Survey of Next-Generation Storage

Tyler Bletsch
Duke University
Lots of possible avenues...

- Wikipedia “list of emerging technologies” for storage:

<table>
<thead>
<tr>
<th>Emerging technology</th>
<th>Status</th>
<th>Potentially marginalized technologies</th>
<th>Related articles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emerging memory technologies</td>
<td>In development</td>
<td>Current memory technologies</td>
<td>T-RAM, memristor, Z-RAM, TTRAM, CBRAM, SONOS, RRAM, Racetrack memory, NRAM, Phase-change memory, FJG RAM, Millipede memory, Skyrmion, Programmable metallization cell, 3D XPoint, Ferroelectric RAM, Magnetoresistive random-access memory, nvSRAM</td>
</tr>
<tr>
<td>Emerging magnetic data storage tech.</td>
<td>In development (HAMR, BPM); diffusion (SMR)</td>
<td></td>
<td>SMR, HAMR, BPM, MAMR, TDMR, CPP/GMR, PMR, Hard disk drive</td>
</tr>
</tbody>
</table>

- That’s a lot of things! Most won’t pan out
- Temper your excitement, remember the hype cycle...
Areas of focus

- Improving HDDs
  - Perpendicular magnetic recording (PMR)
  - Shingled magnetic recording (SMR)
  - Heat-assisted magnetic recording (HAMR)
  - Bit-patterned media (BPM)
  - Just pump a bunch of helium in there
- Improving SSDs
  - 3D NAND structures
- New solid-state memories
  - Phase-change memory (PCM)
  - Ferroelectric RAM (FRAM)
  - Magnetoresistive RAM (MRAM)
  - Resistive RAM (RRAM)
  - Conductive Bridging RAM (CBRAM)
- Memristors: are they a thing?
- Theoretical and proof-of-concept stuff
Improving HDDs
Perpendicular Magnetic Recording (PMR)

Feasible? Yes. Most modern large drives do this.
Shingled magnetic recording (SMR)

- Due to physics reasons, the write head is always bigger than the read head
  - This means that we write a track of X width, but we just read the middle X/2 of it back.
  - Tracks aren’t allowed to overlap, so this leads to waste
- Solution: let them overlap, and deal with resulting destruction

Feasible? Yes. Seagate started shipping in 2013.
Shingled magnetic recording (SMR)

- Dealing with overlap
  - Drive reads neighboring data under threat from a pending write; restores it afterward.
  - If we blindly do that to whole drive, then single write means rewriting whole drive...
  - Solution: Do SMR on track groups.
  - Wow! HDD now like SSD: Small read sectors, big erasure blocks!
  - Lots of cache and optimization opportunities...

Feasible? Yes. Seagate started shipping in 2013.
Seal the HDD and fill with helium

- Reduces mechanical power dissipated in air shear
- Allows platters to be placed closer together enabling more capacity

Feasible? Yes. HGST started shipping in 2013.
Heat-Assisted Magnetic Recording (HAMR)

HAMR: A Whole New Recording System

- Density growth limited by ability to make smaller bits thermally stable
- HAMR combines laser and magnetic field to write the media
- Allows for use of much higher coercivity media and hence enables higher densities

Feasible? Fairly likely. Seagate has prototypes (src). Should be shipping now, but isn’t. Latest news was Feb 2019 (src).
Bit Patterned Media

Granular Media versus Bit Patterned Media

- Extend density by replacing randomly sputtered grains with very uniform, lithographically-defined magnetic islands
- The challenge for bit patterned media is how to fabricate these very small islands precisely and cost-effectively
- Feature sizes will need to be smaller than semiconductor

Have already demonstrated all the steps necessary for 13nm half pitch

Feasible? Somewhat likely. HGST has proved the lithography, but there are lots of problems still left (src).
Longer term

A combo of HAMR and bit-patterned media.
Improving SSDs
• Current SSD/flash design: NAND gates laid out in 2D

• Novel idea: Make it 3D. Lots of ways to do this...

Feasible? Yes. Intel/Micron have chips shipping. (src)
3D NAND structures

• Lots of ways to do this...

From “3D NAND Approaches”, IMW 2011. Figure from here.

Feasible? Yes. Intel/Micron have chips shipping. (src)
New solid state memories
Phase-change memory (PCM)

- Fundamental enabler: Chalcogenide glass
  - A glass compound with sulfur, selenium, or other additive
  - Rate of heating/cooling can produce amorphous or crystalline structure
  - Two structures behave very differently optically and electrically
- This is what makes re-writable CD/DVDs possible
- To “write”:
  - Melt with brief, hot pulse of heat; rapid cooling gives amorphous state
  - Melt with long, low-intensity heat; slow cooling gives crystalline state
- To “read”:
  - Crystalline is low resistance, amorphous is high resistance
  - Measure resistance with circuit, decide which one means “1”

Feasible? Technically, yes; economically, maybe...
Phase-change memory (PCM)

- Array these elements in a grid like any other RAM
- Use electricity to heat cells (write) and to determine their resistance (read)

Feasible? Technically, yes; economically, maybe.

- Shipping memory chips available from many vendors
- Large-scale adoption hasn’t happened; flash still wins for most use cases when you factor in cost
- Roller-coaster development history:
  - In 2012, Micron announced PCM for mobile devices (src)
  - In 2014, flash had gotten better (e.g. 3D NAND), and Micron ditched PCM! (src)
  - In 2015, PCM appeared dead, but then Western Digital showed a PCM prototype with 3 million IOPS (src)
  - Intel/Micron’s “3D Xpoint memory” is a PCM released in 2016 (src)
  - Nothing since…

“A cross-section of two PRAM memory cells. One cell is in low resistance crystalline state, the other in high resistance amorphous state.”

