CROW: A Low-Cost Substrate for Improving DRAM Performance, Energy Efficiency, and Reliability

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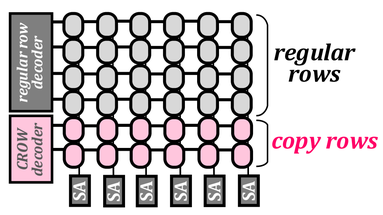
1: Summary

Challenges of DRAM scaling:

- **High access latency** → bottleneck for improving system performance/energy
- **Refresh overhead** → reduces performance and consume high energy
- **Exposure to vulnerabilities** (e.g., RowHammer)

Copy-Row DRAM (CROW)

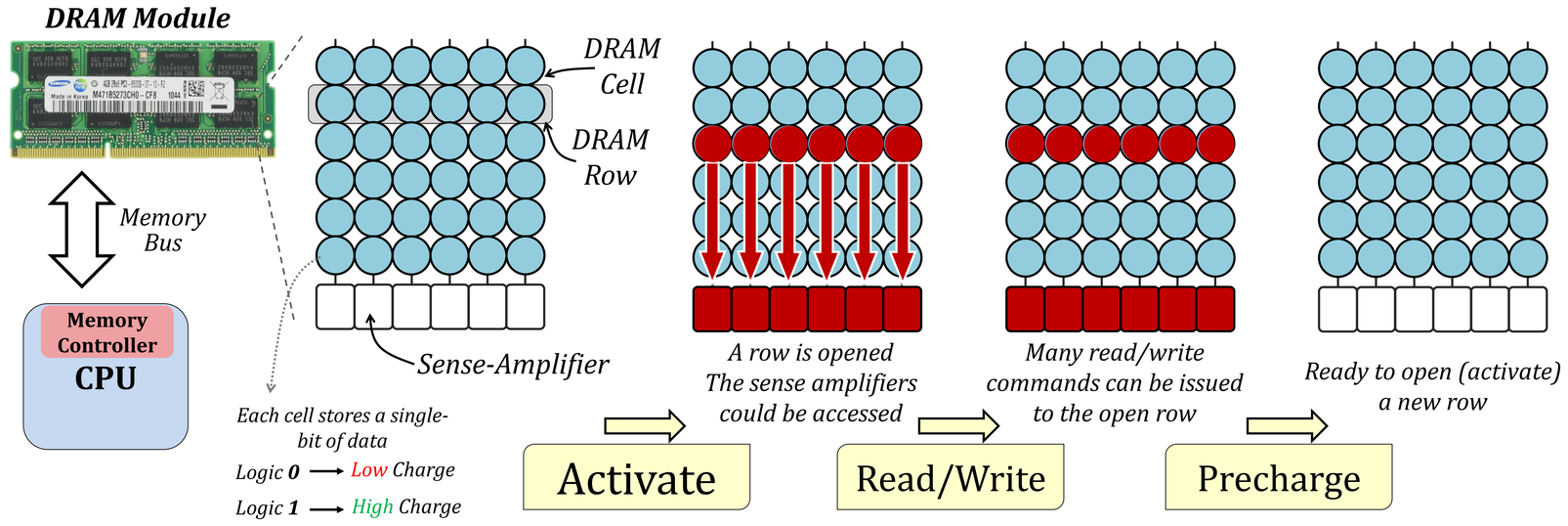
- Introduces copy rows into a subarray
- The benefits of a copy row:
  - Efficiently duplicating data from regular row to a copy row
  - Quick access to a duplicated row
  - Remapping a regular row to a copy row



Use cases:

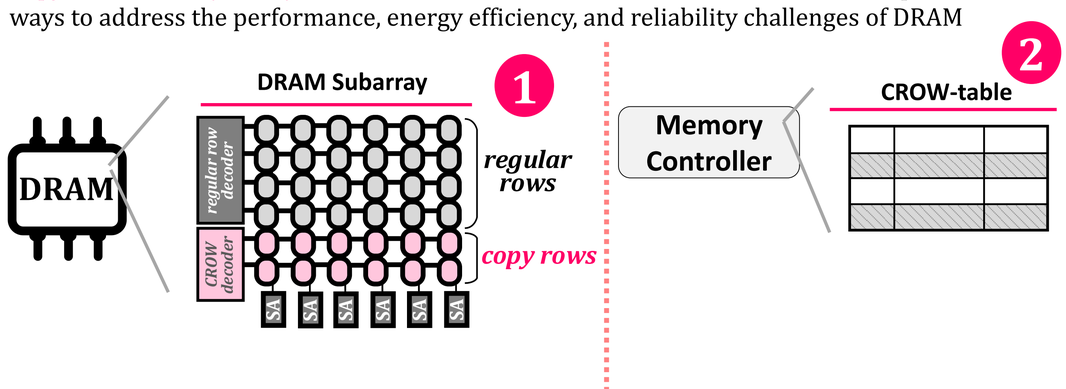
- CROW-cache & CROW-ref **(20% speedup and 22% less DRAM energy)**
- Mitigating RowHammer
- We hope CROW enables many other use cases going forward

