allow random updates
- Some blocks (e.g., FAT, inode table) much hotter than others

General Solution: Flash Translation Layer

- All flash "drives" have embedded μprocessor (usually 8051 series)
- Give block-numbered interface to outside world
- Hold back some memory (e.g., 6GB drive pretends to be 4GB)
- Map externally visible blocks to internal physical ones
- Use metadata to track what's live, bad, etc.

Problems in FTLs

- Wear leveling (what if most blocks are read-only?)
  - Solution: must sometimes move RO data
- File system wants to rewrite randomly
  - Solution: group newly written blocks together regardless of logical address
  - Called "Log-Structured File System" (LFS)
    - (We'll read that paper later. . .)
- Unused block might or might not be live
  - Solution: only reclaim block when overwritten
  - Solution: know that it's FAT and reverse-engineer data as it's written
  - Modern solution: TRIM command to SSD
    - Misnamed
    - Also supported by some non-SSD devices
    - Issued by most file systems

A Better Way

- Pretending to be a disk is just plain dumb
- When disks came out, we didn’t make them look like punched cards
  - Well. . . mostly
- If filesystem designed for flash, don’t need FTL
  - Problem: need entirely new interface
  - Apple has done it in MacBook Air (advantage of making both hardware and software)
  - Now standardized as Open-Channel
  - Supported in Linux 4.x+ kernels
- Some filesystems designed just for flash: YAFFS, JFFS2, TrueFFS, etc.

The Bad News

- Feature-size limit is around 20 nm
- We're hitting that just about now!
- Some density improvement from MLC and 3-D stacking
- This limit might kill flash as a disk replacement

Other Options

Flash isn't the only choice:

- Phase-change memory (PRAM or PCRAM)—now available from Intel?
- Magnetic RAM (MRAM)
- ???

New technologies offer:

- Read/write times slightly slower than DRAM
- Slower (or no) wear-out
- Longer storage life without refresh
- Byte addressability
  - What happens when filesystems are just like memory?
  - Current active research area