From Wikipedia, “Phase-change memory”
Ferroelectric RAM (FRAM)

- Like DRAM, but uses a “ferroelectric” layer instead of the DRAM capacitors’ dielectric.
- Ferroelectric material: Material that has an electric polarization which can be flipped
  - Material consists of polarized molecules (one side positive, other side negative)
  - If you flip one molecule, attraction/repulsion resets it
    - Stable, self-correcting
  - Apply enough voltage, flip all molecules
    - Settable!

Feasible? Technically, yes; economically, maybe.
- Shipping memory chips available from vendors
- Large-scale adoption hasn’t happened; seems unlikely under current trends
- Density isn’t great (130nm), but lower power than flash
- Current niche: storage for very-low-power embedded systems

From Wikipedia, “Ferroelectric capacitor”
Magnetoresistive RAM (MRAM)

- Uses a “ferromagnetic” material
  - Metal that can change magnetic field to match an external field (e.g., normal iron)
- Exploits “tunnel magnetoresistance”
  - Due to wacky probabilistic quantum physics, an electron in the top layer can “tunnel” (randomly transposition to) the bottom layer
  - If both magnets have same polarity, this tunneling is much more likely (src)
  - Macroscopic effect: resistance is lower
- Can flip magnetic polarity with electrically-created field (write), determine polarity by measuring resistance (read)

Feasible? Technically, yes; economically, maybe.

- Only one shipping commercial part (a 4Mbit chip from Everspin)
- Large-scale adoption hasn’t happened; seems uncertain
- Density is lousy (180nm), but great performance and lower power than FRAM
- Current niche: storage for very-low-power embedded systems
- A start-up has announced a microcontroller that includes MRAM (src)
- Other companies are developing MRAM manufacturing capacity (src)
• Conductive bridging RAM (CBRAM): Electrochemical reaction changes resistivity of cells.
  • Development startup Adesto holds the intellectual property, limited products have been realized. **One company wants to use it in space.**

  Feasible? **Technically, yes; economically, unlikely?**

• Resistive RAM (RRAM): Create/fill electron “vacancies” in a thin oxide layer; changes resistivity of cells.
  • Various small commercial chips exist in the kB range. Adesto’s here too.

  Feasible? **Technically, yes; economically, unlikely?**

• “Millipede memory”: Create and fill microscopic holes in a thin polymer.
  • In 2005, IBM was aiming to have this out within 2 years, but other forms of storage advanced faster and wrecked it

  Feasible? **Technically, ???; economically, dead.**
Memristors: are they a thing?

- Memristor: A theoretical circuit element that changes resistance based on past current
  - Existence was proposed by taxonomy in 1971: “If we have components that relate charge, voltage, current, and magnetic flux, shouldn’t this thingy exist”? (src)

- By 2011 we didn’t a good one, but we liked the name, so it changed to: “Any 2-terminal thing that changes resistance” (src)
Memristors: are they a thing?

- Problem: We just changed the definition so that it matches most of the proposed non-volatile RAMs we’ve discussed!
- Result: LOTS OF CONFUSION.
  - Technology press: “Memristors are the next big thing!”
  - Actual semiconductor engineers working on this: “wtf are you talking about?”
- My opinion: “memristor” isn’t a useful concept. Either:
  - It doesn’t exist (original definition), or
  - It is achieved through a dozen different unrelated physical processes (new definition).
- The following shows that it’s not a real thing:

Nothing but a few journals; no actual components to buy!
Speculative future stuff

AKA “A list of things that almost never pan out, except when they do”
Cold data storage in glass

• “Project Silica”:
  • Use Lasik-eye-surgery style lasers to etch shapes into glass
  • Used to store “cold data” (e.g. movie prints)
  • 75GB in one 75mm square disc

• Experimental stages as of 2019

• Sponsored by Microsoft Research and Warner Bros Studios
Other “3D” or “Holographic” optical storage

- Various attempts to store data in depth of optical media
- Focus is often cold data archival (like Project Silica)
- Not much news since 2010…

Feasible? Technically, yes; economically, looking less likely...
Theoretical and proof-of-concept stuff

- Spintronics: Trying to do stuff with the quantum “spin” of electrons

- “Nano-RAM”: Storing data based on position of carbon nanotubes on a chip substrate

- Skyrmion: A hypothetical quantum particle related to magnetism
  - This is a literal sentence used to describe these:
    “A two-dimensional magnetic skyrmion, as a topological object, is formed, e.g., from a 3D effective-spin "hedgehog" (in the field of micromagnetics: out of a so-called "Bloch point" singularity of homotopy degree +1) by a stereographic projection, whereby the positive north-pole spin is mapped onto a far-off edge circle of a 2D-disk, while the negative south-pole spin is mapped onto the center of the disk.”
  - If that makes sense to you, invest in Skyrmion companies I guess?

Any of these feasible? WHO KNOWS??
Theoretical and proof-of-concept stuff

• DNA: Yeah, we’ll just encode data in DNA!
  • Ignore the fact that existing life doesn’t do arbitrary write operations on DNA (cells copy, viruses splice, meiosis mixes, and epigenetics alters attached methyl groups, but **nothing** makes arbitrary in-place changes)
  • Ignore that every aspect of DNA’s evolution has been focused on protein synthesis, not specific “reads” of DNA locations
  • Ignore that even the fastest and most common IO pattern for DNA, copying during mitosis, takes on the order of hours, giving a data rate of around 60 kBps (similar to a dial-up modem)
  • No, DNA is the definitely the perfect way to store my pirated movies

Feasible? **LOL**