2: DRAM Operation Basics



3: The Components of CROW

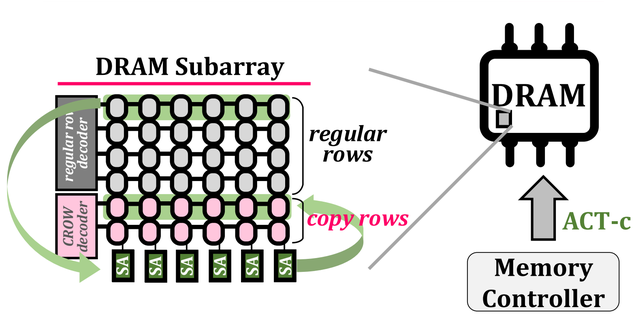
Copy-Row DRAM (CROW): a flexible in-DRAM substrate that can be used in multiple different ways to address the performance, energy efficiency, and reliability challenges of DRAM



4: CROW Operations

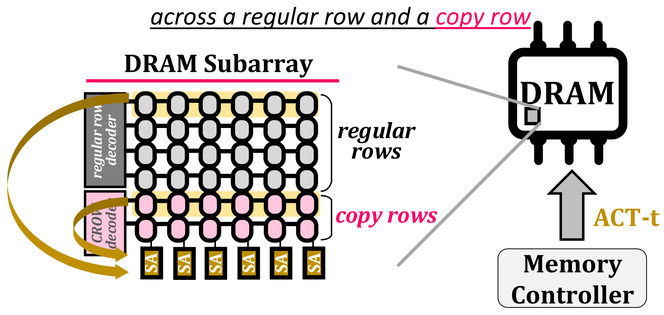
Row Copy

Enables quickly copying a regular row into a copy row



Two-Row Activation

Enables fast access to data that is duplicated across a regular row and a copy row



5: CROW-cache

Problem: High access latency

Key idea: Use copy rows to enable low-latency access to most-recently-activated regular rows in a subarray

CROW-cache combines:

- row copy → copy a newly activated regular row to a copy row
- Two-row activation → activate the regular row and copy row together on next access

Reduces activation latency by **38%**

6: CROW-ref

Problem: Refresh has high overheads. Weak rows lead to high refresh rate

- **weak row:** at least one of the row's cells cannot retain data correctly when refresh interval is increased

Key idea: Avoid storing data in a weak regular row by remapping it to a strong copy row

CROW-ref uses:

- row copy → copy a weak regular row to a strong copy row

CROW-ref **eliminates more than half of the refresh** requests

7: Mitigating RowHammer

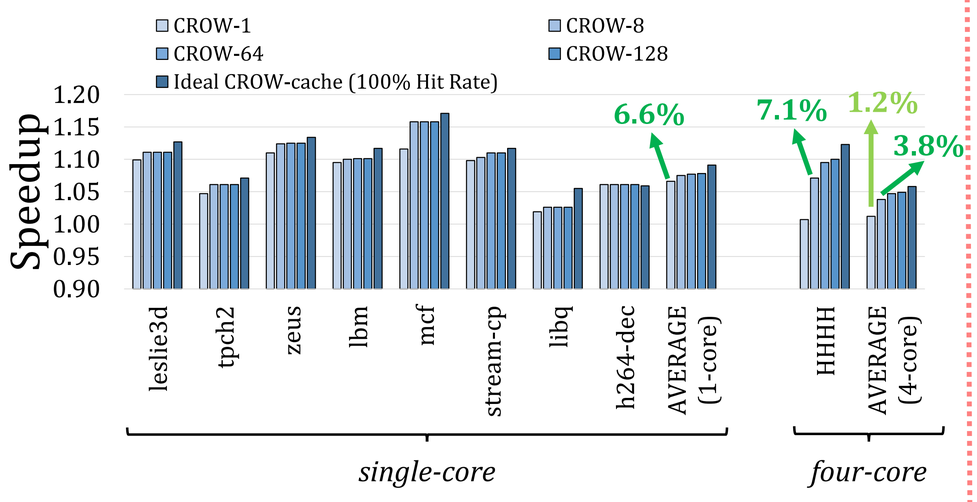
Key idea: remap victim rows to copy rows

8: Evaluation

Methodology

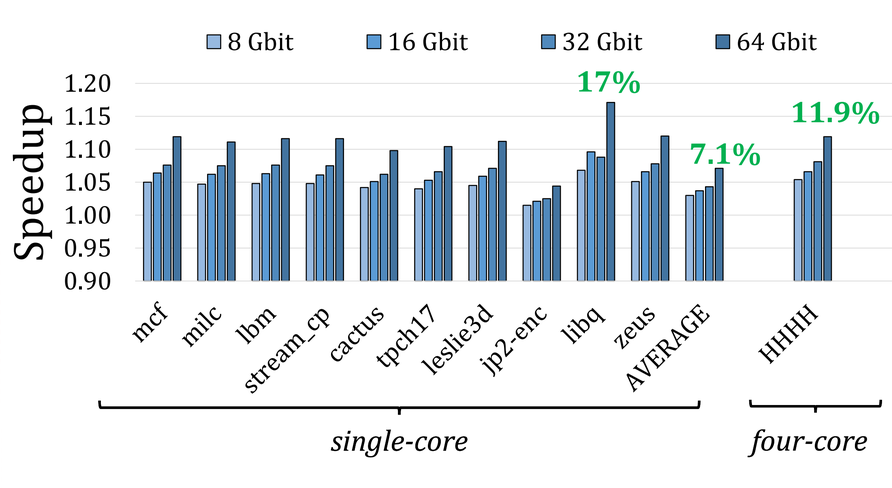
- **Simulator**
  - DRAM Simulator (Ramulator *[Kim+, CAL'15]*)
    https://github.com/CMU-SAFARI/ramulator
- **Workloads**
  - 44 single-core workloads
    - *SPEC CPU2006, TPC, STREAM, MediaBench*
  - 160 multi-programmed four-core workloads
    - *By randomly choosing from single-core workloads*
  - Execute at least 200 million representative instructions per core
- **System Parameters**
  - 1/4 core system with 8 MiB LLC
  - LPDDR4 main memory
  - 8 copy rows per 512-row subarray

CROW-cache Performance



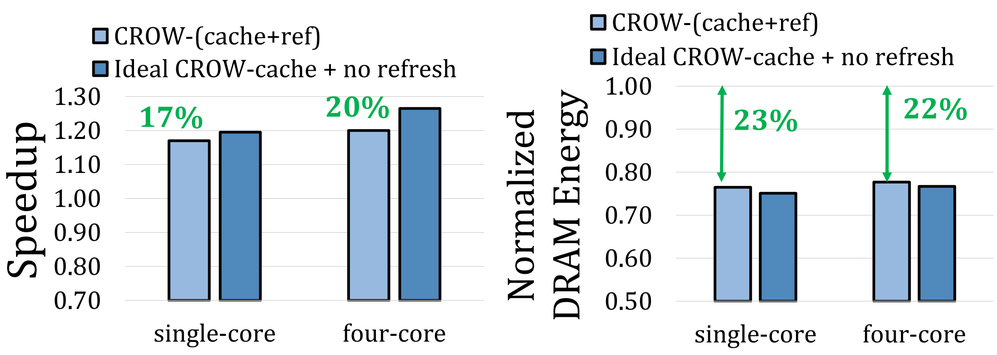
CROW-cache **improves** single-/four-core system **performance**

CROW-ref Performance



CROW-ref significantly reduces the performance overhead of DRAM refresh

Combining CROW-cache and CROW-ref



CROW-(cache+ref) provides more performance and DRAM energy benefits than each mechanism alone

Hardware Overhead

For 8 copy rows:

- 0.5% DRAM chip area
- 1.6% DRAM capacity
- 11.3 KiB memory controller storage

Other Results in the Paper

- Sensitivity to:
  - Number of copy-rows per subarray
  - Chip density
  - Last-level cache capacity
- CROW-cache with prefetching
- CROW-cache against other in-DRAM caching mechanisms:
  - TL-DRAM *[Lee+, HPCA'13]*
  - SALP *[Kim+, ISCA'12]*

Available in July:

github.com/CMU-SAFARI/CROW

SAFARI